ECONOMIC GEOLOGY RESEARCH UNIT

University of the Witwatersrand
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IMPACT CRATERING - A REVIEW, WITH SPECIAL REFERENCE TO THE ECONOMIC IMPORTANCE OF IMPACT STRUCTURES AND THE SOUTHERN AFRICAN IMPACT CRATER RECORD

W.U. REIMOLD

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(Based on an invited lecture presented to the Fourth United Nations/European Space Agency Workshop on Basic Space Science, Cairo, June 27 - July 1, 1994)

by

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ABSTRACT

Only in the past few decades has impact cratering been recognized as an important surface process on all planetary bodies in the Solar System. However, as the significance of impact cratering has not yet been effectively introduced into geological curricula, there is a need to outline and review its importance for (i) planetary formation, (ii) evolution, (iii) understanding the process in the geological context, (iv) the terrestrial impact crater record and its limitations, (v) the recognition criteria for terrestrial impact structures, and (vi) the need for improvement of the impact cratering record in the light of the potential danger of an impact catastrophe on this planet.

In addition, the economic significance and mineralization potential of impact structures is highlighted and the history and progress of impact studies in southern Africa is summarized.

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CONTENTS

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IMPACT CRATERING - A REVIEW, WITH SPECIAL REFERENCE TO THE ECONOMIC IMPORTANCE OF IMPACT STRUCTURES AND THE SOUTHERN AFRICAN IMPACT CRATER RECORD

INTRODUCTION

Since Galileo Galilei's first telescopic studies of the lunar surface, the importance of cratering as a planetary surface phenomenon has been known to man. However, only the space exploration activity of the second half of the Twentieth Century revealed the true extent to which all bodies in the Solar System have been subjected to the continuous bombardment by comets, asteroids, and smaller meteorites. It became abundantly clear that, besides volcanism, which has played a major role on certain extraterrestrial bodies, such as Mars, impact cratering has not only represented an important surface-modifying process, but has arguably been one of the most important processes since the earliest beginning of the evolution of the Solar System. In addition, impact processes are now considered to have played a vital role in planetary formation through accretion of larger bodies as the result of impact of planetesimals (e.g., Melosh, 1989; S.R. Taylor, 1992). The currently most widely accepted theory for the formation of the Moon maintains that this body formed as the result of the impact of a Mars-sized projectile onto the proto-Earth ("Giant Impact Theory" - e.g. reviews by Melosh, 1989, S.R. Taylor, 1992; G.J. Taylor, 1994). Other important processes on planetary surfaces resulting from impacts, are, amongst others, planetary erosion by impact, disruption of smaller bodies, impact-induced volcanism, and the origin of planetary atmospheres (Melosh, 1989; S.R. Taylor, 1992).

During the 1960's and 1970's the impact cratering rates for the terrestrial planets of the Solar System, since the beginning of their circa 4.5 Ga evolution, were well constrained (S.R. Taylor, 1992, and references therein). It was established that during the first 800 Ma, cratering rates were extremely high with a large number of giant projectiles being responsible for the formation of gigantic multi-ring impact basins of up to several thousand kilometres in diameter. At later times the cratering rates decreased rapidly. It is still strongly debated whether a major, final influx of large projectiles (the so-called 'Terminal Cataclysm' - derived from a predominance of 3.95 - 3.85 Ga ages for lunar impact breccias - e.g., Ryder, 1989) took place at about 3.85 Ga ago.

Comparative remote sensing studies of cratered planetary surfaces, detailed analysis of the rock and mineral deformations in positively identified terrestrial impact structures, (compared with those in lunar samples and meteorites), as well as from experimentally impact-deformed minerals and rocks, have led to an integrated (and multidisciplinary) understanding of the processes involved in impact cratering, crater modification, and impact-induced deformation of the target rocks.

A comprehensive treatise of the physical aspects of impact cratering, particularly of the various stages (namely the compression, excavation, and modification stages) in the development of an impact structure, as well as the structures of the final crater types (< 4 km diameter simple, bowl-shaped impact craters; larger, complex structures with central uplifts or central peak rings, terraced rim structure, or multi-ring development) was presented by Melosh (1989).

The importance of impact cratering received widespread publicity following the recent impacts of fragments of comet Shoemaker-Levy 9 into the atmosphere of Jupiter. This event demonstrated the enormous energy release of large comet or asteroid impacts and the need to understand this process and its temporal statistics in the view of the potentially catastrophic effects such impacts could have on Earth.

Nearly 15 years ago, the geological-palaeontological community was stirred by the suggestion that one or several large impact events could have disrupted the biological evolution on Earth at the time of the Cretaceous-Tertiary (K/T) boundary, at about 65 Ma ago (Alvarez et al., 1980). This proposal received much attention because of the debate that developed between proponents of an extraterrestrial versus internal (volcanic) cause for this mass extinction (e.g., papers in Silver and Schultz, 1982; Sharpton and Ward, 1990). In recent times the majority of planetologists, geologists, and palaeontologists have agreed that at least one catastrophic impact event took place at the K/T boundary, and the debate has focussed on the possible source crater for the K/T ejecta, the 200-300 km wide Chicxulub crater off the Yucatan peninsula in Mexico (e.g., LPI, 1994, Sharpton et al., 1993). Attention has also been given in recent years to the question of whether, at other times in the stratigraphic record, large impact events caused environmental catastrophes which could have influenced faunal evolution.

In the light of such potentially catastrophic, life-threatening, forces, there is a clear need to determine precisely the availability and nature of threatening projectiles (e.g., Shoemaker et al., 1990), and to assemble a well-constrained impact crater record for this planet, in order to assess the danger level from such projectiles. Accepting that "knowledge of the historical record can assist in finding solutions for present concerns" leads to the need to document the role of impact right back to the earliest phases in the evolution of planet Earth.

In contrast to this fatalistic approach that centres on the inevitability of possible catastrophic impact on Earth, some terrestrial impact structures have proven to be of much use to mankind, having provided or influenced some of the world's foremost ore deposits.

In this paper the currently established terrestrial impact crater record will be illuminated. Before attempting this, however, it is necessary to discuss the recognition criteria of impact structures. The economic potential of impact structures is discussed and recent progress made on the Southern African impact crater record will be examined.

CRITERIA FOR THE RECOGNITION OF IMPACT STRUCTURES

A number of review articles on the nature of impact craters and the associated deformation phenomena employed for their recognition have been published in recent years (e.g., French, 1990; Sharpton and Grieve, 1990; Koeberl, 1994). First-order morphological indications for the presence of an impact structure include circular crater geometries (some elongated and asymmetrical structures are also known in the terrestrial crater record), the findings of shallow and rootless structures, and crater morphologies with raised rims and/or annular troughs. In general, impact craters smaller than 4 km in diameter will have a simple, bowl-shaped form, whereas larger craters will display complex geometries with central uplifts (peaks) or peak rings, terraced crater rims, and, when larger than ca. 100 km, they may have multiple rings ("multi-ring impact basins") (Figs. 1 and 2). Larger crater structures display a flatter morphology than small, bowl-shaped features, and in the case of older, deeply eroded structures, parts of the central peak formation may be the only recognisable remnants of such large craters.

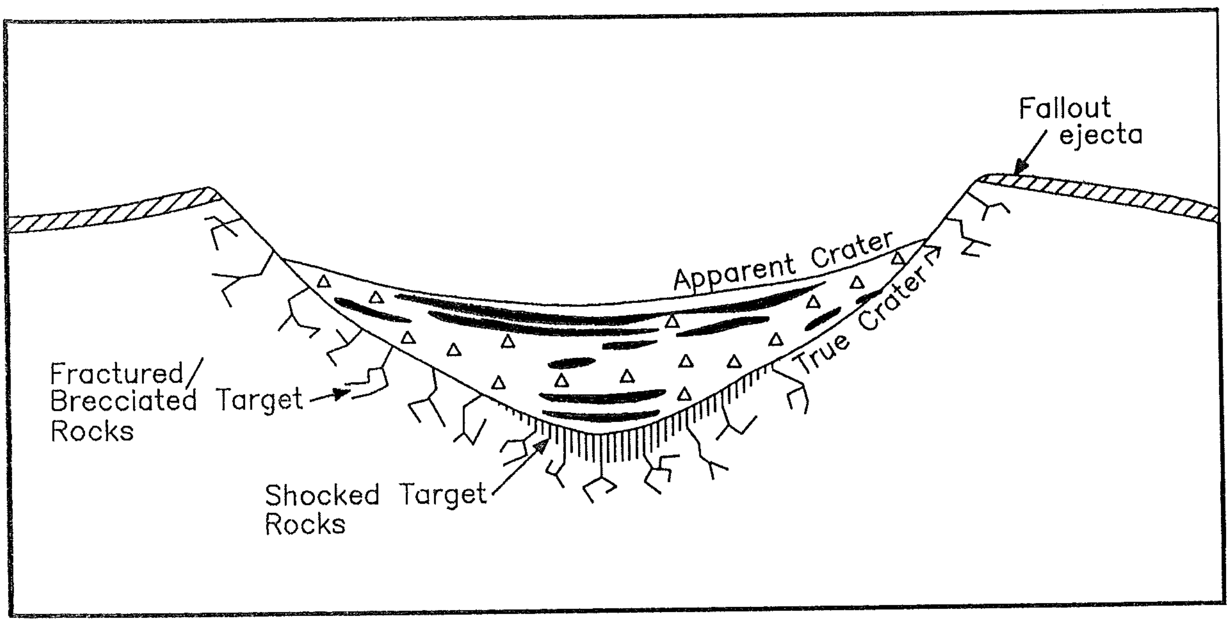

Figure 1: Schematic cross-section through a simple, bowl-shaped impact crater with the generalized setting of different impact formations (after Grieve, 1991). In this case, the crater fill consists of polymict suevitic breccia (triangles), intercalated with lenses of impact melt breccia (black).

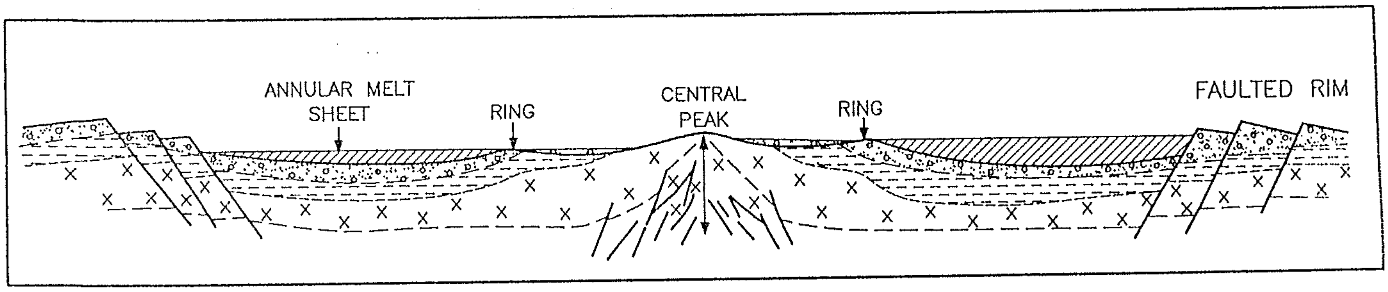

Figure 2: Schematic cross-section through a complex impact structure with central uplift and terraced rim. The annular melt sheet is shown to be underlain by more clastic impact breccia (circles/dots), which in turn covers a stratified basement consisting of sedimentary (dashed horizontal lines) and crystalline (crosses) rocks (after Grieve, 1991).

Geophysical anomalies, in particular gravity anomalies, are often associated with impact structures (Pilkington and Grieve, 1992) and in many cases have provided the only indication of later confirmed impact craters. Information of this type can be particularly important in identifying old, eroded structures or structures that are completely buried underneath later sediments (e.g., Hartung et al., 1990; Sharpton et al., 1993). Considering the fact that about 70% of the Earth's surface is covered by oceans, a large number of impact structures remain to be discovered in this realm. Geophysical methods will provide the necessary tools.

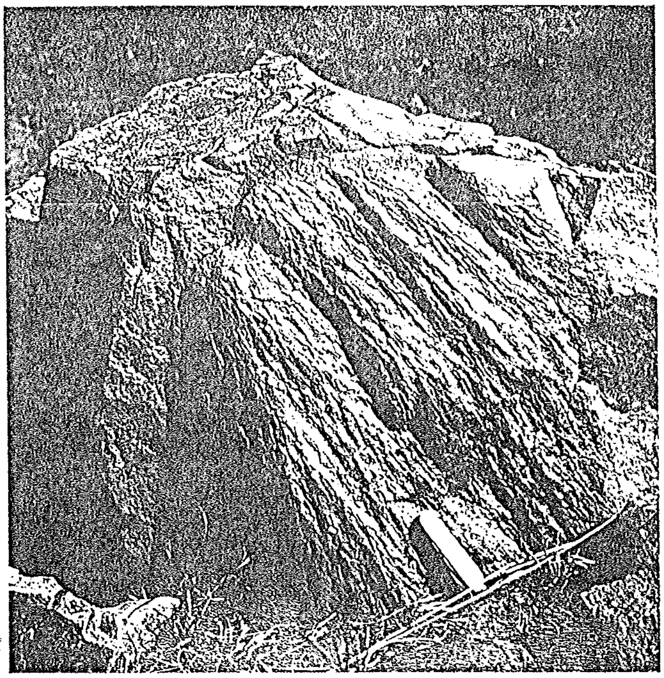

Figure 3: Shatter cone from the Vredefort structure (South Africa) developed against a bedding plane in near-vertical quartzite of the collar. Knife for scale measures 9cm in length.

Another macroscopic indicator of impact structures may be the occurrence of shatter cones (Figure 3). That such striated fracture surfaces represent characteristic impact phenomena is widely believed (e.g., Dietz, 1960, 1968; Milton, 1977), but is not unchallenged. For example, a possible shatter cone from the eastern margin of the Bushveld Complex in South Africa (Reimold and Minnitt, 1994) is shown in Figure 4. However, it is still debated whether these findings represent shatter cones or sedimentary percussion marks. Wind ablation features in desert terranes may also be similar in appearance to shatter cones (Reimold and Miller, 1989, fig. 6b). Most authentic shatter cones may, however, be positively linked to impact structures.

A variety of distinct (impact) breccia types has often been found associated with impact structures (Stöffler et al., 1979; Stöffler and Grieve, 1994). They range from purely fragmental breccia of either monomict (consisting of fragments of one lithology only) or polymict composition, to pure impact melt breccia consisting of a melt matrix with a more or less significant clastic component). A transitional breccia type consisting of a clastic matrix with isolated melt fragments was termed 'suevite' (Hörz, 1965). All these breccia

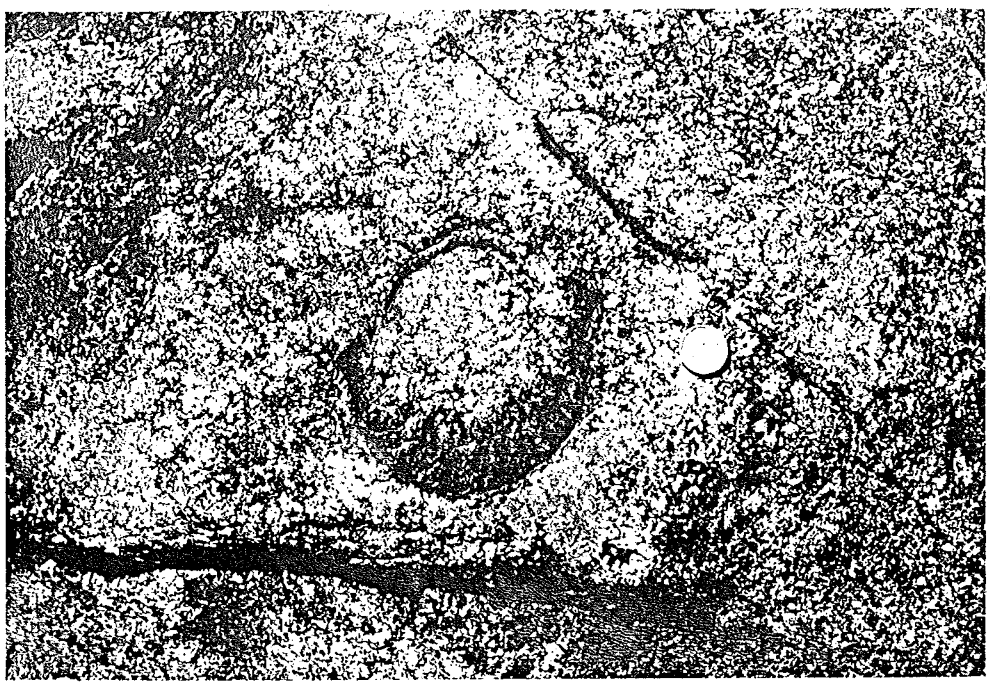

Figure 4: A shatter cone-like fracture from the eastern margin of the Bushveld Complex. Coin diameter: 2 centimetres. (Reimold and Minnitt, 1994).

types may contain shock metamorphosed clasts representing a wide range of shock pressures. Such breccias may occur in the form of coherent breccia layers within the crater, or as locally produced (autochthonous) breccias of the crater floor. Crater floor breccias may also be formed by injection of allochthonous breccia (fragmental or melt breccia) into basement fractures and are then regarded as 'dike breccias' (Lambert, 1981; Bischoff and Oskierski, 1987). In addition, relatively well-preserved impact structures may still show complete or partially preserved ejecta blankets of fragmental or suevitic breccia in the environs of the crater (Newsom et al., 1986). The occurrence of different impact breccias within and outside crater structures is shown schematically in Figures 1 and 2.

On impact of an extraterrestrial projectile a supersonic shock wave is generated that will travel radially away from the point of impact into the target material. Compressive stresses thus induced into the target rock may exceed the stress regime of normal crustal metamorphism (Figure 5) by several orders of magnitude. Temperatures associated with shock wave formation and propagation are also a significant factor with regard to the post-impact (so-called "impact" or "shock" metamorphic) state of the target rocks. Detailed field studies in unequivocal impact structures (containing detectable relics of the projectile), as well as shock experimentation, and comparison with shock metamorphic effects encountered in extraterrestrial rocks (meteorites and lunar rocks), have led to a thorough understanding of the nature and variability of shock deformation effects for most of the important rock-forming minerals (French and Short, 1968; Sharpton and Grieve, 1990; Stöffler, 1972, 1974; Stöffler and Langenhorst, 1994; Stöffler et al., 1988). In particular, the shock effects in quartz have been studied in great detail (review by Stöffler and Langenhorst, 1994) and have proven invaluable as shock (impact) identifiers. Planar deformation features (PDFs - Grieve et al., 1990), diaplectic glass, shock mosaicism, isotropization, mineral melting, and rock fusion are some of the characteristic shock metamorphic effects encountered in the shock

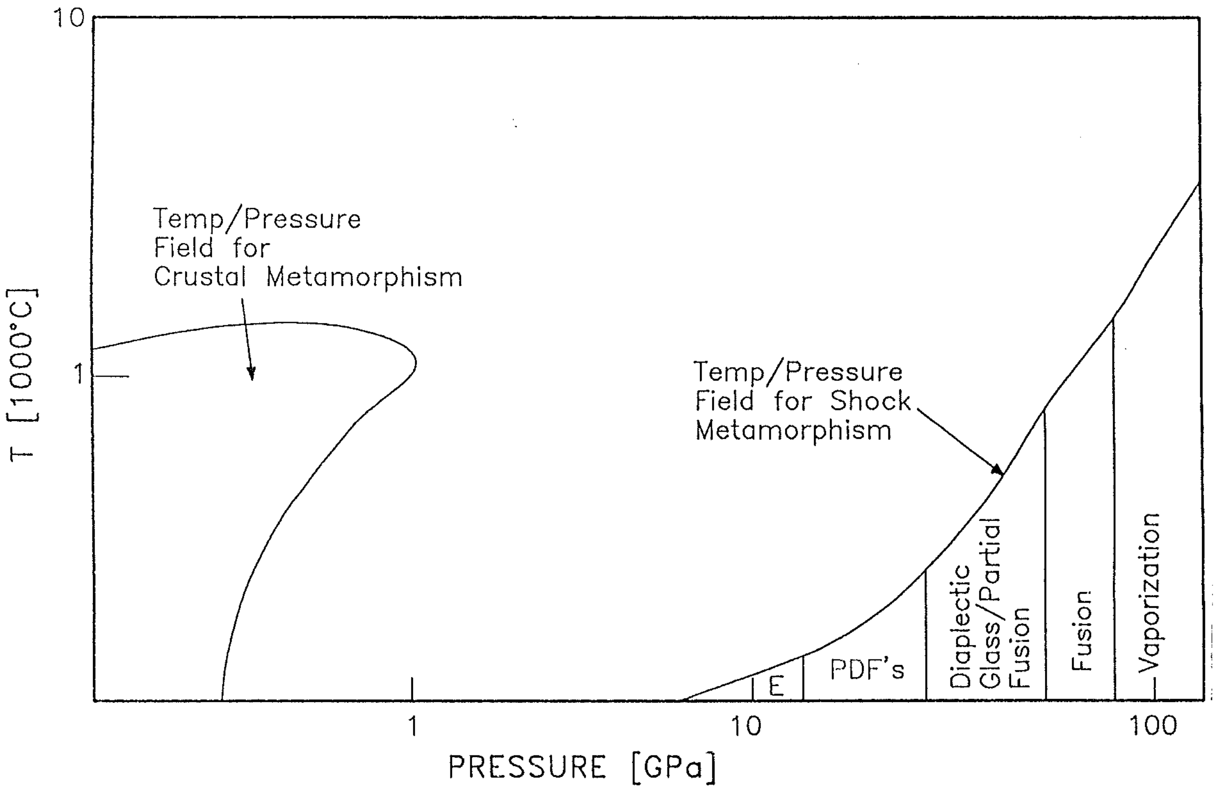

Figure 5: Pressure-temperature diagram with the approximate regimes of 'normal' crustal metamorphism and of shock metamorphism. In the latter, the fields characterized by elastic deformation (E), PDF's, diaplectic glass/partial fusion, total fusion, and vapourization are indicated (after Stöffler, 1972, 1974).

pressure regime between circa 10 and 60 GPa. PDF's that occur in preferred crystallographic orientations, according to the shock pressures at their formation (e.g. in specific minerals like quartz), are extremely useful shock (impact) indicators. Furthermore, PDF orientations can be used for accurate deduction of shock pressures (shock barometry). In addition, it may be possible to identify shock effects generated in successively higher shock pressure regimes within radial traverses through an impact structure, leading to the recognition of 'progressive shock metamorphism' (Figure 6). As many of these shock effects have never been described from internally deformed terranes (involving tectonism and volcanism), and it has not been possible to reproduce them by static high-pressure experiments, shock metamorphism has attained prime importance for the recognition of impact structures or their relics. Recently, much effort has been directed to shock experiments with pre-heated target materials (Reimold and Hörz, 1986; Reimold, 1990; Langenhorst, 1994) in order to understand the effects of large impacts into hot crust and also of post-impact annealing of shock effects. The findings of shock metamorphosed minerals in K/T boundary deposits have been used in arguments favouring disruption of the environment by an impact event at that time (Bohor, 1990; Bohor et al., 1993).

High-pressure and high-temperature polymorphs of certain target rock minerals (such as coesite and stishovite formed from quartz) may be observed in impact formations and could be first-order indicators of an impact structure (Stöffler and Langenhorst, 1994; Martini, 1978; 1991).

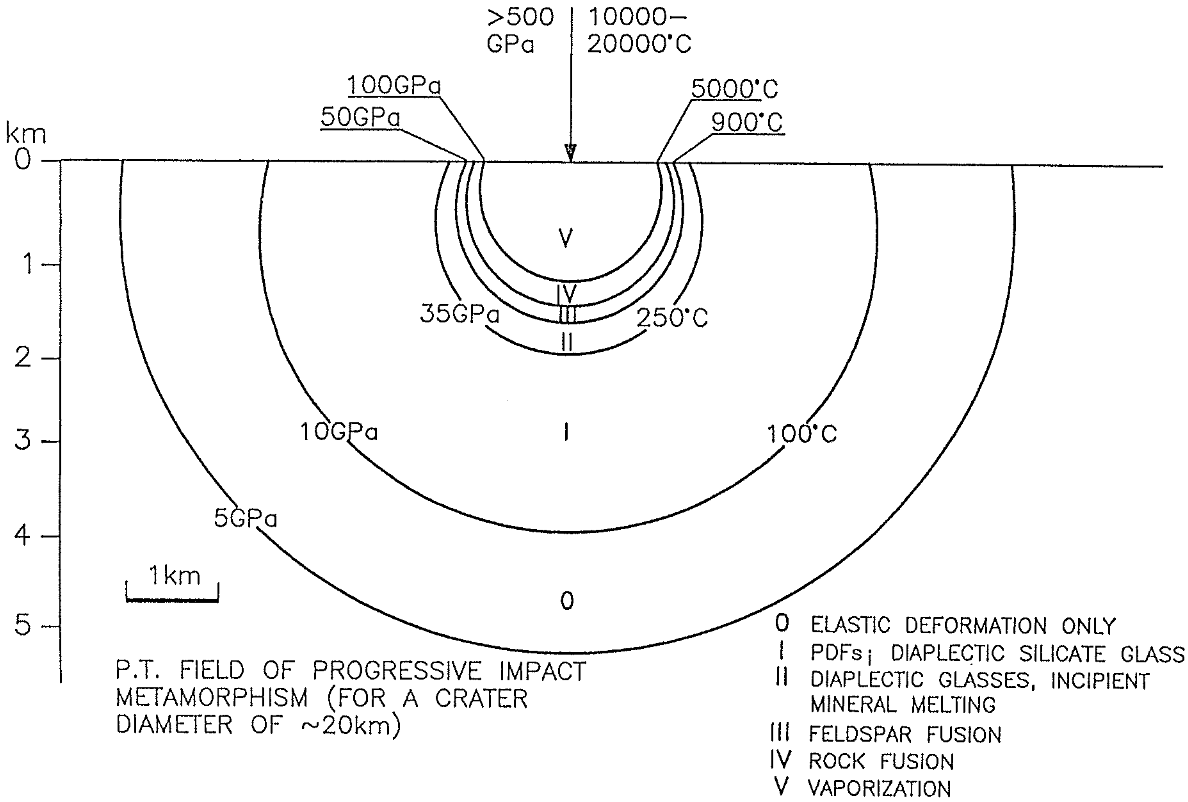

Figure 6: Generalized cross-section through a circa 20 km diameter impact structure to illustrate "shock zoning" (cp. text). (Modified after Stöffler, 1972, 1974).

Impact glass, formed at shock pressures above ca. 60 GPa, may also be a good impact indicator (Koeberl, 1994). Having been generated in the high-pressure, high-temperature regime relatively near to the point of impact, the glass may, in favourable cases, be contaminated by the meteoritic projectile. If it can be shown that elevated concentrations of siderophile elements (e.g., Ir, Ni, Co, and Cr, which are generally enriched in meteorites by comparison with terrestrial crustal rocks) in such glass, were not derived from a mantle-derived target rock component, then recognition of traces of the projectile might be achieved and an impact origin for such material confirmed. Recent advances in mass spectrometric techniques allow for the recognition of small concentrations of the elements Re and Os in crustal rocks as well as for very sensitive measurements of Re/Os isotopic ratios. Consequently, it has been possible to use this isotopic system for the detection of small amounts of meteoritic material in impact breccias (Koeberl and Shirey, 1993; Koeberl et al., 1994a).

In addition to employing these often definitive, impact indicators, it is always essential to have a thorough understanding of the local and regional geology. This is particularly important if old, deeply eroded, and large impact structures are to be recognized.

Recent advances in aerial and satellite photography and the availability of large remote sensing data bases have provided further tools for the search and recognition of impact structures. However, without confirmation from ground-based geological and laboratory-based mineralogical investigations proof for the existence of impact structures can not be obtained.

Not all breccias encountered in impact structures need to be impact-derived. In large, old impact structures multiple phases of deformation have often occurred (e.g. the 2 Ga old Vredefort impact structure, discussed below, where several generations and varieties of pseudotachylitic breccia have been found - Reimold and Colliston, 1995). Pseudotachylites (Shand, 1916) have been described from a number of impact structures, including the abundant occurrences from the Vredefort structure (Fig. 7), the Sudbury impact structure (Grieve et al., 1990), and the breccias from the Roter Kamm impact crater (Fig. 8). Generally, however, pseudotachylite occurrences in known impact structures rarely exceed a few centimetres in width. Pseudotachylite is also known from numerous tectonic

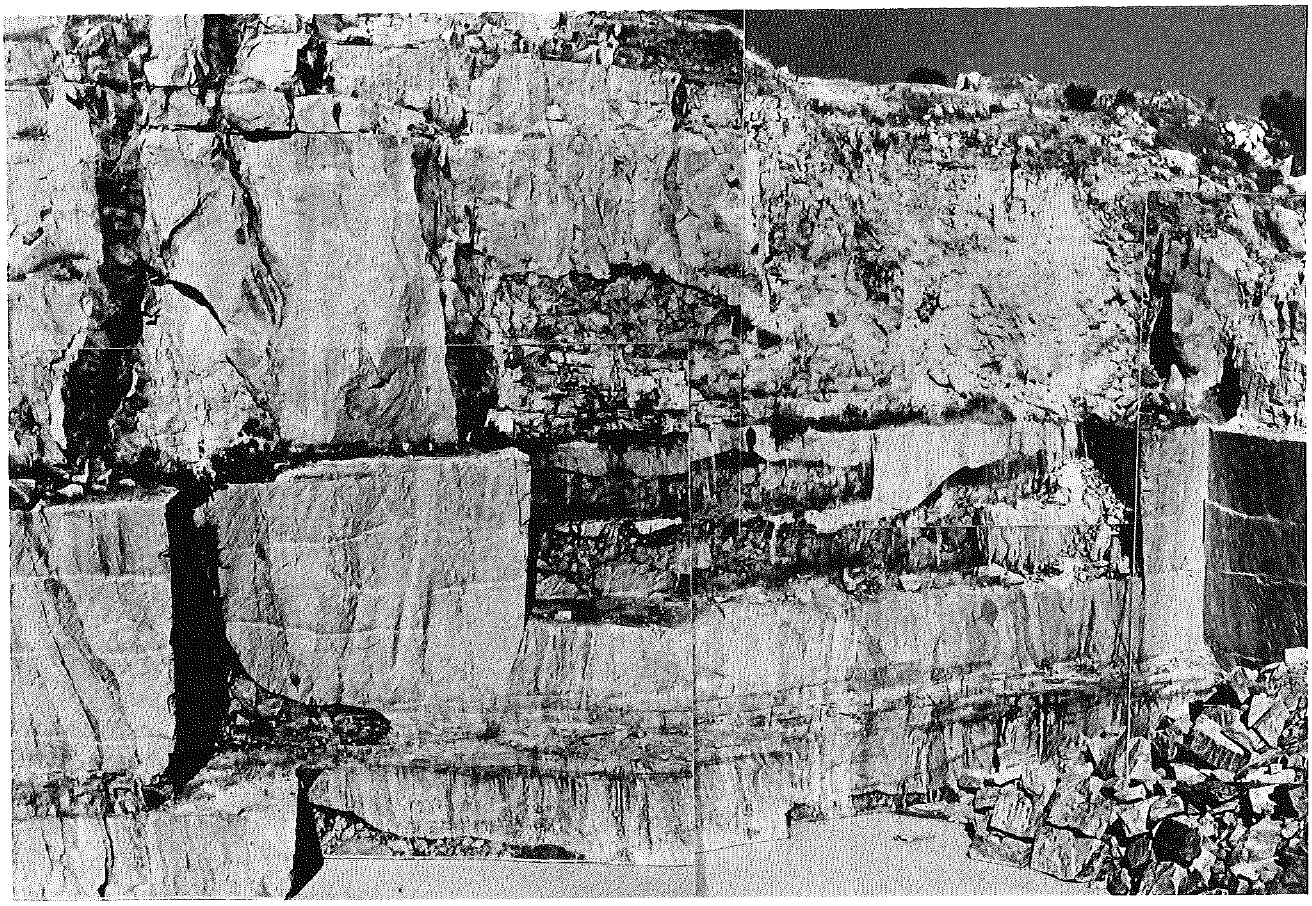

Figure 7: View of the south face of the Leeukop Hill quarry northwest of Parys in the Vredefort structure. Note the massive development of pseudotachylite breccia zones (black) throughout this quarry. The width of this exposure is roughly 70 m.

(fault-related) settings worldwide. It is conceivable that friction melt (= pseudotachylite) could be formed in an impact structure during both the compression and decompression phases of the cratering process, so that multiple generations of such breccia would not be unexpected. Care is required, however, in distinguishing between impact-related friction melts and other pre- or post-impact generations (e.g. Vredefort). Furthermore, the nature of each breccia deposit requires to be examined in order to avoid incorrect characterizations

Figure 8: A typical exposure along the rim of the largely dune-covered Roter Kamm impact crater in southern Namibia. In the foreground massive, pseudotachylite-like breccia is exposed.

of cataclastic or mylonitic rocks as pseudotachylite, and of pseudotachylite as impact melt breccia or as cataclastic dike breccia (Reimold, 1995).

THE TERRESTRIAL IMPACT CRATER RECORD

Figure 9 shows the impact craters so far identified on Earth (modified after Grieve, 1991). Major concentrations are found in the old, geologically rather stable, cratonic regions, whereas areas of more recent geological activity have yielded fewer identifiable impact sites. In the densely populated areas of North America and Eurasia a relatively large number of impact structures have been identified. In Australia, and northern and southern Africa, a number of impact structures have been recognized because they initially constituted exploration targets (e.g. for oil exploration, as in North Africa, or gold mineralization in South Africa), or because individual workers undertook detailed crater research. Impact structures have also been identified within the countries of the former USSR, mainly because these structures were recognized as being of economic geological potential.

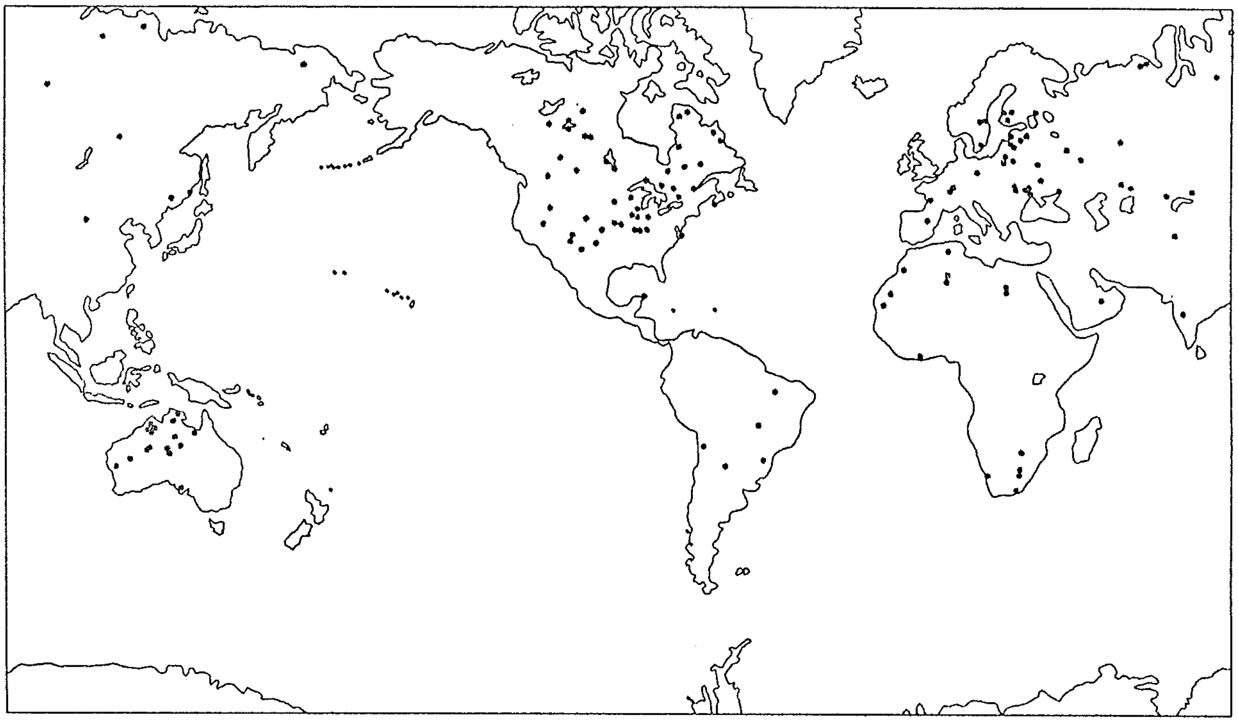

Figure 9: World distribution of currently known impact craters (modified after Grieve, 1991).

Only three impact structures that are partially or completely submerged in oceans are known. Montaguais (Jansa et al., 1989) on the outer shelf off the coast of Nova Scotia, the Chicxulub structure off the coast of the Yucatan peninsula, Mexico and the recently identified Chesapeake Bay structure (Poag et al., 1992, 1994) on the east coast of the U.S.A.

A recent list of proven and probable impact structures, their locations, diameters, and ages is found in Grieve (1991). Good radiometric ages are available for only some impact structures. In Figure 10 the ages of 54 impact structures, dated by radiometric techniques, are plotted in a frequency versus timescale diagram. As indicated in the figure, only the ages of 37 impact structures are deemed reliable for statistical appraisal. Superimposed on this diagram is a 30 Ma periodicity, as various authors have proposed that periodic increases in the terrestrial cratering rate is evident from the impact crater record (Stothers and Rampino, 1990). This contention led to considerable speculation about the cosmic processes that could be responsible for such a periodical increase of projectiles. Other workers (Grieve, 1982; Durrheim and Reimold, 1987) have criticized this proposed periodicity as Figure 10 demonstrates the less than even significance of the crater record with time. Furthermore, only partial coincidence between apparent age clusters and maxima in the periodicity curve is achieved.

Only three impact craters older than about 700 Ma have been dated, namely the 1.69 Ga old Teague Crater in Australia, the 1.85 Ga old Sudbury structure in Canada, and the approximately 2 Ga old Vredefort structure in South Africa. The absence of others older than 700 Ma is due to intense geological activity since Archaean times. However, it remains

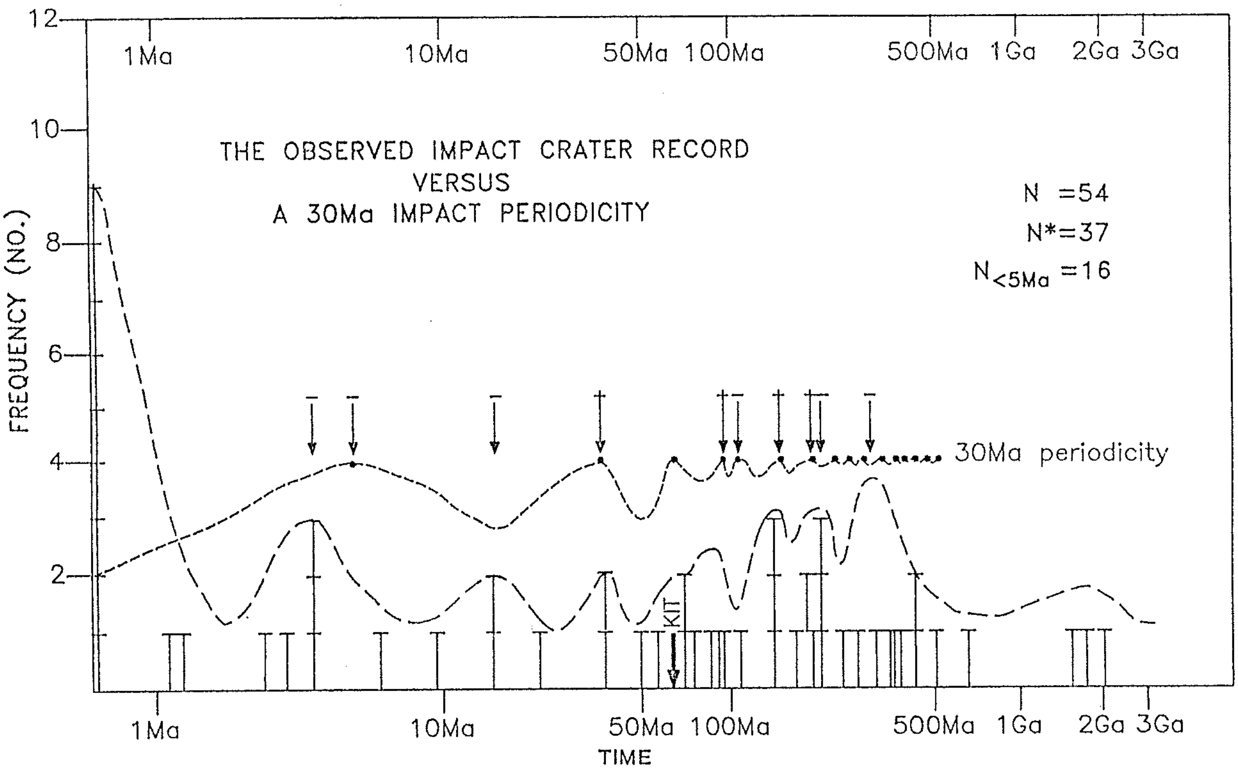

Figure 10: Histogram of 54 well-constrained impact crater ages (after a compilation by Grieve, 1991), where N denotes that the author believes that the crater age record does not contain more than 37 first class radiometric ages) in comparison to a 30 Ma periodicity centred on the 65 Ma age for the K/T boundary event (compare text for discussion).*

debatable (Koeberl et al., 1993a; Glikson, 1993, 1994; Koeberl and Reimold, 1994; Byerly and Lowe, 1994) as to whether it is still possible to recognize remnants of Archaean impact formations in the ancient stratigraphic record. Have the impact formations produced during the early heavy bombardment of this planet been completely removed, recycled, or overprinted? Estimates suggest that early in the evolution of the Earth, prior to about 3.8 Ga ago, several hundred, if not thousands of large impact basins were formed on Earth (Frey, 1980; Grieve, 1980; Glikson, 1993; Koeberl and Reimold, 199). Identification of such remnants may yield important information about the early phase of Earth's geological evolution.

ECONOMIC IMPORTANCE OF IMPACT STRUCTURES

Meteor Crater in Arizona is one of the best studied small impact structures on Earth, and information gleaned from these investigations were vital for the further development of the 'impact cratering' discipline. The main reason for the initial exploration of this crater between 1890 and 1920 was, however, the search for an economic Ni-Fe deposit, believed to exist in the form of remnants of the iron meteoritic projectile in the crater. Since these investigations, focus has been on the economic potential of impact structures (Donofrio, 1981; Koeberl, 1994; Masaitis, 1989, 1990, 1992; Reimold and Dressler, 1990; Sawatzky, 1975). A review of this topic was provided by Masaitis (1992).

In general, five types of impact-related ore deposits can be listed:

1. *Impact structures that were formed in ore-bearing target rocks*

Examples of this type are the uranium-rich sandstones of the basement to the Carswell impact structure in Canada and the ferruginous quartzites in the Ternovka structure in the Ukraine.

2. *Hydrothermal ore formation*

Deposits of this type result from large-scale mobilization and transportation of hydrothermal solutions triggered by the impact-generated energy. An example of such processes may have involved large-scale remobilization of primary detrital gold in the Witwatersrand Basin, in the environs of the Vredefort impact structure (Reimold, 1994a, b). North and northwest of this ca. 2 Ga old structure (Fig. 11) significant hydrothermal alteration, coupled with gold remobilization, has been identified along a number of faults. According to argon chronology and detailed petrographic studies, these faults acted as fluid conduits at the time of remobilization. The assumption therefore appears reasonable that there is a direct correlation between the 2 Ga impact event, coeval fluid movement, and related (secondary) mineralization. Some workers have even suggested that if it had not been for the 2 Ga impact event at Vredefort, the Witwatersrand gold deposits would not have been protected from erosion (due to the structural modification of the crust in the region as well as deep cover by impact formations; McCarthy et al., 1990).

A large number of impact structures are also known to contain sulphide and carbonate mineralization, generally believed to be syn- to immediately post-impact in age (e.g., the Siljan structure in Sweden). Recently discovered base metal sulphide mineralization in the eastern portion of the Highbury impact structure in Zimbabwe (Master et al., 1994) led to the beginning of an exploration drilling programme.

Several impact structures contain economic clay or carbonate deposits. For example, the Vredefort structure is known for its high quality bentonite deposits. Other structures developed crater lakes in which inorganic or biogenic deposits could form. Likewise, oil shales (Boltysch crater, Ukraine), zeolite, coal (Doulon, China; lignite: Ries Crater, Germany), gypsum/anhydrite (Brent Crater), trona (Pretoria Saltpan Crater, South Africa; Lonar Lake crater, India), fluorite (Ries Crater), diatomite (Ragozinka, Russia), and phosphate (Boltysch; Logoysk crater, Belorussia) deposits formed in crater lakes associated with impact structures.

3. *Impact structures as hydrocarbon traps*

Several impact structures have been identified in the course of oil and gas exploration or were, during scientific evaluation, found to be hydrocarbon-rich structures (e.g., the Ames structure in Oklahoma; several structures in the Williston Basin of the American Midwest - Red Wing Creek, Viewfield, Eagle Butte, the Avak structure in Alaska, and several structures in the region of the former USSR). Some of these occurrences are known to contain considerable crude oil and gas deposits. Impact structures consist, to a large extent,

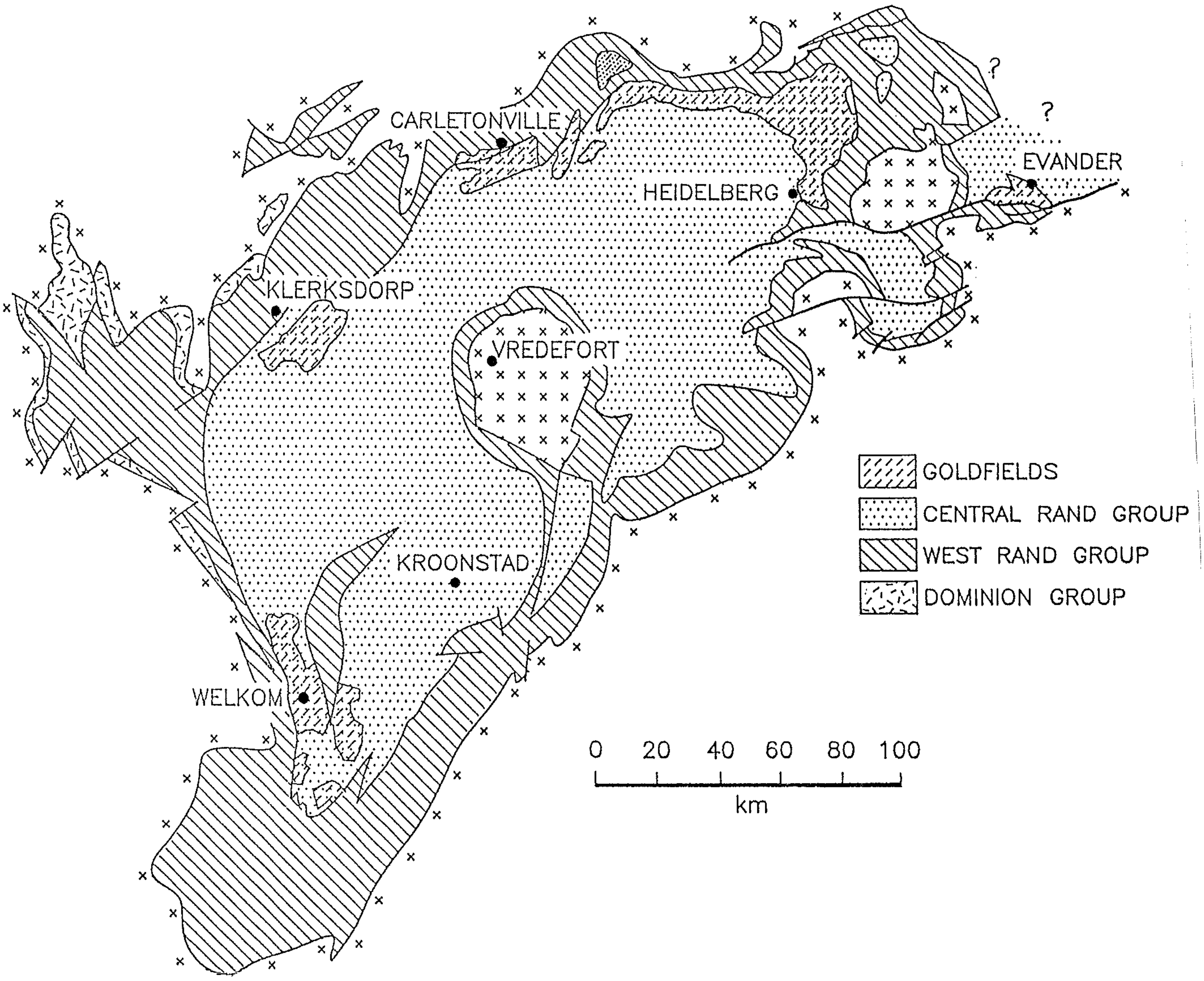

Figure 11: Location of the Vredefort structure near the geographical centre of the structurally preserved and economically important region of the Witwatersrand Basin in South Africa.

of fractured and brecciated target rocks and breccia fill. Such structurally prepared host rocks are effective traps for hydrocarbons.

4. *Massive sulphide ore deposits*

The best example of this deposit type is the Sudbury impact structure in Ontario Canada (Grieve et al., 1991). Nickel, copper, and platinum group metals have been extensively mined in and around the Sudbury Complex, a major impact melt body that has been one of the major ore producers for these commodities for close on 100 years. It is believed that the economic metals were originally disseminated in the target rocks and that impact melting and subsequent fractionation of the metal-sulphide phases from the impact melt led to the concentration of these massive ores.

5. *Diamond deposits in impact structures*

According to Masaitis (1990, 1992, 1993), impact-formed diamonds have been located in the Popigai structure in Russia, as well as in several other smaller impact structures (e.g., Ries Crater in Germany). The formation of these microcrystalline diamonds and lonsdalite appears to have resulted from shock transformation and melting of graphite-bearing target rock. The diamond aggregates were found in large amounts in parts of the Popigai impact melt body, as well as in impact melt dykes. It has been estimated that up to 60 % of the carbon contained in the target rocks of the Popigai structure was converted to diamond/ lonsdalite which was successfully tested for industrial applications by Russian scientists. Shelkov et al. (1994) recently suggested that carbonado from the Central African Republic and from Brazil may have had a similar origin. The possible source structure could be located in the Bangui region of Central Africa, as proposed by Girdler et al. (1992), who observed a significant circular aeromagnetic anomaly in this region.

OTHER USES OF IMPACT STRUCTURES AND IMPACT LITHOLOGIES

Much recent discussion has centred on the possible future construction of large space stations or lunar bases. A major problem to be addressed in this context is the source of appropriate building materials, of oxygen, and of further raw materials to sustain life in space or on a different planet. With much of the Moon's surface being covered by thick, impact-produced regolith, it appears reasonable to consider the applicability of this material and other impact breccias, or of certain components therein, as building material in the construction of space settlements.

Where fresh impact lithologies (impact melt rock or suevite, and well-consolidated fragmental breccia) have been available, they have often been used as construction material. This is particularly evident in the vicinity of the Ries Crater in Germany and of the Rochechouart impact structure in southwest France where impactite material has been used in the construction of churches and the medieval castle of the town of Rochechouart, but has also been widely used in the construction of houses ever since medieval times.

Other structures have provided sources for dimension stone. The Vredefort structure, for example, has a number of dimension stone quarries within the exposed basement to the deeply eroded impact structure. Here the so-called Jiparano 'granite' consists of a strongly migmatized granitic-granodioritic gneiss that has long supplied a thriving export market.

Lake Bosumtwi, a circa 10 km wide impact structure in Ghana, is of regional importance because it represents a major water reservoir. Lonar Lake in India serves the same purpose. The deeply eroded, 80 km wide impact structure at Manicouagan in Quebec is the site of a major hydropower scheme.

Impact structures have also been identified as significant educational and tourism sites. The long-established museum at Meteor Crater in Arizona has been a major financial success, as has the Ries Crater Museum in Germany. Recent initiatives to develop museums were undertaken in Rochechouart, and in South Africa, where development of the Pretoria Saltpan Crater into a multidisciplinary environmental museum is underway. This museum is to be coupled with recreational and ecotourism facilities.

Finally, several impact structures have been recognised as 'closed basins' that allowed undisturbed sedimentation in the crater since its formation. Several craters have proved useful in providing continuous palaeoenvironmental (climatic) records for the period since crater formation. A prime example is again the Pretoria Saltpan Crater that yielded a continuous palaeoclimatic record for the mid-latitudes of the southern hemisphere for the last 200 000 years (Partridge et al., 1993).

HISTORY AND PROGRESS OF IMPACT STUDIES IN SOUTHERN AFRICA

Shortly after the turn of the Century, Shand (1916) recognized the exceptional pseudotachylite exposures in the granitic basement to the Vredefort structure, located in the geographical centre of the economically important Witwatersrand Basin (Figure 11), and proposed a shock origin for this breccia type. However, it was Daly (1947) who first suggested an impact origin for this structure and ever since, the Vredefort structure has proved controversial amongst proponents advocating impact or internal processes of formation (Reimold, 1993; Nicolaysen and Reimold, 1990).

The Pretoria Saltpan Crater was initially described in the mid-1800s and first studied in geological detail by Wagner (1922). Its general appearance and the findings of volcanic rocks in the area led to the firm conclusion that the crater was of volcanic origin. In contrast, Rohleder (1933) proposed an impact origin, and Leonard (1946) included this crater with his compilation of possible meteorite craters. Despite later additional studies no more conclusive evidence could be unearthed, with the result that most South African geologists were convinced that the Pretoria Saltpan Crater represented a volcanic feature. However, this crater structure was frequently cited abroad as a possible impact structure (Reimold et al., 1992).

In southern Namibia, a small crater called the Roter Kamm Crater (Fig. 12), was repeatedly referred to as a possible impact structure (Reimold and Miller, 1989), but an initial geological visit to this desert site (Fudali, 1973) revealed poor outcrop and no proof for a definite mode of origin.

The possibility that the 640 m wide Kalkkop Crater (Fig. 13) in the Eastern Cape (South Africa) could be of impact origin was first mentioned some 20 years ago, but no evidence for or against this suggestion has emerged.

More recently a number of detailed studies of these structures have been undertaken, the reasons for this revival of interest being because of (a) the recognition that studies of the Vredefort structure were vital for the understanding of the evolution of the surrounding Witwatersrand Basin; (b) the worldwide interest in impact phenomena created as the result of the K/T boundary controversy; and (c) the possibility of generating funds for such work within and outside of South Africa, largely due to the creation of joint research efforts with European and North American participants.

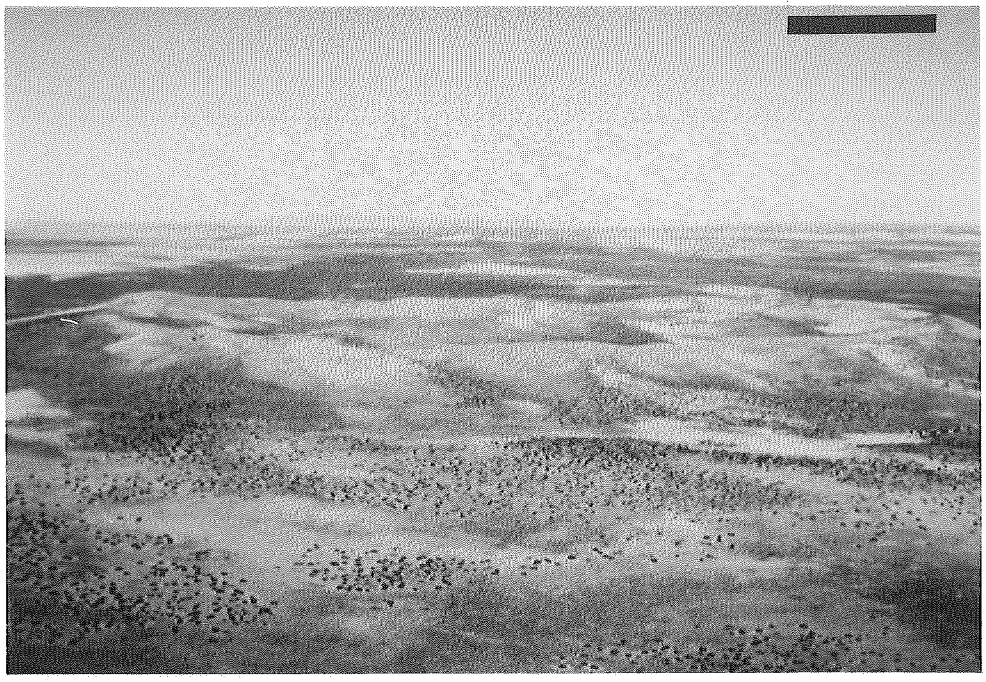

Figure 12: Aerial photograph of the Roter Kamm impact crater. View from the north (right side of photograph). Scale measures roughly 450 m.

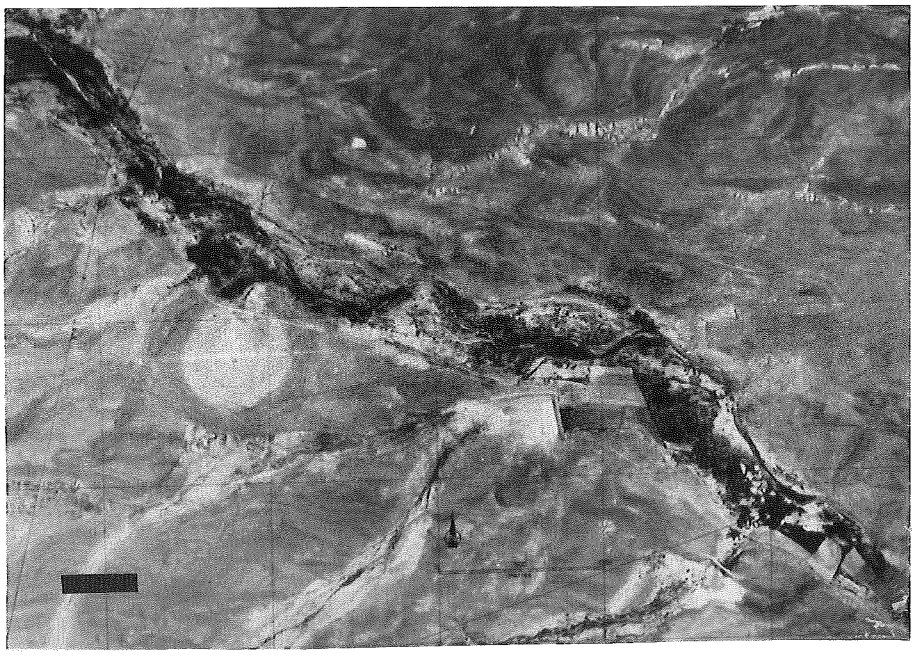

Figure 13: Aerial photograph of the area around the 640 m-wide Kalkkop impact crater visible because the crater sedimentary fill consists of whitish limestone. Note the somewhat darker annulus around the structure, which is thought to represent the ejecta blanket. Scale: 400 m.

For a number of years the detailed studies of the deformation phenomena associated with the Vredefort structure, namely the massive pseudotachylites, the shatter cones, and microdeformations in quartz (Figure 14), produced results that were not readily reconciled with an impact origin and seemed to favour an internal origin for the structure (Reimold, 1993). However, more recently the anomalous microdeformations in quartz were recognized as the remnants of annealing of bona fide planar deformation features (Leroux et al., 1994). Furthermore, unequivocal shock metamorphosed zircon crystals were extracted from Vredefort pseudotachylite (Kamo et al., 1995). Initial Re-Os isotopic analyses of the enigmatic granophyre from Vredefort (Figure 15) resulted in the detection of slight meteoritic contamination, confirming that this rock type represents impact melt (Koeberl et al., 1995).

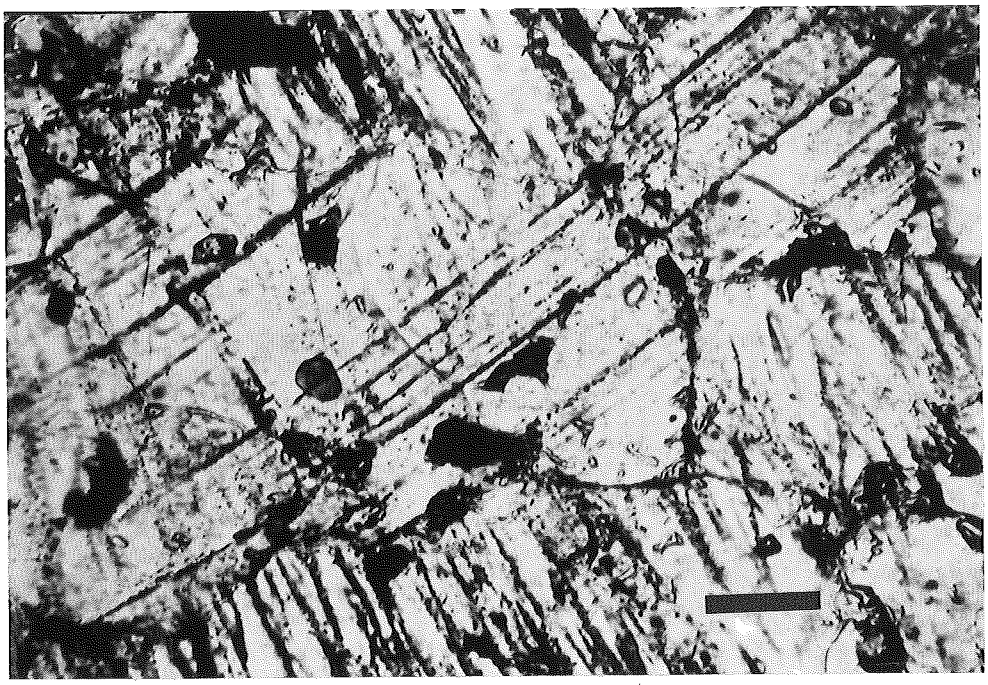

Figure 14: Typical appearance of planar microdeformations in quartz from Vredefort rocks. The scale bar equals a length of 100 microns.

At present there is little doubt that this structure is of impact origin. Therriault et al. (1993) estimated that the original size of this structure could have been as large as 200 to 300 km in diameter, which is the length of the long-axis of the Witwatersrand Basin. Together with the similarly sized Chicxulub Crater in Mexico, Vredefort would thus be the largest known terrestrial impact structure. It is also the oldest impact structure known, with an age of 2024 Ma (Kamo et al., 1995). The structure represents a unique cross-section through the Kaapvaal Craton with current geological studies in this region being focussed on further understanding the relationships between this impact structure and the Witwatersrand Basin.

A research borehole, completed in 1989, was drilled into the Pretoria Saltpan Crater and yielded material for a detailed mineralogical study of the loose breccia encountered at intermediate depths. This study revealed evidence of shock metamorphism in quartz and feldspar minerals, as well as impact glass, melt breccia fragments, and even a slight

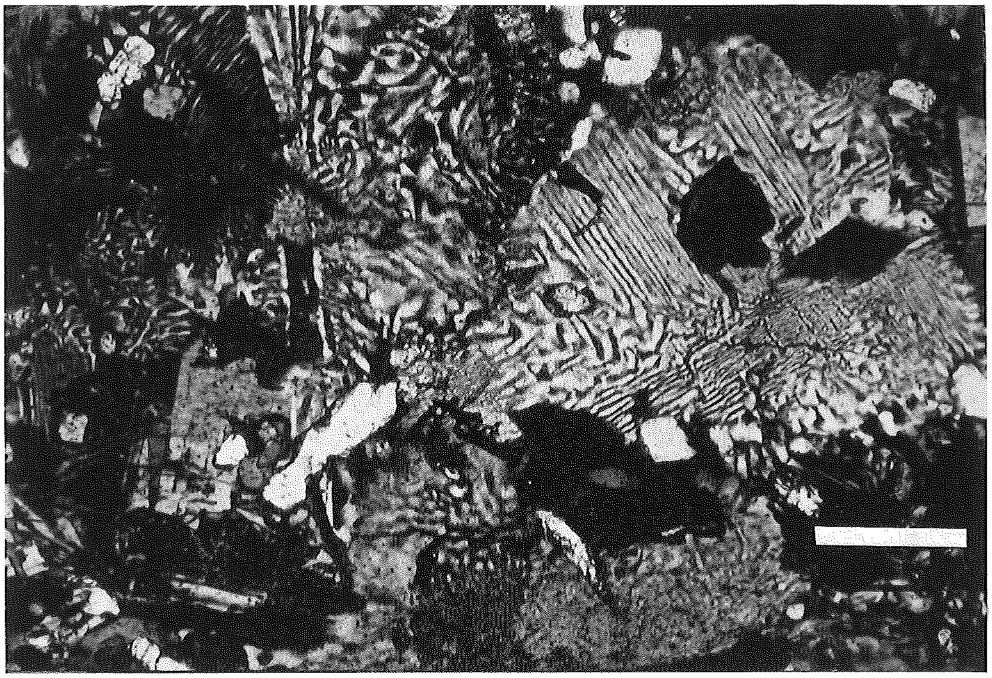

Figure 15: Microphotograph of typical micropegmatitic intergrowth of quartz and feldspar minerals in the matrix of the enigmatic granophyre from the Vredefort structure (Reimold et al., 1990). The granophyre is now believed to represent dykes of impact melt rock intruded into fractured basement. The scale bar equals about 350 microns.

meteoritic component in the glass and melt breccias (Reimold et al., 1992; Koeberl et al., 1994b). Fission track dating of glass fragments yielded an age of 200 000 ± 52 000 years (Koeberl et al., 1994c), whereas detailed geological analysis of the crater area and its environs, together with chronological work, showed that the volcanic rocks belong exclusively to a regional succession of rocks of circa 1.3 Ga in age (Brandt, 1994) and confirming an impact origin for the Pretoria Saltpan Crater. Detailed sedimentological and palaeontological analyses of the crater sediments found in the drillcore yielded a complete palaeoclimatic record since the formation of the crater.

Studies undertaken on the Roter Kamm Crater in the southern Namib desert (Reimold and Miller, 1989) provided samples from exposures on the crater rim. Evidence of shock metamorphism was recorded, confirming an impact origin for the crater which was found to have an age of about 3.4 Ma. Also noted were hydrothermal effects considered to be related to the impact event (Koeberl et al., 1993b; Reimold et al., 1994).

A 153 m-deep borehole drilled into the centre of the Kalkkop structure yielded a coherent breccia layer about 90 m below surface. This breccia macroscopically resembled typical suevite and, together with the findings of glass fragments and of shock metamorphosed quartz clasts, confirmed its suevitic nature and an origin by impact (Reimold et al., 1993). Further confirmation was obtained from Re-Os isotopic analysis of breccia and target rock samples (Koeberl et al., 1994a).

A circular structure, confirmed on SPOT satellite images, was recorded in the Highbury area north of the town of Chinhoyi in Zimbabwe. Preliminary investigations revealed samples containing shocked quartz together with fragmental and glass-bearing breccia. A granophyric rock, very similar to Vredefort granophyre, was recorded. Master et al. (1994) and Reimold (1994b) concluded that the Highbury structure represented another impact feature.

The current impact record for the African continent, in comparison with those for other, better investigated regions, suggests that further impact structures remain to be discovered in southern Africa. The advent of satellite imagery and the establishment of a number of regional remote sensing centres, should contribute to the improvement of the African impact crater record.

CONCLUSIONS

The importance of impact crater studies in the planetological and geological contexts has been outlined and it is concluded that further investigations are required to better constrain the impact cratering record. Detailed crater studies in parts of the world with less developed infrastructure could be facilitated by geologists and remote sensing specialists having access to satellite imagery. Some of these impact-related structures may represent interesting mineral exploration targets.

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