

V. BEN MEEN AND THE RIDDLE OF CHUBB CRATER

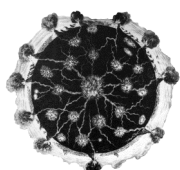
HOWARD PLOTKIN¹ and KIMBERLY T. TAIT²

¹*Department of Philosophy, University of Western Ontario
London, ON N6A 5B8, Canada*

hplotkin@rogers.com

²*Department of Natural History, Royal Ontario Museum
Toronto, ON M5S 2C6, Canada*

ktait@rom.on.ca



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ABSTRACT

Aerial photographs of Chubb Crater, a striking 3.4 km-wide circular basin in the far north of Quebec, led the Ontario prospector Fred W. Chubb to think it might be an extinct volcano, and possibly the site of a diamond-bearing diatreme. V. Ben Meen, the Director of the Royal Ontario Museum of Geology and Mineralogy in Toronto, however, suspected it was an impact crater caused by a meteorite. Meen led two expeditions to the crater in 1950 and 1951. Despite early opposition and the initial absence of corroborative field evidence, he held on to a persistent belief in the crater's meteoritic origin. Later fieldwork ultimately provided strong evidence in support of this view. The discovery of the crater led to the development of a program at the Dominion Observatory in Ottawa to search for additional impact craters on the Canadian Shield, and the development of valuable criteria by which they could be authenticated. The craters discovered through the program fit well on the Baldwin curve relating crater depth to diameter, and lent strong support to the argument for the relationship between the meteoritic origin of lunar craters and terrestrial impact structures. Chubb Crater is of historical importance because it was the first meteorite crater to be recognized in Canada, and the first anywhere to be authenticated in the absence of associated meteorites.

1. BACKGROUND

Chubb Crater (later renamed Ungava Crater, then New Quebec Crater, and now Pingualuit Crater), is a 3.4 km-wide striking circular basin with an elevated rim enclosing a large lake. It is located in Precambrian granite of the Canadian Shield in the northernmost region of Quebec, Canada, at the top of the Ungava Peninsula (see Figure 1). Aside from occasional early visits by Inuit hunting caribou, the structure was first noticed in an aerial photograph taken by U. S. Army Air Force (USAF) planes based in the Canadian Arctic. During a routine weather flight, one plane brought back an oblique photograph taken on 20 June 1943 which clearly showed the unique feature in the barren landscape; this is believed to be the earliest known photograph of the crater (see Figure 2). Because it was useful as a navigational landmark in the Ungava wilderness, it was soon plotted on topographic maps of the region (Millman 1956). When it first appeared on a restricted USAF aeronautical chart in February, 1945, it was designated by the word 'crater' (Wakeham Bay Sheet IIID, USAF Preliminary Base, scale 1:500,000). Since then, the crater has become a well-known landmark as its rim could be seen for a distance of 20–30 miles (32–48 km), and it has appeared on all subsequent large-scale topographical maps of the area.

In the summer of 1946, Royal Canadian Air Force (RCAF) pilots took photographs of the crater while transporting field parties of the Geodetic Service of the Department of Mines and Technical Surveys of Canada who were obtaining astronomical fixes for use in the positioning and scaling of aerial photographs (Millman 1956). One pilot, Squadron Leader W. K. Carr, ran into a line squall on his return to base camp on 28 June, and decided to wait out the storm by landing on the crater lake. Tying up to a spot on the northeast shore, he stayed on the lake for about two hours. Carr (1952, p. 61) noted that the lake "did not appear volcanic in origin, nor

was it similar to any of the other lakes in the region”. He thought it appeared to be the result of a big ‘splash’ of some sort, and later discussed the crater and its possible origin with the other pilots.

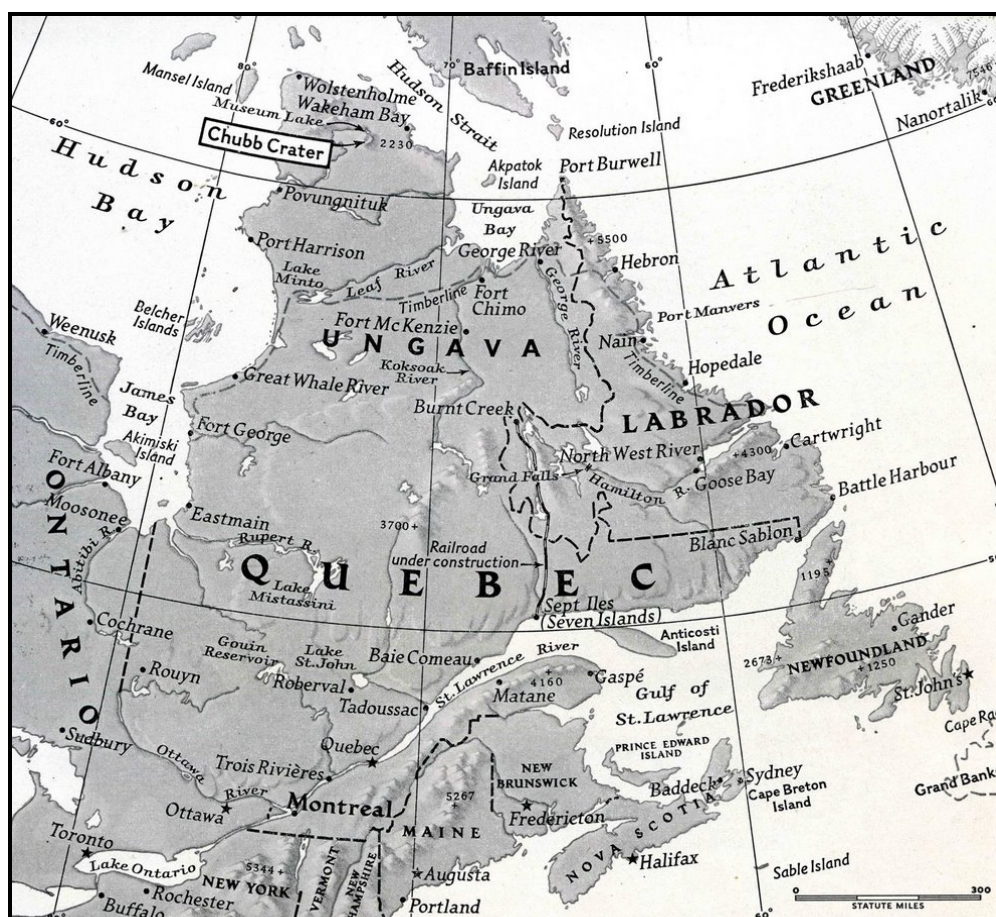


Figure 1. Map of northeastern Canada showing the location of Chubb Crater. The crater is in the remote far north of Quebec, about 98 km from Wakeham Bay on the Hudson Strait (V. Ben Meen, *The National Geographic Society–Royal Ontario Museum Expedition to Chubb Crater, Ungava, Quebec, 1951*, p. 30).

The crater was photographed again in the summer of 1948 in surveys carried out by the RCAF. Puzzling over the unusual looking structure, C. B. Bassett of Legal Surveys, Ottawa wrote the Geological Survey of Canada for an interpretation of it. In response, Y. O. Fortier of the Survey’s Bureau of Geology and Topography filed the following memorandum in June, 1949 (quoted in Millman 1956, p. 3):

One of the pictures submitted by Mr. Bassett had already been chosen for our collection as an example of a meteorite crater. Comparison of these pictures with those shown in the chapter on meteorite craters, especially in Arizona, in [A. K.] Lobeck’s textbook on ‘Geomorphology’ [1939] will convince anyone of the similarities of the features at the two localities. Such a crater to be of volcanic origin would have to be of recent formation, which is not likely in the Canadian Shield.

A meteoritical origin for the crater was also assumed by the astronomers G. V. Douglas and Mary C. V. Douglas in a 1949 unpublished report prepared for the Arctic Institute of North America, although they were quick to point out (quoted in Millman 1956, p. 3) “However, this

crater has never been examined on the ground and the theory is based [solely] on a study of aerial photographs”.

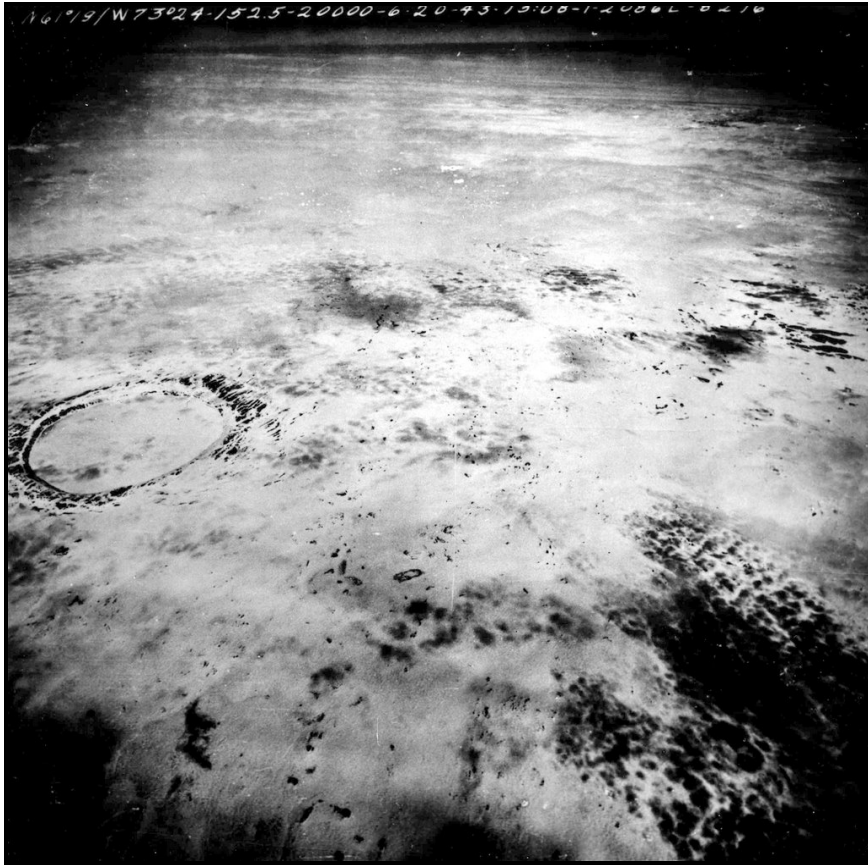


Figure 2. Earliest known aerial photograph of Chubb Crater. It was taken by the U. S. Army Air Force on 20 June 1943. The complete legend on the photo reads U. S. A. F. N61°19'W73°24-152.5-20000-6-20-43-13:08-1-2086L-8216 (V. Ben Meen, *The National Geographic Society-Royal Ontario Museum Expedition to Chubb Crater, Ungava, Quebec, 1951*, p. 2).

In February, 1950, Fred W. Chubb (1906-?) (see Figure 3), an experienced and well-informed Whitby, Ontario prospector, examined maps and aerial photographs of the Ungava portion of Quebec in preparation for carrying out prospecting there. When he saw photographs of the crater, he thought the structure was an extinct volcano and the site of a volcanic pipe, or diatrema. Knowing that diamonds had been found in South Africa in diatremes, he immediately became very excited. His hopes were boosted by knowledge of the fact that several dozen diamonds had been found in the glacial gravels of southern Ontario, Michigan, Wisconsin, New York, and northwestern Pennsylvania, and that it was generally believed that the diamonds had been carried there by glaciers from a source in northern Ontario or Quebec. For many years prospectors had been on the lookout for this source, but without success. Chubb thought that the crater just possibly might be the sought-after source (Meen 1953).



Figure 3. Fred W. Chubb (left), the Ontario prospector for whom the Chubb Crater was originally named, shown while on the 1951 expedition to the crater (Department of Natural History, Royal Ontario Museum). V. Ben Meen (right), the Director of the Royal Ontario Museum of Geology and Mineralogy, Toronto, Ontario, who led two expeditions to the Chubb Crater. He is shown here while on the second expedition, in 1951 (Department of Natural History, Royal Ontario Museum).

Towards the end of the month, Chubb brought a 1948 RCAF photograph of the crater and its enclosed lake to V. Ben Meen (1910–1971) (see Figure 3), a friend he had been on earlier field trips with, and told him what he thought it might signify. Meen, who had just recently been appointed as Director of the Royal Ontario Museum of Geology and Mineralogy in Toronto (ROM), had spent some time a decade earlier doing postdoctoral research at the U. S. National Museum in Washington D.C., which resulted in his description and analysis of the Maria Elena meteorite from Chile (Meen 1941) and the Santa Luzia meteorite from Brazil (Meen 1939). These early studies likely piqued his interest in Chubb's story. Although Meen had examined several hundred aerial photographs, he had never seen anything like the crater Chubb now shown him (see Figure 4). He was astounded, and pondered over how it might have originated. Other than being the neck of an extinct volcano, as Chubb believed, there were two other possibilities: it could be a glacial sink hole, or a meteorite crater. Meen considered the pros and cons of each.

The glacial sink-hole explanation seemed the least likely. Although it was true that retreating glaciers and a warming climate would have caused blocks of ice to be trapped and buried in pockets, eventually giving rise to lakes, it was difficult to explain this lake's remarkable circularity and its high rim. The possibility that the lake might be in the neck of an extinct volcano was interesting to consider, and its crater-like form was suggestive. If it was, it either had to have been formed prior to or after the occurrence of the glaciers. If before, however, then the rim should have been eroded and the interior filled in by the glacier's retreat. If after, the rim would not present a problem, but lava flows and fragments ejected by the volcano should be seen to cover the immediate vicinity.



Figure 4. The aerial photograph of Chubb Crater taken by the Royal Canadian Air Force 3 July 1948 from the east at an elevation of about 6,096 m that Chubb brought to Meen's attention in late February, 1950 (photograph R. C. A. F. T193R-87) (V. Ben Meen, *The National Geographic Society–Royal Ontario Museum Expedition to Chubb Crater, Ungava, Quebec, 1951*, p. 3).

The third possibility, that of meteoritic origin, seemed the most likely. Meen (1953) had seen photographs of Meteor Crater in Arizona, and recognized the great similarity which existed between the two craters. He also knew of a few other recent craters that had been caused by meteoritic impact, such as the small craters associated with the Sikhote–Alin meteorite, which fell in Maritime Territory, Russia in February, 1947 and the 2,700-foot (823 m) wide Wolfe Creek Crater in northwestern Australia, which had been first observed from the air in June, 1947. As with the volcanic origin possibility, Meen thought that a meteorite crater likewise could not have survived the Ice Age intact, as glaciers would have levelled its rim and filled it in. A post-glacial origin was therefore thought most likely. By studying photographs of the crater, its size was estimated to be some 10,000 feet (3,048 m) in diameter. If it was a meteorite crater, it would be more than twice the size of 4,100-foot (1,250 m) wide Meteor Crater, Arizona, then the largest meteorite crater on Earth. Meen (1950b, p. 170) felt that “a crater so large was almost unbelievable and almost too good to be true”.

Chubb and Meen thus had different theories about the origin of the crater. If Chubb was right and the crater was volcanic, there existed the possibility of great economic importance. If on the other hand Meen was right and the crater was meteoritic, it would be of no economic significance but would be of great scientific value. How could the matter be resolved? “Certainly we could obtain no proof on the origin of the crater sitting in an armchair. Though Chubb and I had different opinions, and different hopes, we were one in our desire and determination to get to the site as quickly as possible” (Meen 1951c, p. 65).

Over the next several months, considerable time and effort was spent on trying to raise money for an expedition to make a study of the crater, determine its origin, and stake it if it proved to be volcanic. Because commercial possibilities existed if the crater turned out to be an extinct volcano, funds could not be sought from the usual sources, such as Canada's National Research Council. Proposals were sent to such diverse organizations as the National Geographic

Society, The Diamond Drill Carbon Company in New York, Canadian Breweries Limited in Toronto, and John Labatt Limited in London, Ontario, but failed to produce sponsorship.

With the commercial possibilities in mind, a 'Chubb Crater Exploration Syndicate' was formed, and was accepted for filing by the Ontario Securities Commission in July, 1950. "The sole purpose of the Syndicate is to explore a certain crater-like lake in northern Quebec between Cape Smith and Ungava Bay and prospect for mineral possibilities in the area and for such purposes to finance prospecting expeditions, carry on preliminary mining development and the acquisition of mining properties or any combination thereof" (Salter, Reilly, and Jamieson 1950, p. 2). The capital of the Syndicate was limited to \$35,000 divided into 700 units of \$50 each. It was contemplated that one-third of the total number of units would be issued in such a way that Chubb would own 34% of them, and Meen 26%. To protect Chubb's interests, plans for the investigation of the crater were not announced to the public.

In spite of efforts to keep the plans private, a newspaper man from Toronto's *Globe and Mail*, Kenneth W. MacTaggart (1951, p. 94), "heard a vague statement from a friend that a prospector named Chubb was on the track of a big diamond discovery in Canada," and managed to track him down. This turned out to be a stroke of good luck. After meeting with Chubb and Meen in Meen's office at the museum, MacTaggart was very enthusiastic about the news value of the story, and persuaded his newspaper to provide transportation to the crater in its nine-passenger Grumman Mallard amphibian plane in return for first publication rights. MacTaggart also introduced them to five alumni of the University of Toronto who, along with a prominent Toronto mining man (all of whom wished to remain anonymous), furnished the bulk of the money necessary to purchase equipment and other necessities for the trip. By the time that the finances were finally available, the field season was already well advanced. Within a period of ten days, tents, sleeping bags, climbing rope, sectional canoe, photographic film, food, stoves, cooking equipment, and everything else needed for the expedition was acquired, and final preparations for the trip were made.

2. FIRST CHUBB CRATER EXPEDITION

The *Globe and Mail* amphibious plane left Toronto on 17 July 1950 for its 1,700-mile (2,735 km) journey to the crater with a crew of six: Meen; Chubb; MacTaggart; Robert C. Hermes of Buffalo, who served as naturalist and photographer; William Poag, the plane's pilot; and Andrew Gabura, the plane's engineer. Bad weather delayed the trip, and it wasn't until the 21st that they arrived at their destination. Since the crater-lake was three-quarters covered by floating ice, they landed on a moderately large lake two miles (3.2 km) northwest of the crater. Since neither this lake nor the crater-lake had been previously named, they named them Museum Lake and Chubb Crater Lake, respectively. "This latter was named as a tribute to the very intelligent curiosity of Fred Chubb which started the whole investigation. The association of the name Museum with Chubb Crater will, I hope, keep constantly before the public of the world the fact that museums are continuously carrying on research" (Meen 1952c, pp. 16–17). After a quick lunch, Meen and Chubb set off for their first trip to the crater.

The ground between Museum Lake and the crater was a barren, forbidding region, with large boulders covering the ground as far as the eye could see. Walking over them was extremely difficult and treacherous. Twice on their way they encountered circular ridges 35–50 feet (11–15 m) high, lying at right angles to their path. The rim of the crater was nearly 300 feet (91 m) above the surrounding plain at the place where they approached it (and was as high as 550 feet (168 m) in other places), with a 25 degree slope leading to its top, and seemed to be composed of a jumbled heap of granite fragments. The top of the rim was rounded off, and so broad that neither the outer plain nor the crater-lake could be seen from its crest. Standing there, Meen and Chubb looked across to the opposite side of the rim, more than 11,000 feet (3,352 m) away, then down a steep 45 degree slope to the lake. With the rim highest in the northeast and also wider there, the crater strongly suggested a meteoritic origin: it had the perfect appearance of a giant hole in the earth caused by an explosive impactor coming in from the southwest. After

a climb down to the lake to make elevation readings, they noticed it was getting late and reluctantly returned back to the Museum Lake camp.

Two things were immediately obvious. First, the crater was not a sinkhole, or caused by the melting of a pocket of glacial ice. Secondly, it was not volcanic in origin. There were no signs of lava flows, or fragments of lava or volcanic ash. Instead, everywhere were large blocks of granite, known to be formed at great depths below the earth's surface and laid bare after a long period of erosion of the overlying rock. Chubb's dream of finding an extinct volcano that might yield diamonds had quickly vanished.

Two more trips to the crater were made during the next two days, and on the last Meen made a complete circuit of the rim. By the time of his second visit, Meen (1951c, p. 68) found further evidence suggestive of an impact-caused explosion. "The rim had a joint pattern radiating from the center, as if the original granite bedrock had been cracked and tilted by a gigantic blast. The top of the rim, the outer slopes and the surrounding plain were littered with rock fragments, which evidently lay just where they had originally fallen when they were blasted into the air".

Great valleys or rifts in the rim, ranging from 40–200 feet (12–61 m) deep, occurred in the rim running radially outward. The deepest ones were about 3,000 feet (914 m) apart, and cut through the highest part of the rim on the northeast side. Their appearance suggested to Meen that they might have been caused by a great explosive force which ejected material from the rim and deposited it outside as radial ridges, some of which were noted in the surrounding plain. Meen (1951b, p. 56) compared the rifts to the radial distribution of meteorites outside the rim of Meteor Crater in Arizona, and to rays which could be seen emanating from some lunar craters: "Many astronomers now believe that the craters on the moon are meteorite craters. Many of these show radial pattern and it is thought that these represent material thrown out of the craters by the explosion". We'll have more to say about the acceptance of lunar craters as meteorite craters below.

The two circular ridges encountered on the walk from Museum Lake at distances about three-fifths of a mile (1 km) and again at one mile (1.6 km) northwest of the rim proved to be interesting, and were also suggestive of an impact. They were encountered no matter where the party crossed from the lake to the crater, and could be seen from many points on the rim. On investigation, the ridges were found to be solid granite, and fractured similarly to the granite of the rim itself. Although Meen (1950b) was not sure the ridges were continuous all the way around the crater, their positions seemed to indicate a series of ripples or wrinkles more or less surrounding the major ripple of the rim itself. He felt the ridges could indicate shock or compression ripples, similar to those produced when a stone is dropped in calm water.

Taken together, everything pointed to a meteoritic origin of the crater. It was remarkably similar in appearance to two accepted meteorite craters, Meteor Crater and Wolfe Creek Crater, and in a Table in his report, Meen (1950b, p. 180) compared such features as the type of bedrock the craters were located in; their rim heights, diameters and circumferences; and crater depths. The finding of meteoritic fragments would, of course, clinch the argument, but none were found. Some promising-looking rusty-coloured rocks turned out to be weathered diabase, and no chondrules or appreciable amounts of nickel were present in any of the rock specimens collected. This did not lessen Meen's conviction. He pointed out that fragments might not have survived the colossal explosion of the impact, or they might be scattered far beyond the rim. The expedition was not able to examine much of this area during its three-day visit; in addition to the rim, only a relatively small triangular section was able to be covered (see Figure 5). Moreover, if the meteorite was stony rather than metallic, fragments would be difficult to distinguish amongst all the jumbled rocks. The presence of weathered diabase fragments and rocks covered by lichen increased difficulties. Since no sign of glaciations was observed on or around the crater, and it had not been deformed or filled in, Meen thought it had been produced after the last glacier had receded. He therefore put its age as somewhere between 3,000 and 15,000 years. At 4:45 a. m. on 24 July, the expedition members got up, had breakfast, loaded the plane, and were airborne at 8:30 a.m. for their flight home (Meen 1950a).

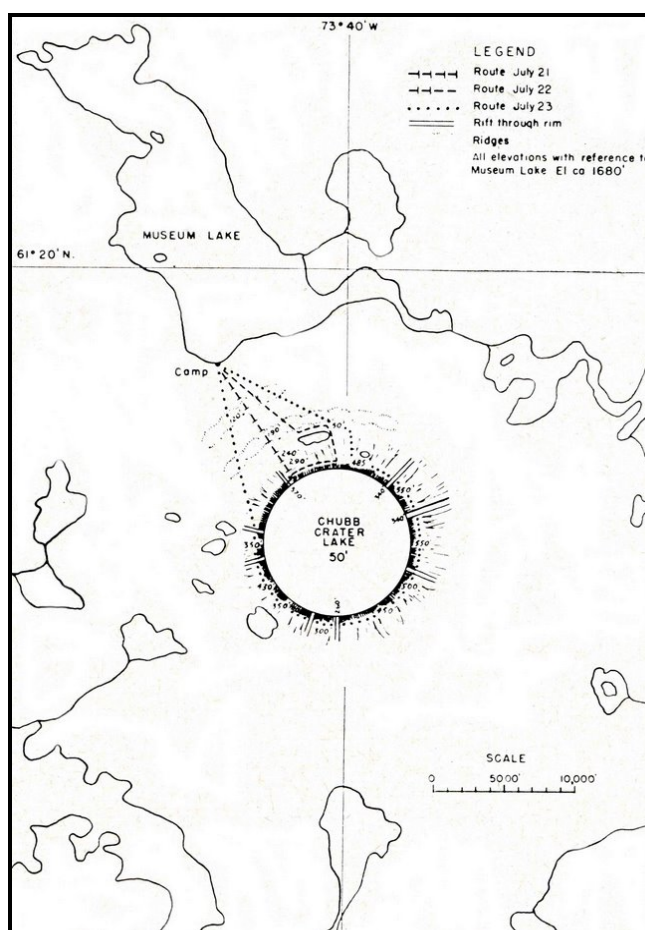


Figure 5. Sketch of Chubb Crater and vicinity by George F. McCauley showing the location of the expedition's camp on Museum Lake and the small triangular area examined during the three-day visit to the crater in 1950 (V. Ben Meen, Chubb Crater, Ungava, Quebec. An account of the Royal Ontario Museum-Globe and Mail expedition, 1950, *Proceedings of the Geological Association of Canada* 4: 53).

Meen felt this expedition, brief as it was, had been very successful, and quickly thought about a second expedition if funds could be raised. This later expedition, larger in staff and remaining for a longer period of time, would make a topographic survey of the immediate area, determine the depth of the crater lake in order to ascertain the total depth of the crater, search for meteorite fragments with magnets and metal detectors, and make a magnetometer survey of the northeast rim to determine if a meteoritic mass was buried beneath it. He felt it was an ambitious program, but one well warranted by the scientific importance of the crater, which if indeed meteoritic, would be the largest known meteorite crater on Earth.

3. INTERLUDE

A week after the story of the expedition appeared in the *Globe and Mail* on the morning of 7 August, 1950, B. R. MacKay of the Geological Survey of Canada and Peter M. Millman (1906–1990) of the Dominion Observatory in Ottawa visited Meen at his summer cottage to discuss the findings. Although they had not been previously aware of the crater's existence, they quickly became convinced that the weight of evidence in favour of it being a genuine meteorite crater was strong, and that a future expedition would be justified. They informed Meen that they would

recommend to the Department of Mines and Technical Surveys that a further study of the crater be undertaken in 1951, with the full participation of the ROM.

In September, Meen wrote to the Canadian Board on Geographical Names, asking them for official approval of Chubb Crater or Chubb Lake Crater for the name of the circular feature, and Museum Lake for the body of water on which the expedition landed and which served as their base camp. These proposed names were not accepted, however. In 1953 the Board decided on the name Ungava Crater, but a year later switched it to le Cratère de Nouveau Québec, at the request of the Quebec Geographic Board. At the same time, Museum Lake became Lac Laflamme (Marvin and Kring 1992).

By mid-December, 1950, Meen learned that there was little chance of Federal Government support for an expedition the coming summer. Writing to Hermes in New York, Meen (1950c) pointed out that he now had to organize the expedition himself, “in order to keep our ‘claim’ to the crater in good standing. If we leave it vacant for a summer, your friends [i.e. Americans] will be in there very quickly”. Meen’s nationalism can further be seen in a letter written the following month to the M. P. for Trinity, Ontario requesting help in securing funding: “Chubb Crater is the biggest crater of its kind and all study of it so far is Canadian. I believe I am justified when I say that I want to see it remain Canadian in all its aspects” (Meen 1951d). Letters requesting financial support were sent to the Canadian Geographical Society, the University of Toronto, the Quebec Government, and—Meen’s nationalism notwithstanding—the National Geographic Society, the Geological Society of America and the Arctic Institute of North America.

During the last three weeks of April and first week of May, Meen visited Harvey H. Nininger (1887–1986) at Meteor Crater, Arizona, in an effort to learn from him how best to carry out a search for fragments of meteorites at Chubb Crater. During field investigations carried out at Meteor Crater between 1946 and 1948, Nininger, the world’s first full-time, self-employed meteorite collector/dealer and co-founder of the Society for Research on Meteorites (the precursor of the Meteoritical Society), had used magnet rakes drawn behind his Studebaker car to comb some 23 acres (9.3 ha) of land within two and one-half miles (4 km) of the crater. Examining the sand and soil particles that were continually collected on the magnets, he found that some particles were extremely rich in nickel. Nininger (1951) interpreted these metallic spheroids as condensation droplets from a cloud of vaporized metal from the impacting meteorite.

Nininger showed Meen how he now used a horseshoe-shaped magnet about three inches (7.6 cm) across the end attached to the end of a pick handle to drag through soil and collect the metallic spheroids. Meen felt that magnets could be used to search for similar spheroids in the small patches of soil at Chubb Crater and if some could be found, this would constitute positive proof of the crater’s meteoritic origin. He told a reporter from the *Globe and Mail* (1951a) “I was delighted to find that it isn’t going to be a difficult task at all . . . I’m as happy as the deuce”. While in the American Southwest, Meen also visited the Institute of Meteoritics at the University of New Mexico, where Director Lincoln LaPaz (1897–1985) showed him the Norton County meteorite and loaned him a large 13 lb (5.9 kg) magnet for the expedition. And it seems likely that Meen’s visit to the Odessa Crater in Texas also took place at this time.

Support for a meteoritic origin for Chubb Crater came unexpectedly and dramatically from a completely different quarter. On 8 May 1951, Meen received a letter from Ralph B. Baldwin (1912–2010), who had a PhD in astronomy from the University of Michigan and had worked briefly at the University of Pennsylvania’s Flower Observatory and Northwestern University’s Dearborn Observatory, but was then working full-time as President of a family firm, the Oliver Machinery Company, in Grand Rapids, Michigan. Two years earlier, Baldwin had published his book *The Face of the Moon* (Baldwin 1949), a book that became “one of the great benchmark books of twentieth-century science” which, together with its 1963 expanded sequel *The Measure of the Moon* (Baldwin 1963), “contain virtually the entire scientific structure for the subsequent decades of research on lunar geology and terrestrial impact

structures” (French 2000). Although some of Baldwin’s ideas had been expressed earlier by geologist Robert Dietz (1914–1995) in his monumental paper ‘Meteoritic impact origin of the Moon’s surface features’ (Dietz 1946), a paper which Baldwin knew nothing of, *The Face of the Moon* was, in the words of historian William Graves Hoyt (1987, p. 360), “the ‘manifesto’ of the impact revolution”.

Baldwin’s book set out in great detail many arguments in support of his belief in the meteoritic origin of the lunar craters. His most convincing argument was a logarithmic plot he had developed showing a relationship between diameters and depths of well-preserved craters of all sizes, from small terrestrial shell pits to bomb and mine craters to the immense lunar craters. He showed that they all clustered along the same smooth curve. To this, he added four terrestrial meteoritic craters whose dimensions had been carefully measured (Meteor Crater, Henbury 1 in Australia, and Odessa 1 and 2 in Texas). These craters also fit the curve well. Baldwin felt that the smoothness of the curve (which came to be referred to as the Baldwin curve) was “too startling, too positive, to be fortuitous” (Baldwin 1949, p. 131).

In his letter to Meen, Baldwin (1951) pointed out that the circular ridges that he had encountered between Museum Lake and Chubb Crater as well as the linear rifts he had noticed in the crater rim, were paralleled in many of the lunar craters; they were especially noticeable in the great Alpine valley and the Apennine region of Mare Imbrium, “the greatest example of meteoritic action on the Moon”. More importantly, he informed Meen that he had statistically developed two equations giving relationships for the rim diameter, rim height, and total depth of meteorite craters on the Earth and craters on the Moon.

Baldwin’s first equation was

$$D = 0.1083d^2 + 0.6917d + 0.75$$

where D is the logarithm of the diameter of the crater measured in feet, and d is the logarithm of the depth, also measured in feet. When Chubb Crater’s diameter of 11,000 feet (3,353 m) is substituted into the equation, it gives a depth of 1,500 feet (457 m) for the crater (i.e., from the average top of the rim to the bottom of the lake). His second equation was

$$E = -0.097D^2 + 1.542D - 1.841$$

where E is the logarithm of the average height of the rim in feet and D is again the log diameter in feet. When solved for Chubb Crater, the equation gives a rim height of 640 feet (195 m). Baldwin noted that this was higher than the average of 400 feet (122 m) that Meen had measured, but explained that erosion possibly decreased the original rim height, and that his formula gives slightly higher values for rim heights of craters between 100–20,000 feet (30–6,096 m) in diameter. The physical characteristics of the crater’s diameter and erosion-reduced rim thus placed it neatly with the other terrestrial meteorite craters on Baldwin’s curve. Moreover, as Meen (1951c) had earlier pointed out, it was the first explosion crater on Earth larger than the smallest crater on the Moon (see Figure 6). Baldwin (1951) heartily congratulated Meen on the work he had done and on the results he had achieved: “It is one of the most important geological discoveries made in recent years and will repay all time and energy which are spent in its study”.

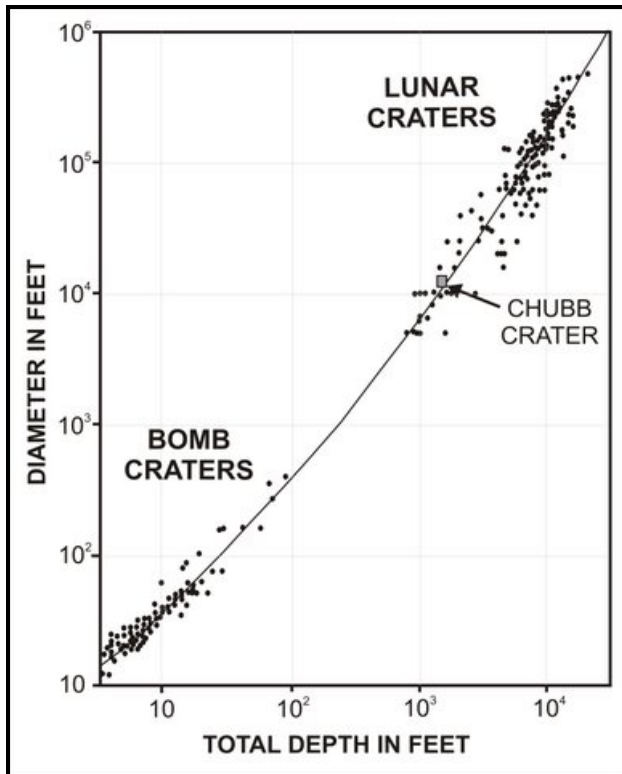


Figure 6.

The Baldwin curve, showing the relationship between the diameter and depth of terrestrial explosion craters and craters on the Moon. Chubb Crater was the first explosion crater on Earth larger than the smallest lunar crater (after C. S. Beals, M. J. S. Innes and J. A. Rottenberg, The search for fossil meteorite craters—I, Current Science 29: 206).

More good news arrived later that month, on 24 May, when Meen received a telephone call from the National Geographic Society, informing him that it would provide \$15,000 U. S. in support of an expedition that summer to be carried out jointly with the ROM, with Meen as Field Director representing both organizations (McKnew 1951a). An official Memorandum of Agreement between the two institutions was signed on 15 June 1951. Under the terms of the agreement, the expedition was to be known as The National Geographic Society–Royal Ontario Museum Chubb Crater Expedition, Meen was to prepare and promptly submit a popular account of the expedition to the National Geographic Magazine, prepare and submit a technical report to the Society, and prepare and deliver a lecture before the Society’s Washington, D. C. membership if requested to do so (National Geographic Society 1951, p. 2). Further, the Society requested for its museum a fair share of any meteoritic fragments or condensation droplets that might be found (McKnew 1951b). With the Agreement firmly in place, Meen prepared plans for a mid-July departure.

4. NATIONAL GEOGRAPHIC SOCIETY–ROYAL ONTARIO MUSEUM CHUBB CRATER EXPEDITION

Meen’s hand-picked team for a four-week-long expedition included Chubb; geophysicist John A. C. Keefe, chosen to carry out a magnetometer survey and its attendant land survey; Leonard I. Cowan, a Preparator in the ROM who would assist Keefe in his survey work and prepare thin sections of rocks and suspected meteorites; limnologist Nigel V. Martin, who would serve as biologist and make depth and temperature readings of the lake; and Richard H. Stewart, who was sent by the National Geographic Society as the expedition’s photographer.



Figure 7. The personnel of the National Geographic Society–Royal Ontario Museum 1951 expedition to Chubb Crater, photographed in front of the Canso amphibious aircraft used by the party. From left to right: John A. C. Keefe, Nigel V. Martin, Fred W. Chubb, V. Ben Meen, Leonard I. Cowan, and Richard H. Stewart (N. G. S. 100664T) (V. Ben Meen, The National Geographic Society–Royal Ontario Museum Expedition to Chubb Crater, Ungava, Quebec, 1951, p. 10).

The expedition left Toronto by train on 19 August 1951 and headed to Montreal and then on to Roberval, Quebec, a quiet lumber town that was one of the last rail stops north of Quebec City. A delay in the arrival of some of their equipment and bad weather prevented their departure from Roberval until 25 August. Transport from there was by a modified World War II Catalina amphibious plane (called a Canso in Canada) piloted by Captain Wilf Allard (see Figure 7). As with the first expedition, the plane landed on Museum Lake, which served as the base camp. Throughout the stay the camp operated under four flags: the Union Jack for Canada, the Stars and Stripes for the United States, and the banners of the expedition's two sponsors, the National Geographic Society and the Royal Ontario Museum (see Figure 8).



Figure 8. Tents at Base Camp No. 2 on Museum Lake. The white tent was used as a cook tent and office, and was white to increase inside visibility and to aid in seeing the site from the air (photographed by V. Ben Meen, R. O. M. 5-10) (V. Ben Meen, The National Geographic Society–Royal Ontario Museum Expedition to Chubb Crater, Ungava, Quebec, 1951, p. 12).

Geological and topographical examination of the crater rim and surrounding plain substantiated the results obtained in the 1950 expedition: the jumble of huge granite rock fragments littering the rim and plain, the jointing patterns in the rim, the trenches or rifts cut radially through the rim, and the two concentric ridges outside the rim (see Figure 9). Transit surveys revealed that the crater and lake were slightly elliptical. The rim-to-rim long axis of the lake was 11,500 feet (3,505 m), while its short axis was 11,000 feet (3,353 m). The long axis of the lake was triangulated to be 9,300 feet (2,835 m), and its short axis 8,925 feet (2,720 m). The maximum height of the rim above the crater-lake was measured as 540 feet (165 m). Seventeen soundings of the lake revealed the greatest depth to be 825 feet (251 m), more than twice the depth of Meteor Crater. Taken together, this made a maximum total depth for Chubb Crater of about 1,365 feet (416 m). If an average rim height of 400 feet (122 m) is assumed, then the average depth of the crater would be 1,225 feet (373 m), in close agreement with the value of 1,500 feet (457 m) given by Baldwin's first equation. Meen (1953) noted that this agreement, along with the rim height agreement noted earlier, helped reinforce the idea that Chubb Crater was an explosion crater due to extraterrestrial forces.

A sharp watch for meteorite fragments or spherical droplets of meteoritic origin was kept at all times, and for distances up to seven miles (11.3 km) from the crater rim. Small three-inch (7.6 cm) alnico magnets fastened to the ends of aluminium rods were used by members of the party, and Meen and Chubb took turns dragging the large magnet loaned by LaPaz behind them over the small patches of soil that were available (see Figure 10). Since the soil was often saturated with water, it had to be dug up and spread out to dry for a day or two before it could be tested with the magnet. No meteoritical material was found, however.

Two metal detectors furnished by the Engineer Corps of the U. S. Army were also utilized in the search (see Figure 11), but they were found to be too sensitive for the work. Although it wasn't unusual for such rocks as gabbro and diabase to give off a resonance, the small amount of magnetite in many of the granite boulders did so as well. Large rusty boulders of diabase scattered sparsely over the whole area, thought at first to be parts of a stony meteorite, gave the greatest resonance. After experimenting with the detectors for many hours at a number of sites, their use was abandoned. In his *Field Notebook*, Meen (1951a, entry for August 13) complained: "Damn mine detector yells at granite, gneiss, gabbro, and peridotite".

One of the most important studies to be undertaken on this expedition was to run magnetometer surveys of the rim to determine if a buried meteorite or fragments of a meteorite might exist there. Keefe and Cowan undertook this work. Lines up to 8,100 feet (2,469 m) long were surveyed at various points on the rim, and magnetometer readings were made at 500-foot (152 m) intervals. Bad weather and magnetic storms slowed this work, and it wasn't until 19 August that the survey reached the northeast part of the rim. This seems very unusual, since the previous expedition had pointed to the northeast rim as the most promising place to investigate, and Meen had already noted a strong local attraction there amounting to a deviation of 15–20 degrees East on his compass. A strong anomaly was located there, and a tight grid of five parallel lines 800 feet (244 m) long and 100 feet (30 m) apart was laid out, with stations set up at 100-foot (30 m) intervals to accurately map it.

Meen (1952a, p. 24) was jubilant:

Positive evidence at last! The anomaly indicated an area elliptical in shape and elongated east-west between the two highest peaks on the crater's rim. From the shape of the underground mass and the character of the magnetometer readings, it is highly improbable that it can be any ordinary body of rock. The most likely explanation, I believe, is that here lies a concentration of fragments from the exploded meteorite which were hurled forward with tremendous force and buried deep in the granite of the rim.

He thought he finally had the positive proof he had been seeking for the crater's meteoritic origin.

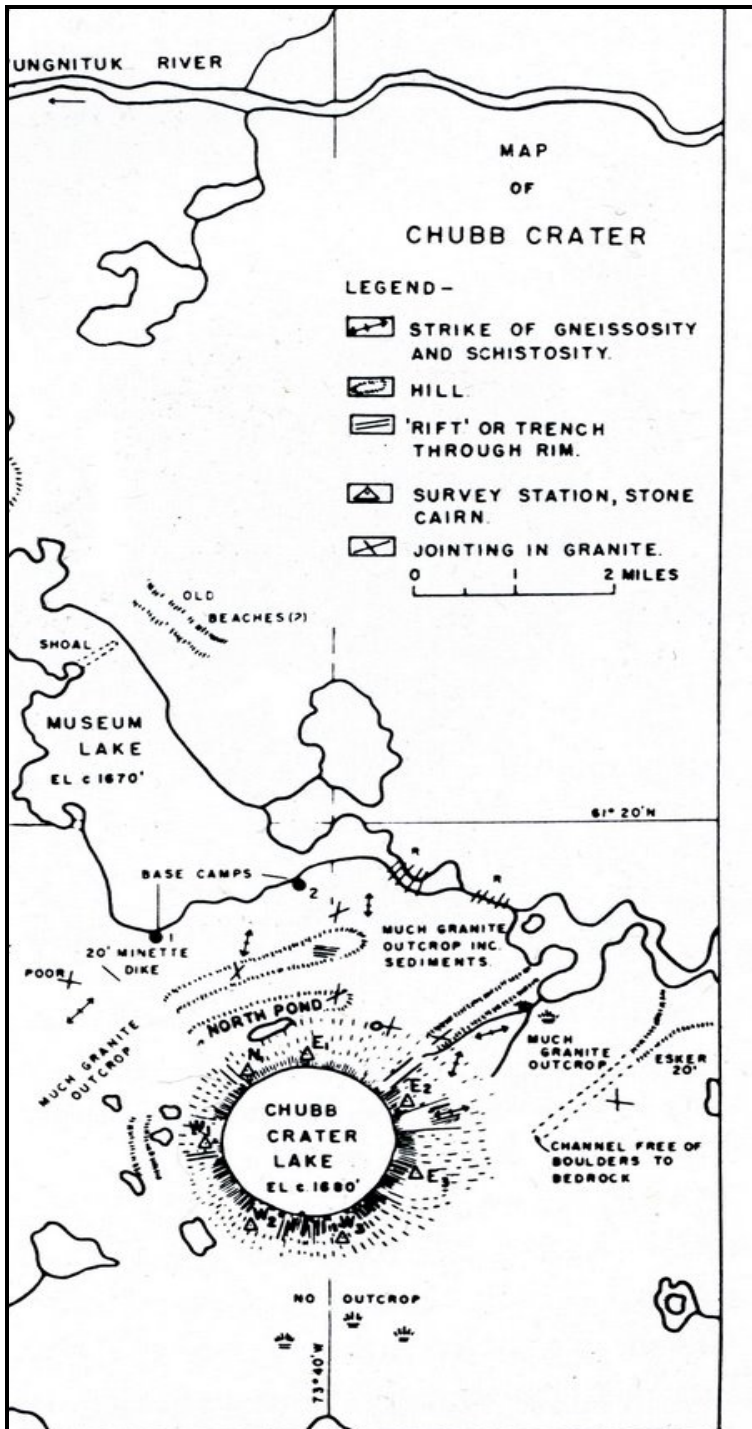


Figure 9.
Generalized geologic and topographic map of Chubb Crater and vicinity drawn following the 1951 expedition (V. Ben Meen, Chubb Crater—a meteor crater, The Journal of the Royal Astronomical Society of Canada 51: 141).



Figure 10.
V. Ben Meen dragging the expedition's 5.9 kg magnet over an area of fine gravel in search of metallic fragments (photographed by Richard H. Stewart, N. G. S. 101927T) (V. Ben Meen, The National Geographic Society–Royal Ontario Museum Expedition to Chubb Crater, Ungava, Quebec, 1951, p. 104).

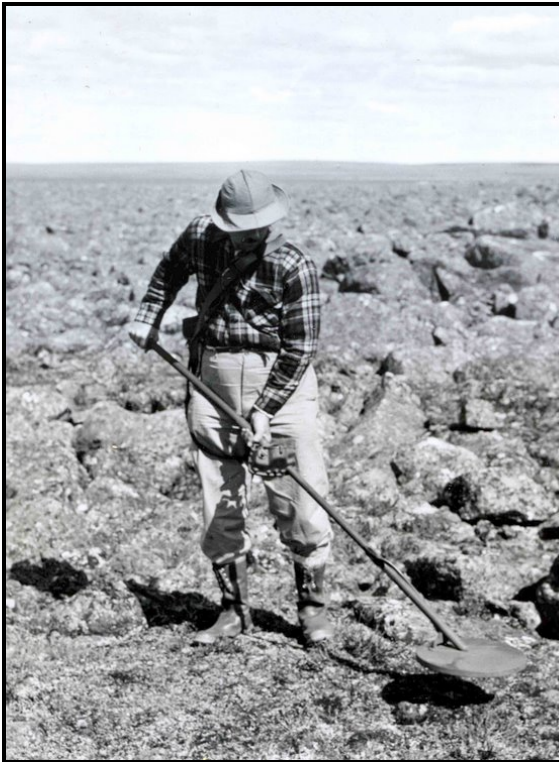


Figure 11.
V. Ben Meen operating a metal detector in a search for fragments of a meteorite (photographed by Richard H. Stewart, N. G. S. 101924T) (V. Ben Meen, The National Geographic Society–Royal Ontario Museum Expedition to Chubb Crater, Ungava, Quebec, 1951, p. 102).

On 21 August, the Canso arrived at 8:00 a.m. for the return flight. It took the entire day to dismantle the camp which had been set up at the crater rim, and portage the equipment two miles (3.2 km) over large boulders to a sheltered beach on Museum Lake where it could be ferried out to the plane. It wasn't until 6:00 p.m. that the last bag was aboard, the canoe pulled in and dismantled, and the plane could take off for the long flight home.

On the day following their Toronto arrival, the expedition team (minus National Geographic Society photographer Stewart) held an exuberant press conference. Newspaper accounts announced "Rock beneath crater held part of meteorite" (*Globe and Mail* 1951b) and "Chubb Crater probes get 'Magnetic Anomaly' hint of big meteorite" ([*Toronto*] *Telegram*

1951). The *Telegram* article quoted Meen as saying “that [the magnetic anomaly] goes along the path of proving beyond any doubt that Chubb Crater is of meteoritic origin”.

5. LATER INVESTIGATIONS OF CHUBB CRATER

But a short time later, J. Tuzo Wilson (1908–1993), a professor of geophysics at the University of Toronto, pointed out to Meen that since granite is slightly gneissic and that the gneissosity was somewhat greater at the location of the anomaly, there could be a sufficient concentration of magnetite there to account for the anomaly. Wilson further noted that such anomalies are reported to occur in northern Manitoba (Meen 1952b). In July, 1952, Keefe used the magnetometer data obtained at the crater to produce a report with the help of Wilson and S. H. Ward, a graduate student studying geophysics at the University of Toronto. Their ‘Report on survey of vertical magnetic intensity near Chubb Crater, July–August, 1951’ (Keefe, Ward, and Wilson 1957) corroborated Wilson’s earlier cautious position:

although the limited amount of data does not preclude the possibility that magnetic anomalies may exist which are caused by meteoritic fragments, no anomalies have yet been found which could not be satisfactorily explained by slight concentrations of magnetite in some bands of the country rock. Anomalies resulting from such slight concentrations are well known in other parts of the Canadian Shield.

Meen reluctantly acknowledged that he no longer had the positive proof he desired and thought he had, but pointed out that “the presence of a magnetic anomaly under the highest and broadest outthrow part of the rim, while not conclusive evidence of the presence of some buried fragments of the meteorite, seems to be more than merely coincidental”. Going further, Meen (1957a, p. 154) unequivocally stated “We can conclude, therefore, that Chubb Crater is an explosion crater and because of its tremendous size is due to extra-terrestrial forces”.

Needless to say, not everyone agreed. Even before seeing Keefe’s report, three astronomers took Meen to task: Paul Healy of the Institute of Meteoritics at the University of New Mexico; Lincoln LaPaz, the Institute Director who had a strongly combative personality; and Frederick C. Leonard (1896–1960), an astronomer at the University of California at Los Angeles, who had earlier co-founded the Society for Research on Meteorites with Nininger but was now LaPaz’s close ally in his battles (see further Plotkin and Clarke 2008). They held that in order for a crater to be authenticated as a meteoritic one, one or both of two criteria had to be met: (1) The discovery of meteorites in or near the crater, or metamorphosed or altered materials known to have resulted from meteoritic impact; and (2) The actual observation of meteorite falls having impact points in the crater areas. Moreover, auxiliary criteria such as the upturning or overthrow of horizontally bedded strata or evidence of bilateral symmetry could offer additional compelling evidence. Since neither of the two principal criteria nor any auxiliary criteria were satisfied at Chubb Crater, they argued (Healy, LaPaz, and Leonard 1953, p. 161) “to claim that a ‘proof’ of the meteoritic nature of a crater can be given merely on the basis of the existence of magnetic anomalies—i.e., magnetic highs, which are known to occur in and near many terrestrial features of obviously non-meteoritic origin—is, scientifically, quite unjustifiable”.

At the Dominion Observatory, Ottawa, Peter Millman had maintained his interest in Chubb Crater ever since reading Meen’s account of his first expedition and speaking with him afterwards. Although he believed the evidence of it being a genuine meteorite crater was strong, he felt that one of the most urgent needs for further scientific study was a detailed aerial study of the crater and its vicinity. At the Observatory’s request, the area around the crater was photographed on large scales by the RCAF in August, 1953.

In the course of this reconnaissance, J. M. Harrison (1915–1990), soon to become the Director of the Geological Survey of Canada, spent six days at the crater. In sharp contrast to Meen, Harrison found substantial evidence that glaciations had occurred at the crater. Glacial striae were noted at several localities around the rim (and could be clearly seen on some of the photographs), and glacially-polished surfaces were common on its rock outcrops; well-rounded

glacial erratic of material foreign to the crater were common; and perched boulders, a feature characteristic of glaciated areas, were common around the crater rim. Harrison further observed that the rifts noted by Meen did not radiate outwards from the center of the crater as he claimed, but instead intersected the rim at various angles, and those that were parallel to the direction of glacial movement were U-shaped sections characteristic of glaciated valleys. As to why the crater was not filled with glacial debris, he postulated that at the time of the formation of continental ice, the crater was filled with snow and eventually ice, so that the glacier would have smoothly slid over it. Moreover, the crater rim would have deflected the even flow of ice, so that most of the flowage would have been around the crater, not over it.

Harrison found magnetic anomalies at the south and southwest part of the rim, which he attributed to magnetite in the granite gneiss. He therefore did not believe the anomaly noted by Meen in the northeast rim was positive evidence of a buried meteorite. Through “inferential and negative evidence,” such as the crater’s round lake, unlike any other in the Canadian Shield; the lack of any vestige of volcanism in the area; and the crater’s high rim above a plain of ancient granitic gneisses, Harrison (1954, p. 16) was led to agree with Meen that “the impact or explosion of a meteorite appears to be the logical explanation for the crater”. He claimed that glaciation had obscured or destroyed so much evidence that it would be impossible to meet the criteria set forth by Healy, LaPaz, and Leonard to establish a meteoritic origin for Chubb Crater.

Predictably, LaPaz and Leonard disagreed. LaPaz argued that since evidences of meteoritic-impact origin had been found inside Meteor Crater, they should also be found inside Chubb Crater (now for a brief time renamed Ungava Crater). While admitting that the deep crater-lake constituted an obstacle to exploration of the crater’s interior, he concluded (1954, p. 229) that “until (and *unless*) systematic probing of the interior of the Ungava Crater reveals undoubted evidence of a meteoritic origin, meteoriticists will be justified in refusing to recognize this remarkable Canadian feature as a meteorite crater”. Leonard (1954, p. 229) was a little less harsh in his conclusion: “In the present state of our ignorance regarding the genesis of the Ungava Crater—an ignorance that must be freely confessed—it does seem rather unsafe, however, to predicate that the crater is of meteoritic origin just because it has not been satisfactorily explained geologically”.

Despite the objections of LaPaz and Leonard, there was growing support beyond that of Harrison for Meen’s contention that Chubb Crater was a meteorite crater. On the basis of the RCAF photographs, a topographic map of the crater area to a scale of approximately 1:25,000 was produced by the Surveys and Mapping Branch of the Department of Mines and Technical Surveys. Its scale was only approximate, however, since there was no ground control at the time the map was constructed. To establish the scale as accurately as possible, Millman drew sixteen uniformly spaced diameters of the crater, and plotted its profile along each of these. From these, he was able to determine the mean diameter of the rim and lake, and to study the variation in the rim height. He also addressed the problem of the rim’s unusually broad, rounded profile.

Comparing the crater’s topographic profile against Baldwin’s equations and using Meen’s value for the depth of the crater-lake, Millman found that the depth agreed reasonably well but that the mean height of the rim was only about half of that predicted. He felt that this could be explained by the fact that glaciations had substantially reduced the rim in its height, and softened its profile. Millman (1956, p. 18) concluded:

There has been nothing in the present investigation to negative [sic] the theory of meteoric origin for this feature. In fact, it is felt that the close agreement between the New Quebec Crater [as it was now renamed] and the normal series of explosion craters, considerably strengthens the meteoric theory and, in the absence of any other satisfactory suggestions, leaves a meteoritic origin as the best explanation for the presence of this large, symmetrical depression in the Pre-Cambrian rocks of the Canadian north.

The same conclusion, based on the same reasons, was reached by G. H. Beall (1960), who geologically mapped the Lac Laflamme (Museum Lake) area for the Quebec Department of Mines in the summer of 1959.

Additional support for the meteoritic origin of the New Quebec Crater came from Eugene M. Shoemaker (1928–1997) of the U. S. Geological Survey, who conducted a reconnaissance geological investigation of the crater under the auspices of the Dominion Observatory over a three-day period in August, 1961. Shoemaker, who had just launched an Astro-Geologic Studies Group at the Survey's Menlo Park, California office, was an authority on Meteor Crater, and noted that the New Quebec Crater bore a strong resemblance to it structurally. He examined what appeared to be throwout debris which formed part of the northeastern rim of the crater, but noted that a positive identification was not possible as the differences between throwout and frost-heaved bedrock were subtle in some places. He found that glaciations had removed a great deal of material from the rim, and felt that it was unlikely that any meteorites would be found outside the crater. Shoemaker (1962, p. 8) concluded: "[t]here seems to be little reasonable doubt that the crater is of impact origin", but critical evidence could only be achieved by drilling beneath the lake beds in the crater floor.

But in another Dominion Observatory study, M. J. Innes (1907–1980) utilized a different approach to arrive at what became the best field evidence yet for an impact origin for the crater. In two expeditions there, one in the winter of 1962–1963 and one the following summer, Innes obtained detailed gravity information over and around the crater. Horizontal and vertical control measurements and numerous soundings of the crater-lake were made in order to prepare a new topographical map of the crater. After correcting for the effects of irregularities in the terrain, water in the lake, and the regional gravity field, he found a well-defined residual negative anomaly of about 6 mgal symmetrical with the crater. Innes (1964) interpreted this as being due to low-density fragmental material underlying the crater floor. By this time, experience with a few other craters had shown that such negative anomalies were diagnostic of meteorite craters. Largely due to studies by the staff of the Dominion Observatory, or studies done under its auspices, strong support for Meen's conviction that Chubb Crater was a meteorite crater now existed.

6. CURRIE'S CHALLENGE

Despite growing support for the meteoritic origin of Chubb Crater, there were still some like Kenneth L. Currie (b. 1934) of the Geological Survey of Canada who were more cautious. In 1962, Currie and Michael R. Dence of the Dominion Observatory spent three months at the crater undertaking an exacting survey of it and its surrounding environment. They mapped about 50 square miles (12,950 ha) surrounding the crater at a scale of 1 to 500 feet (0.8–152 m). Despite such a detailed survey, they failed to find any meteorite fragments or highly shocked or shattered rocks (Currie and Dence 1963). Undaunted by their failure to satisfy the criteria of LaPaz and Leonard, they performed a detailed analysis of the dip—the amount of inclination or deflexion of rocks from their original position—of the rocks in the crater rim and surrounding terrain. From this analysis they concluded (p. 80):

The localized intense upheaval and outward tilting of the bedrock in the rim is consistent with the crater being formed by an explosive event. Because the direction of the symmetry axis of the deformation shows no relation to that of the regional foliation of joint systems, the symmetry is considered to reproduce that of the deforming force. This force is deduced to have originated along an inclined line, a conclusion compatible with the theory of impact origin of the crater.

Currie's first ideas about the crater thus placed him in line with Meen's interpretation. However, this did not last. Over the course of the next few years, Currie began to construct a volcanogenic origin for the crater that he thought better satisfied many of his field observations. He first published his thoughts about this origin for the crater in 1964, as part of a comparison with three other suspected Canadian impact craters. In two later papers published in 1965 and 1966, he focused exclusively on the New Quebec (Chubb) Crater.

The essentials of his volcanogenic hypothesis, which he termed the Volcano–Tectonic theory, were most concisely stated in a 1965 paper (Currie 1965a, p. 157):

This theory assumes that the crater results from the rise of a gas-charged magma which deforms the surface into a dome, eventually bursting through the dome and escaping. The dome then collapses into the void left by the escaping magma. Under this hypothesis the central part of the crater would be underlain by breccia (as it would under the impact hypothesis). The petrographic character of the breccias would, however, be quite different.

This style of volcanism, known as ‘maar’, was assumed to be characterized by an enormous gaseous or fluid/gaseous explosion bursting through the overlying country rock with a consequent collapse of the dome once the pressure is released.

For Currie, the Volcano–Tectonic theory better accounted for the observable facts. It would produce a basin-shaped, circular depression with a raised rim, it accounted for why no one had been able to find meteoritic material (there simply would not be any), and it explained why there was little or no throwout material found. It also accounted for a pervasive mineralogical alteration of the rocks in the rim and crater. These rocks contained high concentrations of the minerals epidote and hematite, which were sparse to absent in the surrounding country rocks. Such minerals form in granitic rocks when they are subjected to hydrothermal metamorphism. Essentially the warm to hot fluids anticipated to be in the uplifting magma would cause a chemical alteration of the precursor minerals.

In conjunction with this plausible volcanic hypothesis, Currie also pointed out the failure of the impact theory to produce convincing physical evidence for the origins of the crater. He interpreted the supposed throwout material previously reported by Shoemaker (1962) as being much more mundane frost-heaved rocks that one would expect in terrain which had been deeply weathered for millennia. He stated outright (Currie 1966, p. 10) that: “no area can be found that obeys the criteria for throw-out”.

Currie (1965a, p. 155) enumerated the criteria listed by Baldwin (1963, pp. 8–9) as being diagnostic for an impact crater:

(1) presence of meteoritic material, (2) presence of high pressure polymorphs (coesite, stishovite) characteristically occurring in impactite [an overall designation for all rocks affected by, or produced by, the shock waves and all other processes generated by hypervelocity meteorite impact events], (3) presence of ejecta (throwout) from the crater, (4) presence of crushed and fused materials in the rim and below the crater, (5) presence of shatter cones, (6) presence of a crater of distinctive shape.

Both Meen and Currie himself had failed to find any trace of meteoritic material, and no high-pressure minerals such as high-pressure polymorphs of quartz (coesite, stishovite) had been found in samples analyzed. Currie refuted Shoemaker’s evidence of ejecta (throwout), no one had yet drilled the bottom of the crater lake for evidence of crushed breccias, and no shatter cones—a diagnostic feature seen in rocks that have been subject to powerful shockwaves—had been seen. Additionally, Currie pointed out that the brecciated rocks anticipated to be under the crater could be formed by either hypothesis, impact or volcanic, and that both could reasonably produce the gravity low measured by Innes. In Currie’s rigorous analysis, Chubb Crater was claimed to be an impact crater based solely on its shape: “With the exception of the form of the crater, evidence for an impact origin of this crater is notably lacking. The shape of the crater may be suggestive, but, as we have seen, is not diagnostic” (Currie 1965a, p. 156).

Fallout or fall-back material, considered diagnostic of impact craters by LaPaz and Leonard, as well as by Baldwin, would be meteoritic or crushed, shocked and/or melted rocks which collapsed back into the crater after impact. However, as Currie mentioned in his initial paper, even after a detailed survey no evidence of such fallout material was recovered (Currie and Dence 1963).

Yet in 1964 Currie (1964b, p. 101) mentioned that he had found two peculiar rocks during his three-month stay at the crater in 1962:

During the search for fall-out, two ovoid bombs of black glassy material containing abundant fragments of partially decomposed granite were recovered. Microscopic examination and chemical analysis show that this material is fresh, vesicular basalt. The retention of fresh, glassy coatings, the preservation of open vesicles [entrapped gas bubbles], and the lack of abrasion suggest these fragments have not been transported very far. No known source of post-Paleozoic volcanics lies within 300 miles [483 km].

Consistent with his hypothesis of a possible volcanogenic origin for the crater, Currie interpreted these two ‘bombs’ as evidence of recent volcanism. The scant number of them was consistent with the maar-style volcanism which did not typically produce much solid ejecta, and given their fragile, vesicular condition, they could not have been transported any great distance glacially or by other natural means (Currie 1964b). Therefore, they must have been locally derived, and so were evidence of volcanic activity within the crater.

As well, the chemical analysis of the samples he undertook indicated that the bombs could not have been derived by a simple melting of the granite gneisses—the target rocks, as they are known—in which the crater had formed. They must have come from a different source, presumably the magma chamber that he posited was beneath the crater. These peculiar objects, however, would be re-examined four years later by other researchers who would come to strikingly different conclusions (see below).

Despite his cogent criticism, Currie recognized a crucial weakness in his Volcano–Tectonic theory. Everything was seemingly consistent with a volcanic origin of the crater except for the fact that other maar-style volcanism was not known to have ever occurred in the region of the crater: “the crater does not very closely resemble any known maar, and, moreover, is located by itself on a crystalline shield, hundreds of miles from any volcano of similar age. No satisfactory answer to these objections is known at present” (Currie 1965a, p. 157). In his 1964 paper and subsequent ones, he attempted to address this by placing the craters in a much broader regional setting, postulating forces which were deforming large areas of the Canadian Shield, and subsequently producing the volcanoes necessary to produce the observed craters. This was merely a postulate or speculation, however, and no evidence to support this was forthcoming.

While support for the impact origin of Chubb Crater was growing in a popular sense, there was still a good deal of debate and no certain answers. Much of the data collected previous to Currie’s work were inferential—the magnetic anomalies observed by Meen and others, the gravity low measured by Innes—or could be refuted outright, such as Shoemaker’s throwout material. By 1966, the proof of the origin of Chubb Crater was still illusive. As Currie himself had earlier stated (Currie 1964b, p. 102), “The cause of the crater remains uncertain”.

7. IMPACTITE AND SHOCK METAMORPHISM CRITERIA

While the impact origins of Chubb Crater and other craters were still being called into question by researchers such as Currie, supporters of the impact theory continued gathering evidence. More data tipping the scales in favour of impact were being steadily collected, even contemporaneously with the work of Currie. In 1963, T. E. Bunch and A. J. Cohen published a paper on their study of coesite and shocked quartz grains collected from drill cores at Holleford Crater, an impact crater that had been recently discovered in Ontario. Coesite, a high-pressure polymorph of quartz, had first been described from samples of the Coconino sandstone at Meteor Crater, Arizona by E. C. T. Chao, Eugene M. Shoemaker and B. M. Madsen in 1960. With a clear connection to a proven meteor crater, the presence of coesite became a diagnostic marker in support of a crater’s impact origin.

In the same year in which Currie first published his ideas on the Volcano-Tectonic theory, his former field partner Dence (1964) published a broad survey of ten suspected meteorite

impact craters in Canada. The largest of these, Manicougan, with a diameter of over 60 km, dwarfed Chubb Crater. Drilling had been done at several of these craters—Brent and Holleford in Ontario, and Clearwater Lake in Quebec—and compelling evidence from their drill cores lent credence to the impact theory (see below for more on the Brent and Holleford craters). Highly brecciated rocks with fused matrices often containing vesicles were encountered in the floors of the smaller craters. Quartz grains bearing characteristic planar deformation features, such as those reported by Bunch and Cohen at Holleford, were seen in these rocks. Under moderate shock pressures, feldspar will typically convert into a glassy material, and such feldspar-glasses were also seen.

Dence wrote that the floors of all the larger craters were lined with enormous quantities of cooled lava. Importantly, there was no evidence that this lava had been emplaced from below by volcanic or any other known geologic process. It had formed as the result of intense shock which melted the rocks lining the crater floors. Dence also noted that the rocks from all the craters sampled showed the characteristic kinds of mineralogical alteration that Currie had reported at Chubb Crater. He related this alteration to the crater-forming process. Heat liberated by the impact—sufficient in the larger craters at least to melt substantial quantities of rock—could drive the kinds of hydrothermal processes necessary to produce the alteration. Additionally, shatter cones had been collected from the West Clearwater Lake Crater.

The data reported by Dence in his 1964 work seemed to satisfy at least four (noted here in bold typeface) of Baldwin's six criteria:

- (1) presence of meteoritic material, (2) **presence of high pressure polymorphs (coesite, stishovite) characteristically occurring in impactite**, (3) presence of ejecta (throwout) from the crater, (4) **presence of crushed and fused materials in the rim and below the crater**, (5) **presence of shatter cones**, (6) **presence of a crater of distinctive shape**.

What were now missing were these sorts of markers from Chubb Crater.

At this time, there was a growing body of work surrounding the concept of shock metamorphism—the petrological transformation of rock by shock effects—and an increased understanding of its characteristic features seen both under the microscope as well as in the field. *The Shock Metamorphism of Natural Materials*, edited by B. French and N. M. Short (1968), was the first book to give shock metamorphism a solid petrologic basis. In this work, a paper by N. M. Short and T. E. Bunch, and another by P. B. Roberston, Michael R. Dence and M. A. Vos, revisited Currie's 'volcanic bombs' that he had found at Chubb Crater in 1962. Both teams of researchers found planar deformation features in quartz grains in the sample—evidence of shock, not volcanism.

Over the next twenty years, further searches for additional impact-related lithologies on the Chubb Crater rim and the immediate environs were unsuccessful. However, in 1986 and in 1988 important new discoveries were made at the crater. James D. Boulger Jr, while visiting the crater privately in 1986, picked up an odd pebble on the shores of Lac Laflamme. This pebble bore no resemblance to any of the surrounding country rock and contained vesicles. The sample was analyzed at the Harvard-Smithsonian Center for Astrophysics, and was found to hold abundant grains of quartz all showing planar deformation features (Marvin and Kring 1992). Boulger returned to the crater in 1988, as did a research team led by Michel A. Bouchard of the University of Montreal. Both teams found additional samples: Boulger one and the Montreal team twenty-one pieces (Marvin and Kring 1992).

Contrary to Currie's findings that the 'bombs' he found could not have been derived from the target rocks at the crater, Richard A. F. Grieve *et al.* (1991) found that the new impactite samples were very plausibly derived from the gneissic target rocks. They could find no reason why Currie's data should have indicated otherwise, but speculated that perhaps those samples were enriched in components that might have skewed the data. They also performed trace element analysis of the samples and found enrichments in iridium, nickel, cobalt and chromium. They interpreted these enrichments as contamination from the actual impacting body, which

appears to have been chondritic. As well, an age for the impact of $1.4 \text{ million years} \pm 0.1 \text{ Ma}$ was calculated based on ^{40}Ar – ^{39}Ar data. This wealth of new material provided some of the best evidence to date for an impact origin for Chubb Crater.

Even as Currie published his Volcano-Tectonic theory—often referred to today as ‘cryptovolcanism’—for the formation of Chubb Crater, the weight of evidence against him steadily grew. More and more work on craters across Canada and around the world built a convincing argument which has ultimately been widely accepted.

8. SIGNIFICANCE OF MEEN’S WORK

Meen’s work on Chubb Crater gave him immediate widespread recognition. His account in the National Geographic Magazine, ‘Solving the riddle of the Chubb Crater’ (Meen 1952a), was the lead article in an edition of two million copies distributed throughout the Western Hemisphere. By January, 1952, the magazine’s clipping service indicated that some 7,000–8,000 news items of the expedition had appeared in daily newspapers throughout the world, and that about 15,000 weekly papers had carried one or more stories on it (Meen 1952e). Meen’s talk to the National Geographic Society in Washington D. C. attracted 3,500 persons, and by year’s end more than 16,650 persons had attended forty lectures by him (Meen 1952d).

Following his Chubb Crater expeditions, Meen (1957) led a National Geographic Society–Royal Ontario Museum–U. S. Air Force Expedition to the Merewether Crater in northern Labrador in 1954 (not currently authenticated as a meteorite crater). He then changed interest away from meteorite impact structures, and much of his later energy at the ROM was devoted to building up its gemmological collection (Tushingham 1972). Perhaps his greatest achievement in this realm was his work on the Iranian Crown Jewels (Meen and Tushingham 1968).

Meen’s crater expeditions and later gemmological work played a large role in drawing attention to and increasing the stature of the ROM. Originally an outgrowth of the University of Toronto, its mineral collection originated with a purchase by the university in 1894 of some 3,000 specimens from the collection of Walter F. Ferrier (1865–1950), an Ottawa-based geologist and mining engineer (Parsons 1949). This collection was registered into the ROM in 1913 (Stevenson 1972), and formed the nucleus of its present collection. From a modest beginning, the ROM has evolved into Canada’s largest museum of world cultures and natural history. Its meteorite collection is now the second-largest in Canada, and is growing steadily; at the present time it contains some 200 distinct meteorites, with about 2,000 fragments in total (Herd *et al.* 2008). Nearly 120 specimens, including some of the most impressive meteorites from the Moon and Mars, are showcased in the recently-opened Vale Inco Limited Gallery of Minerals.

Undoubtedly the greatest significance of Meen’s work was that the tremendous interest aroused by his Chubb Crater expeditions led to an extensive photographic search for other possible ancient meteorite craters in Canada. Within half a dozen years, three were found. The first, the Brent Crater, was brought to the attention of the Dominion Observatory in 1951 by J. A. Roberts, the president of the Spartan Air Services Ltd., who spotted the nearly perfect circular feature from an examination of aerial photographs taken by his company for the Canadian Government. The Brent Crater is located in northeast Ontario, near the northern border of Algonquin Provincial Park, and like Chubb Crater, is approximately two miles (3.2 km) in diameter (Mark 1987).

A photograph of the crater was shown to C. S. Beals (1899–1979), the newly-appointed Dominion Astronomer. At the Dominion Observatory, Beals came under the influence of Millman, who brought Baldwin’s book *The Face of the Moon* to his attention and interested him in impact structures; together they thought it should be possible to locate meteorite craters in Canada like those that pockmarked the lunar surface (Halliday 1991). As a result, they and their colleagues at the observatory began to focus their attention along those lines. In July, 1951 Millman, accompanied by two scientists from the observatory and one from the Geological

Survey of Canada, spent six days exploring the Brent Crater site (Millman *et al.* 1960). In the winter of 1952, when core drilling began on the crater's frozen lake, Beals wrote to Baldwin and asked him how far below the surface of the ice they should expect to encounter impact breccias. Baldwin checked his data, and answered they should strike breccias at about 1,061 feet (323.4 m); they encountered them at 1,049 feet (319.7 m) (Marvin 2003, p. A170). The geophysical investigations that Beals and his colleagues carried out, employing gravity, seismic, and magnetic methods as well as a diamond drilling program, became a model for all later impact crater work.

Beals approached J. M. Harrison, the Director of the Geological Survey of Canada, and proposed a joint program to investigate meteorite craters. His proposal was declined, however. In the face of various degrees of scepticism by Survey members, Beals made the program a Dominion Observatory one (Hodgson 1994). In 1955 he inaugurated there a systematic study of aerial photographs for suspected impact structures. As historian of science Richard Jarrell (2009, pp. 230–231) points out, the observatory was in a unique position to take the lead in such a study:

The Dominion Observatory, with Beals's blessing, had several advantages: it had a long history and expertise in gravity, magnetic and seismological research and it was a Division of the Department of Mines and Technical Surveys (which also controlled the Geological Survey of Canada). Over the following twenty-five years, most of the impact structures discovered and studied lay in the Canadian Shield, about which the Survey had firm knowledge.

The photographs were part of the Canadian Air Photo Library, which contained about 2.5 million photographs taken from heights ranging from 5,000–35,000 feet (1,524–10,668 m). The Canadian Shield was chosen as the search area because of the facts that the Chubb Crater and Brent Crater were found in it; it was extensive in area, covering some 1,800,000 square miles (466,197,860 ha) comprising almost half of Canada; it was recognized to have remained geologically undisturbed for hundreds of millions of years; and, as noted above, was already well studied (Beals, Innes, and Rottenberg 1960a).

A second Ontario crater, the Holleford Crater, was discovered from the Canadian Air Photo Library photographs in 1956 by G. M. Ferguson and A. Landau. Study with a stereoscope revealed a relatively shallow circular depression about 100 feet (30 m) deep and about 1.46 miles (2.35 km) in diameter, with some indication of a raised rim. Beals took a personal interest in the study of this crater, and published the principal paper on its investigation (Beals 1960).

Still another crater, the Deep Bay Crater in northern Saskatchewan, was recognized that same year. Although the large, circular, water-filled depression which forms the southeastern part of Reindeer Lake had been observed from the air in 1947 by M. J. S. Innes, and was suggested to have been formed by a meteorite by D. S. Rawson of the University of Saskatchewan in 1951, it wasn't until 1956 that an expedition was organized to examine it. The results of topographical, geological, and geophysical observations carried out there indicated a meteoritic origin (Beals, Innes, and Rottenberg 1960b).

In 1966, Beals was awarded the Meteoritical Society's Leonard Medal "for his outstanding work in the discovery, the physical investigation, and the study of the origin of ancient Canadian meteorite craters" (Millman 1967, p. 53). Established in 1962 to honour Frederick C. Leonard, the co-founder and first President of the Society, the Leonard Medal is the Meteoritical Society's highest award, and Beals was its first recipient.

9. CONCLUSION

Meen's discovery of Chubb Crater; his efforts to solve the riddle of its nature; his persistent belief in the crater's meteoritic origin, even in the face of initial opposition and the absence of definitive field evidence; and the photographic searches this inspired combined to play a significant role in the development of meteoritic impact studies. In many ways, the meteorite

crater program was a natural one for Canadians to undertake, with their long tradition of geological, geophysical, and mapping studies. Canadian astronomers and geophysicists successfully joined forces in the search for other impact craters on the Canadian Shield, and in developing valuable criteria by which terrestrial meteorite craters could be authenticated. At the present time, thirty Canadian meteorite craters have been authenticated (Earth Impact Database 2006).

At the time of the discovery of Chubb Crater, only eleven terrestrial meteorite craters had been authenticated. It was the first meteorite crater to be recognized in Canada, and the first anywhere to be authenticated in the absence of associated meteorites. As meteoriticists Ursula Marvin and David Kring (1992, p. 594) point out, the crater “is of historical interest because . . . a meteoritic origin was proposed for it, strictly on the basis of its topographic form, at the midpoint of this century when meteorite crater studies were in their infancy”. Additionally, Chubb Crater was the first terrestrial impact structure larger than the smallest lunar crater, and fit well on Baldwin’s curve. The next three Canadian meteorite craters authenticated—Brent, Holleford, and Deep Bay—also fit Baldwin’s curve well (see Figure 12), and lent strong support to the argument for the relationship between the meteoritic origin of lunar craters and terrestrial impact structures.

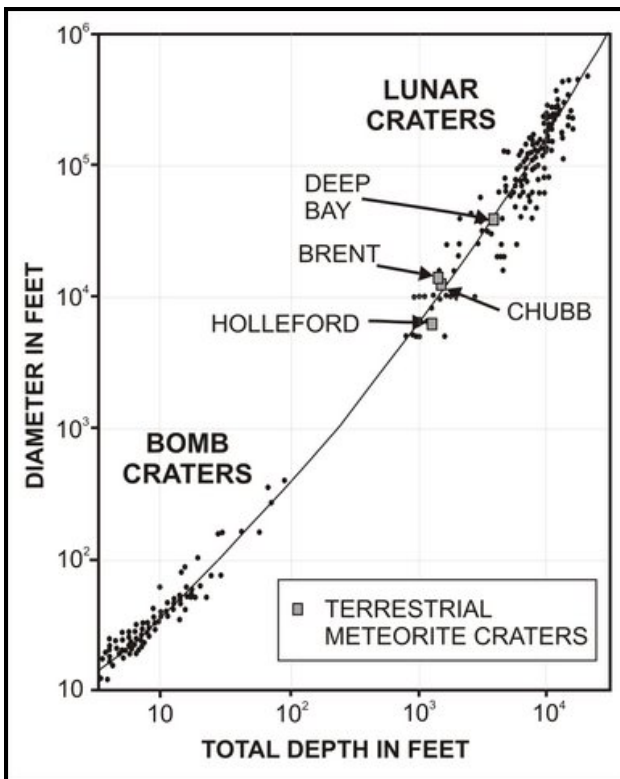


Figure 13.
Baldwin's curve relating crater depth to diameter, showing how well the Chubb, Holleford, Brent and Deep Bay meteorite craters all fit the curve (after C. S. Beals, M. J. S. Innes, and J. A. Rottenberg, *The search for fossil meteorite craters-I*, *Current Science* 29: 206).

Today, impact craters are broadly accepted as normal, though remarkably destructive, natural phenomena, the most famous, or perhaps infamous, being the Chicxulub Crater off the Yucatán Peninsula, Mexico, widely held to be a significant contributor to the demise of the dinosaurs. We now accept that meteoritic collisions have not only taken place on the Earth, but also on the Moon, as well as on some planets, satellites and asteroids. In the six decades following Meen's first expedition to Chubb Crater, we have come to realize that meteoritic impact is a fundamental cosmic process and one that has been operating over the entire 4.6-billion-year history of the Solar System.

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ARCHIVES

Many items relating to Chubb Crater and Meen—including his correspondence, published papers, unpublished talks, and other documents related to meteoritics—were culled by H. Plotkin from a score of boxes of uncatalogued historical papers located in the back of a storage room in the Department of Natural History at the ROM. He organized all the meteoritical documents and placed them in a filing cabinet that he set up in the Department. This material served as the basis for the present paper.

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