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COVER IMAGE

The temple of Apollo at Delphi was the seat of one of the most influential oracles in the Hellenistic World. Its orientation is puzzling, but may be related to the heliacal rising of Vega (α Lyr) and its appearance above the Faidriades in December, which coincided with Apollo's departure for Hyperborea. How this might be related to seasonal variations in the emission of hallucinogenic gas, and other annual astronomical events, is described by Ioannis Liritzis and Belén Castro in their paper starting on page 184.

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HIGHLIGHTING THE HISTORY OF JAPANESE RADIO ASTRONOMY. 2: KOICHI SHIMODA AND THE 1948 SOLAR ECLIPSE

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Abstract: Just two years after Dicke carried out the first radio observations of a solar eclipse, a young Japanese physics graduate, Koichi Shimoda, attempted to observe 3,000 MHz emission during the 9 May 1948 partial solar eclipse. In so doing he unwittingly became the 'founding father' of Japanese radio astronomy. In this paper as our mark of respect for him, we list Shimoda as the lead author of the paper so that his observations can finally be placed on record for the international radio astronomical community.

Keywords: Japan, radio astronomy, solar eclipses, Koichi Shimoda.

1 INTRODUCTION

The early history of Japanese radio astronomy has recently been reviewed by Ishiguro and Orchiston (2013) and Ishiguro et al. (2012), updating the account provided by Tanaka (1984). In the above-mentioned papers Ishiguro and Orchiston and their collaborators mention in passing Koichi Shimoda's pioneering observations of a solar eclipse in 1948. This was the first radio astronomical experiment conducted in Japan, and as such Shimoda must be recognised as the 'founding father' of Japanese radio astronomy. In this short paper we provide details of Shimoda's instrumentation and observations, and place his pioneering experiment in an international context.[1] Japanese locations mentioned in the text are shown in Figure 1.

Figure 1: Japanese localities mentioned in the text. Key: 1 = Hiraiso, 2 = University of Tokyo, 3 = Tokyo Astronomical Observatory (Mitaka), 4 = Toyokawa Observatory, 5 = Nagoya University; and 6 = Osaka City University.

2 SOLAR ECLIPSES AND EARLY RADIO ASTRONOMY

In the years immediately following WWII the angular resolution of radio telescopes was poor, and observations of total and partial solar eclipses offered a particularly elegant way of pinning down the positions of the localised radio-emitting regions. The logic behind this was that as the Moon's limb moved across the Sun's disk during the eclipse and successively occulted and then unmasked different radio-emitting regions there would be associated dips and rises in the chart record. Ideally, more than one observing site was desirable as any dip in the chart record obtained at a single site would only indicate that the emitting region was located *somewhere* along the arc subtended by the lunar limb *at that particular moment*. However, if there were several widely-spaced observing site the intersections of the different limb profiles allowed the positions of the radio-emitting regions to be identified with considerable accuracy (e.g. see Christiansen et al., 1949a).

In addition, radio astronomers could use observations of solar eclipses to determine the distribution of radio brightness across the disk of the Sun, and the shape of the corona at radio wavelengths (see Castelli and Aarons, 1995).

The American scientists, Robert H. Dicke (1916–1997) and E. Robert Beringer (1917–

2000) and Britain's Kenneth F. Sander were the first to use this technique in radio astronomy when they carried out observations of a partial solar eclipse on 9 July 1945 (see Dicke and Beringer, 1946; Sander, 1947).

3 KOICHI SHIMODA AND THE SOLAR ECLIPSE OF 1948

Early in the northern spring of 1948 Koichi Shimoda (b. 1920; see Figure 2) had just begun working at the Institute of Science and Technology on the Komaba Campus of the University of Tokyo. The Institute had been founded the year before to replace the Aeronautical Research Institute, and upon searching through the 'scraps' left over from this earlier institute Shimoda discovered a parabolic reflector:

> The surface of the reflector was made of copper plates mounted on a hardwood frame. The shape of the paraboloid was precise to within a few millimetres with a focal length of about 73 cm.
>
> I was much delighted with this reflector, because it had the quality comparable to, orbetter than the best radar antenna for 10 cm waves. Moreover, the size of 2 m in diameter and 35 cm in depth was just [what] I wanted. (Shimoda, 1982: 32).

From his childhood Shimoda had an interest in astronomy and liked to visit the Tokyo Astronomical Observatory (TAO). As a high school student he had observed a solar eclipse with a small telescope, so when he read in a newspaper about a partial solar eclipse on 9 May 1948 that would be visible from Japan he also decided to observe it—but this time at radio wavelengths.

During the latter part of WWII Shimoda had worked on the development of microwave radar, and by the cessation of hostilities he was thinking about the ways in which radar could be applied to scientific research. Through various conversations with Professor Hatanaka at the TAO he was aware of Jansky's and Reber's research in the exciting new field of radio astronomy, and then he read Dicke and Beringer's 1946 paper about their observation of the 9 July 1945 partial solar eclipse using a small parabolic antenna and a 24,000 MHz receiver.[2] Shimoda noted that they successfully recorded a considerable decrease in the signal strength in the course of the eclipse (see Figure 3), and he decided to observe the 1948 eclipse, but at 3,000 MHz, where he felt there was more chance of detecting limb-brightening. This was his principal motivation for conducting the 1948 eclipse observations.

With just one month in which to assemble the necessary equipment Shimoda hurried to construct a radio telescope. He began by installing a microwave feed at the focus of the dish, and

Figure 2: Koichi Shimoda as a 26-yr old in 1947, one year before he observed the solar eclipse.

connected this to an ex-WWII Japanese "… 3-GHz radar receiver using a magnetron local oscillator [which] was modified into a rudimentary Dicke-type radiometer." (Shimoda, 1982: 32). In order to complete this simple heterodyne receiver he had to develop a crystal mixer, and the components of this are shown in Figure 4.[3] The signal would be displayed on an oscilloscope. Shimoda then fabricated a simple yet effective mounting to support the antenna.

The path of totality of the eclipse passed over coastal China, the Korean Peninsula, the Sea of Japan and between the northern Japanese island of Hokkaido and neighbouring Sakhalin Island, so from Tokyo it would only be visible as a partial eclipse. There, the eclipse would commence at 10h 05m 51.4s local time, reach a maximum at 11h 33m 46.5s, when 77.3% of the solar disk would be covered, and end at 13h 05m 43.3s. Shimoda's simple radiometer had a half-power beamwidth of about 3° (Shimoda, 1982: 35), so it was necessary to move the antenna manually about every 5 minutes in the course of the 3-hour eclipse to make sure the Sun always remained in the beam.

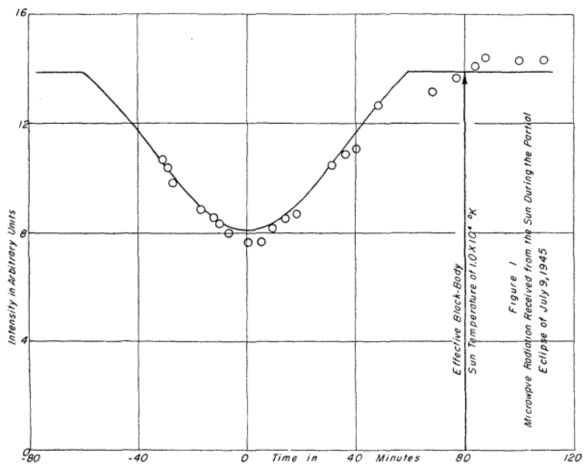

Figure 3: Observations of the 9 July 1945 partial solar eclipse (after Dicke and Beringer, 1946: 376).

Figure 4: Components of the mixer that Shimoda made in 1948 for the 3,000 MHz receiver.

The vital day, 9 May 1948, finally arrived, and Shimoda proceeded to observe the eclipse, recording details of his instrumentation and of the event in a notebook (Figure 5), along with a tracing of the oscilloscope record from the start of the eclipse until just before it ended (he did not have access to a chart recorder). He developed a sawtooth wave generator at ultra low frequency to sweep the oscillator (see Shimoda, 1951). Because he did not make any on-Sun/off-Sun measurements before or after the eclipse Shimoda could not be certain that he actually had detected any solar radio emission.

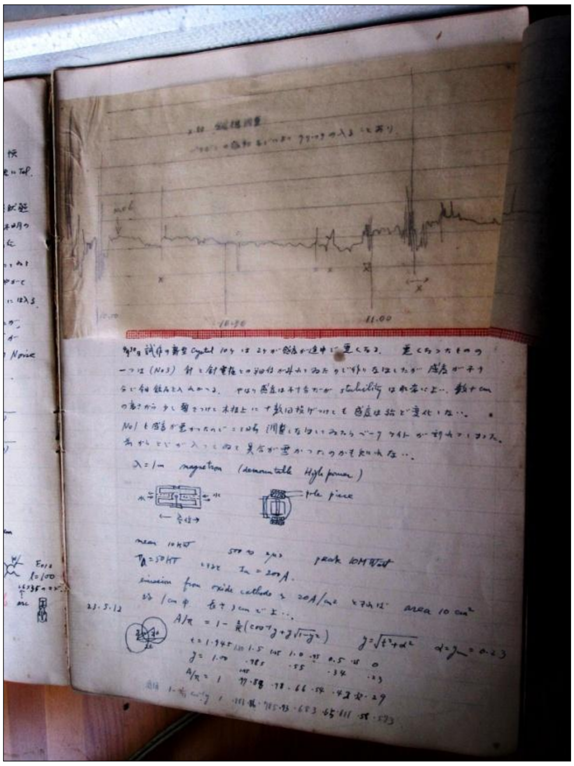

Figure 5: The relevant page of Shimoda's notebook listing details of the radio telescope and the eclipse, plus a tracing of the oscilloscope record.

The oscilloscope display is reproduced here in Figure 6, and it fails to show the anticipated decline in signal strength during the eclipse. As Shimoda (1982: 32-33) was quick to point out:

> Because of the poor sensitivity and stability of the receiver, a decrease in received power can barely be recognized. The background noise and external disturbance prevented me from revealing any fine structures.

Interference recorded at about 1110 and at 1230 local time is very apparent, while the large variations in the signal strength between about 1050 and 1120 make it very difficult to interpret this section of the record.

Fortuitously, this eclipse occurred exactly one year after the previous solar maximum (Aldrich and Hoover, 1954), and at this time the Sun was still very active, with many sunspot groups present (e.g. see Whitney, 1949). Indeed, the sunspot numbers recorded for the months of April, May and June 1948 (187.6, 170.6 and 170.6, respectively), far exceeded those listed for any other month of 1948 (Aldrich and Hoover, 1954: 166). Normally, when sunspots are abundant there is a greatly-increased likelihood that solar bursts will occur in the course of an eclipse (Hey, 1955), but fortunately these are rare at frequencies as high as 3,000 MHz, where Shimoda's radio telescope was operating. So if his equipment had been sensitive enough, then Shimoda should have been able to detect minor variations in the signal strength when major sunspot groups were masked and unmasked by the Moon's disk in the course of the eclipse.

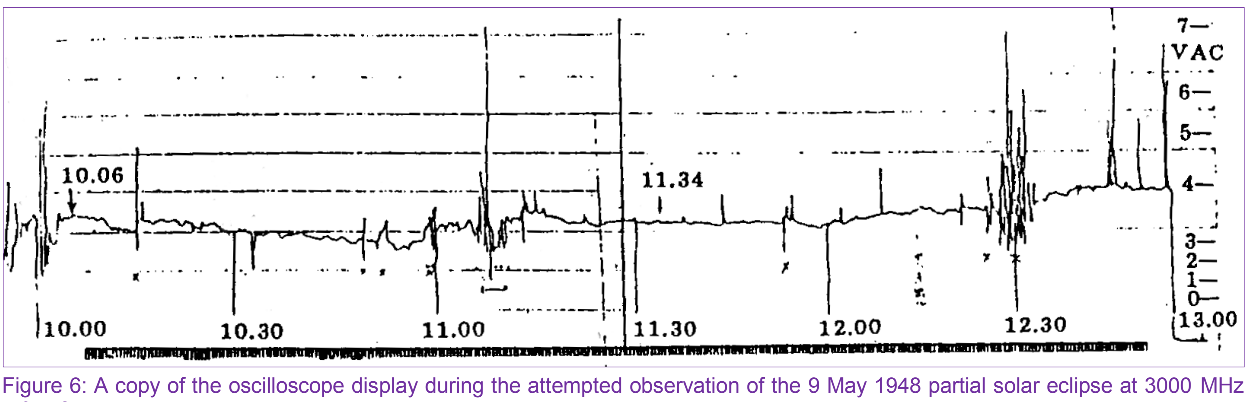

Figure 6: A copy of the oscilloscope display during the attempted observation of the 9 May 1948 partial solar eclipse at 3000 MHz (after Shimoda, 1982: 33).

Because of this rather unsatisfactory outcome, Shimoda chose not to publish his observations. Instead, "The observed result was only orally reported at a meeting and has not been published anywhere." (Shimoda, 1982: 33), and it was only much later, when he realised that this was the first radio astronomical experiment carried out in Japan, that he chose to rectify this by summarising his project during an 'After Dinner Talk' that he presented at the 13th Okazaki Conference in 1982. His account subsequently was published in the record of that meeting (Shimoda, 1982), thus belatedly entering the public domain for the first time

The present paper, for its part, is the first detailed account of Shimoda's experiment, and it is particularly fitting that it is the first of the published case studies in the IAU Early Japanese Radio Astronomy Project, and that as our mark of respect for him, Shimoda can be listed as the lead author of the paper and finally place his observations on record for the international radio astronomical community.

Long after the 1948 eclipse, and only after conducting extensive historical investigations, Shimoda (1982) discovered that his antenna originally was one of two that were manufactured for the Aeronautical Research Institute in 1930 (see Figure 7) and used for experiments in acoustics.

As it turned out, in 1948 Shimoda's little radiometer was merely beginning its 'career' in radio astronomy, even though Shimoda decided to move on to other research projects and had no further use for it. Kenji Akabane from the TAO had a brother who also was a Professor at the University of Tokyo and through him met Shimoda and learnt about the 1948 experiment. By this time TAO had begun regular solar monitoring at low frequencies and Akabane was keen to start observations at much higher frequencies. Shimoda's antenna would be ideal for this, so in 1951 Akabane arranged for it to be transferred to Mitaka. Once there it was remounted (see Figure 8), and for many years was used very effectively by the TAO radio astronomers (as will be detailed by Nakajima et al. in the next paper in this series).

4 DISCUSSION

4.1 Shimoda's Observations in an International Context

Shimoda's interest in solar eclipses during the late 1940s was part of a world-wide trend as radio astronomers from Australia, Canada, England, France, Russia and the USA all sought to use these celestial events to further our understanding of the Sun and its radio emission (see Table 1).[4]

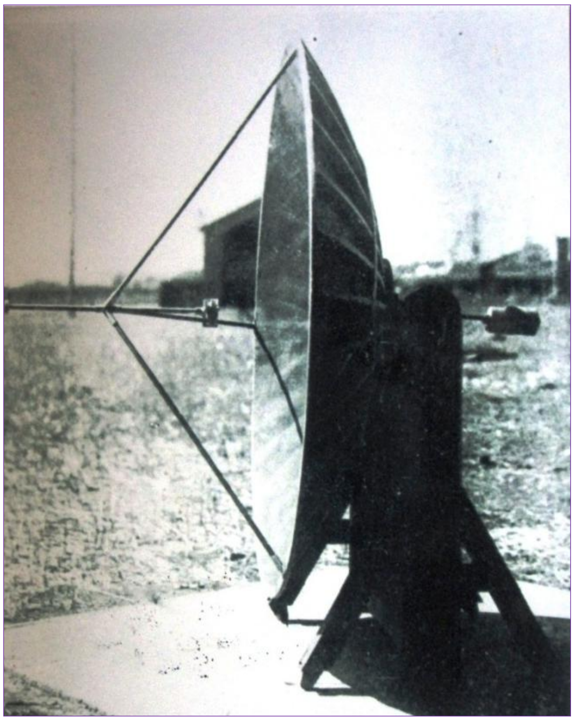

Figure 7: A view of the 2-m parabola at the Aeronautical Research Institute in the 1930s.

By the time Shimoda observed the 1948 eclipse, three earlier solar eclipses had been observed at radio frequencies (see Table 1, and Hey, 1955 and Sullivan, 2009: 290-292 for details), but the breakthrough in the use of solar

Figure 8: The radio telescope at Mitaka, completed by Kenji Akabane, which used Shimoda's original parabolic reflector.

Table 1: Solar eclipses observed at radio frequencies between 1945 and 1952.

1945

• In England, observations of the 9 July partial eclipse at 9,428 MHz using a small parabola (Sander, 1947).[5]
• In the USA, observations of the 9 July partial eclipse at 24,000 MHz using a small parabola (Dicke and Beringer, 1946).

1946

• In Canada, observations of the 23 November partial eclipse at 2,800 MHz using a small parabola (Covington, 1947).
• In the USA, observations of the 23 November partial eclipse at 480 MHz using a small parabola (Reber, 1946).

1947

• Off the coast of Brazil, Russian radio astronomers observed the 20 May total solar eclipse at 200 MHz using a broadside array (Khaykin and Tchikhatchev, 1947).
• At sea in the Atlantic Ocean, an American radio astronomer observed the 20 May total solar eclipse at 9,428 MHz using a small parabola (Hagen, 1949).

1948

• In Japan, observations of the 9 May partial eclipse at 3,000 MHz using a small parabola (Shimoda, 1982; Shimoda et al., this paper).
• In Australia, observations of the 1 November 1948 partial eclipse at 600, 3,000 and 9,428 MHz using an ex-WWII radar antenna and small parabolic antennas (Christiansen et al., 1949a; 1949b; Minnett and Labrum, 1950; Piddington and Hindman (1949).

1949

• In France, observations of the 28 April partial eclipse at 158, 555, and 1,200 MHz using a small parabola and two 7.5m Würzburg antennas (Laffineur et al., 1949; 1950; Steinberg, 1953; cf. Orchiston and Steinberg, 2007).
• In Australia, observations of the 22 October partial eclipse at 60, 100, 200, 600, 1,200 3,000 and 9,400 MHz using Yagi antennas, an ex-WWII radar antenna and small parabolic antennas (Wendt, et al., 2008).

1950

• At the remote site of Attu Island in Alaska, American radio astronomers observed the 12 September total solar eclipse at 470, 3,000 and 10,000 MHz using three small parabolas (Haddock et al., 1951; Hagen, 1951; Reber and Beck, 1951).

1951

• At the remote site of Markala in French Sudan, Africa, French radio astronomers observed the 1 September annular eclipse at 169 and 9,350 MHz using a small parabola and an ex-US radar antenna (Arsac et al., 1953; Blum et al., 1952a; 1952b; Bosson et al., 1951; Denisse, et al., 1952; cf. Orchiston and Steinberg, 2007).

1952[6]

• At the remote site of Khartoum in the Sudan, Africa, French radio astronomers observed the 25 February total solar eclipse at 225 and 555 MHz using a small parabola. French radio astronomers based in Dakar (French West Africa), Bizerte (Liberia), Paris and Onsala (Sweden) also observed this event as a partial solar eclipse at 169 and 255 MHz using three ex-US radar antennas and two 7.5m Würzburg antennas (Arsac et al., 1953; Blum et al., 1952b; Denisse, et al., 1952; Laffineur et al., 1952; 1954; cf. Orchiston and Steinberg, 2007).
• At the remote sites of Lwiro-Bukavu and Ngili-Leopoldville in what then was the Belgian Congo, Africa, Belgian radio astronomers observed the 25 February partial eclipse at 169 MHz using two ex-US radar antennas (Coutrez et al., 1953).

eclipses to investigate the locations of radio-emitting regions only came later in 1948 with the advent of the 1 November partial solar eclipse. This event was observed by five different teams of Australian radio astronomers from three quite separate geographically-spaced sites, and at three different frequencies (see Orchiston, 2004; Orchiston et al., 2006; Wendt et al., 2008; Wendt et al, 2011). Meanwhile, French radio astronomers were the first to derive the form and areal extent of the radio corona, when they analysed 169 MHz observations of the 1951 and 1952 solar eclipses listed below (for details see Orchiston and Steinberg, 2007).

4.2 Shimoda's Career and Subsequent Research Fields

Despite unwittingly being the 'founding father' of Japanese radio astronomy, Koichi Shimoda quickly lost interest in solar observations and chose not to pursue a career in this exciting new field of research. In the early 1950s there were four small research groups active in solar radio astronomy in Japan: Tokyo Astronomical Observatory had a broadside array and two Yagi arrays at Mitaka; Nagoya University a small radiometer at Toyokawa Observatory; Osaka City University a small radiometer at an on-campus site; and the Radio Research Laboratories of the Ministry of Posts and Telecommunications a broadside array at Hiraiso (see Ishiguro et al., 2012 and Ishiguro and Orchiston, 2013; and Figure 1 for relevant localities). Yet by this time Shimoda was already happily employed as an Assistant Professor by the University of Tokyo and was involved in re-search on microwave spectroscopy. It was ironic, therefore, that

> The microwave spectroscopy research led by him made an outstanding contribution to the radio astronomy in Japan. In addition, at the early stage of maser and laser research in the

> 1950s and 1960s, he made achievements in building the basis of the maser and laser study together with C.H. Towns [sic.; see Shimoda et al., 1956; 1957] and other scientists. After that, he proceeded to the study of laser spectroscopy and developed a wide variety of researches ranging from the basic research of Stark Spectroscopy and double resonance to laser-applied technology.
>
> Prof. Shimoda has passionately devoted himself to his research as well as the science and physics education. He served as the chairman of the Physics Education Society of Japan for 16 years until 2 years ago [i.e. until 2006] and he has published numerous educational text-books and study guide. Furthermore, he has produced a large number of leading researchers and educators in the field of physics.
>
> In May 2007, there was a celebration of his eighty-eighth birthday. The highlight of the celebration was Prof. Shimoda's lecture. Three experiments were performed with scientific demonstrations and explanations based on his own ideas. They were performed in front of the people who came for the celebration: the first experiment was a magnetic levitation experiment using permanent magnets only (floated body was completely motionless), the second was an interference experiment using laser and optical fiber, and the third was an automatic Sink-Float experiment [actually it was a self-moving Cartersian diver]. All the experiments were both surprising and amusing. Prof. Shimoda's never-ending affection and curiosity toward physics and his passion for enlightenment left a strong impression on the participants. (Tsubono, 2009).

While he did not follow developments in solar radio astronomy, the above quotation indicates that Shimoda did maintain an active interest in international radio astronomy, and in this context he was one of those who contributed to the detection of interstellar methylamine using the TAO's 6-m millimetre radio telescope (see Kaifu et al., 1974).

In 2008 Professor Shimoda's lifelong contribution to research, education and the training of future Japanese physicists was formally recognized at a national level when he was selected as one of the 'Persons of Cultural Merit' by the Japanese Ministry of Education.

5 CONCLUDING REMARKS

In his 1984 review paper, Tanaka claimed that Japanese solar radio astronomy began in 1949, but he was not aware that Kiochi Shimoda from the University of Tokyo attempted to observe the 9 May 1948 partial solar eclipse at 3,000 MHz using a simple radiometer that he assembled. Nor is Shimoda's experiment mentioned in Woody Sullivan's (2009) *Cosmic Noise. A History of Early Radio Astronomy.*

However, Shimoda's solo pioneering efforts were soon eclipsed as small groups of solar radio astronomers emerged in the early 1950s at Hiraiso, Osaka, Toyokawa and Mitaka (in Tokyo). The Tokyo Astronomical Observatory group at Mitaka and the Nagoya University group at Toyokawa both followed up on Shimoda's work by carrying out successful observations of solar eclipses during the 1950s (see Hatanaka et al., 1956; Tanaka and Kakinuma, 1958; and Nakajima et al., 2013). These investigations followed a world-wide trend at that time when radio observations of solar eclipses were used successfully to pinpoint the locations of radio-emitting regions and examine the distribution of emission across the solar disk at different frequencies (Castelli and Aarons, 1995). However, by the late 1950s solar eclipses had become much less important as the availability of grating interferometers and position interferometers allowed these types of investigations—and others—to be carried out on a regular basis. No longer would radio astronomers have to wait for the next solar eclipse in order to continue their research programs.

6 NOTES

1. This is the second paper in a series reporting the results of an international project conducted under the auspices of the IAU Working Group on Historic Radio Astronomy, which aims to document the early history of Japanese radio astronomy. The first paper in the series (Ishiguro et al., 2012) provided an overview of early Japanese radio astronomy, and the present paper is the first in a series that will examine in detail different aspects of these early investigations.
2. At that time Shimoda did not know of Arthur E. Covington's radio observations of a partial eclipse in 1946, or that the Russians and John P. Hagen had observed a total solar eclipse in 1947.
3. In the immediate post-War years the US Army had banned the construction by the Japanese of any type of radar system, but fortunately there was no prohibition on the construction of receivers.
4. In addition to references listed in this Section and in Table 1, a poster paper on early Australian *and* French solar eclipse observations was displayed at the 2007 Winter Meeting of the American Astronomical Society in Seattle (see Orchiston et al., 2007).
5. Hey (1955) mistakenly associates Sander's observations with the 23 November 1946 eclipse, but Sullivan (2009: 115, 290) shows that he actually observed the 9 July 1945 eclipse.
6. Here we merely list the French teams that were active during this eclipse and used it to determine the shape and size of the solar

corona at 169 MHz, and the Belgian team that conducted research in collaboration with their French colleagues. Sullivan (2009: 290) provides information on the other six teams that also observed this eclipse.

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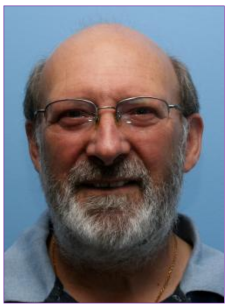
Professor Wayne Orchiston is a researcher at the National Astronomical Research Institute of Thailand in Chiang Mai. In his earlier years Wayne worked at the CSIRO's Division of Radiophysics in Sydney and later at its successor, the Australia Telescope National Facility. He has published extensively on the history of radio astronomy in Australia, France and New Zealand, and he and Masato Ishiguro lead the IAU Project on the History of Early Japanese Radio Astronomy. Wayne was the founding Chairman of the IAU's Working Group on Historic Radio Astronomy, and he currently serves as its Secretary.



Dr Kenji Akabane is a Professor Emeritus of the University of Tokyo. He started solar radio observations at a microwave frequency at the

Tokyo Astronomical Observatory (TAO) of the University of Tokyo in 1952. He stayed in the United States from 1957 to 1960, studying at Cornell University and the University of Michigan. After coming back from the US, he showed a great interest in the field of cosmic radio astronomy and led a project to construct the 6-m millimeter wave radio telescope on the campus of the TAO, which was completed in 1970. After that he was motivated to construct the largest millimeter wave radio telescope in the world, and was appointed as the founding Director of the Nobeyama Radio Observatory in 1982. He was a Professor at the National Astronomical Observatory of Japan from 1970 until he retired in 1987. He then worked at the University of Toyama from 1987 to 1992, and then was the President of Matsusho Junior College for seven years, from 1992.

Dr Masato Ishiguro is a Professor Emeritus of the National Astronomical Observatory of Japan (NAOJ). He started his research in radio astronomy at Nagoya University in 1970 where he investigated radio interferometry techniques. In 1980, he moved to the Tokyo Astronomical Observatory of the University of Tokyo to join the project to construct large millimeter-wave telescopes at the Nobeyama Radio Observatory (NRO) where he was in charge of constructing the Nobeyama Millimeter Array. He was the Director of the NRO from 1990 to 1996 and contributed to the open use of the telescopes. While doing research at the NRO, he worked on a plan for a large array at millimeter and submillimeter wavelengths. Since 1998, he had been leading the Japanese involvement in the international project to construct the Atacama Large Millimeter/submillimeter Array (ALMA) in Chile. He was a Professor at the NAOJ from 1988 until he retired in 2009. He is now the Japanese representative on the Committee of the IAU Working Group on Historic Radio Astronomy.

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A LITTLE-KNOWN 3-LENS CATADIOPTRIC CAMERA BY BERNHARD SCHMIDT

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Abstract: The authors investigate a prototype 3-lens f/1 catadioptric camera, built in 1934 by the famous optician Bernhard Schmidt at the Hamburg-Bergedorf Observatory in Germany, where Schmidt worked before his death in 1935. The prototype is in the observatory's collection of Schmidt artifacts, but its nature was not understood before the authors' recent examination. It is an astronomical camera of a form known as 'Buchroeder-Houghton', consisting of a spherical mirror and a 3-element afocal corrector lens placed at the mirror's center of curvature. The design is named for R.A. Buchroeder and J.L. Houghton who independently published this and related forms of wide-field spherical-lens cameras after 1942. Schmidt died before he could publish his own design. The authors disassembled the prototype and measured its optical parameters. These they present together with a transmission test of the corrector lens. The authors also consider the theoretical performance of the design as built, the theory of Houghton cameras, Schmidt's possible path to his invention, and the place of the prototype in his scientific output.

Keywords: anastigmat, Bernhard Schmidt, Hamburg Observatory, Buchroeder-Houghton, catadioptric camera

1 INTRODUCTION

Bernhard Schmidt's 1929-1930 invention of the aspheric corrector-plate camera—'Schmidt Camera'—started a revolution in optics and instrumentation which continued for decades after his premature death on 1 December 1935. The Schmidt Camera was the first highly color-corrected, catadioptric anastigmat of great speed ever devised. It could be built in small sizes for use in spectrographs, or in large sizes for astronomical survey telescopes. Its principal difficultty consisted in making the aspheric corrector plate. As is well-known, after 1940 other designers such as Albert Bouwers in Holland, Kurt Penning in Germany, Dmitri D. Maksutov in the USSR, and James L. Houghton in the UK succeeded in replacing the difficult-to-make corrector plate with simpler-to-build spherical lenses (Marx and Pfau, 1992: 24-31; Riekher, 1990: 321-347; Wilson, 2007: 148-217). But what is less widely known is that Bernhard Schmidt himself did the same thing as early as 1934. And what has remained virtually unknown is that Schmidt's resulting prototype 3-lens camera still exists at the Hamburg-Bergedorf Observatory in Germany, where Schmidt worked at the end of his life. The authors of this paper examined it there in November 2007 (see Figure 1).

2 HISTORICAL BACKGROUND

The aspheric-plate Schmidt Camera played a leading role in the technological development of fast wide-field imaging in the twentieth century. This was not only so in astronomy, where it served and continues to serve as an important tool for surveying and mapping the 'deep sky'—one has only to think of the 1.2-meter Oschin-Schmidt Telescope on Palomar Mountain—but also outside of astronomy in fields such as X-ray medical diagnostics, television projection, *etc.*

The principal problem with the Schmidt Camera has always been the formation of a usable aspheric corrector plate. Schmidt's preferred method of making correctors required elastic deformation of the glass plates under a partial vacuum (cf. Schorr, 1936b). This can work well as

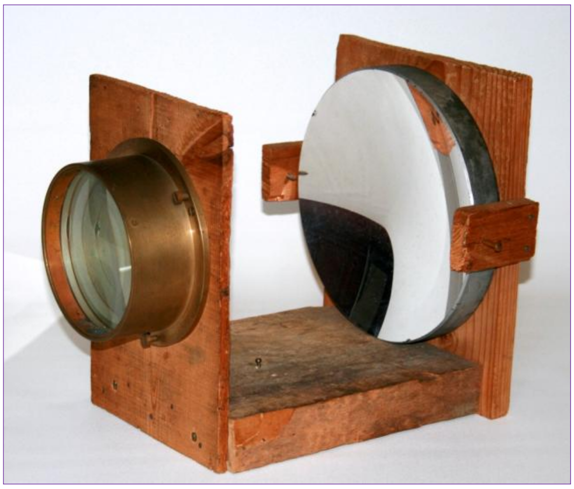


Figure 1: Bernhard Schmidt's prototype camera, consisting of a fast spherical mirror (right), and a 3-lens afocal corrector (left: in a brass lens cell). The optical design is of a type later named 'Buchroeder-Houghton'. Built in 1934, the camera was used by Schmidt to take test images of the sky, shortly before his death (image courtesy: Walter Stephani and the Hamburg Observatory, University of Hamburg).

Figure 2: Bernhard Schmidt (left) and Arthur Arno Wachmann (right) in the summer of 1935 at the Hamburg-Bergedorf Observatory. Wachmann and Schmidt collaborated in the use of the two aspheric-plate cameras that Schmidt built for the Observatory. After Schmidt's death, Wachmann began to compile an archive of documents relating to his life.

Schmidt himself showed in 1930, and as later makers also found (Everhart, 1966; Ohlmüller, 1942). However, the 'vacuum-pan' method of making corrector plates is not without pitfalls, one of which is that the tension induced in the glass plate during deformation can lead to catastrophic failure, when the glass implodes and literally flies to pieces (Cox, 1972: 390-391; Everhart, 1966: 715). Catastrophic failure places a mechanical limit on the extent of elastic bending, and therefore also on the asphericity that may be usefully induced into a corrector plate. This, in turn, constrains the photographic speed. In order to reach speeds faster than about f/1.5, either a change in fabrication methods is necessary, or else a change in the optical system itself (cf. Cox, 1939; the comments by D.O. Hendrix in Ingalls, 1953: 371; DeVany, 1981: 295-296; Riekher, 1990: 327).

Schmidt chose the latter approach. Yet because of his premature death in 1935, when he was on the cusp of achieving fame for his aspheric-plate camera, and also because of his well-attested reserve and secrecy, only a few people at Bergedorf—Richard Schorr, the Director; Arthur Arno Wachmann, an astronomer (Figure 2); and possibly Carl Vick, a staff member—were aware that Schmidt had pushed conceptually beyond the limits of the aspheric-plate camera.

It is true that Wachmann called attention to Schmidt's prototype 3-lens system in articles published in 1955 and 1962, both in the United States (in English) and in Europe (in German and Swedish); and he provided a photograph that depicts the same crudely-mounted instrument as is seen above in Figure 1 (Wachmann, 1955a; 1955b; 1962). Wachmann's photograph is reproduced here as Figure 3. The English-language version of his paper states that:

> … [Schmidt] anticipated increasing the focal ratio to f/1, and, even more, that a lens system would be better than a correcting plate. He made detailed calculations for this and made a first model, a typical wood-and-screw assembly of his which, despite its primitiveness, in the artist's hands took good [stellar] photographs. (Wachmann, 1955a: 9).

The word 'stellar' is added in Wachmann (1962: 32). Nevertheless, since Wachmann's papers provided few concrete details of the construction, optical designers could not easily assess its significance.

Wachmann had worked closely with Schmidt during the last years of Schmidt's life when he was a free-lance consultant (*freiwilliger Mitar-*

beiter) in Bergedorf. Wachmann was also an early and frequent user of the two aspheric-plate telescopes that Schmidt completed there. After Schmidt's death, Wachmann began to assemble an archive of documents relating to his life, starting in the 1940s and continuing for decades. Ultimately, Wachmann passed this archive on to Bernhard Schmidt's nephew, Erik Schmidt, who is still in possession of it. The 'Wachmann-Schmidt archive' is invaluable for any study of Bernhard Schmidt.

One scholar who has studied the archive is Barbara Dufner. She accessed it in 1998 during preparations for her doctoral dissertation, which was later published as a book (Dufner, 2002a). Dufner's study remains the only full, scholarly assessment of Schmidt's optical and scientific work. Erik Schmidt's (1995) own biography of his uncle focuses more on personal and family history. Nevertheless, both books contain a great deal of important information that goes far beyond earlier sketches of Schmidt, revealing the complexity, brilliance, and tragedy of his life (for earlier sketches, see e.g., Hodges, 1948; Ingalls, 1953: 365-373; Silverman, 1950).

Recently, the present authors also were granted access to the Wachmann-Schmidt archive, as part of an ongoing study that they have jointly undertaken. It was at an early stage of their work that they stumbled across the existence of Schmidt's prototype 3-lens camera, which still exists at Bergedorf but has not been understood since Wachmann's time. The discovery occurred in the following way.

3 FINDING THE PROTOTYPE CAMERA

After visiting the Hamburg-Bergedorf Observatory in the northern summer of 2004, we determined on a plan to survey, electronically scan, and study all known evidence (texts, documents, artifacts) relating to Bernhard Schmidt. In addition, we have conducted an extensive search for additional information. Evidence is abundant both at Bergedorf itself and elsewhere in Germany, such as at Mittweida, the town in Saxony where Schmidt lived, studied, and worked from 1901 until the late 1920s. Both the Hamburg-Bergedorf Observatory and the Technikum-Mittweida ('University of Applied Sciences') contain archives with Schmidt documents and artifacts. Early in our joint study, when we first encountered Wachmann's printed articles, we were impressed not only by his words but also by his photograph of the prototype camera (Figure 3).

In her biography of Schmidt, Dufner expressed the idea that, although Schmidt had gone beyond merely conceiving a spherical-lens camera and making drawings and calculations for it, "Only these notes and drawings have been pre-

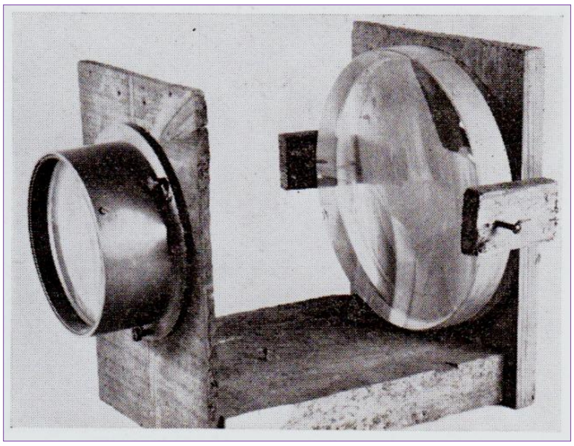


Figure 3: Schmidt's prototype 3-lens camera as shown in Wachmann's 1955 photograph (image courtesy: Ekkehard Wachmann).

served." (Dufner 2002a: 237; our English translation). She also published a synopsis of her book in the popular astronomy magazine, *Sterne und Weltraum*. There she displayed a copy of Wachmann's 1955 photograph, but stated in the caption that it showed a prototype of the correction-plate camera: "Prototype of the Schmidt telescope. With this wooden model, Schmidt tested the effect of [a] correction plate and spherical mirror." (Dufner 2002b: 34; our English translation).

Having seen Wachmann's papers, we realized that the great depth of the brass lens cell attached to the wooden upright in front of the mirror must contain not one lens—and certainly not a thin corrector plate—but two or probably three normal lenses. In addition, as a result of intensive document searches we became aware of drawings such as the one shown in Figure 4, preserved in the Hamburg-Bergedorf archive of Schmidt papers. It depicts a deep lens cell containing a triplet composed of one biconcave and two plano-convex lens elements. All the finite

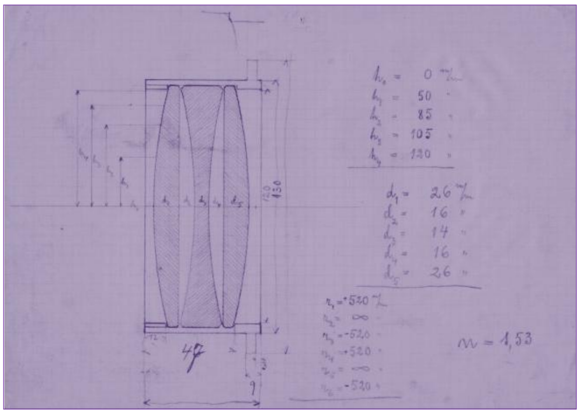


Figure 4: Schmidt's scale drawing of a 3-lens afocal corrector with construction parameters specified. The incidence heights of five rays to be trigonometrically traced are given at upper right (h_0, h_1, h_2, *etc.*). The marginal ray (h_4) intercepts the front lens surface at a radial height of 120 mm, implying a clear aperture of 240 mm (image courtesy Hamburg Observatory, University of Hamburg.

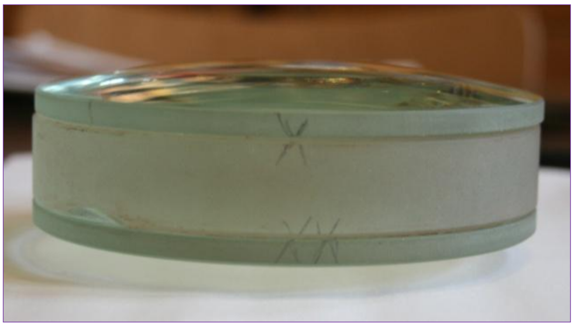


Figure 5: Lens-triplet of the prototype camera removed from its brass cell in 2007. 'Maker's marks' in the form of penciled 'X's' show how the lenses were meant to be assembled. The obvious greenish coloration indicates that common soda-lime 'plate glass' was used rather than expensive optical glass for this prototype instrument (image courtesy: Walter Stephani and the Hamburg Observatory, University of Hamburg.

radii of curvature are listed on the drawing as identical (520 mm). Five incident ray-heights are specified (h_0 to h_4), as well as the axial thicknesses of the lenses and air-gaps (d_1 to d_5). Given these numbers, it is clear that a 240 mm

Figure 6: Wolfgang Busch displays the middle (equi-concave) lens element. On the left of the illustration is the brass lens cell. At the top is the mirror, which is thought to have been aluminized in the 1980s for display when the original Schmidt Museum was opened at the Hamburg-Bergedorf Observatory (image courtesy: Walter Stephani and the Hamburg Observatory, University of Hamburg).

Figure 7: Wolfgang Busch is shown with the spherometer in his left hand which was used to measure the lens radii during the 2007 examination. (image courtesy: Walter Stephani and the Hamburg Observatory, University of Hamburg).

clear-aperture triplet was intended.

Yet at the same time, in a seemingly less formal style of handwriting, the inside diameter of the retaining ring is shown as '120', while the outside diameter of the cell is specified as '130'. The number '47' is written below the lenses. This corresponds to the depth in millimeters of the prototype's cell wall down to the bottom retaining flange. An hypothesis to explain all of this is that initially a triplet of 240 mm clear aperture was projected, but later it was scaled down by one-half to 120 mm, the size of the prototype camera that actually exists.

We therefore obtained permission to disassemble the prototype camera and to inspect and measure its optical and mechanical parts. This we did in 2007 (see Figures 5-7), and again in 2010. Upon disassembling it, we found that the metal cell contained a triplet lens like that depicted in Figure 4, only at half-scale. So the photograph in Figure 3 showed not an aspheric corrector-plate camera, but a novel lens system, just as Wachmann had indicated in his papers.

4 THE BUCHROEDER-HOUGHTON DESIGN

Schmidt did not live long enough to develop his invention further, and never published anything about it. Wachmann's 1955 and 1962 papers appear to be the only indications in print that such a camera ever existed. Thus, it was left to other designers independently to re-invent this optical system, as well as related forms, which they did, starting in 1940.

The first people to publish anything analogous to Schmidt's prototype camera were Robert Richter and Hermann Slevogt in Germany, who obtained a patent announcement in 1941. Their system did not involve a triplet lens like Schmidt's, but rather a doublet of somewhat lesser performance. We shall discuss the optical theory of doublet and triplet designs in a moment. For now let us briefly review the history of their development.

Richter and Slevogt seem not to have published any papers about their design in professional journals, but only to have obtained a patent announcement for Zeiss. Because this occurred during WWII, little or nothing was known of the invention outside of Germany. It was mentioned after the War in a paper published by Horst Köhler (1949: 9 and 16). But Richter and Slevogt themselves only obtained a completed patent in 1954 (Richter and Slevogt, 1954; see Figure 8).

In the meantime, James L. Houghton independently developed more generalized forms of the spherical corrector-lens system, and obtained patent rights both in the UK (1942) and the USA (1944). He also published a paper discussing doublet and triplet forms of his invention in the *Proceedings of the Physical Society* (Houghton, 1945). So although Richter and Slevogt deserve credit for pioneering work, especially outside of Germany attribution for this type of optical system is typically given to Houghton since he was the first to publish in a scientific venue (cf. Wilson, 2007: 213-215).

Houghton's triplet designs are not identical to Schmidt's system, but involve different lens shapes and a much different choice of glass types (see Figure 9). Schmidt's design can thus be viewed as a variant form of a Houghton triplet corrector. The details of the form make it attractive for use in a prototype instrument, since they reduce the number of radii in the total system (including the mirror) to just two, and use just one type of low-index optical glass. Indeed in Schmidt's case, the glass actually employed in the prototype lens is likely just the same as that used for his mirror, namely common soda-lime crown glass.

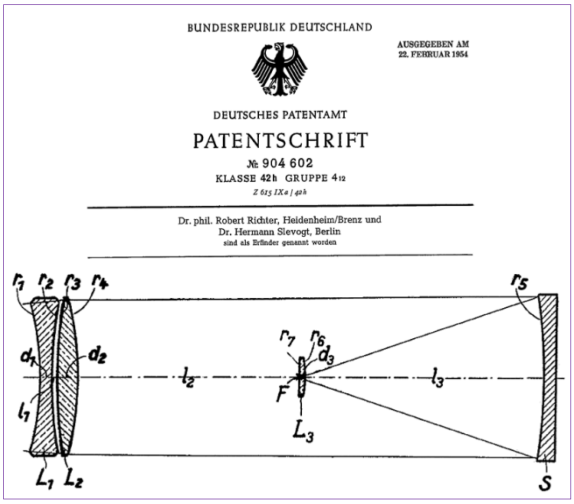
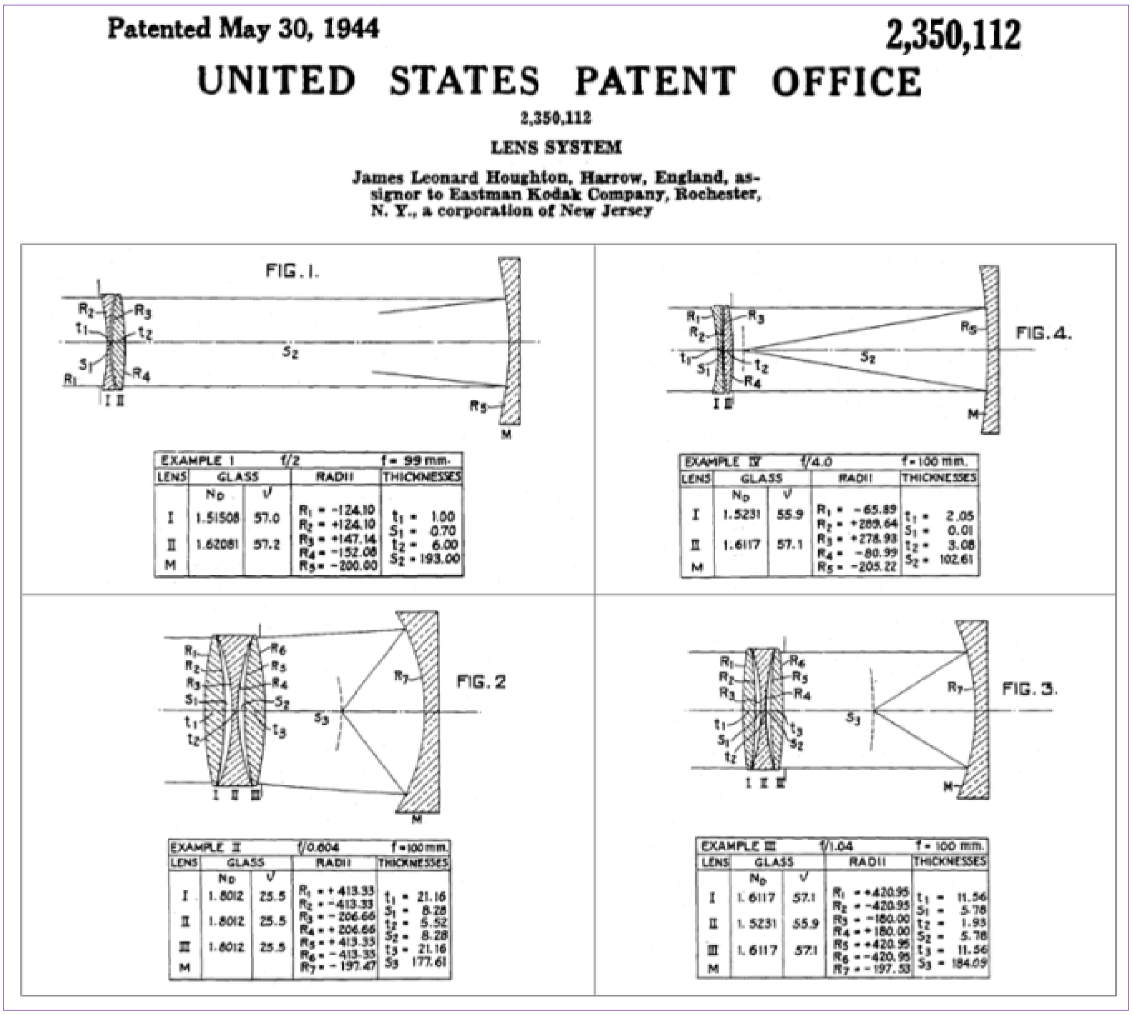


Figure 8: Drawing and title from the completed 1954 German patent of Robert Richter and Hermann Slevogt for a 2-lens afocal corrector plus spherical mirror, similar to the simpler form of the Houghton camera. Richter and Slevogt originally applied for their patent in 1941.



EXAMPLE I	f/2		f = 99 mm.	
LENS	GLASS N_D	V	RADII	THICKNESSES
I	1.51508	57.0	R_1 = −124.10, R_2 = +124.10	t_1 = 1.00, S_1 = 0.70
II	1.62081	57.2	R_3 = +147.14, R_4 = −152.08	t_2 = 6.00, S_2 = 193.00
M			R_5 = −200.00	

EXAMPLE IV	f/4.0		f = 100 mm.	
LENS	GLASS N_D	V	RADII	THICKNESSES
I	1.5231	55.9	R_1 = −65.89, R_2 = +289.64	t_1 = 2.05, S_1 = 0.01
II	1.6117	57.1	R_3 = +278.93, R_4 = −80.99	t_2 = 3.08, S_2 = 102.61
M			R_5 = −205.22	

EXAMPLE II	f/0.604		f = 100 mm.	
LENS	GLASS N_D	V	RADII	THICKNESSES
I	1.8012	25.5	R_1 = +413.33, R_2 = −413.33	t_1 = 21.16, S_1 = 8.28
II	1.8012	25.5	R_3 = −206.66, R_4 = +206.66	t_2 = 5.52, S_2 = 8.28
III	1.8012	25.5	R_5 = +413.33, R_6 = −413.33	t_3 = 21.16, S_3 177.61
M			R_7 = −197.47	

EXAMPLE III	f/1.04		f = 100 mm.	
LENS	GLASS N_D	V	RADII	THICKNESSES
I	1.6117	57.1	R_1 = +420.95, R_2 = −420.95	t_1 = 11.56, S_1 = 5.78
II	1.5231	55.9	R_3 = −180.00, R_4 = +180.00	t_2 = 1.93, S_2 = 5.78
III	1.6117	57.1	R_5 = +420.95, R_6 = −420.95	t_3 = 11.56, S_3 = 184.09
M			R_7 = −197.53	

Figure 9: Drawings and title from the 1944 United States patent of James L. Houghton for 2- and 3-lens correctors, similar to those in Richter/Slevogt's patent and Schmidt's prototype camera. Note that for his triplets, Houghton employed equi-convex positive lenses, rather than plano-convex as in Schmidt's prototype. In addition, Houghton's system shown as 'Fig. 2' of his patent, although containing just one glass type, employed an extra-dense flint similar to Schott SF6. This would produce a markedly yellow triplet corrector, unsuitable for surveying the night-sky. Houghton's other triplet, shown as 'Fig. 3' of his patent, uses two different crown glass types, unlike the single crown glass of Schmidt's design. Hence, Houghton's patented systems differ in significant details from Schmidt's.

The first person to publish this same design type was Richard A. Buchroeder in the United States. He did it in 1972, having conceived the design and built a set of optics in 1968 (see Buchroeder, 1972; 1980; 1986). For this reason the type of Schmidt's 1934 system is sometimes called the 'Buchroeder-Houghton camera' in English (see Rutten and van Venrooij, 1999: 131-133). Despite the anachronism of applying that name to Schmidt's prototype, for convenience we shall maintain the nomenclature.

5 THE OPTICAL THEORY OF HOUGHTON CAMERAS

The theory of the Houghton or Richter-Slevogt systems is closely related to Schmidt's aspheric-plate camera. Third-order aberration theory predicts that shifting the aperture stop of a spherical mirror to its center of curvature automatically eliminates both off-axis coma and astigmatism (Wilson, 2007: 148-149). Spherical aberration can be eliminated either by use of a figured plane-parallel plate—as in the classical Schmidt telescope—or by use of two or three lenses of zero net optical power. The Richter-Slevogt system uses two lenses, as does the simpler form of the Houghton camera. But more interesting is the use of a symmetrically-arranged set of three lenses.

Analytical equations published by Houghton in his papers show that for any symmetrical arrangement of three thin lenses in the stop position, regardless of the powers of the individual lens (but maintaining zero net-power), to the third order the lens system will contribute no coma or astigmatism (Houghton, 1971-1973). Thus, the Houghton system with a symmetrical triplet corrector can form a wide-angle anastigmatic camera.

Assuming the Buchroeder form of the Houghton design in which the corrector triplet contains one equi-concave and two plano-convex lenses, with a single finite radius of curvature, a single glass type, and zero net optical power, thin-lens theory allows us to derive an exact relationship between the radius of curvature of the lenses and the mirror for spherical aberration control:

$$(1/r_m)^3 = -\,[2(n^2-1)(n-1)/n] \times (1/|r_l|)^3 \qquad (1)$$

where r_m is the mirror's radius of curvature (assumed negative), $|r_l|$ is the finite radius of all the lens surfaces, and n is the n_d index of refraction for the glass. The n-function will equal 1 if $n_d = 1.55139$. Since Schmidt's design shown above in Figure 4 specifies $n_d = 1.53$, r_m should equal $-1.025|r_l|$—or in other words, the mirror should have a radius of curvature 2.5% longer than the lenses. Of course, since Equation (1) is an approximation based on thin-lens theory and is valid only to the third order, in practice it has been found feasible to make the mirror's radius the same as the lenses' when using ordinary crown glasses. If the speed of the system is kept slow enough, performance can still be diffraction limited. Buchroeder's published design came close to this at f/3.

Longitudinal and lateral chromatic aberration are nominally zero in the Buchroeder-Houghton design, since the corrector lens has no net optical power. Field curvature is proportional to the Petzval sum, which is determined by the radius of the concave mirror, just as for an aspheric corrector-plate camera. To the third order, the field curvature is equal to the mirror's focal length. A curved focal surface was not an insurmountable problem in the days of film photography, when the emulsion could often be bent onto a curved platen. This was already done by Schmidt for his earliest aspheric-plate camera (cf. Dufner, 2002a: 225; Mayall, 1946: 287; Schmidt, 1931: 25; 1938: 16). An alternative is to use a field-flattening lens. Whether Schmidt might have done this for his 3-lens camera is not known.

6 SCHMIDT'S PATH TO HIS PROTOTYPE SYSTEM

6.1 Proposal For a 60 cm 2-Lens Camera in 1932

A surviving note by Richard Schorr, the Hamburg-Bergedorf Observatory Director, reveals that already in 1932, that is, about a year after Schmidt's first 36-cm f/1.75 aspheric-plate camera became fully operational, Schmidt was proposing to build a 60-cm 2-lens camera. Schorr's note is preserved in the Wachmann-Schmidt archive (our English translation):

> Schmidt's mirror system 60cm/aperture. 13 April 1932. I resume the discussion with Schmidt about making the 60 cm f/2 mirror system from the available glass disk. Schmidt tells me that he has very recently been busy with the possibility of making an f/1 mirror from the disk. For that purpose, 2 lenses (1 converging + 1 diverging) would certainly have to be used rather than the correction plate: these lenses would be made from simple mirror-glass of about 40 mm thickness. Since the ~~brightn~~ light concentration for extended objects is in this case 4-fold [greater] than at f/2, the change seems very desirable to me, even if the advantage of the longer focal length falls by the wayside. In a few days, we will discuss the business further after mutual reflection.

This 2-lens system is likely to have been a form of Houghton or Richter-Slevogt corrector, possibly consisting of just a plano-convex and a plano-concave lens. Certainly the latter is shown on another of Schmidt's drawings from the period. This is reproduced in Figure 10.

How Schmidt came to the idea of this camera is uncertain. We know from the testimony of Walter Baade (who also worked with Schmidt at Bergedorf), that before he conceived of the aspheric-plate camera, Schmidt had proposed some sort of wide-field system involving lenses. Baade later wrote:

> In 1926 Schmidt had proposed to me to correct the field of a reflector by putting in contact with the mirror a lens of the same size. He was very much in love with this idea but the astronomical trend was against this type of correction, because it would obviously have been impossible to provide lenses of very large sizes. (Ingalls, 1953: 370-371).

Optically, the meaning of Baade's statement is unclear. Literally placing a single lens in contact with a mirror to act as a corrector requires either forming a deep meniscus element, like a Maksutov shell, and setting it against a separate mirror, or else silvering the rear surface of a lens to act as the mirror. The latter type of optical element is called a 'Mangin' mirror. Neither of these possibilities, however, provides enough optical 'degrees of freedom' to correct coma, which was the chief rationale for the design. More probably, Schmidt proposed a different type of construction, which is not clearly conveyed by Baade's words. Possibly it was a Houghton doublet or triplet. Compared to a thin aspheric corrector plate, a thick Houghton lens would be subject to Baade's objection.

Yet a Houghton corrector could hardly be considered as "… in contact with the mirror ..." Instead there would be a significant air-space, as we see in the Houghton-type systems of Figures 1, 3, 9, and 10. If we are to take Baade's words as literally as possible, then another possibility is an *achromatic* corrector, consisting of a crown-flint pair, either placed directly in front of a separate mirror, or with the final lens surface silvered. The last possibility would make an achromatic Mangin mirror. In either case, the doublet could be termed "a lens" and it would be "in contact with the mirror."

6.2 Miethe and the 40 cm Goerz Astrograph of 1914

Before WWI Schmidt had worked extensively with the Royal Astrophysical Observatory at Potsdam, and its Directors, Hermann Carl Vogel and Karl Schwarzschild. Schmidt had also worked with the Berlin optical house of C.P. Goerz, and its client Dr Adolf Miethe, a Professor at the *Technische Hochschule* ('Technical College') *Berlin*. Miethe directed the college's photo-chemical laboratory. He specialized in the development of panchromatic emulsion and an early system of tri-color photography. He also had a strong interest in astrophotography, and purchased large telescope optics from Schmidt, which he had mounted by Goerz. Letters between Miethe, Schmidt and Goerz survive from the period.

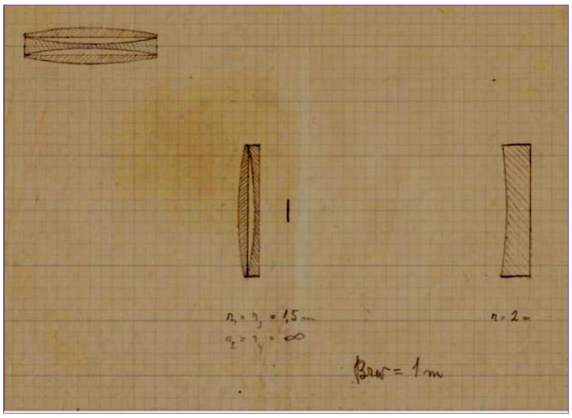


Figure 10: Scale drawing in Schmidt's hand, showing a two-lens corrector (center) and mirror (right). The lenses are plano-convex and plano-concave with finite radii of 1.5 meters; the mirror has a radius of 2 meters. Above left seems to be an alternative idea: a triplet of the Buchroeder-Houghton type (image courtesy: Hamburg Observatory, University of Hamburg).

Miethe had a double-reflector built, consisting of a 30 cm and a 50 cm Cassegrain, with mirrors by Schmidt mounted side-by-side on an equatorial mounting by Goerz (Kühn 2012; Seegert 1927). He used the instrument for many years, praising its optics and even allowing Goerz to show the telescope in its sales literature (cf. Figure 11, after Kühn, 2012: 324). In 1913, the company publicly drew attention to its connection with Schmidt (Goerz, 1913: 12-13; our English translation):

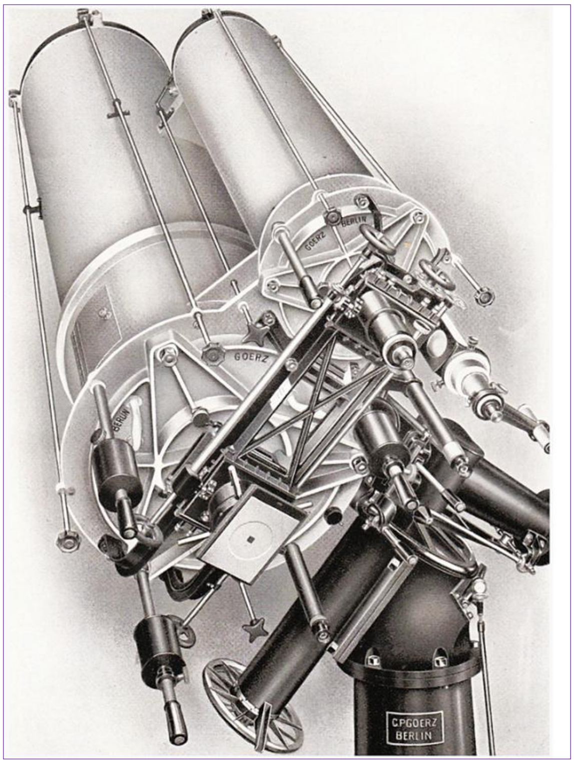


Figure 11: Adolf Miethe's photo-visual double-Cassegrain with 30 cm and 50 cm primary mirrors. The optics were by Schmidt and the mounting by C.P. Goerz. (after Kühn, 2012: 324).

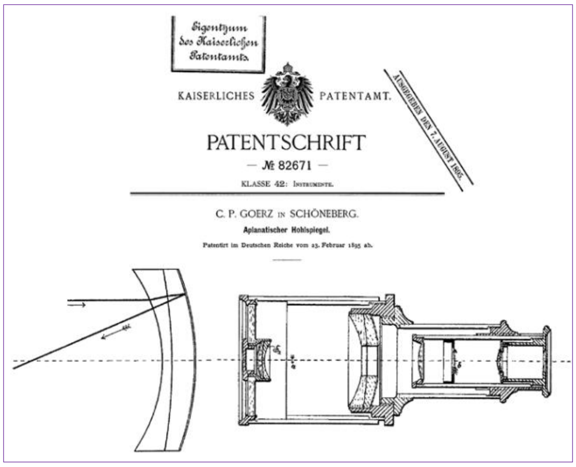


Figure 12: Drawings and title from Goerz's 1895 German patent for an erect-image telescope employing two cemented achromatic Mangin mirrors, each termed an '*aplanatischer Hohlspiegel*' by Goerz. On the left is a blow-up to illustrate the construction of a Mangin mirror. On right is a sectional view of the telescope, constructed in a Gregorian configuration.

> We build larger astronomical telescopes … in all sizes and call special attention to the fact that the well-known workshop for objective-lenses and parabolic mirrors (Cassegrain and other) of Bernhard Schmidt (Mittweida), which enjoys an outstanding reputation in professional circles, has been joined to our optical institute, and that as a result we are in a position to deliver reflectors together with mountings from 200 mm diameter up to the largest sizes.

Privately Goerz (1911) went further, informing Karl Schwarzschild by letter on 10 August 1911 that in future he should send all orders for Schmidt optics directly to them! This amounted to an attempt to commandeer Schmidt's customers, and although Goerz failed in this (Schmidt never agreed to work exclusively for them), it does say something about the closeness of his relationship with Goerz at the time.

Miethe's double-Cassegrain consisted of two standard all-mirror telescopes. But nearly twenty years earlier, in 1895, Goerz had already patented achromatic Mangin mirrors for use in a small erect-image telescope, constructed with a Gregorian configuration (see Figure 12). For this instrument, standard 1st-surface aspheric mirrors were replaced with all-spherical cemented crown-flint lens pairs, the final surface being silvered. The Goerz patent specification emphasizes that with careful glass selection, not only can the Mangin mirrors be individually made achromatic and corrected for spherical aberration, but they can also eliminate off-axis coma "… in a highly perfect manner." The document goes on to say that individual Mangin mirrors can be used at very fast focal ratios down to f/1. In the case of the present telescope, it concludes, by removing

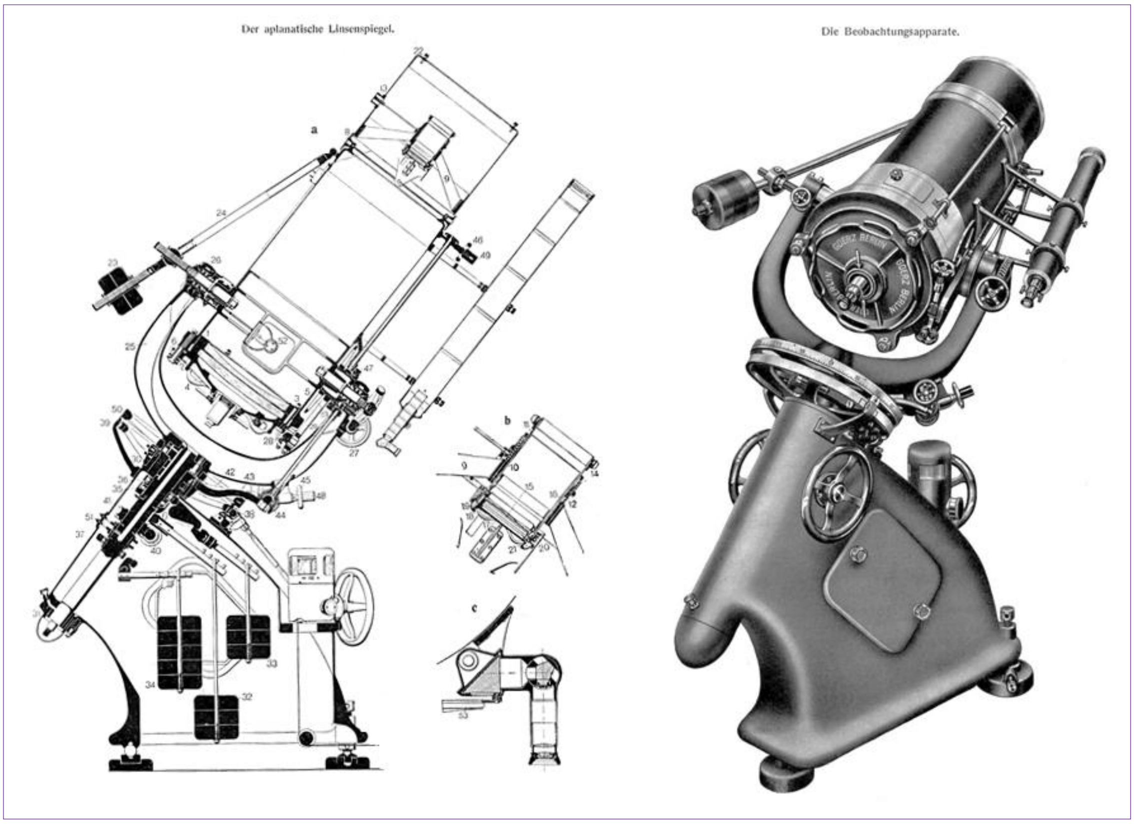


Figure 13: Goerz's 'aplanatischer Linsenspiegel' astrograph, built for Miethe to observe the August 1914 total solar eclipse from Norway. The unit contained a 40-cm air-spaced doublet achromatic Mangin mirror, corrected for coma to give a wide field. On the left of the figure is a sectional view of the astrograph, showing the Mangin at the bottom of the telescope tube. On the right is an exterior representation. By removing the prime-focus photo plate and inserting a second Mangin mirror, the instrument could also be used in Cassegrain mode (after Miethe et al., 1916: 79-80).

the eyepiece and substituting a photo-plate the compound system can also be used as a telephoto lens (Goerz, 1895).

Goerz called such a Mangin mirror an 'aplanatischer Hohlspiegel' (aplanatic concave mirror). Later they changed the term to 'aplanatischer Linsenspiegel' (aplanatic lens-mirror). And they did not stop at small ones. For the August 1914 total solar eclipse whose line of totality crossed Norway, Sweden, and the Russian Empire, Goerz constructed a 40-cm f/3 all-spherical coma-free achromatic Mangin astrograph. It was to be used by Miethe for coronal research at Sandnessjøen in Norway. His colleague, Goerz employee F.M. Weidert, later discussed the instrument in print and illustrated it (Miethe et al., 1916: 71-82; see Figure 13). This instrument was shown as late as 1922 in a published description of Goerz's product-line (Feldhaus, 1922: 366). So the optical configuration of the coma-free Mangin astrograph was technologically current in the years immediately prior to Schmidt's 1926 proposal to Baade.

Although it is not known who figured the optics for Miethe's eclipse telescope, an obvious possibility is Schmidt. He had just successfully refigured the defective 50-cm Steinheil visual achromat for Potsdam. This received high praise from Schwarzschild, who hoped in turn to have Schmidt refigure the defective 80-cm Steinheil photographic objective. But that venture was forestalled by Rudolph Steinheil, using his connections to the German Government, since he feared it would prove a fatal blow to the prestige of his company (Dufner, 2002a: 51-59).

In the event, WWI broke out in the first days of August 1914 and the German astronomers sent to Norway were unable to use the Goerz astrograph for the proposed coronal research and had to return to Germany empty-handed. For Schmidt, however, in Mittweida the situation was far worse. As an Estonian he was considered a Russian citizen and therefore an enemy alien in Germany. He was detained and interned for five months, along with other Russian nationals, in nearby Sachsenburg prison. While there he wrote a postcard to Schwarzschild, dated 26 October 1914, asking for news (our English translation):

> Despite the confusion of the war, I would still be interested to find out what's become of the 80 cm objective lens, and what of the solar eclipse expeditions? In Norway there were also things by me. As a Russian national I have been interned here as a prisoner of war, and can get no information. At the beginning I did hear that the astronomers of the Berlin Observatory were arrested in southern Russia.

What "things" by Schmidt were in Norway is uncertain, but the optics of the 40-cm Goerz astrograph are a possibility. Be that as it may, even if Schmidt did not make these novel coma-free lenses, he must surely have known about them, since he worked so closely with Goerz and Miethe. He had a deep interest in optical design, as well as great skills in fabrication. In speaking with Ejnar Hertzsprung, Karl Schwarzschild went so far as to declare about Schmidt: "He knows more about optics than everyone else put together." (Hermann, 1994: 93).

6.3 The Development of Reflecting Telescopes in the Early Twentieth Century

On other grounds too it is clear that by 1926 Schmidt had long been thinking about alternatives to conventional Newtonian or Cassegrain telescopes for astrophotography. This is not surprising because astronomers had by then sought for several decades to find relief from the off-axis aberrations of their conventional reflectors (coma mainly, but also astigmatism). These errors degraded image sharpness, and made wide-field astrophotography impossible using mirrors. Already in 1905 Schwarzschild (1905: 20-28) himself had made a stab at the problem, proposing a two-mirror coma-free design operating at f/3. Unfortunately, the system had disadvantages which prevented its widespread adoption (see Dimitroff and Baker, 1945: 93-94; Wilson, 2007: 115, 117-119).

Somewhat later, the French designer, Henri Chrétien, working with American optician, George Ritchey, had devised another solution: an unconventional Cassegrain now known as the 'Ritchey-Chrétien' (Chrétien, 1922). After WWII, many Ritchey-Chrétiens were constructed for professional observatories. But their relatively slow speeds (~f/6-f/10) and large plate-scales made them unsuitable for survey work. In the 1930s, Frank E. Ross (1934) at Yerkes Observatory worked out a set of correcting lenses to help to widen the prime-focus field of the 60-inch f/5 reflector at Mt. Wilson, and later also the 200-inch f/3.3 Hale Telescope on Palomar Mountain. But high-performance prime-focus correctors for fast mirrors did not arrive until the 1960s (Wilson, 2007: 348-363).

So at Bergedorf during Schmidt's time there remained a pressing need for a fast wide-field reflecting telescope. Both Baade and Schorr urged Schmidt to think of a solution. Baade, in particular, was hampered in his research on galaxies by the large amount of coma seen on plates taken with the Bergedorf 1-meter f/3 Zeiss reflector (Schramm, 1996: 198). Its field of good image sharpness was only a few minutes of arc in diameter (Ross, 1935: 157-158). Schorr (1936a: 45-46), for his part, desired a still faster reflector of f/2 for wide-field imaging (cf. Mayall, 1946: 283).

Since Schmidt was an accomplished astrophotographer and had been making very fast paraboloidal mirrors for deep-sky imaging since 1905, he was well aware of the problems that coma and astigmatism created in reflecting telescopes (Vogel, 1906a; 1906b). His own interest, however, was high-resolution solar and lunar imaging; and for this type of work, he had devised two solutions by the mid 1920s. One required a very long focal-ratio concave mirror mounted horizontally and fed via a siderostat. To gain access to the image, Schmidt tilted the concave mirror and warped it in a harness to compensate the tilt-induced aberrations. With this 'horizontal mirror-installation' (Horizontal-spiegelanlage) he obtained outstanding images of the Moon and sunspots (Schorr, 1936a: 45-46).

A second solution involved what Schmidt termed "… a type of un-pierced sidewise Cassegrain with complete removal of coma and astigmatism despite the oblique layout." (our English translation). The precise nature of this construction is uncertain, but a type of Schiefspiegler seems likely (Dufner, 2002a: 167).

Schmidt announced the "sidewise Cassegrain" to Schorr in June 1926, the same year he first proposed to Baade the correction of a fast wide-field reflecting telescope. Ultimately, whether Schmidt's first proposal was for an achromatic Mangin, like Miethe's 40-cm instrument or something else, Baade curtly rejected the use of large conventional lenses. In a private letter that Baade wrote to Wachmann on 2 June 1955, he stated (our English translation): "I know very precisely his original solution. He was very much in love with it and I rightly ripped it down at the time." The blunt choice of words is noteworthy: Baade put his foot down *firmly* when it came to Schmidt.

Thereafter, Schmidt fell silent for two years, according to Baade's letter. Then suddenly he announced his aspheric corrector-plate camera. The steps in his thought process leading from the lens proposal to the aspheric corrector plate are unknown. Baade questioned Schmidt repeatedly about this afterwards, but Schmidt refused to answer (Dufner, 2002a: 190). Yet it is clear at the same time that Schmidt never forgot the use of lenses as a means of correcting spherical mirrors. After Baade left Bergedorf to take up a permanent position at Mt. Wilson in 1931, and after the success of the aspheric corrector-plate camera, Schmidt returned to the idea of large standard lenses. But this time, instead of placing them in contact with the mirror, he profited from the lessons of the 'Schmidt Camera' and moved them far away. This led to the Houghton-type of telescope.

6.4 Schmidt's Development of Large and Small Houghton Systems

Returning now to Figure 10, what is depicted there is a telescope of 1-meter focal length, since a notation at bottom right of the drawing in Schmidt's characteristic script reads: "Brw = 1 m," in other words, "focal length [*Brennweite*] = 1 meter." A short, dark vertical line placed on the graph paper 2½ divisions to the right of the corrector would seem to mark the position of the focal surface. Since this is exactly 20 divisions to the left of the mirror, the drawing scale is apparently 1 division = 5 cm, that is, 1:10. If so, then the system aperture would be 60 cm and the focal ratio would be f/1.67, closely matching Schorr's 1932 suggestion. But note also at upper left in Figure 10 a triplet lens consisting of one equi-concave and two plano-convex lenses —in other words, a Buchroeder-Houghton corrector. Unfortunately the drawing is undated.

The ambitious size of Schmidt's proposed systems as well as the rather hazardous notion of employing common soda-lime 'mirror-glass' instead of precision optical glass for the thick doublet (or triplet) corrector may have dissuaded Schorr from final agreement. Money was naturally tight since the years of these developments coincided with the worst part of the Great Depression. In any case, Schorr had another idea which he determined to implement using the available resources. He wanted to build a 'double reflector' consisting of a 60-cm f/5 conventional Newtonian telescope teamed with an identically-sized Schmidt aspheric-plate camera. With this he hoped not only to obtain coma-free images on a larger plate scale using the Schmidt camera, but probably also he wanted to show its decisive superiority over the Newtonian (Dufner, 2002a: 253-263; Schorr, 1936a: 45-46). The astronomical world had not beaten a path to the Hamburg Observatory after the initial announcement of Schmidt's revolutionary coma-free telescope (cf. Baade's remarks in Ingalls, 1953: 371).

Unfortunately, the combined double reflector (completed in 1935 and housed in a roll-off roof shelter) was so easily shaken by the wind that good exposures were almost impossible to obtain. A.A. Wachmann, one of the principal observers to use this telescope (for many years the largest Schmidt camera in the world), later termed it "the still-born child" (das totgeborene Kind—a hand-written notation on a photograph in the Wachmann-Schmidt archive; cf. Dufner, 2002a: 262).

As for Schmidt's spherical-lens cameras, they soon evolved toward smaller sizes. Figure 14 shows the only complete drawing from Schmidt to depict one of his Buchroeder-Houghton designs at scale (Hamburg-Bergedorf archive; cf.

Dufner, 2002a: 235). The focal length is listed as 62.5 cm, and all the radii are listed as 1250 mm. Since the position and diameter of the focal plane or film platen are clearly shown at the drawing center, we can see that the scale of the drawing is about 2.5 cm per division of his graph paper. From this we can deduce the size of the corrector triplet as 400 mm, and the mirror diameter as 475 mm. The film platen would be 100 mm in diameter.

But even this was apparently deemed too large, and in a packet of drawings and trigonometric calculations in the Hamburg-Bergedorf archive of Schmidt documents, dated 4 May 1934, there is a corrector 240 mm in diameter. This was shown above in Figure 4. Another page of the packet gives a corresponding dimensional drawing of the lens cell. In addition, the packet contains detailed trigonometrical ray-traces of the system for five ray heights in the entrance pupil. Longitudinal intersection lengths are calculated, and then graphed to show the higher-order spherical aberration error curve.

Who it was that performed the ray-tracing is unclear. The handwriting is not Schmidt's, being far less legible. Probably the answer is Carl Vick, a Bergedorf staff member who is known to have performed ray-tracing for Schmidt in connection with the double reflector, a project which was ongoing in 1934.

In the end, a further reduction of the triplet corrector camera to 120 mm clear aperture was decided on, and that is what was actually built. A new ray-trace was not needed since all the geometrical ray errors simply scaled down by one-half. Figure 15 reproduces the first page of notes connected to the ray-trace of the 240 mm version. The page is entitled: "Ray-tracing formulae for the Schmidt mirror with pre-placement lens" (Durchrechnungsformeln für den Schmidt'schen Spiegel mit Vorsatzlinse). A complete design is specified, utilizing one equi-concave and two plano-convex lenses, all of mean refractive index 1.53. A notation is added to the effect that the mirror radius—to first approximation—should be the same as the finite lens radii, namely 520 mm, but in case the mirror's radius is altered, its center of curvature should still coincide with the center of the 'pre-placement lens' (i.e. the corrector) by altering the air-space between the last lens element and the mirror (d_6 in the drawing). In fact, further up the page of notes we see that the mirror's radius was taken as 542 mm for the purposes of the ray-tracing. How this number was arrived at is unclear. Equation (1), given earlier in this paper, would predict 533 mm for a corrector with refractive index of 1.53.

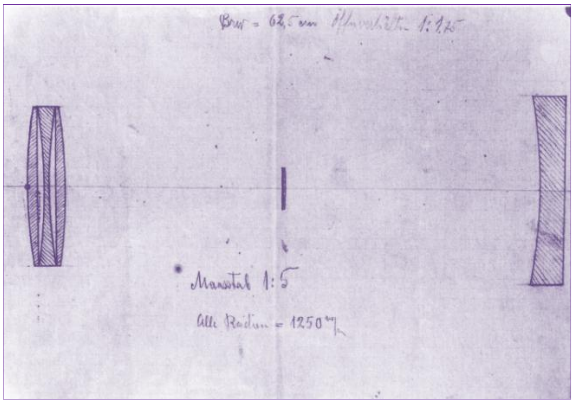


Figure 14: The only surviving scale drawing in Schmidt's hand for a full Buchroeder-Houghton camera. The focal length is listed as 62.5 cm and the drawing scale is 1:5. The notation at upper center-right, "Öffn[ungs]verhältn[is] 1:1.75" appears not to be in Schmidt's hand (image courtesy: Hamburg Observatory, University of Hamburg).

6.5 Symmetry and the Plane-Parallel Plate

However it was that Schmidt arrived at the idea of the Buchroeder-Houghton, he likely started from considerations of symmetry. Symmetry lay at the heart of his coma-free aspheric-plate cam-

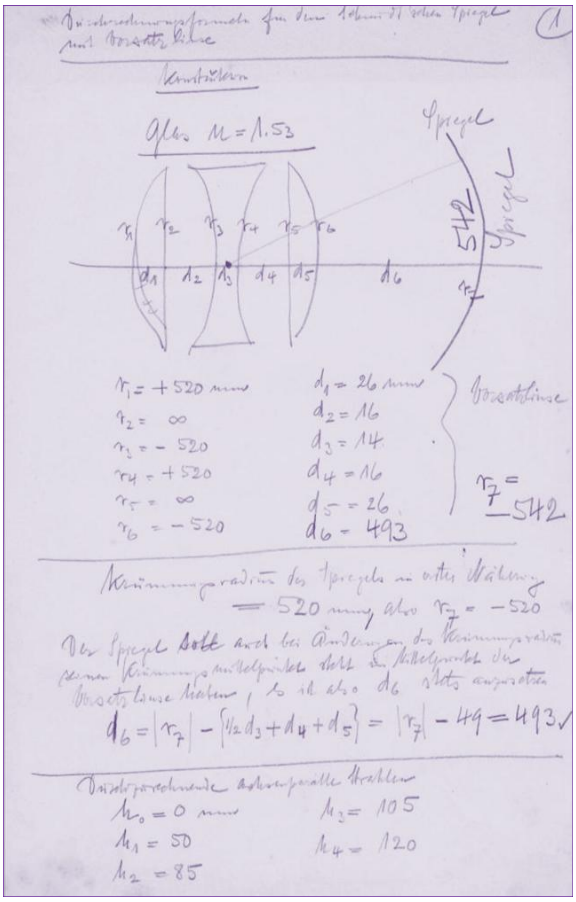


Figure 15: A page of notes accompanying the trigonometrical ray-trace of a 240 mm f/1.1 Buchroeder-Houghton camera. The notes contain a complete system prescription. All the finite lens radii are set at 520 mm, and the mirror's radius at 542 mm. Rays at normalized incidence heights of 0% (paraxial), 41.7%, 70.8%, 87.5%, and 100% (marginal) are traced on the following pages of notes in the packet (image courtesy: Hamburg Observatory, University of Hamburg).

era, and Schmidt understood the connections between optics and pure geometry. The greater the symmetry of a set of imaging optics around its aperture stop, the smaller in general will be the residual geometrical aberrations. Complete symmetry automatically eliminates coma, astigmatism, lateral color, and distortion. Lens designers have long utilized symmetry to design camera optics; in theoretical discussions, they speak of 'the symmetrical principle' (Smith, 2000: 401). Schmidt's aspheric-plate camera succeeded so admirably because it is almost completely symmetrical about its aperture stop; only the introduction of the plate's asphericity creates a weak axis that degrades symmetry. If the aspheric plate were to be discarded—or turned into a plane-parallel 'window'—leaving only the spherical mirror plus aperture stop as effective optical elements, the system would be perfectly symmetrical about the stop and hence would suffer none of the off-axis aberrations mentioned above. It would be afflicted with just spherical aberration and field curvature.

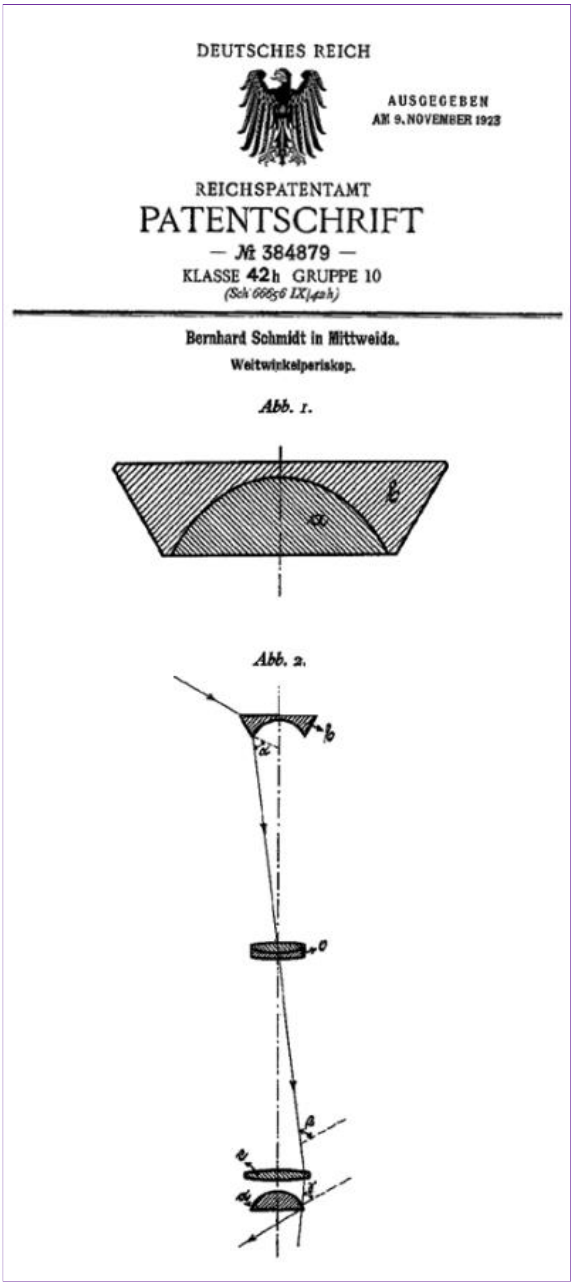


Figure 16: Drawing and title from Schmidt's 1923 German wide-angle periscope patent. The upper illustration (*Abb. 1*) shows how the plano-concave (b) and plano-convex (a) lenses conceptually fit together to form a plane-parallel plate.

The Buchroeder-Houghton corrector is a nearly symmetrical construction, if the aperture stop is placed on the middle lens element. It resembles a Cooke triplet lens, the most economical anastigmatic camera lens ever devised (Conrady, 1960: 817-818). But while the Cooke triplet must converge light to a focus, the Buchroeder-Houghton corrector exists only to contribute overcorrected spherical aberration which cancels the undercorrected aberration arising from the spherical mirror. At the same time, the corrector must not introduce other image errors. So it is given net-zero optical power which avoids longitudinal and lateral chromatic aberrations, and an overall symmetrical shape which avoids off-axis monochromatic aberrations.

Returning to the notion of a plane-parallel plate, Schmidt recognized that bundles of parallel rays traversing a flat plate suffer no aberration, even when they arrive at oblique incidence. But the plate can also be imagined as consisting of two lenses, one plano-concave, the other plano-convex, with their curved surfaces fitting one another exactly. The surfaces can even be mating aspheres and still the transmitted bundles will pass without aberration.

Schmidt had employed this idea as the basis for his invention of the wide-angle periscope that he patented in 1923. The patent drawing for this device is shown in Figure 16. Toward the top of the figure (*Abb. 1*) we find the plano-concave and plano-convex lenses fitted together, forming between them a plane-parallel plate. Schmidt's essential insight was that if these two lenses are separated and a relay lens of unit magnification is set between them—imaging the concave lens onto the convex—then by the proper choice of curves this simple device can act as a 1× periscope covering a visual angle of 120º with excellent sharpness. It lies beyond the scope of the present paper to explore this design in greater detail, but suffice to say that modern computer ray-tracing easily confirms Schmidt's claims.

The idea of a plane-parallel plate also figures in Schmidt's aspheric-corrector camera, as indicated above. Schmidt set a thin parallel plate at the center of curvature of a spherical mirror and figured an axisymmetric polynomial profile onto it, of such a form that it compensated the mirror's spherical aberration. This yielded a revolutionary instrument: the Schmidt Camera. But alas, it has physical limits imposed by the material strength of the glass, if a vacuum-pan is used to fabricate the corrector plate. If there is too much surface deflection under pressure the plate will shatter.

Still another use for a plane-parallel plate is to imagine that it consists of a plano-convex and plano-concave lens in contact—but now with the convex lens appearing first in the light path. Both lenses would be positioned at the center of curvature of a spherical mirror. In effect, they would form a 'lensless' Schmidt Camera, fitted with an optical window instead of an aspheric corrector plate (Ashcraft 1974). If the convex lens element is now reversed so as to point its convex face forward, towards the oncoming light and away from the concave lens, then together the two lenses would still exhibit no net optical power, but the changed lens orientation would drastically alter the combined spherical aberration. In particular, the convex lens would contribute far less undercorrected spherical aberration than in its former orientation. The balance of aberration would tip in favor of the concave lens, and the pairing as a whole would introduce *overcorrected* spherical aberration into the system—just what is needed to compensate the undercorrected aberration of the spherical mirror. Proper choice of radii (keeping lens curves equal but opposite, and using a single type of glass) can produce good compensation. This is the rationale behind the two-lens Houghton camera.

But unfortunately, this corrector lacks constructional symmetry. Coma and astigmatism cannot be eliminated by placing this two-lens corrector at the mirror's center of curvature as the system stop. Either it must be shifted from the center of curvature, or additional degrees of freedom (lens radii, glass types, aspherics) must be utilized. Schmidt himself seems to have understood this, since his doublet corrector as shown above in Figure 10 has been displaced from the mirror's center of curvature to a position near its focus (cf. Figure 9, upper right, for J.L. Houghton's analogous design). It lies beyond the scope of the present paper to delve more deeply into the design of two-lens Houghton or Richter-Slevogt telescopes. For further information, see Lurie (1975), Rutten and van Venrooij (1999: 299-300) and Sigler (1978).

A way to circumvent this problem is to reflect the doublet around its plano-concave element. One then obtains a symmetrical 3-lens construction of the Buchroeder-Houghton type, which is capable of very good off-axis performance when set at the spherical mirror's center of curvature. Indeed, in more elaborate forms this 3-lens design is *superior* to the corrector-plate Schmidt camera (e.g., in the Baker-Nunn camera; see Carter et al., 1992; Henize 1957).

That Schmidt may have proceeded conceptually from a plane-parallel plate to his two-lens and thence to his 3-lens corrector is suggested by another drawing in the 4 May 1934 packet of papers. This is shown as Figure 17. It appears on the reverse of the sheet already illustrated above as Figure 4—in other words, on the reverse of Schmidt's scale drawing of his 240 mm Buchroeder-Houghton corrector. In Figure 17, the plano-convex lenses have been reversed and the ensemble drawn as a plane-parallel plate, resembling the similar drawing in the wide-angle periscope patent.

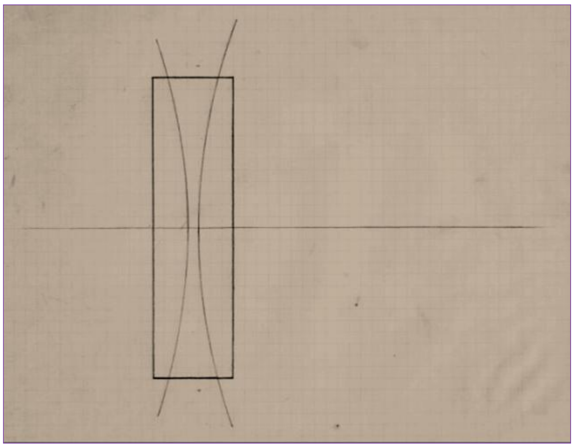


Figure 17: Reverse of the drawing shown previously as Figure 4. Here the plano-convex lenses of the Buchroeder-Houghton triplet have been inverted so that the ensemble forms a plane-parallel plate. In this orientation the glass will produce zero spherical aberration in transmitted parallel light (image courtesy: Hamburg Observatory, University of Hamburg).

7 MEASUREMENTS AND TESTS

Despite the uncertainty of how Schmidt arrived at his designs, he did build a 3-lens prototype and tested it in 1934, according to A.A. Wachmann. This is the instrument that we examined in the Schmidt Museum at Bergedorf and measured in 2007. Figures 6 and 7 above show the work in progress. We measured the surface *sagittae* using a precision spherometer, and then calculated the radii of curvature. We also measured other constructional parameters. These are presented in Table 1, where the numbers are expressed in millimeters.

As can be seen, the design matches rather closely the one-radius form of the Buchroeder-Houghton camera. The divergences in the case of the lens radii may have resulted either from spherometer inaccuracy or slight grinding and polishing errors. They can be shown by optical ray-tracing to have little effect on the final result. One must remember that this prototype was built for photographic purposes and so did not need to form diffraction-limited images.

Table 1: Our measured construction parameters for Schmidt's 1934 3-lens catadioptric camera. The old Schott optical glass 'O15' is conjectural (see the text), chosen to model the probable properties of Schmidt's soda-lime 'mirror glass'. The back focal length, curvature of the image surface, and image diameter are derived parameters.

Surface	Radius (mm)	Thickness (mm)	Glass	Diameter (mm)
Object				0
1		50		----
2	260.4	13	[O15]	125
3		7.3		125
Stop	–261.7	6.8	[O15]	125
5	261.7	7.3		125
6		12.8	[O15]	125
7	–260.4	243		125
8	–266.0	–130.192	Mirror	218
Image	–118.946	-----		28.6

Of more significance to the performance is the radius of the mirror. This was found to be 266 mm, while Equation (1) would predict 267.6 mm (assuming an average lens radius of 261.1 mm, and an n_d glass index of 1.53). The difference between the measured mirror radius and the theoretically-correct number is already enough in principle to cause a perceptible under-correction of spherical aberration. Despite this, the 'as-built' parameters would give reasonable prototype performance. For the purposes of completing our engineering model we have assumed the old Schott glass O15, a crown type with the constants, n_d = 1.53088 and v_d = 58.99. The actual properties of the glass in the prototype are not known, but its greenish coloration suggests common soda-lime 'plate glass', which was widely used at the time to make mirrors. Such glass would be similar to O15. The ray-trace drawing shown in Figure 15 specifies a glass with n_d = 1.53.

Figure 18 presents a schematic layout according to the parameters of Table 1. In principle, the diameter of the prototype's mirror (218 mm in clear aperture) allows a field of 20° (± 10°), covering a curved film platen 47 mm in diameter. That is what is shown in Figure 18. For the purposes of image evaluation, however, in succeeding diagrams the field has been reduced to 12° (± 6°), since beyond that the geometrical images begin to swell noticeably.

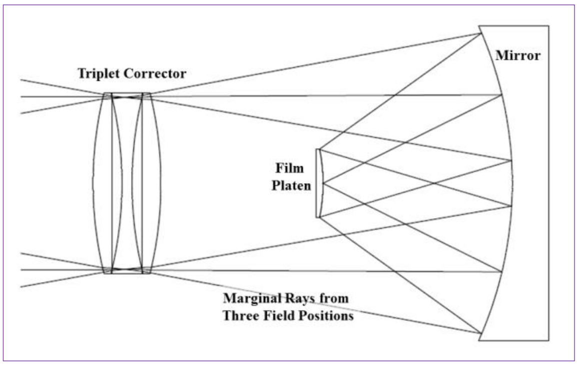


Figure 18: Schematic layout of the 120 mm f/1.1 prototype Buchroeder-Houghton camera as built. The mirror would allow a field coverage of up to 20° on the sky, but with considerable fall-off in edge sharpness. Over a more limited field of 12°, image sharpness is good.

7.1 Theoretical Imaging Properties

Figures 19 and 20 show the theoretical imaging properties of the camera according to the as-built parameters given in Table 1. For reference we should note that typical emulsions intended for faint-light detection in astronomy before the 1980s had rather coarse resolution. For example, the Kodak 103a series of plates, which were used in the first Palomar Sky Survey on the 1.2-meter Oschin-Schmidt Telescope, were rated to resolve 80 line pairs per millimeter, giving a resolution of 12.5 microns (Everhart, 1981: 100; Hartley, 1994: 118). Since for round images, the resolution is one-half the diameter of the image, this means that the smallest images recorded with these emulsions were about 25 microns across. Moreover the reciprocity failure of films meant that only the image cores would actually be recorded for fainter stars. Bright stars, on the other hand, would appear as 'burnt-in' spots many times larger than their actual image size, due to diffusion of light in the emulsion. In addition, 'halation' would create 'halos' of light around these burnt-in images (Kodak, 1987: 30-31, 37-39).

The upshot is that the size of the geometrical spots seen in Figure 19 should not be taken too seriously. In the case of most stars, only the bright cores would actually register, and these are in general only about 25-30 microns in extent over the field evaluated. Bright stars, on the other hand, would show images much larger than 30 microns, regardless of the geometrical spot size. Hence, the imaging properties of this crude prototype camera were in principle good by the standards of the 1930s, and justified A.A. Wachmann's statement that the camera, "despite its primitiveness, in the artist's hands took good photographs." (Wachmann, 1955a: 9).

Figure 20 shows the transverse ray-fan plots according to the as-built parameters. The main residual aberrations are 3rd- and higher-order spherical aberration across the field (balanced against defocus), and coma and astigmatism off-axis. Traces of other aberrations are also present. The 3rd-order spherical aberration is caused mainly by the non-optimum mirror radius, which as we noted previously is too short. Coma mainly results from a non-optimum separation of the mirror from the corrector. This should be enlarged by about 5 mm compared to the as-built separation of 243 mm. The error is small, and an adjustment of the existing collimation screws located behind the mirror would allow for this re-spacing. But in any case, especially in blue and green light, the colors to which the 1930s astronomical emulsions were most sensitive, the image cores are small enough over a 12° field to

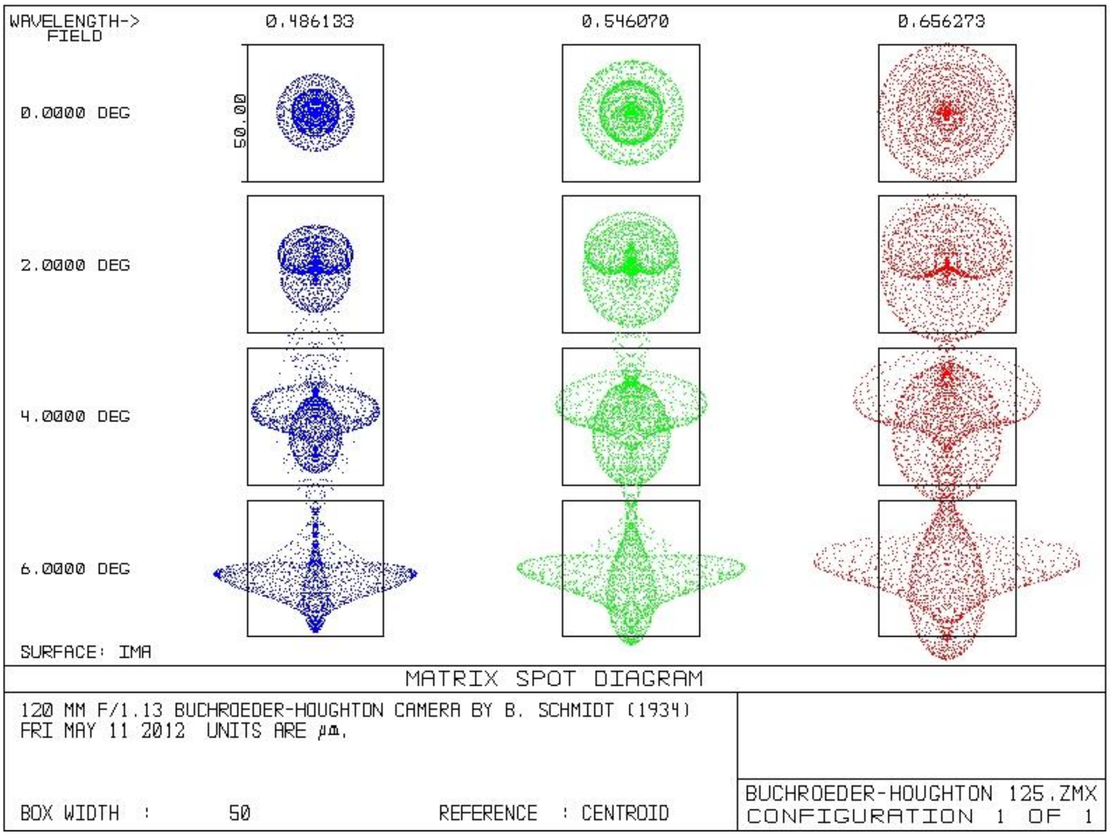


Figure 19: Geometrical optics spot diagrams for three wavelengths (486 nm, 546 nm and 656 nm) and 4 field positions (on-axis and at 2°, 4°, and 6° off-axis) of the 120 mm f/1.1 Buchroeder-Houghton camera as built, referenced to a curved image surface. The image cores of the spots are small enough that stars would look satisfactorily sharp on the astronomical emulsions of the 1930s.

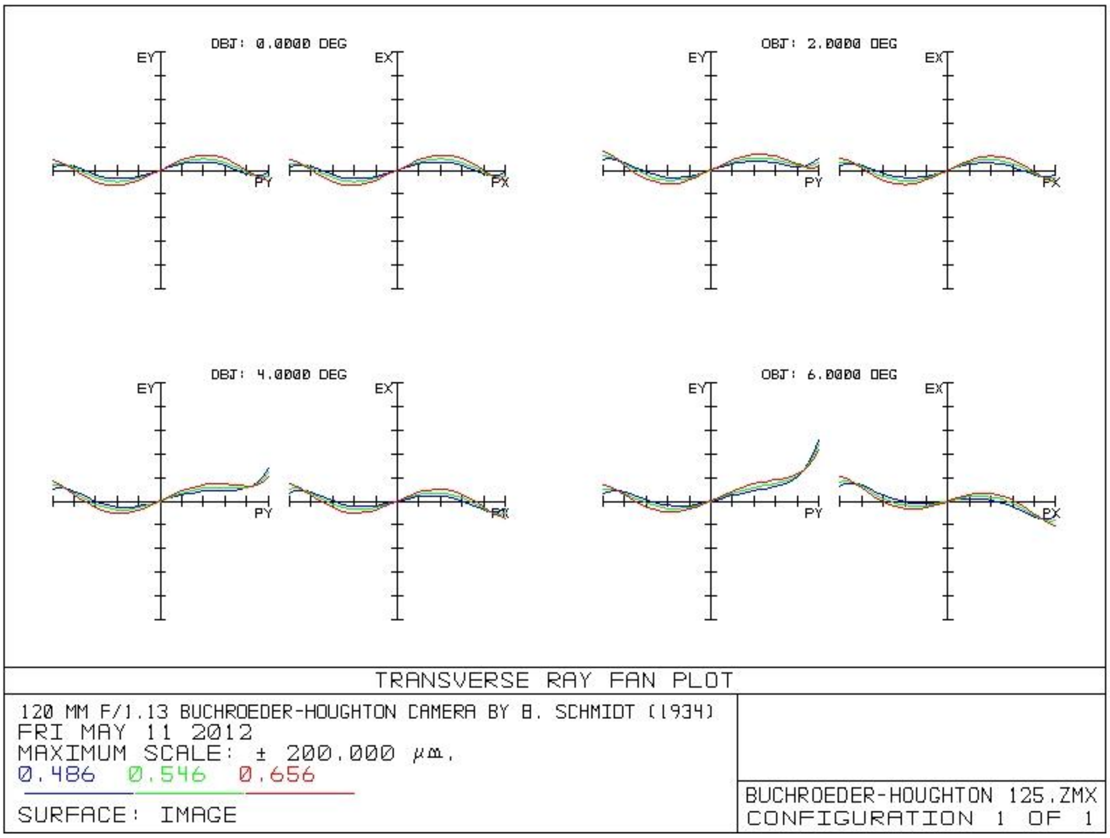


Figure 20: Transverse ray-fan plots for the Buchroeder-Houghton camera, referenced to a curved image surface. The on-axis error curves show the characteristic sinusoidal shape of a slight, undercorrected 3rd-order spherical aberration (plus defocus), and its chromatic variations. Off-axis are seen principally the effects of residual coma and astigmatism, in addition to the spherical aberration.

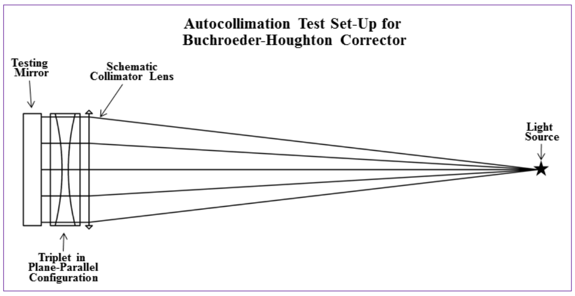


Figure 21: Schematic layout for testing a Buchroeder-Houghton corrector lens. The corrector elements are set into their 'parallel-plate' configuration. On right is a light source. Rays proceed from the source to a collimator lens, represented schematically in Figure 21 as a line with arrowheads at its tips. After passage through the collimator, the light traverses the corrector triplet and arrives at a testing flat on left. After retro-reflection, the light bounces back to a point beside the source where it can be viewed through a Ronchi grating or by means of another testing device.

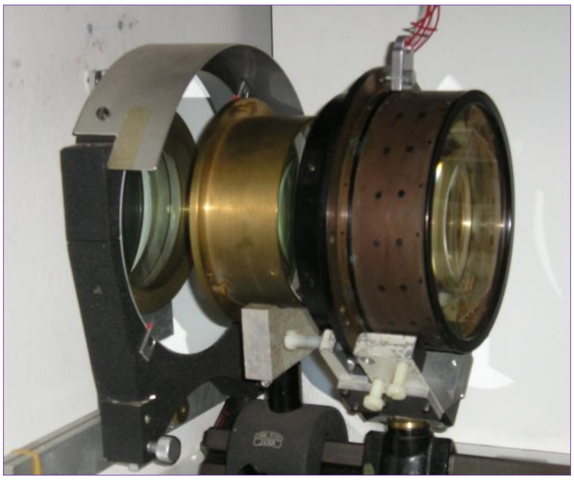


Figure 22: Our actual test set-up. A ZEISS-B apochromat, on the right, acts as a collimator from the light source into the lenses of the Buchroeder-Houghton corrector. On the left is an aluminized autocollimation flat, which receives the light and reflects it back through the system to a point beside the light source (image courtesy: Wolfgang Busch and Walter Stephani).

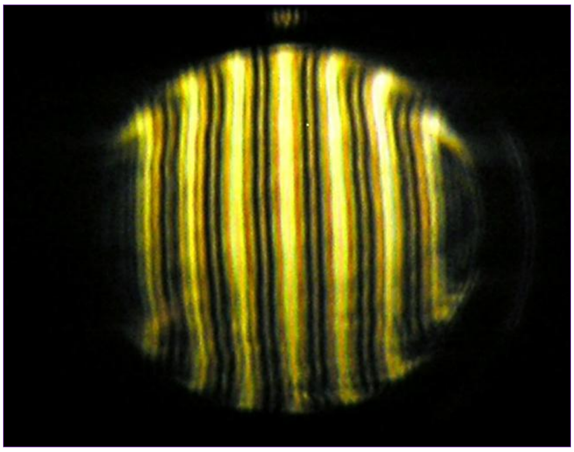


Figure 23. Test results using a Ronchi grating of 2 lines/mm, and testing configuration involving a double passage of the light through the lenses. Straight fringes in the test-image would indicate a spherically-converging wavefront and therefore a sharp focus (image courtesy: Wolfgang Busch and Walter Stephani.)

register as essentially perfect (on a curved film surface)—assuming that the lens and mirror figures were good, and that the homogeneity of the 'plate glass' was not overly bad.

7.2 Optical Testing Methods

Testing of the lens figures and homogeneity may be accomplished in a surprisingly easy way. We noted earlier that Schmidt's conceptual process for developing his Buchroeder-Houghton triplet might have begun with a plane-parallel plate, out of which he 'scooped'—so to speak—two convex lenses. These were then reversed in order to obtain lens bendings that minimized the under-corrected spherical aberration of the convex lenses, while leaving the overcorrected spherical error of the concave lens intact.

With this model in mind, we can easily see that it should be possible to restore the 'original' lens orientations, 'reassembling' so to speak the plane-parallel plate. Doing this should nullify the corrector's spherical aberration in parallel light, if the glass is good and the lenses correctly formed. In order to test the glass, one could utilize a collimator lens and an autocollimation flat. Light from a pinhole or slit source would proceed to the collimator, and after transmission would emerge in a parallel bundle. The bundle would proceed through the corrector lenses set in 'plane-parallel configuration', and finally arrive at the flat mirror. After reflection by the mirror, light would proceed back through the system and arrive at the focus.

Quantitative results could be derived using a laser interferometer, if one were available, but a Ronchi tester or Foucault knife-edge could also give a useful qualitative test. In particular, the Ronchi tester with its diffraction grating will generate the appearance of dark and light bands running across the optics under test. If the bands appear perfectly straight, it means that the transmitted wavefront is spherical and converges precisely to a focus. Any deviation from straight bands indicates aberration. Since the light passes twice through the lens system, any errors appear doubled. Of course the flat and especially the collimator lens must be of high quality so that their optical errors do not confuse the testing. Figure 21 shows a schematic layout of the testing configuration just described.

During the examination of the Buchroeder-Houghton camera, we tested the corrector triplet in just this way, using a large ZEISS-B apochromat as the collimator. The arrangement is shown in Figure 22, where on the right is the ZEISS-B, at the center is the Buchroeder-Houghton triplet in 'plane-parallel plate' configuration in its brass lens cell, and on the left is an aluminized autocollimation flat. Out of the picture, on extreme right, is the light source and Ronchi tester.

Figure 23 shows an image of the test results. Completely straight dark and light bands would indicate a perfect test result. Although these were not obtained, nevertheless the deviations from straightness are relatively small. We must remember first that the test was conducted in 'double pass', that is, with a double passage of the light through the optics. This means that the apparent errors in the wavefront will be double their magnitude when the lens system is in actual use. If we mentally 'unbend' the bands by 50%, they will obviously become much more linear.

And secondly, the lenses are not made of precision optical glass, but 'mirror-glass'. This means that the homogeneity in the index of refraction could easily be uneven in the substance of the glass. Some of the error in band straightness, particularly the high frequency kinks toward the bottom of the image, could be attributable to this source. Despite the possible testing errors, the bands appear remarkably straight nearly to the periphery of the image. Although they clearly betray a 'rolled off edge' in their sudden kinking at the periphery, it is clear that the corrector should perform nearly as well as suggested by the spot diagrams in Figure 19.

8 CONCLUDING REMARKS

On the basis of our examination of these optics, we may conclude that Schmidt's novel camera should have performed reasonably well by the standards of the 1930s, and had he lived longer he might be remembered not just for his epoch-making aspheric-plate camera, but for taking the first steps beyond it toward still faster imaging systems using only spherical optics. Certainly he would be credited with the invention of the Buchroeder-Houghton camera, and possibly he would have developed more general Houghton-type systems. It is important to remember that for several decades (in the 1950-1970s) the fastest wide-field imager in use for scanning the skies was the Baker-Nunn satellite tracking camera, which is an elaborated form of the 3-lens Houghton system (Henize, 1957). Thus the design form pioneered here by Schmidt had great intrinsic significance, and found important applications later in the twentieth century.

Documentary evidence reviewed by Dufner in her book shows conclusively that Schmidt was in the midst of a great burst of design creativity at the end of his life. Not only did he conceive and build this remarkable all-spherical f/1 camera, but he also conceived and proposed to build what we now think of as the 'Schmidt-Cassegrain', and a form of catadioptric Cassegrain using a sub-aperture Mangin mirror for the secondary mirror. This might have been analogous to the 'Klevtsov-Cassegrain', or J.L. Richter's 'Acme Telescope' (Klevtsov, 2000; 2004; Richter, 1981). What is clear is that continued study of Schmidt will certainly reveal more surprising details about his fascinating life and creativity.

9 ACKNOWLEDGEMENTS

We wish to thank the staff of the Hamburg-Bergedorf Observatory for assistance, and the administration for permission to disassemble, measure, test, and photograph the 3-lens prototype camera in 2007 and again in 2010, as well as for permission to publish these results together with images of the camera and Schmidt documents found in their archives. We also wish to thank Erik Schmidt for permission to access and quote from materials found in his archive relating to his uncle. We further thank the *Niedersächsische Staats- und Universitätsbibliothek* (Göttingen University) for permission to quote from the papers of Karl Schwarzschild; and Ekkehard Wachmann for permission to reproduce Figure 3. And finally, we thank Professor Manfred Steinbach and Dr Andrew Rakich for valuable feedback on earlier versions of this paper. All remaining errors are solely our responsibility. An earlier version of the paper was published in German (see Busch, Ceragioli and Stephani, 2011), and we thank Professor Steinbach for permission to revise, expand and pubish an English-language version of that paper.

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11 APPENDIX: BIOGRAPHICAL NOTES

11.1 Wilhelm Heinrich Walter Baade (1893–1960): Astronomer and astrophysicist. After graduation from Göttingen University in 1919, Baade was employed at Hamburg Observatory from 1919 to 1931. In 1926-1927, he travelled to the USA on a Rockefeller Foundation grant. Later he was employed at Mt Wilson and Palomar Observatories from 1931 to 1958. Baade studied stellar populations and galaxy structure, and made important contributions to the distance scale of the Universe. He was a friend of Bernhard Schmidt, and contributed to the introduction of the Schmidt telescope in the USA.

11.2 Richard Alfred Buchroeder (b. 1941): Optical designer and proprietor of Optical Design Service. Buchroeder holds a Ph.D. in optical sciences from the University of Arizona (1976), as well as 13 patents. He is the author of numerous publications, and specializes in the design of innovative optical systems. He works with large astronomical observatories. In 1972, he announced development of a simplified 3-lens Houghton-type catadioptric camera, identical in form to Schmidt's unpublished 1934 system.

11.3 James Leonard Houghton (1911–1995): Optical designer and theorist. Houghton worked for more than 30 years at Kodak Ltd. in the UK. In March 1941, he applied for a British patent on a catadioptric camera with a corrector consisting of two or three spherical lenses to replace the aspheric corrector plate of the Schmidt telescope. He obtained a United States patent for the same invention in 1944. He published papers on the theory of his designs in 1945 and 1971-1972.

11.4 Robert Richter (1886–1956): Optical designer. After graduating from Göttingen University, Richter worked at Voigtländer from 1914 to 1923. Then he joined C.P. Goerz, until Goerz merged with Zeiss-Ikon in 1926. Richter then worked for Zeiss until his death in 1956, serving as the chief of Zeiss's photographic division from 1939 to 1945. After resettlement in Heidenheim following WWII, he participated in building the West-German branch of Zeiss at Oberkochen. His work centered principally on aerial reconnaissance lenses, but also binoculars, and film projection and microscope optics. Together with Hermann Slevogt, he developed an all-spherical 2-lens catadioptric camera which anticipated the work of J.L. Houghton. They applied for a patent in 1941.

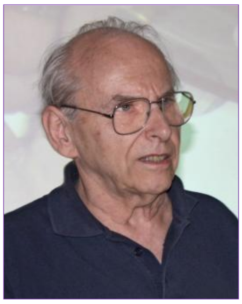
11.5 Bernhard Voldemar Schmidt (1879–1935): Optician and optical designer. Born in Estonia, at age 15 Schmidt lost his right hand when experimenting with gunpowder. He worked as a draftsman from 1899 to 1901 in Tallinn. After moving to Germany, Schmidt studied electrical and mechanical engineering at the Technical College ('Technikum') of Mittweida from 1901 to 1904. Then he founded an optical workshop in Mittweida, and won acclaim in 1906 for the production of a 41-cm f/2.26 paraboloidal telescope mirror for the Royal Astrophysical Observatory in Potsdam. In 1912, Schmidt refigured the 50-cm visual objective for Potsdam. His first contact with Hamburg Observatory came in 1916. For Hamburg he designed and constructed a 60-cm long-focus horizontal reflecting telescope with heliostat. Later he refigured the photographic objective of their 60-cm photographic refractor. By the end of his life, he held three patents and had built numerous optical systems for observatories at, e.g., Breslau (modern Wrocław), Vienna, Prague, Leiden and Leipzig. Today he is best-known for the invention of the aspheric corrector-plate 'Schmidt telescope' in 1929-1930.

11.6 Richard Reinhard Emil Schorr (1867–1951): Astronomer and observatory director. Schorr was Assistant Editor of the *Astronomische Nachrichten* from 1889 to 1891. Then he became assistant to the *Astronomisches Recheninstitut* in Berlin in 1891. Subsequently, he was Observer at Hamburg Observatory from 1892 to 1902, and then Director from 1902 until his retirement in 1941. Schorr planned and executed the move of the Observatory from central Hamburg to its present site at Bergedorf during the years 1900-1912. He specialized in positional astronomy. He was an occasional patron of Bernhard Schmidt from 1917, and regularly employed him from 1926 to 1935. In 1936, Schorr initiated plans for a large Schmidt telescope at Bergedorf, which was finally completed as an 80-cm instrument in 1955.

11.7 Hermann Slevogt (1909–1984): Optical engineer and physicist. Slevogt studied physics, mathematics, and astronomy in Bonn, graduating in 1932. He joined Carl Zeiss, Jena, in 1935, developing astronomical instruments. After resettlement in Heidenheim in 1945, he took part in building the West-German branch of Zeiss at Oberkochen. In 1952 he was appointed to the Chair of Technical Optics at the Technical University in Berlin, and served as Director of the Optical Institute. His areas of specialty were Seidel theory, diffraction theory, and the evaluation of image errors.

11.8 Arthur Arno Wachmann (1902–1990): Astronomer and Schmidt researcher. Wachmann studied at Kiel University, graduating in 1926. In 1927, he began working at Hamburg Observatory, first as Scientific Assistant, later as an Advisor, Supervisor, and finally Chief Observer, until his retirement in 1969. In 1962 he was made an Honorary Professor at Hamburg University. A dedicated observer and accomplished astrophotographer, Wachmann discovered four comets and a sub-class of T Tauri variable stars. Early on he recognized the importance of Bernhard Schmidt's work, and was one of the first people to take photographs through the original Schmidt corrector-plate telescope. He began his biographical work on Schmidt in the 1940s.

Wolfgang Busch (Ahrensburg, Germany) originally studied opto-mechanics and optical computation (the latter at the Hamburg-Bergedorf Observatory), beginning in 1948 after discharge from war service and completion of his secondary education. Later he altered his plans and devoted himself to the piano at the conservatory and to geography at the University of Hamburg. After taking his degrees, he taught gymnasium in Hamburg until his retirement in 1989. A lifelong amateur astronomer and telescope-maker, since the 1950s Busch has produced aspheric mirrors. In 1992, he devised special aspheric grinding techniques to build instrumentation for the Max Planck Institute of Flow Research in Göttingen. In the early 1970s, he invented the first modern oil-spaced apochromatic triplet telescope objectives for amateur astronomy, which he then described in print. More recently he has been involved in restoration projects. He has cleaned, measured and tested the 200-mm achromatic guiding telescope on the historic 1-meter Zeiss reflector at the Hamburg-Bergedorf Observatory; and he has developed specialized machining methods to restore worn Zeiss-B air-spaced apochromatic triplets—the most refined and delicate of all Zeiss' telescope objectives for amateur astronomy. He has published a detailed paper describing these methods. The largest of his restored Zeiss triplets (200-mm in diameter) was used as the collimator for the present study.



Dr Roger C. Ceragioli (Vancouver, Canada) obtained a Ph.D. in Classical Philology from Harvard University in 1992. Later he worked for a decade as an optician at the University of Arizona's Steward Observatory Mirror Lab, specializing in the production of aspheric mirrors and lenses in the half- to one-meter class. At present he designs lens systems for commercial production, and engages in historical research, serving on the History Committee of the Royal Astronomical Society of Canada. He is the author of several papers on the history and design of telescope optics, and is co-author (with Gregory Hallock Smith and Richard Berry) of *Telescopes, Eyepieces, and Astrographs: the Design, Analysis, and Performance of Modern Astronomical Optics*, (Willmann-Bell, 2012). He will soon complete a major study of the telescopes of William Herschel, and is producing the first English translation (from Latin) of Johannes Kepler's seminal book on the telescope, *Dioptrice* (1611). He and Walter Stephani are engaged in a long-term biographical study of Bernhard Schmidt.

Walter Stephani (Kiel, Germany) works in information technology for a company that specializes in the installation of air purification systems. During the 1980s and 1990s he published technical computer manuals. His academic training is in musicology and the history of music. Beginning in 1972 and mentored by Wolfgang Busch, Stephani learned optical fabrication and testing methods, which he used to build his own telescopes. Since 2004 he has devoted himself intensively to the historical study of Bernhard Schmidt, and has uncovered a vast array of new documentary sources, previously unavailable for scholarly study. Recently, he secured the donation of the priceless Wachmann-Schmidt archive of documents and photographs from Mr Erik Schmidt (Mallorca, Spain) to the University of Hamburg. Combined with the Bergedorf-Schmidt archive and artifacts, together they comprise the largest collection of materials in the world for the study of Bernhard Schmidt's life and scientific achievements.

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THE FLYNN CREEK METEORITE IMPACT SITE AND CHANGING VIEWS ON IMPACT CRATERING

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Abstract: Flynn Creek is one of two confirmed meteorite impact sites in Tennessee, USA. The first published mention of the Flynn Creek Structure was by J.M. Safford, Tennessee's State Geologist, in his *Geology of Tennessee* (1869). Subsequently, the site was investigated briefly in the 1920s and 1930s, but it was only in the 1960s following the founding of the United States Geological Survey's Astrogeological Studies Group as a lead-up to manned lunar exploration that Flynn Creek assumed international importance. This was because it was seen as the best terrestrial analog of a 'typical lunar crater'. As a result, CALTECH graduate student D.J. Roddy used Flynn Creek as the focus of his Ph.D. research, under the supervision of the Group's leader, Gene Shoemaker. After graduating, Roddy continued to conduct on-going investigations at this site up until the time of his death in 2002. Roddy's research has provided a wealth of information regarding the formation and structural features of the Flynn Creek site and shown that the crater was formed during Middle to Late Devonian times as a result of a shallow marine impact. Impact folding and faulting and subsequent uplift and erosion led to the formation of a system of caves at Flynn Creek that is unique among US impact sites.

Keywords: Flynn Creek, Tennessee, impact structure, shatter cones, extreme brecciation, marine impact events, faulting, cave-formation, D.J. Roddy

1 INTRODUCTION

The state of Tennessee in the USA boasts two undisputed impact sites, Wells Creek and Flynn Creek, and two possible impact craters, the Dycus Structure and the Howell Structure (e.g. see Berwind, 2006; 2007; Born and Wilson, 1939; Deane et al., 2004; 2006; Ford et al., 2012; Mitchum, 1951; Price, 1991; Schedl et al., 2010; Stearns, 1988; Wilson, 1953; Wilson and Stearns, 1966; 1968; and Woodruff, 1968), and these are shown in Figure 1. Of these, the Wells Creek crater has played a major role in increasing our awareness of the nature of terrestrial impact cratering (see Ford et al., 2012), but the Flynn Creek Structure[1] has also made a valuable contribution to our knowledge of marine impact events and the subsequent formation of cave systems associated with such impact sites. In addition, from the 1940s the Flynn Creek site was regarded as more closely resembling a typical lunar crater than any other known terrestrial crater, and this would later prompt its intense investigation in the era leading up to the first American Moon landing. In this paper we review the accumulating evidence that has been provided by the Flynn Creek impact site.

According to Dietz (1959: 498), "An event, if there is any possibility of its happening, becomes a commonplace occurrence within the enormous span of geologic time …" We see a myriad of craters on our nearby neighbor, the Moon, so similar impacts should have occurred and be evident on the surface of our own Earth. In late Devonian or early Mississippian times, a nearly circular crater, about 3.6 km in diameter, formed at the location that is known today as Flynn Creek in Jackson County, Tennessee, and was soon after filled with and preserved by sediments from the Chattanooga Sea (Baldwin, 1963; Schieber and Over, 2005). Today the Highland Rim entirely surrounds the Nashville Basin in central Tennessee, and the Flynn Creek Structure is located on the northern section of the Eastern Highland Rim escarpment (Roddy, 1966c) where the strata are essentially horizontal and dips >5° are rare (Roddy, 1963, Wilson

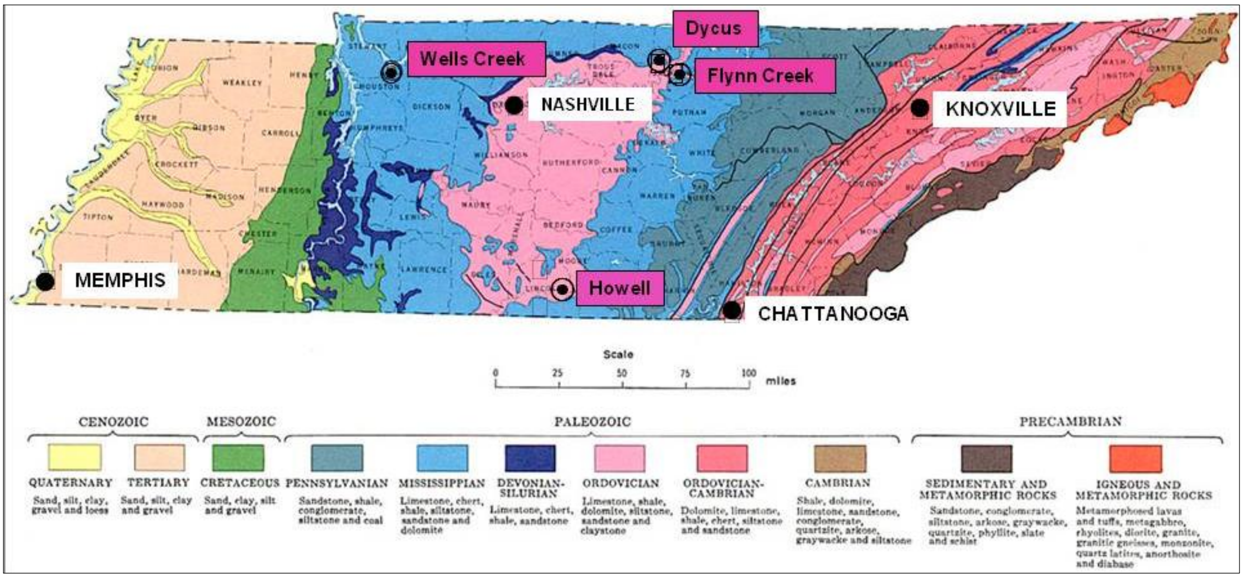


Figure 1: Generalized geological map of Tennessee showing the locations of the four largest cities (black dots) and the two confirmed and two suspected meteorite impact sites (small black dots with circles). These sites are located on the Highland Rim (Wells Creek), a Highland Rim outlier remnant (Howell), or on the Highland Rim escarpment (Dycus and Flynn Creek). The Highland Rim is the sky blue region on the map (base map after Tennessee Department Conservation, Division of Geology, 1966).

Figure 2: View of the Flynn Creek area on Safford's 1869 geological map of Tennessee (adapted from: http://alabamamaps.ua.edu/historicalmaps/us_states/tennessee/index2_1851-1900.html), showing no indication whatsoever of the Flynn Creek Structure.

and Born, 1936). In fact,

> The average regional dip is about 0.25 degrees … [and] In such a region, characterized by relatively underformed strata, the presence of a small area of highly disturbed, contorted and brecciated strata, locally vertical and overturned, is of more than passing interest … (Roddy, 1966c: 96).

This is especially true since faults and fault zones are rare in central Tennessee, and faulting has not been observed in the several hundred square miles surrounding the Flynn Creek area (Roddy, 1966c). However, at Flynn Creek itself,

> … fault zones are present in the region of the innermost rim, crater wall, and outermost crater floor region, and are continuous around at least the western, northern, and eastern sides

of the crater … (Roddy, 1980: 941).

The Highland Rim of Tennessee is included in the Central Forest Region of eastern North America, and the area in which Flynn Creek is located is heavily wooded and dense undergrowth makes field work rather difficult. Ridge tops in the area lie at a nearly uniform level of 300 meters above sea level with the valleys, including parts of the Flynn Creek Valley, on average some 160 meters above sea level.

The Flynn Creek Structure was named after the largest stream that flows through the area. This stream is fed by a large spring located at the eastern edge of the crater rim, and it drains directly into the Cumberland River some 8.0 km northwest of the crater (Roddy, 1966c). This feature is not prominent on photographs taken by the United States Department of Agriculture, Production and Marketing Administration (Baldwin, 1963: 89), due, in part, to the fact that it "… does not greatly affect the present topography except along the northwest rim …" (Roddy, 1966c: 25). In this particular section, one of Flynn Creek's larger tributaries follows the outline of the crater rim as "… it erodes into the less resistant, overthickened Chattanooga Shale …" (ibid.). It was here at Flynn Creek, during an early mapping expedition by James M. Safford (1822–1907), a Professor of Natural Science and the State Geologist for Tennessee, that this unusual geological structure was first noticed.

2 HISTORICAL CONTEXT

The first mention of a disturbance at Flynn Creek was made in Safford's report, *Geology of Tennessee*, which was published in 1869:

> Another area of disturbance is in the upper part of the valley of Flynn's Creek, in Jackson County. This area is limited in extent, and has comparatively little importance, yet the formations are greatly disturbed. The rocks are seen to dip at high angles, and are occasionally almost vertical. The valley is narrow, and the hills on each side high. In their normal position the *siliceous* is at the top of the series of formations, and the *Black Shale* next below. In several places both are brought down, by great folds and faults, to the bottom of the valley, and, at one point, may be seen abutting against the Nashville Formation. One fault shows a displacement of a thousand feet [300 meters]. The lines of disturbance run nearly north and south. (Safford, 1869: 148).

Although Safford considered the Wells Creek Basin of sufficient importance to be included on his map of the State of Tennessee which accompanied the geology report (see Ford et al., 2012), the Flynn Creek structure was not even noted on the map. For example, see Figure 2, which is a close up view of the Flynn Creek area as depicted on Safford's 1869 map.

The area was mapped again in 1925 by the Topographical Branch of the United States Geological Survey, with no mention or indication of the disturbance, and then again in 1926 by R.G. Lusk for the State Geological Survey of Tennessee. Lusk wrote that "An interesting result of the summer's work was the discovery of an extraordinary local thickness of the Chattanooga Shale …" which was generally 3-15 meters thick in the Nashville Central Basin and adjacent areas and "According to general observation, the thickness does not vary more than five or ten feet [1.5 to 3 meters] in many miles …" (Lusk, 1927: 579). However, Lusk (ibid.) found the thickness in Flynn Creek to be greater than 45 meters along the creek where the Shale is exposed in several places with up to 23 to 27 meters of strata visible in a continuous outcrop. He wrote (ibid.) that the Shale "… lies in an irregular closed depression … [and] in a limestone conglomerate-breccia …" Lusk did not observe actual contact of the breccia with formations other than the Chattanooga Shale, but he did note that the breccia was greater than 30 meters thick in some locations. Lusk concluded (1927: 579-580) that the structure was a "… pre-Chattanooga Sink Hole …", with a depth of almost 60 meters.

Wilson and Born (1936: 815) visited the structure in 1935 and concluded that Flynn Creek was not a sink hole, but that "All the data accumulated indicates a crypto-volcanic origin of the structure." Dietz (1946: 466; our italics) disagreed, and also explained why Flynn Creek was important in the study of astrogeology:[2]

> A resemblance between these crypto-explosion structures and lunar craters is most clearly apparent in the Paleozoic-aged Flynn Creek structure which, although filled and covered with later marine sediments, uplifted, and subaerially eroded in the few hundreds of millions of years that have elapsed since its formation, contains a nearly two-mile-wide [3.2 km] explosion crater with a central uplift. Here, then, is an example of a terrestrial explosion crater with a central hill as well as other shape aspects such as a circular outline, radial symmetry, a rim of rock detritus, and a crater depressed below the surrounding terrain all of which are characteristic of lunar craters. As reconstructed by Wilson and Born, *the Flynn Creek crater probably bears a closer resemblance to a typical lunar crater than any present-day terrestrial feature*.

Roddy (1965: 50) notes as a result that the Flynn Creek structure "… has been under study as part of a larger program of crater investigations by the Branch of Astrogeology … " It was one of two impact structures located in the United States selected for this study (*Astrogeologic Studies*, 1967), and a series of *Astrogeologic Studies Annual Progress Reports* from the

1960s and 1970s describe research conducted by the United States Geological Survey on behalf of the National Aeronautics and Space Administration. The long-range objectives of this project were

> … to determine and map the stratigraphy and structure of the crust of the Moon and other planets, to determine the sequence of events that led to the present condition of the surfaces of the planets, and to describe how these events took place. (*Astrogeologic Studies*, 1967: 1).

Denson (2008: 13) describes the result of the Flynn Creek investigation undertaken by the Astrogeologic Studies Group:

> It was not until the 1960s and 1970s that the true nature of the site came to light under the careful scrutiny of one of the great planetary scientists of the twentieth century, Eugene Shoemaker [who founded the Group], when one of his graduate students chose to do his dissertation on the site. That individual … [was] Dave Roddy ...

Figure 3: Dave Roddy, 1932–2002, who spent about forty years researching the Flynn Creek Structure (adapted from Chapman, 2002).

We have to thank the late Dave Roddy (Figure 3) for much of what we now know about the Flynn Creek Structure. David John Roddy

> … was born in Springville, Ohio, in 1932 to Jack and Nellie Roddy. He attended the U.S. Air Force School in Harlington, Texas, from 1957 to 1958. Dave got his A.B. and M.S. degrees from Miami University in Ohio in 1955 and 1957, respectively. He was a distinguished graduate of the U.S. Air Force ROTC program at Miami University. From 1957-1960, he was in active service as an Air Force navigator. He attended California Institute of Technology in southern California from 1960 to 1966, receiving a Ph.D. on the dissertation topic of "Impact-cratering mechanics of Flynn Creek, Tennessee" working under Dr. Gene Shoemaker. In 1962, he was induced by Gene to work in an interim capacity at the USGS in the newly-formed Branch of Astrogeology. He joined the Astro Team full time in 1965. Dave was Associate Branch Chief of the Astrogeology Team from 1983-1984. He retired from the USGS in 1992, but remained with the Team as an Emeritus and was extremely active in Science to the very end. David was a member of Sigma Gamma Epsilon, the Geological Society of America, the Mineralogical Society of America, Sigma Xi, American Geophysical Union, and the American Society of Industrial Security …
>
> The prestigious Barringer Award was presented to David Roddy at the International Meteoritic Society Meeting in Prague, Czechoslovakia, on August 3, 1994, in recognition of his outstanding scientific contributions and lifetime work in the field of impact crater mechanics …
>
> Throughout the 1980s and early 1990s his constant companion was a small white terrier named Michelle. Clad in sunglasses and leather pilot jacket with Michelle trotting at his side, Dave was a driven scientist with a Colonel Flag persona, who aspired to the highest of standards, but usually had time for lunch with friends …
>
> Most of his life Dave was a vital man with a passion for running and staying fit. Although the last ten years of his life were marked by a battle with Parkinson's disease, he fought it every inch of the way ...
>
> U.S. Geological Survey, Astrogeology Team Emeritus David John Roddy passed away at 9:40 in the morning, March 21 [2002] at St. Louis hospital while on a short trip. He had gone into the hospital complaining of chest pains and ruptured an aorta while undergoing a heart scan. He died immediately. (Chapman, 2002).

Roddy was a graduate student at CALTECH when he first investigated the Flynn Creek site and began publishing papers about it in the *Astrogeologic Studies Annual Progress Reports* for the U.S. Geological Survey. These early reports were followed by many more papers on Flynn Creek that Roddy wrote throughout the rest of his career. Roddy's research and field work associated with his Ph.D. thesis was supported by the U.S. Geological Survey's Branch of Astrogeology, as well as by a National Aeronautics and Space Administration (NASA) grant from 1963 to 1965 (Roddy, 1966c: 33). His thesis involved a comprehensive study of the Flynn Creek Structure, and he noted that "Since 1961 increased interest in the lunar craters has been stimulated by the efforts directed toward manned lunar exploration. This interest in lunar craters in turn revived an interest in terrestrial crater studies …" (Roddy, 1966c, 10).

Unfortunately this interest did not spread very far, as noted by Denson (2008: 15), a native of the area:

> During the days of Apollo, some of the astronauts visited this site while Dr. Shoemaker was giving them their "crash course" in the geosciences. I find it very frustrating in retrospect that I cannot remember this ever being the topic of discussion during my elementary school years, which were spent just a few miles away.

Roddy (1966c: 14) states that "The Flynn Creek crater was chosen for the current study because the local and regional exposures are among the best of all the 'cryptoexplosion' structures in the United States." He concluded that the Flynn Creek crater "… appears to have been formed during the impact of either a comet or a meteorite …" (Roddy, 1966c: 217).

Not all agreed, however, that such structures were the result of meteorite impacts. As late as 1964, in the Introduction to Volume 2 of the *Developments in Sedimentology*, Amstutz (1964: 1, 3, 5) expressed his skepticism:

> We tend to approach the outcrop and set up an experiment on the basis of preconceived hypotheses – consciously or, more often, subconsciously – and in interpreting these observations, we are prone to use only those assumptions which are indigenous with us …
>
> These figures also illustrate how, actually, ore genesis theories at present go through exactly the same crisis and change as did paleontology one hundred years ago, when Darwin and others proposed to look for factors "from within", and rejected the exogenous creationistic theories.
>
> This process of evolution of thought from epi-exo-patterns to syn-endo-patterns is one which takes place all the time in all fields of human culture, including the sciences. It suffers relapses of course as recently seen when the myth of flying saucers and of meteor impact structures swept around the world and even affected the scientists …
>
> It is interesting to note that the hidden sources for the emanating solutions are almost always at "unknown depth". The movement away from the myth of the "unknown depths" and the myth of replacement is most interesting and valuable historically because it parallels the general integration of a sound knowledge and acceptance of the realm of the subconscious in the human mind. This acceptance eliminates the need for a mythological compensation in form of a "scientific" theory on emanations from unknown depth or impact from unknown outer space sources.

Progress in understanding the formation of crypto-explosive structures was being made in both the astronomical and geological communities, however (McCall, 1979; Mark, 1987; Shoemaker, 1977). In 1963, another luminary of impact cratering, Robert Dietz (1914–1995) wrote:

> In view of the growing literature on impact structures and the topical interest in lunar craters … it has been satisfying to witness the changing view of geologists toward the impact rationale from virtually non-acceptance, and even ridicule, to its present position as the favored hypothesis. (Dietz, 1963: 650).

Koeberl (2009) points out, however, that opposition to the meteorite impact hypothesis remained right up until the time of the first manned landing on the Moon. He states that "Planetary exploration and extensive lunar research eventually led to the conclusion that essentially all craters visible on the moon (and many on Mercury, Venus, and Mars) were of impact origin …" (Koeberl, 2009, 12). These observations led to an understanding that the Earth has also experienced significant meteorite impacts (Hoyt, 1987; Melosh, 1989), and "Today, astronomers and geologists recognize that impact processes are among the most common mechanisms to have shaped the Earth …" (Koeberl, 2009: 12-13).

3 STRUCTURAL FEATURES AND AGE

Miller (1974: 56) states that in contrast to the Wells Creek Structure, the event that formed the Flynn Creek crater can be dated with a fair amount of accuracy:

> This crater presumably formed in Middle to Late Devonian time (350-375 million years ago), for it is filled with Chattanooga Shale. This indicates that erosional alteration of the crater itself had been occurring for only a geologically brief time prior to deposition of the Chattanooga Shale in Late Devonian time.

When formed, the crater was most likely around 100 to 120 meters deep relative to the surrounding surface and "Since the rim was completely removed by erosion and yet the pit was not filled with air-borne sediments, the explosion is dated as shortly before the deposition of the Chattanooga shale, or in late Devonian time." (Baldwin, 1963: 89).

Figure 4 shows a composite stratigraphic section for Middle Tennessee by Miller (1974: 59) as a reference for discussing the Flynn Creek crater. Referring to Upper Devonian units, Roddy (1966c: 59) writes that "Until the present work on the Flynn Creek structure, Richmond strata had not been recognized in the area." According to the United States Geological Survey, the Upper Ordovician units in Tennessee include the Richmond Group (name not shown in Figure 4), which is composed of the Mannie Shale, Fernvale Limestone, Sequatchie Formation, and the Arnheim Formation; the Maysville Group, which includes the Leipers Formation; the Eden Group, which includes the Inman Formation; the Middle Ordovician with the Nashville Group, which includes the Catheys Formation, Cannon Limestone, and Hermitage Formation; and then the Stones River Group, which includes the Pond Spring Formation. In Tennes-

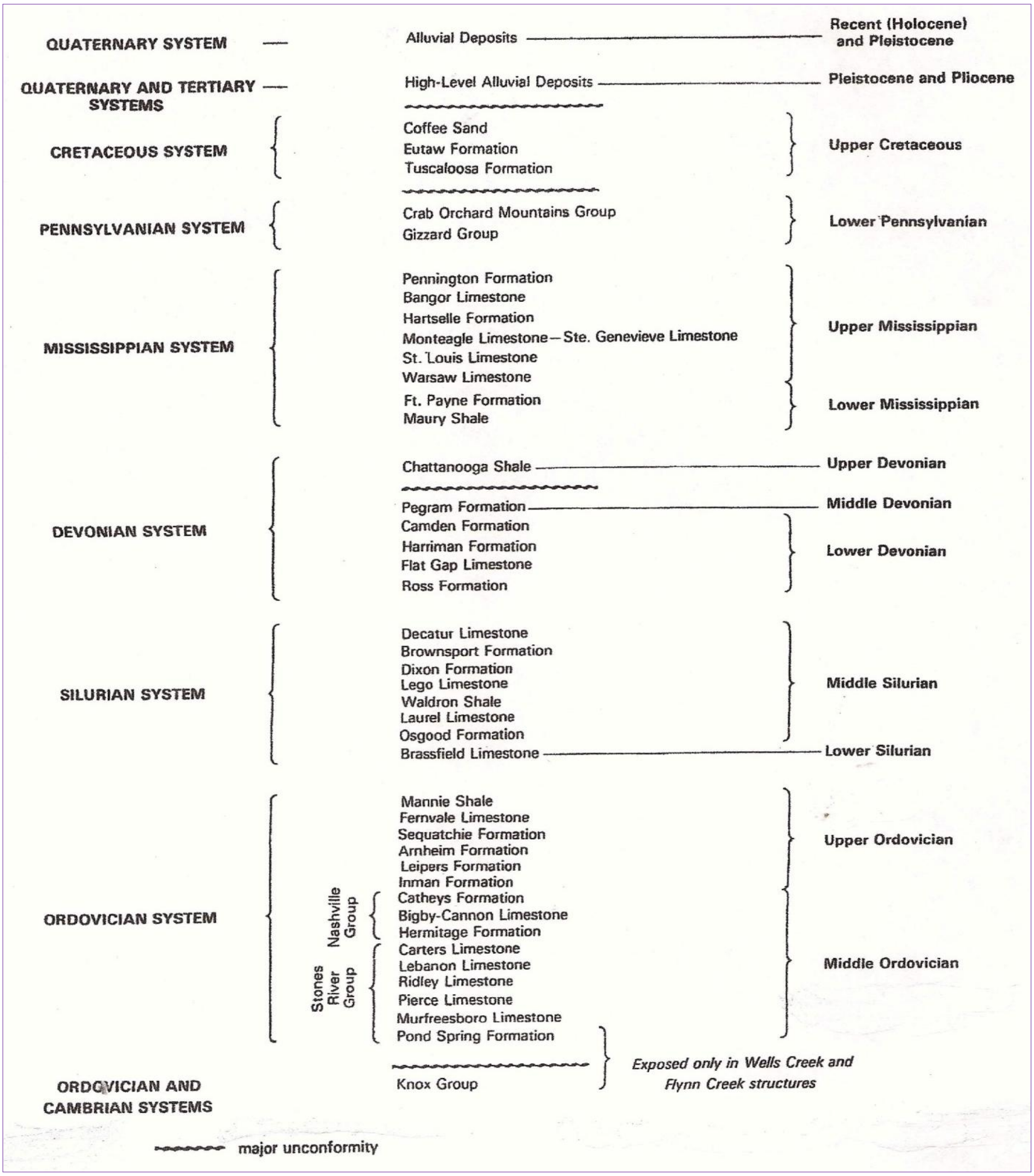


Figure 4: Composite stratigraphic section for Middle Tennessee (after Miller 1974: 59).

see usage, the Pond Spring Formation is equivalent to the Wells Creek Formation (Brahana and Bradley, 1985).

The oldest rocks in central Tennessee are dolomite and limestone of the Knox Group, which range in age from Upper Cambrian to Lower Ordovician, and these are found exposed "… at the surface only in the faulted, folded and brecciated central parts of the Wells Creek and Flynn Creek structures …" (Roddy, 1966c: 34; cf. Miller, 1974). Roddy (1966c: 46) states that "… it is common in subsurface studies to refer to the strata below the Wells Creek dolomite only as upper Knox Group." Normally, the Knox strata are over 300 meters below the middle Tennessee surface in flat-lying beds (ibid.). The Knox Group in central Tennessee is around 1.5 km thick and may rest directly on the crystalline basement. As can be seen in Figure 4, a major unconformity exists in central Tennessee between the Stones River Group and the Knox strata.

It is interesting to compare and note the similarities in Miller's stratigraphic section for Middle Tennessee, shown in Figure 4, and Figure 5, the "Generalized columnar sections from the Western Rim to the Central Uplift of the Flynn Creek Crater" by Roddy (1966c: 38). Out-

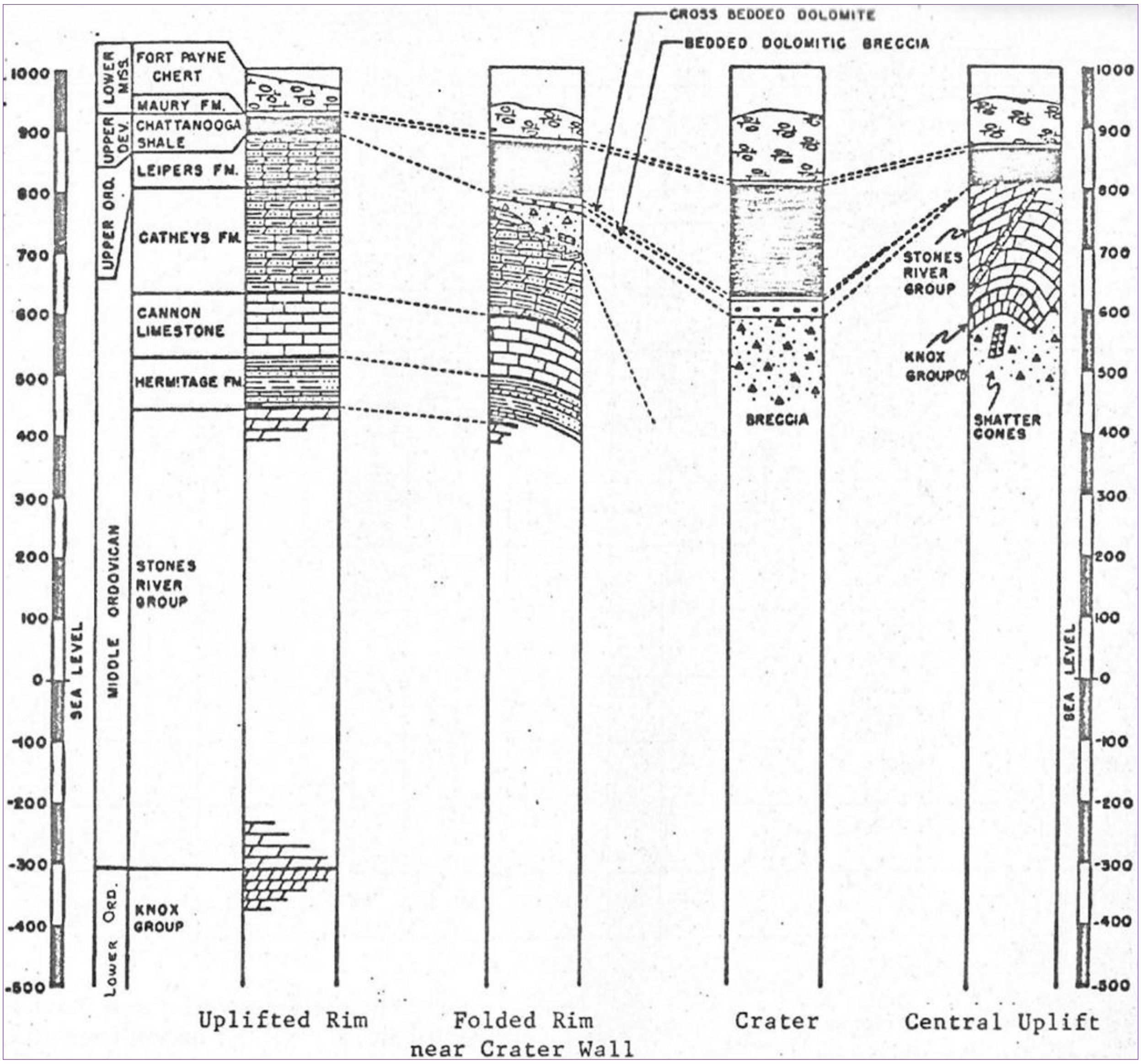


Figure 5: Generalized columnar sections from Flynn Creek Western Rim to Central Uplift (after Roddy, 1966c: 38).

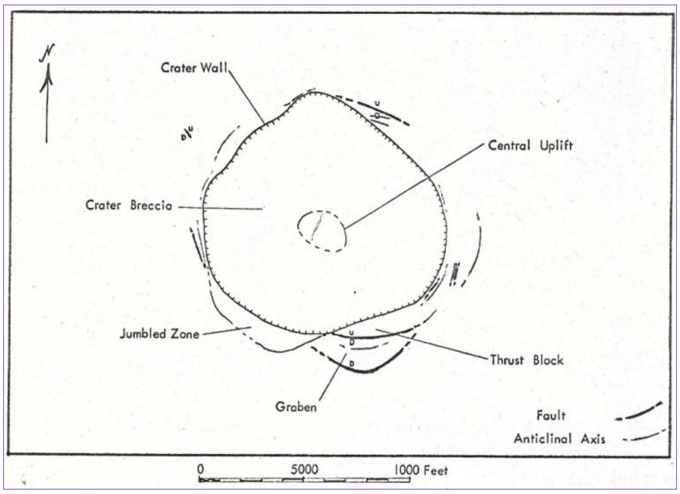
side of the Flynn Creek area of deformation, rocks range from the Cannon Limestone of the Middle Ordovician to the Fort Payne Formation of Early Mississippian age (Roddy, 1968b). Inside of the crater, however, rocks from the upper Knox Group of Early Ordovician age through the Stones River Group and Hermitage Formation of the Middle Ordovician age are exposed (ibid.). Beds of Cannon Limestone up to the Leipers Limestone are exposed in the crater rim and walls. The only rocks found to be involved in the structural deformation of the crater are of pre-early Late Devonian age. Roddy (ibid.) also points out that no Silurian or Lower or Middle Devonian strata have been recognized in the area of the Flynn Creek impact site.

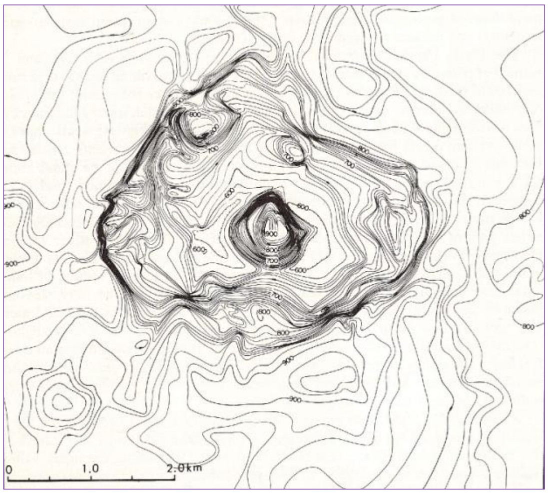
The Flynn Creek event occurred on either "… a low, rolling coastal plain or in the very shallow waters of the Chattanooga Sea." (Roddy, 1977a: 211). Breccia first washed down from the crater rim onto the crater floor, followed by dolomites derived from the rim crest and then early Late Devonian marine conodonts of the Chattanooga Sea. Flynn Creek

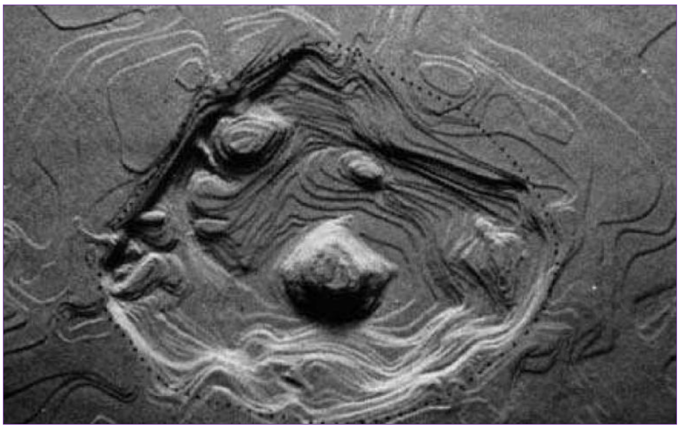
> … experienced both limited erosion in the higher elevations as well as marine deposition at approximately the same time on the crater floor, or shortly thereafter … The important result was that the crater experienced relatively little erosion before complete burial under the fine silty muds of the Chattanooga Shale … (ibid.).

Unlike most impact structures, because of its quick burial Flynn Creek suffered little alteration and thereby retained the basic morphology of the original crater (cf. Boon and Albritton, 1937).

As an overview, the Flynn Creek Structure's primary features are its central uplift, which consists of limestone blocks raised over 150 meters, and a depressed ring of breccias that surrounds the uplift and contains blocks of all the rock layers involved in the disturbance (Baldwin, 1963). Breccia overlying a graben in the southern rim is still preserved and this "… is the







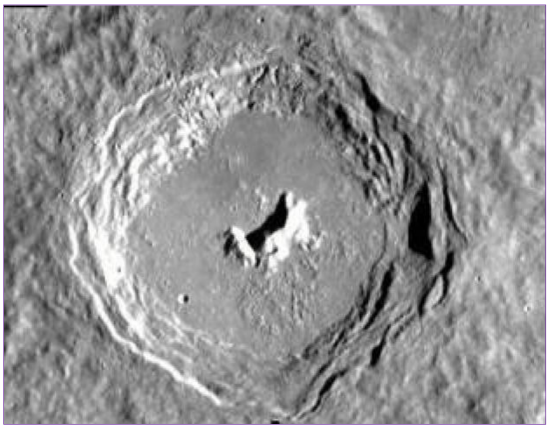


Figure 6 (top left): Schematic map of major structural elements at Flynn Creek (after Roddy, 1966c: 98). Figure 7 (top right): Contour map of the Flynn Creek Crater (after Roddy 1977b: 280). Figure 8 (bottom left): The 3-D model of the Flynn Creek Crater made by Roddy (1968b: 303; courtesy: Planetary and Space Science Centre, University of New Brunswick, Fredericton, New Brunswick, Canada). Figure 9: The lunar crater Pythagoras (courtesy: European Space Agency).

first indication from any of the cryptoexplosion structures that an ejection of crater breccia definitely occurred …" (Roddy, 1968b: 297). The breccia layers are covered by Chattanooga Shale which apparently filled the crater when a lake occupied the crater during pre-Chattanooga times. Strata dip away from the central uplift on the western, northern, and eastern sides of the Structure; however, to the south of the uplift the rock layers dip inward and are overturned. In the central zone of the Structure, powdered breccia is found injected into dikes along fractures in the limestone, along with some injections of rock flour into minor fissures, only visible on a microscopic scale (Baldwin, 1963).

Roddy (1979b: 2519) summarizes the morphological and structural classes of craters formed by a hypervelocity impact as follows:

> Impact craters on most of the terrestrial planets and satellites have been shown to follow a clear trend of increasing morphological complexity with increasing size, ranging from (a) bowl-shaped at the smaller sizes, to (b) flat-floored, to (c) flat-floored with a central peak, to (d) flat-floored with a central peak and terraced walls, to (e) flat-floored with multiple central peaks and multiple terraced walls, to (f) flat-floored with multirings and multiple terraces, and finally to (g) large, flat-floored basins.

Flynn Creek falls into category (d).

Figure 6 is a schematic map of the Flynn Creek Crater by Roddy which shows the basic structural similarity to lunar craters, with terraced walls and central uplift. Figure 7 is a much more detailed contour map of the Flynn Creek Crater by Roddy (1968b: 302; cf. 1977b: 280). Note that though the crater is basically circular in shape, sections of the crater walls, specifically the northeastern and northwestern rims, are relatively straight for around 1500 meters (ibid.). Roddy (1968b: 303) utilized this particular contour map to construct the 3-D model shown in Figure 8. In this model, Flynn Creek is seen to be flat-floored with a single central uplift and terraced walls, and the dotted line "… indicates the position of the top of the crater wall in areas where large volumes of ejecta have washed back into the crater, modifying the original crater shape …" (ibid.). The terraces are not prominent due to this erosional redistribution of ejecta on the crater rim (Roddy, 1979b). Large hills visible near the outer sections of the crater are underlain by megabreccia blocks, derived from the crater walls, which also washed back into the crater along with the ejecta and formed "… a terraced effect along the crater walls …" (Roddy, 1968b: 302). Note that the Flynn Creek model, with its central uplift, shallow flat floor, and terraced walls, bears a remarkable similarity to the lunar crater Pythagoras, as seen by comparing Figures 8 and 9.

Lusk (1927: 580) described his 1926 observations at Flynn Creek as follows:

> The extent of the increased thickness of the Chattanooga shale and the presence of the conglomerate-breccia coincide in an irregular area about two miles [3.2 km] in diameter with outcrops visible in the valley of Flynn Creek and its tributaries, Rush Fork, Cub Hollow, Lacey Hollow and Steam Mill Hollow, where they join that stream. Outside this area the Chattanooga shale is about 20 feet [6 meters] thick…
>
> The shale is completely exposed in sections up to ninety feet [27 meters] thick in single outcrops, and it crops out practically continuously in the bed of Flynn Creek and its tributaries with the same system of joints throughout.

In the surrounding region the Ordovician limestone strata dip is gentle, but in the Flynn Creek area the dips are 15-20º or even greater. On the south, east, and north sides of the Structure, the dips are only for short distances and toward the center, but that to the west "… there may be surficial faulting of the Ordovician ... [and] The top of the Chattanooga shale is at a lower altitude where it rests upon the brecciated limestone than at adjacent outcrops, in general being lowest where the shale is thickest …" (ibid.). This difference in altitude is greater than 30 meters. In contrast, in locations where the shale is near its normal altitude, it is thin and lies upon hills of the conglomerate-breccia. Lusk (ibid.) surmised that the shale's fissility, its ability to split, was determined by the orientation of the flakes of minerals during the deposition and dehydration processes. He observed that the fissility of the Chattanooga Shale is parallel to the bedding "… except where it conforms to ancient hillslopes …" and on these slopes he found that "… the fissility is inclined as much as 30° …" (ibid.).

Wilson and Born (1936: 815) visited the area in 1935 and concluded that the Flynn Creek Structure is "A small, intensely disturbed area … [with] highly disturbed beds along Flynn Creek." After mapping and studying the Structure in detail, they wrote the following historical description:

> The history of this disturbed area is interpreted as follows: Shortly preceding Chattanooga deposition an explosion took place near the surface, blowing out a crater 2 miles [3.2 km] in diameter and 300 feet [90 meters] deep. The Ordovician limestones forming the floor and walls of this crater were shattered into breccia composed of angular fragments of varying sizes imbedded in a matrix of smaller fragments and "rock flour." The deeper parts of the crater were filled with redeposited breccia, either as talus breccia or as bedded breccia deposited in a fresh-water lake that occupied the crater at one time. The Chattanooga sea invaded central Tennessee and filled the crater with black mud, now represented by about 250 feet [75 meters] of black shale. Fort Payne chert was later deposited upon the relatively smooth surface of the black shale.

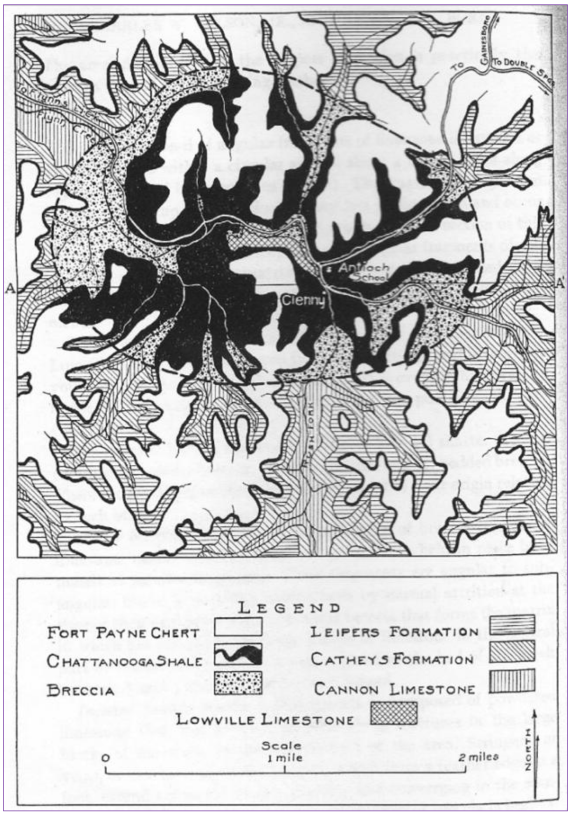
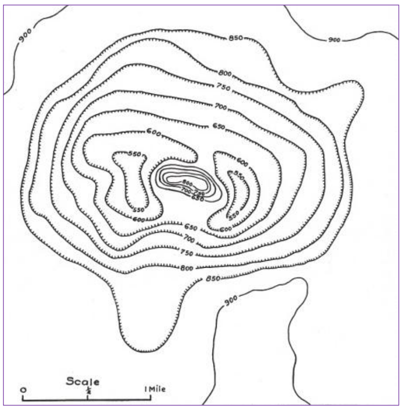
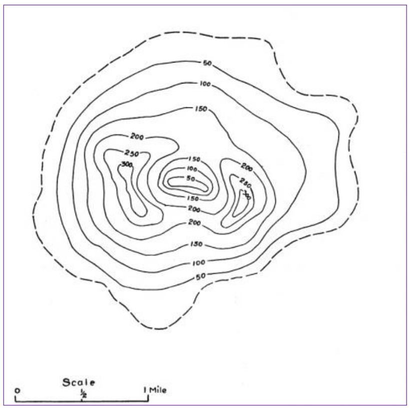


Figure 10: Areal geologic map of Flynn Creek area (Wilson and Born, 1936: 818)

The consolidated rocks in the area were found to range in age from Ordovician to Mississippian, the oldest rock being dense Lowville Limestone which was found in "… the center of the disturbed area and is composed of many large, disconnected blocks, some of which are several acres in size …" (Wilson and Born, 1936: 817). Figure 10 is a geological map of the Flynn Creek area by Wilson and Born which shows that this area of intense brecciation is somewhat elliptical in shape. They note an interesting fact concerning the Hermitage Formation at Flynn Creek:

> In the normal stratigraphic succession along the eastern edge of the Central Basin, the Hermitage formation overlies the Lowville limestone; but this formation was not found in the Flynn Creek area. It is believed that the Herm-





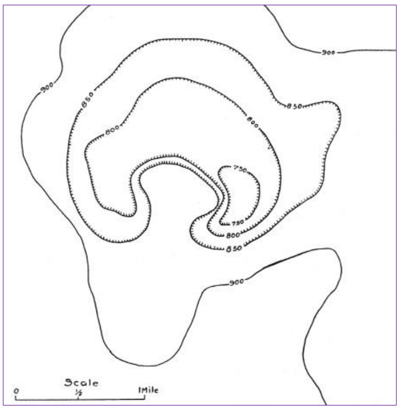


Figure 11 (left): Contour map on the pre-Chattanooga topographic surface (after Wilson and Born, 1936: 827). Figure 12 (centre): Isopach map showing thickness of Chattanooga shale (after Wilson and Born, 1936: 828). Figure 13 (right): Contour map showing the post-Chattanooga structure (after Wilson and Born, 1936: 829).

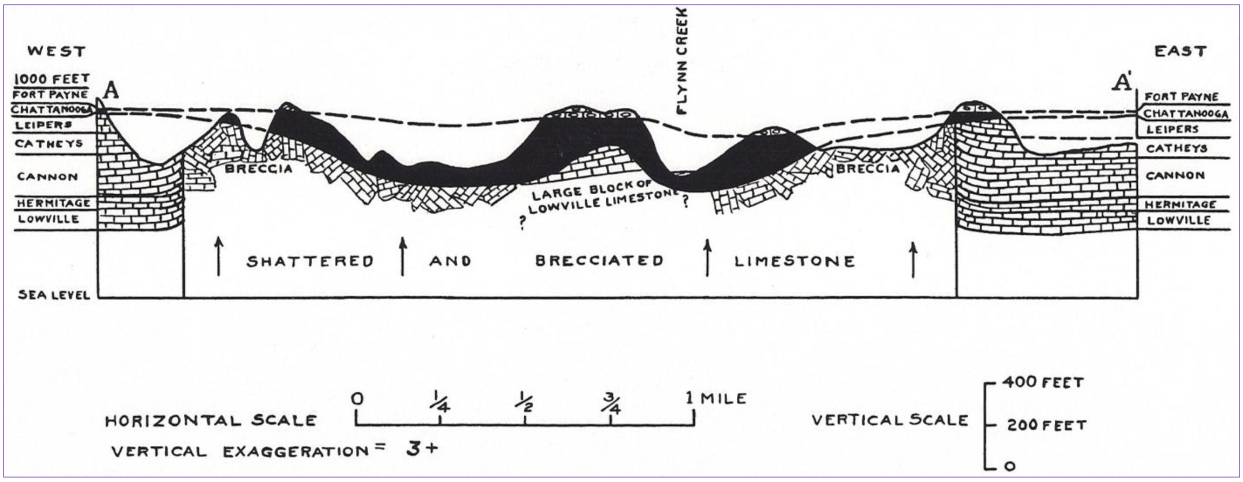


Figure 14: East-west structural cross section of the Flynn Creek site (after Wilson and Born, 1936: 824).

> itage formation was originally deposited in this region but that during the local deformation and subsequent erosion all traces of it were removed. (Wilson and Born, 1936: 819).

The Lowville, Cannon, Catheys, and Leipers Formations were found to comprise the underlying intensely-deformed Ordovician strata, and are limited to a circular area with a diameter of about 2 miles [3.2 km] (Wilson and Born, 1936). The black Chattanooga Shale and Fort Payne Chert made up the overlying, relatively undeformed strata, with the Chattanooga Shale directly covering the intensely-deformed Ordovician strata.

At the Flynn Creek site the Chattanooga Shale had "… its characteristic lithology, being a black, fissile, highly carbonaceous shale." (Wilson and Born, 1936: 822). Figure 11 is a contour map by Wilson and Born showing the topographic surface on which the Chattanooga Shale was deposited and Figure 12 is a map by Wilson and Born which shows the thickness of the black shale in the Flynn Creek structure. Around the structure, the shale has its normal thickness for the region, which is around 6 meters, but within the structure, the shale attains a thickness of more than 75 meters. Wilson and Born (1936: 826) explain that "Such variations in thickness indicate that the black shale filled a pre-existing topographic basin …", which would have been some 90 meters deep at the time. Figure 13, after Wilson and Born, is a structure contour map showing Flynn Creek to be a closed, synclinal basin. Wilson and Born (1936: 826) note that "The overlying Fort Payne chert was deposited upon a relatively level surface of black shale …" and unlike the Chattanooga Shale, does not show any abnormal areas of thickness within the structure. The Fort Payne Chert does gently dip toward the center of the basin "… paralleling the slightly greater dips of the underlying black shale …" (ibid.).

Figure 14 is an east-west structural cross section, as mapped by Wilson and Born, which shows the thick black Chattanooga Shale overlying the shattered and brecciated Ordovician limestone. These two series of strata were found by these researchers to be separated by a marked unconformity with a maximum differential relief of around 90 meters within 0.8 kilometers. Wilson and Born (ibid.) give the following description:

> The plane of the unconformity coincides with the pre-Chattanooga surface, which was a

> closed topographic basin about 2 miles [3.2 km] in diameter and about 300 feet [90 meters] below the level of the surrounding area. In the center of this depression was a hill, composed chiefly of large blocks of Lowville and possibly older limestone, that rose 200 feet [60 meters] above the general floor level.

The blocks were found to vary "… in size from several acres down to small fragments, and abutting against each other at all possible variations of strike and dip …" (Wilson and Born, 1936: 825).

Flynn Creek breccia consists of angular fragments of limestone that range from pea-size to large blocks in a matrix of shatter breccia and powdered limestone. The breccia contains limestone from the Leipers Formation and is, therefore, younger than the Leipers: "As it is overlain by normally bedded Chattanooga shale, its age must be post-Leipers, pre-Chattanooga …" (Wilson and Born, 1936: 820).

According to Wilson and Born (1936: 820), there are four main types of breccia found in the Flynn Creek area along the Creek itself as well as its tributaries. The shatter breccia "… consists of limestone blocks and fragments of various sizes held in place by a matrix of smaller fragments …" This is the breccia that forms the matrix in which the large limestone blocks in the center of the disturbance are imbedded. The injected powder breccia flowed around the blocks and was found to consist of "… powdered limestone that was injected dikelike along fractures in the large blocks of limestone …" in the central zone of the Flynn Creek structure (ibid.). Stringers, or veins of this breccia range in width "… from a feather edge to a foot …" and extend across the limestone blocks (ibid.). The injections seemingly took place "… while the material had a 'mushlike' consistency …" (Wilson and Born, 1936: 821). Milam and Deane (2005) note that the term 'microbreccia' is used interchangeably with the terms 'breccia dikes' and 'clastic dikes' by other researchers.

The talus breccia is composed of fragments and subangular blocks which display a "… slight rounding, such as would result from traveling a short distance down a steep slope under the influence of gravity rolling or slope wash …" (Wilson and Born, 1936: 821). The bedded breccia was measured along a road and on a hillside and found to have a maximum thickness of 3.7 meters. "The fragments in this bedded deposit grade in size from course grained in the lowest beds to medium grained in intermediate beds, and to fine grained in the upper beds of each local sequence …" (ibid.). Wilson and Born observed that this breccia was deposited in layers that are parallel to the overlying layers of Chattanooga Shale. Their explanation for this observation is as follows:

> The most plausible explanation of the origin of this breccia is that it was deposited in a fresh-water lake occupying the depression that existed in the Flynn Creek area for part of the post-Leipers, pre-Chattanooga interval. The uniform stratification, locally suggesting lamination, demonstrates its aquatic origin. It is believed that any Silurian or Devonian epi-continental sea which might have reached this region would have filled the crater with sediments that would have been preserved, for the later Chattanooga sea filled the depression with its sediments and these have been preserved. For this reason the origin of the bedded breccia is attributed to deposition in a fresh-water lake, such as would have formed in the depression. (Wilson and Born, 1936: 821-822).

Various researchers noted the abnormal thickness of the black, highly carbonaceous Chattanooga Shale in the Flynn Creek Structure. In the greater part of central Tennessee this Shale has a uniform thickness of around 6 meters, but in several localities within the Flynn Creek Structure 30 to 60 meters of continuous exposures of the black Chattanooga Shale were measured (Wilson and Born, 1936: 821). Near the junction of Flynn Creek and one of its tributaries, Rush Fork, a continuous section of some 40 meters of Chattanooga Shale was encountered. Wilson and Born (1936: 822) noted that next to Flynn Creek itself, the lower 15 cm of the black shale contained of "… rounded fragments of the underlying breccia …" On the higher hills in the area, Fort Payne Chert covers the Chattanooga Shale, and this lower Mississippian formation is not strongly tilted and is the youngest exposed formation in the area (ibid.).

According to Wilson and Born (1936: 825), "The major structural feature consists of a circular uplift which has raised a small central mass of blocks of Lowville limestone vertically into juxtaposition with the Liepers formation …", a vertical distance of some 150 meters. Around the central uplift is a ring of breccia which contains blocks of all the Ordovician formations involved in the disturbance. The strata dip away from the central uplift on the eastern, northern, and western flanks of the structure. However, the strata dip toward the center of the uplift on the southern flank. Wilson and Born (1936: 826) explain this as being "… the result of thrusting outward from the center, evidence for which is seen in an exposure on the south bank of Flynn Creek …" where the outward-pushed strata are seen to be overturned and thrust away from the central uplift.

Figure 15 is a "Diagrammatic restoration of a section across the Flynn Creek disturbance" by Wilson and Born. The diagrams show Wilson and Born's interpretation of the structure shortly after the Flynn Creek event in diagram A, after a period of erosion and pre-Chattanooga deposition in diagram B, and after the compacstion of the Chattanooga Shale in diagram C (ibid.). In their opinion, the Flynn Creek explosion blew limestone blocks out of the crater, with some of the debris falling back into the crater and the rest scattering around the rim within a radius of several kilometers (ibid.).

Post-explosion and pre-Chattanooga erosion succeeded in removing all traces of the 'cone' of brecciated limestone that surrounded the crater, as the writers were unable to find fragments of breccia at the base of the Chattanooga Shale around the crater. The time interval between the explosion and the deposition of the Chattanooga Shale must have been sufficiently long for the removal of the debris from the vicinity of the crater. On the other hand, the explosion could not have occurred long before Chattanooga

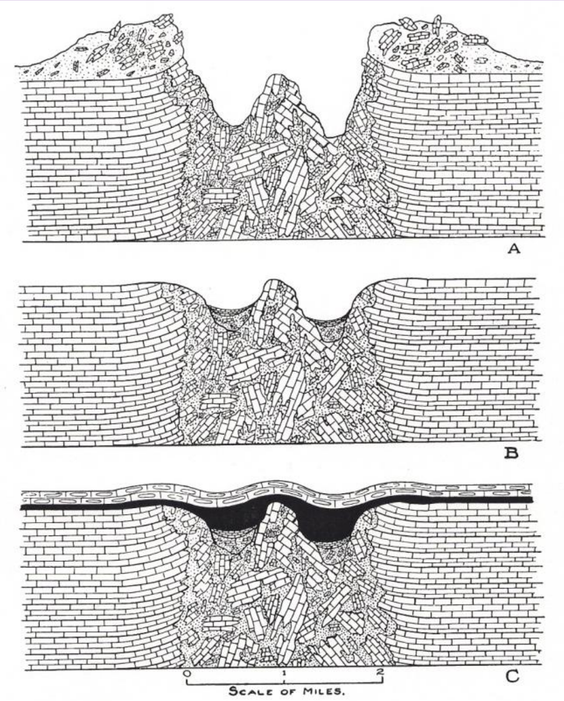


Figure 15: Diagrammatic restorations of a section across the Flynn Creek Structure (after Wilson and Born, 1936: 834).

times as the crater would probably have been filled with sediments. Since the time necessary for the removal of the unconsolidated debris would not have been long geologically, and since the crater probably would have been filled during its long existence as an open depression, the writers believe that the explosion shortly predated the deposition of the Chattanooga Shale.

In diagram C in Figure 15, the abnormal thickness of the Chattanooga Shale is seen, which can be attribute to the filling of the crater during the deposition of this formation. According to Wilson and Born (1936), the gentle dips, also shown in diagram C, are a result of the following:

1. The initial dip of the steeply-sloping walls of the crater and the central hill would undoubtedly have been an appreciable factor in explaining the high dips (as high as 25°) present in the base of the thick Chattanooga Shale, as contrasted with the much lower dips at the top of the Shale.
2. Compaction and proportional thinning of the 20 feet [6 meters] of Shale around the crater and of the 250-300 feet [75-90 meters] within the crater would form an appreciable synclinal basin on top of the Shale.
3. Subsurface collapse and settling due to deep-seated readjustment would undoubtedly have resulted in post-explosion synclinal sagging and possible faulting due to differential settling.

Boon and Albritton (1937: 58) agreed on some points with Wilson and Born, stating that in their opinion Flynn Creek "… was partly filled with lake deposits and the surrounding region eroded before it was covered over by the sediments of the Chattanooga sea." They also noted that the Ordovician limestones found around the crater walls dip radially away from the Structure's center on all sides except to the south where "… they have been thrust away from the center and overturned …" (ibid.). The points on which they disagree with Wilson and Born will be discussed in a subsequent Section of this paper.

Roddy (1963: 118) began his work on the Flynn Creek Structure around 1962 when he began preparing a detailed geological map of the structure. His numerous publications on Flynn Creek provide a steady stream of information regarding his research on the structure that lasted until the earliest years of the current century. In 1963, Roddy gave the following description of the Flynn Creek Structure in that year's *Astrogeologic Studies Annual Progress Report* for the United States Geological Survey:

> It consists of a circular rim of folded and faulted limestone beds of Ordovician age; the circular rim encloses an area of brecciated rocks two miles [3.2 km] in diameter. Steeply dipping, faulted, and brecciated limestone of Ordovician age occupies the central part of the structure. The deformed rocks are overlain by structurally simpler formations, which include the Chattanooga Shale (Devonian) and the Fort Payne Chert (Mississippian). The Flynn Creek structure is moderately well exposed as the result of dissection of the Eastern Highland Rim by the nearby Cumberland River and its tributaries. (Roddy, 1963:18).

Two years later, Roddy (1965: 50, 52) again described the Flynn Creek Structure based on his continuing fieldwork:

> Flat-lying Middle and Upper Ordovician limestones and dolomites surround the Flynn Creek structure but are folded and faulted into a circular rim which encloses a partly buried crater

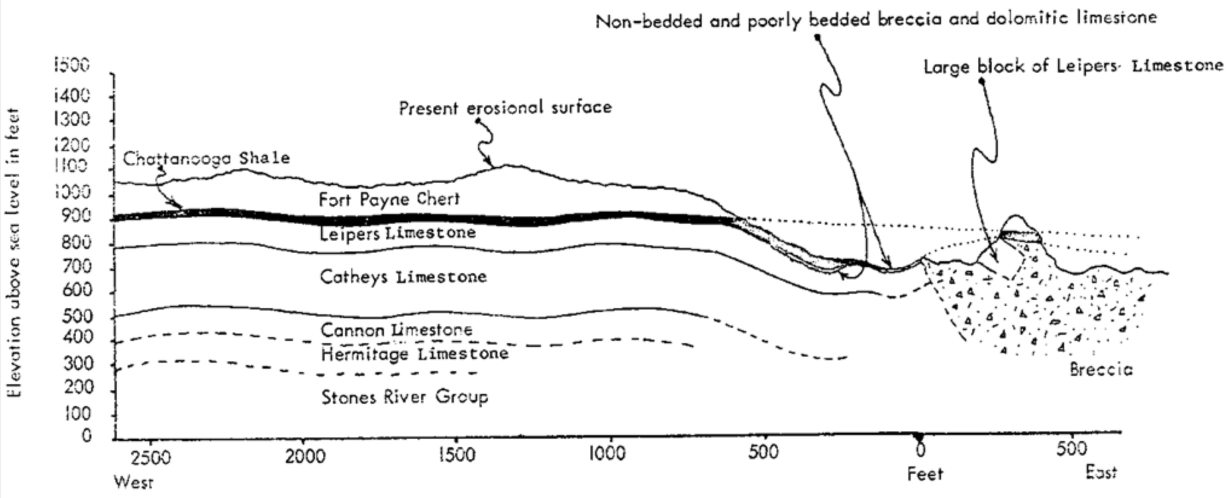


Figure 16: Cross-section of the western rim of the Flynn Creek Structure (after Roddy, 1963: 121).

> about 3.5 km in diameter. The crater floor is underlain by breccia of Middle and Upper Ordovician limestone and dolomite fragments ranging in size from a fraction of a millimeter to nearly 100 meters. In the central part of the crater, a partly buried hill consisting of intensely deformed Middle Ordovician limestones and dolomites of the Stones River and Knox Groups rises nearly 100 meters above the surrounding crater floor. Brecciated rocks of the Knox Group containing shatter cones have been raised at least 300 meters above their normal level.

This is the first mention of the existence of shatter cones, which are a diagnostic feature of meteoritic impact structures (Milton, 1977). Roddy (1965) also pointed out that sections of the raised crater rim experienced nearly 50 meters of uplift, while in other sections, only a few meters of uplift occurred, and later he noted that the original crater was some 100 meters deep on average "… after an unknown amount of breccia washed back over the earliest crater floor …" and that its walls were moderately to steeply dippiing (Roddy, 1966c: 154). He believed that the crater had experienced only moderate erosion.

Roddy's (1963: 121) diagram of the stratigraphic succession he found in the western section of the Flynn Creek Structure and the geological cross-section of the western rim of the Structure is shown in Figure 16. He notes in his description that the valleys surrounding the structure have as their lowest exposed stratigraphic unit Cannon Limestone which is conformably overlain by the Catheys Limestone, both from the Middle Ordovician. The Catheys Limestone is in turn overlain by the Late Ordovician Leipers Limestone. The next youngest stratigraphic unit is a breccia mass that "… occurs in a nearly circular area slightly more than 2 miles [3.2 km] in diameter …" (Roddy, 1963: 120). This breccia unit contains fragments of the Cannon, Catheys and Leipers Limestones as well as the even older Stones River rocks from the Middle Ordovician, all of which range in size from under a millimeter to blocks measuring up to hundreds of meters. In exposures, fragments of these different formations appear to be unsorted and set in a matrix of very fine crystalline and dolomitic limestone (ibid.).

In the center of the breccia core are steeply-dipping, slightly brecciated limestone beds of the Stones River Group which contain shatter cones (ibid.). Next youngest is a ~6 meter thick breccia sequence which is non-bedded at the base but bedded at the top, and this material "… is a record of deposition that is found nowhere else in the region, presumably it was deposited in a local topographic depression in an otherwise nearly featureless surface …" (Roddy, 1966c: 124). A thin unit of dolomitic limestone up to 1.5 meters thick locally caps this breccia sequence which in turn overlies the dipping central beds and the central core breccia as well as the deformed rock (Roddy, 1963).

The entire Flynn Creek Structure, as described above, is overlain by undeformed Chattanooga Shale of the Late Devonian. Fort Payne Chert of Early Mississippian age in turn overlies the Chattanooga Shale. Roddy (ibid.) concluded that since the youngest brecciated rocks were from the Late Ordovician, the Flynn Creek Structure must have formed sometime between the Late Ordovician and the Late Devonian.

Roddy (1963) noted that in this region of Tennessee the Chattanooga Shale was an extensive black shale unit with a nearly uniform thickness of some 8 meters. He also pointed out that outside of the Flynn Creek structure the Chattanooga Shale overlies the Upper Ordovician Leipers Limestone and that the contact does not contain breccia. Within the Flynn Creek Structure the Chattanooga Shale increases abruptly to over 35 meters above the depressed and deformed rim and to some 60 meters above the main breccia mass; however, it is only the

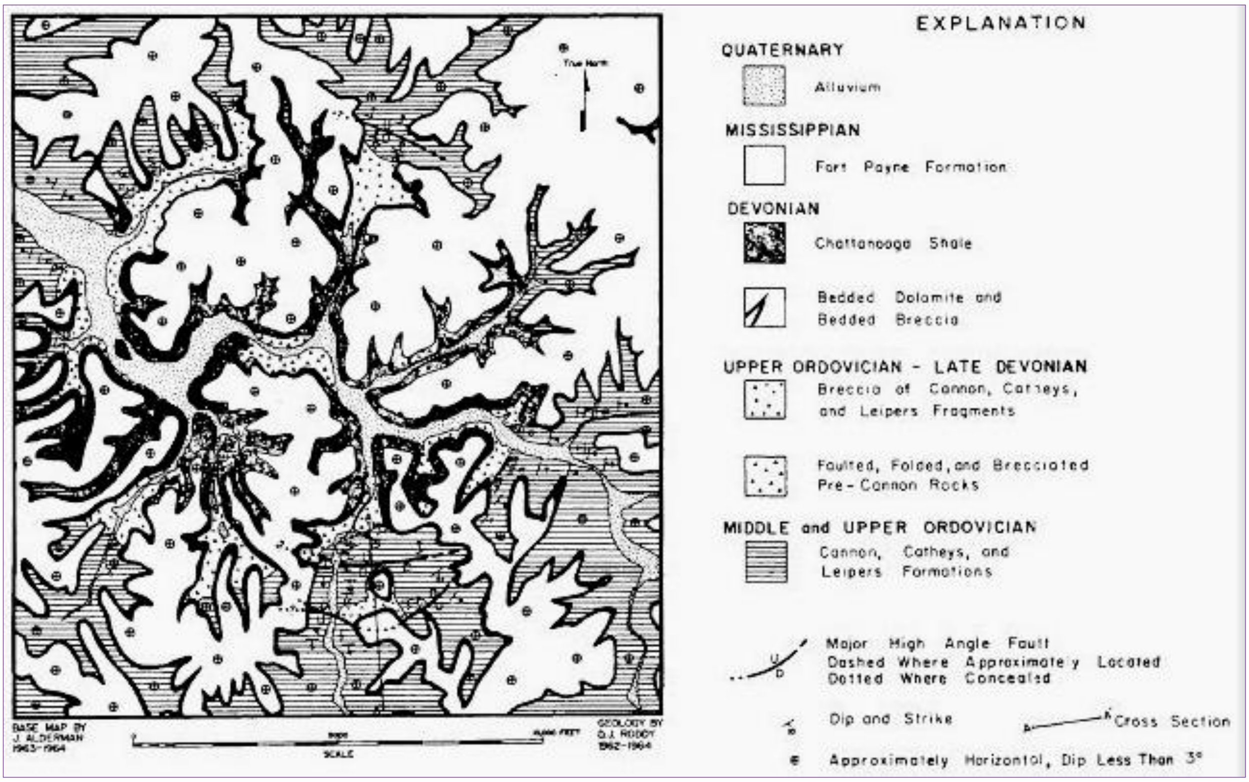


Figure 17: Generalized geological map of the Flynn Creek Structure (after Roddy, 1964: 166)

lower member of the Chattanooga Shale that appears to increase in thickness (ibid.). In addition, away from the Flynn Creek Structure the Chattanooga Shale is nearly flat-lying, although in the Structure it dips as much as 21° and "All of the relatively high dips are inclined toward the thicker parts of the shale, which overlies the breccia …" (Roddy, 1963: 123).

Figure 17 is a 1964 generalized geological map of the Flynn Creek Structure by Roddy. During the Late Devonian to the Early Mississippian time the structure was buried under hundreds of meters of rock, much of which was later removed by erosion. The crater floor is underlain by a mixed breccia except at the center where the partly-buried central hill rises around 100 meters above the crater floor. Roddy (1964: 164-165) describes this central uplift:

> The hill consists of steeply dipping, folded, faulted, and brecciated Middle Ordovician dolomitic limestone that has been raised several hundred meters above its normal stratigraphic position. A thin marine deposit of bedded breccia and cross-bedded dolomite overlies the mixed breccia of the crater floor and covers the lower slopes of the central hill. These marine beds have been identified as early Late Devonian in age.

Before erosion, the central uplift was completely covered by the Chattanooga Shale (Roddy, 1964), and "In the Flynn Creek area the Knox Group is exposed only in the central uplift of the crater." (Roddy (1966c: 46). The Stones River (including Wells Creek dolomite) and Knox strata occur in the crater's center as "… folded, faulted, and brecciated rocks which form the central uplift. Neither the Stones River Group nor the Knox Group are exposed elsewhere in the Flynn Creek area." (Roddy, 1966c: 63). The Flynn Creek central hill consisted entirely of breccia and megabreccia.

According to Roddy (1966c: 104), "Deformation along the extreme northwestern rim is the least complex of the whole crater." Here the rim strata 300 meters from the crater wall are raised 6 to 9 meters above the local level and gently dip into the crater at 1-2°. Within 75 meters of the crater breccia the dips increase to 7-10° as the folded rim strata displays an increasingly jumbled aspect. The jumbled zone dips into the crater at an angle which varies from 25-35°. Roddy (1966c) noted that a complex set of tight folds trend in a manner parallel to the rim and are cut by two faults that are also parallel to the crater rim. The rim strata rise some 35 meters toward the crater starting about 760 meters from the crater wall. This rim uplift continues for around 1.2 km to the east. The rim strata and crater breccia contact consists of a jumbled zone "… which varies in dip from vertical to about 50° towards the crater …" (Roddy, 1966c: 106).

The eastern rim of the Flynn Creek Structure includes "… chaotic crater breccia which includes many large megabreccia blocks …" (Roddy, 1966c: 107). These blocks are around 45m long and 15m thick and dip toward the crater center at various angles. Here the rim tilts away

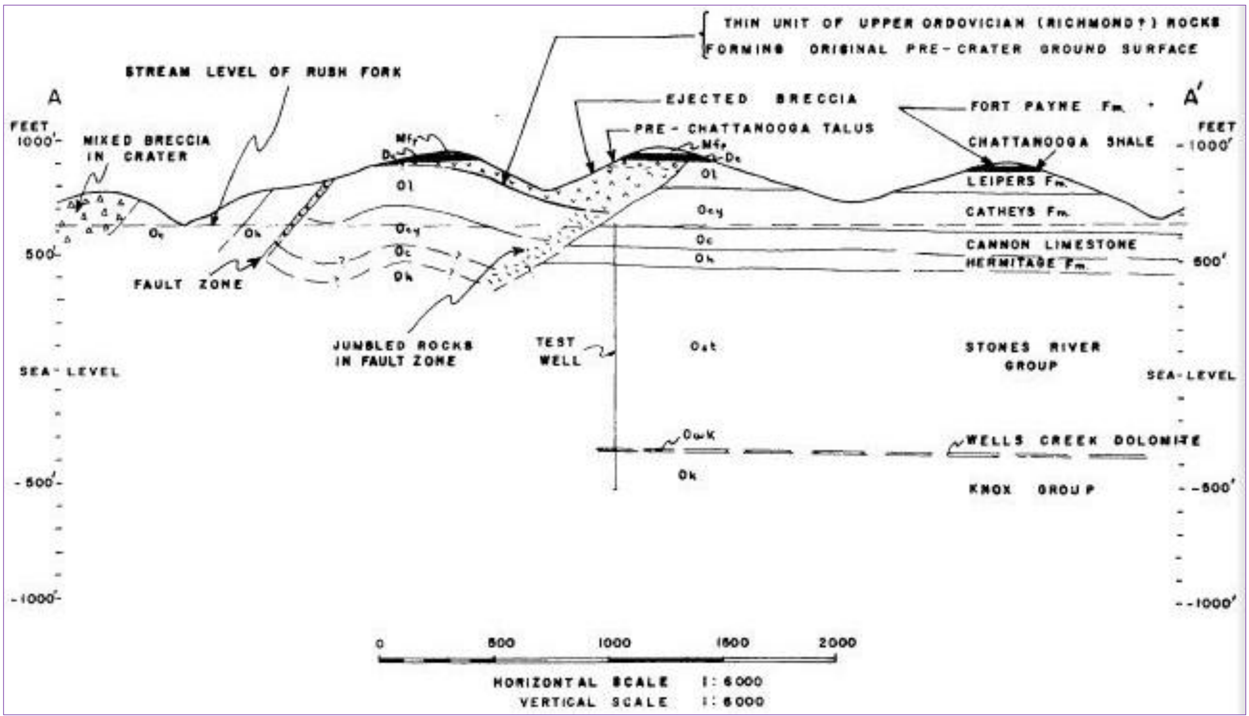


Figure 18: Geological cross-section of the southeastern rim of the Flynn Creek Structure (after Roddy, 1964: 167).

from the crater and observed uplift near the breccia contact is some 45 meters over a horizontal distance of 760 meters. Roddy (1966c: 108) notes an unusual find in the eastern side of the Flynn Creek structure:

> At 100 feet [30 meters] east of the breccia contact the dip of the beds steepens to 25° on the eastern flank of an asymmetrical anticline. The trend of the nearly vertical axial plane of this anticline is approximately parallel to the eastern crater wall. The beds on the western flank of the anticline dip as steeply as 80° west, but flatten rapidly and proceed through a reversal in dip until the beds dip again to the east. Beds 100 feet [30 meters] above this incline are nearly flat-lying, a most remarkable change in attitude considering the very sharp folding in the adjacent lower beds.

Roddy (1964: 163-164) states that his previous Flynn Creek field studies left some unanswered questions and did not address "… the geologic history of the southeastern rim and its bearing on the origin of the Flynn Creek structure." Breccia overlying the graben in the southeastern rim are 50 meters above the crater floor, and yet are essentially identical to the breccia on the floor, "… except for a crude inversion of stratigraphy, and is interpreted as ejecta," (Roddy, 1968b: 297). Roddy (ibid.) determined that a section of the original, pre-crater ground surface is located at the base of the ejecta, and he noted that "The southeastern and southern rim contains the most complicated structures exposed in the entire rim …" (Roddy, 1966c: 115). Figure 18 is the geological cross-section of the southeastern rim of the Flynn Creek Structure by Roddy (1964: 167). Roddy points out that although the entire rim surrounding the Flynn Creek crater is tilted, folded and locally faulted, it is this southeastern section that is most intensely deformed; in this section "… there are faults with displacements on the order of 100 meters …" (ibid.).

Starting from 1200 meters south of the point where the crater breccia makes contact with the southeastern deformed rim, the Middle and Upper Ordovician beds are found to be in their normal sequence (Roddy, 1964). Going 400 meters north, these beds are found to be 10 to 15 meters higher. Another 150 meters north, "… a 300 meter deep test well showed no deformation of the subsurface strata …" except for the slight 10 to 15 meter uplift previously noted in the beds (Roddy, 1964: 168). About 50 meters north of the test well is a major, curved fault that is approximately concentric with the contact of the crater breccia, and the north side of this fault is displaced a minimum of 100 meters downward and dips north at angles that vary from 30º to 70º. Roddy (ibid.) reports that "… the displacement dies out to the northeast, and within 600 meters is only 10 meters …" The fault grades into a fractured, brecciated zone around some 800 meters to the west.

North of this fault the rocks of the Catheys and Leipers Formations, both Upper Ordovician, along with the Leipers Formation, are stratigraphically higher than any of the other Upper Ordovician beds observed in the region around Flynn Creek, and it is here that Roddy (ibid.) makes a most interesting observation:

> A few feet of pale green, argillaceous, dolomitic limestone occurring at the top of this section are unlike any units in the Silurian and Devonian sections of central Tennessee but closely resemble rocks of the Richmond Group (Upper Ordovician) found elsewhere in central Tennessee. If these beds belong to the Richmond Group, they furnish the first proof that seas covered this part of the Nashville Dome in Richmond time.

These beds are overlain by a thick unit of mixed breccia similar in lithology and texture to the breccia found within the crater (Roddy, 1964). The lower part of the breccia includes angular fragments from the upper part of the Leipers Formation mixed in with angular fragments from these underlying beds which decrease as a percentage of the fragments higher up in the breccia. The percentage of rocks fragments high in the breccia that is from the lower part of the Leipers Formation and the upper part of the Catheys Formation increases. In other words, "… the breccia fragments roughly are distributed in an order inverted from the normal sequence of the beds from which they were derived …" (Roddy, 1964: 169). The mixed breccia near the fault is in turn overlain by a few meters of breccia that consists solely of upper Leipers Formation fragments; perhaps a talus deposit formed soon after the mixed breccia was emplaced (ibid.).

Some 150 meters south of the crater rim and breccia contact is another steeply-dipping fault that is concentric with the crater (Roddy, ibid.). To the north of this fault, the rock beds, Hermitage Formation of Middle Ordovician age, are raised 100 meters and tilted to the north up to 65 degrees. These beds are overlain by Cannon Limestone of Middle Ordovician age which is intensely deformed farther to the north.

Roddy (1964) believes that the folding and tilting with simultaneous faulting described above occurred during the formation of the Flynn Creek crater, and he summarizes his findings regarding the southeastern rim of the Flynn Creek:

> It also seems likely that rock fragments in the breccia in the down-faulted block were forcefully ejected from the crater because they are older than the surface on which they are now found and a topographic high probably separated them from the crater. The crude inversion of stratigraphy in the fragments of this breccia is consistent with ejection from the crater, and the similarity in lithology and gross texture of breccias inside and outside of the craters suggest that they were formed by the same process. (Roddy, 1964: 170).

Using field evidence gleamed from his study of the southeastern rim of the Flynn Creek Structure Roddy (1964) was able to estimate the thickness of strata removed by erosion before deposition of the Chattanooga Shale commenced. In the down-faulted block, the probable Richmond age beds underlying the ejected breccia were the pre-crater ground surface and "With this information, it is calculated that about 60 meters of rock were eroded from the structure before deposition of the Chattanooga Shale …" (ibid.). Additionally, Roddy (ibid.) noted that a pre-crater ground surface on the probable Richmond age beds explains the absence of Silurian and Devonian age fragments in the crater breccia: either these rocks had not yet been deposited or they were removed by erosional processes before the event that formed the Flynn Creek Structure.

After two years of further field work, Roddy (1966c: 183) added the following observation:

> Field studies have shown that the pre-crater ground surface is present in the tilted graben on the southeastern rim. Thickness measurements made from this surface down to older horizons indicate that less than 150 feet of strata, and more probably less than 50 feet, have been removed after the crater was formed.

The crater rim experienced only moderate erosion in pre-early Late Devonian times on the north, central and the southwestern parts of the rim, and "The heads of these ancient valleys did not erode completely through the raised rim strata to the lower level of the surrounding surface, and the crater was not exposed to external drainage systems …" (Roddy, 1966c: 122). Roddy (ibid.) also found that some parts of the rim displayed minor irregularities in the form of short shallow valleys and gulleys in an otherwise relatively smooth crater wall.

In the outermost sections within the crater structure the surface on top of the breccia presents a complicated picture. Near the western and northwestern wall, there is a continuous mass of breccia underlain by megabreccia blocks for over 900 meters, and "In fact, it seems to be the rule that where extensive masses of breccia are located near the rim, they are underlain by many large megabreccia blocks …" (ibid.). On the western side, the deepest low within the crater is around 90 meters below the highest area on the on the western rim and about 105 meters below the highest area on the southeastern rim. The eastern low point in the crater, however, is only about 5 meters shallower than its western counterpart (Roddy, 1966c).

The base of the central uplift is about 920 meters in diameter. The central uplift is some 5 meters higher than the average rim height, but 5 meters lower than the highest point on the southeastern rim. The sides have an average dip of 10-15º, but some are up to 30º (ibid.). The uplift is composed of Stones River, Wells Creek, and Knox strata which primarily dip to the west and northwest from 24-60º (ibid.).

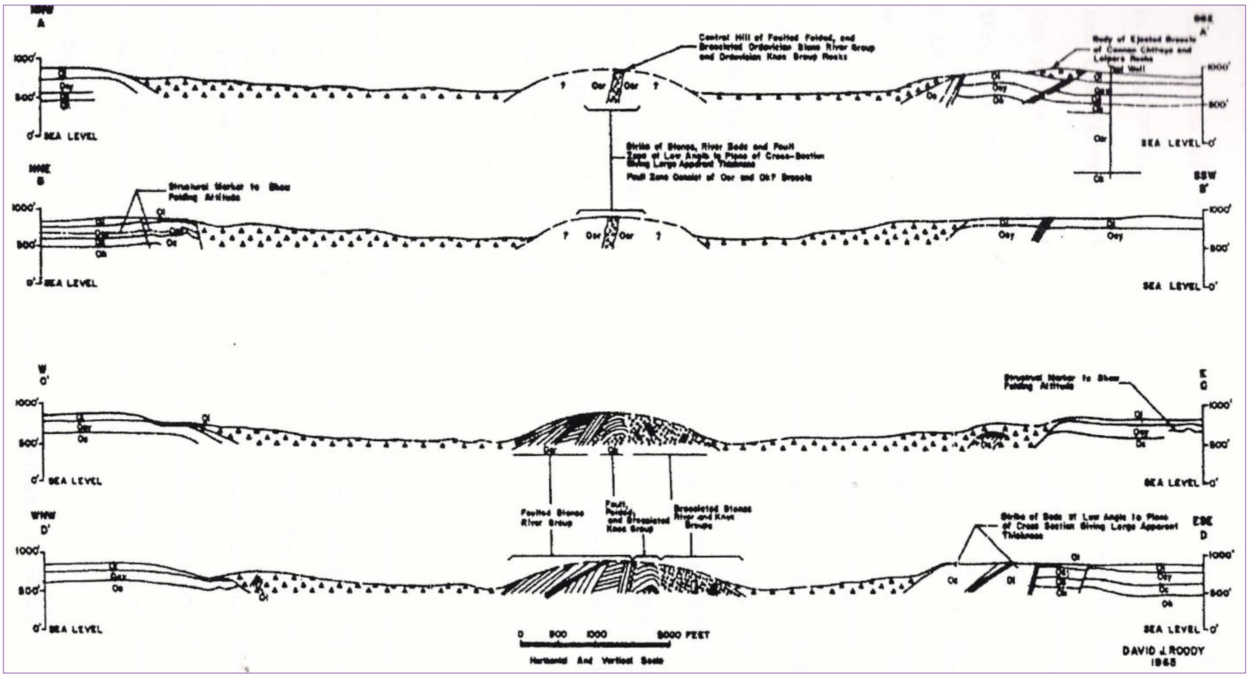


Figure 19: Generalized geological cross sections of the Flynn Creek Structure (after Roddy, 1965: 57).

Roddy (1966a: 270) adds to the growing body of knowledge concerning Flynn Creek in a discussion of his finding that "… a thin deposit of cross-bedded carbonates and bedded breccia form a unique and unusual basal facies of Chattanooga Shale within the crater." These units thicken to a minimum of 15 meters in the center of the structure, but rapidly thin on the upper parts of the crater walls. Evidence for a Late Devonian age for the Flynn Creek crater had previously led to speculation that these beds are actually lake deposits that consist of fresh-water limestones and breccia cemented in a matrix of fresh-water limestone. However, early Late Devonian conodonts found in the rocks indicate deposition took place in a shallow-water, marine environment that preceded the introduction of sediments of the Chattanooga Shale (ibid.).

Based on his field work, Roddy (1965: 52) found that the structural deformation of the Flynn Creek crater "… occurred in the interval between Richmond and early Late Devonian time (between about 420 and 350 million years ago)." He adds (ibid.) that "Dissection during Recent time by Flynn Creek and its tributaries has produced one of the best exposed crypto-explosion structures in the United States …"

Roddy's fieldwork led him to conclude that any post-explosion debris on the crater rim was removed before the deposition of the black Chattanooga Shale since the contact between the basal unit of the Chattanooga Shale and the early Late Devonian erosional surface rocks is quite sharp. He also concluded that the crater was not in existence for a long enough period of time to have completely filled during the time the rim eroded and was probably around 100 meters deep before deposition of the Chattanooga Shale began (Roddy, 1965).

Figure 19 shows generalized geological cross-sections of the Flynn Creek Structure prepared by Roddy "… shortly before deposition of Chattanooga Shale in early Late Devonian time." He points out an unusual type of fold shown in cross sections B-B' (northeast rim) and in C-C' (east rim) that suggests strong horizontal compression. These two folds "… have vertical axial planes, approximately concentric with the rim, and with horizontal shortening on the order of 35 percent …" (Roddy, 1965: 59). The rock beds below the folds are not exposed, but the beds above flatten rapidly which suggests that considerable bedding plane slippage took place within the tightly folded strata, and "The beds forming these folds were less than 100 meters below the ground surface when the Flynn Creek deformation occurred …" (ibid.).

The cross-sections in Figure 19 show "… a major body of continuous breccia within the crater; a localized body of probable forcefully ejected breccia; and a central uplift of faulted, folded, and brecciated rocks." (Roddy, 1965: 58). Analysis of the breccia indicated that it was derived from the upper quarter of the rim's deformed strata. The breccias in the structure were all formed from the same rocks that are exposed in the surrounding sedimentary section, but do not contain any igneous or metamorphic rocks from depth, and "Deposition of the bedded breccia and cross-bedded dolomite probably occurred in a coastal plain environment in the shallow waters of the slowly advancing Chattanooga sea …" (Roddy, 1965: 54). Roddy (1965) believed that for some time after the crater formed, the area consisted only of very low hills ranging from a few meters to perhaps as much as 20 meters with slopes less than 4º.

After several years of study, Roddy (1966b: 494) still described Flynn Creek as a probable impact crater formed in the Middle or Late Devonian time, around 3.5 km in diameter and some 110 meters deep, in a region of flat-lying carbonates. He again described the limestones of Middle and Upper Ordovician age as being folded, faulted, and brecciated in an irregular band several hundred meters wide in the rim of the crater. In addition, an irregular and discontinuous zone next to the crater wall, ranging in width from just a few to several hundred meters, was found to contain extensive fractures, microfractures, and calcite twin lamellas. Irregular fractures and microfractures were abundant in the breccia and in the central uplift, especially in the gradational transition between the breccia and deformed rim strata. Roddy (ibid.) determined that microtwinning was prominent close to

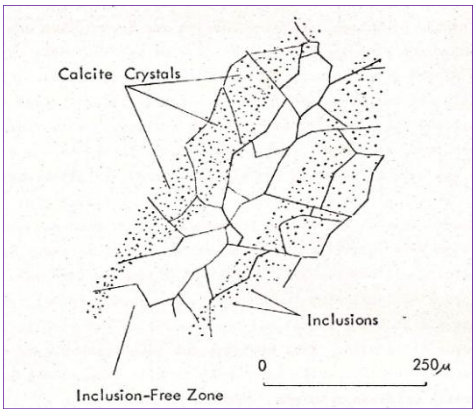


Figure 20: Calcite crystals with abundant inclusions cut by a zone free of inclusions (after Roddy, 1966c: 130).

the crater wall in crystals as small as 20 microns and that kink bands occurred in calcite crystals larger than 100 microns. He noted that the patterns of deformation for the calcite appeared to be consistent with patterns for explosive shock loading and were, therefore, "… interpreted as caused by high stress imposed during the passage of a shock front(s) produced during impact …" (ibid.). Rocks that contained moderately- to intensely-twinned calcite were distributed in a fashion similar to the strata containing the microfractures which was abundant in the central uplift, the crater breccia, and in a narrow band around the rim adjacent to the crater wall. The exception was in the fine-grained dolomites of the central uplift and other fine-grained rock strata; these did not exhibit noticeable twinning.

According to Roddy (1966c: 157) "… the most intense twinning and microtwinning … is generally confined to the rocks immediately adjacent to the crater wall." Normal twin lamellae were common in the calcite found both within the Structure and in the surrounding undeformed strata. In the undeformed strata, however, twin lamellae were seen only in calcite crystals that were larger than ~100 microns. Twinning in these crystals consisted of one, two, or occasionally three sets of lamellae which ranged from 50 to 100 microns in width. These crystals rarely contained more than 10 lamellae and these were usually spaced at least 150 microns apart. Roddy (1966c) found two to three times the normal twin lamellae in the same size crystals outside of the deformed area and these were more likely to have two or more sets of normal twin lamellae as well as twinning in crystals as small as 20 microns. He also found a large increase in microtwinned lamellae in the deformed rim strata and some of the breccia fragments. In addition to highly-twinned calcite found in the crater rim, Roddy (1966c: 127, 129) found microfractures to be common in the fine-grained dolomites of the central uplift that appeared to be recrystallized or 'healed' fractures. Figure 20 is a sketch by Roddy of some of these calcite crystals. Roddy (1966c: 129) states that in these rocks, "… thin, irregular, clear bands up to 50 microns wide cut across grain boundaries without visibly disturbing each individual crystal, except that all inclusions are absent from the band."

The report on the last phase of Roddy's Astrogeologic Studies at Flynn Creek, which was included in the 1967 *Annual Progress Report*, involved core drilling at six locations along an east-west line across the crater (*Astrogeologic Studies*, 1967: 28). The cores were 5.5 cm in diameter and totaled 762 meters (Roddy, 1980). The results, combined with Roddy's surface geological mapping, showed that the Flynn Creek structure was comprised of a crater containing "… a very shallow, bowl-shaped lens of breccia underlain by faulted and folded limestone …" (Roddy, 1980: 941). The drill core sequence was reported by Roddy:

> The drill cores contain a sequence of bedded dolomite 1 to 2 m thick which is underlain by a graded, bedded dolomitic breccia as much as 15 m thick … The bedded dolomitic breccia is underlain by a course, chaotic breccia with fragments derived from the local strata; the size of these fragments increases near the base of the chaotic breccia. The Hermitage Formation, a 20-m-thick shale with interbedded limestone, is the lowest unit completely brecciated … it forms the matrix for much of the chaotic breccia. The thickness of the chaotic breccia lens averages about 35 m.
>
> Limestones directly below the base of the breccia lens are highly faulted and folded, but the deformation decreases downward and the rocks are nearly flat-lying and relatively undisturbed below about 100 m beneath the breccia lens … Folding immediately below the base of the breccia lens extends 30 to 40 m deeper on the eastern side of the crater than on the west-

ern wide [side].

> The absence of lake deposits and a fall-back zone and the occurrence of the bedded dolomitic breccia containing marine conodonts suggest that the shallow waters of the initial Chattanooga Sea occupied the area when the crater formed, probably in early late Devonian time. (*Astrogeologic Studies*, 1967: 29).

In his research for the Branch of Astrogeologic Studies, Roddy's (1968a: 272) final conclusion was that the Flynn Creek crater, "… was formed in flat-lying limestones in northern Tennessee approximately 360 × 10^6 years ago." He pointed out that most of the structural elements he found at Flynn Creek, "… including a central uplift, occur in two craters formed by a 500-ton TNT hemisphere and a 100-ton TNT sphere detonated on alluvial surfaces at the Defense Research Establishment, Alberta, Canada …" (ibid.). The structural similarities between Flynn Creek and these chemical explosion craters indicated that a shock-wave process was responsible for the formation of the structure at Flynn Creek and that the deformational energy was concentrated in only the upper 300 meters of rock strata. This was confirmed to be the case by the six drill cores which also indicated that a surface-generated energy source was responsible for the cratering event:

> These conditions … and the similarities in rim deformation and central uplift between Flynn Creek crater and surface-produced explosive craters, are interpreted as consistent with a hypervelocity impact process … (ibid.).

Roddy stated that his calculations indicated that the "… depth of impactor penetration was less than 150 meters, which is in agreement with field evidence …" (ibid.).

In 1968 Roddy confirms his previous findings by stating that the highly-deformed Lower and Middle Ordovician limestone and dolomite were uplifted in the center of the crater over 300 meters resulting in a central hill some 100 meters high. This central uplift consisted of the oldest Flynn Creek strata and contained shatter cones. Rim strata were raised 10-50 meters as well as forced outward which resulted in moderate to intense folding and faulting. Breccia was ejected onto the crater rim and was found to still be partly preserved in a rim graben, although erosion had removed most of the ejecta blanket and also filled the crater "… until it was 100 m deep …" (Roddy, 1968c: 179). The crater then completely filled with Chattanooga Shale during early Late Devonian times.

In his 1966 thesis, Roddy stated that the crater first filled with Upper Devonian shale which was later covered by Lower Mississippian chert. Strata in some sections of the rim were lifted by as much as 50 meters and tilted outwards. "Most axes of folds in the rim are concentric with the crater wall, but some folds have axes radial to the crater wall …" (Roddy, 1966c: 179). Tight folding in some sections of the rim produced radial shortening as great as 35 percent. Roddy (1966c: 216) also discussed the age of the Flynn Crater in his thesis:

> The apparent absence of any type of Silurian and Lower or Middle Devonian rocks in the bottom of the crater suggests the age is considerably younger than post-Richmond and more probably is Middle to post-Middle Devonian age. If the crater had been present during this period of time, and if no Silurian or Devonian seas had covered the area, then almost certainly lake deposits would be present above the crater breccia. Instead, the first bedded deposits that are observed are marine breccias derived locally within the crater and which are of early Late Devonian age.

Roddy (1966c: 218) noted that "… it does not appear that the rim was ever breached and opened to outside drainage."

After receiving his Ph.D. and completing his Astrogeologic Reports for NASA and the U.S. Geological Survey, Roddy continued his field work and research on the Flynn Creek Structure for many years. A decade after completing his Ph.D. he explained the preliminary information he gathered from a second set of cores drilled in the Flynn Creek Structure, commencing in November 1978:

> This crater, approximately 360 million years old, was initially ~3.8 km in avg. rim crest diameter (~ 3.5 km apparent) and ~ 180 m in avg. rim crest depth (~80 m apparent). Previous core drilling of six holes (762 m total) in the crater floor showed limestone and dolomite beds immediately below the base of the breccia lens (35 m avg. thickness) are intensely faulted and locally folded and brecciated, however deformation decreases downward and the strata is nearly flat-lying at depths of about 100 m below the base of the breccia lens.
>
> Core drilling completed in the outer crater floor area shows the strata underlying the breccia lens to be nearly 50 m lower than that in the adjacent inner rim and that the rocks are extensively faulted and locally brecciated. At depths of 350 m to 400 m in the same drill cores the relative displacement between the sub-crater floor and inner rim strata decreases to less than 30 m ...
>
> Preliminary reduction of the drill data from the central uplift indicates an abrupt transition from limited deformation in the rocks underlying the breccia lens on the crater floor to very complex deformed rocks beneath the central uplift. Uplift, including extensive faulting and brecciation, beneath the flanks of the central uplift is over 130 m at a depth of 50 m below the level of the original crater floor. Uplift in this same region decreases to only 15

> m at depths of 340 to 360 m below the original floor. Exposures in the top of the central; uplift show a maximum uplift of Knox strata of about 450 m. The drill data confirm uplift is due, in part, to extensive faulting and brecciation beneath the uplift region creating a locally decreased mass/volume relationship. The ring fault and clear-cut inward movement of sub-crater floor strata also contribute to sustained uplift. The drill data completed to date suggest that the central uplift formed so rapidly that the large sequence of exposed Knox strata was violently uplifted over 450 m to form a massive detached block underlain by previously higher strata. (Roddy, 1979a: 1031).

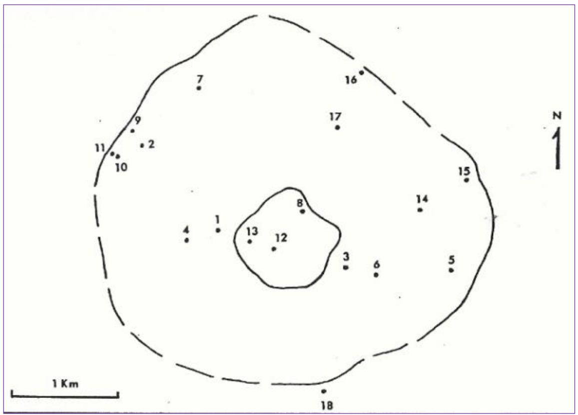


Figure 21: Location of 1967 and 1978-1979 drill holes at Flynn Creek (after Roddy, 1980: 942).

Originally, six cores were drilled in 1967 for the Astrogeologic Studies, but at least 14 more were drilled by 1979. In 1979, at the Lunar and Planetary Institute's tenth conference, Roddy described his interpretation of the preliminary results from the second round of deep drilling at Flynn Creek. During the impact and subsequent explosion, approximately 3 × 10^9 metric tons of rock were brecciated to a depth of 130 to 150 meters below the original ground surface and around 2 × 10^9 metric tons or rock was ejected from the crater (Roddy, 1979b). Beneath the central uplift, rock was brecciated and excavated to a depth of 200 to 250 meters with the deeper strata uplifted over 450 meters. The resulting uplift reached 110 to 120 meters above the crater floor. Roddy (ibid.) estimates that the initial rim crest diameter was about 3.8 km on average with the depth measured from the rim crest averaging 198 meters.

Figure 21 is a map by Roddy (1980: 942) showing the locations of the 1967 and 1978-1979 drill holes at Flynn Creek. Drill hole numbers 1 through 6 were drilled in 1967 along an approximate east-west diameter of the crater in order to investigate the thickness of the breccia lens and determine the nature of the underlying formation. The second phase of core drilling at Flynn Creek occurred from November 1978 to November 1979 and consisted of 12 holes that were 3.5 cm in diameter and totaled 3064 meters:

> Four holes, up to 625m deep, were devoted to determining the structure of the innermost western rim, crater walls and floor. Four holes, up to ~ 166m deep were devoted to crater floor structure along north and northeast radials. Three deep holes, up to 853m deep, were drilled in the central uplift, and one 216m deep hole was drilled in the terrace graben on the southern rim. (Roddy, 1980: 941).

The "… shallow depth of excavation and deformation underlying essentially all the crater floor, except for the central uplift region …" was absolutely confirmed (ibid.). The crater floor averaged around 80 to 98 meters in depth below the pre-impact crater surface, the breccia lens was only 35 to 50 meters in thickness, and the strata underlying the breccia were undeformed, continuous, and flat-lying around 100 meters below the base of the lens which was around 200 meters below the pre-impact ground surface. The crater was the result of a broad, but shallow excavation cavity, with "… the crater diameter/ depth of cavity ~ 1/23 …", associated with a deep, but narrow central cavity containing the uplifted strata in the center (ibid.). The new 216 meter drill core from the southern graben in-

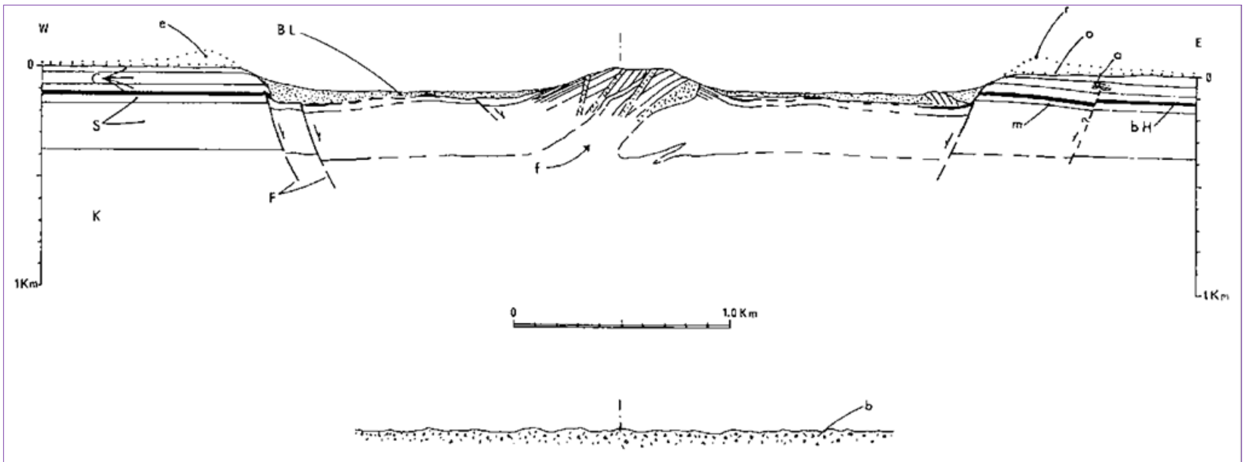


Figure 22: Schematic geological cross-section of Flynn Creek (after Roddy, 1979b: 2523).

dicated that the strata were basically flat-lying at depths of 50 to 75 meters below the pre-impact ground surface which led Roddy (1980: 942) to conclude that "… the graben or terrace block moved downward and slid towards the crater with relatively little secondary deformation or tilting."

Figure 22 is a cross-section of the Flynn Creek impact crater based upon surface geological and core drilling studies. Deformation in the eastern rim was primarily due to simple uplift. The western and northern rims were relatively flat except for some limited folding immediately outside the walls which caused the rock to dip into the crater. It was the southern rim that was home to the most developed terraces and the most complex deformation of Flynn Creek including "… a major rim graben partly overlain by a large thrust sheet …" (Roddy, 1979b: 2524).

Surface mapping and drill data indicated that the folded strata in the inner rim, crater wall, and outer crater floor were underlain by one or more concentric ring faults on the western, northern, and eastern sides of the crater. The down-dropped sides of these faults were towards the crater and maximum displacement appeared to have been no more than around 40 meters. "These faults appear to be relatively high-angle normal faults immediately below the folded strata …" as is shown in Figure 22 (Roddy, 1979b: 2527). The net effect of the concentric faulting served to lower the outer part of the crater floor from a few meters up to some 40 meters and tilt the subcrater floor strata away from the crater center. Roddy (ibid.) states that "… the drill data indicate that the total vertical displacement across the rim to the outer crater floor strata commonly takes place in a horizontal distance of 50 m or less …"

The most complex structure in the Flynn Creek crater was still considered to be the large graben and thrust sheet contained in the southern rim. This section was of great interest due to the "… 0.5 km^3 of ejecta with a crudely inverted stratigraphy that remained trapped in the down-dropped part of the southern rim graben …" (ibid.). Of additional interest was the original ground surface from the time of impact that was partially exposed beneath the ejecta. Roddy (1977b: 303) estimated that the original ejecta blanket had an approximate radius of 2.5D, where D is the diameter of the crater.

The second round of drill data also showed that a thin breccia lens underlay the crater floor and averaged 35 to 50 meters in depth. The lens thinned a little towards the central uplift and covered its lower flanks. The lower part of the breccia lens was well defined in the drill cores and contained "… fragments with lithologies mixed from all of the rock formations encountered in the cratering, except for the central uplift strata …" (Roddy, 1979b: 2528). The breccia lens plus the ejecta that washed back into the crater increased the thickness to around 100 meters near the outer edges of the crater floor. Roddy (ibid.) states that the additional drill data showed that rock immediately beneath the breccia lens base was highly faulted, fractured, and locally brecciated; however, no lithological mixing was noted in the disturbed rock. Deformation decreased rapidly downward and was basically absent around 100 meters below the breccia lens, which would be around 250 meters below the original ground surface. The lower limit of brecciation and ejection as determined by the deep core drilling was interpreted by Roddy (1979b: 2530-2531) to "… define the approximate extent of the transient cavity formed during the cratering event." The deep sub-surface strata beneath all but the central uplift

> … of Flynn Creek *do not* exhibit total fragmentation and mixing, such as that expected with a deep transient cavity and subsequent deformation ... We therefore conclude that Flynn Creek formed with only a broad shallow flat excavation cavity and a central uplift … [and never did go through] a deep transient cratering phase … (Roddy et al., 1980: 944; his italics)..

Roddy's field studies suggested that the upper part of Flynn Creek's central peak was composed of a complex sequence of highly brecciated, faulted, fractured, and locally folded limestones and dolomites which "… moved inward and upward to form a domical-shaped central peak that rose 110 to 120 m above the initial crater floor." (Roddy, 1979b: 2529). Extensively uplifted and deformed Stones River and Knox strata are now exposed due to a narrow valley that eroded through the central uplift by Flynn Creek. Numerous stratigraphic omissions and repeats occur in the uplift due to fault zones which vary from low to high angle. A road cut through the central peak exposes a westerly dip, varying from 24º to 60º, in most of the western and central sections of uplifted strata. Chaotic breccia separates the westward-dipping strata from the eastward-dipping strata found in the eastern section of the central uplift. Upper Knox stratigraphic units in the central hill contain shatter cones and were "… uplifted through 450 m to the original level of the pre-impact ground surface …" (ibid.). Deep drilling in the central uplift and its outer flanks produced 8 cores which indicated that the disrupted zone under the central peak "… has an irregular shape that dips asymmetrically to the west …" (ibid.). Roddy (1979b: 2529) explains the significance of this:

> Both the extensive surface exposures through the middle of the central peak above the crater floor level and the deep drill data indicate a westward plunge of this zone of subsurface

> deformation. The continuation of the dipping geologic contacts in the exposed rocks with the deep subsurface data on Knox and Stones River contacts indicates that the source of the uplifted Knox lies under the western flanks of the central peak and that it was uplifted and displaced strongly to the east.

The drill core results are important for our current understanding of the Flynn Creek central uplift since "The southern two-thirds of the central uplift remains buried beneath the Chattanooga Shale and Fort Payne Formation, making study difficult …" (Milam and Deane, 2006b: 1).

Interpretation of the drill core data by Roddy indicated that total fragmentation and ejection only extended some 200 to 250 meters below the original ground surface and below that massive readjustments took place in which blocks tens of meters across were either uplifted or down-dropped tens of meters. According to Roddy (1979b: 2530, his italics),

> This would suggest that a narrow, *partly open* transient cavity may have extended to perhaps as deep as 300 to 500 m to allow the mega-blocks to rapidly shift into their final positions. Ejection of rocks from this deep level does not appear to have occurred … The gradual termination of major disruption in the strata beneath the central uplift appears to be approximately 700 m below the pre-impact ground level … No structural uplift could be determined below this level.

Roddy (1979b: 2532) summarized his interpretation of the sequence of cratering events at Flynn Creek as follows: (1) oblique impact of a low density body such as a comet nucleus or carbonaceous chondrite … (2) oblique penetration into the rocks, including a possible very shallow body of water, to depths on the order of 100 to 200 m; (3) vaporization and melting of carbonate rocks and impacting body along penetration cavity; (4) total brecciation and ejection of a small bowl- to conical-shaped region which had a diameter of less than ~900 m and a very approximate depth of 200 to 250 m; (5) intensive bulking and disruption of the rock surrounding the central impact area and violent expansion and uplift into the *partly opened* central transient cavity; (6) broad anticlinal folding and faulting of sub-crater floor region caused by shock compression and initial outward expansion and relaxation; (7) continuous brecciation and excavation of the strata over the present crater floor area to a depth no greater than 150 m and out to approximately the present crater walls. This stage is probably continuous with the ends of stages (5) and (6); (8) continuous ejection of rocks from crater floor region to form an ejecta blanket with crudely inverted stratigraphy surrounding the crater; (9) formation of concentric ring fault zones, probably as early as the end of state (6), with down-dropping and inward movement of sub-crater floor strata completing final reposition of deeper rocks. Terrace formation probably continued to occur during this time. Final inward movements in the lower disrupted central uplift zone probably continued to close the deepest part of the *partly opened* transient cavity and sustain the uplifted strata. Elsewhere in this paper Roddy (ibid.) points out that these suggested stages most likely overlap and are transitional in time with each other.

From time to time during the latter half of the last century researchers other than Roddy were interested in Flynn Creek. Miller (1974) summarized the structural features of the Flynn Creek crater by stating that the rocks there are intensely deformed and brecciated and there are numerous faults and folds. He noted that there is a central uplift in which the Knox and Stones River strata are not only exposed, but are found to have been raised some 300 meters above their normal position. He also mentioned the fact that shatter cones are present in the Flynn Creek Structure.

Officer and Carter (1991: 24) state that the Flynn Creek structure "… consists of a shallow crater, 3.6 km in diameter and about 150 m deep …" with a large central uplift, deformed rim strata, and a breccia lens. Shatter cones were found within the central uplift where strata are raised some 350 m above their normal stratigraphic position. More than 2 km^3 of Upper and Middle Paleozoic limestone and dolomite were brecciated and mixed to a depth of 200 m. Officer and Carter believe that around half of the Flynn Creek breccia was ejected from the crater, but the rest remained as a lens of chaotic brecciated dolomite and limestone with fragments ranging from under a meter to blocks up to 100 meters long. Drill core reports indicated that "… the limestone and dolomite beds immediately below the base of the breccia lens are highly faulted and folded, but deformation decreases downward, and the rocks are nearly flat lying and undisturbed about 100 m beneath the breccia lens …" (ibid.). Officer and Carter state that no gravity or magnetic anomalies were ever found to be associated with the Flynn Creek Structure (ibid.).

Recent research has led to the recognition that some of the Flynn Creek breccias primarily consist of black shale clasts that are most likely derived from the Upper Devonian Chattanooga Shale and apparently do not contain limestone or dolomite clasts derived from the Nashville, Stones River, or Knox Groups which are Ordovician in age, which "… suggests an early syn-depositional impact event rather than Ordovician or pre-Chattanooga Shale impact …" (Evenick et al., 2004: 1). Thin sections prepared from Flynn Creek breccia have been found to display rare flow textures and minor spot melt at grain

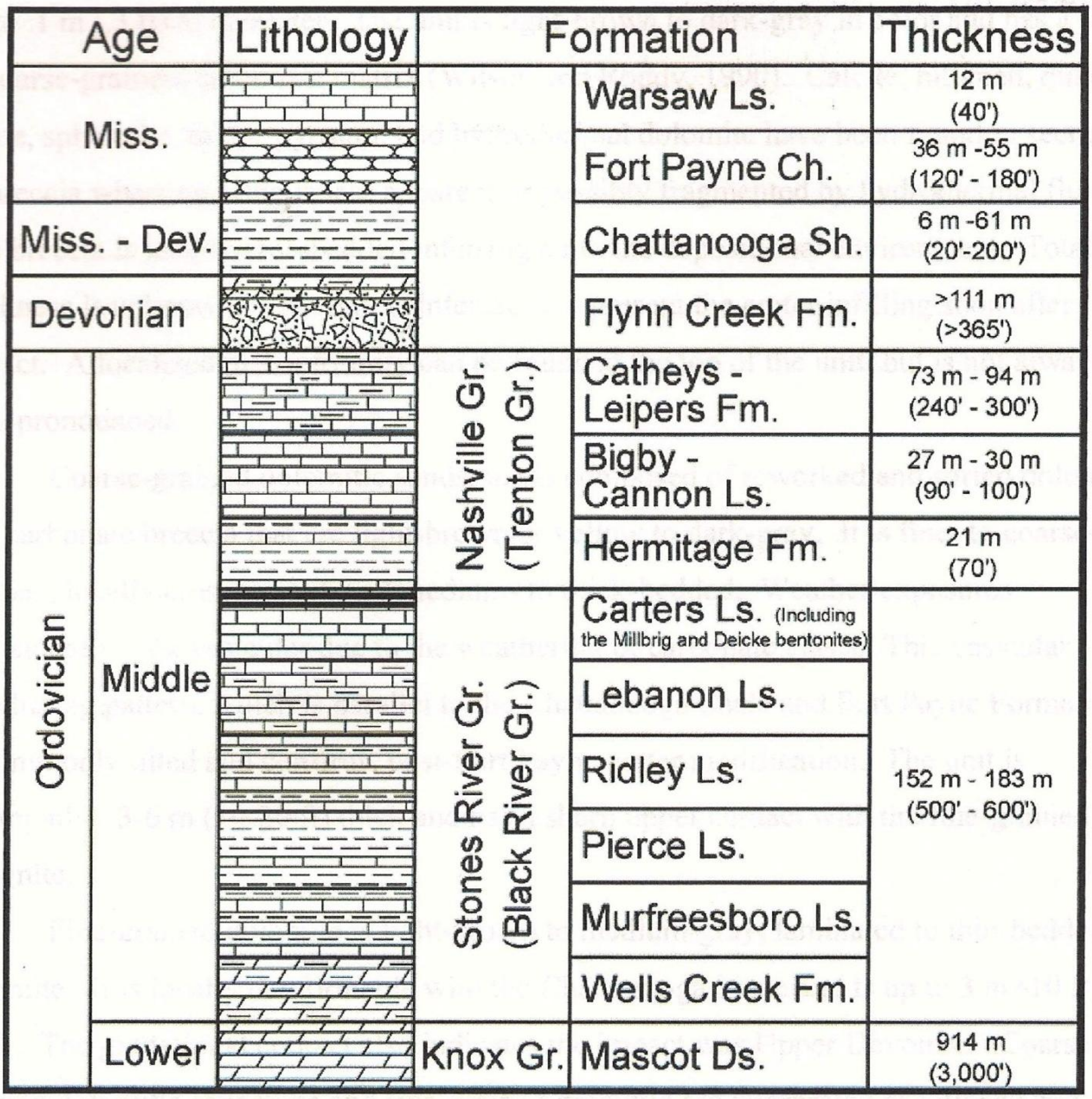


Figure 23: Stratigraphic column of Gainesboro quadrangle (after Evenick, 2006: 3).

boundaries. "The presence of spot melt and flow textures further confirm the structure's impact origin …" (ibid.).

The Flynn Creek crater fill recently has been "… separated into four categories (called the Flynn Creek Formation): non-bedded breccia, bedded breccia, course-grained dolomitic sandstone, and fine-grained dolomite. The Formation is found only within the crater …" (Evenick, 2006: 1). Drilling data indicate that the Flynn Creek Formation is over 111 meters thick, as is shown in Figure 23, a stratigraphic column of rock exposed in the Gainesboro quadrangle, which includes the Flynn Creek area (cf. Evenick et al., 2005). The basal breccia unit in the Flynn Creek structure is the non-bedded breccia, predominately composed of angular and unsorted limestone along with minor dolomite and chert clasts that are up to 0.3 meters in diameter.

The bedded breccia overlies the non-bedded breccia and is composed of angular and unsorted limestone, minor dolomite, chert and shale clasts up to 0.1 meters in diameter. "The breccia is locally crossbedded inferring a marine depositional environment … This unit is inferred to represent the crater infilling soon after impact …" (Evenick, 2006: 4).

The coarse-grained dolomitic sandstone is around 3 to 6 meters thick and composed of reworked and sorted dolomite and carbonate breccia. It has a sharp upper contact with the fine-grained dolomite which is light-brown to medium-gray and laminated to thin-bedded dolomite. This unit is up to 3 meters thick and locally conformable with the Chattanooga Shale. The gradational contact also indicates the impact was upper Devonian. "Course-grained dolomitic sandstone and fine-grained dolomite are interpreted as fallback and ejecta that washed into the crater following impact …" (ibid.).

Although most previous researchers have placed the age of the Flynn Creek Structure at ~360 ± 20 Ma, corresponding to the initial deposition of the Chattanooga Shale, fossil evidence found in the breccias indicates that the impact most likely occurred around 382 Ma (Evenick, 2006: 4; Schieber and Over, 2005: 51). Confirmed Flynn Creek target rocks range from the Knox and Stones River Groups in the central uplift to the Catheys-Leipers Formation in the rim exposures (Evenick, 2006). Recent field mapping yielded the following results:

> 1) fracture patterns in the Flynn Creek Formation are similar to Devonian fracture sets; 2) a gradational contact between the basal Chattanooga Shale and the uppermost unit in the Flynn Creek Formation (fine-grained dolomite); 3) hydrothermal dolomite in the crater rim and fill; 4) Chattanooga Shale clasts reworked into the basal member of the Chattanooga Shale near the modified crater rim; and 5) rare impact breccia clasts with possible Chattanooga Shale affinity. This new information, along with the previously confirmed thickened Chattanooga Shale sequence and the Devonian conodonts within the basal impact breccias, strongly constrains the impact age to the Upper Devonian. (Evenick, 2006: 4-5).

This Upper Devonian impact crater filled with the dark marine mud which became the Chattanooga Shale, then uplift during the late Paleozoic led to partial exposure of this buried crater at Flynn Creek (Evenick, 2006).

Schieber and Over (2005: 64) state that

> Conodonts from the fill of the Flynn Creek structure clearly constrain the relative age of the Flynn Creek Member basal breccia, bedded breccia, and black shale submembers, as well as the overlying Dowelltown Member of the Chattanooga Shale.

The basal and bedded breccia submembers were found to contain mixed fauna of Late Ordovician and Devonian conodonts. Overlying the Flynn Creek Member and Ordovician strata, the Dowelltown Member is marked by a disconformity and basal lag which, regionally, contains Ordovician through Late Devonian conodonts. Schieber and Over (2005: 66) come to the following conclusion concerning the age of the Flynn Creek impact crater:

> With some limitations, and acknowledging analytical error ranges of ±2 m.y. for published radiometric dates, as well as competing geochronological schemes … the 0.42 m.y. time interval from 382.24 to 381.82 Ma. thus brackets the time of impact.

Schieber and Over (2005: 66-67), therefore, conclude that "The asteroid that produced the Flynn Creek crater struck … during the Lower Frasnian, approximately 382 million years ago, and the marine crater fill sedimentation commenced immediately after impact." They also note:

> The late Dave Roddy generously shared his understanding of the Flynn Creek Structure and provided access to drill cores and sample materials. Dave was able to comment on the first draft of this manuscript, but his untimely death in 2002 prevented him from seeing it go into print. Flynn Creek was one of Dave's favorite impact structures. (Schieber and Over, 2005: 67).

4 CRATERING MECHANICS

Roddy (1977b: 278) pointed out that "Hypervelocity impact cratering has proven to be one of the dominant physical processes affecting the surfaces and evolution of the terrestrial planets." He also noted that large craters apparently have played a major role in the evolution of the crusts and upper mantles of most of the bodies in our Solar System that have solid surfaces, and concluded that "… an understanding of their cratering processes is essential to any comprehensive study of the terrestrial planets …" (ibid.).

According to Boon (1936), it is difficult to determine the energy changes that occur when a meteorite impacts the surface of the Earth or the Moon. An early unexpected finding noted is that meteorite impact craters, such as the Barringer Crater in Arizona, "… show little evidence of heat." (Boon, 1936: 57). Small meteorites lose most of their high initial velocity, and thus their kinetic energy, to friction while passing through the Earth's atmosphere. Massive meteorites, on the other hand, are many times heavier than the column of air they displace as they descend, therefore, their impact velocities are close to the velocities with which they travelled through space before entering the Earth's atmosphere (see Boon and Albritton, 1936). The kinetic energy, *KE*, of a massive falling meteorite is given by the following equation:

$$KE = (\tfrac{1}{2})MV^2 \qquad (1)$$

where *M* in the mass and *V* is the initial velocity. Given their high velocities, Boon and Albritton (1936: 3) conclude that massive meteorites must possess huge amounts of kinetic energy and, therefore, "… must explode when they strike the earth …"

The radial distribution of ejecta (both country rock and meteorite fragments) around craters, the intense local brecciation and powdering of the country rock, the occasional manifestations of intense but localized thermal metamorphism, and the radially-outward dip of rim rocks lead to the same conclusion: that tremendous explosions have occurred at these localities.

In their discussion, Boon and Albritton divide an explosive event due to meteoritic impact into three intervals in order to discuss the ways in which a meteorite's kinetic energy is either converted or dissipates during the event. The first interval covers the time the meteorite spends traveling through the Earth's atmosphere "… which may last for several seconds …", and due to friction with the atmosphere "A relatively small amount of this energy is dissipated as heat …" (Boon and Albritton, 1936: 4). Boon and Albritton (ibid.) also point out that since the time interval is so short, frictional heat will penetrate only the outermost layer of the meteorite and note that "The inside of a large meteorite would probably have a temperature near absolute zero at time of impact …"

Boon and Albritton's second interval covers the time period in which the meteorite comes to rest after striking the Earth's surface. The impact of a massive meteorite would deal surface rocks "… a terrific blow … [and in only] a fraction of a second the body would penetrate the earth a short distance and be brought to rest." (ibid.). During this brief time interval, the meteorite's energy is stored in two places: the first is "*In a thin, intensely hot, gaseous layer surrounding the bottom of the meteorite* …" (ibid.; their italics). If all of the massive meteorite's kinetic energy was transformed into heat, then the meteorite itself would likely be melted or vaporized (ibid.). However, "… it would be impossible for more than a small part of the kinetic energy to be so transformed in the fraction of a second between impact and explosion …" (ibid.). Heat travels by convection and conduction with comparative slowness, so this 'zone of vaporization' would comprise only a small part of the transformed kinetic energy. This small portion of the energy would likely vaporize only a thin layer of material underneath the meteorite, but this would be an intensely hot zone and "… would be the locus for thermal metamorphism …" which accounts for the silica glass that is found in some meteorite impact craters (see Boon and Albritton, 1936: 5).

The second and greater portion of the transformed kinetic energy "… is momentarily stored in *a zone of highly compressed rock beneath the locus of impact …"* (ibid.; their italics). As a massive meteorite penetrates the Earth and comes to rest, it compresses the target rock beneath, and by the time the meteorite has come to rest the greater portion of its energy is stored "… in this zone of compression as *pressure potential energy …*" (ibid.; their italics).

The third time interval designated by Boon and Albritton is that of the explosion. They state that

> The instant a large meteorite is brought to rest, the highly compressed materials beneath it would expand with explosive violence … (Boon and Albritton, 1936: 6).

The energy released would dissipate during the formation of a crater by the brecciating or pulverizing and then excavation of target rock, the formation of elastic waves, and the deformation of rock strata. Taking into consideration

> … all of the explosive forces brought into play by meteorite impacts, it would seem that a body sufficiently large to reach the earth with virtually undiminished velocity would be backfired and shattered upon impact … (ibid.).

Boon and Albritton (1936: 6) suggest that the target material of a meteorite strike has

> … a limited degree of freedom, and a high degree of elasticity of volume … Brittle substances are not shattered by pressure, if pressure be applied to all sides, but by tension. Hence after compression they all rebound.

They point out that after a meteorite impact and explosion, concentric waves would be expected to move outward in all directions from the center of impact forming ring anticlines and synclines. Roddy (1977b: 295) infers that the expanding shock wave may likely be "… slightly flat due to differential travel velocities in the vertical and horizontal directions." The waves, however,

> … would be strongly damped by the overburden and by friction along joint, bedding, and fault planes. *The central zone, completely damped by tension fractures produced by rebound, would become fixed as a structural dome …* (Boon and Albritton, 1936: 7; their italics)

Boon and Albritton (ibid.) give the following description of a meteorite impact structure:

> The general and simplest type of structure to be expected beneath large meteorite craters would, therefore, be a central dome surrounded by a ring syncline and possible other ring folds, the whole resembling a group of damped waves.

Roddy (1977b: 296) points out that an effect of the very high shock pressures during an impact event is that the impactor and the target rock "… respond hydrodynamically, temporarily exhibiting a fluid behavior." This is because the strength of the impactor and the target rock would be exceeded by factors of 10^3 or more, literally causing them to flow. Roddy (1977b: 297) describes the excavation of a crater as follows:

> The basic mechanism for pressure release lies in the interaction of the shock waves with all free surfaces. Stated simply, material semi-infinitely deep in a shocked zone moves only in the direction induced by the shock wave. Near a free surface, however, material experiences a different unloading path due to the fact that an unconfined free surface cannot support stress across that surface, i.e., continuity conditions require an instant equilibration

> of the stress field. Consequently, the high pressure zones created in the target and projectile, together with very low surface pressures, define a decreasing stress gradient along which material can be accelerated and ejected. The practical result is that the free surface moves. The point is that impact craters, at least in hard rock systems, are *not* formed during the very high pressure compression stage. Instead, they form as a response to the later dynamic rarefaction fields developed along all free surfaces.

Boon and Albritton (1937: 56) point out that long after a meteorite crater and its associated ejecta and meteorite fragments have been removed by erosion and weathering, an impact structure, the "... meteorite scar …", may long persist in the geologic record. Figure 24 is a section through a typical meteorite impact crater according to Boon and Albritton, but the actual appearance of the crater will depend on the extent to which it has been eroded (as shown in Figure 24):

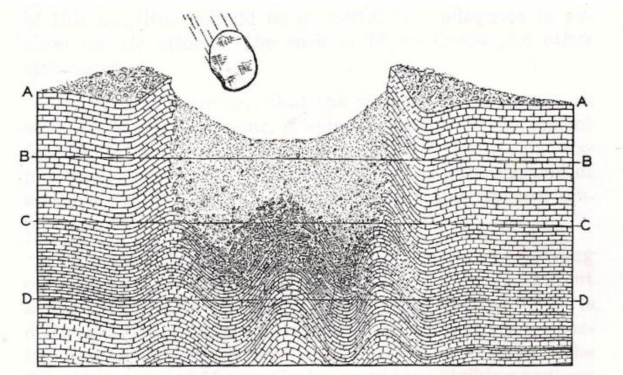


Figure 24: A section through a typical explosive impact crater caused by a meteorite (after Boon and Albritton, 1937: 57).

> It is only in the initial stage (along the profile AA) that the crater clearly reflects its origin in the rim of ejected material, silica glass, and meteorite fragments distributed around it. The scar will become inconspicuous when the country is denuded to level BB. When the area is down to the level CC the underlying structures begin to appear, and when the depth DD is reached the central uplift and ring folds become apparent. Should erosion proceed to depths below those affected by the meteoritic disturbance, the scar would be obliterated. On the other hand if the scar should be submerged and covered with sediments, it might be preserved and subsequently revealed in the course of regional uplift and erosion. (Boon and Albritton, 1937: 56).

Roddy (1976: 121) describes Flynn Creek as a "… large, flat-floored crater, 3.6 km in diameter and over 200 m deep." He then discusses the formation of this crater, and states that the impactor violently fragmented over 2.0 cubic km of flat-lying Middle and Upper Paleozoic limestone and dolomite. He then describes the structural deformation and cratering process as follows:

> Total brecciation and mixing of rock units to a depth of about 0.2 km were completed in seconds with over 1.5 cubic km of rock ejected during the event. Within the crater a thin breccia lens of limestone and dolomite, averaging 40 m in thickness, remained as fallback and locally disrupted country rock. Fragments in this lens lie in chaotic orientations in a carbonate powder matrix and range in size from a fraction of a millimeter up to blocks 100 m across. Drill core data now indicate that the limestone and dolomite beds immediately below the base of the breccia lens are highly faulted and folded with deformation rapidly decreasing downward until the rocks are nearly flat-lying and relatively undisturbed at depths of about 100 m beneath the breccia lens.
>
> During the evacuation phase, a massive central uplift over 1.0 km across and 120 m high formed in the middle of the crater. This dynamic structural uplift consists of steeply-dipping, faulted, folded, and brecciated Middle Ordovician limestone and dolomite which have been raised as much as 350 m above their normal stratigraphic positions. Shatter cones are common in the dense dolomites from the deeper units.
>
> During the latter stages of excavation, flat-lying Middle and Upper Ordovician limestones and dolomites in the rim were moved outward during compression and abruptly uplifted a minimum of 10 to 50 m … During the final stages of cratering normal, reverse, and thrust faulting remained a common mode of structural failure. (ibid.).

Roddy (1968b: 307) notes that the Flynn Creek ejecta blanket, which has for the most part been lost to erosion, is partially preserved overlying a rim graben and displays only the local sedimentary rock in a "… crude inversion of the stratigraphy."

Milam and Deane (2005: 2) describe the probable sequence of events for formation of the central uplift of a complex crater such as Flynn Creek. Pre-impact deposition of target rock and its subsequent lithification and diagenesis may involve the generation of some microfractures. However, the passage of the compressional front of the shock wave due to impact results first in the production of shatter cones and shocked minerals and then, due to subsequent decompression, the generation of microfractures (ibid.). The result of such deformation is the weakening of target rock material which in turn allows for "… potential pathways for subsequent movement of large blocks of material from the centers of craters …" (Milan and Deane, 2005: 1). During the rise of the central uplift, microfault movement and microbreccia generation take place which is immediately followed by major fault movement and fault breccia generation.

Major faults are likely responsible for and represent the final stages of central uplift formation. Roddy (1977b: 302-303) estimates that for Flynn Creek, the entire cratering process and sequence of events took 20-60 seconds. Following formation of the central uplift, more fracturing due to weathering will most likely occur as part of the overall, long-term modification process (see Milam and Deane, 2005).

5 CRYPTO-CONTROVERSIES

Many decades passed between the first recognition of a disturbance at Flynn Creek and the acceptance of the fact that massive meteorites had not only impacted the Earth in the past, but that the scars of these impacts are in some cases still visible today. According to Lusk (1927: 580), "Several hypotheses were considered at the time the writer was investigating and mapping this peculiar feature." Although the figure obtained for the thickness of the Chattanooga Shale found in the Flynn Creek structure was questioned, Lusk (ibid.) found it was "… completely exposed in section up to ninety feet [27 meters] in single outcrops, and it crops out practically continuously in the bed of Flynn Creek and tributaries …"

Another suggestion was that there were post-Chattanooga local forces that were restricted just to this structure with the result being a "… subsidence, or perhaps uplift followed by subsidence which deformed the shale so that at this one place it is exposed in the bed of Flynn Creek …" (ibid.). Lusk noted that in contrast, though, the base of the Chattanooga Shale was only found high on the valley sides both upstream and down-stream from the Structure. In such a scenario, these same local forces would also have to be responsible for the brecciation and high dips in the limestones that Luck observed. However, Lusk noted (ibid.) that the great thickness of the Chattanooga Shale and the lack of folding or brecciation of not only the Shale, but also the overlying beds, showed that the Chattanooga Shale and the later formations were not affected by these local forces. In addition, where the contacts of the Shale and breccia were observed, there were irregular erosion surfaces which were not parallel to that of the Chattanooga Shale or to the formation overlying it.

Lusk (ibid.) pointed out that "Bucher has described a circular area of intense folding and faulting … [and referred to it as a] crypto-volcanic … [structure]. However … the conglomeratic nature of the breccia and the absence of veins or dikes of possible igneous origin discourages the view that sub-surface vulcanism may have been the cause …" (ibid.). After considering all of the observed facts discussed above, Lusk (1927: 580) concluded:

> It is clear that at the inception of the deposition of the Chattanooga shale there must have been a depression with an irregular outline and an uneven floor. In the bottom of the depression and along the walls there were considerable thicknesses of slightly rounded fragments of limestone derived in part from the Ordovician limestones still represented in the surrounding area. Possibly there were also fragments from still higher strata, now eroded and entirely removed except at this one place where they are thus represented.
>
> A depression of this sort could be formed by the collapse of the roof of an irregular branching cavern or series of caverns. The fragmentation induced by collapse, together with the slope wash of talus towards the lines of collapse, would form the conglomerate-breccia.
>
> The Chattanooga shale was deposited in this depression when the general area was receiving carbonaceous mud in the latest Devonian or earliest Mississippian time. With the loading of the region by later sediments, the mud was compacted by the squeezing out of its fluids… The average altitude of the top of the shale is generally less in this area because in so thick a body of shale the total amount of compacting was proportionally greater.

Lusk (ibid.) concluded that the existence of a sinkhole some 60 meters deep could only be possible, though, if this region was at least 60 meters above sea-level for a long enough period during pre-Chattanooga time for a sinkhole of this depth to form.

Although Lusk (1927) considered the Flynn Creek structure to be a pre-Chattanooga sinkhole with a depth of some 60 meters resulting from a cavern collapse, Wilson and Born (1936: 832-833) disagreed with the cause and the depth:

> The only possible means of excavation by agents of erosion is by sinkhole solution, as the topographic basin was completely closed, having no outlet. There are no evidences of sinkhole solution in the pre-Chattanooga rocks of this region; and, also, it is believed that elevation above sea-level of central Tennessee during the Maysville-Chattanooga interval was never sufficiently high to permit the erosion of a 300 foot [90 meters] sinkhole, of which this would be the only known example.

They concluded (Wilson and Born, 1936: 831) that although Lusk correctly eliminated any post-Chattanooga volcanic origin, he was not correct in eliminating a pre-Chattanooga volcanic origin on the basis of the conglomeratic nature of the breccia and the absence of veins or dikes of igneous origin:

> The present writers did not find sufficient evidence of rounding, or "conglomeratic nature," of the breccia, and hence believe that all breccia but that designated as talus breccia resulted from the mechanical fragmentation of

> limestone and subsequent cementation. Also, they cannot accept the absence of veins or dikes of igneous origin at the surface as sufficient to eliminate a possible volcanic origin.

Wilson and Born (1936: 815-816), in fact, agreed with R.S. Bassler (1932) and stated that for Flynn Creek, "All the data accumulated indicate a crypto-volcanic origin of the structure." Boon and Albritton (1936: 7) concisely describe 'cryptovolcanic structures' as "… subcircular, complex, domical structures characterized by intense deformation and brecciation within an area of a few square miles." Bucher (1936: 1075-1076) describes cryptovolcanic structures in great detail as a natural series of disturbances which mark the beginning or the attempted beginning of volcanism in a region and which may be classified as follows:

> 1. Disturbances produced by the explosive release of gases under high tension, without the extrusion of any original magmatic material, at points where there had previously been no volcanic activity ("abortive volcanism"): Cryptovolcanic structures.
> (a) The explosion, too deep-seated, too weak, or too-unconcentrated ("muffled"), results merely in the more or less circular dome and ring structure …
> (b) The explosion, shallow and strong enough, blows out a shallow more or less circular explosion basin filled with a jumble of distorted blocks and surrounded by a zone of materials blown or pushed out from it …
> 2. Features produced largely by the explosive release of gases under high tension, with magmatic materials more or less subordinate to fragments of the overlying rocks, at points where there had previously been no volcanic activity ("embryonic volcanism"): "Funnels," "chimneys," "pipes" filled with volcanic breccias or tuffs …
>
> The explanation of the cryptovolcanic structures here presupposes that in plateau regions seemingly devoid of volcanic activity magma is at times working its way locally upward through the crystalline basement complex into the sediments above, without actually breaking through. The few examples in which erosion has cut low enough to expose such places are of unusual interest.

Roddy (1966c: 17) notes that Bucher (1936), although greatly interested in cryptovolcanic structures, apparently never visited Flynn Creek even though he was aware of the site and it was only recently that Wilson and Born "… proved the cryptovolcanic nature of …[the] structure …" In this context, Wilson and Born (1936: 832) conclude that

> … the closed, topographic depression on the pre-Chattanooga erosion surface was a crater formed by explosion … [and the Flynn Creek disturbance is] of volcanic origin and should be classed in the general group of crypto-volcanic structures … It is believed that (1) the small circular central uplift of approximately 500 feet [150 meters], (2) the intense brecciation of limestone, (3) the intrusive character of the breccia, and (4) the shattering and jumbling of limestone blocks could have been caused only by a relatively rapid, deep-seated volcanic explosion accompanied by a gas explosion near the surface. The features are diagnostic of the examples of crypto-volcanic structures described by Bucher.

Wilson and Born (1936) point out that the Flynn Creek disturbance is not unique, and that there are other small, circular structures similar in shape, size, and depth in many locations on Earth. Suggested origins for these structures (after Wilson and Born, 1936: 828-829) include all of the following:

> (1) fall of a meteorite, with the resulting impact and explosion crater;
> (2) local collapse of a cavern roof;
> (3) salt domes;
> (4) local expansion by hydration of anhydrite;
> (5) natural gas explosion; and
> (6) crypto-volcanic (gas and steam) explosion.

Wilson and Born (1936: 828) considered each of these possible origins for the Flynn Creek Structure, taking into account the fact that any theory of origin for the structural features in the Flynn Creek area must explain the following: (1) a central uplift of approximately 500 feet [150 meters], bringing relatively old beds (Lowville) up to the level of younger beds (Leipers); (2) the intense brecciation of the Ordovician limestone, and the grinding, or pulverizing, of much of the limestone into 'rock flour'; (3) the striking ability of breccia to actually force its way into fractures in unbrecciated limestone in a way suggesting dike intrusion; (4) the shattering of the Ordovician limestone into large blocks, and the irregular jumbling of these blocks; (5) the dip away from the central uplift on the northern, eastern, and western flanks; (6) the dip into the central uplift on the southern flank, and the thrusting away from the center of uplift on that side; (7) a closed, irregular topographic depression with 300 feet [90 meters] relief on the pre-Chattanooga surface, the deformation being post-Leipers, pre-Chattanooga in age; (8) the abnormal thickness of the black shale (250 feet) [75 meters]; (9) the closed synclinal basin in the black shale and overlying Fort Payne chert, centered over what was originally an uplift (this is rather unusual in a region where anticlines and synclines were formed early in the Paleozoic, and all subsequent diastrophic movements rejuvenated these earlier structures as anticlines and synclines, respectively); (10) a well-developed magnetic high centered about 4 miles south-southwest of the disturbed area. (This magnetic high is believed to be the surface expression of the postulated buried plug of igneous material responsible for the Flynn Creek disturbance. The offset of 4

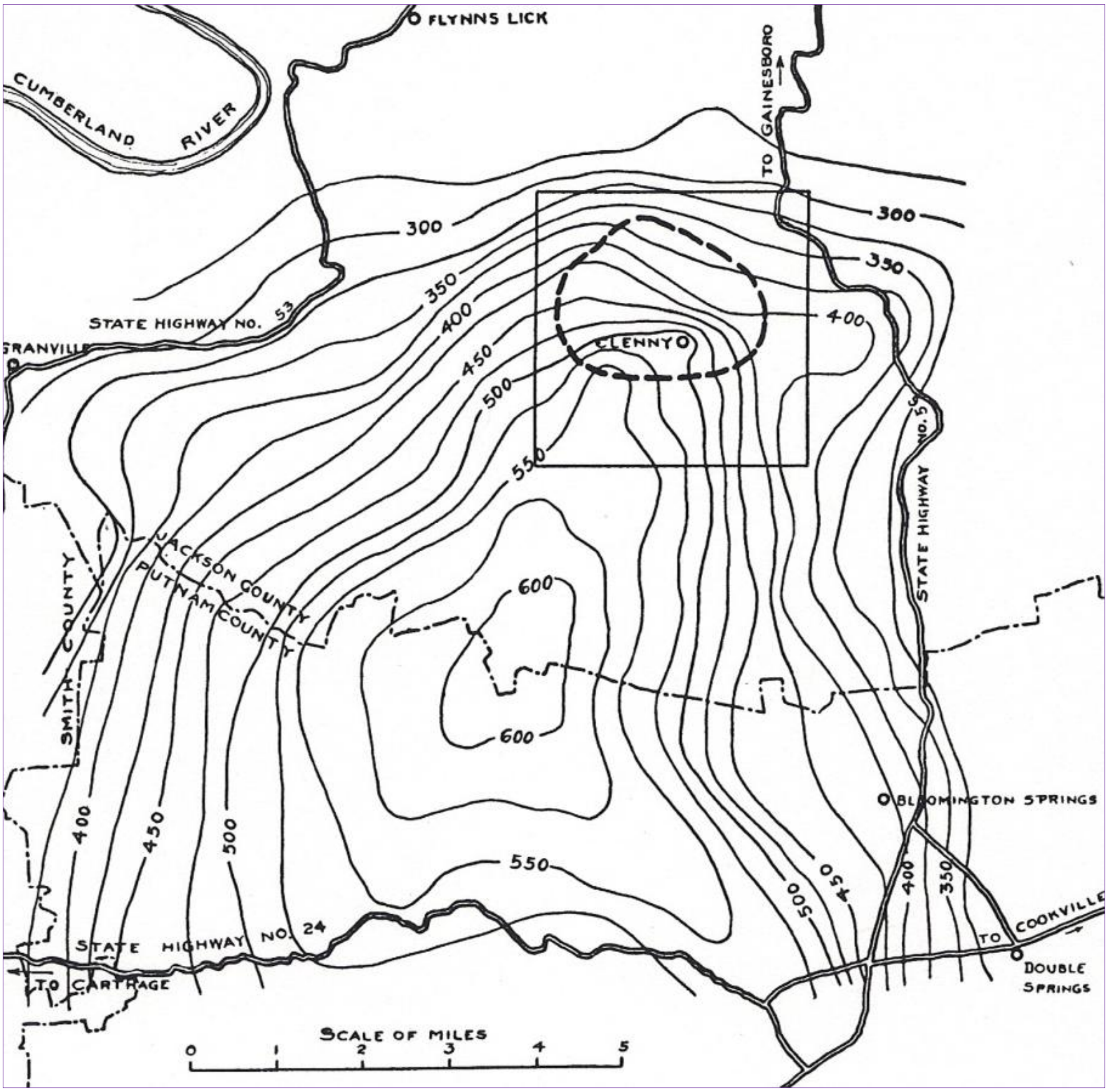


Figure 25: Isogammal map showing magnetic intensity in the Flynn Creek area (after Wilson and Born, 1936: 830).

miles [6.4 km] to the south-southwest is the result of the high-angle dip to the north of magnetic lines of force in the earth's surface.) Figure 25 is a map showing magnetic intensity found in and around the Flynn Creek structure, as well as the location of the crater in relation to the magnetic high mentioned above.

With all of the requirements as listed above in mind, Wilson and Born (1936: 829-830) ruled out most of the possible explanations for the Flynn Creek crater:

> The central uplift of 500 feet [150 meters] in the Flynn Creek area that raised the Lowville limestone up to the level of the Leipers formation definitely eliminates a meteorite crater or collapse of a cavern. The absence of any known salt or anhydrite deposits in this region makes an origin by salt-dome intrusion or by expansion of anhydrite unlikely. The stratigraphic horizon (Lower Ordovician) makes it improbable that sufficient natural gas occurred deep enough below the pre-Chattanooga surface to have blown out a crater. Further, although natural gas occurs at other localities in great quantities and under enormous pressure, it has never been known to have formed such a crater by natural explosion. Cryptovolcanic explosion is the only possible origin among those listed that cannot be readily eliminated.

In hindsight, it is interesting that Wilson and Born so confidently ruled out a possible Flynn Creek meteorite impact based on the existence of a central uplift.

Wilson and Born (1936: 832) believed that "… this pre-Chattanooga topographic basin was an actual crater formed by explosion …" but they make special note of the fact that the Flynn Creek crater coincided in position with the central uplift. They also point out that "… rocks were forced upward as much as 500 feet [150 meters], giving an excess of material near the surface that must be accounted for …" (ibid.). As a possible explanation for cryptovolcanic structures such as Flynn Creek that possess central uplifts, Wilson and Born suggested: "… it is probable that a shallow saucer-shaped explosion funnel was first formed and that the central hill was formed a short time later by a second weaker explosion …" (ibid.).

Taking into account Bucher's description of cryptovolcanic structures, Wilson and Born (1936: 835) summarize the order of events they believe took place at Flynn Creek:

> 1. Deposition of the Lowville, Hermitage, Catheys, Cannon, and Leipers formations. If younger Ordovician or Silurian formations were deposited, they were removed by pre-explosion erosion, as the Leipers is the youngest formation involved in the explosion.
> 2. A volcanic explosion, blowing out a crater 300 feet [90 meters] deep and 2 miles [3.2 km] in diameter, and piling up limestone debris in the vicinity of the crater at some time between the deposition of the Leipers and Chattanooga formations [see Figure 15A]. This explosion preceded the deposition of the Chattanooga shale sufficiently to permit removal of all blocks of limestone around the crater [see Figure 15B].
> 3. Accumulation of talus in the deeper part of the crater, resulting from gravity rolling and slope wash of rock debris into the crater [see Figure 15B].
> 4. Formation of a fresh-water, ring-shaped lake that occupied the crater and surrounded the central hill leaving it an island. In this lake was deposited as much as 12 feet [3.7 meters] of bedded breccia [see Figure 15B].
> 5. Transgression of Chattanooga sea, which filled the crater with 250-300 feet [75-90 meters] of black mud and covered the surrounding region with 20 feet [6 meters] of similar sediments [see Figure 15C].
> 6. Deposition of Fort Payne chert.
> 7. Subsequent local synclinal sagging caused by compaction of the underlying Chattanooga shale and by subsurface readjustment following explosion.

Boon and Albritton disagreed with this interpretation. They noted that prior to 1927 the Barringer 'Meteor Crater' in Arizona was the only known structure of that kind, and using this as an example of a confirmed impact crater they pointed out that "… in addition to creating ephemeral depressions, meteorites deform surficial rock layers when they strike the earth." (Boon and Albritton, 1936: 2). Therefore, a meteorite impact will produce a geological structure underlying the actual impact crater which may be preserved long after the crater itself has been destroyed by erosion. Boon and Albritton (ibid.) then posed an important question: "… where is the evidence for the falling of meteorites on the earth during geologic antiquity?" In seeking to answer this they suggested that certain structures "… previously described by geologists as 'cryptovolcanic' may be old meteorite scars …" (Boon and Albritton, 1936: 3). They then pointed out that adopting a meteorite hypothesis for the origin of structures like Flynn Creek

> … removes the embarrassing question as to the reason for lack of associated volcanic materials. Finally, it gives a tentative answer to astronomers who have long reasoned that large meteorites must have fallen in the geologic past … (Boon and Albritton, 1936: 9).

Boon and Albritton (1937: 56-57) also noted the striking similarity between certain American so-called 'cryptovolcanic structures' and those that would be produced by the impacts of giant meteorites (cf. Bucher, 1963). They pointed out that both the cryptovolcanic and meteoritic hypotheses postulate structural deformation through "… tremendous explosions …", but whereas the cryptovolcanic hypothesis assumes a sudden release of subterranean gases, it cannot account for two features which are explained by an explosive meteorite impact: (1) bilateral structural symmetry, and (2) the lack of volcanic material or other local signs of thermal activity (Boon and Albritton, 1937: 57-58). They reminded their colleagues that no volcanic material had been found in association with the Flynn Creek Structure.

Boon and Albritton (1937) also addressed one of the features that led Wilson and Born to conclude that Flynn Creek was a cryptovolcanic structure. They noted that Wilson and Born dismissed an explosive impact origin for the disturbance because "The central uplift of 500 feet [150 meters] in the Flynn Creek area that raised the Lowville limestone up to the level of the Leipers formation definitely eliminates a meteorite crater …" (Wilson and Born, 1936: 829). However, Boon and Albritton (1936: 7; their italics) stated that "… as a result of impact and explosion … *The central zone*, *completely damped by tension fractures produced by rebound*, *would become fixed as a structural dome.*" Furthermore, the argument put forth by Wilson and Born

> … overlooks the fact that elasticity of rocks would cause a strong rebound following intense compression produced by impact and explosion … [and] It is not unreasonable to suppose that the height of this rebound would be directly proportional to the diameter of the crater … [a ratio of around one to ten, and that] a rebound of this amplitude would be quantitatively adequate to explain the elevation of the rock in Flynn Creek … (Boon and Albritton, 1937: 58-59).

Dietz (1959: 498) believed that the most remarkable aspect of a cryptoexplosion structure is the central uplift, surrounded by a ring syncline which gives the structure a remarkable resemblance to that of a damped wave. A meteorite-impact structure therefore should have the following characteristics:

> (1) it would appear to have been instantaneously and completely formed;
> (2) it would show evidence of great shock by the presence of breccia, rock flour, etc. (this intense deformation would be centrally concentrated and would rapidly diminish outward and downward);
> (3) it might have extensive concentric and radial fracturing, dominated by high-angle normal faulting;
> (4) it would be 'geophysically empty' (especially magnetically), since there would be no intrusive body or salt plug or any large buried meteorite (it is physically naïve to expect the preservation of such a body; in fact, the preservation of any meteorite fragments in ancient scars seems unlikely);
> (5) the explosion crater would be essentially circular, regardless of the angle of impact, but the underlying rock deformation might display some asymmetry, since this is mainly a percussion feature; and
> (6) as explained above, the crater would tend to have the form of a damped wave. Cryptoexplosion structures seem generally to conform to these criteria.

Dietz (1959: 499) explained that according to the meteorite hypothesis, a central uplift may be formed by an elastic rebound of the highly-compressed target rock following an explosive impact, and it "… is likely that giant meteorites strike the earth's surface at hypervelocities, defining this term here to mean velocities in excess of the speed of sound in average rock, i.e., in excess of 5 km/sec …" (ibid.). The target rock would be subjected to an intense shock wave which would greatly compress a cylinder of rock beneath the meteorite. Following the impact explosion, "… compressed rocks might elastically recoil past the zero position into a dome. This dome would be damped or 'frozen' by the formation of tension cracks …" (ibid.).

In contrast, according to the cryptovolcanic hypothesis, the central uplift is a product of a 'muffled steam explosion', which would require an initial strong explosion followed by a second, muffled explosion. Further, Dietz (1959: 499) stated that this double explosion requirement appears to be reasonable when applied to an isolated case, but "… becomes suspect when it is necessary to apply the same unusual explosion sequence to several cryptoexplosion structures."

Boon and Albritton (1937: 59) also addressed the conclusion that Wilson and Born came to regarding the magnetometer survey of the Flynn Creek area. Wilson and Born (1936: 828) found "… a well-developed magnetic high centered about 4 miles [6.5 km] south-southwest of the disturbed area." Boon and Albritton (1937: 60) reasonably pointed out that magnetic anomalies are not uncommon in this region of the United States, as can be seen on any magnetic map, so this association may be coincidental. However, Wilson and Born (1936: 828) stated that "This magnetic high is believed to be the surface expression of the postulated buried plug of igneous material responsible for the Flynn Creek disturbance …", to which Boon and Albritton (1937: 60) responded:

> Granting this magnetic high reflects the presence of a plug, one wonders if the offset of four miles from the center of the disturbance is adequately explained by the 'high-angle dip to the north of magnetic lines of force in the earth's surface'.

Taking the magnetic dip from Boon and Albritton (ibid.) to be 68° in order to solve for the depth of the igneous plug and utilizing the complementary angle, gives tan 22° = 0.40. If the right angle is placed well below the magnetic high at the location of the supposed igneous plug and the side opposite to the complementary angle measured to be 4 miles [6.4 km], the distance from Flynn Creek to the magnetic high, then the adjacent side, the depth of the igneous plug, is given by adjacent = 4 miles **/** (0.40) = 10 miles, or 16 km. Boon and Albritton concluded that "It is difficult to see how a relatively small plug at this depth could greatly affect the magnetic field at the surface …" (ibid.). These researchers also pointed out that even if "Granting that the plug is approximately beneath the structure, it is not evident why the shattering of the roof above the intrusion did not allow ejection of igneous materials …" (ibid.). Boon and Albritton concluded: "With the exception of the anomalous magnetic high to the south of the structure, the meteoritic hypothesis seems adequate to account for the Flynn Creek disturbance …" (ibid.).

Dietz (1959: 496) noted that the term 'cryptovolcanic' comes from the fact that structures, such as Flynn Creek, are assumed to have formed by volcanic explosion, even though the evidence of volcanism is not obvious. The missing evidence includes features such as volcanic rocks, hydrothermal alteration, contact metamorphism, and mineralization (ibid.). Dietz agreed that the evidence indicated these structures were the result of an explosion, therefore, he preferred the term "… *cryptoexplosion structures to cryptovolcanic structures,* so as not to exclude the possibility of an extraterrestrial origin …" (Dietz, 1960: 1782; his italics). He also said that he favored the 'Boon-Albritton hypothesis':

> According to the meteorite-impact hypothesis, cryptoexplosion structures are explosion-per-

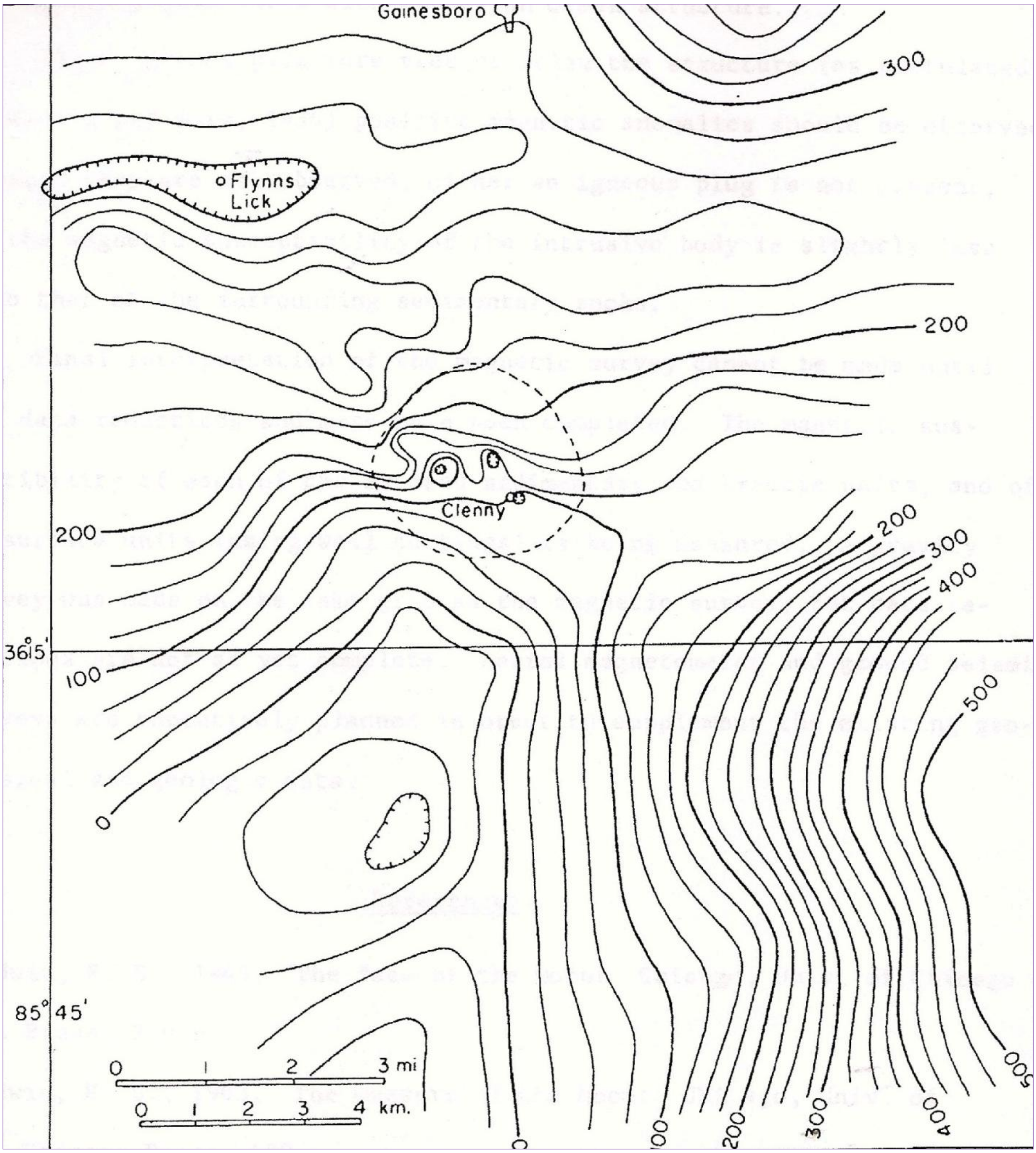


Figure 26: Total intensity magnetic anomalies in the Flynn Creek area (after Roddy, 1964: 176). The Flynn Creek Structure is shown by the dashed outline.

> cussion deformations produced by the hypervelocity and explosive impact of crater-forming meteorites of asteroidal dimensions – a concept developed by J.D. Boon and C.C. Albritton … [These] meteorite-impact scars … [are] ephemeral geologic features which are rapidly eroded away, but the jumbled mass of shattered rock which must extend for several thousand feet beneath an impact crater stands an excellent chance of geologic preservation. (Dietz: 1959: 497-498).

Dietz (1959) reported that in 1946, he and Wilson, in the faint hope of discovering small meteorite fragments, surveyed an outcrop of explosion breccia exposed in the central uplift of Flynn Creek with a mine detector, but no nickel-iron siderites were found (ibid.). He then pointed out that the chance of finding meteorite fragments was extremely small anyway considering the high percentage of stony meteorites, the rapid weathering of any meteorite, the probably almost complete vaporization of any impacting bolide, as well as the eroded nature of the structure itself.

Roddy (1963: 124) agreed with the conclusions reached by Dietz, and Boon and Albritton, and included the following comment in his 1963 paper on Flynn Creek:

> The presence of a core of unsorted, angular breccia, surrounded by a circular, depressed ring of strata; associated structurally complex beds containing low-angle faults, bedding plane faults and shatter cones; and both broad and detailed stratigraphic relations, can best be interpreted as having formed during or after meteorite impact.

The following year Roddy (1964: 171) again explained why he considered a cryptovolcanic origin for the Flynn Creek Structure to be unlikely:

> If a gas is introduced under high pressure from depth, failure of rocks near the surface by brittle fracture is to be expected. Although such a process is capable of explaining the origin of the breccia, it encounters difficulties in application to the rim structure which appears to have had the major stress component in a horizontal direction. Preliminary calculations of the dynamic conditions necessary to produce the rim folding indicate that … It is not likely that gas pressures could build up to the necessary level before fracturing the rocks and thereby releasing the pressure. Large meteorite impacts, on the other hand, can generate pressures that are adequate to cause the rim folding and as well cause brecciation.

Roddy's 1964 report on the Flynn Creek Structure included a magnetic field study in order to obtain information on the subsurface structure. The result of the magnetic measurements "… shows there is no large magnetic anomaly associated with the structure …" (Roddy, 1964: 175). Roddy noted the northeast-southwest trending magnetic trough extending across the area, as is shown in Figure 26. This map shows that a closed magnetic low around 6.5 kilometers southwest of the crater forms the lower end of the magnetic trough. Based on this map, Roddy (1964: 175, 177) made the following observations:

> The observed magnetic anomaly is opposite to the magnetic data reported by Wilson and Born (1936). The total magnetic intensities and trends of this anomaly suggest it is not directly associated with the Flynn Creek structure.
>
> If an igneous plug were present below the structure (as postulated by Wilson and Born, 1936) positive magnetic anomalies should be observed. Because they are not observed, either an igneous plug is not present, or the magnetic susceptibility of the intrusive body is slightly less than that of the surrounding sedimentary rocks.

Neither gravity nor magnetic studies indicated any large anomalies directly associated with the Flynn Creek structure (Roddy, 1966c). Figure 27 is a complete Bouguer anomaly map of the Flynn Creek area (after Roddy, 1968c: 305), which shows the location of the Flynn Creek crater in relation to the locations of the gravity stations utilized in the geophysical study.

Roddy (1964: 173) states that a search also was made at the Flynn Creek site for the high-pressure polymorphs coesite and stishovite. Seven rock samples, four from the shattered Knox Group beds in the center of the structure where the shatter cones were located and three more samples from the mixed breccia near the structure's eastern rim were collected for examination, but no trace of either coesite or stishovite was found (ibid.). Roddy (1965: 55) tellingly also pointed out that an analysis of the breccia mix and breccia fragments found in Flynn Creek indicated that there were no traces of either meteoritic or volcanic constituents in any of the ten samples studied. In addition, he reported that in six cores drilled across the Flynn Creek Structure, no volcanic or meteoritic materials were found (see *Astrogeologic Studies*, 1967: 29).

Miller (1974: 58) also reported that neither volcanic nor meteoritic material has ever been found at Flynn Creek and that "… studies show no magnetic anomalies which might be associated with buried meteoritic material." He concluded that "Comparison with other craters of known meteorite impact origin shows similarities, therefore, it is assumed that either a meteorite or comet impact formed this structure …" (ibid.). Milam and Deane (2007: 1) also examined Flynn Creek breccias, and their preliminary results suggest "… a lack of chondritic or iron meteoritic component remaining in the breccias or post-impact fill of the Flynn Creek impact structure …"

In his Ph.D. thesis Roddy (1966c: 152) addressed various origins suggested for the Flynn Creek structure. He rejected the possibility of a cavern collapse because rocks in the crater were raised far above their normal stratagraphic level. The possibility that Flynn Creek was a salt dome or the result of anhydrite expansion or a natural gas blowout was rejected, primarily because neither evaporites nor high pressure gas deposits had ever been found in central Tennessee, nor did Flynn Creek resemble the types of structures these would produce. He ruled out tectonic folding, stating that the type necessary to form a structure such as Flynn Creek was not present in the area. Hydraulic fracture by water was not considered to be likely because there was no known way for sufficient water pressure to build up; nor would this method produce a structure that resembled Flynn Creek. He also noted that "Mineralization related to hydrothermal or volcanic processes has not been recognized in the Flynn Creek area …" (Roddy, 1966c: 179), and "No thermal metamorphic effects have been noted either in the field or in petrographic studies …" (Roddy, 1966c: 183). He further pointed out that in the Flynn Creek rim strata, large-scale folding appears to have had the major stress compon-

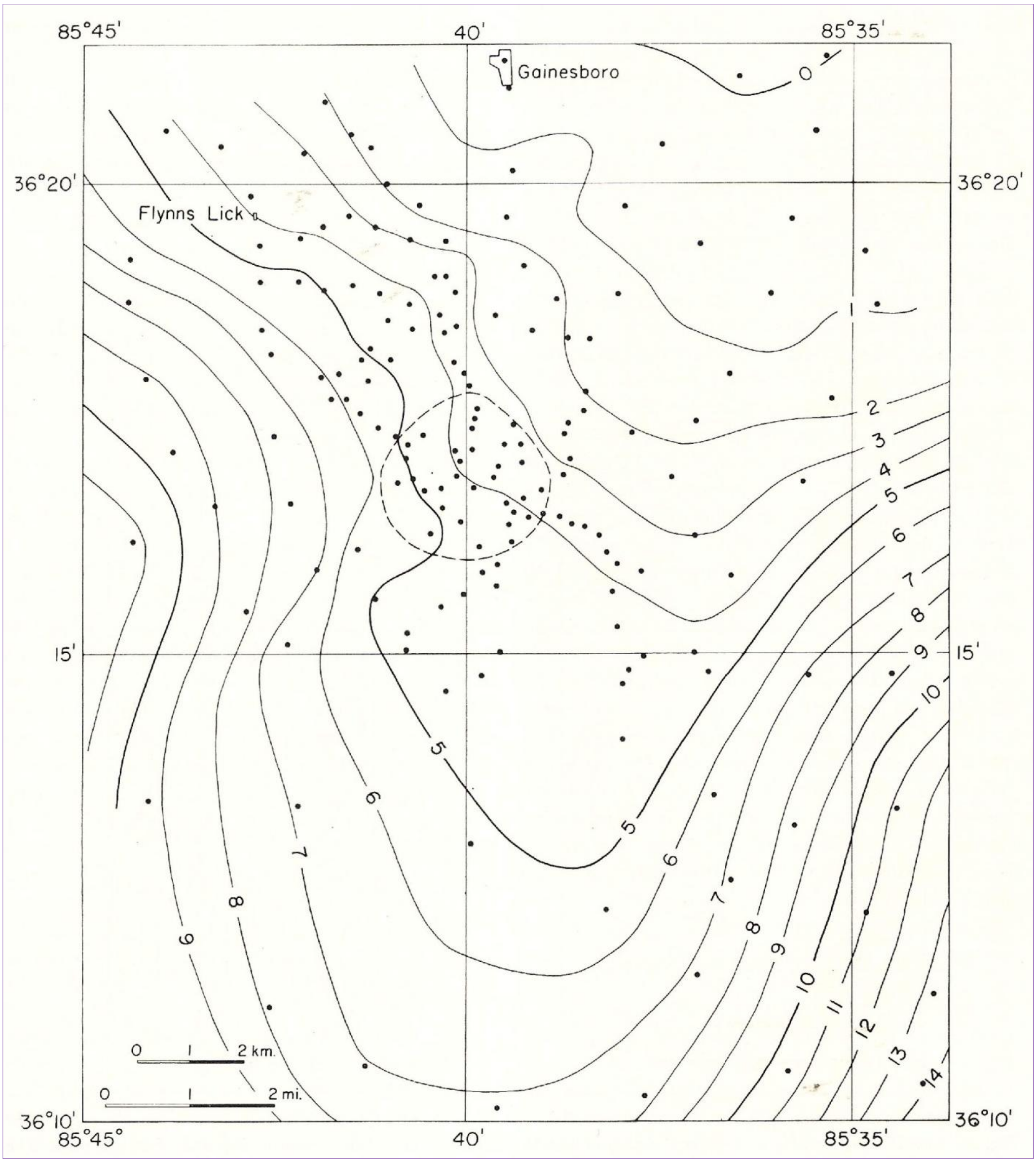


Figure 27: Complete Bouguer anomaly map of the Flynn Creek area (after Roddy, 1968b: 305). Gravity stations are indicated by dots. The Flynn Creek Structure is shown by the dashed outline.

ent in the horizontal direction. Roddy (1966c: 186) therefore concluded that the simple build up of gas pressure near the surface, in other words, a volcanic gas or steam explosion, would not explain the Flynn Creek rim folds having their major stress component in the horizontal direction.

In his 1967 *Astrogeologic Studies Annual Progress Report*, Roddy stated that core drilling gave evidence of "… a shallow lower boundary of the chaotic breccia lens … [and] a decrease in deformation in the rocks below the breccia lens …", which indicate an impact origin (*Astrogeologic Studies Annual Progress Report* (1967: 29). Roddy's overall conclusion as to the origin of the Flynn Creek structure is:

> The very shallow breccia lens, the absence of mineralization and volcanic or meteoritic materials, the types of rim deformation, and the central uplift are consistent with the impact of a low-density body, possibly a comet. The structural information from surface mapping, combined with the core-drilled data strongly suggests that the Flynn Creek crater was produced by the impact of a cometary body. (*Astrogeologic Studies Annual Progress Report*, 1967: 29-30).

Roddy (1968a) was of the opinion that the formation of a central peak in an impact crater was dependent on a low-density ($\rho \leq 1$ g/cm^3) body that volatized upon impact. He observed that

> … deformation at Flynn Creek, particularly the central uplift, has marked structural analogs with most of the other cryptoexplosion structures … [so] It is suggested that terrestrial (and lunar) craters with central peaks produced by structural uplift are formed by comet impact … (Roddy, 1968a: 272).

When Roddy was close to completing his Ph.D. research, and his Astrogeologic Studies reports on Flynn Creek for the United States Geological Survey, he made the following observation:

> The study at the Flynn Creek crater has now provided sufficient information to see close structural similarities with several of the different "shocked-produced" craters such as meteorite craters, nuclear craters and chemical explosion craters. Deformation in the rim strata, ejecta, and crater breccia are similar in these craters to that seen at the Flynn Creek crater. One of the chemical explosion craters has a pronounced central uplift and exhibits deformed rim strata with types of deformation nearly identical to that at the Flynn Creek crater. (Roddy, 1966c: 187).

Researchers at the Suffield Experimental Station in Alberta, Canada, detonated a 500 ton TNT charge on the ground surface in June 1964 which produced a chemical explosion crater with "… such pronounced structural similarities to the Flynn Creek crater that a visit was arranged for the author [Roddy] by the U.S. Geological Survey and the Canadian Government." (Roddy, 1966c: 201). The resulting crater was shallow, flat-floored, around 100 meters in diameter, and originally 6.5 meters deep with a 5.5 meter high central uplift (Roddy, 1968b). Material thrown out of the crater formed an ejecta blanket that was continuous to around 130 meters from the crater walls (ibid.). The following quotation is taken from Roddy's (196cb: 203, 205) Ph.D. thesis, and is based on his observations and on interviews with Suffield Experimental Station personnel, including Dr. G.H.S. Jones, who was in charge of the large-scale explosion experiment (see Schaber 2005: Appendix A, page 256):

> The explosive was stacked in a hemispherical shape measuring about 30 feet [9 meters] in diameter and 15 feet [4.5 meters] in height and was detonated at the center of the charge at ground level. The resulting crater was somewhat irregular in outline and measured from about 240 to 330 feet [75 to 100 meters] in diameter at the original ground level, and was about 15 feet [4.5 meters] in final depth after a later deposition occurred. The most striking departure from normal explosion craters included a large central uplift, a local depression or down-folding of parts of the rim, and large concentric and radial fractures …
>
> Tension fractures began to open and continued to open for several days after the event. Less than 5 minutes after the detonation, water started to flow into the crater from fractures in the central mound. Within ten minutes or less water was also flowing from fractures in the crater floor and continued until the crater contained a lake with the central mound forming an island. Large concentric fractures in the rim at a distance of about 210 feet [65 meters] and 260 feet [80 meters] from the crater wall also continued to open for several days after the detonation …
>
> A few feet from the original crater wall the slightly depressed rim rises abruptly into a tightly folded and distorted anticline … although the sand beds are unconsolidated, it appears that a thrust was developing during the folding of the anticline. The beds are highly deformed and mixed with other fragments in the crater wall and appear similar to the highly jumbled to brecciated rim strata in parts of the crater wall at Flynn Creek …
>
> Although the beds in the central mound are greatly disturbed by folding, shearing, brecciation and a great amount of thickening and thinning, a general pattern can still be seen … it is clear that the type of structural deformation bears a close similarity to parts of the central uplift at Flynn Creek.
>
> Information recording total ground movement was accurately determined by burying 1650 marker cans in ordered arrays and excavating these cans and surveying their position after the detonation. The down warping beyond the crater wall and the central uplift are confirmed by these markers.

Figure 28 is a schematic cross section of the 500-ton TNT Crater at the Suffield Experimental Station based on sketches Roddy (1966c: 204) made in the field. Affectionately known as the 'Snowball Explosion Crater', this "… has nearly identical structural deformation in all respects with the Flynn Creek crater … In fact, this particular surface burst produced nearly every structural feature found in the Flynn Creek crater …" (Roddy, 1966c: 207, 210), and "The three ratios of diameters vs. shear strengths, diameters vs. distances to concentric fracture zones, and diameter vs. depth to deepest horizons exposed in the central uplifts, are nearly identical for both the Flynn Creek crater and the 500-ton TNT crater …" (Roddy, 1968b: 318).

Figure 29 is a view of the 'Snowball Explosion Crater' one day after its formation. The photograph shows the central uplift as an island, in addition to the concentric fractures which formed around the crater. Figure 30 is another view of the crater on the same day from a different angle, allowing a better view of the terraced wall. Jones (1977) states that the terracing was

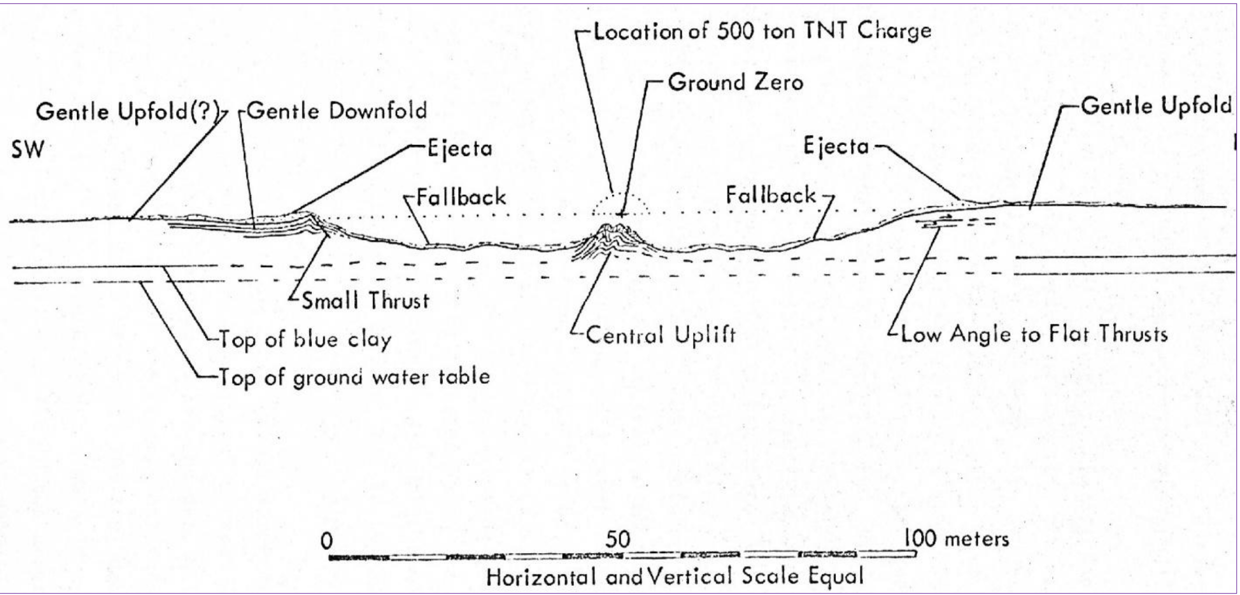
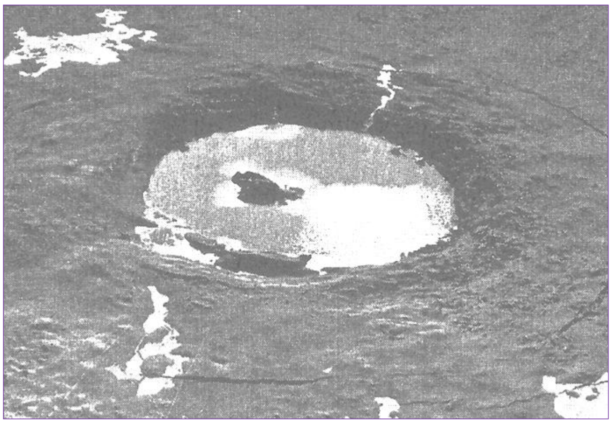


Figure 28: Schematic cross section of the 500-ton TNT Crater at the Suffield Experimental Station, Alberta, Canada (after Roddy, 1966c: 204).



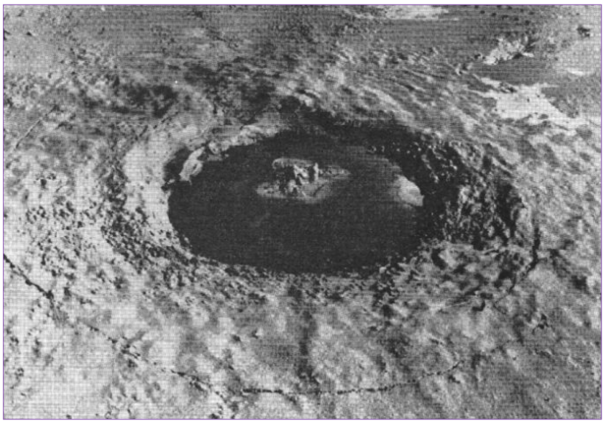


Figure 29 (left): An aerial view of the 500-ton TNT Crater one day after formation, showing concentric fractures and the central hill. The light-colored areas are sands deposited during water flow from the fractures and the lake in the crater was formed by water flow from fractures within the crater (after Jones, 1977: 164; cf. Roddy, 1968b: 314).
Figure 30 (right): Another aerial view of the 500-ton TNT Crater one day after formation, showing concentric fractures, the central hill, structural terraces on the crater walls and the irregular distribution of eject blocks (courtesy: Dr G.H.S. Jones; after Roddy, 1968b: 315).

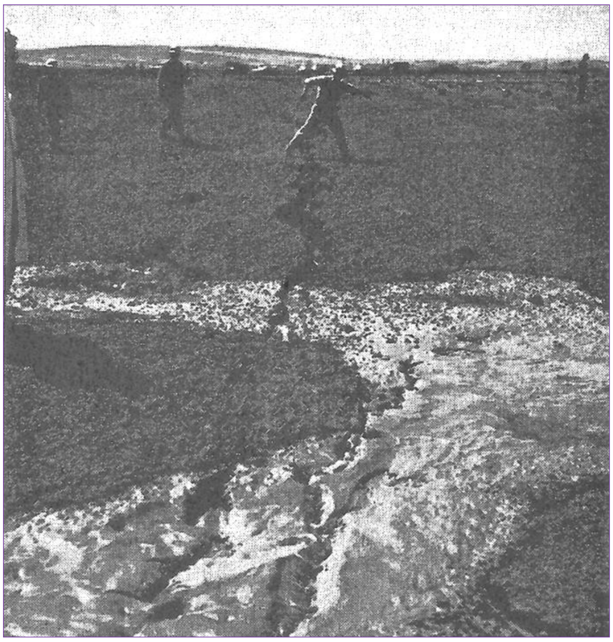


Figure 31 (left): A close-up view of one of the concentric fractures at the 500-ton TNT Crater, and the light-colored sand deposited during water flow from the fracture (after Roddy: 1968b: 317).

produced by late stage slumping. Figure 31 is a ground view of the crater showing a close up of the concentric fracture that developed around 110 meters from ground zero and the sand that was deposited when water flowed from the fractures. Jones (1977: 182) stated that "… the ejecta blanket consisted of a coherently over-turned, stratigraphically inverted expression of the pre-existing stratigraphy." Jones also pointed out that "This overturning is clearly not due to sequential fall-out of the ejected material, but is a coherent roll-back of the strata …" (ibid.). Taking into consideration the close structural similarities between Flynn Creek and the 500-ton TNT crater, Roddy (1966c: 201) concluded that the Flynn Creek crater was "… also produced by

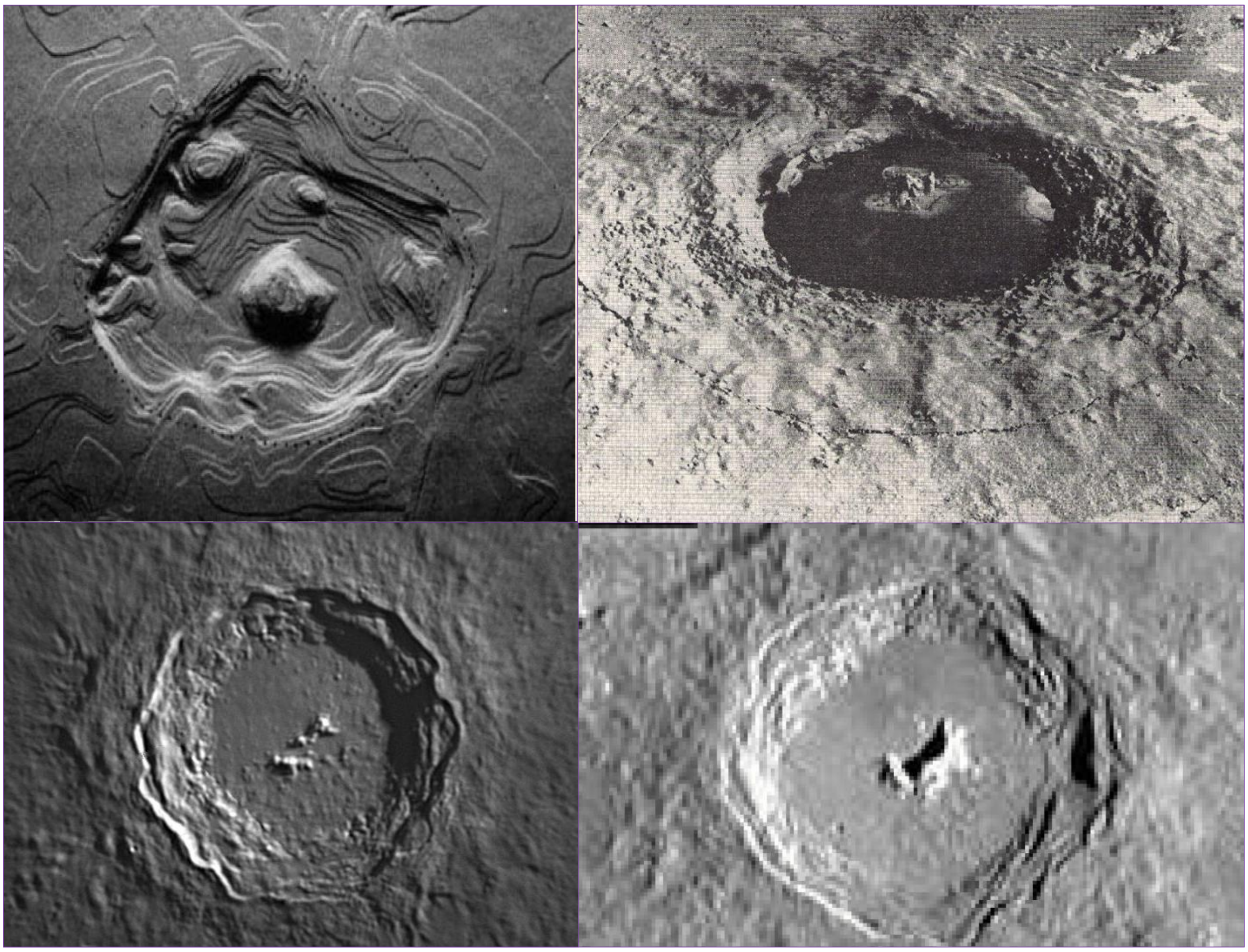


Figure 32: Crater comparisons. Left top: The Flynn Creek model (Roddy, 1977b: 206); right top: the 500-ton TNT 'Snowball Crater' (Roddy, 1977b: 206); bottom left: the lunar crater Copernicus (www.footootjes.nl/Astrophotography_Lunar); and bottom right: the lunar crater Pythagoras (European Space Agency).

a shock-mechanism, in this case an impact …"

The morphological and structural features of the Flynn Creek Crater, the 500-ton TNT 'Snowball Crater' and the lunar crater Copernicus were then compared by Roddy (1977a: 205). The terrestrial, the chemical explosion and the lunar crater all display a flat floor, central uplift region, and terraced walls, as does the lunar crater Pythagoras, which is shown in Figure 32 with the other three craters. The similarities are striking, and Roddy (1977b: 302) concluded that all of the terraces resulted from late-stage slumping. Figure 33 further explores their similarities, with geological cross-sections of the Flynn Creek crater, the 'Snowball' 500-ton TNT explosion crater and lastly, a "… schematic of the lunar crater, Copernicus, drawn with the actual lunar curvature …" (Roddy, 1977a: 209). Roddy (1977a: 193) pointed out another interesting similarity that these three craters share: estimating the immediate post-crater diameter, *D*, and depth, *d*, based on their rim crests, he found *D*/*d* to be 3830m/198m = 19 for Flynn Creek, 108.5m/7.5m = 15 for 'Snowball', and 79km/4km = 20 for Copernicus.

Roddy (1966c: 211-212) discussed the physical parameters of the Flynn Creek impactor as follows:

> Considering the shallow nature of the Flynn Creek crater, the presence of a central uplift, and the anticlinal folding in the rim, one would conclude that if an impact occurred, it probably was a "shallow impact." That is to say the center of energy was near the surface … It appears possible that such conditions could be met by a comet impact in which the comet would not act as a dense body and would not penetrate as deeply as an iron meteorite.

Two years later Roddy (1968b: 318) stated that since the Flynn Creek crater is shallow and has a central uplift, this may indicate that a large amount of deformational energy was concentrated within 200 m of the surface. He was of the opinion that "Shallow penetration and large energies …" appear to be necessary in the formation of a central uplift (Roddy, 1968b: 319), and he pointed out that since a comet is primarily composed of frozen volatiles, a cometary impact would explain the absence of chemical, mineral, and magnetic anomalies (ibid.). Roddy (1968b: 320) then discussed various origin and impactor possibilities based on his study of the Flynn Creek crater:

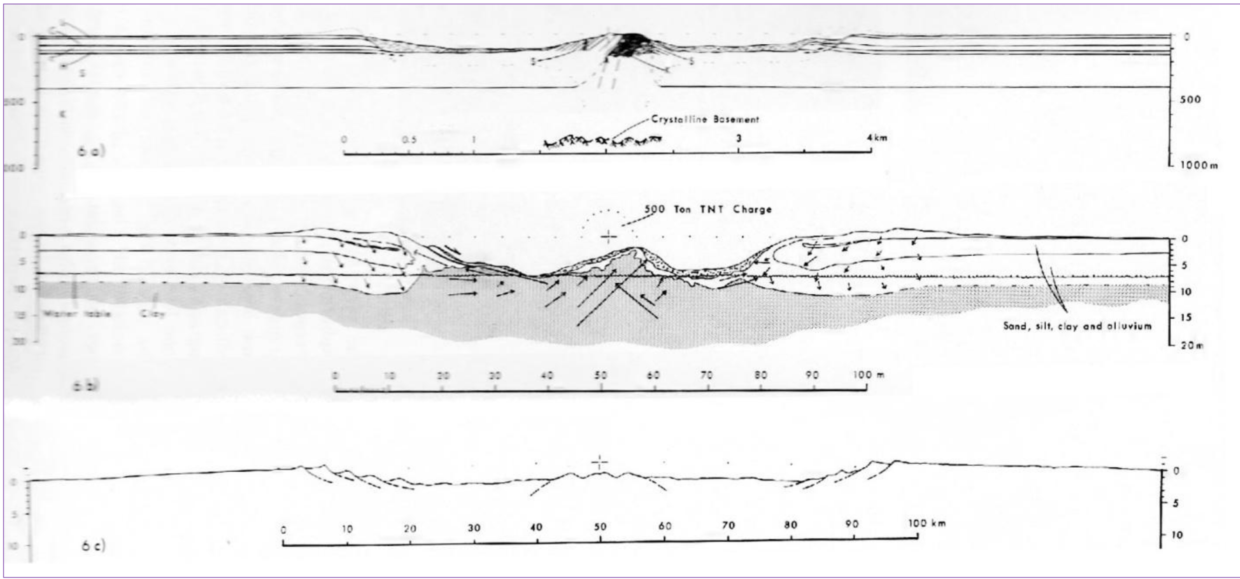


Figure 33: Geological cross-sections of the Flynn Creek, 'Snowball' and Copernicus craters (after Roddy, 1977a: 208-209).

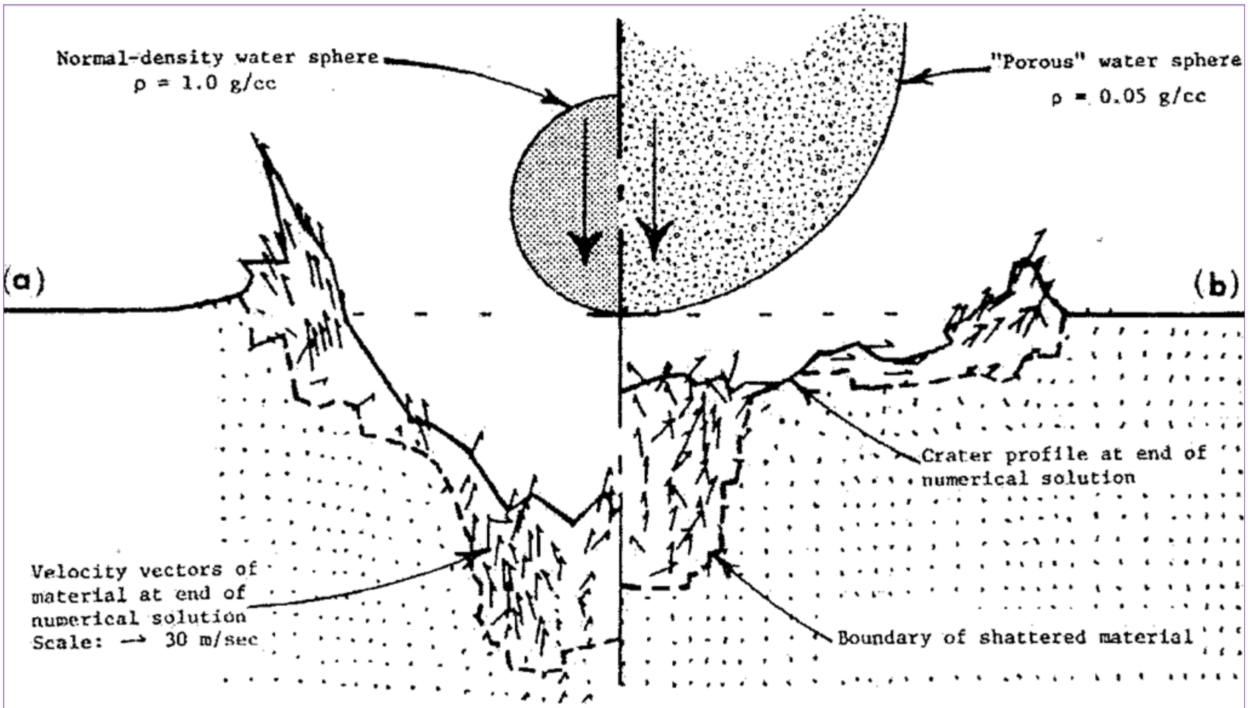


Figure 34: Calculated profiles of craters formed by ρ = 1.0 g/cc and ρ = 0.05 g/cc impactors (after Roddy et al., 1980: 945).

> If volcanic material had been initially present in the breccias, even in small amounts, it would be difficult to explain their present absence by weathering processes, since such materials have remained in similar environments for equal lengths of time. The same argument can be made for the silicate phases of a stony meteorite. Fragmental material from an iron meteorite, however, most probably would not survive the weathering processes that have operated since middle Paleozoic time. A cometary body, on the other hand, presumably would leave no mineralogical or chemical evidence of impact and is considered, at present, as the most likely type of impacting body.

Roddy (1966c: 213) calculated that if a comet was the impactor that produced the Flynn Creek crater, then it would have had a diameter of around 85 meters. Two years later, based on updated information, he (Roddy, 1968b) calculated that for a comet with a density of 1.0 g/cm^3 and an impact velocity of 15 km/sec to have formed the Flynn Creek crater, it would have had a diameter of around 250 meters. He also acknowledged, though, that a "… very high velocity meteorite … is a possible alternative to a comet impact …" (Roddy, 1968b: 319).

Later Roddy et al. (1980: 943) argued that low-density impactors such as cometary nuclei or carbonaceous chondrites would form flat-floored craters with central uplifts because "… the impacting bodies act as distributed energy sources that never produce deep transient cavities … [and that Flynn Creek] is quite shallow with an aspect ratio of crater diameter/crater depth ~ 1/35 …" In addition, excluding the central uplift, the depth of the breccia lens underlying the crater floor plus the depth to the bottom of the deformed strata underlying the breccia lens is around 250 meters below the pre-impact ground surface, which indicates a crater diameter/deformation depth ~1/14. Figure 34 shows "… calculation profiles of two impact craters at end of numerical solutions in graphite target …" (Roddy et al., 1980: 945); Figure 34a shows "… a water sphere (ρ = 1.0 g/cm^3) impacting a graphitic solid at ~4 km/sec …" which results in a bowl-shaped crater (Roddy et al., 1980: 944); and Figure 34b shows a comparison impact produced by "… a *very low density* (0.05 g/cm^3) porous water sphere onto the same graphite …" also traveling at 4 km/sec, and producing "… a very broad, shallow, flat-floored crater with an aspect ratio of *only* ~1/14," (ibid.; his italics). Roddy (ibid.) pointed out that the theoretical calculations of such a cratering event indicated that a low-density impactor was at least capable of producing a flat, shallow crater, with the subsurface deformation limited to very shallow layers and to a small central section, as is seen at Flynn Creek.

Utilizing his own observations of the 'Snowball' Explosion Crater in addition to data provided by Jones (1977: 165), Roddy (1977b) estimated the energy of formation for Flynn Creek by scaling from explosion cratering data. It is interesting to note that high explosive chemical charges "… are twice as efficient as nuclear charges in excavating a crater … due, in part, to the nuclear release of other types of energy, such as radiation, that do not effectively contribute to cratering …" (Roddy: 1977b: 287). For cube-root scaling, where *E* is the energy of formation and *D* is the diameter of the resulting crater, the equation is:

$$D_1 = D_2\,(E_1/E_2)^{1/3} \qquad (2)$$

Roddy (ibid.) states, however, that "… as crater sizes increase into the tens-of-meters range new exponents have been found necessary …" and the best empirical fit for craters larger than a few tens of meters is the 1/3.4 root. In addition, utilizing volume and equivalent length factor scaling also gave "… an average energy of formation of approximately 4 × 10^{24} ergs …" (ibid.). Roddy chose to scale from the 'Snowball' Explosion Crater data due to its great similarity in morphology and structural deformation to Flynn Creek (ibid.). He also determined that based on the fact that a "… simple comminution estimate of fragment crushing energies also gave 10^{24} ergs … the value of 10^{24} ergs is reasonable using scaling of dynamic explosion energies …" (ibid.). Assuming that the energy of formation as determined by explosion scaling is about equal to the kinetic energy of the impactor allows for some 'back-of-the-envelope' calculations.

For an impactor velocity, *V*, of 20 km/sec and for a kinetic energy, *KE*, of 4 × 10^{24} ergs, which equals 4 × 10^{17} Joules, the mass, *M*, of the impactor can be estimated by the following equation.

$$KE = (½)MV^2 \qquad (3)$$

This gives the mass of the impactor as 2.0 × 10^9 kg.

Roddy (1977b) believes that the Flynn Creek impactor was not an iron meteorite but more likely a stony meteorite or a cometary mass. Assuming the stony meteorite to be an ordinary chondrite, then the density, *ρ*, would have been ~3300 kg/m^3. The volume, *vol*, can then be found by rearranging the following equation:

$$\rho = M/vol \qquad (4)$$

The volume would then be 6.1 × 10^5 m^3. Since the volume of a sphere with radius, *r*, is (4/3)πr^3, the chondrite's diameter would be 105 meters.

An icy comet would have a density less than that of water, but for simplicity, a density, *ρ*, of 1000 kg/m^3 is assumed. Using Equation (4) gives a volume of 2 × 10^6 m^3, and thus a diameter of 156 meters. But Roddy (1977b: 292) reminds us that such low density bodies "… may not survive the atmospheric passage, as with Tunguska."

A second chemical explosion crater was produced at the Suffield Experimental Station with a 20-ton TNT detonation (see Roddy, 1966c). Figure 35 shows the alluvium displacement patterns below the 20-ton TNT hemispherical charge, as determined by marker cans that were buried in sand columns located on radial lines from ground zero. The post-shot positions of the marker cans shown in this figure "… were used to determine the direction and displacement of the ground …" (Roddy, 1966c: 206). The major horizontal component of displacement is easily seen. Another interesting find from the study of this chemical explosion crater is visible in this figure and is described by Roddy (1966c: 207):

> A significant result in the 20 ton TNT experiment is the reversal in displacement direction below ground zero … Possibly under higher energy explosions, such as the 500 ton experiment which has a central uplift, the reversal in particle displacement aids in the formation of an uplifted zone. It is not known as yet what specific conditions are necessary to form the central uplift, but it is now clear that shock mechanisms from a surface burst can produce such a structure.

Roddy (1968b: 316) reports that another con-

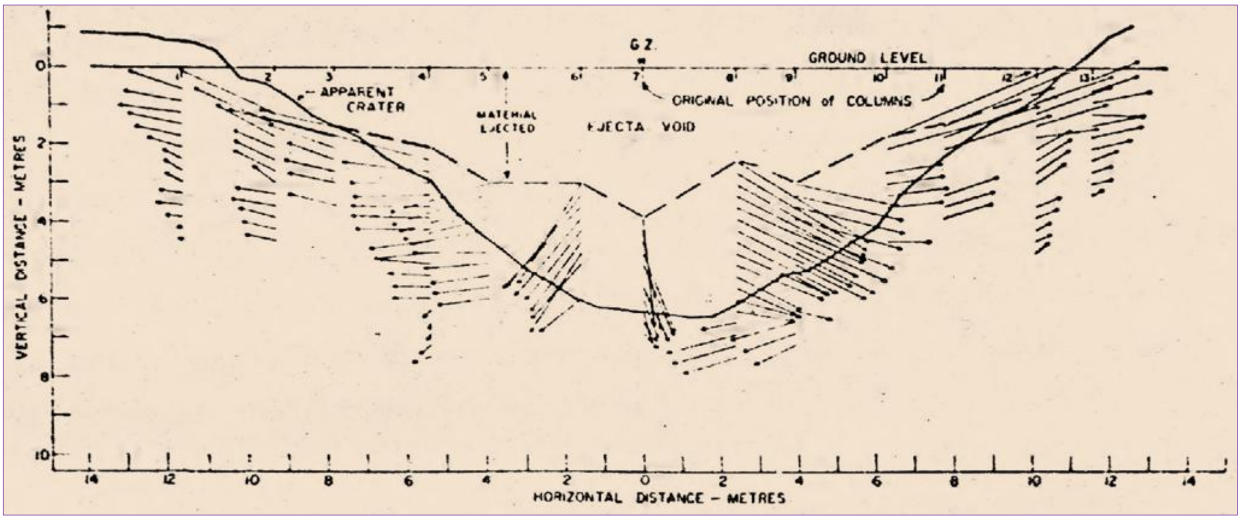


Figure 35: Alluvium displacement below the 20-ton TNT Crater at the Suffield Experimental Station, Alberta, Canada (after Roddy, 1966c: 206).

firmation in support of an impact origin for Flynn Creek came in July 1967 when "… the Defence Research Establishment, Suffield, Canada, detonated 100 tons of TNT in the shape of a sphere lying tangential to the ground surface …" thereby producing a third chemical explosion crater for comparison. The resulting crater was 30 meters across, ~5.5 meters deep and also included a "… large, well-developed central uplift …" (ibid.). Beds in the central uplift were raised 3 to 5 meters and formed a "… tightly folded and faulted dome …" (Roddy, 1968b: 317). The 100-ton TNT crater displayed "… low-angle thrust zones and high-angle faults and folds that are concentric to the crater walls … [plus] pronounced structural similarities to the Flynn Creek crater …" (Roddy, 1968b: 318).

In contrast, Roddy (ibid.) noted that "… structural comparisons of the Flynn Creek crater with volcanic explosion craters and their vents have demonstrated a notable lack of similarity." He also pointed out that drill core evidence indicated a shallow, lower boundary to the breccia and a decrease in deformation in the rocks below this breccia lens, both of which strongly indicated an origin involving a surface or near-surface explosion. He concluded (Roddy, 1968c: 179) that Flynn Creek was an impact crater which "… was formed during a single dynamic event in Middle or Late Devonian time …" based on the following evidence:

> Structural comparisons between Flynn Creek crater and volcanic explosion craters show little or no similarities in type of deformation … Structural comparisons between Flynn Creek crater and meteorite impact, nuclear-explosion, and chemical-explosion craters, however, show good agreement in nearly all types of deformation. Considerations of impact mechanics and similarities in structural deformation between shock-produced craters and Flynn Creek crater indicate an impact origin. (ibid.).

An impact origin can be confirmed with the identification of unambiguous shock features such as shatter cones. Dietz (1960: 1781) pointed out that a massive meteorite, too large to be appreciably decelerated by Earth's atmosphere, "… should on the average strike the earth with a velocity of about 15,000 meters per second." An impact of this magnitude would generate an intense, high-velocity shock wave that would spread out from the point of impact, 'ground zero', and engulf a great volume of rock before it decays into an elastic wave (ibid.).

He also pointed out that volcanic steam explosions only involved "… pressures of not more than several hundred atmospheres, so it is extremely doubtful that a shock wave can be developed in rock as a part of volcanic phenomena …" (ibid.). Dietz (1959: 500) noted that volcanic explosions involved the expansion of steam and other compressed gasses which was why they were not likely to be sufficiently violent to produce an intense enough shock wave in rock to form shatter cones. In fact, he stated that "Shatter cones seem to be completely absent from rocks which have definitely been subjected to volcanic explosion …" (ibid.). He reasoned then that "… if one can produce evidence that a large volume of rock has been intensely and naturally shocked, this would constitute definitive evidence of a meteorite impact …" Dietz (1960: 1781). Dietz stated that fortunately, rocks, when shocked, fracture into striated cup-and-cone structures called shatter cones, which often are easily identified in the field (ibid.).

Dietz (1960: 1783) noted that the Flynn Creek structure was studied by Wilson and Born, "… who [originally] considered that it was created by a cryptovolcanic explosion. Wilson now has revised this opinion, attributing the origin of the structure to a meteorite impact …"

This was in part due to the fact that he, Wilson and Stearns found shatter cones along a new road cutting near the Structure's center in November 1959 (Dietz, 1960: 1783; cf. Baldwin, 1963: 89;). Whereas the dolomite shatter cones from the Wells Creek site are described by Dietz (1968) as 'excellent', the limestone shatter cones from Flynn Creek were "… poorly developed … [but] the identification is unquestionable." (Dietz, 1960: 1783). Dietz (1968: 271) described the Flynn Creek shatter cones in more detail:

> I have always tended to consider the shatter cones at Flynn Creek to be of rather marginal quality, and not as fully confirmed as those I have collected elsewhere. However, Roddy (1963 and personal communication), who is mapping the structure in great detail, assures me that Flynn Creek is definitely shatter-coned in its center although there is a very limited outcrop area of shatter-coned rock.

Dietz also noted that the shatter cone orientation at Flynn Creek was upwards. This determination is important since "The orientation of shatter cones is useful for establishing the impact direction … In most cases the cones point … toward the locus of pulse source …" (Dietz, 1960: 1784). This upwards orientation of the shatter cone at Flynn Creek suggests impact percussion rather than volcanic forces which would have come from below (ibid.). Dietz (1963: 661) stated that "… shatter cones are truly indicative of intense transient shock loading far in excess of any known volcanic forces … a valid criterion for intense shock such as can be derived only from cosmic impact."

Later on, Roddy also found shatter cones in the vertical megabreccia beds of Knox strata in the Flynn Creek central uplift. Roddy (1966c: 65) described the shatter cones he found in the Flynn Creek structure:

> Where cones are present, they generally consist of many cones pointing in a common direction … The most common orientation for the cone axis is normal to the bedding, but many examples were found where a freshly fractured block had one set of cones pointing in one direction, while another set of cones pointed in the opposite direction. In some blocks sets of cones axes were seen to point in several different directions.

Milam et al. (2006: 1) state that "… the Knox Dolomite contains the only known shock indicators, shatter cones, at the Flynn Creek structure…", while after more than a decade of research, Roddy (1979a: 1032) finally added that "Excellent shatter cones also now have been recognized at a depth of ~406 m (below original pre-impact surface) in the drill cores in the same stratagraphic units exposed at the surface." The pre-impact depth of these rocks was around 420 meters below the original pre-impact ground level."

6 BILATERAL SYMMETRY

Boon and Albritton (1936: 9) stated that the meteorite hypothesis explained the folded rocks and evidence of violent explosions, such as breccias and shatter cones found in structures such as Flynn Creek, just as well as the cryptovolcanic hypothesis, however, the meteorite hypothesis "… offers a better explanation for the bilateral symmetry of many of the structures than does the volcanic hypothesis." They pointed out that "If these structures had been formed by a single upward- and outwardly- directed explosion, as postulated by the cryptovolcanic hypothesis, they would possess radial rather than bilateral symmetry …" (ibid.). Few, if any, meteorites strike the Earth at right angles; therefore, unless a falling meteorite does strike the Earth's surface vertically, a meteorite impact structure should not be expected to display radial symmetry (Boon and Albritton, 1936: 7). They pointed out that bilateral symmetry is significant in a meteorite impact structure since this feature would be indicative of "… an obliquely-impinging meteorite …" (Boon and Albritton, 1936: 8).

Boon and Albritton (ibid.) noted that meteorite crater rims "… commonly show opposed points of minimum and maximum uplift …" which is suggestive of oblique rather than vertical impact. Though an oblique impact would impart bilateral rather than radial symmetry to the underlying impact structure, the crater itself, which is the result of the upward and outward-moving explosion, should display radial symmetry. Boon and Albritton (1937: 59) stated that the bilateral symmetry noted at Flynn Creek, with only the beds to the south overturned, "… appears to be a cogent argument in favor of the meteoritic hypothesis, for it is difficult to imagine an upwardly-directed gas explosion causing overturning on one side of the crater only."

In 1967 Roddy (*Astrogeologic Studies*, 1967: 29) stated that the asymmetry he noted in the surface and subsurface deformation indicated that the Flynn Creek impactor traveled from southeast to northwest. More than a decade later Roddy (1979b) concluded from a second round of drilling that the basic shape of the Flynn Creek transient cavity was that of a very shallow, flat-floored crater with a deep and narrow central core of disruption dipping to the west, as shown in Figure 36. He determined that the depth of total disruption and uplift in the center of the crater extended to around 450 meters and then continued downward with decreasing deformation to around 770 meters, again dipping to the west. "The implication is that the impacting body has an oblique angle of entry tentatively interpreted here to be from the east or southeast …" (Roddy, 1979b: 2531). Roddy (ibid.) then pointed out that the "… per-

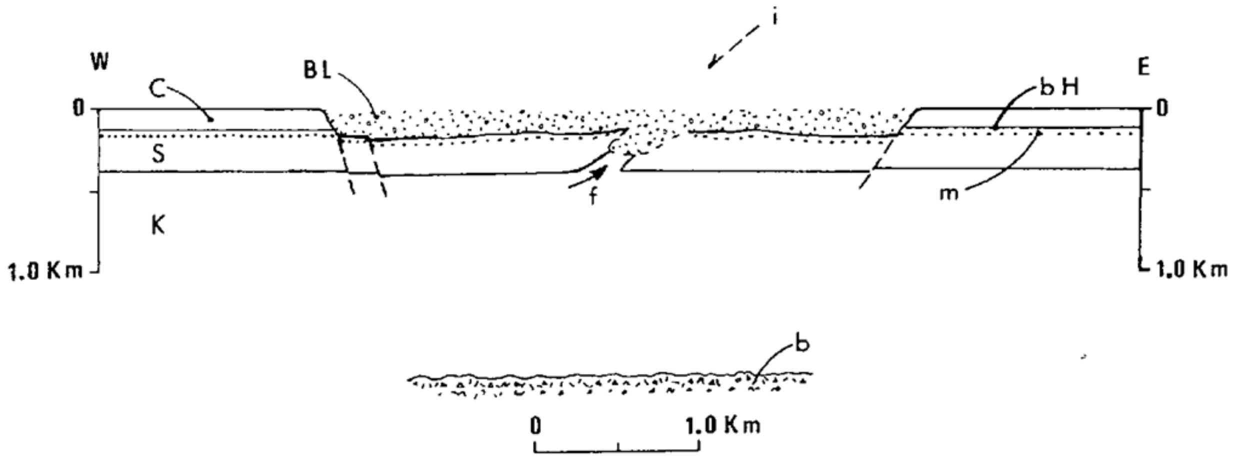


Figure 36: Schematic cross-section showing the Flynn Creek cratered region, where ‘i’ is the inferred direction of the impactor. The ‘b’ region immediately above the scale is the crystalline basement beneath the crater; there is no vertical exaggeration (after Roddy, 1979b: 2531).

vasive westerly to northwesterly dips [of the exposed rocks in the central peak] … are consistent with such an entry angle …” Although other researchers agree that Flynn Creek’s bilateral symmetry indicates an oblique impact, not all agree with Roddy on the azimuthal impact direction.

Gault and Wedekind (1978: 3856) state that “… bilateral symmetry around craters on planetary surfaces is a firm basis for recognizing structures formed from oblique trajectories and provides a basis for determining the direction of approach of the impacting object.” Lunar craters which result from oblique impact consistently have depressed rims in the up-range direction (Forsberg et al., 1998). For craters that result from shallow impact angle, less than ~30º, “… the circularity of the rim, the crater profile, the distribution of the ejecta, and other characteristics are all affected by the lateral transfer of energy in the downrange direction …” (Milam and Perkins, 2012: 1). Obliquity of impact craters on Solar System bodies, including the Earth, can be determined by studying these characteristics, unless erosion or sedimentary processes have obscured or destroyed all of the evidence (ibid.). For example, the Flynn Creek ejecta pattern has been removed by erosion, and observation of the crater shape is difficult due to the fact that it is partially buried, however, “… topographic and structural data have provided a means of assessing the impact trajectory, obliquity, and post-impact erosion associated with the Flynn Creek impact event …” (ibid.).

Data from the Milam and Perkins’ study (ibid.) suggest that the Flynn Creek impact occurred at a shallow (5°) impact angle along an approximately NW to SE present-day trajectory (uprange: ~310-323°; downrange 130-143°). This conclusion is supported by additional asymmetrical and morphological relationships that exist around the crater rim. The largest dip angles, around +30°, occur in the SE crater rim between 135-185°, “… suggesting the downrange portion of the trajectory lies in the present-day SE …” (Milam and Perkins, 2012: 2), and this section of the rim displays the greatest uplift, between 110° to 130°, “… which is consistent with a NW to SE impact …” (ibid.).

An interesting observation is that the Dycus Disturbance, a suspected Tennessee impact site, is only 13 km north-west of Flynn Creek, so close that they may be the result of a double impact (Stratford, 2004). If the Flynn Creek impactor broke into two major, but unequal, parts during its transit through the Earth’s atmosphere, then the smaller fragment would be expected to fall short of the larger section, which could explain the close proximity of the small Dycus Disturbance. Of particular interest is the fact that Herrick and Forsberg-Taylor (2003, 1576) point out that “… at the lowest impact angles, the planform becomes elliptical …”, and Dycus is oval-shaped (Deane et al., 2006: 2), indicating another possible oblique impact.

On the other hand, the oblong lunar crater Messier is thought by Gault and Wedekind to be the result of a grazing impact event (with θ <5°). Gault and Wedekind (1978: 3843) state that “Impacts at shallow incidence, which are not uncommon, lead to ricochet of the impacting object … at velocities only slightly reduced from the pre-impact value.” In addition, ricochet may occur with the projectile remaining intact, rupturing into several large fragments, or shattering into a myriad of small fragments. They note (Gault and Wedekind, 1978: 3873) that “Lunar crater Messier is, of course, the prime type-example of an oblique impact along a grazing trajectory …” Herrick and Forsberg-Taylor (2003, 1556) support this interpretation: “Messier A appears to have resulted from a ricochet downrange from Messier, the original point of impact …” The shape of Messier A resembles shapes formed by experimental impacts with impact angles of 5° (Herrick and Forsberg-Taylor, 2003, 1557). Messier and Messier A, shown in Figure Figure 37 with their ejecta patterns, may be the result of a single impactor first creating Messier and its butterfly ejecta pattern and then ricocheting to form Messier A with its forward ejecta rays.

Herrick and Forsberg-Taylor (2003: 1557-1558) noted that "Messier A also bears some resemblance to experimental clustered impacts … [which] are more shallow than similar diameter craters resulting from a single impactor …" Interestingly, Roddy et al. (1980) considered Flynn Creek to be a shallow impact crater. Of course, Flynn Creek and Dycus could simply be the result of a double impact. "Doublet craters are a product of binary asteroid impact, and the amount of asteroid separation determines whether overlapping or separated craters form … [around] 16% of the near-Earth asteroid population are doublets …" (Herrick and Forsberg-Taylor, 2003: 1558; cf. Bottke and Melosh, 1996).

7 MARINE IMPACT

At Flynn Creek, the bedded breccias and dolomite "… were apparently deposited in a marine environment, because conodonts of early Late Devonian age are present in these rocks." (Roddy, 1966c: 219). A decade later, Roddy (1976: 121-122) describes the process as follows:

> Erosion began to modify the crater immediately after its formation, washing part of the debris back into the crater and lowering the regional surface of the order of a few meters. A thin deposit of marine sedimentary breccia overlain by a thin marine dolomite of early Late Devonian age form the first crater deposits. Deposition remained continuous during this time until the crater was filled by the black muds of the early Late Devonian Chattanooga sea.

Therefore, sometime during the early Late Devonian, Chattanooga Shale filled the crater and prevented further erosion. After that "… the Flynn Creek area remained under water through at least Early Mississippian time, when the Fort Payne sediments were deposited." (Roddy, 1976: 123).

At the Lunar and Planetary Institute's Tenth Conference, Roddy (1979b: 2519) stated that the Flynn Creek Crater was formed "… by a hypervelocity impact event in a shallow-water coastal plain environment." He continued by describing the crater as being around 3.8 km in diameter and 200 meters deep, which initially had "… a broad flat floor, a large central peak, locally terraced walls, and an ejecta blanket …" (ibid.). Subsequently, he stated that Flynn Creek was the result of "… an impact event in a very shallow-water (~10 to 20m deep) coastal plain environment …" (Roddy et al., 1980: 943). The Flynn Creek impact has been described:

> The impact event occurred in a well-consolidated, flat-lying, sequence of limestone and dolomite overlying crystalline basement at a depth of about 1700 m. Field studies indicate that the impact occurred on a low, rolling coastal plain at the edge of the Chattanooga Sea, or actually, in its very shallow coastal waters which are tentatively interpreted from field relationships to have been on the order of only 10 to 12 m deep. (Roddy, 1979b: 2520).

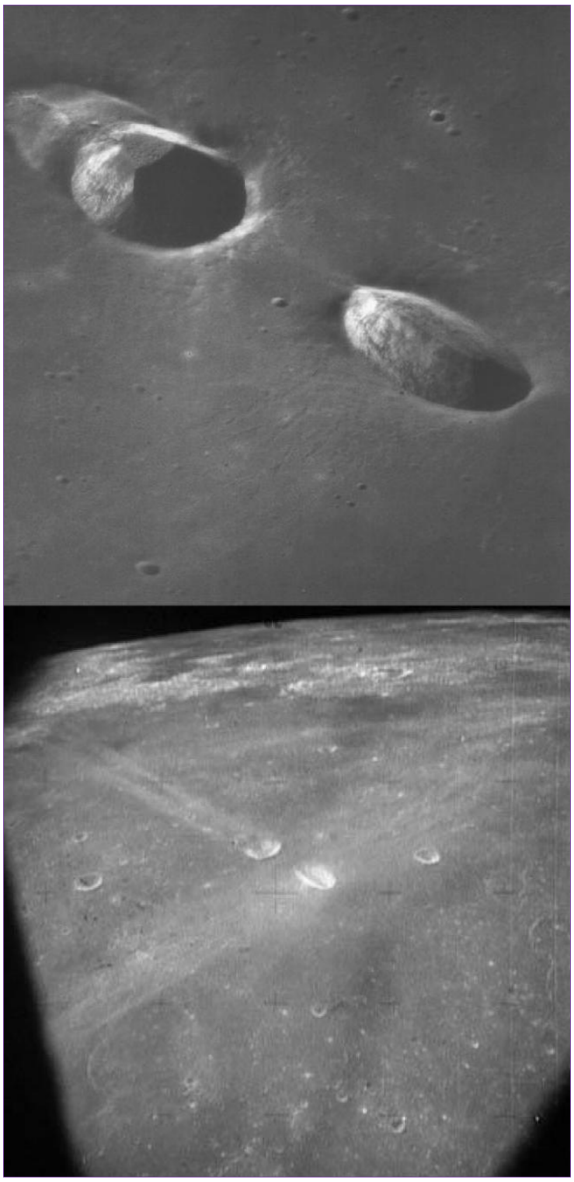


Figure 37: NASA Apollo 11 photographs showing the lunar craters Messier, on the right, and Messier A, on the left—with its two prominent downrange ejecta streaks (after Forsberg et al., 1998: 1).

Immediately upon formation of the crater "… very shallow subaqueous erosion apparently associated with the Chattanooga Sea …" began to wash much of the fallout and ejecta blanket from the crater walls and central uplift and deposit it over the crater floor (Roddy, 1979b: 2522). Any sub-aerial erosion that occurred, however, was limited. Around 10 meters of bedded breccias and bedded dolomite were deposited over the crater floor and lower walls, which was then directly overlain by the black muds of the wide-spread Chattanooga Sea of early Late Devonian age. These muds were later overlain by hundreds of meters of other sediments before regional uplift along the Nashville Dome allowed for enhanced erosion of the region to occur (Roddy, 1979b).

Roddy (1977b: 298) stated that even though the Flynn Creek impact most likely took place in a shallow sea about 10 m deep, "… it probably would not have seriously affected the penetration or cratering process of this impact event …" because such shallow water would simply be "… equivalent to a layer of rock with no effective tensile strength." If the Flynn Creek impactor was around 100 meters in diameter and the water depth only 10 meters, then the primary effect of such a thin layer of water would simply be the production of steam and water vapor that dispersed over such a large area that "… probably did not seriously augment the cooling or deceleration of high speed ejecta …" (ibid.). According to Dypvik and Jansa (2003: 332), though, the steam expels more ejecta than would be generated by a dry impact.

After crater formation, the rim "… was apparently above water for a period of time long enough to develop talus deposits, but was breached shortly thereafter …" (Roddy, 1977b: 278). When the crater rim was breached, the deposition abruptly changed to the black, silty, muds of the shallow Chattanooga Sea which eventually filled the crater (ibid.), and "The entire crater and central uplift were quickly protected from any significant erosion by the rapid deposition and complete filing by marine sediments of early Late Devonian age …" (Roddy, 1977b: 279). Meanwhile, the limited erosional lowering of the rim "… indicate[s] that the crater … is very close to its original gross morphologic form except for the erosion of the ejecta blanket …" (Roddy, 1977b: 283).

This indicates that whereas most terrestrial impact craters have been subject to long periods of erosion and only their basement structures have survived, Flynn Creek was basically cocooned in mud, and thus its form was preserved. As such, it is one of the few ancient terrestrial impact structures that can be reasonably referred to today as a 'crater'. Mitchum (1951: 29) notes that one reason the Flynn Creek Structure is especially interesting is that the actual explosion crater has been preserved.

Roddy (1977b: 283) points out that if the Flynn Creek event occurred in a standing body of water, "… and the waters were moderately deep, then the impact would involve a two-layered target with the attendant terminal, but transient, result of one layer being fluid." On the other hand, if the water was shallow, only a few meters deep, then its effect would be negligible (ibid.). Roddy (1977b: 283-286; his italics) discussed in detail his interpretation of the impact event environment:

> The thick mass of very crudely lineated breccia locally overlapping the crater walls and terrace blocks strongly suggests the inner part of the ejecta blanket was redeposited into the crater very irregularly as a chaotic mass on top of the breccia lens …
>
> Another result of the erosional processes leads to the deposition of a variety of types of sediment in the crater and on the rim grabens. The important yet puzzling aspect of these rocks, however, is that those on the crater floor are definitely of marine origin whereas those on the higher rim graben do not appear related to marine processes. No lake or playa beds are present in either exposed sections or in drill cores anywhere on the crater floor. Instead, the first crater floor deposits are related to marine waters clearly indicating that a sea was in the area. Isolated subareal-like talus deposits on the rim graben, however, imply that the sea was quite *shallow* and *below* the uplifted rim area …
>
> The bedded dolomitic breccia and bedded dolomitic are thickest on the lowest parts of the crater floor and thin out entirely part way up the crater walls. The bedded dolomite, up to 3 m thick locally, is the last unit to be deposited in the crater that includes very fine fragments of the underlying breccia and fragments from the upper Leipers rocks. The important point regarding these last two units is that they both contain *marine* fossil fragments of early Late Devonian age … and consequently were deposited with *access* to the marine sea water in the area. A second critical point is that the specific marine fossil fragments in the bedded dolomite breccia and bedded dolomite are identical to those in the basal Chattanooga Shale Formation which has an extremely widespread distribution over several states and lies in conformable contact immediately on top of the bedded dolomite. A third critical point is the distinct change in lithology from the dolomite to the black Chattanooga Shale sediments, a transition that takes place vertically and very abruptly over a centimeter or two. Obviously the extremely wide-spread black muds of the Chattanooga Sea were not introduced immediately onto the floor of the crater since other deposits have been identified, yet the same marine conodonts in the basal Chattanooga *were* included, at least, in the earliest bedded dolomitic breccia on the crater floor. This suggests the waters of the Chattanooga Sea were in the immediate area at the time of impact but were not deep enough to flow directly over the crater rim and ejecta blanket. Instead, it appears that the marine waters carrying the microscopic conodonts fragments flowed or were initially filtered through the

> ejecta blanket and rim into the crater at a reduced rate such that the coarser black silty muds were initially deposited outside the crater … Immediately thereafter, the black silty muds of the Chattanooga Shale appear to have spilled over the crater rim to eventually fill the crater over the next few million years. The conclusion one draws is that of a shallow sea with abundant black silty muds … that did not immediately flood the crater, perhaps because of the barrier of the uplifted rim and the 100 m or so thickness of ejecta blanket. After a limited period of probable wave and other types of erosion, the ejecta was removed and the black silty muds were rapidly deposited over the crater floor, walls, and rim …
>
> Another line of evidence regarding the *depth* of the Chattanooga Sea at the time of impact lies in an explanation of *talus-like* deposits at the base of a cliff formed by the rim graben. This ancient talus has the character and composition of subareal deposits with no apparent marine influence of its matrix chemistry and no black, silty, mud additions. Since the presence of the Chattanooga Sea in the immediate area has been established, it would appear that the evidence of no direct communication of the talus with the sea indicates that it was formed above the local water level … This shallow sea depth would still allow local wave action to remove the ejecta, flow over the stripped rim, and deposit marine sediments on the crater floor. In any case, the overall impression remains that of a very shallow sea, a few meters or so in depth, in this area *at* the time of impact …
>
> The actual impact event may have occurred *in* these very shallow waters, but the depths were apparently only on the order of approximately 10 m.

Schieber and Over (2005: 67) also agree that evidence indicates the regional water depth at the time of the Flynn Creek event was around 10 meters or even less, and furthermore, due to a general sea level rise, gradually increased after impact. Evidence from the crater fill shows that repeated regressions and transgressions occurred during the time of this gradual rise in the sea level (ibid.).

Acceptance of Flynn Creek's marine origin was noted by Shoemaker (1983: 484) when he stated that the Flynn Creek crater was formed in the Devonian on the floor of a shallow epicontinental sea and then buried beneath marine sediments. According to Milam and Perkins (2012: 1), Flynn Creek "… formed in a marine environment with a seabed of Middle Ordovician carbonates …" and was rapidly buried by Late Devonian and younger sediments. Redistribution of the ejecta due to water column collapse following impact and erosion from resurge removed most of the ejecta from the crater rim. The crater fill and remaining target rock in the crater rim, floor, and central uplift has only recently been exposed by stream erosion (ibid.).

Studies of the Flynn Creek crater stratigraphy and sedimentary features by Schieber and Roddy (2000: 451) suggest the following sequence of events in the formation of the Flynn Creek Crater:

> (1) impact in shallow water during the lower Frasnian (381-382m.y.); (2) formation of the basal chaotic breccia as a fall-back deposit; (3) deposition of graded breccia as displaced water rushed back into the crater; (4) while the sea was still shallow, ejected material was washed back into the crater by storm-induced waves and currents; (5) with rising sea level, black shales were able to accumulate, first in the crater, and later also outside the crater.

Four years later, Schieber and Over (2004: 165) added the following description and details:

> The Flynn Creek crater … was produced by a meteorite that struck a flat lying succession of Ordovician carbonates. The crater is filled by a basal breccia and a thick succession (55 m) of Late Devonian black shales. Lower Frasnian conodonts in shallow water lag deposits that overly the Ordovician succession in the region indicate that the Devonian sea had flooded the area by that point in time. The impact occurred in shallow water and marine sedimentation commenced immediately after settling of impact-related deposits …
>
> The post-impact fill of the crater consists of black shales that were long thought to be equivalent to the Late Devonian Chattanooga Shale. Only the upper third of the black shale succession, however, is correlative to the Chattanooga Shale. Most of the black shales in the crater are older, and are separated from the overlying Chattanooga Shale by an erosional truncation.

One year on, Schieber and Over (2005: 51) explained some apparently conflicting features found in the Flynn Creek crater, which

> … was produced by an asteroid that struck a flat lying succession of Ordovician carbonates …The continuous stratigraphic record in the crater spans impact and post-impact deposits; the recovery of shallow water components and lower Frasnian conodonts in initial marine deposits above the crater fill breccia indicate that marine sedimentation commenced immediately after impact and that the impact occurred in shallow water …
>
> Because the target rocks were lithified carbonates, the Flynn Creek crater has the morphologic characteristics of a subaerial impact. The sediment fill, however, reflects the shallow marine setting of the impact site.

In addition, Schieber and Over (2005: 53) state that sedimentological and petrographic examination of the Flynn Creek Crater fill gives conclusive evidence of a shallow marine impact. These researchers determined that the Chattanooga Shale only comprises a small part of the black shale fill inside of the crater and that "…

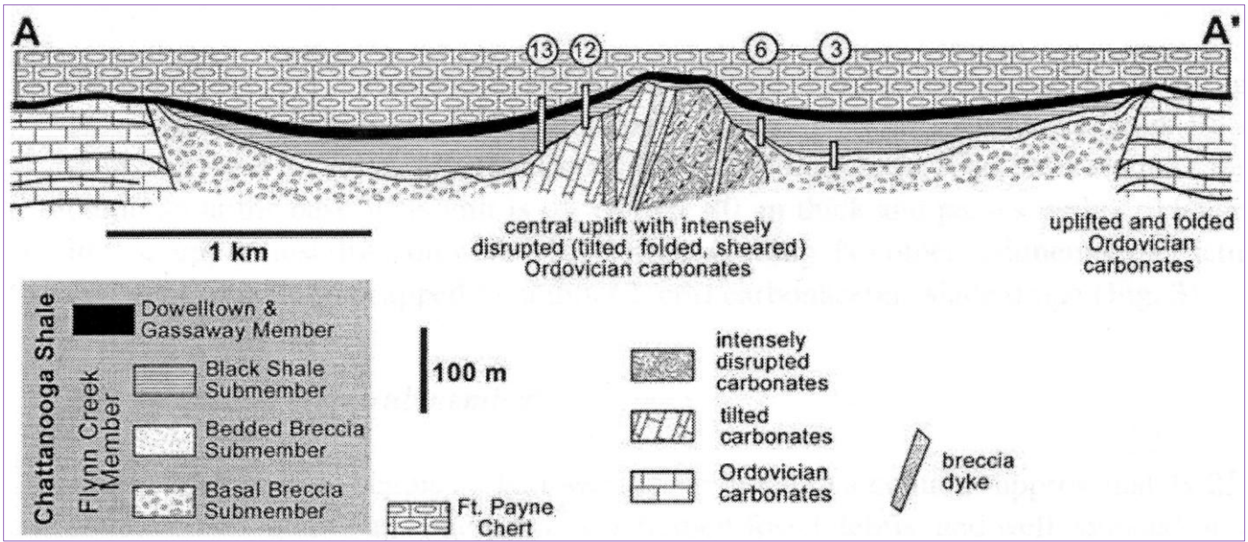


Figure 38: Schematic presentation of the Flynn Creek crater stratigraphic relationships (after Schieber and Over, 2005: 53).

the bulk of the black shale is part of an earlier deposited member of the Chattanooga Shale, largely absent elsewhere, that extends the record of Devonian black shale deposition in central Tennessee …" (ibid.). They propose the name 'Flynn Creek Member' "… for the portion of the crater fill that underlies the Dowelltown Member of the Chattanooga Shale …", which consists of three distinct units that in ascending order are the basal breccia, bedded breccia and black shale submembers (ibid.). The distribution of these litho-stratigraphic units in the Flynn Creek crater is shown in Figure 38, along with the locations where drill cores 3, 6, 12 and 13 were obtained (ibid.). Meanwhile, Figure 39 shows the black shale stratigraphy based on information from drill cores 12 and 13, obtained from the western flank of the Flynn Creek central uplift (after Schieber and Over, 2005: 62).

Results indicate that the basal breccia averages 40 meters in thickness and consists of a poorly sorted, chaotic mix of angular carbonate clasts which range from granule to boulder size and were derived from the underlying strata. This unit is capped by a 2 cm carbonaceous shale drape. The bedded breccia unit starts at the lowest shale drape and contains "… around 25% carbonate clasts, quartz and chert grains, silicified fossil debris, and well-rounded phosphate granules in a fine-grained matrix of organic matter, dolomicrite, and clays …" (Schieber and Over, 2005: 54). The shale is overlain by beds of gravel, granule, sand, and silt-size carbonate debris ranging in thickness from 0.5 to 1.5 meters and cemented by dolomite. These beds vary in number depending on their location in the crater, but are each separated by shale drapes. They "… are massive to crudely wavy-parallel bedded …" on a centimeter to decimeter scale, and in places, fine upwards (ibid.). The poorly-bedded breccia is primarily located along the crater margins, while the bedded dolomitic breccia and bedded dolomite is prominent in the crater interior. "Within bedded dolomite layers occur thinner (2-5 cm), graded dolomite beds that have horizontal lamination, water escape structures, and fading ripples … in the basal portions …" (ibid.). Dolomite beds that are overlain by a shale drape have "… an irregular bumpy surface, probably a result of water escape …" (ibid.).

Depending on the location within the crater, the bedded breccia and bedded dolomite may be directly overlain by Devonian black shales or by a layer of course sandstone consisting of 75% carbonate clasts, subordinate quartz and chert grains, silicified fossil debris, and rounded phosphate granules (Schieber and Over, 2005). Sandstone layers ranging from a few millimeters up to 3 cm in thickness occur throughout the basal 13 meters of the black shale succession, and "Thin beds containing sand-sized quartz and pyrite grains, usually with diffuse lower and upper boundaries, carry the imprint of early diagenetic infilling of cysts of the marine alga *Tasmanites* …" (Schieber and Over, 2005: 56). Schieber and Over (2005: 57) also pointed out that the "… black shale of the Flynn Creek Member forms a thick succession … and lacks an obvious equivalent outside the crater."

After comparing it with other marine impact craters, Schieber and Over (2005) interpreted the chaotic basal breccia in Flynn Creek as a fall-back deposit that formed immediately after impact. They noted that the graded top portion indicates that the deposition was controlled by the settling velocity of particles, which is "… commonly observed where particles settle through a turbulent fluid/sediment mixture …" (Schieber and Over (2005: 59). They concluded:

> Thus, impact occurred while the area was cov-

ered by water. Impact-displaced water rushed back into the void and carried freshly ejected material back into the crater. The turbulence associated with such a scenario is extreme and allows for short-term suspension transport of pebble-size particles … The basal breccia submember, including the graded top portion, probably represents a time interval measureable in hours.

The shale drape over the basal breccia indicates low energy conditions after impact-related turbulence had subsided … Outside the crater … Conodonts from the basal Dowelltown lag range in age from upper Givetian to lower Frasnian and suggest that shallow water conditions persisted for a long time period in the region and prevented accumulation of fine-grained sediments … The epicontinental setting of the Devonian inland sea and water depth estimates for shale deposition in the Chattanooga Shale suggest a water depth of 10 m or less … The composition of the shale drape that covers the basal breccia implies that the carbonate particles were derived from an ejecta blanket outside the crater, were washed across the crater rim during storm events … Considering the overall shallow water conditions in the area this should have been a frequent occurrence. Abundant course material in this shale drape suggests rapid accumulation, possibly representing only a few hundreds to thousands of years ...

Because the bedded breccia and black shale submembers span several conodonts zones … this suggests an initial time interval of several hundred thousand years when black shale deposition occurred only within the crater, while shallow water conditions and lag formation persisted outside. (Schieber and Over, 2005: 59-61).

Preservation of the Flynn Creek Member equivalent outside of the crater indicates that the sea level rose sufficiently during its deposition to allow mud accumulation outside of the crater. Thus, water depth may have increased from 10 meters up to 50 meters (Schieber and Over, 2005).

Dypvik and Jansa (2003: 309) state that in subaerial impacts, the target rock is generally hard igneous or metamorphic rock, but in submarine impacts, the target rock is primarily composed of "… unconsolidated or poorly lithified sediments, or sedimentary rocks, with high volumes of pore water." They point out that the lack of an elevated rim in a shallow-water marine impact is thought to result from current reworking and resurge of the water back into the excavated crater as the water in the crater is vaporized during impact. Another characteristic they noted of marine impact sites is the presence of resurge gullies that cut across the rim: "Such erosional features result from submarine erosion which bevels off the crater rim, causing lower, more subtle rims or almost complete removal of a rim …" (Dypvik and Jansa, 2003: 332; cf. Dalwigk and Ormo, 2001). Schieber and Over (2005: 64) point out that Flynn Creek, in contrast, possessed "… an uplifted rim that was not significantly beveled by post-impact erosion and was not dissected by resurge gullies." This indicated that the Ordovician target rock was already lithified by the time of the Flynn Creek impact (ibid.). In fact, the Flynn Creek Crater's morphology was " … a close match to that expected of a sub-aerially produced crater …" (ibid.), but Dypvik and Jansa (2003) pointed out that in shallow submarine impacts, the top of the central uplift is usually flat as a result of waves and shallow currents scouring and reworking the impact deposits. As can be seen in Figure 8, Flynn Creek possesses a flattened central peak in contrast to the sharp central peaks most terrestrial impacts craters display, suggesting that

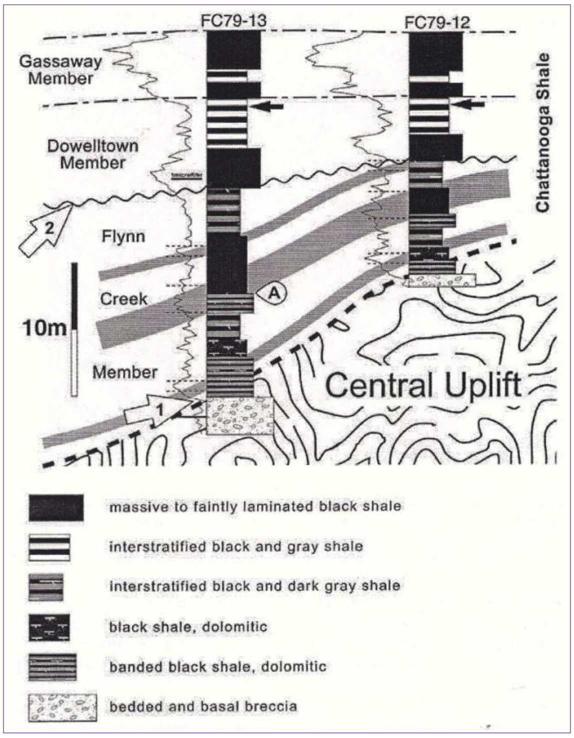


Figure 39: Black Shale stratigraphy from western flank of the central uplift drill cores (after Schieber and Over, 2005: 62).

post-depositional modification by wave action, associated with the shallow water at this site altered the crater's morphology to an extent (Schieber and Over, 2005).

The Wetumpka impact crater in Alabama, a coastal state bordering Tennessee to the south, is a confirmed shallow marine impact that took place 83.5 million years ago in 30 to 100 meters of sea-water (King and Petruny, 2003; King et al., 2002; 2008). Field work completed by Roddy, Schieber, and Over proves that Flynn Creek is the result of an *extremely* shallow (~10 meters deep) marine impact. At the outset of this study, it was hoped that comparisons between known shallow marine impact sites such as Wetumpka,

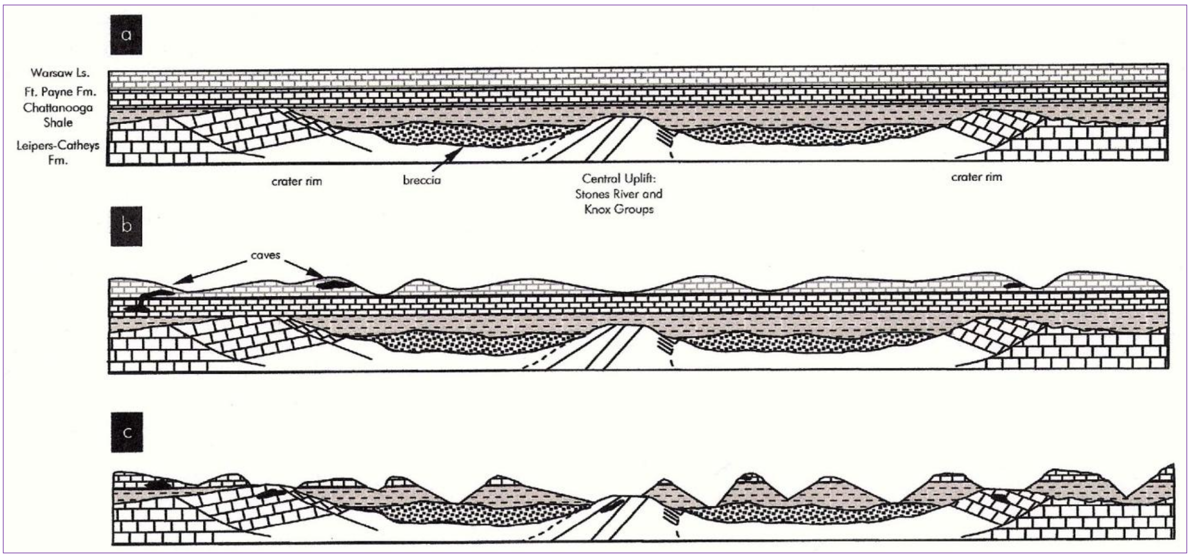


Figure 40: Generalized model for the speleogenetic modification of the Flynn Creek Structure; for details see the associated text (after Milam, Deane and Oeser, 2005b: 34).

and extremely shallow marine impacts sites such as Flynn Creek, might provide an understanding on a macroscopic level of the similarities and differences in shallow and extremely shallow impact craters that could then be applied to identify liquid depth at times of impact on other Solar System bodies, perhaps Titan, or Mars of long ago. Unfortunately, this has not proven to be possible since the morphology of the Flynn Creek crater so closely resembles that of sub-aerial impact craters.

8 CAVE DEVELOPMENT

Caves have formed in the Flynn Creek Structure where slightly acidic groundwater has leaked through cracks and crevices in the limestone gradually dissolving it and creating passages and caverns. Caves form by dissolution along zones of weakness "… such as bedding planes, fractures, and faults …" (Milam and Deane, 2006a: 82). Milam and Deane (ibid.) have discovered that "… impact cratering, one of the dominant surface-modifying forces on Mars and elsewhere in the Solar System, can also exert control over cave passage development …" Regional uplift due to the formation of the Nashville Dome in what is now central Tennessee caused the uplifted strata to have higher potential erosive energy. The Pennsylvanian rocks were breached and erosion exposed the underlying Upper Mississippian Warsaw Limestone and Lower Mississippian Fort Payne Formation, and "It was in these geologic units (and once overlying Upper Mississippian rocks) that a first generation karst landscape developed …" (Milam et al., 2005b: 30). Cave passages developed in Flynn Creek along strike and/or dip and/or joint orientations, and continued erosion exposed the underlying Chattanooga Shale and below that, the Ordovician carbonates. As a result, "… a second generation karst landscape was formed locally in the Leipers-Catheys, Bigby-Cannon, and Hermitage Formations, as well as the underlying Stones River and Knox Groups …" (ibid.). Figure 40 shows Milham, Deane and Oeser's (2005b) generalized model for the speleogenetic modification of the Flynn Creek Structure. Figure 40a shows the buried crater, with only the Knox Group through the Warsaw Limestone sediments depicted (ibid.). Figure 40b shows the first generation karst development, and Figure 40c the second generation karst development (along the rim of the crater and in the central uplift).

One cave apiece is known to be associated with the Wells Creek and Howell Structures (Deane et al., 2004: 2; Milam, Deane and Oeser, 2005b: 31), but there are at least twelve caves at the Flynn Creek Structure, although two of these, in the crater fill, do not seem to correlate with Flynn Creek's structural features (Milam, Deane and Oeser, 2005b). The other ten formed in Flynn Creek target rock and seem to be controlled by the crater's structural geology (ibid.). Nine of the caves are concentrated along or just outside of the crater rim and one is located in the Stones River Group strata of the central uplift (Milam and Deane, 2006a). At one cave per 2.38 square km, the Flynn Creek target rocks contain 5.5 times the concentration of solutional caves that are known to exist elsewhere in Jackson County (ibid.). In addition, "… 7.5x more total cave passages can be found associated with the crater area, compared to surrounding areas …" (Milam, Deane and Oeser, 2005b: 32).

Flynn Creek cave development first occurred at the highest elevations of the limestone and dolostone exposures along the crater rim with the lowering of the regional base level. Though many of the Flynn Creek caves developed according to the strike and dip of the crater rim, "… others formed along extensional fractures in the fold axes of anticlines and along major faults where compression of the crater rim and wall collapse, respectively, occurred …" (Milam and Deane, 2006a: 82). Fractures and faults are zones of weakness where limestone dissolution is enhanced resulting in longer passage lengths. Though caves have developed in other parts of Jackson County, the Flynn Creek impact seems to be responsible for most of the cave development seen in the area today (Milam, Deane and Oeser, 2005b).

In the absence of the Flynn Creek impact Structure, a dual-generation karst landscape would have developed in this area anyway, similar to that seen outside the crater and elsewhere in Jackson and surrounding counties. However, the higher density of caves in target rocks, longer average cave lengths, their spatial association with Flynn Creek crater, and specific correlation with impact-related structures suggest that the impact crater has exerted some control over subsequent karst development in target rock caves.

Milam and Deane (2006a: 82) point out that caves may have formed on Mars in ways that are similar to those that formed in Flynn Creek, and may provide subsurface environments that are potential environmental niches for extant life:

> The control of cave development by impact-related geomorphology and structural geology features have resulted in subterranean environmental niches along the crater rim and central uplift. The caves here are home to diverse fauna and somewhat buffered ecosystems common to caves elsewhere in the region. Thus, the constraining of karstification in impact craters may serve as a predictive tool for locating subterranean environments on Mars.

The two crater fill caves, Mahaney Pit and Antioch School Cave, are first generation caves that formed in the Fort Payne Formation. Mahaney Pit is located along the southwestern rim of Flynn Creek at an elevation of ~280 meters above sea level (ibid.). The cave entrance consists of two 5 meter drops, beyond which exploration has not continued (Milam, Deane and Oeser, 2005a). Antioch School Cave is located in the eastern half of the crater, ~244 meters above sea level, and is 198 meters long. This cave developed along joints in the Fort Payne Formation (ibid.).

Additional uplift of the Nashville Dome allowed the Chattanooga Shale to be breached, exposing the underlying target rock in the crater's rim, floor, and central uplift. A second generation karst development began, and continues to this day. Nine of the second generation caves have formed along the crater rim in anticlines and along bedding planes (ibid.).

Wave Cave "… is located in the outermost concentric fault that defines the modified crater …" (Evenick, 2006: 7), and was formed in a tightly-folded asymmetric anticline on the east side of Flynn Creek (Roddy, 1966c: 109). The fragmented rock in the anticline core has been replaced by the cave (ibid.). A lack of tectonic deformation in this area indicates that this anticline formed as a result of the Flynn Creek impact (Evenick, 2006). The passageway is around 43 meters long and near the end, two side crawls lead to a ~6 × 12 meter room, and "An unusual inverted breakout dome is forming on the western side of this room due to gravitational collapse along bedding planes …" (Evenick, 2006: 7). Figure 41 shows two structural

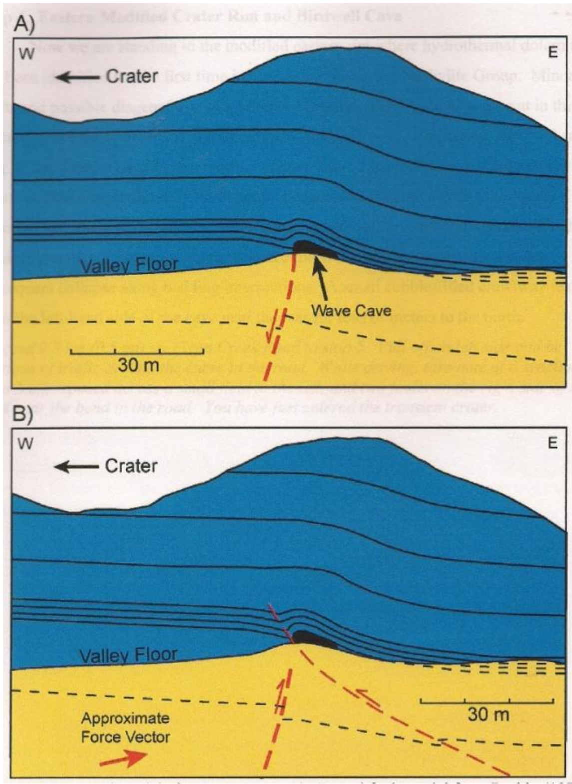


Figure 41: Two different structural models for Wave Cave (after Evenick, 2006: 9).

models for Wave Cave. Model A shows that Roddy's "Normal fault model … does not balance nor take asymmetry into account …" (Evenick, 2006: 9), while Model B is a new interpretation of Wave cave:

> Most normal faults that define the crater's modified crater rim are associated with a breached anticline, suggesting the region beyond the transient crater is first uplifted via thrusting during the initial excavation phase and later inverted during the final crater development and modification phases (ibid.).

Figures 42 and 43 show the entrance area of Wave Cave and an interior view, and Figure 44 is a map of the Cave (after Milam, Deane and Oeser, 2005a: 43). The Tilted Room in Wave Cave shown on the map "… developed along the

Figure 42: Jana Ruth Ford (foreground) and Larry Knox (to her left) examine the entrance to Wave Cave (courtesy: Jessica Tischler).

strike of steeply-dipping (61°) beds of the western limb of the anticline …" (Milam, Deane and Oeser, 2005b: 33).

Another Flynn Creek cave is Birdwell Cave, which formed in the eastern modified crater rim parallel to a modified crater fault (Deane et al., 2005). Both Birdwell and Wave Cave are oriented approximately north-south, which is perpendicular to the center of the crater and probably perpendicular to the maximum stress of impact (ibid.). Birdwell Cave is at least 116 meters in length with a 3 meter-high entrance (see Milam,

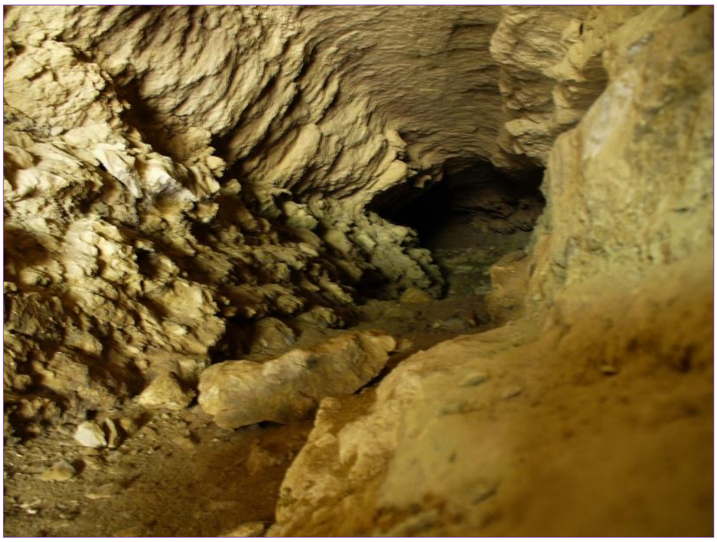


Figure 43 (above): A view within Wave Cave (courtesy: Rebecca Tischler).

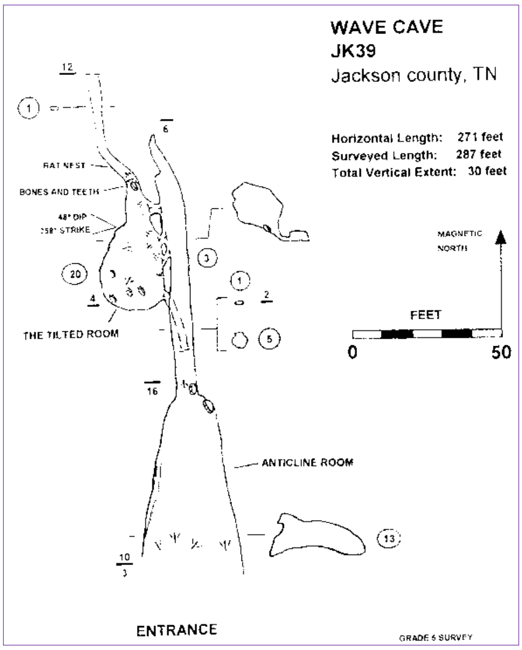


Figure 44 (right): A map of Wave Cave (after Milam, Deane and Oeser, 2005a: 43).

Deane and Oeser, 2005a). A passageway continues from the entrance for some 30 meters, and then splits. A short climb up to the right leads to a small passage that lies 2.5 meters above the entrance elevation. The left branch is a crawlway, only 30-40 cm high in some places, which developed along bedding planes. This crawlway in turn opens to a passage which is in places filled with pools of water. A blue hole, located around 100 to 150 meters to the south, is split by a north-south trending natural rock bridge as shown in the upper right of Figure 45, a map of Birdwell Cave. Milam, Deane and Oeser (2005a: 37) suggested that "Based on the proximity of Birdwell Cave to this blue hole and their similar structural patterns, it is possible that these two karst features may be connected hydrologically …" A small cobble-filled crawlway leads from the left, rear side of Birdwell Cave northward for some tens of meters (Deane et al., 2005).

Cub Hollow Cave is located along the eastern rim of the crater around 232 meters above sea level (Milam, Deane and Oeser, 2005a). The cave entrance is reached by descent into a narrow gorge which has flooded repeatedly. Inside, a stream flows swiftly through a wide crawlway to the northwest. This cave has only been mapped for 30 meters, but "… during low water, the cave was observed to continue to the northwest for another 12 to 15 meters …" (Milam, Deane and Oeser, 2005a: 38).

Flatt Cave is located along the southern crater rim and may have been mined in the past (Milam, Deane and Oeser, 2005a). A small, 1 by 2 meter entrance opens to an approximately 122 meter long dry passage which formed along an anticline. At the end of the passageway is a crawlway, which leads to a large, ~15 by 23 meter room. Several passages branch from this room and contain even more small side passages and wet drains. "At least four major (and sharp) changes in bedding orientations occur through-out Flatt Cave …" (Milam, Deane and Oeser, 2005a: 38). Flatt Cave developed within at least four major fault blocks (Milam, Deane and Oeser, 2005b). The bounding faults do not limit passageway development, but rather serve as groundwater conduits along which speleothems have formed in the cave (ibid.).

Forks Creek Cave is about 172 meters above sea level and was exposed in a road cut along

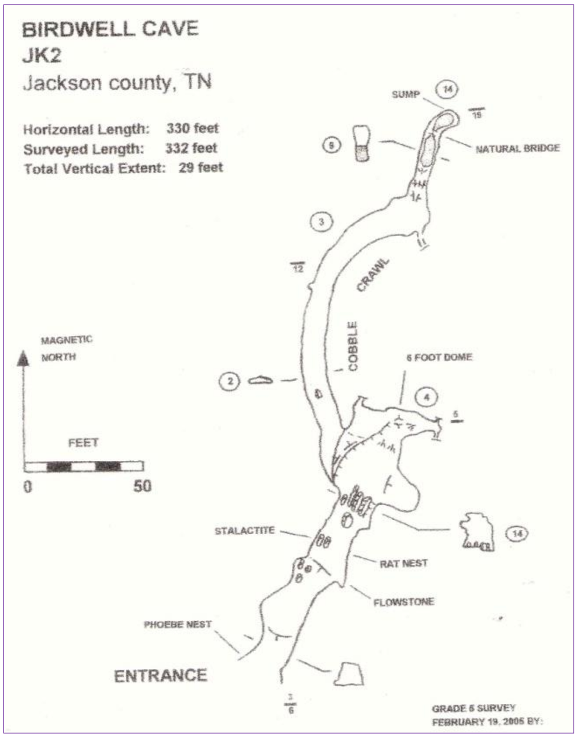


Figure 45: Map of Birdwell Cave (after Milam, Deane and Oeser, 2005a: 44).

the southern bank of the Flynn Creek. This cave has four entrances that lead to tight and interconnected crawlways (Milam, Deane and Oeser, 2005a).

Spalding Cave is located along the southeastern crater rim at an elevation of ~213 meters above sea level Milam, Deane and Oeser, 2005a). It is estimated to be 91 meters long with an entrance that is 1 meter high and 2 meters wide. Water flows out of the entrance which is located on the east side of Steam Mill Hollow, a tributary of Flynn Creek. A wet crawlway leads east from the entrance for some 17 meters. The crawlway is 50 to 60 cm in height with only 15 to 18 cm of airspace, but leads to a small room that is 4.5 meters long, 1.5 meters wide and 4.5 meters high. From here, a waterfall can be climbed 2.5 meters to a 1 meter by 1 meter passage that continues around 70 meters to another waterfall dome. This second dome is 4.5 meters high, 2.5 meters wide, and 4.5 meters in length. About 3 meters above the floor, a small waterfall flows in from the east wall. At the top another small passage leads to a second entrance which is simply a small hole on the side of a hill (ibid.).

Kelson Cave is located along the rim to the southwest of Spalding Cave in Steam Mill Hollow (Milam, Evenick and Deane, 2005). The entrance is 50 cm in diameter and leads to a small room that is about 1 meter tall. “A low, wet, sinuous crawl to the southwest and an upward squeeze leads into a muddy room in which three side passages diverge …” (Milam, Evenick and Deane, 2005: 39).

The entrance to Mahaney Cave is located at the base of a hill on the southwest side of Flynn Creek (Milam, Deane and Oeser, 2005a). “A low, tight crawlway, artificially opened about 1947, leads into a cave of several irregularly-shaped chambers …” (Milam Deane and Oeser, 2005a: 40). The entrance leads to a crawlway that slopes down to the left for 9 meters to a junction. Another crawlway to the right of the entrance is 9 meters long leading to a climb-up that is blocked by boulders, but a room can be seen on the other side. Other passages lead to a stream, “… a room with flowstone hanging on the walls …” a stoopway that continues for 21 meters, and even more crawlways (ibid.).

Rash Spring Cave has a 2 by 3 meter entrance on the west bank of Flynn Creek itself. This cave is 262 meters long with an active stream which runs through it to the entrance where it has served as a water source for the property owners (ibid.).

In addition to these caves in the Flynn Creek structure, collapsed caves can be seen along road cuts in the crater, such as one along Flynn Creek Road, which are indications of fault or fracture systems that are associated with the western modified crater rim (Evenick, 2006).

Of special interest is Hawkins Impact Cave, “… the only known cave in the world developed in a central uplift of a complex crater …” (Milam and Deane, 2006b: 81). The central peak, ~0.75 km in diameter, “… was buried by Devonian/ Mississippian-aged marine sediment that later became the Chattanooga Shale, Fort Payne, and other formations …” (Milam et al., 2006: 1). Milam and Deane (2006b: 81) believe that the Hawkins Impact Cave exposures “… provide a unique perspective into processes of central uplift formation …” This cave was discovered by the landowner, Michael Hawkins, in 1989 and was subsequently mapped in 2003 and found to be 277 meters in length (ibid.).

Expeditions to Hawkins Impact Cave reveal that around 30 large megablocks comprise the central uplift (Milam et al., 2006). Within some megablocks, there are bedding and monoclinic folds that are dissected by extensive networks of microfractures and microfaults (Milam and Deane, 2006b). Some megablocks contain no microfractures or microfaults while others have up to 3.1 per centimeter. Major fault dissection of the microfractures and microfaults indicate that subsequent movement occurred after their formation. Megablocks investigated inside Hawkins Impact Cave have volumes ranging from 20 to 3,200 cubic meters, whereas the megablock volumes on the northern flank of the central uplift are as large as 72,000 cubic meters. The former megablocks “… are separated by discrete major faults that both truncate and occur normal to bedding … Bedding orientations to either side of some major faults indicate that substantial rotation (up to 90°) occurred during megablock transport …” (Milam and Deane, 2006b: 81). Both microfractures and microfaults are less than 0.25 mm in width and extend for several meters through strata at angles of 60-85° to the bedding (ibid.).

Exploration of Hawkins Impact Cave indicates that after compression due to impact, the initial microfractures were generated (Milam et al., 2006). Cross-cutting relationships show that this first generation of microfractures was subsequently cut by microfaults and both terminate at major fault boundaries. Microfault movement followed with the subsequent generation of more microfractures and microfaults followed in turn by the rise of the central uplift, and “This is expressed by major fault movement along megablock boundaries, which truncate all of the above features …” (Milam et al., 2006: 2). Figure 46 is a map of the Hawkins Impact Cave (after Milam, Deane and Oeser, 2005a: 45). “Two large rooms (the Mars and Upper rooms) were formed by dissolution and subsequent collapse at the

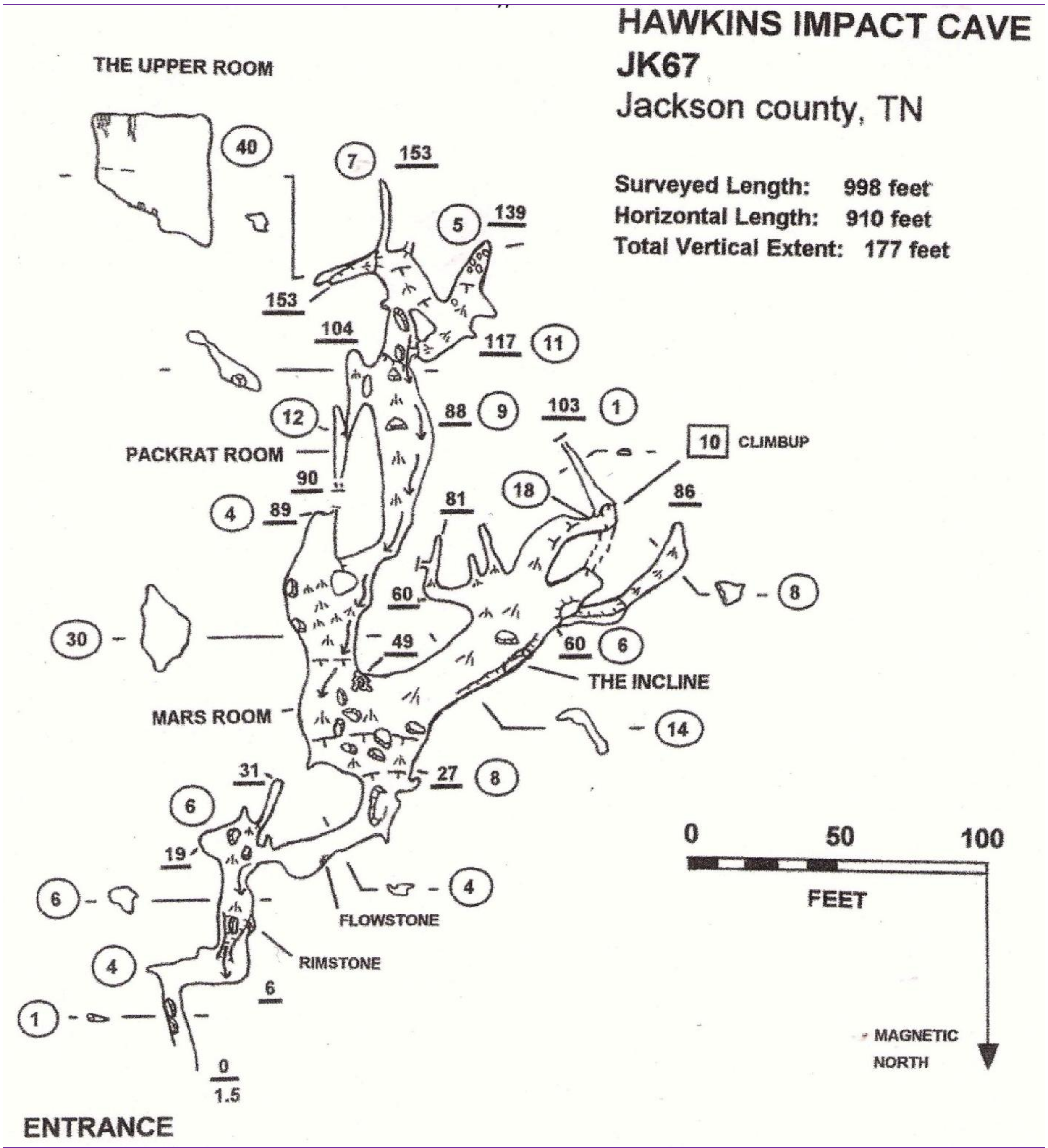


Figure 46: Map of Hawkins Impact Cave (after Milam et al., 2005a: 45).

intersection of several major faults …" (Milam, Deane and Oeser, 2005a: 33).

9 CONCLUSION

The Flynn Creek Structure is located on the Highland Rim escarpment in middle Tennessee and was first noted by Safford in his 1869 report of the geology of Tennessee. Described originally as a sinkhole, then as a cryptovolcanic structure, it was finally recognized as a site of meteorite impact when shatter cones found in the structure confirmed its origin. Decades of research by Roddy have provided a great deal of information regarding its formation and structural features. Masursky (1977: 637) explains a primary reason for studying impact craters such as Flynn Creek:

> We have learned from past planetary missions that an understanding of the processes involved in both crater formation and degradation provides clues to the age and geologic history of an area. Additional studies of the mechanics of crater formation and degradation derived from Earth-analogue studies … will help to define the geologic age relationships of the various geologic units on Mars; from these studies a more detailed history of the planet can be developed.

Flynn Creek is thought to be the result of an extremely shallow marine impact that occurred in perhaps 10 meters of sea water. Comparisons of Flynn Creek with confirmed shallow marine impact craters such as Wetumpka, in Alabama, show that Flynn Creek closely resembles subaerial impact craters except for its central peak, which is thought to have been flattened by subsequent wave action. It was hoped at the outset of this study that similarities and differences in the features of these two marine impact structures could be used to identify similar impact craters, which also occurred in a surface liquid, on other Solar System bodies such as Mars or Titan. Specifically, the differences might indicate liquid depth at the time of impact. However, water depth during the Flynn Creek impact was apparently too shallow to produce marine impact features that would be obvious to spacecraft such as the Mars Reconnaissance Orbiter.

Flynn Creek did prove valuable, however, to the National Aeronautics and Space Administration (NASA). Unlike most terrestrial impact structures, rapid burial by sediment that would later become Tennessee's Chattanooga Shale preserved the form of this crater, which is strikingly similar to lunar craters such as Pythagoras and Copernicus. As such, a detailed study of the Flynn Creek Structure was supported by NASA and the United States Geological Survey's Branch of Astrogeologic Studies in preparation for the Apollo Program, which resulted in astronauts walking on the lunar surface.

Flynn Creek may prove useful again in the exploration of our Solar System. Since Flynn Creek is home to numerous caves, and is the "… birthplace of impact speleology …" (Milam and Deane, 2006a), understanding cave development within an impact structure may serve as a basis for predicting the locations of caves on other planets, such as Mars (see Cushing et al., 2007). Such subterranean locations could offer protection to human explorers from hazards such as UV radiation, solar flares, high energy cosmic particles or even Martian dust storms.

The NW to SE bilateral symmetry noted by several researchers in the Flynn Creek Structure and the complex deformations found in the southeastern rim indicate that this crater was formed by an oblique impactor that came from the present-day northwest. It is of interest that the small oval-shaped Dycus Disturbance, a suspected site of meteorite impact, is located just 13 km to the northwest of Flynn Creek. As to future research, it would be most useful to determine whether or not there is a relationship between Flynn Creek and the Dycus Disturbance, and if so, the nature of that relationship. Comparison with the lunar craters Messier and Messier A may prove useful in this context.

10 NOTES

1. Koeberl (2009: 14) explains the distinction between an 'impact crater' and an 'impact structure':

> The distinction between an impact *crater* (i.e., the feature that results from the impact) and an impact *structure* (i.e., what we observe today, long after formation and modification of the crater) should be made clear. Unless a feature is fairly fresh and unaltered by erosion, it should be called an "impact structure," rather than an "impact crater."

2. Dietz (1963: 663) describes 'astrogeology' as "… a subject which must concern the earth, as well as the moon."

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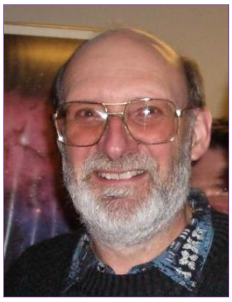

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DELPHI AND COSMOVISION: APOLLO'S ABSENCE AT THE LAND OF THE HYPERBOREANS AND THE TIME FOR CONSULTING THE ORACLE

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Abstract: Keeping an exact calendar was important to schedule Delphic festivals. The proper day for a prophecy involved a meticulous calculation, which was carried out by learned priests and ancient philosophers. The month of Bysios on average is February, but in reality it could be any 30-day interval between January and March. Bysios starts with a New Moon, but the beginning of the month is not easily pinpointed and thus Bysios and the 7^{th} day for giving an oracle cannot be identified according to the Gregorian calendar. The celestial motions of Lyra and Cygnus with regards to sunrise and sunset are related to the Delphi temple's orientation and the high altitude of steep cliffs of the Faidriades in front of it. Light from the rising Sun shines at the back of the temple where the statue of the god is located, while the appearance and disappearance of Lyra and Cygnus, two of Apollo's favorite constellations in the Delphic sky, mark the period of absence of the god to the Hyperboreans. This coincides with the 3-month interval from the end of December to the middle of March. During the later part of this period, on the 7^{th} day of Bysios, the oracle was given. At any rate, the Delphic calendar was a lunar-solar-stellar one, and was properly adjusted to coincide with and preserve the seasonal movements of those constellations.

Keywords: Temple of Apollo, Delphi, Pythia, consulting, oracle, Hyperboreans, stars, sunrise, constellations

1 INTRODUCTION

The Temple of Pythian Apollo at Delphi was constructed in 550 BC, and is located on the Greek mainland on the southern slopes of the Parnassus mountain range (see Figures 1 and 2 for Greek localities mentioned in the text). The puzzling orientation of the Temple has been questioned by Salt and Boutsikas (2005) and Vassiliou (2007), while a preliminary investigation regarding sunrise locations and α Lyrae in relation to the landscape at Delphi has been introduced without any firm result by Liritzis et al. (2011). Much earlier orientation measurements were made by Penrose (1897), who discussed the complex setting of the Temple and the difficulty in drawing any definite conclusions. Lack of a thorough investigation led him to consider the importance for dating purposes of the heliacal setting of β Lupi.

The most recent working hypothesis regarding the northeastern-facing entrance of the Temple in relation to the oracles delivered by the Pythian priestess was made by Salt and Boutsikas (2005) who related the heliacal rising of the constellation Delphinus to the timing of the consultation of the Oracle at Delphi during the month of Bysios.

Here we revisit the orientation of the Temple in relation to Apollo's departure and return from the land of the Hyperboreans[1] and thus define the timing when Pythia[2] was able to give oracles.

Our work reinforces the infrequent and vague textural evidence and contemporary archaeoastronomical research indications that ancient Hellenic religion may have included ritual elements inspired by astronomy but connected with the properties of the god Apollo (Liritzis and Vassiliou, 2002; 2003; 2006). Moreover, one should bear in mind that the symbolic language employed by philosophers at the time was used to hide the prevailing beliefs (Liritzis and Coucouzeli, 2007). Further to the intentional orientation of the Temple, we examine the relevance of astronomical issues, ancient calendars, ancient sources that refer to triggering agents (Plutarch, Strabo and others) and hydrocarbon vapors (De Boer, et al., 2001) that affected Pythia in delivering oracles (Fontenrose, 1981). We also consider relevant archaeological data (Courby, 1927; Radet, 1901; Roux, 1976).

2 ORACLES AND ORACULAR DAYS

Apollo is a many-talented Greek god of prophecy, music, intellectual pursuits, healing, plague, and sometimes, the Sun. Writers often contrast the cerebral, beardless young Apollo with his half-brother, the hedonistic Dionysus, the God of Wine.

The site of the oracle of Apollo at Delphi was an *antron* (cave) or *adyton* (restricted inaccessible area) where, according to the geographer Strabo, fumes rose from the ground to inspire a divine frenzy (Jones, 1924: 9.3.5).

Plutarch and his friends in his *De Defectu Oraculorum* (*On the Obsolescence of the Oracles*) discuss the reasons why the oracle ceased to offer consultations, amongst which he recalls demons, gods, water and the 'spirit' of the deity that varied and changed in the course of time (see Sieveking, 1972). Current research-

Figure 1: Greek localities mentioned in the text. Soli in NW Cyprus and Tyane is in eastern Asia Minor are not shown on this map. For a close-up of the Delphi region see Figure 2, below.

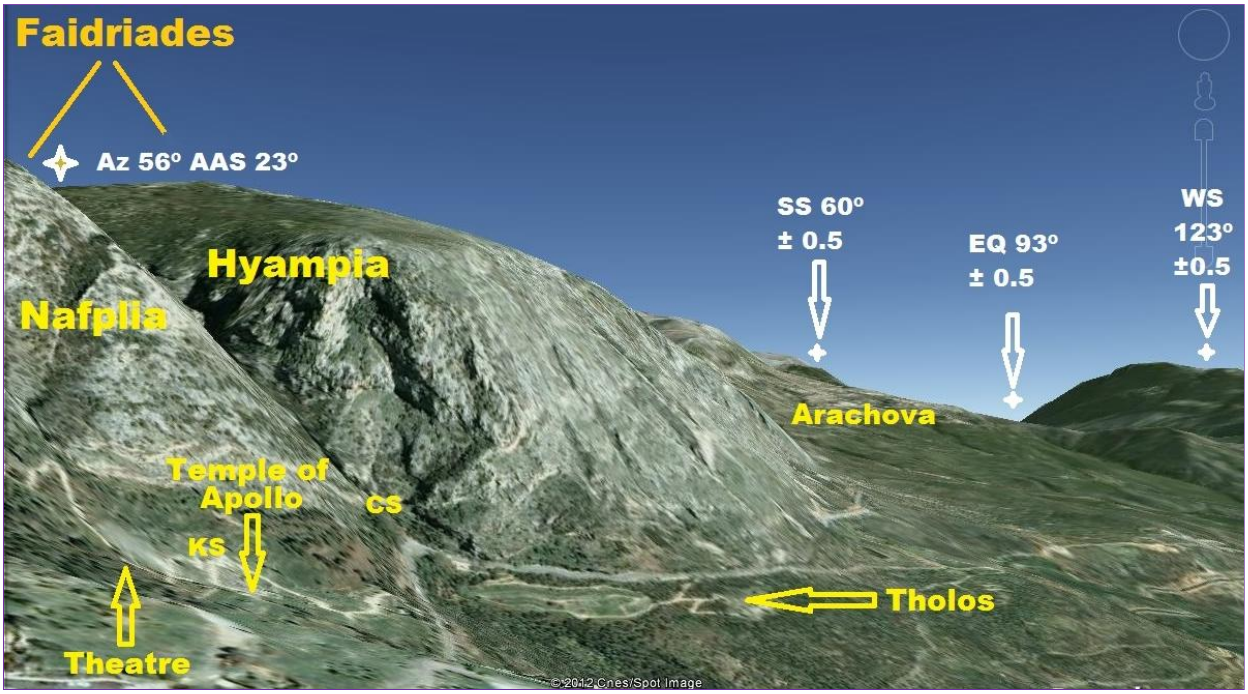

Figure 2: Localities in the vicinity of the Temple of Apollo at Delhi, together with the angular altitude of the skyline (AAS) of the Faidriades and summer and winter solstices (SS and WS) and equinox (EQ) azimuths. CS and KS are the Castalia and Kerna Springs, respectively, while the Faidriades Spring, between Nafplia and Hyampia, is not visible here. The Livadhi Valley is to the left, and beyond the top of this photograph.

ers interpret this theologically, culturally or politically.

The ancient literature provides useful information regarding the determination of the days suitable for delivering oracles to individuals or city representatives.[3] Plutarch (*Moralia*, 389c) mentions Apollo's absence from Delphi for the three winter months (see Sieveking, 1972). Parke (1943) thinks that when Plutarch (*Questiones graecae*, Stephanos 292 E-F) refers to months when oracles were given he does not include the winter period. But taking into account that an extra month could be added to the solar year as an intercalary month, this period varies and could extend to mid March.

Initially, in older times the oracular day was the seventh day of the lunar month of Bysios, the birthday of Apollo (which was sometime be-

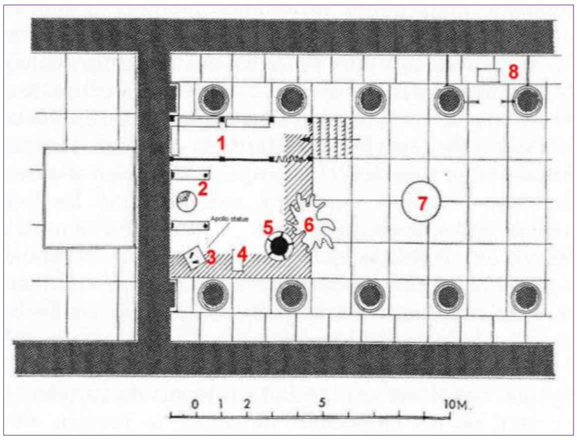

Figure 3: A reconstructed ground plan of the Temple of Apollo, the *adyton* and the positions of statues etc. based on ancient texts. Key: 1 = *oikos*, the waiting room for the opropoi. 2 = the beehive-shaped stone *omphalos*. 3 = the statue of Apollo. 4 = the tomb of Dionysos, the son of Semeli. 5 = the *adyton* where vapor ascend while Pythia is sitting at the tripod. 6 = the secret laurel tree. 7 = Estia's room. 8 = the sanctuary of Poseidon (after Roux, 1976: 134).

tween the end of January and the middle of March). This day was calculated from the New Moon that marked the beginning of the month. For example, in 412 BC, Euripides' tragedy *Ion* refers to the appropriate day for a consultation to Xouthos, who transmits the mythical report to the Late Bronze Age (Hannah, 2005; Roux, 1976).

Later, the priestess was consulted once on the seventh day of the month, nine times a year, except during the three months when Apollo was absent. So nine times each year the priestess mounted the tripod, entered a trance state and spoke for the god. These sessions were held on 'Apollo's Day', the seventh day after each New Moon in spring, summer and fall.

This could be partially verified, but at a later date, by Plutarch's work *Oracles at Delphi no Longer Given in Verse* (398 A), where Boethos, an epicurean skeptic, and one of his companions discuss the Temple of Apollo at Delphi: " … it is not sufficient that the god confines [himself] in a mortal body once a month …" (Sieveking, 1972). So when this fictitious conversation was taking place (i.e., during Plutarch's lifetime) the oracle was probably not as active, and in the following paragraph Plutarch says that in his day only one Pythian priestess was required, while elsewhere (*Moralia* 414 B) he states that in earlier times two full-time Pythian priestesses were employed and a third acted as a backup, (Sieveking, 1972). Taking into account the large numbers of visitors to Delphi, and the various exceptions in granting the right of priority oracles (*promanteia*) found on inscriptions, rather we have to entertain the possibility that the Pythian priestess was giving oracles more than once a month, at least during Classical and Hellenistic times. Two such active periods were the meetings of amphictyonic reunion during autumn (in mid-September, probably around the autumn equinox), and in spring (in mid-March, probably around the spring equinox), which is attested also on inscriptions (e.g. see Lefevre, 1991).

Plutarch (see Sieveking, 1972) also states that in very early times the Pythian priestess gave oracles just once per year, quoting Callisthenes (who wrote his *Hellenika* narrative sometime between 356 and 327 BC,[4]) and Anaxandridis (a Delphian contemporary of the third century B.C, historian Polemon, and writer of two books: *On the ill-omened Pylae oracular days in Delphi* and *On the Delphic Oracle*). Therefore, oracles were given once per year at least until the middle of the fourth century BC, and from that time on they were given monthly. It is not feasible to determine what this day was with respect to the present Gregorian Calendar due to the complex movement of the Moon and the insertion of an extra month in the middle of winter every 3, 5 and 8 years which would bring the month back into its proper season, and complexities that existed between the calendars of the different Greek city-states (see below, and also Manitius, 1898: 8.33).

Later on, as early as 480 BC, the oracles were delivered on the seventh day of the month for nine months, except during the three months that Apollo was absent. However, the priestess would sometimes provide oracles on ill-omened days, so exceptional appeals for an oracle could be made at other times. Initially Pythia could usually be consulted on the seventh day of each month—if this was not an inauspicious day—except when the gas flow in the sanctuary was too strong. Geological factors therefore could influence the successful functioning of the Temple of Apollo at Delphi.

Delphi was an amazing center of information at that time and of all the oracle sites Strabo considered it amongst "... the most reliable." (Jones, 1924: 9.3.6). However, politics exerted an influence, as the prestige of this oracle made Delphi the most important, influential and wealthy sacred place in the entire Greek World. For at least a thousand years, the pronouncements of the Delphic oracle offered divine guidance on issues ranging from the founding of colonies to declarations of war, to advice on personal issues (Spiller et al., 2002)

It transpired that Pythia was giving oracles amidst hallucinogenic hydrocarbon gases at the sanctuary, which are now known to have been released by trapped bituminous material in a seismic fault located below the rear of the Temple of Apollo (Hollinshead, 1999).[5] This current interpretation runs counter to the earlier opinion pronounced by Amandry (1950), the French excavator of the Temple, who maintained that there was no archaeological evidence in the Temple itself to support the belief in a fissure or gaseous emission. Moreover, he claimed that such an emission would be geologically impossible in the limestone rocks of Mount Parnassus (Figure 2), and he wrongly stated that such vapors are only produced in volcanic areas. Figure 3 shows a plan of the Temple and the location of the *adyton* which funneled the vapours up into the Temple.

The Temple of Apollo at Delphi is now known to be sited at the intersection of two major tectonic faults, the Kerna and Delphi Faults (De Boer et al., 2001) that are part of the Corinth rift zone, a region of crustal spreading. Subvertical fissures existed underneath the Temple (Courby, 1927, II: 66 and Figure 45), and sheets of travertine along the largest north-northwest faults (De Boer et. al., 2001: Figure 3) provided a pathway along which groundwater enriched with light hydrocarbon gases rose to the surface (see de Boer and Hale, 2000: Figure 7; Muller, 1992: Figure 2).[5] Even today, the smell of hydro-carbons has been reported in the vicinity of the Temple of Apollo, as well as in the modern town of Delphi.

Evidence of recent geological activity relating to one of these faults includes earthquakes and landslides. In addition, methane, ethane and ethylene are released along these seismic faults, but the most active vent occurred beneath the Temple of Apollo. These biogenic (bituminous) gases are shallow subsurface gases (in contrast to thermogenic gases which are from deep-seated sources), and when they are present visitors to the Temple would have experienced an altered mental state. Ethylene, the most unstable and powerful hallucinogen of the three, is often described as sweet-smelling, and even in small quantities can produce euphoria (De Boer et al., 2001; Etiope et al., 2006; Littleton, 1986).

These gases were first detected by De Boer et al. (2001) when they were researching the Kerna Spring to the north of the Temple, and they were subsequently detected, but in much lower volumes at the Castalia Spring and the Faidriades Spring (see Figure 2). Springs were traditionally associated with the cult of Apollo at Delphi, and along the Kerna Fault there were at least six springs. Of those springs that were known in antiquity only two are still flowing today—at Castalia and Kerna. During geological times, migrations of springs along faults were common in regions with frequent seismicity.

Normally, at any one time, there is a reciprocal relationship between gas production at a spring and the water flow: that is, as the amount of water in a spring increases gas production reduces. But there is one exception. If the water flows from a deep-seated aquifer and flows through a shallow gas-bearing reservoir then in that case we can expect more gas with more water production. In regions where there are seismic faults with bituminous gases this status also may change with the passage of time, as tremors may cause changes in the location of water and gas fissures.

Variations in temperature (T) also influence gas production, according to the following equation:

$$PV = nRT \tag{1}$$

where P is pressure, V is volume, n is the number of moles of gas, R is the universal gas constant, and T is in Kelvin.[6] Thus, if T changes and the number of moles is kept constant, then either P or V, or their product, will change in direct proportion to the temperature.

The gaseous emissions at Delphi are known to have been variable, and a likely explanation is the seasonal variations that were associated with temperature and water flow. At Kerna, the climate was warmer and there was increased rainfall during at least the first half of first millennium BC, and the volume of water reaching the Temple had naturally diminished, but was more pronounced after spring and in the summer. This was because of reduced snow cover on Mount Parnassus, and drainage of the Livadhi wetlands valley (Figure 1) below where the water entered fractures in the calcitic bedrock and made its way southwest into the Telphousa/ Kerna fault zone. This implies that there was less water during winter, while more snow and rainfall during the winter months led to the filling of the water reservoirs and abundant water flow in the springs during spring and summer.

Consequently there were seasonal variations in gas flow through the fissures at the *adyton*, most obviously during winter when the temperature was lower and the water flow was also reduced. Thus, during the winter months the 'pneuma entousiastikon' (= spirit of euphoria) was rarely triggered due to the absence of gas, and this also was the time when Apollo was away, in the land of the Hyperboreans.

There are numerous ancient reports from Classical, Hellenistic, Roman and proto-Christian times about the Delphi oracle. However, all are vague as to how the day to deliver an oracle was determined (e.g. see Falconer, 1923: Div. 1.37-38, 1.115, II.57.117; Jones, 1918: 10.24.5; Jones, 1924: *IX*, 3, 416-425; Rackham, 1952; Sieveking, 1972: *Moralia*, 38, 387; *De defectu oraculorum*, 409e-438d).

How then was the ideal day for a consultation defined? The answer is found in the sky, with the constellations of Lyra and Cygnus, which were associated with Apollo.

Table 1: Orientation measurements from the Temple of Apollo at Delphi, looking due northeast and southwest from the rear and the entrance of the Temple (latitude: 38º 25′ 55.4″, longitude: 22º 30′ 2.5″).

Location in The Temple	AAS (º)	Azimuth (º) (corr: + ~3.5º)
From the rear northeast foundation line (the *opisthodomos*) to Hyampia	27 ± 1	56 ± 2
From the entrance to Hyampia	35 ± 1	56 ± 2
From the *opisthodomos* to the intersection of the two cliffs of Faidriades	23 ± 1	56 ± 2
Towards the southwestern side (distorted sides)	4.5 ± 0.5	228 ± 2*

* Penrose (1893: 189) published a value of 227.88º for β Lupi.

3 THE ORIENTATION OF THE TEMPLE OF APOLLO AT DELPHI

Orientation measurements from the Temple in a southeastern direction give azimuths of between 112º and 124º and altitudes of 3.5 ± 2º, which together with Google Earth simulations indicate interesting sunrises throughout the year.[7] We can relate these to Apollo's departure for and return from Hyperborea, the delivering of oracular consultations, and the first illumination of the statue of Apollo in the *opisthodomos* of the Temple at the time of the winter solstice.

Using a magnetic compass with clinometer and a GPS, azimuths and the angular altitude of the horizon or skyline (AAS) were taken. The calcitic environment does not affect azimuth values taken with a compass. Measurements were taken frequently between 2004 and 2012. Table 1 gives the mean measurements and calculated declinations. Azimuths were taken along the length of the parallel foundations, which have been distorted by slumping of the area because of the seismotectonic setting of the Temple. We also observed a curving rise in the middle of the Temple, while a downward displacement of the southeastern foundation by about 10-15 cm, hence actual fracturing, was also noted by De Boer (2007). These made azimuth measurements problematic, leading to a larger than usual error.

In fact, light from the rising Sun illuminates the Temple of Apollo from the southwest (i.e. the rear where the chasm and golden statue of Apollo are located) to the northeast (i.e. the entrance of the Temple), and touches Hyampia, which is the right hand one of the two Faidriades cliffs, at the Castalia Spring (see Figures 2 and 4). It should be noted, also, that sunlight earlier illuminates the peripteral Tholos, at the entrance to the sanctuary and at a slope of 8º downwards from the Temple, something that may be related to the Temple.

Lighting within the temple is an open question. Although the existence of windows is not supported, door and window openings in ancient Greek temples (*naos*, in Greek) were spanned with a lintel, which in a stone building limited the possible width of the opening. The distance between columns was similarly affected by the nature of the lintel, columns on the outside of buildings and carrying stone lintels being closer together than those within the temples, which carried wooden lintels. Door and window openings narrowed towards the top. Given the absence of windows, the main light in a temple entered through the door, but it also has been suggested that some temples were lit from openings in the roof. A door of the Ionic Order at the Erechtheion in Athens is 17 feet high and 7.5 feet wide at the top, and retains many of its features intact, including mouldings, and an entablature supported on console brackets (see Boardman et al., 1967; Fletcher, 2001).

The entrance of the Temple of Apollo at Delphi is aligned due northeast, and points towards the two Faidriades cliffs (see Figures 2 and 4). Due to the proximity of the Temple to the Faidriades, the angular altitude of the skyline (AAS) of the Faidriades from the Temple of Apollo varies between 23º and 35º, depending on whether one was viewing from the back or the front entrance of the Temple, with a corrected azimuth of 56 ± 2º, which is well beyond the azimuth of the rising Sun (Figure 2). The Delphi landscape is bounded by mountains, and the rocky Faidriades in front of the Temple are in close proximity, thus, the AAS is important for the rise of stars and constellations at particular dates and times. This northeastern orientation does not appear to be random but relates to the three adjacent constellations of Lyra, Cygnus and Delphinus, which rise over the Faidriades in that order. The first two constellations always appear in front of the Temple at the exact azimuth that points to the intersection of Hyampia and Nafplia, while Delphinus is a little further to the east (see Figures 2, 4 and 5).

The path across the sky of these constellations is always the same: they appear at a northeastern azimuth of ~56º and disappear at a northwestern azimuth of 310º, corresponding to declinations of δ = 40^o- 41^o and 24^o- 28^o for these two orientations, respectively.

The combination of the appearance of these constellations at sunrise and their positions in the Delphic sky created the impression that they 'left' and 'returned' with the God Apollo (who was related to them).

4 THE ORIGIN OF CONSTELLATIONS IN BRIEF

Regarding the origin of the constellations and their stars—and their uses—they were developed between Old Babylonian times and the Seleucid period. The Babylonian constellations were largely developed and consolidated during the latter half of the second millennium BC (Rogers, 1998a; 1998b).

However, there is no firm evidence that the Greeks 'borrowed' constellations directly from Mesopotamia. During the Hellenistic Period it is possible that Berossus, the Phoenicians and Egyptians, and other Chaldean contemporaries made the Babylonian night sky familiar to the Greeks. It also is likely that there were 'competitive' schemes of Greek celestial astronomy until the wide adoption of the scheme developed by the Greek astronomer Eudoxus of Cnidus (see Lasserre, 1966) and diffused through his written works on the constellations in the fourth

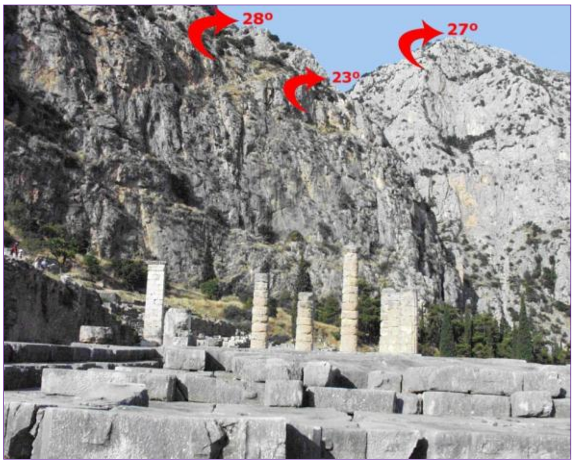

Figure 4: A view of the Faidriades from the rear of the Temple of Apollo, showing associated AAS values (photograph by IL).

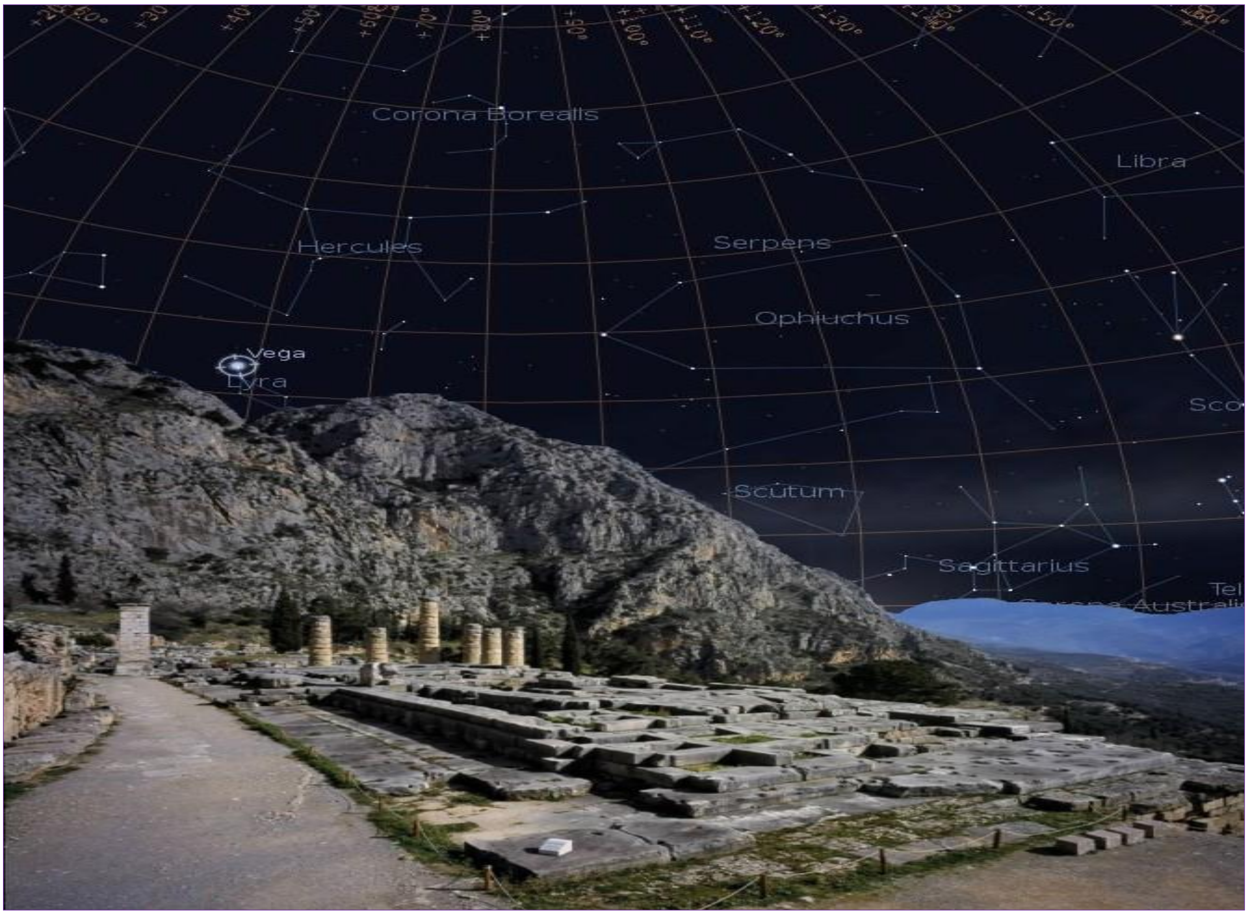

Figure 5: The heliacal rising of Vega above the Faidriades in the northeastern Delphi sky at dawn on 21 December 480 BC.

Figure 6: Star configurations in the constellations of Lyra, Cygnus and Delphinus (left), and corresponding images (right).

century BC, and through the Greek poet Aratus of Soli in the third century BC. This was the ultimate success of the *Sphaera Graecanica* as we have it today (i.e. its complete acceptance by the Greek world and later the Roman world). Eudoxus (see Schaefer, 2004) catalogued the stars in the Greek sky and delineated the various constellations in his works *Enoptron* and *Phaenomena*, and Aratus (Mair and Mair, 1921) later turned the contents of these two works into a poem concerning the constellations in his *Phenomena (*315-318). The *Phaenomena* became hugely popular in the Graeco-Roman world. Without this popularisation by Aratus, the works of Eudoxus may never have exerted the lasting influence they achieved. The final consolidation of the Greek constellations was based on the work of Hipparchus of Rhodes and the writings of Ptolemy.

The constellations of Cygnus and Lyra were originally listed by the Greek astronomer Ptolemy in the second century A.D., and earlier in a parapegma by Euctemon as recorded by Geminus (see Hannah, 2001; cf. Evans, 1998) where Cygnus was referred to as ‘Ornis’: ‘The Bird [Ornis] begins setting at nighfall.’ (see Hannah, 2001: 145). Due to precession, around 12,000 BC α Lyrae (Vega) was the pole star.

Crediting the Minoans of Crete—as some like to do—as the ‘makers’ of the classical constellations and offering explanations based on the destruction of Minoan civilization and the later ineptitude of the Greeks as observers is plausible. There is no evidence that the classical Greek scheme of constellations existed anywhere prior to its development in Greece circa 500 BC. There is no compelling reason to believe that the constellations were specifically established, at a particular time and place, as a reference system. The scheme proposed by Ovenden (1966) and the work carried out by Blomberg and Henriksson (1996; 1999; see, also, Henriksson and Blomberg, 2011; cf. Rogers 1998b) apparently does not try to identify the Greek constellations known prior to Eudoxus (i.e. the earlier Greek constellations of Homer and Hesiod).

Moreover, there is a lot of speculation regarding ‘the birds’ and the mythological birds that were orbiting the North Celestial Pole in Palaeolithic times (e.g. see Rappengluck, 1999; 2006; 2009).

It has been suggested that in certain Egyptian tombs which contain paintings of a woman and a swan these possibly depict the goddess Nut and the Milky Way and the constellation Cygnus, but this is only speculation (Belmonte, pers. comm., 2012). However, although of interest, these types of arguments are highly speculative and entirely deductive, and depend on *a priori* assumptions.

Nevertheless, a rational view is that knowledge based on (archaeo-)astronomical observations of star configurations was transmitted from generation to generation on a local and a regional scale, through cultural interactions that occurred between the Aegean area and the southeast Mediterranean from the end of the third millennium BC (e.g. see Betancourt, 1998; Branigan, 1973; Dicks, 1970; Wachsmann, 1998).

Lyra is a very conspicuous constellation (see Figure 6), with Vega at apparent visual magnitude 0.03 and other stars between magnitudes 3 and 5. Vega is the first conspicuous star in this constellation to rise above the Faidriades, even though the constellation covers an area of 2º × 7º. The brightest star in Cygnus is Deneb, which has an apparent visual magnitude of 1.25, while other stars in the constellation are between 2 and 4; meanwhile, its cross-like figure extends ~17º from Deneb, and the wings span ~23º. Finally, following Cygnus is the small and rather inconspicuous constellation of Delphinus, with its distinctive parallelogram shape that extends ~2º × 5º and contains stars of the 4th magnitude.

5 LYRA, CYGNUS, DELPHINUS AND APOLLO

The constellations of Lyra and Cygnus were most important to Apollo. The Greek word for swan is *κυκνος* (*kuknōs*), and the Latin word is *Cygnus*. Swans carried the souls of sacrificial kings to Hyperborea (Graves, 1955: § 161.4), while to be 'swan-like' was to greet one's death with a song of exceptional beauty, as in *Phaedo*, 84D-85B, a famous passage by Plato (Wagner, 1870; Wilson, 2007), where Socrates hopes his own prophecy will match that of swans: "... who, though they also sing in earlier times, sing especially well when on the point of death, because they are about to go off to the god whose servant they are." Their god, of course, was Apollo, who was famous for his association with singing swans and their distant northern retreat in the land of the Hyperboreans. Indeed, after Phaethon's death, his friend Cygnus was metamorphosed into a swan, whose lamenting death song is of proverbial beauty. Apollo was the son of Zeus and Leto (who took the form of a quail when she conceived him). He was born on the island of Delos (see Figure 1) on a seventh day, the Sun's day. On the day of his birth, swans came from the golden stream of Pactolus, and flew seven times around Delos, uttering songs of joy. The swan was a recurring motif in Greek and Roman mythology, generally as a bird associated with the Sun. Each Greek tribe had its own favourite myths, and additional stories constantly were being imported into Greek religion from foreign sources.

The swan also was the bird of the Muses. It was sacred to Apollo and to Aphrodite. Aeschylus, a Greek playwright, mentioned swan maidens. Several depictions of the swan and Apollo are on Greek vases and coins (e.g. see Head, 1893: *Pontus* Pl.28.5).

Similarly, Lyra (Greek *Λύρα*) was the beloved musical instrument of Apollo, the God of Music. Apollo was a gifted musician, who delighted the Gods with his lyre performances. He also was a master archer and a fleet-footed athlete, credited with being the first victor in the Olympic Games. He also is said to have taught humans the art of healing.

Ancient sculptors showed Apollo as a beautiful youth with flowing hair tied in a knot above his forehead, wearing a laurel wreath, holding his lyre or a bow. One of the most famous statues is the 'Apollo Belvedere', a Roman copy of a Greek bronze original, now kept in the Vatican Museum, in Rome, Italy. Also, painted on a circa 480 BC kylix (a shallow, stemmed, two-handled drinking bowl) in the Delphi Museum (No 8140), is a seated Apollo who pours the libation from a bowl, with a raven to his left.

Apollo also had a special relationship with dolphins, and he appointed Cretan sailors as the Delphi sanctuary's first priests. Having seen a Cretan ship sailing from Knossos in Crete to Pylos in the Peloponnese (see Figure 1), he turned himself into a dolphin and guided the ship into the Crisaean Gulf (the Phocian section of the northern coast of the Gulf of Corinth). From Crisa, the Cretan sailors came to Parnassus, led by Apollo. Having become priests of Apollo, they called the city Delphi, for the God, who appeared to them in the shape of a dolphin and told them:

> I sprang upon the ship in the form of a dolphin, pray to me as Apollo Delphinius; also the altar itself shall be called Delphinius ... (Richardson, 2010: 493; cf. Chappell, 2006).

Each year the constellations of Lyra and Cygnus travel to Hyperborea and so are only visible in much of the Greek world in summer, but in the north of Greece they are circumpolar and therefore can be seen all year long.

6 THE POSITIONS OF LYRA AND CYGNUS IN THE SKY, AND IMPORTANT DATES

To the Greeks, the dates upon which Lyra and Cygnus were located at certain positions in the sky just before sunrise or at sunset were particularly important. Although the heliacal rising or setting normally refers to stars and Lyra and Cygnus are constellations with several stars occupying large areas of the sky, the rising, setting or zenith positions of their brightest stars served as visual sky markers in relation to the Temple of Delphi's orientation.

Moreover, it is interesting to note that the Sun also plays a key role in the orientation of the Temple, in that the rising Sun directly illuminates the rear (*opisthodomos*) of the Temple around the winter solstice and also during summer at a later morning hour (because the steep sides of Hyampia, behind the town of Arachova hide the Sun from view earlier—see Figure 7).

All orientations point to the *opisthodomos*, and the existence of openings (windows) at least on the southeastern side of the Temple is plausible, an architectural element known at least from the architectural remains of Greek and Egyptian temples of the same era, and possibly implied by inscriptions on the Stele of Prusias, which is located on the right at the entrance to the temple (see Section 7 below).

Regarding the celestial paths of Lyra and Cygnus, just 15 minutes after midnight at the time of the vernal equinox, Lyra appears above the intersection of Hyampia (the eastern cliff) and Nafplia, in front of the temple.

In order to complete the picture of Apollo who, according to a legend "… travels with his lyre on the chariot drawn by many Cygnus ..." (the Greek lyric poet, Alcaeus, from Lesbos Island (Figure 1) speaks of the swans bringing him back from the Hyperboreans to Delphi at the appointed time of his ephiphany—see Treu, 1952; Farnell, 2010), one should establish when Lyra and Cygnus appear in front the entrance to the Temple of Delphi. Due to the rocky surrounding landscape the most clear and obvious position to have viewed them was at the zenith, that is, when these constellations were directly above the temple at midnight.

The following interesting pattern unfolds from summer time onwards. During the summer solstice Lyra and Cygnus appear successively directly in front of the entrance of the Temple of Apollo at sunset (22 June, at 21.15 local time), with Delphinus there a little later, so that the bright stars in all three constellations one after another will predominate during the night as they traverse the celestial sphere along an 'ideal' circumpolar path that follows a circle above the temple. At 21.15 at sunset in summer Lyra and Cygnus are found in front of the Temple, and in the course of the summer nights these constellations will be seen at higher altitudes. On 01.05 Lyra reaches the zenith, directly above the temple, then two hours later (at 03.05) Cygnus is at the zenith. At the end of the night (at 05.42) the view of these two constellations is lost to the northwest of the Temple with the first rays of the Sun appearing behind the town of Arachova (rising on the right in Figure 8). The Sun first appears a few hours later, when it illuminates the rear of the temple. However, over a period of more than a thousand years, the constellations that predominated during the summer solstice have changed.

Then, during autumn (22 September, at 19.55 local time), Lyra, Cygnus and Delphinus are found at or near the zenith when the Sun sets, and they start their descent until they are lost sight of behind the Temple. From that date onwards they give the impression that they have 'departed' or 'gone', becoming visible for fewer and fewer hours after sunset, and always towards the northwest of the *opisthodomos*. In the early hours after midnight, and certainly well before the dawn, they are lost below the Temple's northwestern skyline. Yet although they have 'gone', the Sun continues to illuminate the statue of Apollo at the rear of the Temple. At sunset on the autumnal equinox the last rays of the summer Sun illuminate the *opisthodomos* and the statue of Apollo (see Figures 3 and 4b).

Towards the end of December (from 21 to 26 December, when Apollo has gone to Hyperborea) the most interesting phenomenon occurs: the constellations of Cygnus, Lyra and Delphinus are lost behind the Temple a few minutes after sunset, then are absent all night, only to reappear over the Faidriades and above the entrance of the Temple a few minutes before sunrise the next day (at 06.05 am). At this time Lyra is only visible for a few minutes until it is 'drowned' by the sunlight. So these constellations that are closely associated with Apollo have disappeared, or 'departed' (and they will only reappear, or 'return', when Apollo comes back from the land of the Hyperboreans). Yet the rising Sun continues to shine on the back of the Temple, where the statue of Apollo is located, possibly to remind him of their absence. Nevertheless, as long as these constellations are visible for fewer and fewer hours each day from the entrance of the Temple, they never will rise high in the sky before they disappear from view.

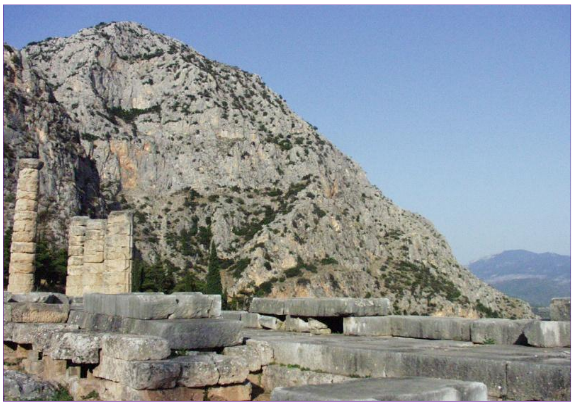

Figure 7: Hyampia seen from the rear of the Temple of Apollo. At the mid slope the sunrise appears during summer in the late morning (photograph by IL). (See, also, Figures 2 and 4).

Throughout the first millennium BC, Lyra and Cygnus were at the zenith in Delphi at some time before sunrise during the third week of March (see Figure 8), and from 18 to 21 March these constellations for the first time reached their highest positions in the sky, directly above the Temple, for a short time before sunrise. This is why the seventh day of Bysios always fell between early March and the middle of March. The variation in these days would have been used by the priests to determine exactly when Apollo would return, somewhat akin to the

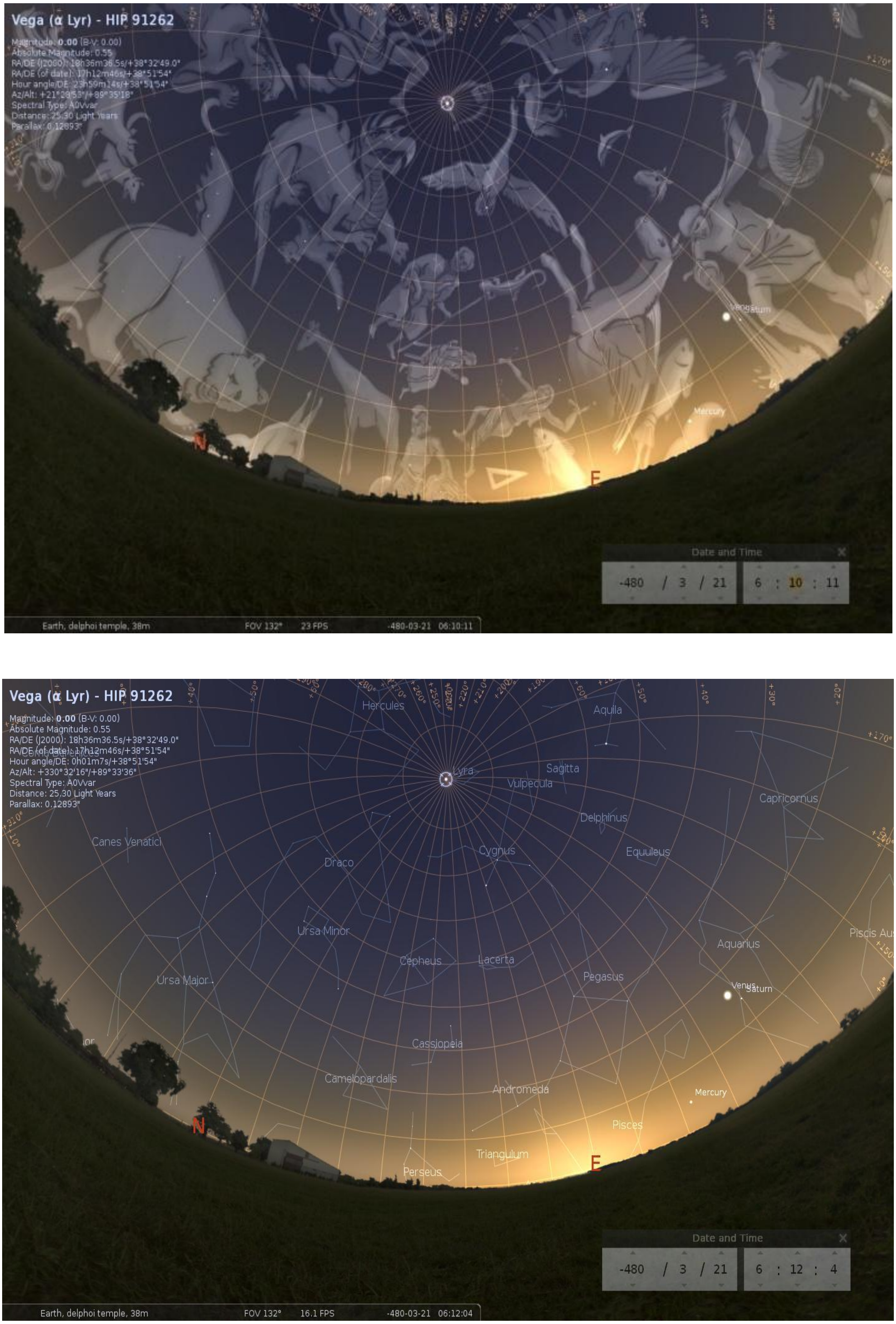

Figure 8: Lyra and Cygnus are at the zenith of Delphi a little before the sunrise during the third week of March on Julian date at 480 BC (the upper figure is in image form and lower figure shows the status of the sky at this time).

manner in which Christians choose the dates of Easter festivities each year.

Table 2 gives the times of the heliacal risings and settings of the brightest stars in Lyra and Cygnus for different dates between 1200 BC and AD 300, and their time differences in their appearances are negligible. At Delphi, the same orbital patterns remained during this long period, within a narrow range. For example, the heliacal rising of Vega on 21 December at 6.00 a.m. in 1200 BC was Az = 56° 25' and Alt = 22° 51', while the corresponding values for 480 BC were Az = 56° 06' and Alt = 21° 51', and for AD 300 Az = 57° 10' and Alt = 21° 03'.

From summer these constellations are visible for greater period of time each night. Thus, Lyra appears above the Faidriades before the dawn and Cygnus follows, so one could say that "The God gradually returns", but these two constellations will only reach the zenith during the first three weeks of March in the Julian calendar. The heliacal rising of Cygnus above the Faidriades occurs about a month later than Lyra.

Table 2: Heliacal rising and setting times for Vega (α Lyrae) and Deneb (α Cygnus) during the year and for 1200 BC to AD 300. During these heliacal risings the angular altitude of the skyline above Faidriades varied within ±0.5° and the respective azimuth within ±1°.

Year 480 BC

	March 21st	June 22nd	September 23rd	December 23rd
	Zenith at the Temple	*The Opisthodomos of the Temple*		*Faidriades Cliffs*
Vega rising	6.15 a.m.	5.35 a.m.	Not visible	7.15 a.m.
Deneb rising	6.10 a.m.	5.30 a.m.	Not visible	7.10 a.m.
		.	NB: Both constellations disappeared from the rear of the temple (= *opisthodomos*) during the night (Vega at 2.25 a.m. and Deneb at 4.25 a.m.), hours before sunrise.	
		Faidriades Cliffs	*Zenith at the Temple*	*The Opisthodomos of the Temple*
Vega setting	Not visible	21.10 p.m.	19.50 p.m.	18.00 p.m.
Deneb setting	Not visible	21.15 p.m.	19.55 p.m.	18.05 p.m.
	NB: Both constellations rise over the Faidrades during the night (Vega at 0.15 a.m. and Deneb at 2.15 a.m.), hours after sunset. Both are visible for only a few hours before sunrise (Vega from 0.15 a.m. to 6.15 a.m. and Deneb from 2.15 a.m. to 6.10 a.m.).	NB: Both are visible all night.	NB: Both are visible for a few hours after sunset (Vega from 19.50 p.m. to 2.25 a.m. and Deneb from 19.55 p.m. to 4.25 a.m.).	NB: Both are visible for a few minutes after sunset and again for a few minutes before sunrise, but they are not visible all night.

	January 15th	February 15th
	Faidriades Cliffs. At 52° altitude instead of 23° between Faidriades. Above the horizon seen from the front of the Temple, but not yet at the zenith as seen from the Temple.	*Faidriades Cliffs.* At 73° altitude instead of 23° between Faidriades. Above the horizon seen from the front of the Temple, but not yet at the zenith as seen from the Temple.
Vega rising	7.15 a.m.	7.05 a.m.
Deneb rising	7.10 a.m.	7.00 a.m.
	The Opisthodomos of the Temple	*Faidriades Cliffs* NB: Both constellations rise over the Faidrades during the night (Vega at 2.35 a.m. and Deneb at 4.35 a.m.), hours after sunset.
Vega setting	18.00 p.m.	Not visible
Deneb setting	18.05 p.m.	Not visible

Year 1200 BC

	March 21st	June 22nd	September 23rd	December 23rd
	Zenith at the Temple	*The Opisthodomos of the Temple.*		*Fedriades Cliffs*
Vega rising	6.25 a.m.	5.35 a.m.	Not visible	7.25 a.m.
Deneb rising	6.20 a.m.	5.30 a.m.	Not visible	7.20 a.m.
			NB: Both constellations dis-appear from the rear of the temple (the *Opisthodomos*) during the night (Vega at	

			2.35 a.m. and Deneb at 4.35 a.m.), hours before sunrise.	
		Faidriades Cliffs	*Zenith at the Temple*	*The Opisthodomos of the Temple*
Vega setting	Not visible	21.10 p.m.	20.00 p.m.	18.10 p.m.
Deneb setting	Not visible	21.15 p.m.	20.05 p.m.	18.15 p.m.
	NB: Both constellations rise over the Faidriades during the night (Vega at 0.25 a.m. and Deneb at 2.25 a.m.), hours after sunset. Both are visible for a few hours before sunrise (Vega from 0.25 a.m. to 6.25, a.m. and Deneb from 2.25 a.m. to 6.20 a.m.).	NB: Both are visible all night.	NB: Both are visible for a few hours after sunset (Vega from 20.00 p.m. to 2.35 a.m. and Deneb from 20.05 p.m. to 4.35 a.m.).	NB: Both are visible for a few minutes after sunset and again few minutes before sunrise, but they are not visible all night.

	January 15th	February 15th
	Faidriades Cliffs. At 54º altitude instead of 23º between Faidriades. Above the horizon seen from the front of the Temple, but not yet at the zenith as seen from the Temple.	*Faidriades Cliffs*. At 76º of altitude instead of 23º between Faidriades. Above the horizon seen from the front of the Temple, but not yet at the zenith as seen from the Temple.
Vega rising	7.25 a.m.	7.15 a.m.
Deneb rising	7.20 a.m.	7.10 a.m.
	The Opisthodomos of the Temple	NB: Both constellations rise over the Faidrades during the night (Vega at 2.45 a.m. and Deneb at 4.45 a.m.), hours after sunset.
Vega rising	18.10 p.m.	Not visible
Deneb rising	18.15 p.m.	Not visible

Year AD 300

	March 21st	June 22nd	September 23rd	December 23rd
	Zenith at the Temple	*The opisthodomos of the Temple*		*Faidriades Cliffs*
Vegas rising	6.05 a.m.	5.35 a.m.	Not visible	7.05 a.m.
Deneb rising	6.00 a.m.	5.30 a.m.	Not visible	7.00 a.m.
		.	NB: Both constellations disappear from the rear of the temple (*the opisthodomos*) during the night (Vega at 2.15 a.m. and Deneb at 4.25 a.m.), hours before the sunrise.	
		Faidriades Cliffs	*Zenith at the Temple*	*The opisthodomos of the Temple*
Vega setting	Not visible	21.10 p.m.	19.40 p.m.	17.50 p.m.
Deneb setting	Not visible	21.15 p.m.	19.45 p.m.	17.55 p.m.
	NB: Both constellations rise over the Faidrades during the night (Vega at 0.05 a.m. and Deneb at 2.05 a.m.), hours after sunset. Both are visible for a few hours before sunrise (from 0.05 a.m. to 6.05 a.m. for Vega and from 2.05 a.m.to 6.00 a.m. for Deneb).	NB: Both are visible all night.	NB: Both are visible for a few hours after sunset (Vega from 19.40 p.m. to 2.15 a.m., and Deneb from 19.45 p.m. to 4.15 a.m.).	NB: Both are visible for a few minutes after sunset and then again for a few minutes before sunrise, but they are not visible all night.

	January 15th	February 15th
	Faidriades Cliffs. At 49º altitude instead of 23º between Faidriades. Above the horizon seen from the front of the Temple, but not yet at the zenith as seen from the Temple.	*Faidriades Cliffs.* At 71º altitude instead of 23º between Faidriades. Above the horizon seen from the front of the Temple, but not yet at the zenith as see from the Temple.
Vega rising	7.05 a.m.	6.55 a.m.
Deneb rising	7.00 a.m.	6.50 a.m.
	The Opisthodomos of the Temple	NB: Both constellations rise over the Faidrades during the night (Vega at 2.25 a.m. Deneb at 4.25 a.m.), hours after the setting of the Sun.
Vega rising	17.50 p.m.	Not visible
Deneb rising	17.55 p.m.	Not visible

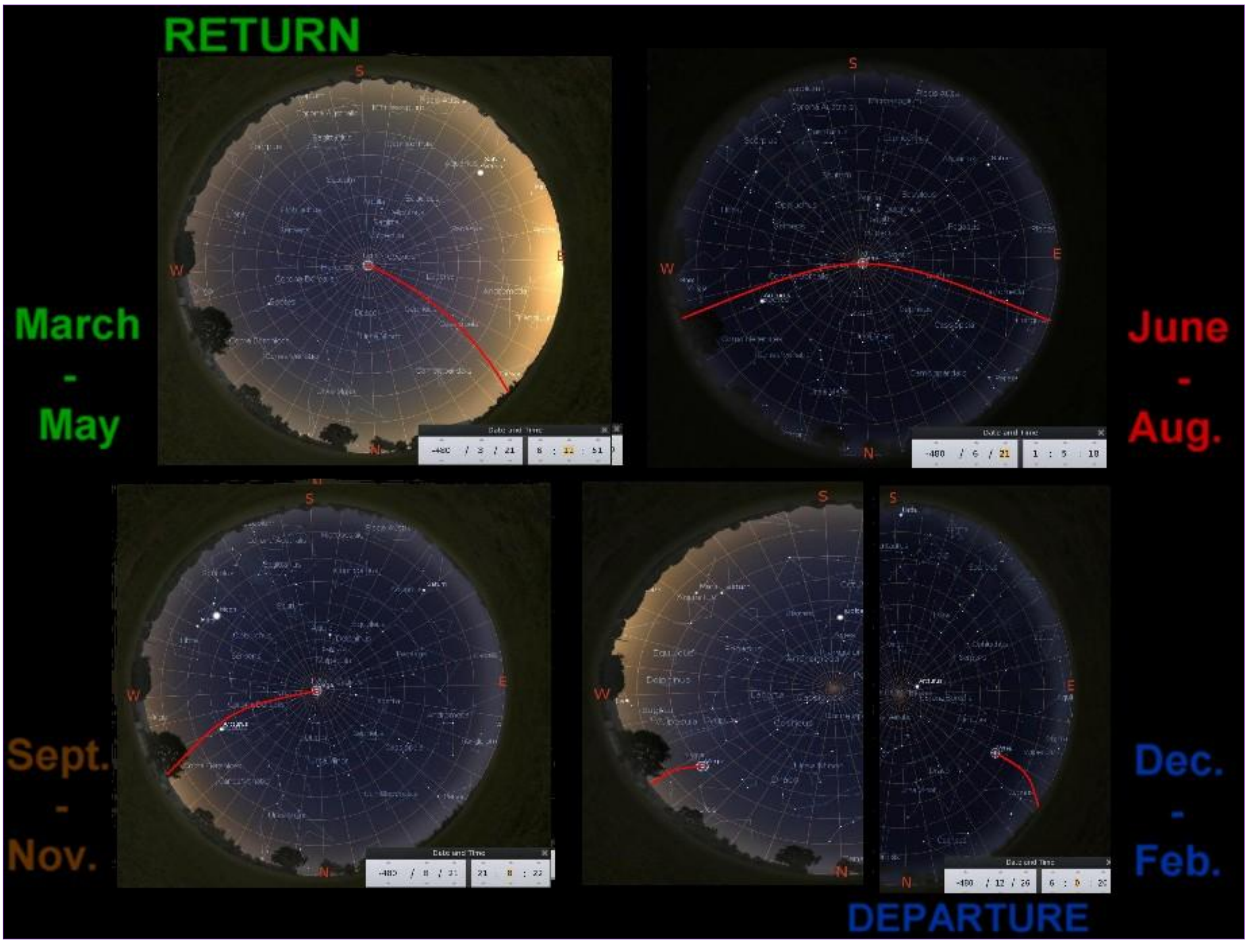

Figure 9: The transits of Lyra and Cygnus in the Delphic sky for the four seasons.

Figure 9 shows the appearance of Lyra and Cygnus in the Delphic sky for the four seasons of the year. Visibility was always going to be a significant factor, as due to weather conditions in the mountains during winter sometimes it would have been difficult—if not impossible—to observe those constellations. However, their absence from the zenith at Delphi in January, February and March may have signalled the interval when Apollo was supposedly in Hyperborea. Obviously, the difference in the AAS between a site on a flat landscape and one with a high rocky horizon, as at Delphi, meant that the heliacal rising of critical stars and constellations was delayed at the latter location. Thus in the case of both Athens in 480 BC and Pella (Macedonia) in 334 BC, with their flattish surrounds, Lyra appeared 0-5º above the horizon at dawn around 21 November, one month earlier than when it rose above the Faidriades in Delphi. Nevertheless, for all three cities Vega transited the zenith simultaneously at dawn on the same day (i.e. around the vernal equinox). In other parts of Greece, Lyra goes close to but does not actually reach the zenith. For example, from the Temple of Apollo in Rhodes (see Figure 1) which faces due east, Lyra has the same heliacal rising time, but the Sun overwhelms the event due to the Temple's orientation towards the Sun-god—poetically identified with Apollo—who was worshipped in Rhodes (Fontenrose, 1939).

An oracle that was known to have been given to the Athenians about 'wooden walls' (Bowden, 2005: 102) led to the Salamis naval battle on 22 September 480 BC, with the oracle given on the seventh day of the Delphic Boukatios or the Athenian Metageitnion (in July/August).

Thus, this earlier heliacal rising of Lyra, followed successively by Cygnus and Delphinus, could mark the time for would-be visitors to depart for Delphi one month earlier, initially, during March, the seventh day of Bysios, and later on the seventh lunar day of each of the nine months. This is a much more plausible interpretation than the one suggested by Salt and Boutsikas (2005), as Vega (α Lyra) and even Deneb (α Cygnus) were much brighter stars than any in Delphinus, and these two constellations were more strongly associated with Apollo than Delphinus was.

The same star configurations seen above the Temple of Apollo at Delphi, bordered by the rocky Faidriades and with its open southern landscape, persisted throughout the period ~1000 BC to ~ AD 300, although there were some

Figure 10: The red-figure hydria related to Hyperborean Apollo (Museo Gregoriano Etrusco 16568, Vatican. Height is 58 cm).

minor changes at the beginning and end of this long interval due to precession of the equinoxes. The earlier date marks the establishment of the Delphic oracle (as mentioned by Homer in his Hymn to Apollo—see Chappell, 2006), and there is archaeological evidence that there even was a cult here in Mycenaean times (Nilsson, 1950), while the latter dates recalls the last recorded oracle, which was delivered to Roman Emperor Julian in AD 361. The Greek historian, Philostorgius, who was born in Cappadocia in about AD 364, mentions Julian and the Delphic oracle (see Walford, 2009).

The afore-mentioned appearance and disappearance of a particular prominent star or constellation recalls the Egyptian dating based on the Sothic cycle, that is, on the heliacal rise of Sirius. Each year for a period of seventy days Sirius was not visible due to sunlight, and its heliacal return was very important and was referred to as 'the coming of Sirius'. The first day of the new year was marked by the first day of the lunar month immediately after the annual reappearance of this star at dawn (Ingham, 1969; Parker, 1950: 13, 29, 30-32).

7 SUPPORTIVE DATA

Apollo's travel to Hyperborea is depicted on an Attic red-figure hydria (see Figure 10), that was painted by the 'painter of Berlin'.[8] The god Apollo playing his lyre is seated on an open-winged tripod that depicts Cygnus (the swan), and implies that his medium, the priestess Pythia, is giving oracles. He rides over the sea, which is denoted by fish and an octopus. Two dolphins leaping over the waves accompany him. The setting corresponds to the correct order of the constellations Lyra, Cygnus and Delphinus in the Greek night sky.

Another piece of evidence that supports the determination of festivities and oracular dates comes from a written source. To the right of the entrance to the Temple of Apollo at Delphi there is the restored Stele of Prusias (see Figure 11). On this there is an epigram written in ca. AD 120-130 on the calcitic surface, a dedication to the scientist Aristoklides from Tyane, a member of the Delphic amphictyonee,[9] that reads (*inter alia*, our English translation): *"...* offered/placed inside the door/window/niche, sacred objects …" This refers to sacred objects that were placed inside a door or niche or window, and which have since disappeared. Several interpretations have been given about this phrase and the meaning of the door/window/hole, the types of sacred objects (instruments?), and why they were placed there (for a dedication, for regular use, or for repairs?). The inscription suggests that both the place and the objects would have been well known to users of the Temple (see Courby, 1927: III: 4, 1; IV: 131-132, sect. 83; addenda au fase, I: 39). One working hypothesis would be that they were astronomical instruments that were used to observe the positions of the rising Sun, the Moon and the stars in connection with the departure and return of Apollo

Figure 11: A general view of the entrance to the Temple of Apollo at Delphi (left) with the restored Stele of Prusias to the right of the entrance. The central photograph shows another view of the Stele, and the right hand photograph is a close up of the epigraphy on the Stele (photographs by IL).

and the delivery of oracles by Pythia. Meanwhile, this inscription would also seem to indicate that a harmonious relationship existed between science and religion in Delphi at that time.

9 ON CALENDARS AND THE DETERMINATION OF THE SEVENTH DAY OF BYSIOS

Of all ancient calendar systems, the Greek calendar is one of the most confusing. The Greek calendar is much like ancient Greece itself: it shared a certain basic similarity from region to region, but each city-state kept its own version. All the Greek calendars were luni-solar and had the same basic features of other luni-solar calendars: twelve months, with a periodic intercalation of a thirteenth.

Therefore, in ancient Greece the lunar calendar consisted of twelve lunar months, which was shorter than the solar tropical year by about 11 days, which were added in the course of years with respect to the seasons (Hannah, 2005). In fact, there were 30 intercalary days in the third year, another 30 days in the fifth year and a further 30 days in the eighth year. In order to assess this correction, Salt and Boutsikas (2005: figures 2 and 3) illustrate the change of a lunar month in a century as a function of the Gregorian calendar and the insertion of the additional months during the eight years.

Keeping an exact calendar was important for scheduling festivals, but also for travel, for everyday work, and for agricultural and stock-breeding activities. Astronomical observations for pastoral movements and everyday needs were accumulated over the centuries, as textural (Hesiod, *Works & Days*—see West (1996); Homer, *Iliad and Odyssey*—see Fagles, 1996) and archaeoastronomical research has shown.

The proper day for a prophecy was a meticulous calculation that was carried out by learned priests and ancient philosophers. The month of Bysios (or Physios),[10] on average is February but could be any 30-day interval between January and mid-March (Lefevre, 1991). Bysios starts with a New Moon, but the beginning of a month is not easily pinpointed; thus, the month of Bysios and the seventh day, for giving oracles, cannot be identified and automatically associated with the Julian (or Gregorian) calendar.

The necessity to decide when people actually managed to sight the crescent Moon in Greece on the critical occasions was vital (much like the same problem that confronts those researching Islamic astronomy who have to identify specific dates). This would actually mean that the first day of the month was at least two days after the New Moon/conjunction, and if there was stormy weather even more. Indeed, this difficulty still plagues the Muslim world today—despite access to superior resources and (theoretically?) a more rigorous approach compared to the one followed by the ancient Greeks. Yet the ancient Greeks were perfectly capable of calculating the average lengths of months and thus a New Moon/conjunction (Pritchett, 2001). Lunar months average 29.53 days and that is why many Greeks had full months of 30 days followed by 'hollow' months of 29 days, because 2 × 29.53 = about 59 and 30 + 29 = 59 days.

The uncertainties that cause variation in the lunar month make determination impossible. An important factor relates to variations in the Moon's orbital velocity. Therefore there was some uncertainty about the determination of the beginning of Bysios (and the other nine vital days of the year), and flexibility is unavoidable in deciding when to insert an 'extra' (intercalary) month, based on subjective observations of seasonal drift. Hence, it is impossible to always pinpoint exact month-sequences in specific years (through not knowing whether or not an intercalary month had been inserted).[11] In addition, the occurrence of the New Moon has also been subjected to manipulation, and in fact some inscriptions found in Athens give two different dates, one using the 'civic calendar' and another using 'the goddess' (McCluskey, 2000: 18). References to local calendars would therefore not only carry religious and hence political connotations, but they also would be inherently chronologically unreliable.

In Greece the scientific application of current and traditional knowledge in the first millennium BC dealt with particular astronomical phenomena and calculations, while the three favourite constellations relating to Apollo were known. What was publicised in Athens (Figure 1) and other Greek cities was apparently much more than just a notice about the solstices. Rather, it looked very much like a combination of what we find in full-blown parapegmas—which not only recorded information about the solstices and equinoxes, but also provided indications of the weather which were allied to stellar phenomena, and the 19-year 'Metonic' cycle.

A parapegma keeps track of the solar year via various star movements, and thus it presumably provided the means to enable users of the Metonic cycle to keep track of the date of the solstice.[12] The Octaeteris (called by some the Enneateris when counting years inclusively) is, as Geminos (1898) tells us, an earlier intercalation scheme in years three, five and eight of an eight-year period that utterly failed to keep the months aligned with the seasons. According to Geminos (ibid.), it was replaced by the Metonic cycle, which in Athens was certainly being used by the fourth century BC. The traditional date of its discovery is 432 BC, but it was almost certainly not instituted until later. The Metonic cycle also was used by the Babylonians from around 500 BC. We have no evidence, however, that the Delphians or Athenians ever used the Octaeteris.

However, in Hellenistic times (i.e., by the second century BC), there is ample evidence that those at the Temple of Apollo in Delphi were employing the Metonic cycle, since its calendar was synchronized with several other Phokian calendars and the only reasonable way of doing this was if all of them were following the Metonic cycle. There is some evidence that by the second century BC Delphi and Athens normally intercalated in the same month, and if not the same month then certainly in the same year (Perlman, 1989; Rigsby, 2010). Thus, Bysios was probably normally coincident with the Athenian Anthesterion, and thus normally fell in February-March. But as mentioned above, the trick was to try and find out which historical lunar month Bysios corresponded to, and this is made difficult by not knowing in which year they intercalated and by what principles they did this. According to Hannah (2012, work in progress, pers. comm.), if the Delphic calendar was run according to a hypothetical 8-year cycle (for 421-431 BC), where years three, six and eight were intercalary years and all dates were Julian, Bysios could occupy the period between 25 January and 20 March, but would not be in March in years two (431/430 BC) and five (428/427 BC). Any conversion from the Julian to the Gregorian or Astronomical Calendar would involve a few days, or range between one and ten days for the first millennium BC. This is only a working hypothesis, and the experts regulating the Delphic calendar would have made their calendar corrections and adjustments based on the positions of certain critical constellations in the Delphic sky.

Moreover, turning to some historical issues, if instead of Physios (of nature) that Roux (1976) discusses we take 'pysios' for the Bysios month, as Plutarch (Sieveking, 1972) thinks is the right term, this could mean the month that men inquired about and heard from the God. In this month there used to be oracular activity (Sieveking, 1972: *Moralia* 292 E-F) on the seventh day, which they considered to be the birthday of Apollo, and they call this 'the day of many utterances', not because they baked cakes but because it was a day of many inquiries and utterances. Thus, only during Plutarch's time and from the fourth century BC were monthly oracles (αἱ κατὰ μῆνα μαντεῖαι) given to those who made inquiries, whereas in earlier times Pythia only gave responses once a year throughout this day, according to Callisthenes (see Hansen, 1998). The use of the term 'κατά' (= during) above actually suggests that oracles were given throughout the month, not just on a single day, and not during one single month of a year. Even more, it does not imply that in later times Delphic oracles were only given on the seven day of every month. We can only state that in earlier times the seventh of Bysios was the only day for giving oracles because it was considered to be Apollo's birthday.

Regarding constellations discussed here, the inclusion of the three constellations of Lyra, Cygnus and even Delphinus in a parapegma confirms that they were known to the Greeks from at least the fifth century BC (Hannah, 2002). Modern astronomical calculations agree with the records of the parapegma of Euctemon (e.g. see Schaefer, 1985; van der Waerden, 1984) that the helical rising of the aforementioned constellations occurs on what is now the third week of December.

Information regarding the analogous heliacal rising of star clusters (e.g. the Pleiades) and constellations (e.g. Bootes, Orion, etc.) is found in the works of Homer (Fagles, 1996: *Odyssey* 5.270) and Hesiod (West, 1996). The heliacal rising of Cygnus may also have been used to calculate the seventh day of Bysios for giving oracles following Apollo's return from Hyperborea. Indeed, the primary sources for pastoral-related astronomy are Hesiod's *Works and Days* and Homer's *Odyssey,* where both refer to the movement of the stars and the fauna of Greece, and assign to both the status of seasonal indicators. The astronomical sections in Hesiod and Homer include a variety of astronomical events, and have been the subject of analysis (e.g. see Aveni and Ammerman, 2001: 83-97; Papamarinopoulos et al., 2012; Theodossiou et al., 2011; West, 1996: 376-381). The most commonly-cited astronomical phenomenon relating to heliacal rising is in the *Works and Days*, where the time for harvesting and sailing is signalled by the dawn rising of certain stars and constellations (e.g. see West, 1996: 383-387, 571-573, 597-600).

Lyra and Cygnus are the most obvious heliacal rising markers, separated by one month, but the relatively inconspicuous constellation of Delphinus would appear only to an experienced observer with excellent eyesight watching on a clear night. Difficulties owing to weather conditions that are most evident during February and March would also hamper observations of this little constellation. Therefore, it is more plausible that the heliacal rising, not at sunrise but in the northeast, of the constellations Lyra and Cygnus, were used in the Delphic calendar to determine the three months of Apollo's absence in Hyperborea. As a first magnitude star, Vega also had the advantage that its appearance warned of the imminent heliacal rising of the constellation of Lyra.

For the officials, knowledge of the length of the solar year would have been important, so that religious festivals centring on agricultural events, such as sowing and harvesting, could be held at the appropriate seasonal times. In Delphi an additional factor was important in defining the calendar, and this was the decrease in vapours emanating from the subterranean chasm during the winter months, which had to be precisely determined every year.

At any rate, visitors from the outlying areas beyond Delphi (and Athens) who wanted to attend festivals or other activities on the *noumenia* (new month) had to rely, firstly, on getting information on the crescent Moon from calendars, and secondly, on finding out when the constellations of Lyra and Cygnus rose in their skies. This way they could time their arrival at Delphi in advance of the day when oracles would be given, even if this particular day was not precisely known to them beforehand.

10 THE DELPHIC CALENDAR

Regarding the ancient Greek calendars (see Fontenrose, 1974: 383; Hannah, 2005; Mikalson, 1975: 9; Trumpy, 1997: 212) and systems of measuring time and the duration of years, months and seasons we have the references given by ancient writers like Censorinus, Geminus and Herodotus (see Hannah, 2005; Heath, 2004;). It is Geminus who speaks clearly of a soli-lunar calendar:

> The ancients had before them the problem of reckoning the months by the moon, but the years by the sun. For the legal and oracular prescription that sacrifices should be offered after the manner of their forefathers was interpreted by all Greeks as meaning that they should keep the years in agreement with the sun and the days and months with the moon. Now reckoning the years according to the sun means performing the same sacrifices to the gods at the same seasons in the year, that is to say, performing the spring sacrifice always in the spring, the summer sacrifice in the summer and similarly offering the same sacrifices from year to year at the other definite periods of the year when they fell due, for they apprehended that this was welcome and pleasing to the gods. The object in view, then could not be secured in other way than by contriving that the solstices and equinoxes should occur in the same months from year to year. Reckoning the days according to the moon means contriving that the names of the days of the month shall follow the phases of the moon. (Manitius, 1898: c.8,6-9, p.102.8-26).

The dealing with months, years and cycles in ancient Greece towards a solar calendar or a calendar in accordance with saving the phenomena, has produced a striving involving the Sun and the Moon's phases, and several critical reviews have been produced. The development involved 'hollow' and 'full' months, and it can be assumed that the intercalation (the *trieteris*) occurred every third year as Geminus says that "… the ancients made the months 30 days each, and added the intercalary months in alternate years …" (Manitius, 1898: c.8.26), while Censorinus called it the *trieteris* because the intercalation took place every third year (Maude, 1900: Chapter 18.2). According to Censorinus, the *pentaeteris*, or four years, was the next change, but Geminus says nothing about this.

Meanwhile, the *trieteris* system did not follow the Sun's path with accuracy: "… days and months did not agree with the moon nor the years keep pace with the sun …" (Manitius, 1898: c.8. 34-5), so the final long-term solution was to create cycles of eight years. The *Oktaëteris* (where the sacrifices always were offered to the Gods in the same seasons of the year, by introducing the intercalary months in the third, fifth and eighth years) is thought to have been known in earlier times, and certainly well before the eighth century BC (Ginzel, 1911; Heath, 2004: 289-290). Then, the 16-year and 160-years cycles (Manitius, 1898: 8), Meton's 19-year cycle (Oldfather, 1933: xii, 36) and Callippus' cycle of 76 years all were discussed by Geminus too (Manitius, 1898), and there also was Hipparchus' cycle of 304 years where the mean lunar month is 29 days 12h 44m 2.5s (Heath, 2004, 297).[13]

In Delphi we have noticed how the architecture of the Temple of Apollo was oriented so as to allow observation of the stars, and especially those constellations that were related to the myth of Apollo riding his ‘swan-chariot’ while playing the lyre. It is shown below that from the 8-year period, 484 to 477 BC, it was necessary to add a whole month to the New Moon Calendar every three years in order to achieve a Moon-based calendar that followed as closely as possible the annual seasons. This could be done by observing the position of certain constellations relative to the Temple of Apollo on the days of the equinoxes and the solstices.

Indeed, we have a calendar that always started with the first New Moon after the summer solstice, as long as an intercalary month was added every third year. Translating this to Delphic festivities, it means that the New Year begins with the intercalary month that starts the night when Apollo with his lyre and his swans shines the whole night long over his temple, i.e. on the summer solstice.

When should this intercalary month be added? Here we have two possibilities. The first scenario would be to add this extra month after the eighth month of the calendar (i.e. after Bysios, the sacred month of Apollo’s birthday). This extra month always ends around the day when Lyra reaches the highest point in the heavens at sunrise, on 21 March. In this scenario, the occurrence of a very early month of Bysios (around January) would give the clue to add an extra month that year, that always would come to an end around the date when Lyra reaches the zenith at sunrise (using a luni-solar-stellar calendar). This is illustrated in Table 3.

A second, and perhaps more plausible scenario, would be to add the extra month before Bysios (see Table 4). Here again, if the sacred month of Bysios was very early (in January), an extra month would be added beforehand so that the celebration of Apollo’s birthday always happened around middle of February, when the constellations of Lyra, Cygnus and Delphinus were prominent in the night sky in front of the Temple—the famous pattern of the “… God re-

Table 3: 484 BC to 477 BC First scenario: Adding an intercalary month after Bysios every third year (column in red). Dates calculated with SkyMap Pro11.

DELPHIC CALENDAR MONTHS		YEAR 484 BC	YEAR 483 BC	YEAR 482 BC	YEAR 481 BC	YEAR 480 BC	YEAR 479 BC	YEAR 478 BC	YEAR 477 BC
1.	Apellaios	20/07	09/07	28/06	16/07	05/07	25/06	14/07	03/07
2.	Bucatios	19/08	08/08	28/07	15/08	04/08	24/07	12/08	01/08
3.	Boathoos	17/09	06/09	27/08	03/09	02/09	23/08	11/09	30/08
4.	Heraios	16/10	06/10	25/09	13/10	02/10	21/09	10/10	29/09
5.	Daidaphoro s	15/11	05/11	25/10	12/11	01/11	21/10	09/11	28/10
6.	Poitropios	14/12	04/12	24/11	12/12	01/12	20/11	08/12	27/11
7.	Amalios	13/01	03/01	23/12	10/01	30/12	19/12	07/01	26/12
8.	Bysios	11/02	01/02	22/01	09/02	29/01	18/01	06/02	25/01
Intercalary				20/02			17/02		
9.	Theoxenios	13/03	02/03	20/03	10/03	28/02	19/03	07/03	24/02
10. pios	Endispoitro	11/04	01/04	19/04	08/04	29/03	17/04	05/04	25/03
11.	Heracleios	11/05	03/04	18/05	08/05	27/04	16/05	05/05	24/04
12.	Ilaios	10/06	30/05	16/06	06/06	27/05	15/06	03/06	24/05

Table 4: 484 BC to 477 BC Second scenario (more plausible). Adding an intercalary month before Bysios every third year (column in red).

DELPHIC CALENDAR MONTHS		YEAR 484 BC	YEAR 483 BC	YEAR 482 BC	YEAR 481 BC	YEAR 480 BC	YEAR 479 BC	YEAR 478 BC	YEAR 477 BC
1.	Apelaios	20/07	09/07	28/06	16/07	05/07	25/06	14/07	03/07
2.	Bucatios	19/08	08/08	28/07	15/08	04/08	24/07	12/08	01/08
3.	Boathoos	17/09	06/09	27/08	03/09	02/09	23/08	11/09	30/08
4.	Heraios	16/10	06/10	25/09	13/10	02/10	21/09	10/10	29/09
5.	Daidaphoro s	15/11	05/11	25/10	12/11	01/11	21/10	09/11	28/10
6.	Poitropios	14/12	04/12	24/11	12/12	01/12	20/11	08/12	27/11
7.	Amalios	13/01	03/01	23/12	10/01	30/12	19/12	07/01	26/12
Intercalary				22/01			18/01		
8.	Bysios	11/02	01/02	20/02	09/02	29/01	17/02	06/02	25/01
9.	Theoxenios	13/03	02/03	20/03	10/03	28/02	19/03	07/03	24/02
10. pios	Endispiotro	11/04	01/04	19/04	08/04	29/03	17/04	05/04	25/03
11.	Heracleios	11/05	03/04	18/05	08/05	27/04	16/05	05/05	24/04
12.	Ilaios	10/06	30/05	16/06	06/06	27/05	15/06	03/06	24/05

Table 5: Moon calendar year from 432 BC to 425 BC with an intercalary lunar month (column in red) every third year before Bysios (2nd scenario).

DELPHIC CALENDAR MONTHS	YEAR 432 BC	YEAR 431 BC	YEAR 430 BC	YEAR 429 BC	YEAR 428 BC	YEAR 427 BC	YEAR 426 BC	YEAR 425 BC
1. Apellaios	15/07	05/07	23/07	11/07	30/06	19/07	09/07	28/06
2. Bucatios	14/08	03/08	22/08	10/08	30/07	18/08	07/08	27/07
3. Boathoos	12/09	02/09	21/09	09/09	29/08	16/09	06/09	25/08
4. Heraios	11/10	01/10	20/10	08/10	27/09	16/10	05/10	24/09
5. Daidaphoros	10/11	31/10	19/11	07/11	27/10	15/11	04/11	23/10
6. Poitropios	09/12	29/11	18/12	07/12	26/11	15/12	04/12	22/11
7. Amalios	08/01	28/12	17/01	05/01	26/12	14/01	03/01	22/12
Intercalary		27/01			24/01			20/01
8. Bysios	06/02	25/02	15/02	04/02	23/02	12/02	01/02	19/02
9. Theoxenios	08/03	27/03	15/03	05/03	24/03	14/03	02/03	21/03
10. Endispoitropios	07/04	25/04	14/04	03/04	22/04	12/04	01/04	19/04
11. Heracleios	06/05	25/05	13/05	03/05	22/05	11/05	30/04	19/05
12. Ilaios	05/06	24/06	12/06	01/06	20/06	10/06	29/05	17/06

turning with his lyre in a chariot pulled by swans …" (e.g. see Figure 10). Checking the same pattern 50 years later, during the period 432-425 BC (Table 5), shows a calendar that repeats the same stellar configurations. We get a calendar with twelve months by adding an intercalary month every third year.

Observation of the constellations of Lyra and Cygnus from the Temple of Apollo at Delphi allowed the creation of a lunar-heliacal calendar that ran according to the Moon's phases yet managed to respect heliacal risings and accommodate seasonal phenomena ('saving the phenomena'), which were important, and at the same time was tuned harmoniously to changes in localized natural phenomena, like the flow of gaseous vapors and spring waters.

Therefore, even over a long interval of fifty years this system does not lack accuracy, and maybe only in the very long term would adjustments need to be made. The Temple of Apollo at Delphi certainly had astronomers who were capable of measuring and correcting for it, using their observations of the Moon, the Sun and certain stars. Based in this system they were in a position to give an approximate day when it was appropriate to consult the oracle, or at least show how it could be calculated for the next half millennium.

11 CONCLUSION

The landscape of the Temple of Apollo at Delphi had special astronomical associations. Observations of the constellations of Lyra and Cygnus as they crossed the Delphic sky, along with their sunrise and sunset positions, signified the departure and the return of Apollo from the land of the Hyperboreans. The progressive disappearance of these two constellations in December marked his departure, and their presence at the zenith, directly above the Temple in March, signalled his return and that the time for the delivery of oracles had arrived once more.

The positions in the night sky of Apollo's favorite constellations were fixed by the equinoxes and solstices, so the Temple functioned as a seasonal solar observatory. The seventh day of Bysios, when oracles originally were offered, could be identified when Lyra and Cygnus had risen over the Faidriades and were at the zenith at midnight, which occurred in February or March. Lyra, followed by Cygnus, only was at the zenith when the first rays of sunlight appeared on the vernal equinox or near this date. On other months of the year these constellations crossed the zenith either after midnight (e.g. during summer) or a little later (in autumn), but never at sunrise.

We can summarize the departure and return of Apollo as follows:

1. The only months when the constellations of Lyra and Cygnus were visible for a very short time (weather permitting) and they never reached the zenith was December to March, and during these three winter months Apollo was away, in the land of the Hyperboreans.

2. We propose that he returned to the Temple around the time of the vernal equinox, when Lyra and Cygnus for the first time reached the zenith at sunrise.

3. The absence of Apollo may also have been related to the diminution of vapours in the Temple.

4. Despite the controversy surrounding the ancient Greek calendars, our research using available textural evidence and computed Julian dates shows that the ancient Delphian astronomers sought to maintain a seasonal calendar which reflected the celestial movements of the constellations of Lyra and Cygnus, and they did this by adding an intercalary month every third year, immediately before the start of the eighth lunar month.

Although the exact dates shift, depending on precisely when the intercalary months were introduced, our calculations show that the seventh day of Bysios occurred between the later part of February and 21 March. The configuration of Lyra, Cygnus and Delphinus with Apollo shown here on the red-figure hydria in Figure 10 is consistent with the written sources. The priestess, Pythia, gave oracles on days that were determined by astronomical observations, following the long-established Greek astronomical tradition that is well recorded in ancient texts, in mythology and in art. The Delphic calendar was a luni-solar-stellar one, and apart from its primary ritual functions the Temple of Apollo at Delphi also served as a type of solar observatory.

12 NOTES

1. According to Wikipedia,

   > In Greek mythology the Hyperboreans … were a mythical people who lived far to the north of Thrace. The Greeks thought that Boreas, the North Wind, lived in Thrace, and that therefore Hyperborea was an unspecified region in the northern lands that lay beyond the north wind. Their land, called Hyperborea or Hyperboria – "beyond the Boreas" – was perfect, with the sun shining twenty-four hours a day, which to modern ears suggests a possible location within the Arctic Circle."

   See, also, Bowra, 2000: 401; Macaulay, 1890: Book IV, Chapters 32-36; Mair and Mair, 1921: Hymn to Apollo, Hymn 4 to Delos 275 ff; Oldfather, 1933: Book II, 47-48; Rackham, 1952: 4. 88 ff; West, 1824: 224; etc.
2. The priestess Pythia served as a medium for the God Apollo, who was believed to take over her body and voice during her prophetic trances. The high priest Plutarch described the supposed relationship between Apollo, Pythia, and the natural forces by picturing Apollo as a musician, Pythia as his musical instrument, and the pneuma (spirit), or vapour, as the plectrum or tool which he used to draw sounds from the instrument.
3. In this regard, Flacelier (1938) notes that the value in money for the consultation was eleven times more for a city than for a citizen.
4. Callisthenes was a nephew and pupil of Aristotle whose *Hellenika* started with the King's peace of 386, and covered the 30-year period down until the destruction of Delphi in 356 BC. So Callisthenes must have written his narrative after 356 BC and probably before 335 BC, when he left with Alexander on his expedition to Asia—where he died in about 328.
5. This is one of three ways that subsurface gases can reach the surface of the Earth. The other two are: through porous overburden, or due to artificial opening of a gas-bearing reservoir (e.g. through drilling).
6. This equation is exact only for an ideal gas, and ignores various intermolecular effects. However, it is a good approximation for most gases that are under moderate pressure and temperature.
7. The software used in this paper to simulate the ancient sky at particular dates and declinations were: a) SkyMap Pro Version 11 (SkyMap Pro v11.0.6), Copyright 1992-2005 C.A. Marriott, www.Sky-map.com, b) Stellarium 0.10.6.1, Copyright 2000-2010, Stellarium developers, Free software Foundation, inc., c) Voyager 4.5.7 Carina software, and d) home-made software (Stars & Sundays) to get declinations of stars and days of sunrise (Liritzis and Vassiliou, 2002). Exemplary images were derived from Stellarium that before 1582 automatically gives Julian dates. These were used in conjunction with Google Earth.
8. This is the conventional name given to an Attic Greek vase-painter who is widely recognised as a rival to the 'Kleophrades Painter', one of the most talented vase-painters of the early 5th century BC. (see Beazley, 1964). There is an outstanding collection of their vases in the Museum of Berlin.
9. An 'amphictyony' is a league of neighbouring ancient Greek states sharing a common religious centre or shrine, especially the one at Delphi. An 'amphictyonee' is a member of this league.
10. From Physis = nature, the blossomed season, the spring, or Pysios and verb "to ask for and get informed", as Plutarch preferred (Sieveking, 1972: Moralia 9, 292 E-F; see also Roux, 1976: 71-72; Parke, 1943).
11. For dates of New Moons see: http://eclipse.gsfc.nasa.gov/phase/phasecat.html, which uses proleptic Julian dates extrapolated backwards.
12. For modern constellation equivalents see Hannah (2001: 76-9, 145, 147), and for star charts illustrating each entry, see star charts from ancient excerpts in Diels and Rehm (1904: 104).
13. These astronomical concepts also found other practical applications. For example, Philochorus explains that the original division of the Athenian people into 4 filae, 12 factions and 360 kinships corresponded to the seasons, months and days of the year (see Bekkeri, 1854: 239).

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AURORAE IN AUSTRALIAN ABORIGINAL TRADITIONS

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Abstract: Transient celestial phenomena feature prominently in the astronomical knowledge and traditions of Aboriginal Australians. In this paper, I collect accounts of the *Aurora Australis* from the literature regarding Aboriginal culture. Using previous studies of meteors, eclipses, and comets in Aboriginal traditions, I anticipated that the physical properties of aurora, such as their generally red colour as seen from southern Australia, would be associated with fire, death, blood, and evil spirits. The survey reveals this to be the case and also explores historical auroral events in Aboriginal cultures, aurorae in rock art, and briefly compares Aboriginal auroral traditions with other indigenous groups, including the Maori of New Zealand.

Keywords: Cultural Astronomy, ethnoastronomy, geomythology, Aboriginal Australians, *Aurora Australis*, and Space Science

1 INTRODUCTION

Oral tradition and material culture are the mechanisms by which knowledge about the natural world is transmitted to successive generations of Aboriginal Australians. These traditions contain a significant astronomical component (Haynes, 1992; Johnson 1998; Norris and Hamacher, 2009) useful for navigation, calendars, and food economics (Clarke, 2007; Hamacher, 2012: 71-86; Hamacher and Norris, 2011c). Aboriginal people would move from place to place within their country to seek out food sources and shelter throughout the year. The motions and positions of celestial bodies with respect to the surrounding landscape were of great importance to this end, signaling the changing seasons and the availability of particular food sources. For example, the heliacal rising of the star Fomalhaut signals the coming of the autumn rains to the Kaurna people of the Adelaide plains (Hamacher, 2012: 79-82). Another example is the acronychal rising of the celestial emu (traced out by the dust lanes of the Milky Way between Crux and Sagittarius) signaling the start of the emu breeding season, when emu eggs are used as a food source (Hamacher, 2012: 71-75; Norris and Hamacher, 2009). Astronomical traditions also contain a social component (Johnson, 1998). Celestial objects serve as mnemonic devices for remembering laws and customs and inform traditions regarding marriage classes, totems, and ceremonies (Clarke, 2007; Hamacher, 2012; Fuller et al., 2013).

The study of the astronomical knowledge and traditions of Aboriginal and Torres Strait Islander people—part of the inter-discipline of *cultural astronomy*—is a growing subject of public and academic interest in Australia. One component of ongoing research in Australian cultural astronomy involves the investigation of transient celestial phenomena. This includes studies of variable stars (Hamacher and Frew, 2010), eclipses (Hamacher and Norris, 2011a), comets (Hamacher and Norris, 2011b), meteors (Hamacher and Norris, 2010) and cosmic impacts (Hamacher and Norris, 2009; Hamacher and Goldsmith, 2013) in Aboriginal traditions.

The main goal of this research paper is to investigate the knowledge and traditions relating to the *Aurora Australis*. This includes understanding how the phenomenon was and still is perceived by Aboriginal people; how knowledge of aurorae are incorporated into astronomical traditions; and how the aurora is represented in material culture (i.e. artefacts or rock art).

We begin by discussing the background theory and methodology of this study, followed by a discussion of the physics of aurorae and the solar cycle. We then discuss how previous studies of transient celestial phenomena can be combined with the physical properties of aurorae to predict how Aboriginal people might perceive this phenomenon. Next, we explore the Aboriginal traditions related to aurorae, including explanations of the phenomenon. We also investigate oral traditions for historical auroral events to determine if Aboriginal people noted or predicted the reoccurring frequency and intensity of aurorae over the 11-year solar cycle. We then search for possible representations of aurorae in rock art and discuss how Aboriginal auroral traditions compare with those of the Maori of New Zealand and other indigenous groups that live in or near auroral zones.

2 THEORY AND METHODOLOGY

The cross-disciplinary field of cultural astronomy, including the sub-disciplines of archaeoastronomy and ethnoastronomy, is a social science informed by the physical sciences; it is a science asking social questions (Ruggles, 2011). There is currently no all-encompassing theoretical framework for cultural astronomy and attempts to develop one have thus far been unsuccessful (Iwaniszewski, 2011). Cultural astronomy currently relies on the methods and theories of the academic disciplines from which it draws. Generally, these include archaeology, anthropology and history. In this paper we draw from historic, ethnographic, linguistic and archaeological records. We reviewed the literature for any sources containing references to aurorae (including 'southern lights' or 'sky glow') in

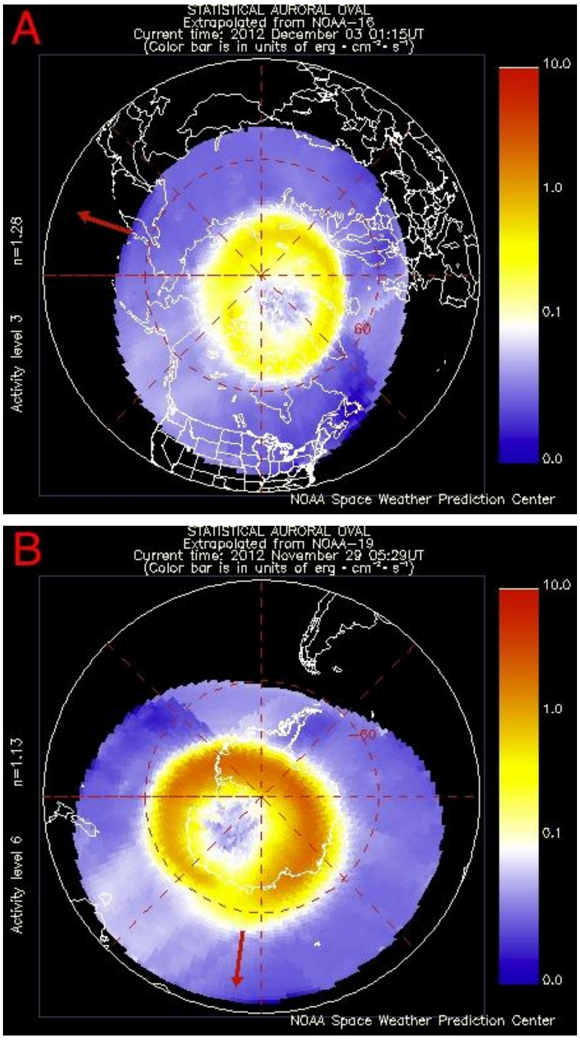

Figure 1(a) (upper): A snapshot of the extent and position of the auroral zone in the northern hemisphere at 23:06 UT on 2 December 2012. Figure 1(b) (lower): A snapshot of the southern auroral zone at 05:29 UT on 29 November 2012. Both were relatively quiet days in terms of magnetic disturbance. Under more disturbed conditions the auroral zones are thicker and displaced equator-ward. The plots are derived from measurements obtained from the NOAA POES satellite showing the power flux of auroral activity (0 to 10 ergs cm^{-2} sec^{-1}). Plots taken from the POES Auroral Activity page on the National Weather Service's Space Weather Prediction Centre, NOAA. URL: http://www.swpc.noaa.gov/pmap/

Aboriginal cultures. These sources included ethnographies, archaeological surveys, historical documents, stories, songs, magazines, newspaper and journal articles, audio and video sources, reputable web sites, post-graduate theses, rock art and other artistic forms.

Since this research addresses both Western science and Aboriginal traditions regarding aurorae for a wide audience of readers, it is important to describe the phenomenon from both perspectives. For this reason, a brief, non-mathematical description of auroral physics is provided in the next section. This information is then combined with previous cultural studies of transient celestial phenomena to predict how Aboriginal people, as reported in the literature, perceive aurorae.

3 THE PHYSICS OF AURORAE

Aurorae are light displays, generally seen at high (i.e. polar) or middle latitudes, caused when energetic charged particles in near-Earth space bombard the atmosphere, increasing the energy of oxygen and nitrogen molecules, which then emit visible light. The entire process is governed by solar activity, and in particular the solar wind, which normally is blocked from reaching the Earth's surface by the Earth's magnetic field. However, due to the configuration of the magnetic field, solar wind energy can access low altitudes near the Earth's magnetic poles, where magnetosphere particles (mostly electrons and protons) can be accelerated along field lines into the upper atmosphere (>80 km above sea level). These particles impact with and energize oxygen and nitrogen molecules, which then release photons (particles of light). The photons are released in discrete packets of energy, which correspond to different colours of the electromagnetic spectrum. Oxygen atoms, liberated from their molecules by collisions, are excited to higher energy levels. They give up energy by going back to lower levels (de-exciting) either in large steps, with the emission of green light, or in smaller ones, with emission of any of several wavelengths in the red. Nitrogen emissions are due to nitrogen molecules, either neutral or ionized, giving up energy at any of a number of wavelengths in the red, blue or violet.

The colour of an aurora to an observer on the Earth's surface is dependent on the aurora's altitude. The time for oxygen ions to emit green light is only three seconds, while the time needed to emit red light is up to two minutes. Oxygen is more abundant in the upper atmosphere where collisions between molecules are low. Because of this, red colours dominate in the lower atmosphere, where the air density is higher and collisions are more frequent.

Aurorae are referred to as *Aurorae Borealis* in the northern hemisphere and *Aurorae Australis* in the Southern Hemisphere. Although aurorae technically can be seen from many places on the Earth, they tend to be most active in oval ring-shaped regions located in each hemisphere about 10°-20° equator-ward from the Earth's magnetic poles. The South Magnetic Pole was

~150 km off the coast of Antarctica towards Tasmania (64.497° S, 137.684° E) in 2007, and the North Magnetic Pole was ~740 km north-west of Ellesmere Island in northern Canada in 2012 (85.9° N, 147.0° W) (NOAA, 2012). The magnetic poles are not antipodal, and they wander at a relatively high rate: currently 10-15 km yr^{-1} in the south and 45-62 km yr^{-1} in the north (Zvera, 2012).

The width and location of the auroral zones varies with the intensity of disturbance of the geomagnetic field, and the location over time of the wandering geomagnetic poles. In the Northern Hemisphere, the auroral ring generally covers Alaska, Canada, northern regions of the United States, northern Europe and Siberia (Figure 1(a)). In the southern hemisphere, the auroral zone generally covers Antarctica and the southern fringes of Australia and New Zealand (Figure 1(b)). Under average, magnetically-undisturbed conditions, observers from southern Australia and much of New Zealand only have a slight chance of witnessing an aurora (Bond and Jacka, 1962; McEwan, 2006).

The intensity of the solar wind and hence the rate and level of magnetic disturbance at the Earth depends on the Sun's magnetic activity. This activity waxes and wanes during the solar cycle, the duration of which is approximately 11 years. Periods of high solar activity are marked by an increase in sunspots, which denote a rise in the Sun's magnetic activity. This increase in activity leads to larger and more frequent solar eruptions, such as coronal mass ejections, causing more frequent and intense magnetic storms at the Earth. During solar maxima, aurorae are therefore more frequent and intense. Major coronal mass ejections can cause aurorae to be visible from areas of the Earth that rarely witness such a phenomenon. For example, a major solar event on the night of 25-26 September 1909 caused aurorae that were visible in both hemispheres, with aurorae visible as far north as Queensland (Duncan-Kemp, 1952: 44). The physics of solar-terrestrial magnetism and aurorae are more complex than is described in this section, and curious readers should explore Carlson and Egeland (1995), Chapman (1970) and Jones (1974) if they wish to learn more.

4 PREDICTIVE ETHNOASTRONOMY

As listed above, on page 207, we have surveyed a range of transient celestial phenomena in Australian Aboriginal cultures, and each of these studies revealed similarities in the ways these types of phenomena are incorporated into Aboriginal traditions. In a majority of cases, transient astronomical events were seen negatively and often were associated with evil spirits, black magic, or omens of war, death and disease. Studies like these help cultural astronomers in their efforts to develop a theoretical base for the discipline. These studies are useful for informing us on how humans think about the natural world and how they develop knowledge to explain it.

By combining these studies and taking into account the physical properties of aurorae it may be possible to predict how people interpreted this phenomenon and which groups of people would likely have traditions about it. Six primary attributes relate aurorae to human perception:

1. The location on the Earth from which aurorae are visible;
2. The probability of witnessing an aurora;
3. The direction from which aurorae are visible to an observer;
4. The physical appearance of an aurora;
5. The colour of the aurora; and
6. The intensity of the aurora.

Technically, aurorae can be seen from many places on the Earth, but seeing one from an area far from the auroral zone is extremely rare. Since the southern fringes of continental Australia, Tasmania, and the South Island of New Zealand are near and under certain conditions within the edges of the southern auroral zone, we expect that aurorae will be incorporated into the traditions of indigenous communities in these regions. Since aurorae are primarily seen toward the south, we expect that indigenous knowledge of this phenomenon relates to this direction. In many Aboriginal cultures, the direction of an astronomical phenomenon is significant. For example, meteors denote the direction of an enemy in the traditions of Aboriginal people near the Tully River, Queensland (Roth, 1984: 8) and to the Ngarigo people of south-eastern New South Wales (Howitt, 1904: 430). To the Arrernte of the Central Desert, the tail of a comet points toward the direction of a neighboring community in which someone has died (Spencer and Gillen, 1899: 549).

The appearance of aurorae is broken into two basic categories: diffuse and discrete. As the name suggests, diffuse aurorae lack clear patterns and generally appear as a glow. They are formed when interactions between wave-particles scatter electrons parallel to the magnetic field lines. Discrete aurorae, on the other hand, appear in various shapes, such as draperies ('curtains'), rays or arcs. They are formed due to electrons accelerating parallel to the Earth's magnetic field lines in the atmosphere. Both diffuse and discrete aurorae can appear to move, with draperies being among the most obvious and dramatic examples (see Livesey, 2001). We might expect that oral tradition describe these different types of aurorae.

Unlike the Northern Hemisphere, no inhabited land lies under the highest flux areas of displays visible from Australia. The aurorae visible from Australia tend to be high altitude and are generally visible lower on the horizon (i.e. not overhead). Since high altitude aurorae are dominated by oxygen-red (as discussed in the previous section), a majority of aurorae visible from Australia are reddish in colour (Figure 2). However, in low light conditions, the human eye cannot discern colour and the aurorae appear a faint white. This is different from the bright white displays that are visible under very active conditions. Aurorae can appear to be a range of colours, including red, pink, orange, green and white. Aurorae visible from lands under the higher flux regions of the northern auroral zone tend to reflect this range of colors, particularly white and green, and can be seen directly overhead. From studies of transient celestial phenomena in Aboriginal traditions, red was often associated with blood, fire and death. For example, the red colour of the Moon during a total lunar eclipse was commonly associated with blood, fire and evil (Hamacher and Norris, 2011a). In Lardil traditions on Mornington Island, red- or blue-coloured meteors were associated with sickness, while white meteors were signs of good luck (Hamacher and Norris, 2010). In Aboriginal cultures near Ooldea, South Australia, the red stars Betelgeuse and Aldebaran signified fire that was cast between celestial beings engaged in battle (Hamacher, 2012: 17-18). Therefore, we expect accounts of aurorae in Aboriginal traditions to relate to blood, fire, war and death.

Aurorae also vary in visible intensity. Some are faint to the naked eye, while sometimes under very active conditions they may be bright enough to enable an observer to read a newspaper at night. We therefore expect that peoples' reactions to bright aurorae are more severe than fainter aurorae. If they relate to negative attributes, such as blood or fire, intense (bright) aurorae would probably induce a reaction of fear and panic more so than aurorae that are of low intensity. While we are confident that not all perceptions of aurorae will be negative, we expect this to be largely the case, based on previous studies of transient celestial phenomena in Aboriginal traditions (c.f. Hamacher and Norris, 2009; 2010; 2011a; 2011b).

A survey of auroral traditions from across the world (e.g. Eather, 1980; Falck-Ytter, 2000; Section 9 of this paper) suggests that in areas where aurorae are a frequent occurrence, they possess benign attributes. But in areas where they are less frequent, they tend to be associated with evil, omens and death. Since far southern Australia is at the edge of the auroral zone, we expect aurorae to be generally negative in perception since they are infrequent.

Figure 2: An *Aurorae Australis*, as seen from Victoria, Australia, on the night of 22 January, 2012 (courtesy: Alex Cherney).

5 AURORAE IN ABORIGINAL ASTRONOMICAL TRADITIONS

We analysed the sources of data mentioned in Section 2 and found they reveal major themes in the perceptions of aurorae, as predicted in Section 4. Not all views were associated with negative attributes, but most were associated with blood, fire and death. Aurorae cause great fear in the people who witness them and in some communities they are taboo—only to be viewed and interpreted by initiated elders. Interpretations of auroral displays vary widely, even within the same communities.

Stories or accounts of aurorae were found in all Australian states and territories (Figure 3), but most of the accounts and oral traditions are from Aboriginal groups in Victoria and South Australia. All accounts were from regions south of the Tropic of Capricorn. The data are broken down by theme in Subsections 5.1-5.3. This study produced 26 literary sources representing five unidentified Aboriginal groups, and thirteen identified groups. Of the five unidentified groups, three were from Tasmania and one each from Queensland and New South Wales. The Queensland community is probably Yarluyandi, but this is not certain.

Some of the accounts of aurorae were vague or did not attribute either positively or negatively to aurorae. For example, the Nuenonne people of Bruny Island, Tasmania, call the Aurora *nummergen* (Wilson, 1999), but no associated stories or interpretations of this name are provided. A brilliant, multi-coloured aurora visible from Hobart, Tasmania, on 4 September 1851 made a crackling sound that was described by the local Aboriginal people as similar to snapping their fingers (Anonymous, 1877).

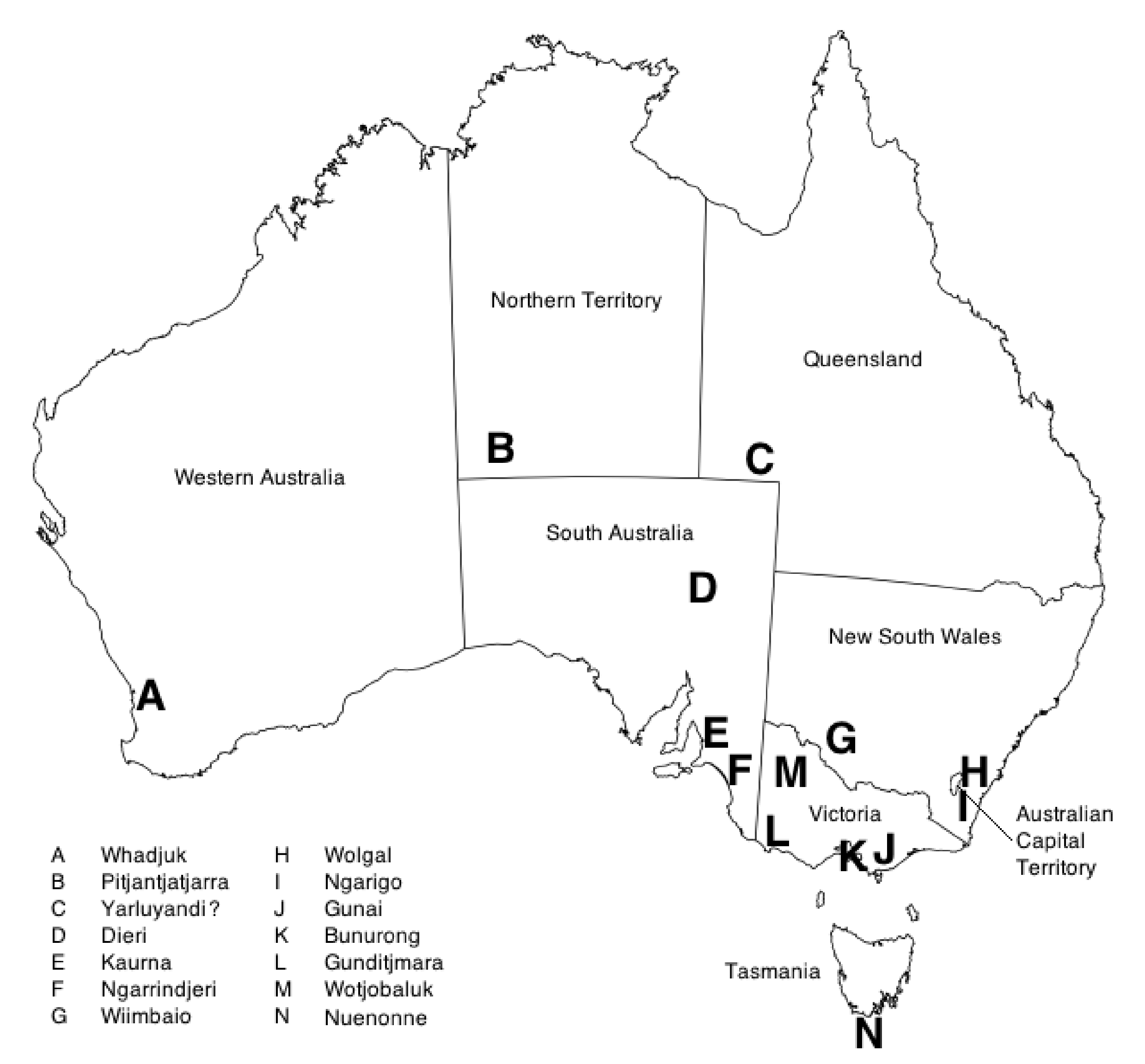

Figure 3: Places in Australia from which Aboriginal traditions describing aurorae were found. Accounts of aurorae are found in all States and Territories, although they are restricted to the southern half of the continent, consistent with the rarity of these events at lower latitudes.

5.1 Fire, Smoke and Ash

Since aurorae generally appear red in the sky as seen from Australia, they are commonly associated with fire. This association may include flames, smoke or ashes. For example, the Gunditjmara people of coastal western Victoria called aurorae *Puae buae*, meaning 'ashes' (Dawson, 1881: 101). The Gunai of Gippsland, eastern Victoria, perceived aurorae as bushfires in the spirit world (Massola, 1965: 213). They also attributed them to the fire of an ancestral hero warning of a coming catastrophe (Worms, 1986: 112). When the Dieri people of Cooper's Creek, South Australia, saw an auroral display in 1869, they claimed it was a *Kootchee* (an evil spirit) creating a large fire (Smyth, 1878: 458). Similarly, the Narringeri people of Encounter Bay, South Australia, interpreted an aurora seen over Kangaroo Island (Karta) as the campfires of spirits in the 'Land of the Dead', located in the heavens (Tindale, 1974). The Narringeri considered Kangaroo Island to be the land of the dead (Berndt, 1940:182; Tindale and Maegraith, 1931). The Island was uninhabited when the first European, Matthew Flinders, arrived, but archaeological data revealed that Aboriginal people lived on the Island as long ago as 16,000 years BP but mysteriously disappeared some 2,000 years ago (Draper, 1987).

The solar eruption from 25-26 September 1909 caused bright aurorae that were visible across the northern and southern hemispheres (Silverman, 1995). On 24 September, Duncan-Kemp (1952: 44) described the appearance of bright aurorae visible from Windorah in far southwest Queensland. A group of Aboriginal people (possibly the Yarluyandi or Karuwali people) said the aurorae were the 'feast fires' of the *Oola Pikka*—ghostly beings who spoke to the people through auroral 'flames'. Only male elders were permitted to view the display and interpret their messages, as tribal law forbade women or uninitiated men from seeing the sacred lights. When aurorae appeared in the sky, the Aboriginal women would turn away.

Several accounts from the Gunai people describe aurorae as a physical manifestation of a powerful sky deity's anger. This seems to be slightly different than the 'bushfires in the spirit world' as described by Massola (1965: 213). The accounts describe the deity as *Mungan Ngour. Mungan* set the rules for the initiation of boys into manhood and put his son, *Tundun*, in charge of the ceremonies. Information about male initiation ceremonies was restricted to men, and was taboo to women. A person in the community revealed initiation secrets to the women, greatly angering *Mungan*. In a rage, he cast down a great fire to destroy the Earth, which the people saw as an aurora.

According to Howitt (1904: 430), the appearance of *Mungan's* Fire caused a reaction of fear, prompting the people to shout "… send it away; do not let it burn us up!" As they yelled this, they swung a dead hand, called a *bret*, at the portent. The hand served as a charm and a warning device. When a relative or close friend passed away, his or her hands were removed then smoked and dried over a fire. They were then suspended by a cord of possum fur, fingers down, around the neck over the left arm. The *bret* was believed to pinch or tap the wearer whenever danger approached. The wearer would then face in different directions, holding the *bret* in front of him. When it shook violently the man knew the direction of the danger.

Massola (1968: 162) explained that *Mungan's* fire caused everyone to turn on each other; men speared one another and killed their wives, while mothers killed their children. The aurora filled the whole of the sky from the land to the sky and was followed by a tsunami that rushed over the land and drowned most of the people (Thomas, 1906a: 219). Those who survived became the Muk-Kurnai, the 'Superior Animals'. Tundun, the Great Man's son, and his wife, became porpoises. The Great Man then went to the sky. After his anger subsided, he allowed the men to again carry on the ceremonies on the condition that they not tell women initiation secrets. If his laws and customs are disregarded, he shows his anger by lighting up the sky at night with the fires of the aurora (Keen, 2004: 214-215).

Thomas (1906b:143) noted that an auroral display caused the Gunai people to engage in temporary promiscuity. To avert the evil of *Mungan's* fire, elder men would exchange wives in a practice called *beamu* (Keen, 2004: 182). Howitt (1891: 101) also noted this practice, explaining it as a reversion to the ancient custom of group marriage. This practice was also found among the Dieri people (Montagu, 2004: 219). Auroral traditions among the Bunurong people of the Mornington Peninsula, south-east of Melbourne, are similar to the Gunai (McCrae, 1934).

A final account that attributes aurorae to fire is from the Pitjantjatjarra people near Uluru (Ayer's Rock) in the Northern Territory. The story describes hunters breaking a taboo by cooking a sacred emu (*kalaya*). They saw smoke rise to the south, towards the land of *Tjura* (a Pitjantjatjarra word meaning 'glowing light visible at night'; Goddard, 1992: 160). This was the glow of the *Aurora Australis*, which the Pitjantjatjarra believed were poisonous flames (Harney, 1960: 74). In the story, the flames served as a portent of punishment to the hunters.

5.2 Blood and Death

The appearance of an unexpected transient event in the sky is often met with fear (e.g. Hamacher and Norris, 2010; 2011a; 2011b). The appearance of a red aurora in the southern evening skies as seen from the central-western coast of Tasmania caused astonishment and incited shouting by Aboriginal people (Anonymous, 1838). The Whadjuk people in Perth had a similar reaction on the night of 11 July 1838 when a bright auroral display was visible (Anonymous, 1838). Similar to the appearance of comets and meteors, an auroral display was an omen to the Dieri people that a person in a neighboring community had condemned someone to death (Frazer et al., 1895: 175-176). Thus, the appearance of an aurora—as with many transient phenomena—was met with great fear.

To the Dieri people, the *Aurora Australis* is called *pilliethillcha*. Whenever an auroral display is seen, it causes great fear and anxiety. The Dieri believe it is a warning from the devil (Kootchie) to keep a strict watch, as an armed party (*pinya*) is killing someone for breaking traditional laws. Aboriginal people in the camp then huddle together, when one or two step out and perform a ceremony to charm the Kootchie (Gason, 1879: 297). Fear of an aurora was developed and utilised to control behavior and social standards. Breaking traditional laws would result in a *pinya* coming to kill the lawbreakers when they least expect it.[1]

The red colour of most aurorae visible from Australia was commonly associated with blood and death, as anticipated in Section 4. Auroral displays represented blood that was shed by warriors fighting a great battle or by massacre victims rising to the sky. This view was shared by Aboriginal people in the Riverine areas of New South Wales and South Australia, the Ngarigo and Wolgal people near Canberra, the Wotjobaluk people of north-western Victoria (Gibbs, 1974: 50; Howitt, 1904: 430) and the Dieri people (Gason, 1879: 297).

5.3 Spirits and Omens

Smith (1913) records accounts from two unspecified Aboriginal groups that attribute aurorae to the spirits of ancestors dancing in the sky or a portent of trouble. Aurorae served as omens of disease to the Wiimbaio near the junction of the Murray and Darling Rivers (Thomas, 1906b: 143). A bright pink aurora visible from Adelaide on 7 February 1840 (Anonymous, 1840) was believed to be the harbinger of a plague. The nearby Putpa, Wirra, and Marimeyunna clans believed aurorae were caused by sorcerers from the north and were an omen (Schurmann, 1987: 86). The Ngarrindjeri people of Point McLeay mission, South Australia, shared a similar view. A combination of rare astronomical phenomena caused fear and anxiety to the local Ngarrindjeri people in 1859. In August of that year, an aurora was visible around the time of a lunar eclipse (Anonymous, 1859; Taplin, 1859: 2 September 1859;). The Ngarrindjeri believed this signaled the arrival of dangerous spirit beings they dubbed 'wild blackfellows'. These were Aboriginal people living outside the areas of European settlements (Merlan, 1994). Like their Wiimbaio neighbors, the Ngarrindjeri considered 'wild blackfellows' to be great sorcerers with supernatural powers and were greatly feared.

6 HISTORICAL AURORAL EVENTS

Aurorae and sunspot cycles have been recorded throughout human history, particularly in eastern Asia (Keimatsu, 1970-1976; Lee et al., 2004; Matsushita, 1956; Stephenson and Willis, 1999, 2008; Willis and Davis, 2014; Willis and Stephenson, 2000, 2001; Willis et al., 2005, 2007). Since there are no written records from Australia prior to colonisation, it is difficult to connect historical aurorae in antiquity with Aboriginal traditions since the latter do not necessary record a single point in linear time. It is probable that aurorae visible in antiquity were the basis, or re-emphasis, of auroral traditions in Australia. However, since colonisation of Australia by the British in 1788, historical records of auroral events and written accounts of Aboriginal traditions can be matched.

These historical records revealed six auroral events noted by Aboriginal people. They occurred during major solar eruptions in 1838, 1840, 1851, 1859, 1869 and 1909. Each of these years coincides with a peak in the solar cycle (Figure 4). A bright auroral display on 11 July 1838 was visible from Tasmania to Perth (Anonymous, 1838) and a bright pink aurora was visible from Adelaide on 7 February 1840 (Anonymous, 1840). An aurora seen on 4 September 1851 from Hobart made sounds the local Aboriginal people described as being similar to snapping fingers. The aurora visible on 2 September 1859 from the Point McLeay mission, South Australia (Taplin, 1859: 4-7 June) coincided with the strongest geomagnetic storm ever recorded (dubbed the '1859 solar super-storm' or 'Carrington Event'). The bright aurorae witnessed by the Dieri people in 1869 (Smyth, 1878: 458) were part of the many auroral displays visible across the globe in April/May and September 1869 (Murray, 1869; Prowde et et al., 1869; Tebbutt, 1870; Wintle, 1869). Major solar eruptions peaking on 25-26 September 1909 produced bright, multi-coloured aurorae visible as far north as southern Queensland (Duncan-Kemp, 1952: 44). It is worth noting that all three auroral displays occurred during the month of Sep-

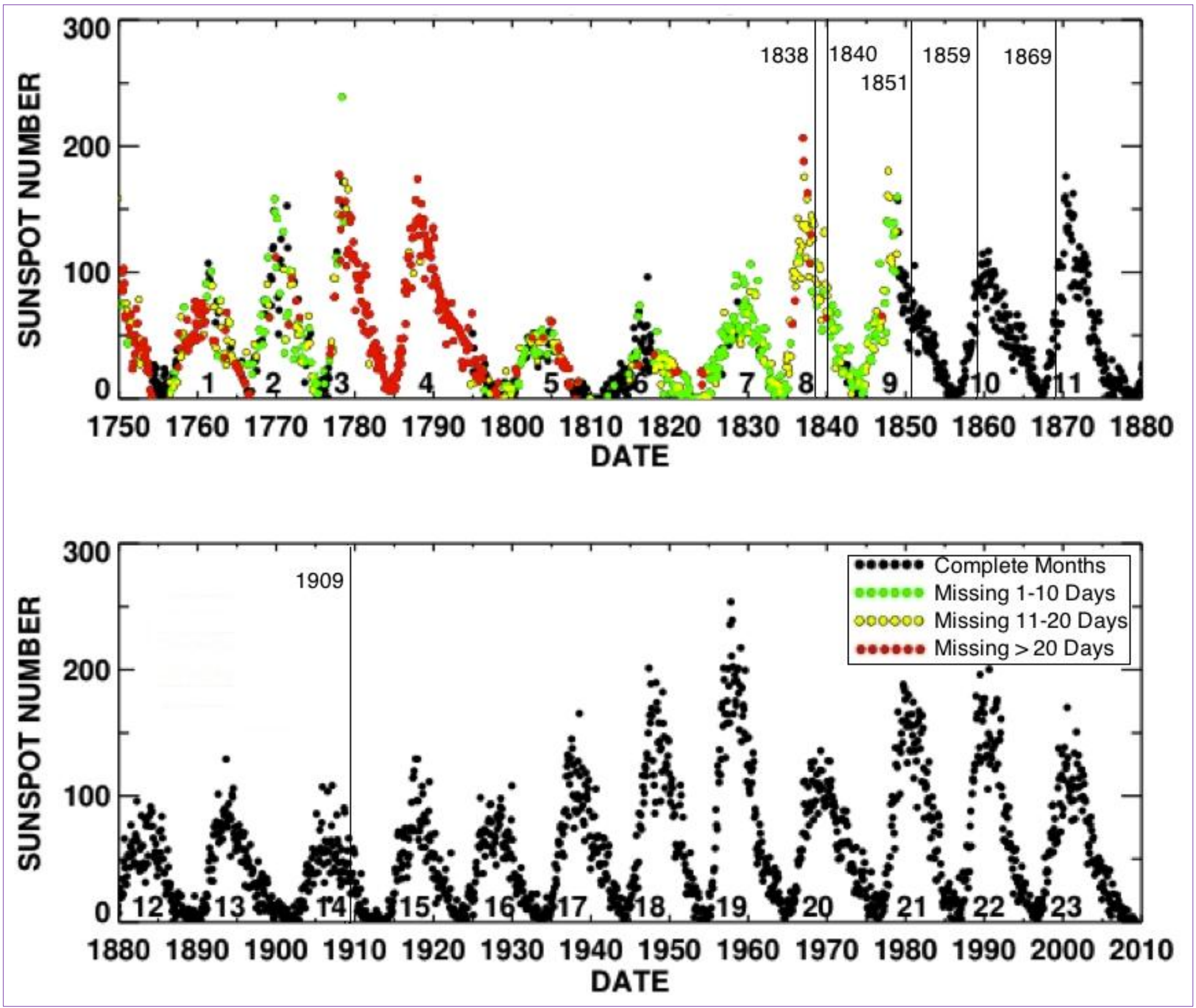

Figure 4: The number of sunspots observed between 1750 and 2010. After Hathaway (2010: Figure 2). The vertical lines show the years when historic aurorae were described in Aboriginal culture from Section 6.

tember. This accords with the general increase in geomagnetic disturbances near equinoxes (see below). Since the auroral zone only barely covers the southern edge of Australia, the discovery that historical literature only records accounts of aurorae in Aboriginal traditions during peaks in the solar cycle is to be expected.

It should be noted that a significant geomagnetic storm led to strong aurorae visible around the world on 4-5 February 1872 (Silverman, 2008). Accounts from Australia describe brilliant aurorae in Perth, Adelaide, and Melbourne on these days. While the aurorae may have been visible at more northerly latitudes (ibid.), no accounts were recorded from more northerly latitudes in the TROVE newspaper database. There were no recorded accounts of Aboriginal perspectives of the aurorae, although it is almost certain that Aboriginal people would have seen them in the skies.

7 ABORIGINAL RECOGNITION OF THE 11-YEAR SOLAR CYCLE?

Aurorae are connected with the solar sunspot cycle and are more frequent and intense during solar maxima, which occur every 11 years. Since Aboriginal people were careful observers of natural phenomena, we might expect to find a description of this cycle in Aboriginal traditions.

A survey of the literature revealed only one case of Aboriginal people recording the solar cycle in their traditions. According to Bodkin (2008: 70) the Dharawal people south of Sydney used the appearance of the aurora to announce the start of the 11-12 year Mudong weather cycle. The aurorae appear during the annual season of *Ngoonungi*. *Ngoonungi* is the period of gradual warmth, during September and October. The appearance of aurorae signalled the start of the first of the eight Mudong cycle phases: *Gadalung Burara*—the hot and dry phase. This season can last up to 20 complete lunar cycles ('20 moons') but no more (Bodkin, 2008: 72). In an interview with CNN in 2003,[2] Bodkin claimed that the 11-year Mudong cycle started in 2001 with the appearance of aurorae. This coincided with the peak in sunspots and the start of the last solar cycle (Figure 4). Bodkin stated that the aurorae are seen less frequently because of increasing light pollution.

In some media interviews following the publication of her book on Dharawal seasons and climatic cycles,[3] Bodkin claimed that during October aurorae were visible in the western skies as well as to the south. Historical records describe aurorae visible to the west from the Hunter Valley north of Sydney (Anonymous, 1846). It is worth noting that geomagnetic storms tend to peak in the months around the equinoxes, in particular March-April and September-October (Papitashvili et al., 2000; Stamper et al., 1999). This is when both hemispheres of the Earth are most uniformly exposed to the solar wind and its embedded interplanetary magnetic field. Accordingly, many of the aurorae identified in Aboriginal traditions were linked to auroral displays during, or around, these months, particularly September.

A higher than normal rate of observed aurorae, especially those seen from the Sydney region, could be useful for recognising the 11-year solar cycle. There has been much discussion on whether climate follows an 11-12 year cycle in phase with the solar cycle (e.g. see Haigh, 2007; Weart, 2013). Such an effect has not been established and is a topic of current research.

8 REPRESENTATIONS OF AURORAE IN ROCK ART

Clear representations of aurorae in Australian rock art have not been reported in the literature. Plausible, but unconfirmed, representations of aurorae in Australian rock art are reported from a group of researchers led by Anthony Peratt (Peratt, 2003; Peratt et al., 2007; Van Der Sluijs and Peratt, 2010). Peratt and his colleagues claim that in antiquity, intense solar activity directed a significant amount of plasma energy towards the Earth, interacting with the Earth's magnetic field and causing brilliant aurorae that would have been seen worldwide. Based on the visible shapes derived from computer simulations of these proposed auroral events, Peratt and his colleagues then compared the auroral shapes to rock art motifs from around the world. The team noted several motifs that are evident in rock art around the world and suggest that they depict this auroral display (Figure 5). The interested reader is directed to the papers of Peratt and colleagues for an in-depth explanation and analysis of this work. At this stage there is no clear evidence that any rock art motifs in Australia represent these auroral displays or that the artistic motifs described by Peratt and colleagues represent these proposed auroral events. Without oral traditions or ethnohistorical evidence to explain the meaning of artistic forms, these motifs are open to interpretation.

It is worth noting that auroral displays are affected by increases and decreases in the Earth's magnetic field. The magnetic poles reverse on long timescales (450,000 years on average), with the magnetic field decreasing significantly before reversing. This could result in significant auroral displays. The last geomagnetic reversal occurred 780,000 years BP, but recent evidence indicates that an excursion occurred approximately 41,000 years BP (Nowaczyk et al., 2012). This is within the period of human habitation of Australia, although we urge caution in stretching these claims too far.

9 VIEWS OF AURORAE IN OTHER CULTURES

Aurorae are included in the oral traditions and mythology of numerous cultures across the world (see Akasofu, 1979; Holzworth, 1974; Stothers, 1979). To the Inuit of the Hudson Strait in the far north of Quebec, Canada, aurorae represented the torches of spirits who were leading the souls of the recently-deceased to paradise (Holzworth; 1974). The Inuit of the Coronation Gulf in eastern Nunavut, Canada, perceived aurorae as a manifestation of the spirits that brought good weather (Weyer, 1969: 243). In Point Barrow, Alaska, aurorae were greatly feared and the people armed themselves for protection (ibid.). Associations with death, spirits or battles were found among the people of Scotland (Mackenzie, 1935: 222), Siberia (MacCulloch, 1964: 398), Finland (ibid.), and Estonia (ibid.).

The Maori of New Zealand call aurorae *Tahunui-a-rangi*, which roughly translates as 'great glowing sky' (Reed, 1999:194-195; cf. Moorfield, 2011). Descriptions of aurorae in Maori traditions are numerous. For example, a Maori man from Wanganui on the south-western coast of the North Island was interviewed in 1869 and explained that when their ancestors migrated to New Zealand, one *waka* (canoe) continued sailing south towards the horizon where aurorae were seen, settling a land in the far south (Best, 1955: 71). The Maori see aurorae as a reflection of the fires cast by these ancestors, which signal their presence. Another story describes aurorae as *Maru*, the name of a Maori war-deity (Craig, 1989: 160). According to Kingsley-Smith (1967), "… anyone going on the war-path and seeing an aurora would not continue on his way, for such conduct would have been considered suicidal."

10 CONCLUDING REMARKS

Accounts and descriptions of aurorae are found in the oral traditions of Aboriginal Australians

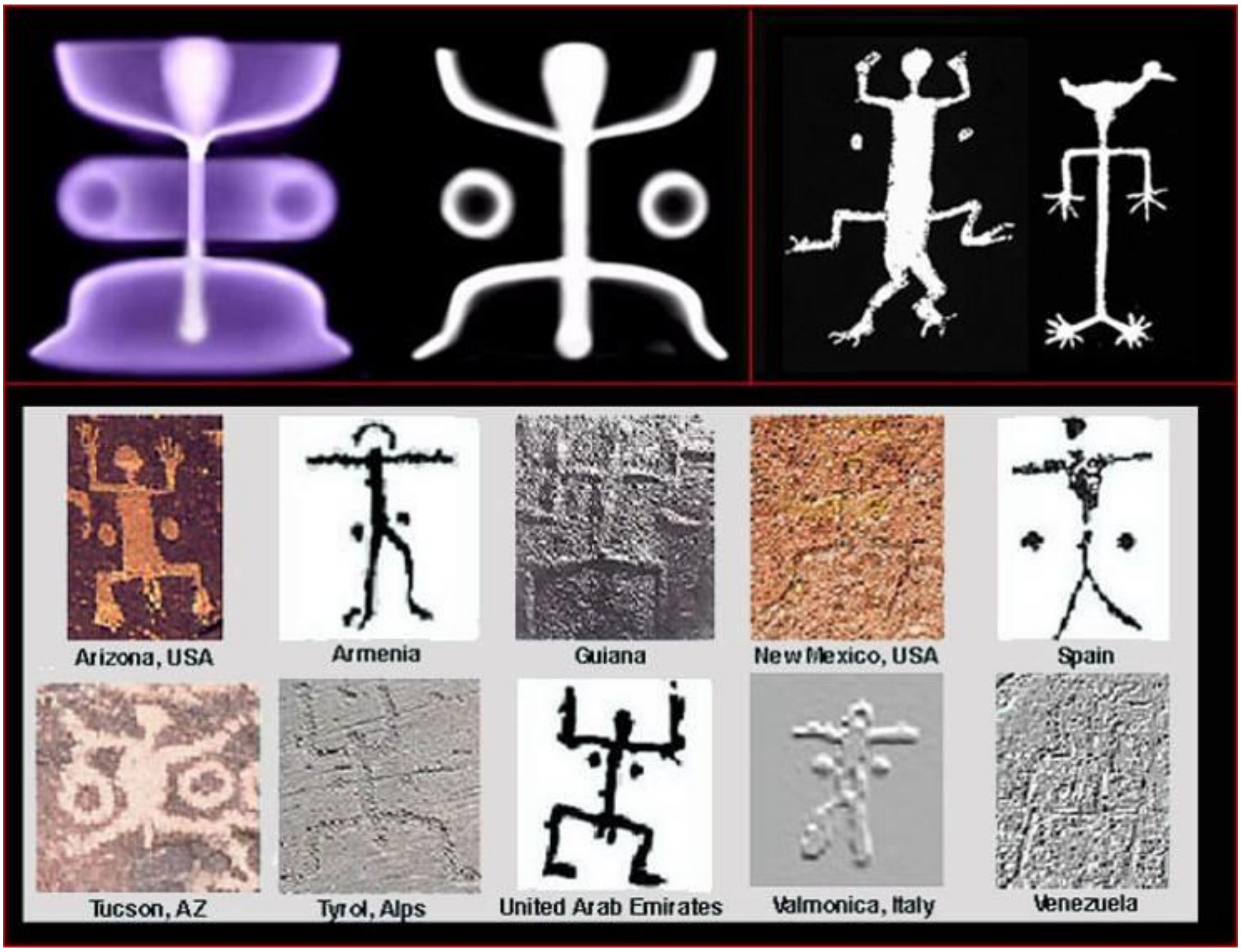

Figure 5: A computer simulation of one of the shapes caused by the proposed high-intensity auroral display (top left), an interpretation of what it may have looked like (top middle), and various rock art motifs that Peratt and his colleagues believe may represent this phenomenon (top right, bottom). Similar motifs are found in Australia (e.g. McCarthy 1976), although any connection to the proposed auroral display is speculative (after Peratt, 2003).

across the southern half of the continent. Significant solar eruptions caused auroral displays that were visible as far north as southern Queensland, but no examples are recorded from areas north of the Tropic of Capricorn. As predicted in Section 4, most Aboriginal accounts describe aurorae in negative terms and associate them with blood, death, fire or evil spirits. Aurorae are also associated with a southerly direction. This is due largely to their generally reddish appearance on the southern horizon. A comparison of cultural interpretations of aurorae from other parts of the world, particularly New Zealand, showed a similar association.

Aurorae play an important role in the oral traditions of Aboriginal Australians. Aurora traditions provide us with a more complete understanding of Aboriginal sky knowledge and cultural astronomy. Aboriginal views of the phenomenon are similar to those of the Maori of New Zealand and other cultural groups across the world.

11 ACKNOWLEDGEMENTS

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12 NOTES

1. An account of retribution from a sky deity for careless behavior is reported by Berndt (1947). A Wiradjuri man (central New South Wales) claimed that when someone is careless, Kurikuta would come down from the sky, turning the night into day. Berndt suggests this is a reference to an aurora. Kurikuta, an emu, was the wife of the sky deity *Baiame*. She had a quartz body and when she came down from the sky, she was seen as a brilliant flash of light that made a great thunderous sound (Berndt, 1947: 28). Given her association with a brilliant flash of light accompanied by the sound, it is probably a reference to lightning or possibly a fireball/airburst (bright/exploding meteor) as opposed to an aurora. Quartz was believed

to be a material manifestation of celestial deities that were brought to Earth by meteors (Hamacher and Norris, 2010).

2. http://edition.cnn.com/2003/TECH/science/03/18/offbeat.weather.aborigines.reut/
3. http://www.murrindindiclimatenetwork.org.au/24/Fran-Bodkin/

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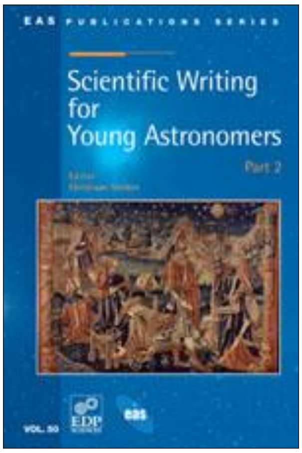
BOOK REVIEWS

Editorial Comment: Following is a review of the last book that the late Hilmar Duerbeck was reviewing for this journal when he died. Hilmar's partly-finished review was published in the March 2012 issue (Volume 15, pp. 72-73), as a salute to his years of dedication to this journal. In his review, Hilmar pointed out that Chris Sterken's book "... may at first glance be of little interest to historians of astronomy. But this is not the case: it is at least a quarry for historians of modern astronomy, offering an insight into the strata of a major journal *Astronomy and Astrophysics.*" Given Chris Sterken's long record of publishing papers on the history of astronomy, it also makes good sense to include a review of his book in this journal. We now wish to thank Michael Geffert for kindly preparing the following review of the second volume of Chris Sterken's very useful book, and to apologise for its delayed publication (caused by the loss of the relevant email during my international travels in 2012).

***Scientific Writing for Young Astronomers*, *Part 2*, edited by Christiaan Sterken (Les Ulis, EDP Sciences, EAS Publication Series Volume 50, 2011), 298 pp., ISBN 978-2-7598-0639-3, 35 x 155 mm. US$32.05.**



The first issue of *Scientific Writing for Young Astronomers* is related to a more common background of a researcher starting with writing scientific papers. In the second volume Christiaan Sterken, as editor and sole author, focuses directly on the creation of a scientific paper: the writing process, communication using graphics and ethical issues. The chapters are written by an astronomer with long experience as a scientist, writer and referee. It is the first aim of this book to give helpful information to young scientists at the beginning of their careers, information which normally is collected over the lifetime of a scientist. But the book is more than a simple collection of good advice. From the beginning, and throughout the book, the author goes to a lot of trouble to not only write a technical description on the writing of research papers. The question of the responsibility that a scientist has is also important. Consequently, the last chapter of this book relates to "… truthful communication of scientific results …" and is titled "Ethical Aspects".

Often scientists writing up the first paper describing their results are confronted by a large number of unfamiliar procedures, like authorship, the refereeing process, copyright, etc. The chapter on "The Writing Process" outlines the basic principles of the complete procedure, and one may read this chapter as a guide for beginners. It deals with many aspects, ranging from basic points like the different categories of scientific papers to the very special question "when to thank a referee", which might also be an important question for a first paper. Useful collections on "what to avoid at all price" and "FAQs about the editorial process" complete this chapter.

Visual communication by, for example, graphs and photographs is perhaps the most important part of a scientific publication. It is extensively treated in the second chapter on "Communication by Graphics". With the development of computer technology a large variety of possibilities for visualizing scientific results became available. Today it is the responsibility of every author to provide suitable graphics for his/her scientific papers. After discussing some general aspects of visual communication this chapter presents the different types of graphs and elements of a graphical image (such as axes, plot symbols and size ratios). A large number of examples is used to demonstrate the different aspects of graphics. At the end of this chapter the scientific treatment (outliers, perception of linearity, curve fitting) is considered. The reader will find a lot of useful practical information in this chapter.

More than a hundred pages of the second volume of *Scientific Writing for Young Astronomers* are devoted to the "Ethical Aspects" of writing a scientific paper. At first some general considerations on truth, error, quality and value of scientific work are given for the reader. Then bibliometric indices are explained, which help to define the quality of scientific work. The last part of this chapter, however, points out that the process of scientific writing may also be affected by different kinds of human errors. The discussion ranges from different types of misconduct to the bias of bibliometric indices, and is exhaustive. Throughout the chapter examples from history, like van Maanen's false estimation of the motions in spiral galaxies or the authorship of the paper on the Millikan experiment, which led to a Nobel Prize, nicely illustrate the general considerations.

The second volume of *Scientific Writing for Young Astronomers* contains not only useful material for all astronomers who start writing scientific papers, but also gives a lot of interesting additional information. The very comprehensive presentation of all aspects of publication of scientific results, the historical citations and also the occasional philosophical considerations make this book interesting—and not only for young astronomers.

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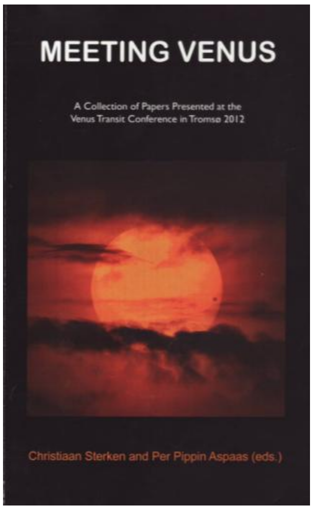
***Meeting Venus. A Collection of Papers Presented at the Venus Transit Conference in Tromsø* 2012, edited by Christiaan Sterken and Per Pippin Aspaas (Brussels, Vrije Universiteit Brussel and the Faculty of Humanities, Social Sciences and Education, University of Tromsø, 2013). Pp. xii + 255, ISBN 978-82-8244-094-3 (paperback).**



The 2012 transit of Venus spawned a number of new books focusing on the historical transits, and this one, under the capable editorship of Chris Sterken and Per Pippin Aspaas, reports on the results of a conference held in Tromsø, Norway, and originally published in the electronic *Journal of Astronomical Data*. In their Preface, the editors explain the reasons for this conference:

> First and foremost, the last transit of Venus of this century lent itself to be observed on the disc of the Midnight Sun in this part of Europe during the night of 5 to 6 June 2012. Second, several Venus transit expeditions in this region were central in the global enterprise of measuring the scale of the solar system in the eighteenth century. (Page vii).

It is the second of these reasons that sets this book apart from others already published, as it focuses mainly on Scandinavian observations of the 1761 and 1769 transits.

This lavishly-illustrated 267-page book contains four Parts dealing with the transits, along with a biographical account of our recently-departed dear friend and colleague, Professor Hilmar W. Duerbeck, and detailed general, name and author Indexes.

Part 1 contains just one chapter, of only 16 pages, but this is jam-packed with information, tables and figures about Scandinavian observations of the 1761 and 1769 transits (and a little on the following 1874 and 1882 transits), and sets the scene, as it were, for the chapters that follow. I found this introductory chapter and the supporting page and a half of references invaluable.

Part 2, "Venus Transit Histories from Northern Europe, 1761–1769" contains seven chapters about research policy and astronomy in Sweden, how Catherine II used these two transits to bring the Russian Academy of Science international recognition, Denmark-Norway's very limited involvement in these transits, observations of the two transits by the Swedish amateur astronomer Anders Hellant, Bayly and Dixon's British expedition to northern Norway in 1769, Anders Johan Lexell's investigation of the solar parallax, and some cultural and political repercussions of Maximillian Hell's expedition to Denmark-Norway in 1769. While the expeditions associated with Hell, and Bayly and Dixon, are well known to transit of Venus specialists I found much new information in the other chapters, and the Lexell paper was fascinating. Another aspect that could not escape my attention was the extensive literature on these two transits published in languages other than English and therefore not widely available to the international transit of Venus scholars. *Meeting Venus* … is an excellent way of bringing some of this literature to a wider audience.

While the 1761 and 1769 transits are not always the focus of papers on the near 200-page long Part 3 ("Other Transit Histories 17th to 20th Century"), there is much of interest here for historians of astronomy. The first paper deals with Keplerian orbits and the 1631 and 1639 transits of Mercury and Venus respectively, while Suzanne Debarbat's brief paper which follows examines various attempts using transits and other methods to solve what Airy (1857) "… considered the noblest problem in astronomy", and culminates in listing the results of the 2012 IAU Resolution B2: that the 'astronomical unit' is exactly 149,597,870,700 meters. The next paper —which I found engrossing—follows a quite different path and looks at "Venusians: the planet Venus in the 18th-century extraterrestrial life debate", and in the process manages to make some concessions to transits by discussing various observations purporting to document the atmosphere of Venus. The following papers on Jesuit Austrian-Hungarian observatories and J.-N. Delisle and J.-J. Lalande both relate to the 1761 and 1769 transits, while Chris Sterken's paper on J.-C. Houzeau relates to the two 1882 Belgian transit of Venus expeditions to Texas and Chile. The final paper in Part 3 deals with some French attempted observations of the 1882 transit and how subsequent observations of transits of Mercury led to successful observations of the 2004 transit of Venus.

In a marked departure from other academic volumes on historic transits of Venus, Part 4 in *Meeting Venus* contains three papers that report on attempted observations of the 2012 transit by various member of the audience who attended the conference. The first two papers are short (and deal with observations made from Tromsø and during an aeroplane flight), but the final copiously-illustrated 30-page multi-authored paper captures the excitement of travelling by ship to view the transit from northern Norway, only to have their hoped dashed by cloudy skies. As the authors lament:

> The description of the Vardø weather conditions ... vividly illustrates the extreme impact of the weather on the outcome of a scientific enterprise of the magnitude of a Venus transit expedition today … and even more so in the past. (Pages 227-228).

As indicated earlier, Part 5, titled simply "Leaves of History" and penned by Chris Sterken, rounds out this book by recording a few of his memories

> … of a very lovely person who should have been with us in Tromsø and Vardø, but who passed away suddenly and unexpectedly on January 5, 2012. This short paper is meant to evoke the memory to the very special person and scientist that Hilmar Duerbeck was. (Page 235).

This paper brought back a flood of memories for me too, as Hilmar was also my friend, IAU colleague on the Transits of Venus Working Group Committee, academic companion (we co-supervised Ph.D. students) and an Associate Editor of this *Journal*. He is sadly missed.

Meeting Venus may end on a sad note for those of us who knew Hilmar Duerbeck, but this should not deflect us from the joy of a book that contains a wealth of new material about transits of Venus—particularly those of 1761 and 1769. I feel that this book deserves to be in the library of all those with a fascination for historic transits of Venus, but as only a very limited number of hard copies were printed it is not readily available in book form. However, those wanting to download specific papers can do so by accessing the electronic journal in which the papers first appeared. This is: *The Journal of Astronomical Data*, Volume 19, Part 1, 2013.

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