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IMPACT CRATERING STUDIES AT THE EARTH PHYSICS BRANCH: CURRENT STATUS AND FUTURE DIRECTIONS

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OVERALL STATEMENT

Impact is a ubiquitous physical process in the solar system. It is an important, often dominant process in solid-body accretion, planetary differentiation and early crustal evolution, and in the surface evolution of airless bodies. For example, the current favoured hypothesis for the origin of the Earth's moon is that a Mars-sized body impacted the early, growing Earth. Also, there is increasing evidence that large-scale impact can exert control over short-term changes in the Earth's climate and biological history. Impact, however, is not an easy process to study and fully understand. It is a highly transient, high energy process occurring for the most part at pressures, temperatures and time-scales not normally associated with geological processes. Present understanding is based primarily on observational data from terrestrial and planetary impact craters and their products and on the results of computational analyses and relatively small-scale experiments.

The Earth Physics Branch's pioneering work in impact crater studies dates back some thirty years. Initial studies were largely descriptive commentaries on probable impact structures in Canada. They evolved into detailed geologic and geophysical surveys and characterization of many structures, and encompassed an ambitious program of scientific drilling. With time the emphasis has become increasingly quantitative. Over the years, the Branch has established an international reputation as a centre of knowledge on terrestrial impact cratering and related studies, and has entered into a number of cooperative projects with scientists from universities and institutions in Canada, and also in the Federal Republic of Germany, the United States and the Union of Soviet Socialist Republics.

Early work on impact craters was often regarded by the scientific community as esoteric, if not part of the lunatic fringe of the geosciences.With U.S. and Soviet results of the planetary exploration program, it became regarded as an important planetary process but still with little relevance to the terrestrial environment. Most recently, there is a growing opinion that impact has an importance in terrestrial geosciences well beyond that exemplified by the relatively few (~ 100) known craters. At the present time, the bulk of academia and many workers in institutions at the federal level are cognisant of terrestrial impact as a geological phenomena, and the more progressive industrial groups are seriously considering the resource potential of impact structures.

As the acceptance of the occurence and importance of impact craters expands, it is more and more common to see publications by non-specialists actively seeking and describing possible new impact sites. While this is gratifying and, in part, an acknowledgement of the efforts of Branch personnel in this field, there is a down-side. These studies are often only cursory as the individuals or groups lack the experience and depth to expand their efforts. On the other hand, while some groups working in impact cratering-related studies have expanded their size and research interests, there has been an erosion of resources available to the equivalent group in the Branch. At this time, the Branch program in cratering studies is in a period of non-growth. There is concern that it is in danger of becoming a service organization or branch plant for outside groups, such as the Forschergruppe "Erde Mond-System" headed by D. Stoffler at the Univ. Munster, FRG, supplying samples and data that cannot be analyzed in house for various reasons.

There is no shortage of interesting problems to be tackled in the area of cratering studies. A factor in recent Branch efforts has been the amount of time that can be brought to bear on these problems given the limited personnel. To forestall further erosion of the Branch's pre-eminence in cratering studies, the cratering group hopes to concentrate on high-profile problems which in part address questions relevant to other aspects and processes in the earth sciences. Hopefully, basic documentation and first description type work will continue to be undertaken by utilizing students at the graduate level. While making use of student help and actively seeking cooperative research with workers at other institutions will make a contribution, it is important that there be clearly identifiable Branch products. With the limited personnel this requires rethinking of priorities and some commitment of additional resources, on an as needed basis.

PAST ACHIEVEMENTS

Prior to 1950 roughly a half-dozen meteorite craters had been recognized world-wide. Their discoveries were largely by chance, and their recognition relatively straightforward because they contained meteorite fragments. These early investigations were generally haphazard and piecemeal, carried out (with notable exceptions) by individuals who were more familiar with, and more interested in, recovering the meteorites. The EPB program was the first in which the talents and interests of a group of professional scientists were pooled to actively and systematically search for impact craters, make detailed field surveys, collect a suite of representative materials, and carry out subsequent laboratory studies. Fifteen years later, fourteen Canadian craters had been confirmed. The most recent addition, Eagle Butte, was confirmed only this summer by workers from Pan Canadian Petroleum. In addition, the number of confirmed craters in the world has increased to 112, in no small part due to searches stimulated by the interest generated through the scientific publications and more popular-style accounts of the Canadian discoveries.

The fundamental recognition of simple crater and complex crater morphologies was formulated from the surface and subsurface observations at impact structures in Canada. In Canada, a sufficiently large number of craters had been discovered, spanning a wide range of diameters, to permit intercomparison and correlation of the simple, small, and deep bowl-shaped features with the larger, relatively shallow structures containing a central uplift or rings that define the complex crater form. It was thus established that the latter were not attributable to a different origin, or a vastly different impact process, but that there is a progressive mophological variation and change in late stage cratering motions as crater diameter increases.

Several achievements of the EPB cratering studies have relied heavily, or exclusively on the drilling and core recovery program. The program itself is a notable achievement as it represented the first drilling for scientific purposes in Canada. Drilling from the ice over 100-200 m of water presented a challenge to the diamond drilling companies, and the techniques developed were useful to the drilling industry in general. Thirty-two holes were drilled at seven sites between 1955 and 1968, and the 10,000 m of core recovered continues to provide a source for a variety of structural, petrographic and geothermical studies. In particular, the twelve drill holes at Brent provided the first and still the only adequate physical definition of the crater floor in a structure of this size. The depth-diameter relationships established for Brent have become the datum for simple craters and the starting point for a number of crater modelling studies. In addition, examination of the core allowed characterization of the vertical distribution of shock effects beneath the crater floor, which led to calculation of shock attenuation rates and aided in understanding transient cavity formation through a combination of excavation and compression processes.

Samples of both allochthonous and autochthonous shocked material collected at Canadian impact sites furnish a complete spectrum of shock metamorphism in crystalline rocks, ranging from shatter cones to impact melt deposits. This collection was used for the initial, systematic characterization of progressive shock effects in common tectosilicate minerals, and various aspects of this classification scheme are routinely used to estimate shock levels in silicate materials thoughout the world. The lack of meteorite fragments in large impact structures was a principal argument used by those who advocated that such sites are not the result of meteorite impact and that so-called "shock" metamorphic effects resulted from endogenic, geologic processes. Although these arguments have no basis in physics, they are still advanced today. They have been rendered even more ineffectual, however, by geochemical analyses at the sensitivity level of parts per billion which reveal a meteoritic component in the form of anomalous siderophile element contents in impact melts at six Canadian craters. These discoveries were made in cooperative studies between Branch scientists and others at the Univ. of Chicago and the Max-Planck Institute, F.R.G..

The cratering program at EPB achieved early recognition because of the opportunities uniquely available in the Branch for combining various disciplines towards a more complete definition and understanding of impact craters and their environs. Whereas the efforts of other institutions are concentrated on either geology or geophysics, or on even more restricted aspects, such as geochemistry of impact melts, EPB studies have utilized geology, geochemistry, gravity, seismology, magnetism, paleomagnetism, and geothermics data and observations, plus empirical and theoretical modelling procedures. Scientists in the program have played important roles in the NASA space exploration and planetary geology programme. Their expertise was recognized in the field training of Apollo astronauts at Canadian impact sites, and in their participation as investigators of the first returned lunar samples. They have served and continue to serve on a number of NASA-sponsored committees and review organizations.

Like most new concepts, the idea that meteorite impact had been and continues to be an important physical process received slow acceptance. Later, although the presence of some terrestrial meteorite craters was generally accepted, studies of impact processes and shock metamorphism were still not fully integrated into geoscience studies. This has been changed, in part, by the synergistic relations between the high-profile results of planetary exploration and data supplied by terrestrial cratering studies. Planetary geology courses are now offered at many major universities. Several have Departments of Earth and Planetary Science with large, formal divisions devoted to planetological research. Although Canada is not a principal player in planetary studies, some Canadian universities have at least one faculty member who maintains an ongoing and active interest in cratering processes through his or her own research and the supervision of graduate students. At present, or in the past academic year, impact crater-related research has been carried out at Carleton (Carswell, Charlevoix), Ottawa U. (impact and catastrophic extinctions), Univ. Saskatchewan (Haughton, Carswell), Alberta (K-T boundary siderophile anomaly), Laurentian (Sudbury), Laval (Clearwater Lake). A listing of recent cooperative research studies between EPB personnel and outside agencies is given in Appendix I.

CURRENT AND FUTURE DIRECTIONS

Examination of the Program Book for the past few years indicates that research efforts fall into three major categories: (i) basic characterization of impact craters and associated features, (ii) investigation of physical processes associated with cratering phenomena, and (iii) the relevance of impact to other geologic studies, including practical or resource-related studies. The categories are not mutually exclusive as projects can evolve between categories and, in some cases, arise from targets of opportunity presented by work and interests outside the impact cratering study group at the Branch.

Examples of earlier contributions have been given above but not identified with a particular category of project. To illustrate more clearly the types of projects and the rationale involved, additional clarification is given below.

(i) Basic characterization projects contribute to the data-base on cratering phenomena. They are an essential background to any studies related to understanding how physical processes operate. Typical projects describe the nature and spatial extent of shock metamorphic features and characterizing impact melt rocks.

(ii) Process-oriented studies build upon the empirical data derived from (i) and include efforts to determine scaling laws and crater formational mechanics at both simple and complex craters. These studies often draw upon other experimental and/or computational studies performed outside the Branch.

(iii) Questions regarding the relevance of impact to other studies are often stimulated by contacts outside the immediate group at the Branch. Examples include cratering phenomena and their relation to the evolution of planetary volcanism and early crustal evolution. More practical studies include the relevance of cratering studies to the Siljan Deep Gas Project, the stability of nuclear waste depositories on geologic time-scales and as a geologic analog to certain facets of nuclear winter scenarios.

While acknowledging the scientific contributions of impact cratering studies at the Branch, it is recognized that such studies cannot continue as in the past. The continuing erosion of personnel resources requires that the program of study be organized to address highly visible, relevant research topics. This will require a readjustment of current resources and an effort to design projects attractive to other workers, in order that other scientific resources within and outside the Branch can be utilized. The major problem with the current program is that there are too few resources to do first-rate science on all projects. Effort must be prioritized and supplemented when possible. With this in mind, the following suggestions are made for future directions.

(i) Basic characterization studies

Much remains to be done with respect to the nature of impact craters and their products. Although this is an area where Branch personnel have made important contributions and gained considerable reputation, it is not clear whether this can continue to be a prime area of study. It is a waste of limited resources to have experienced scientists engaged in performing all aspects of basic characterization. However, as this is a fundamental component of impact studies, it cannot be completely abandoned. Specifically, it is suggested that efforts be made to have much of the data acquisition aspects undertaken by students or young professionals, with experienced Branch scientists acting in a supervisory role. An example of such an approach was the recent work on the Boltysh melt rocks, which was completed in four months by Mr. G. Reny at minimal cost. To this end, the cratering group has compiled a list of basic characterization studies which may be suitable for junior personnel. An abbreviated listing of these projects is given in Appendix II. The pool of available resources drawn upon includes senior undergraduates in COSEP and COOP programs, staff and graduate students at Canadian and other universities and term employees. There are, however, two immediate areas which can draw upon in-house talent. These are:

(a) SEM-TEM work on shocked materials. Apart from some limited work in Europe, this an open field which is relevant to understanding the behavior of geologic materials subjected to strong shock waves. It is proposed to utilize the talents of Mr. P. Chernis. He is an AECL employee with considerable experience in micro fracture analysis. Mr. Chernis has agreed to spend some of his own time on this study area in order to make comparisons with previous studied materials for AECL. It is planned for him to begin by examining the nature of from the Brent crater. The project is in cooperation with NASA-JSC and will utilize optical and electron microscopy techniques, as well as electron microprobe. It also illustrates the continuing need for basic descriptive studies. Granitic gneisses are the target rocks for the majority of impact craters on the cratons but no experimental data is available on the pressures required to produce impact melting in such lithologies.

(b) A review of the geophysical character of impact craters. There is currently no comprehensive work on this subject. Considerable effort has been made by the Branch to acquire geophysical data over craters but it is in fragmentary form. For example, it is not known how or why the gravity signature of impact craters changes with diameter. Such a study will provide basic information for use in modelling cratering dynamics and assessing the signature of craters where no data are available. That such a need exists can be made clear by the following example. The Swedish Power Board is extremely interested in the geophysical nature of the 50 km Siljan structure, which is currently the focus of a multi-million dollar project for deep gas. We are able to supply details with respect to specific examples such as Manicouagan. We cannot, however, provide a coherent, cogent picture of the geophysical nature and a sub-surface interpretation for large impact structures in Precambrian terranes. Such a review, as envisioned here, would be comprehensive and would require the assistance of other personnel from the Branch.

(ii) Process Studies

As with previous work, the characterization projects outlined above will undoubtedly lead to process studies. For example, how does impact melting proceed and what variations in the geophysical signature of craters relate to changes in crater formational processes. A shortcoming in tackling process problems is the geological background of present personnel. To circumvent this problem, it is necessary to become involved with outside workers who are, at least in part, familiar with details of impact processes. Examples of future efforts in this area include:

(a) The Haughton Impact Structure Study (HISS) Project. During the 1984 field season, considerable effort and money was expended to acquire multi-disciplinary data at the Haughton structure on Devon Island. A formal research agreement was entered into with Dr. Z. Hajnal at the Univ. of Saskatchewan with regard to the gathering and interpretation of seismic data. Structural, petrographic and other geophysical data were acquired, in large part by representatives of Dr. D. Stoffler's group at the Univ. Munster, FRG, which also defrayed part of the cost. The objective of the study goes beyond the full characterization of this well-exposed structure. It is intended provide details of the processes that lead to ring formation at large impact structures. The final results of the project will appear as a series of individual scientific contributions and a synthesis. Although EMR-EPB provided a good portion of the funds, logistical support, and scientific expertise there may be problems in maintaining continuity and coordination. Our scientific input into this study is severely limited by lack of personnel, when compared to the student body that can be drawn upon by the universities of Munster and Saskatchewan.

(b) Impacts and the biosphere. This is a very topical research area and will continue as such for many years. Our current participation is concentrated on the search for physical evidence of impact at the Cretaceous-Tertiary boundary, and to addressing the question of the reality of periodic cometary impacts on earth due to solar system perturbations. This work can be extended in two areas: searches of the record for evidence of major impact at other mass extinction events, and a detailed assessment and search for the effects of large impacts on both the geosphere and biosphere. Large impacts must affect the geosphere outside the immediate area of the crater, but as yet no effects have been documented. The question is whether this results from a poorly preserved record or the simple fact that insufficient effort has been made to recognize such effects.

(c) Scaling relationships. Crater scaling relationships remain an elusive objective. Current scaling laws based on empirical data from craters can be shown to underestimate the energies involved. Conversely, laws based on dimensionless relationships derived from experiments overestimate energies for large events. A major shortcoming of the dimensionless relationships is that they ignore energy losses associated with irreversible waste heat and its variation with impact velocity. It is proposed to design a series of experiments using the NASA-Ames facility to investigate the effect of impact velocity on scaling laws. This project would be in cooperation with personnel at NASA-JSC.

(iii) Relevance of impact to other studies

This area is considered to be increasingly important. Two main objectives outlined below assess the relevance of impact phenomena to planetary evolution and resource development.

Planetary evolution studies

These studies are designed to take advantage of the vigorous research environment afforded by the NASA planetary geology program.

(a) Early crustal evolution. This study has grown from a semi-quantitative assessment of the role of large-scale impact in crustal evolution, to quantitative models of the thermal effects, rates of heat loss and thermal subsidence in very large impact basins. Considerable additional modelling is required to fully assess the relative importance of impact. As with other projects, current efforts involve cooperation with outside workers. The original concept was developed at the Branch and efforts so far have led to three extended abstracts and contributed to a general paper. Once the current stage of modelling convective heat-losses is completed, it may be advantageous to utilize available in-house expertise in tectonophysics.

(b) Microgravity cratering. NASA is planning to explore the microgravity environment for experiments that address problems in planetary geology. These are designed to be flown initially on Shuttle and ultimately Space Station. Initial experiments are being undertaken on NASA's KC-135, which can sustain low gravities and even zero gravity for several seconds. Although NASA personnel are the lead players, we anticipate participation in experiment design and interpretation with the immediate questions to be addressed concerning crater growth. One of the principal advantages of the microgravity environment is that growth time is effectively slowed and high speed cameras can record details of growth phenomena and relative size. Initial experiments will be full-space, and half-space designs will follow.

Resource-related studies

(a) Impact and mineral resources. Until recently the possible importance of impact in the control of economic mineral and fossil fuel deposits received little consideration by the exploration industry. For

example, although it became accepted by some that Sudbury was associated with an impact event, this was regarded as a unique circumstance and an understanding of cratering processes wasn't necessary or useful in the search for and delineation of the ore bodies. This notion has been at least modified and an INCO geologist has reported on the relationship between the emplacement of the ore bodies and the morphology of the crater, in particular the development of sulphide deposits in troughs and slump terraces whose equivalents are readily observed in large lumar craters.
Similarly, AMOK geologists have realized that the uranium deposits at Carswell are highly influenced by the crater structure and are, therefore, actively pursuing and encouraging research on the structure. This summer AMOK provided full support in the field and total access to the 300,000 m of drill core to a graduate student from the University of Munster in pursuit of his doctoral thesis, in return for a sharing of information and interpretation.

On a general level, it is well known that the increased fracturing and hydrothermal activity at impact sites can lead to secondary mineral enrichment. The whole question, however, of the potential of impact sites for ore deposition has not been considered fully and constitutes an obvious area for research and documentation.

b) Impact and Hydrocarbon resources. Oil and gas deposits have been discovered at a few subsurface structures of probable impact origin in the Williston basin in Canada and the United States. There is an increasing awareness of this association in the oil industry such that possible impact structures are now actively sought, including ones in the deep crystalline basement which had been regarded as barren terrane. As an example, two large enigmatic circular features in Alberta were recently examined from an impact structure viewpoint by Mobil Oil to assess their potential for oil reserves. In Sweden, the State Power Board drilled 7 holes in 1984-85 at the Siljan impact structure in a search for deep-seated, abiogenic gas. Although the hypothesis of primordial gas doesn't require an impact for its origin or concentration, the belief that large structures like Siljan generate fractures that allow migration of the gas into a more accessible region is receiving serious consideration. The considerable current interest in the industrial community on this question is evidenced by the AAPG's recent decision to create a sub-committee on Impact Cratering Geology. Again, however, there is no definitive work on the hydrocarbon potential of impact structures. Such a project would build heavily on the basic characterization of the geophysical signature of impact craters and discuss the various types of traps

that can result. Such a project would have to involve personnel conversant with seismic data, as this is a major exploration technique for oil companies. If performed correctly, this work could provide a benchmark for industry.

SUMMARY STATEMENT

In terms of research discoveries, cratering studies of the Earth Physics Branch have had an enviable record. The present sitution, however, is potentially less favourable. With effective resources approaching 1 PY there is a consequent slow down in productivity and the Branch is currently at risk of losing its eminent position in cratering studies.

It is debatable whether it is possible to regain the research vigor of 5-10 years ago. Nevertheless, it is proposed to attempt to revitalize cratering studies by identifying a number of relevant research problems which have high visibility in the community and/or represent benchmark studies.

Successful completion of these problems will require commitment on the part of the appropriate research staff and the visible support of management. The latter is required to ensure, as needed, the participation of personnel outside the cratering studies group. Without this commitment and infusion, it is likely that cratering studies will atrophy and ultimately cease to be viable due to neglect rather than the completion of a defined research program.

APPENDIX I Cooperative research outside EPB since 1972.

INSTITUTION	SUBJECT
Univ. Toronto, Canada	$Ar^{39}-^{40}$dating of impact melt rocks
Univ. Chicago, U.S.A.	Meteoritic contamination in melt rocks
Max-Planck, FRG	
Brown Univ., U.S.A.	Crater morphometry and late-stage modification processes
	Cratering mechanics and scaling
	Impact and early crustal genesis
NASA - Johnson Space Center, U.S.A.	Shock recovery experiments. Microgravity cratering.
NASA Goddard Space Center, U.S.A.	Periodic impact and biosphere effects.
Univ. Munster, FGR	Crater structure, formational processes and shock studies, as part of HISS Project. Rb-Sr dating of impact melt rocks.
Univ. Saskatchewan, Canada	Seismic interpretation study as part of HISS Project
Geological Survey, Canada	Lunar sample analysis and interpretation. Siderophile-rich particles in melt rocks.
Geological Survey, U.S.A.	Lunar basin and crustal evolution
Vattenfall, Sweden	Siljan Deep Gas Project

N.B. Only two of these cooperative projects are the results of formal research agreements.

APPENDIX II Research topics suitable for MSc thesis projects.

1. Shock Metamorphism of Carbonate and/or Sulfate Minerals

A number of Canadian impact structures occur in terranes that comprise entirely, or largely carbonate lithologies. A scheme of progressive shock metamorphism has been developed for the common rock-forming minerals of granitic or crystalline rocks, which permits an estimate of the shock level in samples collected from various regions of a crater. A similar scheme has not been defined for carbonate minerals. It has been assumed that calcite may recrystallize readily at low shock pressures and dissociate at higher pressures so that no permanent shock features are preserved in this mineral. Insufficient work, however, has been done to verify this. Questions to be addressed include: Do the minerals calcite and gypsum display a definitive type of shock metamorphism in the 2 to 20 GPa range? Can a progressive scheme of intensifying deformation with increased pressure be established?

2. Mobility of Potassium in Shocked Rocks and Minerals

As a sidelight to earlier petrochemical studies of shocked crystalline rocks it has been noted that potassium occurs in anomalous situations and concentrations. In maskelynite, for example, a solid-state transformation to a vitreous feldspar, electron microprobe analyses reveal potassium in excess of the normal host plagioclase that may result from migration in the solid state from antiperthite inclusions. Also, up to 3% K_2O has been discovered in shocked sillimanite, a mineral that normally contains no measurable potassium. Questions to be addressed include: At what shock level does potassium become mobile? Are there preferential sites for migration? Is an anomalous potassium content a possible geobarometer or geothermometer? This study could be expanded to include the physics of diffusion mechanics. In this case, it seems very unlikely that potassium movement is due to the usually considered thermal diffusion.

3. Distribution of Shock Effects in Three Dimensions.

The occurrence and distribution of distinctive macroscopic and microscopic shock effects as a function of distance from the point of impact has been characterized in the horizontal plane from surface samples at complex craters, and shock attenuation rates have been calculated on this basis. Data available from drill core samples to extend this study to the third dimension are comparatively few. What are available are generally not interpreted from this aspect or, from cursory analysis, apparently inconsistent. Recent drilling at Siljan and acquisition of drill cores from Carswell could provide sufficient material to clarify, and hopefully define the distribution of shock effects beneath a large crater, and possibly contribute to an understanding of large scale movement involved in complex crater formation.

4. Petrology and Chemistry of Shocked Rocks from the Deep Bay Crater:

Drilling at sites near the centre and margin of Deep Bay have furnished cores of disturbed and shocked basement gneisses, allochthonous impact breccia, plus post crater sediments. This material has already provided samples for a variety of specific studies, but the general petrography of these rocks is very poorly documented. Although there are similarities with shocked rocks at other impact structures, the petrologic nature of the Deep Bay high grade gneisses with abundant garnet and graphite, plus cordierite, should lend a distinctive character to the impact breccias which furnish an interesting suite for a detailed petrochemical analysis.

5. Petrology and Chemistry of Shocked Rocks from the Wanapitei Impact Crater

Wanapitei presents a similar situation to that at Deep Bay in that a fundamental characterization of the suite of shocked materials is lacking, although samples of the allochthonous breccia have yielded critical data in support of a number of shock metamorphism studies. The Wanapitei problem has its own unique character, however, in that all material collected to date is from glacial float, most of the cratered lithologies are quartzitic meta sediments, and the relatively young impact age has allowed preservation of abundant, fresh, glassy material. Coesite has been recognized in this material and is sufficiently prominent to be identifiable in thin section so that its development and occurrence could form a significant aspect of this study, or provide the basis for a separate and specific treatment for coesite using materials from here and other coesite occurrences, such as Haughton.

6. The Steen River Impact Structure, Alberta

Steen River is a buried structure without surface expression whose form and impact origin were established from preliminary examination of drill core samples and drilling records. Since its discovery and somewhat simplistic interpretation approximately 25 years ago, the general state of knowledge and understanding of the formation of complex craters and their structural aspects has advanced considerably, yet no attempts has been made to expand or re-assess the data and its interpretation at Steen River. At 25 km in diameter, well preserved by a thick sedimentary cover and formed in sedimentary and crystalline rocks, Steen River has significant potential for comparison with older, highly eroded structures of similar size and situation. As the crater lies in a region of oil and gas exploration activity, examination of core from more recent wells and assessment of geophysical records should be possible, and could provide the necessary information to delimit this structure and possibly resolve some long-standing problems common to a number of buried impact sites.

7. Shock Metamorphism from X-Ray Analysis

The presence of planar deformation features in quartz is a distinctive and readily observed result of shock metamorphism. As the number of sets and their orientations has been correlated with ranges of shock pressure from laboratory experiments, their development in naturally shocked materials can provide a reasonable estimate of shock stress in these rocks. Characterization of the population of planar features in a given sample is a laborious task, however, involving exacting universal-stage microscope techniques, and is not often undertaken. Experiments have also demonstrated that x-ray properties of shocked quartz are progressively affected. Since X-ray analysis is generally a rapid and routine procedure, it would be advantageous to assess shock level in this manner. A quantitative relationship between degree of shock and amount of disturbance of X-ray properties might be established through a program of X-ray analysis of naturally and laboratory shocked materials whose shock levels are known.