Meteoritics & Planetary Science 38, Nr 9, 1341–1350 (2003)
Abstract available online at http://meteoritics.org

Characterization and significance of shocked quartz from the Woodleigh impact structure, Western Australia

R. M. HOUGH,[1*] M. R. LEE,[2] and A. W. R. BEVAN[1]

[1]Department of Earth and Planetary Sciences, Western Australian Museum, Francis Street, Perth, Australia
[2]Division of Earth Sciences, University of Glasgow, Glasgow G12 8QQ, Scotland, UK
[*]Corresponding author. E-mail: robert.hough@csiro.au

(Received 16 January 2003; revision accepted 11 September 2003)

Abstract–We re-examined the buried Woodleigh structure in Western Australia, which has been inferred to be a multi-ringed, 120 km diameter impact crater, because the proposed size and possible synchronicity with one of the pre-Mesozoic mass extinction events has attracted controversy. We undertook a detailed study of the petrology and mineralogy of a number of samples of core from the Woodleigh-1 borehole that was drilled into the central uplift of the structure. Crystalline Proterozoic basement rocks comprising granites and gneisses in the Woodleigh-1 core contain minor brecciation in discrete veins and reveal clear evidence of shock metamorphism over the full extent of the core. Imaging of laboratory-etched quartz showed that a large number of grains contain shock deformation lamellae. Microstructural and crystallographic analysis of these lamellae by TEM showed that they are planar deformation features (PDFs) that have subsequently undergone annealing and water assisted recrystallization. The available geological, petrographic, and mineralogical evidence suggest that Woodleigh is an eroded impact crater that is nearer to 60 km than 120 km in diameter. Future drilling projects should better constrain the level of erosion, and may reveal any preserved impact lithologies.

INTRODUCTION

The Woodleigh structure (26°03′19.3″ S and 114°39′56.3″ E), located on Woodleigh Station near Shark Bay in Western Australia (Fig. 1), has been proposed by Mory et al. (2000a) and Uysal et al. (2001) to be a buried, 120 km in diameter, multi-ring impact structure. However, this interpretation and the suggestion that the impact event may have been associated with an extinction event has been seriously questioned (Reimold and Koeberl 2000; Renne et al. 2002). The buried circular feature is characterized by a Bouguer gravity anomaly ~60 km in diameter, and the structure is comparable to other buried complex impact structures exhibiting a central feature surrounded by 2 annular positive gravity anomalies. An overall diameter of 120 km has been inferred from a subtle arcuate feature east of the obvious gravity anomaly, as an apparent incursion into the regional N-S trending Wandagee-Ajana ridge, and by subtle drainage patterns in the region (Mory et al. 2000a; Iasky et al. 2001; Uysal et al. 2001). The Geological Survey of Western Australia record 2001/6 compiled by Mory et al. (2001) is more circumspect, suggesting 120 km only as a possible diameter for Woodleigh.

An impact origin for the Woodleigh structure was originally proposed following work on a cored borehole, called Woodleigh-1, that was drilled directly through the center of the structure (Mory et al. 2000a). Using light microscopy (no U-stage), Mory et al. (2000a) reported planar deformation features (PDFs) in quartz and feldspars, and subsequently in zircons (Mory et al. 2000b; 2001). The Proterozoic basement rocks encountered throughout the core were also reported to contain extensive glass-bearing pseudotachylite veining of the S-type (Mory et al. 2000a), although these features have not been characterized in detail (e.g., see Reimold and Koeberl 2000). Mafic enclaves were also reported (Mory et al. 2001) and interpreted to have been mixed with granitoids by the impact.

The age was originally reported to be the earliest Jurassic and, therefore, coincides with the Jurassic-Triassic boundary (Iasky and Mory 1999). Subsequently, workers reported that apatite fission track dating pointed toward a possible Permian-Triassic boundary age but that a lack of Triassic fossils in the crater fill suggested a late Triassic age (Mory et al. 2000a). Uysal et al. (2001, 2002) report a late Devonian age (359 ± 4 Ma) from dating of authigenic, coarse fraction pure illite clay minerals, interpreted by them to be a hydrothermal product. This method and the corresponding age for the impact has been questioned (Renne et al. 2002) but reiterated by Uysal et al. (2002, 2003).

Although the impact age is poorly constrained and many

© Meteoritical Society, 2003. Printed in USA.

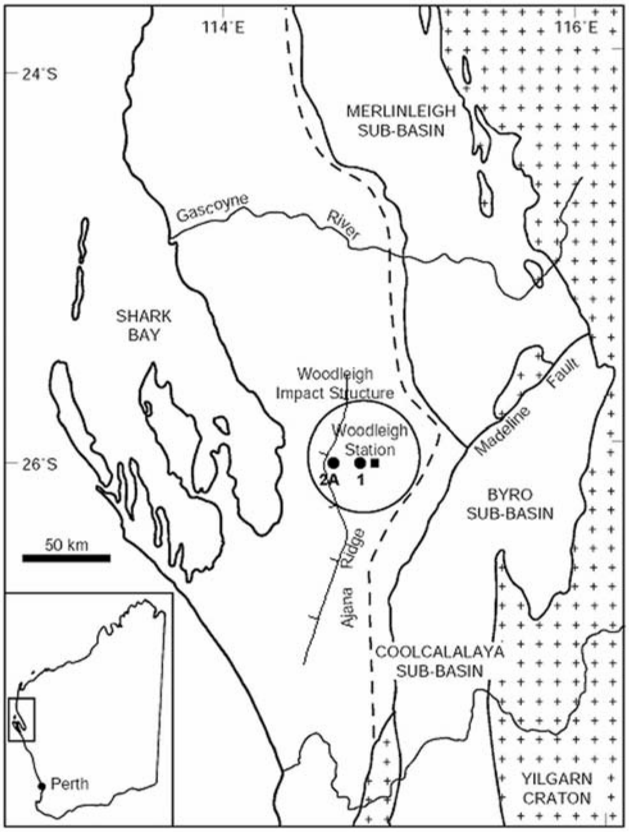

Fig. 1. Location map of the Woodleigh structure in Western Australia and the main tectonic features of the region. The locations of the W-1 and W-2A drill-holes are marked (adapted from Mory et al. [2000] and Iasky et al. [2001]).

features of the Woodleigh structure remain unresolved, the discovery of even a 60 km-sized impact structure is globally important. The critical comments of Reimold and Koeberl (2000) and reply by Mory et al. (2000b) highlight the fact that insufficient studies have been performed to allow the use of the terminology and interpretations reported in Mory et al. (2000a). The size of the structure (Mory et al. 2000a) and its classification as multi-ringed (Mory et al. 2000a; Iasky et al. 2001; Uysal et al. 2001), combined with its age being postulated as synchronous with an extinction event (Mory et al. 2000a; Uysal et al. 2001, 2002, 2003), have led us to follow the defined convention, as applied to K/T boundary shock mineralogies, to differentiate between shock and tectonic features in the assumed target rocks. We have also attempted to constrain the shock facies presented by the target rocks in the Woodleigh-1 (W-1) core.

Here, we report results of a detailed study of the mineralogy and some of the structural features described from the W-1 drill core samples (Mory et al. 2000a, 2000b, 2001) and results from a preliminary study of the Woodleigh 2A (W-2A) core (from <15 km west of W-1). Microstructures preserved within quartz grains in W-1 were examined using optical microscopy, acid etching, scanning electron microscopy (SEM), and transmission electron microscopy (TEM) to confirm the presence and nature of shock deformation features (Gratz et al. 1996; Montanari and Koeberl 2000). These are complimentary to the U-stage studies of Koeberl et al. (2001) and Reimold et al. (2003).

SAMPLING AND EXPERIMENTAL TECHNIQUES

W-1 had been drilled by Layton and Associates in 1981 (see Iasky et al. 2001), but no samples were preserved. The hole was subsequently re-entered and cored from a depth of 190.5 m to 333.1 m into the center of the central uplift (Mory et al. 2001). A second core, W-2A, was drilled into the first annular gravity trough. Both W-1 and W-2A drill cores are housed in the Geological Survey of Western Australia core repository in Perth. The W-1 core was laid out to enable observations of its full length and for thorough sample selection. This core solely comprises mixed crystalline basement lithologies (Fig. 2; Reimold et al. 2003 [Fig. 2]) including gneiss, micro-granite, granite and amphibolite. The complex is strongly deformed and shows evidence of granulite facies metamorphism including porphyroblasts of garnet. We sampled various intervals (Table 1) throughout the length of the core with an emphasis on identifying features that were potentially impact-related or provided potential macro-indicators of shock metamorphism. A striking feature of the core in general is that brecciation has not been so severe as to leave the core friable; it is a competent, uninterrupted section of core (Fig. 2), with only weathered/altered mica-rich zones being fragile. Samples were removed using a band saw and further split into specimens for study while leaving the facing section back in the core. In our sample selection, we noted the sampling of previous workers and attempted to collect from different horizons to ensure a greater understanding of Woodleigh geology (Table 1). In hand specimen, all lithologies show alignment of minerals, often illustrated by the biotite mica that also occurs as whisps, thus indicating that they have all been deformed to some degree. The basement lithologies are typical of strongly deformed Precambrian metamorphic/igneous complexes, and the foliation, which is present throughout the core, is inferred to be the product of such regional metamorphism (e.g., Myers 1993). The W-2A core was also examined, and as described in Iasky et al. (2001), the main horizon of interest is a red-colored conglomerate (66 m thick) containing sparse, rounded basement clasts (2–3 cm in size). The base of the core is marked by a dolomitic breccia that is possibly Silurian in age (Mory et al. 2001) and mudstone with sub-horizontal laminations.

Samples (Table 1) were examined in hand specimen and prepared as polished thin sections for petrographic observations using conventional optical microscopy. A Philips XL-40 SEM operating at 30 kV, was used to observe some textures in the thin sections, and EDS analyses were used for mineral identification. The SEM was also used for

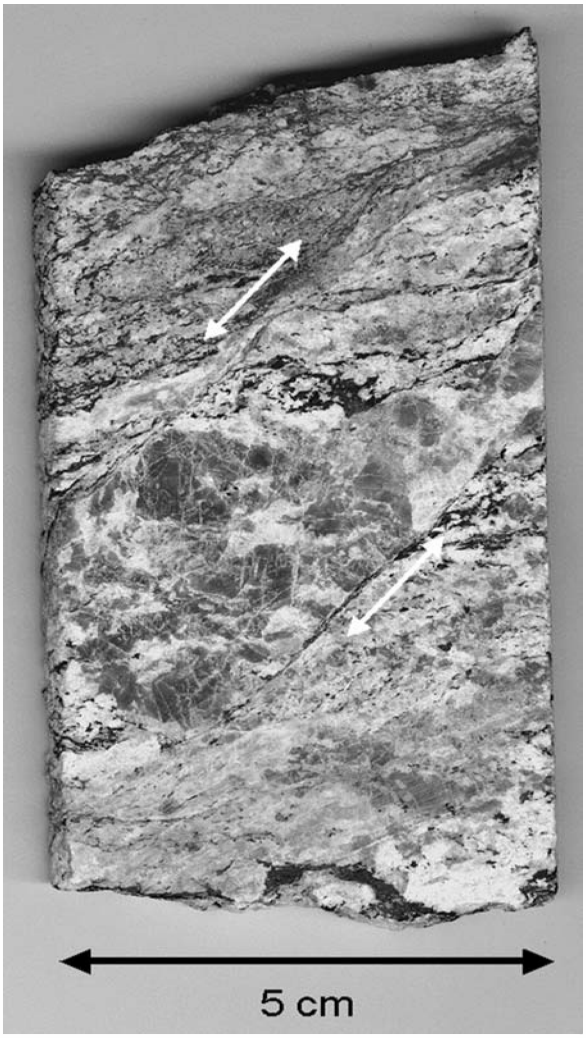

Fig. 2. Crystalline basement displaying brittle fractures from the W-1 core (sample #W-15 from 193.7 m). The arrows point to the area of possible shear deformation.

Table 1. Woodleigh-1 drill-core samples used in this study.

Sample no.	Sample depth	Lithology[a]
W-1	258.9 m	Biotite gneiss
W-2	245.5 m	Microgranite
W-3	224.3 m	Banded gneiss (quartz-biotite)
W-4	264.3 m	Garnet-rich biotite gneiss
W-5	240.5 m	Granite
W-6	200 m	Biotite gneiss
W-7	194.5 m	Biotite quartz feldspar gneiss
W-8	219.9 m	Amphibole-rich gneiss
W-9	220 m	Garnet-rich biotite gneiss
W-10	192.6 m	Biotite gneiss
W-11	295.5 m	Quartz biotite gneiss
W-12	326.7 m	Granite
W-13	272 m	Amphibole-rich gneiss
W-14	191.6 m	Quartz-rich gneiss
W-15	193.7 m	Quartz-rich gneiss

[a]See Reimold et al. (2003) for core stratigraphy.

high magnification images of individual mineral grains that had been separated and etched to reveal structural characteristics following the techniques of Gratz et al. (1996). A sample of the microgranite (245.5 m) was crushed in a pestle and mortar and sieved to isolate the 250–500 micron fraction, and the white-colored mineral grains, presumably quartz and feldspar, were separated by hand-picking. Mineral etching was performed on these grains using concentrated liquid hydrofluoric acid (40%), following the method described by Gratz et al. (1996). Care was taken only to expose the grains to the acid for a maximum of 10 sec. Even during the subsequent thorough washing with water, the acid remains sufficiently concentrated to continue etching the silicate grains until neutralization is achieved. The grains were then mounted onto sticky tape and examined optically under the microscope. No further preparation was necessary before imaging in the SEM, and the grains were not coated.

For the TEM work, doubly polished thin sections, also of the microgranite sample (245.5 m), were prepared using Lakeside as the mounting medium. Quartz grains displaying 1 or more sets of planar features were identified by optical microscopy. Once identified, 3.05 mm diameter copper discs, with a central hole 0.4 mm in diameter, were glued to the surface of the thin section using Araldite, with the central hole positioned over the grain of interest. After the Araldite had cured, the surrounding rock material was scraped away with a razor blade and the thin section was heated, softening the Lakeside and allowing the copper discs, with mineral grains, to be lifted off. The samples were then thinned using a Gatan duo-mill operated at 5 kV with the guns oriented at 6° to the sample. Following perforation, each sample was lightly coated with carbon and studied by TEM. The instruments used were a JEOL 2000 FX, operated at 200 kV, and a Philips Biotwin, operated at 120 kV. In both cases, a double-tilt holder was used for correct orientation of the foils; most images were taken with the foils oriented close to the [$1\bar{2}10$] zone axis of quartz.

RESULTS

Petrographic Observations

As noted by Mory et al. (2000a, 2001), polished thin sections of samples from the W-1 core reveal abundant evidence for shock deformation (Figs. 3a–3d). These shock features have been analyzed and described in more detail by Reimold et al. (2003) but include brecciation, kink bands in biotite, planar deformation features, and lowered birefringence in quartz, feldspar, and diaplectic quartz. The rare, rounded, gneissose and granitic clasts in the W-2A conglomerate reveal planar lamellae, presumably shock deformation features, in quartz. No melt, or possible impact melt breccias have been found to date in the W-2A samples.

The only macroscopic signs of cross-cutting sub-vertical brecciation are preserved in the uppermost samples from the

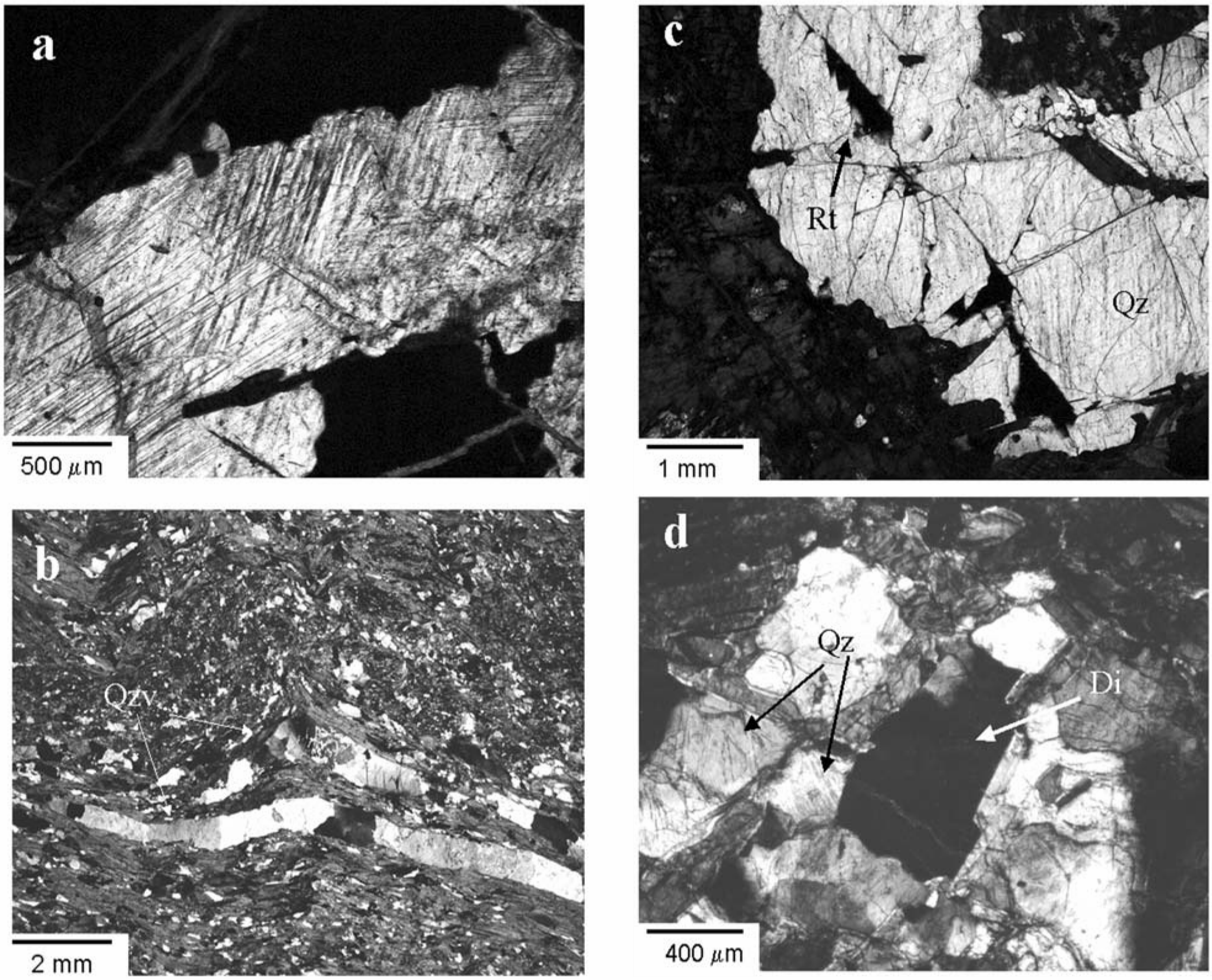

Fig. 3. Cross-polarized transmitted light microscope images of quartz from W-1 granitic basement samples: a) shocked quartz grain displaying intersecting sets of decorated PDFs (#W-9 from 220 m); b) quartz vein (Qzv) in mica-rich gneiss. The quartz displays PDFs and fracturing. Note the sub-horizontal foliation displayed by the biotite mica (#W-10 from 192.6 m); c) reticulate (Rt) black veining in quartz (Qz) represents holes in the slide from loss of material due to abundant fracturing rather than diaplectic glass (#W-14 from 191.6 m); d) diaplectic glass (Di) in shocked biotite-rich gneiss surrounding quartz grains (Qz) that display decorated PDFs (#W-10 from 192.6 m).

W-1 core (Fig. 2). This includes some apparent shear deformation zones lined with biotite mica, indicating areas of brittle deformation, possibly as a result of shear, though this is not determinable from the limited sample area of the core (Fig. 2). Such fracturing is markedly different from that preserved in the uppermost section of the autochthonous basement at the center of the Ries structure; there, abundant vertical fracturing has totally altered the original texture, while at Woodleigh, it has not. Evidence for mixed mineral melts in the form of intergranular grapnophyric textures occur in W-1 samples but are localized near grain boundaries and cataclastic breccia veins. The nature of the brecciation and granophyric clasts is not diagnostic of impact and could represent tectonic deformation leading to localized migmatization. Quartz is locally highly fractured, which has led to the loss of material during thin section preparation, resulting in a reticulate texture of apparently isotropic areas when examined by cross-polarized light microscopy (Mory et al. 2000a [Fig. 3a]). These artifacts could be mistaken for diaplectic glass (Fig. 3c). Areas of diaplectic glass (isotropic) do occur in some W-1 samples, both within quartz and feldspar grains, and also as discrete grains (Fig. 3d).

Grains of quartz often display multiple sets of planar features (Figs. 3a–3b), up to 4 sets in rare cases but predominantly 1–2 sets. Universal stage orientation measurements of these features are described in Koeberl et al. (2001) and Reimold et al. (2003). We also note that quartz often occurs as mineral veins, the quartz crystals within the veins displaying ubiquitous PDFs (Fig. 3b), even around plastically deformed zones, thus indicating the zones were pre-existing. Globular quartz grains within feldspars that are inferred to be products of recrystallization also contain planar features that extend across the grain, indicating the globules predated the shock deformation. In the brecciated/fractured zones from the upper part of the W-1 core, occasional quartz crystals that have planar features are themselves fractured. In most lithologies studied, ample evidence exists that the metamorphic textures pre-dated the passage of shock waves. Subsequent annealing of the planar features is suggested by the presence of inclusion trails, features previously noted by Mory et al. (2000a, 2001). Thus, the planar features can be considered decorated and are similar to those described from other, usually ancient, impact structures (Robertson et al. 1968). Bead-like textures are present at some quartz and quartz-feldspar grain boundaries, with individual quartz crystallites that appear sub-rounded up to 10 µm in size, forming mosaic chains that line the length of grain boundaries.

Electron Microscopy of Quartz

The quartz grains (W-2 from 245.5 m) that were hand picked from crushed samples range in size from 200–500 µm, and SEM-EDS analysis confirmed that they were, indeed, composed of Si and O. When immersed in water and studied by reflected light, the white grains appear opalescent, a feature thought to be related to internal strain (Triplehorn, personal communication). Back-scattered electron imaging in the SEM clearly illustrates that the HF acid has exploited lines of weakness in the grains, and numerous intersecting sets of planar features are apparent (Fig. 4a). The etched-out planes range from sub-micron up to 4 µm in thickness, with the majority that are easily observable being ~2 µm thick (Fig. 4b) with a variable spacing (1 to 20 µm). The thicker (>4 µm) planar features may have been tectonically-formed, but the thinner (<2 µm) varieties were not. These thinner planes are sometimes characterized by trails of inclusions that also have been preferentially etched and by the presence of 'pillars' made from thin lines of unetched material that connects both sides of the plane. At higher magnification (Fig. 4c), the inclusion trails decorate the planar features with individual spherical holes from sub-micron up to 2 µm in size. Not all of the quartz displays these features, however, and Fig. 4d illustrates this. This grain has conchoidal fractures,

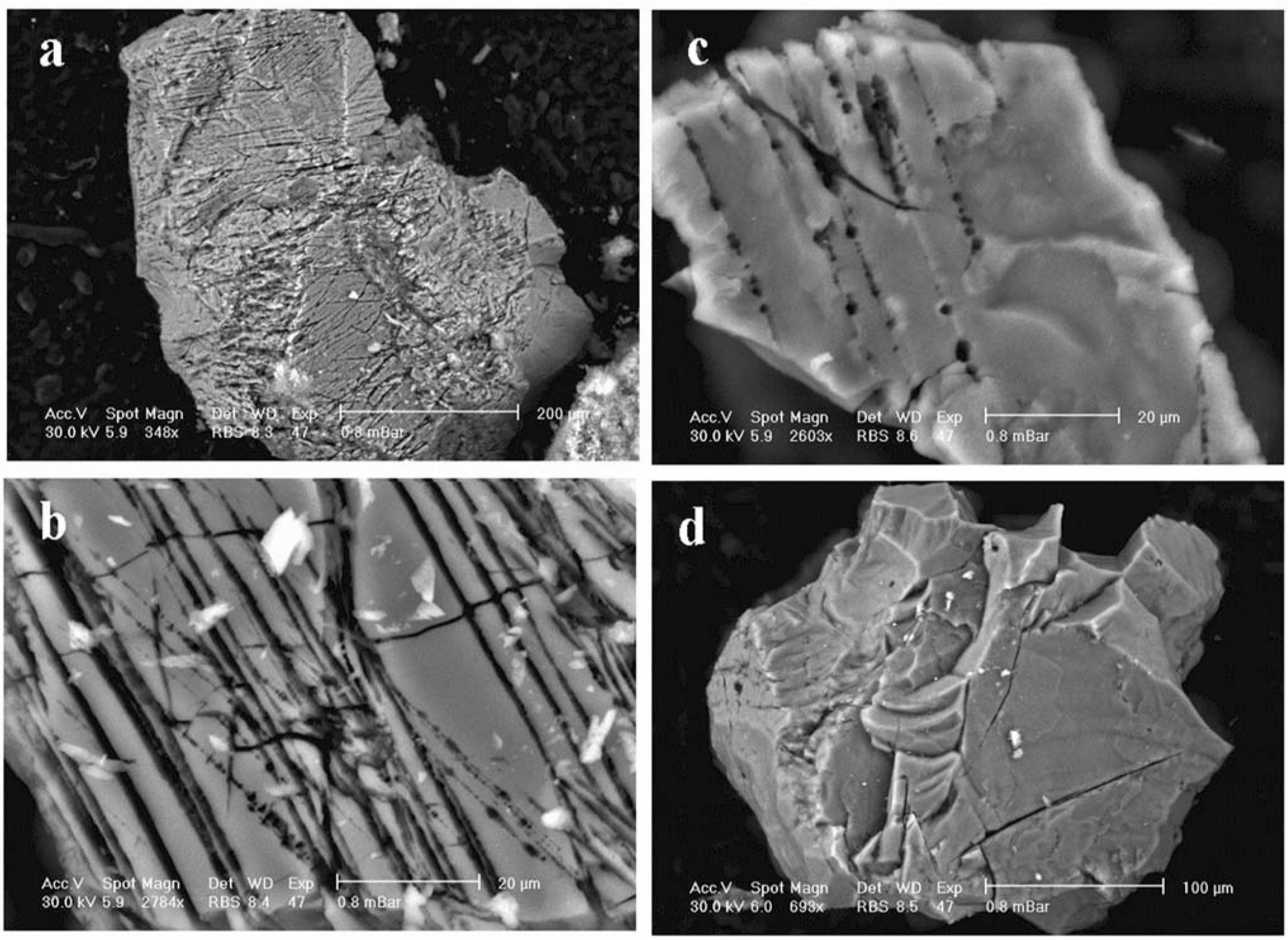

Fig. 4. Back-scattered electron images from the SEM of liquid HF-etched quartz grains separated from microgranite (#W-2 from 245.5 m): a) displaying finer elements to the planar features including fine lamellae; b) pillaring in the planes; c) open inclusion trails; and d) non-shock features in tectonically deformed quartz.

but no planar features are exposed by the etching, and it is clearly unshocked. The curved fractures are typical of tectonically deformed quartz that displays features such as Böhm lamellae (Carter 1965; Gratz et al. 1996).

The majority of the planar structures identified in the quartz grains (W-2 from 245.5 m) by light microscopy correspond to PDFs in TEM images. These PDFs range from ~70–200 nm in width and are spaced a few 100 nm to several µm apart (Fig. 5a). Trace analysis using electron diffraction patterns and corresponding images taken in 3 different crystallographic orientations demonstrates that most PDFs are oriented parallel to $\{10\bar{1}2\}$. In some TEM foils, 2 intersecting sets of PDFs have been imaged (Fig. 5b). The PDFs are distinguished from surrounding quartz by a very high density of dislocations and the presence of ~50 nm-sized quartz crystallites and micropores (possibly originally fluid inclusions) that are up to 500 nm along their longest axis. Many of these micropores have negative crystal shapes, confirming that these features are genetically related to the PDFs rather than artifacts of ion thinning. Some of the PDFs were observed to wedge out along their length. The quartz between PDFs also has a high density of dislocations. In addition, large (µm-sized) subgrains occur in quartz. These subgrains are misoriented by ~1.5°, and PDFs can be traced continuously across subgrain boundaries (Fig. 5a). No amorphous material was detected along the PDFs.

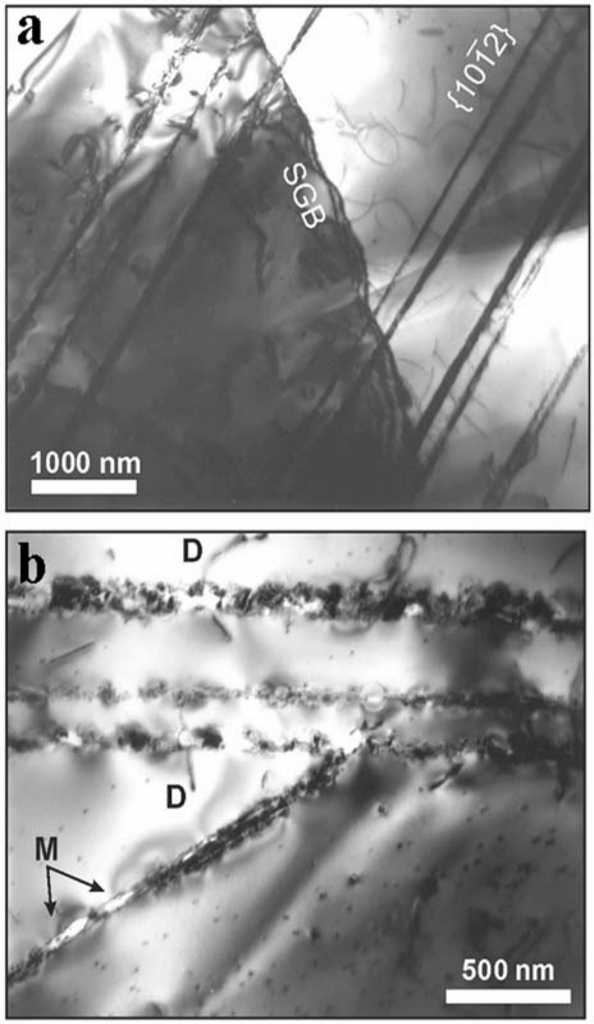

Fig. 5. Bright-field TEM images of quartz from the microgranite (#W-2 from 245.5 m) with the electron beam oriented close to $\{1\bar{2}10\}$: a) image showing the characteristic width, length, and spacing of PDFs in quartz. These PDFs are oriented parallel to $\{10\bar{1}2\}$. Note the abundance of dislocations in the quartz between PDFs. This field of view contains 2 subgrains (the one on the left side of the image is oriented closer to the zone axis), and the PDFs can be traced continuously across the subgrain boundary (SGB); b) image showing an area of quartz containing 2 intersecting PDFs. Both sets of PDFs contain abundant dislocations (D) and micropores (M; arrowed). In addition, the PDFs contain ~50 nm-sized quartz crystallites that can be distinguished by their slightly different crystallographic orientation to the host quartz grain. Electron diffraction data were insufficient for an unambiguous determination of the crystallographic orientation of these PDFs.

DISCUSSION

Tectonic Versus Shock Deformation

Shock deformed quartz grains occur throughout basement samples in the W-1 core and have also been identified from basement clasts within the paraconglomerate of W-2A (Mory et al. 2000a, 2001). Doubts surrounding the nature and origin of the deformation features within the quartz necessitated a detailed study beyond optical microscopy to be performed (Mory et al. 2000a; Reimold and Koeberl 2000). Within basement samples from the W-1 core, which largely comprise mixed gneisses and granitic rocks, quartz occurs in several forms, including but not limited to crystalline igneous quartz with an overprinted foliation, vein quartz, quartz grains in breccia, and globular quartz crystals often hosted by feldspars. All show the effects of extreme deformation including fracturing, some of which may be attributed to tectonic deformation, as well as planar deformation features (some decorated) of 2–4 sets that are indicative of shock metamorphism. These deformation features overprint the tectonically-formed textures that dominate the lithologies and include quartz veining and some plastic and brittle deformation and recrystallization features. Also, fracturing clearly has occurred after shock-deformation, as several shocked quartz grains display reticulate textures with abundant 'black veining' (Mory et al. 2001), which may represent thin section artifacts rather than diaplectic glass (Fig. 3c). Quartz with lowered birefringence and diaplectic glasses (Fig. 3d) do occur in the samples, although in our observations, the latter do not occur abundantly. Diaplectic glass grains, up to 500 µm across, were observed, indicating a local maximum shock level of approximately 35 GPa (Stöffler and Langenhorst 1994).

Planar Features and PDFs in Quartz

Owing to the high level of tectonic deformation and the regional metamorphic history of the mixed crystalline basement at Woodleigh, we performed acid-etching experiments to further confirm shock deformation lamellae (Gratz et al. 1996; Montanari and Koeberl 2000), and these experiments compliment the U-stage analyses of Reimold et al. (2003). Our SEM images (BSE imaging) of HF-liquid-etched quartz clearly reveal abundant PDFs in the quartz grains, as well as quartz grains that are unshocked and display open tectonic fractures. The thicker lamellae that can be observed optically are further revealed during etching. By using this etching technique and combining it with electron microscopic imaging, we have been able to view submicroscopic PDFs and reveal their fine structure (Gratz et al. 1996). These structures cannot be observed using conventional microscopy and were not recorded in other studies of Woodleigh target rocks (Mory et al. 2000a, 2000b, 2001). Using the convention to characterize shocked quartz at the K/T boundary and quartz from Haughton, Canada, etching revealed very thin deformation lamellae and pillaring at the sub-micron level; the pillaring may be indicative of amorphous silica (Gratz et al. 1996). Etching, using liquid HF, of tectonically deformed grains has been shown to yield wider >5 µm lamellae.

The PDFs in quartz from microgranite in the W-1 core, are consistent with PDFs that have undergone water-assisted recrystallization. Such recrystallized PDFs have been studied in detail by TEM (Goltrant et al. 1991) and occur in a number of ancient impact structures including the late Cretaceous Manson structure, Iowa (Leroux and Doukhan 1996) and the late Devonian Alamo Breccia, Nevada (Leroux et al. 1995). The characteristics of these recrystallized PDFs include a narrow width (~100 nm), a very high dislocation density, and a close association with sub-µm-sized fluid inclusions that have negative crystal shapes (decorated PDFs). The recrystallized PDFs have orientations common to amorphous silica-lined PDFs from more recent impact sites, including $\{10\bar{1}2\}$ and $\{10\bar{1}3\}$, and the same as those found in the U-stage studies of these samples (Koeberl et al. 2001; Reimold et al. 2003). Grieve et al. (1996) suggest that amorphous silica-bearing PDFs recrystallize readily because the amorphous silica can contain considerable quantities of water (up to 6 wt%). Over time, annealing, commonly assisted by further interaction with water, leads to recrystallization of the originally amorphous silica-bearing PDFs. This recrystallization is associated with exsolution of water and growth of quartz crystallites and generates a very high density of dislocations. Further water interaction over time at Woodleigh is also indicated by the formation of clays, as described by Uysal et al. (2001). These clays infill fractures and some deformation features, clearly indicating that the alteration is post-impact and may represent either the onset of weathering that is typical of the granitic rocks of this region or a hydrothermal event. The bead-like textures that line some quartz grain boundaries are similar to those reported for intense recrystallization (Leroux et al. 1994) and could be primary tectonic features, shock related, or the result of later hydrothermal activity.

The orientation of the decorated PDFs measured by TEM and by U-stage (Koeberl et al. 2001; Reimold et al. 2003) indicates an average pressure of formation of about 20 GPa. Kinetic effects during a pressure pulse lasting ~1 sec in the central uplift could mean that these PDFs and diaplectic glasses could form at lower pressures, though further work is needed to better constrain these effects (Bowden et al. 2000; De Carli et al. 2002).

The presence of diaplectic glass puts the peak pressure realized in these rocks nearer to 35 GPa. The lack of distinctive melts, or evidence of individual minerals melting and flowing in the samples studied here, suggests that the rocks are from a deep level within the overall architecture of the impact geology of this structure. Following the studies by Dence (1968) of centrally uplifted and shocked crystalline basement at Canadian craters, the $\{10\bar{1}2\}$ orientations of the PDFs and the presence of diaplectic glass in W-1 samples point to shock zone (v). These also correspond to shock Stage (I) to (II) of Engelhardt and Stöffler (1968) from their study of crystalline material at the Ries crater, Germany and are very strongly or extremely shocked according to the shock stages of Grieve et al. (1996). If the diameter of the structure is accepted as 120 km, then these samples from almost the exact center of the structure would have to be derived from great depths, following the model of Ivanov and Deutsch (1999). This is easily accounted for by the formation process of the centrally uplifted portion of the crystalline basement; however, significant volumes of material must have been removed from above it as we see no impact melts or injected melts and no evidence for material with a shock level above an estimated maximum of 35 GPa and averaging around 20 GPa. Indeed, the rare basement clasts in the paraconglomerate from W-2A also reveal shock features but no melt component, and no melt or breccia clasts have been reported from this sediment as a whole, further supporting significant erosion. In this case, the absence of melts or breccia clasts suggests that the sediment must have been deposited a considerable time after this erosion, also explaining the rounded nature of the basement clasts in the paraconglomerate, even though they were probably very locally derived.

Implications for the Size of the Woodleigh Structure

Following criticism from Reimold and Koeberl (2000), Mory et al. (2001) accepted that, with present knowledge, the main gravitational signature of the Woodleigh structure is ~60 km in diameter and that it is only a possibility (Mory et al. 2001) that the structure is larger, up to 120 km in diameter, as claimed by Mory et al. (2000a) and Iasky et al. (2001). W-1 samples are taken from almost the center of the central gravity anomaly of the Woodleigh structure (Iasky et al. 2001; Mory et al. 2001). The abundant shock features are not accompanied by melting, vertical fracturing, or melt injection, and, as noted here and in Hough et al. (2001), no impact melt breccia or impact melt sheet overlying the central uplift is intersected by the W-1 drill core or any other cores in the area. This strongly suggests that the Woodleigh structure has been deeply eroded, removing lithologies with a higher shock signature and melts/breccias. As a result of this erosion, the diameter of the central uplift is probably exaggerated. Scaling laws ($Dcp = 0.31 \times D^{1.02}$) established by Grieve and Pesonen (1992) from a large number of structures indicate that the sizes of the central uplifts related to the overall diameter of the impact structures are skewed toward larger diameters. In Mory et al. (2000a), these calculations gave an overall crater diameter for Woodleigh nearer to 74 km. Taking a smaller crater diameter for Woodleigh of 60–70 km, scaling indicates a central uplift of 19.7 km to 23.1 km diameter compared with the present-day figure of 25 km interpreted from geophysics (gravity data) (Iasky et al. 2001). Conceivably, then, erosion would have increased the apparent diameter of the central uplift from near that range to its present size of 25 km. As Mory et al. (2000a) and Iasky et al. (2001) noted, scaling laws are difficult to constrain because mixed target lithologies can have a controlling effect. However, in comparison with other, better defined structures, for the Woodleigh structure to be 120 km in diameter, a much larger central uplift would be required. By comparison, the Popigai structure in Russia has an overall diameter of approximately 100 km, and its central uplift is about 35 km; Chesapeake Bay in North America is near 85 km in diameter with a central uplift some 30 km in diameter. The true diameter of the central uplift at Woodleigh is yet to be determined. Gravity data indicate a "ring" at 25 km diameter that may or may not represent a central peak ring. The structural information interpreted from available seismic sections (Iasky et al. 2001) proves inconclusive in this regard. Without taking into account the effects of erosion, Uysal et al. (2002) now claim a new diameter for the central uplift at Woodliegh of 31–37 km, based on the same seismic data but with a new interpretation of an uplifted sedimentary collar. This equates (using scaling) to an overall diameter for Woodliegh ranging from 90–109 km, ignoring erosion, and is still considerably less than 120 km. No direct evidence of an uplifted sedimentary collar at Woodleigh exists at present. In fact, taking the cross-section interpretation of Mory et al. (2000a, 2001) and Uysal et al. (2002), W-2A would have been drilled into such a collar; however, the Silurian samples from the base of the W-2A core are relatively flat-lying with no steep dips that could be indicative of such a collar. The structure is further complicated by younger tectonic activity (Iasky et al. 2001), with a normal fault (Fig. 1) (down-throwing to the west) that is apparently younger than the structure, cutting and extending across it in an almost N-S direction. The extent to which it alters the framework of the impact structure, especially the centrally uplifted portion, is unclear, but this is of fundamental importance to interpretations of scaling and stratigraphy.

The regional structure of the Wandagee and Ajana ridges may be controlled by a tectonic framework involving the western margin of the Yilgarn craton. The Madeline and Darling faults, and interaction with the abundant West-East trending faults that lie to the east of the Woodleigh structure, toward the northern margin of the Yilgarn craton could easily account for any apparent pulling of the ridges to the east. This feature was interpreted as an arcuate incursion of the Woodleigh impact by Mory et al. (2000a) and Iasky et al. (2001) and used to support a 120 km diameter for the structure. In an early report (Iasky and Mory 1999), a post-Permian age was claimed to be necessary for a 120 km diameter impact structure at Woodleigh by the regional geology. In the interpretation, of Iasky and Mory (1999), the "arcuate" magnetic anomaly aligned with the eastern margin of the structure "straddles uninterrupted over the bounding faults between the Gascoyne platform and the Permian sub-basins to the east." Hence, Woodleigh would post-date the last movements on those faults in the middle Permian. Therefore, either the impact is indeed post-Permian and present age estimates are incorrect (Uysal et al. 2001, 2002), or it is smaller than 120 km. Recently, Whitehead et al. (2003), albeit from a small number of samples, concluded that combining shock attenuation rates with levels of uplift suggests a diameter for the crater nearer to 60 km.

Detailed seismic surveys at the Chicxulub structure in Mexico (Morgan et al. 1997; Morgan and Warner 1999) helped to identify its structural elements and to reveal a concave top to the central uplift, probably infilled with impact melt and impact breccia, that, in turn, is bound by the peak ring. Similar studies are needed at Woodleigh to reveal its structural elements, assuming that they have survived prolonged erosion.

CONCLUSIONS

Our observations confirm the presence of abundant decorated planar deformation features of shock origin in quartz grains from the rocks of the W-1 core and, thus, an undisputed impact origin for the Woodleigh structure identified by Mory et al. (2000a). Specifically, SEM and TEM analysis shows that abundant, sub-micron PDFs in quartz are oriented parallel to $\{10\bar{1}2\}$ crystallographic planes and are characterized by pillars of interplanar material; features typical of intense shock-induced deformation identified in quartz grains from other impact structures (Leroux et al. 1995). The orientations of these planes (this study; Reimold et al. 2003) support shock pressures of 20 GPa, and the presence of diaplectic glass suggests local elevation to 35 GPa, corresponding to the shock zone (v) of Dence (1968) and stage (I) to (II) of Engelhardt and Stöffler (1968) in crystalline rocks from Canadian and the Ries impact craters.

These shock features, however, are superimposed on, and superceded by, a complex history of terrestrial deformation, metamorphism, and alteration. Many quartz grains from the W-1 core exhibit curved fractures and some wide (>5 µm) planar lamellae that can be interpreted as resulting from tectonic deformation during regional metamorphism. Recrystallization of feldspar before impact is inferred from included quartz spherules that display shock-induced lamellae. Similarly, quartz veins and features indicative of plastic and brittle deformation are locally overprinted by shock-induced lamellae and clearly represent episodes of deformation that predate the impact event. In contrast, other fractures in shocked quartz appear to post-date shock induced deformation, producing reticulated textures in some grains.

In detail, shock-induced PDFs in quartz are associated with trails of inclusions that indicate a period of post-shock annealing (see also Goltrant et al. 1991). Amorphous material expected to occur within PDFs has not been observed using the TEM; however, evidence for its presence was found in the form of pillaring in SEM images of acid-etched grains. Recrystallized interplanar material and quartz crystallites along the boundaries of some grains are consistent with water-assisted recrystallization that post-dated the impact event. Further, later and more extensive water-assisted alteration is evidenced by the growth of clay minerals (illite and smectite groups) along some shock deformation features (Uysal et al. 2001) and fractures.

The lack of an impact melt breccia or melt sheet in the W-1 core is evidence of erosion of the structure. We consider this to be significant erosion as basement in the W-1 core shows a limited shock level. Although abundant brecciation exists, it is not vertical, e.g., at the Ries and in our observations, no direct unequivocal evidence of impact melting or melt injection exists, which is surprising for the central-most part of a large (even at 60 km diameter) impact structure. As noted by Reimold et al. (2003), any melt component in W-1 samples is very minor and not in the form of pseudotachylites, thus supporting the deep level origin. The lithologies in W-1 also show abundant evidence of strong deformation before the impact event. Some brecciation in the form of cataclasites may also be related to this.

With increased erosion, the dimensions of impact structures are significantly altered (Grieve and Pilkington 1996), producing apparently larger central uplifts. We believe this is the case at Woodleigh, and the idea is supported by scaling relationships using the formula of Grieve and Pesonen (1992), whereby an overall diameter for Woodleigh of 60 km gives a diameter of nearly 20 km for the central uplift, 5 km smaller than the interpreted present-day figure from the gravity data (Iasky et al. 2001). Even though scaling relationships are difficult to constrain due to other limiting factors such as target lithology, a diameter of 120 km for Woodleigh would require a central uplift of nearer 40 km in diameter. Clearly then, an eroded and modified central uplift at Woodleigh is strong evidence for a smaller total diameter, probably nearer 60 km, as has been suggested.

Acknowledgments–Michael Verrall (CSIRO) is thanked for assistance with the SEM. We would like to thank Colin How, Billy Smith (Department of Physics, University of Glasgow), and John Findlay (Department of Botany, University of Edinburgh) for help with ion thinning and TEM. Dr. T. Griffin, Director of the GSWA is thanked for permission to view and sample the Woodleigh cores (approval S31459). Dr. A. Mory is thanked for assistance with sampling. Christian Koeberl and Dieter Stöffler provided insightful and beneficial reviews that, together with Walter Huebner's comments, greatly improved the manuscript. The Royal Society (UK), PPARC, and the Corporation of London provided funding.

Editorial Handling—Dr. Walter Huebner

REFERENCES

Bowden E., Kondo K., Ogura T., Jones A. P., Price G. D., and DeCarli P. S. 2000. Loading path effects on the shock metamorphism of porous quartz (abstract #1582). 31st Lunar and Planetary Science Conference. CD-ROM.

Carter N. L. 1965. Basal quartz deformation lamellae: A criterion for the recognition of impactites. *American Journal of Science* 263: 786-806.

Dence M. R. 1968. Shock zoning at Canadian craters: Petrography and structural implications. In *Shock metamorphism of natural materials,* edited by French B. M. and Short N. M. Baltimore: Mono Book Corp. pp. 169–184.

DeCarli P. S., Bowden E., Jones A. P., and Price G. D. 2002. Laboratory impact experiments versus natural impact events. In *Catastrophic events and mass extinctions: Impacts and beyond,* edited by Koeberl C. and MacLeod K. Geological Society of America Special Paper 356. pp. 595–605.

Engelhardt W. V. and Stöffler D. 1968. Stages of shock metamorphism in the crystalline rocks of the Ries Basin, Germany. In *Shock metamorphism of natural materials,* edited by French B. M. and Short N. M. Baltimore: Mono Book Corp. pp. 159–168.

Goltrant O., Cordier P., and Doukhan J. C. 1991. Planar deformation features in shocked quartz: A transmission electron microscope investigation. *Earth and Planetary Science Letters* 106:103–115.

Gratz A. J., Fisler D. K., and Bohor B. F. 1996. Distinguishing shocked from tectonically deformed quartz by the use of the SEM and chemical etching. *Earth and Planetary Science Letters* 142: 513–521.

Grieve R. A. F. and Pesonen L. J. 1992. The terrestrial impact cratering record. *Tectonophysics* 216:1–30.

Grieve R. A. F. and Pilkington M. 1996. The signature of terrestrial impacts. *AGSO Journal of Australian Geology and Geophysics* 16:399–420.

Grieve R. A. F., Langenhorst F., and Stöffler D. 1996. Shock metamorphism of quartz in nature and experiment: II. Significance in geoscience. *Meteoritics* 31:6–35.

Hough R. M., Lee M. R., and Bevan A. W. R. 2001. Shocked quartz and more: Woodleigh impact structure, Western Australia (abstract). *Meteoritics & Planetary Science* 36:84–85.

Iasky R. P. and Mory A. J. 1999. Geology and petroleum potential of the Gascoyne Platform, Southern Carnarvon Basin, Western Australia. Western Australia Geological Survey Report 69. 46 p.

Iasky R. P., Mory A. J., and Blundell K. A. 2001. The geophysical interpretation of the Woodleigh impact structure, Southern Carnarvon basin, Western Australia. Western Australia Geological Survey Report 79. 41 p.

Ivanov B. A. and Deutsch A. 1999. Sudbury impact event: Cratering mechanics and thermal history. In *Large meteorite impacts and planetary evolution II,* edited by Dressler B. O. and Sharpton V. L. Geological Society of America Special Paper 339. pp. 389–397.

Koeberl C., Hough R. M., Boamah D., French B. M., McDonald I., and Reimold W. U. 2001. Woodleigh impact structure, Australia: Shock petrography and geochemical studies (abstract). *Meteoritics & Planetary Science* 36:101.

Leroux H., Reimold W. U., and Doukhan J. C. 1994. A TEM investigation of shock metamorphism in quartz from the Vredefort dome, South Africa. *Tectonophysics* 230:223–239.

Leroux H., Warme J. E., and Doukhan J. C. 1995. Shocked quartz in the Alamo breccia, southern Nevada: Evidence for a Devonian impact event. *Geology* 23:1003–1006.

Leroux H. and Doukhan J. C. 1996. A transmission electron microscope study of shocked quartz from the Manson impact structure, In *The Manson impact structure, Iowa: Anatomy of an impact crater,* edited by Koeberl C. and Anderson R. Geological Society of America Special Paper 302. pp. 267–274.

Montanari A. and Koeberl C. 2000. Impact Stratigraphy: The Italian record. In *Lecture notes in earth sciences.* Heidelberg-Berlin: Springer Verlag. 364 p.

Morgan J., Warner M., and The Chicxulub Working Group. 1997. Size and morphology of the Chicxulub impact crater. *Nature* 390: 472–476.

Morgan J. and Warner M. 1999. The Chicxulub seismic experiment: Crater morphology, In *Large meteorite impacts and planetary evolution II,* edited by Dressler B. O. and Sharpton V. L. Geological Society of America Special Paper 339. pp. 269–279.

Mory A. J., Iasky R. P., Glikson A. Y., and Pirajno F. 2000a. Woodleigh, Carnarvon basin, Western Australia: A new 120 km diameter impact structure. *Earth and Planetary Science Letters* 177:119–128.

Mory A. J., Iasky R. P., Glikson A. Y., and Pirajno F. 2000b. Response to "Critical Comment on A. J. Mory et al., 2000, Woodleigh, Carnarvon basin, Western Australia: A new 120 km diameter impact structure" by W. U. Reimold and C. Koeberl. *Earth and Planetary Science Letters* 184:359–365.

Mory A. J., Pirajno F., Glikson A. Y., and Coker J. 2001. GSWA Woodleigh 1, 2, and 2A well completion report, Woodleigh impact structure, Southern Carnarvon Basin, Western Australia. Western Australia Geological Survey Record 2001/6. 147 p.

Myers J. S. 1993. Precambrian history of the West Australian craton and adjacent orogens. *Annual Review of Earth and Planetary Sciences* 21:453–485.

Reimold W. U. and Koeberl C. 2000. Critical comment on: A. J. Mory et al. "Woodleigh, Carnarvon basin, Western Australia: A new 120 km diameter impact structure." *Earth and Planetary Science Letters* 184:353–357.

Reimold W. U., Koeberl C., Hough R. M., McDonald I., Bevan A., Amare K., and French B. M. 2003. Woodleigh impact structure, Australia: Shock petrography and geochemical studies. *Meteoritics & Planetary Science* 38:1109–1130.

Renne P. R., Reimold W. U., Koeberl C., Hough R., and Claeys P. 2002. Comment on: "K-Ar evidence from illitic clays of a Late Devonian age for the 120 km diameter Woodleigh impact structure, Southern Carnarvon Basin, Western Australia," by Uysal I. T., Golding S. D., Glikson A. Y., Mory A. J., and Glikson M. *Earth and Planetary Science Letters* 201:247–252.

Robertson P. B., Dence M. R., and Vos M. A. 1968. Deformation in rock forming minerals from Canadian craters. In *Shock metamorphism of natural materials,* edited by French B. M. and Short N. M. Baltimore: Mono Book Corp. pp. 433–452.

Stöffler D. and Langenhorst F. 1994. Shock metamorphism of quartz in nature and experiment: I. Basic observation and theory. *Meteoritics* 29:155–181.

Uysal I. T., Golding S. D., Glikson A. Y., Mory A. J., and Glikson M. 2001. K-Ar evidence from illitic clays of a late Devonian age for the 120 km diameter Woodleigh impact structure, Southern Carnarvon Basin, Western Australia. *Earth and Planetary Science Letters* 192:281–289.

Uysal I. T., Golding S. D., Glikson A. Y., Mory A. J., Glikson M., Iasky R. P., and Pirajno F. 2002. Reply to comment on "K-Ar evidence from illitic clays of a Late Devonian age for the 120 km diameter Woodleigh impact structure, Southern Carnarvon Basin, Western Australia" by Renne et al. *Earth and Planetary Science Letters* 201:253–260.

Uysal I. T., Golding S. D., Mory A. J., and Glikson A. Y. 2003. Mineralogic and isotopic constraints on impact related clay mineral alteration, in the Woodleigh impact structure, Western Australia (abstract #03315). *Geophysical Research Abstracts* 5.

Whitehead J., Grieve R. A. F., and Spray J. G. 2003. Planar deformation features in the Woodleigh impact structure, Western Australia, and their bearing on the diameter and degree of structural uplift in the structure (abstract). Annual Meeting of the NE section of the Geological Society of America, Halifax, Nova Scotia, March 27–29th.