Meteoritics & Planetary Science 36, 747–752 (2001)
Available online at http://www.uark.edu/meteor

Comment and Reply

Comment on "Origin of a late Eocene to pre-Miocene buried crater and breccia lens at Fohn-1, North Bonaparte Basin, Timor Sea: A probable extraterrestrial connection" by J. D. Gorter and A. Y. Glikson

(Received 2000 October 2; accepted 2001 February 5)

Abstract–Gorter and Glikson (2000) proposed that the Fohn-1 structure in the Timor Sea north of Australia probably is an impact structure. Examination of their evidence reveals that it is almost impossible to confirm any of their conclusions, as the authors do not provide sufficient detail of their experimental methods. Problems with the presentation of both seismic and geochemical data cast further doubt on their conclusions. Absence of evidence for shock metamorphism and non-chondritic siderophile element patterns in the few samples analysed make it likely that Fohn-1 is neither a probable, nor even a possible, impact structure.

INTRODUCTION

Gorter and Glikson (2000) have presented some evidence from which they concluded that the Fohn-1 structure in the Timor Sea is a probable impact structure. Here, we reevaluate their evidence, using established criteria for the verification of impact structures (*e.g.*, French, 1998), and discuss problems with their data and presentation.

GEOPHYSICS

The discussion of the seismic section (their Fig. 4) is very brief and contains no detailed information on instrumentation and data collection and processing (*e.g.*, migration of data). A plot of the stratigraphic section for Fohn-1, superimposed on the seismic section, would be essential to allow inferences about the validity of the interpretation of Fohn-1 as an impact structure. Reliable interpretation of the observed features requires good resolution of lateral and vertical velocity variations, which can be large in young, offshore sedimentary basins, and are not discussed. Valid conclusions require evaluation of the following: (1) could the anticlinal features and the associated lack of clarity of features represent processing artifacts due to inadequate velocity resolution? (2) Does the area of reflector topography and disruption occur in a region where there is an old river channel close to the surface (between locations 2700 and 2800), with associated changes in local lithology and seismic velocity? (3) What is the possibility that the synclinal feature emphasized by the authors could represent some other geological feature, besides a possible impact structure? A synclinal feature in a seismic section from an oil and gas field might, alternatively, indicate overlying gas-filled rocks or be caused by tectonically-induced slumping. The major disturbances in the areas of the alleged rim and central uplift structures of Fohn-1 that appear in the seismic section extend to the base of the profile and possibly deeper. They also affect the overlying strata including the northeastern rim area, where disturbance seems to extend to the surface. Neither the nature of borehole Fohn-1 (oil or gas well, or non-productive site) nor the extent to which its anomalous sonic logs have been used to optimize processing have been discussed.

Imagine crossing the so-called rim of the disturbed structure in Gorter and Glikson's Fig. 4, towards the northeast. In this direction, reflections that can be correlated across the section are noticeably offset towards longer times (greater depths or, possibly, slower seismic velocities). This suggests tilting of the entire section towards the northeast. Is it possible that the disturbed region between locations 2700 and 2800 could result from subsidence of faulted basement rocks (not visible on the section), which is represented in unconsolidated sediments by zones of disruption with no clear evidence of faulting?

PETROGRAPHY

Several aspects of the "lithological" section in the paper require discussion. The authors present a mixture of results by other workers and their own, somewhat limited, observations. Given the untraceable, that is, unreferenced, and, thus, unverifiable observations cited as Martin (1997), and the lack of any petrographic photographs or other data that would show the presence of (impact) glass, the interpretation that suevite is present remains unsubstantiated. What remains in the reader's mind is the last sentence of this section: "None of the samples contained discrete quartz grains that could show conventional shock lamellae (we note that this term was discontinued in 1990; Grieve *et al.*, 1990) or PDFs".

The lithological section does not contain the word "pseudotachylite", but the next section begins with "Analyses for trace metal and platinum group elements (PGE) within the pseudotachylite breccia cuttings…". Does the "volcaniclastic/ suevitic/volcanic clast" material described equate with "pseudotachylite breccia"? Glikson (*e.g.*, 1996) has previously taken the view that the presence of pseudotachylite is equivalent to shock metamorphic effects and, by implication, is diagnostic for impact structures. However, only two of the three largest known terrestrial impact structures, namely Vredefort and Sudbury, have abundant pseudotachylitic breccias. And in smaller impact structures, pseudotachylitic breccia is generally rare (Reimold, 1995, 1998). The term "pseudotachylite" in earth science usage refers solely to "friction melt rock". The authors seem to equate pseudotachylite with the glassy(?) fragments observed in a few samples, which are clearly of unknown origin and, thus, should be designated non-genetically.

As Gorter and Glikson analyzed this material for traces of a meteoritic component, they seem to try to confirm the presence of impact melt fragments at Fohn-1, and not of friction melt (= pseudotachylite), because friction melt in the crater floor has never been shown to contain a meteoritic component elsewhere.

PLATINUM GROUP ELEMENT GEOCHEMISTRY

This section contains omissions, mistakes in tables and figures (figure captions do not agree with the figures in Figs. 6–8; in Fig. 6, the axis labels indicate Ir plotted *vs.* Ir and Pd *vs.* Pd!), and—in our view—misrepresentations of data. Descriptions of the analytical procedures are either insufficient or absent. The platinum group element (PGE) data presented fail to meet even the most basic reporting criteria (McDonald, 1998). The fire-assay method used inevitably introduces blank PGE from the reagents (*e.g.*, McDonald *et al.*, 1994). This is a perennial worry when dealing with low-level samples such as possible impact rocks (Koeberl *et al.*, 2000), but no information on the PGE blank is provided. As the authors report 62 ppb Ru in one sample (not 623 ppb Ru, as given in their Table 2a; based on the ratios in Table 2c and the normalization in Fig. 7) and values of 31, 23.5, and 12 ppb Os in others, without accompanying enrichment in other PGE (particularly Ir), contamination may be involved.

Perhaps the most serious analytical problem is the absence of any data for recognized PGE certified reference materials, with which to assess the accuracy of the analyses (and highlight any blank contamination). Given the importance assigned to the PGE data, such an omission is unacceptable. Furthermore, there is no measurement of the precision (uncertainty) on each PGE concentration, and it is unclear whether analyses have been adequately replicated. This makes assessing the uncertainty on PGE concentrations and ratios impossible (McDonald, 1998).

Even taking the data at face value, we strongly disagree with many of the authors' conclusions. The Ir and Ru concentrations present in some Fohn-1 samples appear higher than those in many other sediments, but the burden of proof for impact requires more than just apparently high Ir and Ru concentrations (*e.g.*, Koeberl, 1998). Contamination has to be excluded, and the absence of any data concerning accuracy, precision, and reagent blanks in the paper does not allow the reader to do this. Furthermore, the PGE must be considered together as a group. With the exception of the sample from 710–720 m, all other samples show at least 4 out of 5 PGE ratios deviating from chondritic values by a factor >2. Without information on analytical uncertainty, it is impossible to say whether this deviation is statistically tolerable in terms of the proposed impact model, or not. In the sample from 710–720 m, Pd/Ir, Pt/Ir, Os/Ir and Pt/Pd are all within 50% of the corresponding chondritic ratios; but Ru/Ir—the ratio believed most diagnostic by Evans *et al.* (1993)—is 3.3× chondritic. In fact, none of the samples produces a Ru/Ir ratio within a factor of 2 of the chondritic value. Ru/Ir, which should be least susceptible to change during diagenesis, actually offers the *least* support for a chondritic signature. Despite the authors' own appeal to PGE remobilisation, after integration of the Os, Ir and Ru concentrations, the integrated Os/Ir and Ru/Ir ratios (cf., Evans *et al.*, 1993) are 6.00 and 6.58, respectively. These values are 5.5 and 4.2× the corresponding chondritic ratios and are skewed by unusually high Os and Ru concentrations in some samples. This is hardly supportive of a chondritic signature and reinforces our view that the uncertainties in these data are simply too great to reliably determine the source of the PGE at Fohn-1.

Similar arguments pertain to other trace element data (in their Table 2b). With the exception of only one (the 970–980 m) sample, none of the others produces more than one ratio—out of six—which matches the corresponding chondritic ratio. Many diverge by more than a factor of 10. In the sample from 970–980 m, Co/Cr, Ni/Ir and Ni/Pt ratios are close to chondritic values, but Ni/Co, Ni/Cr and Ni/Cu are significantly deviant. Furthermore, only Pt/Pd in this sample is chondritic, so the authors' conclusion that "near chondritic PGE patterns…are accompanied by nearly chondritic Ni/Cr, Co/Cr, Ni/Ir, Ni/Pt and Cu/Pd ratios" is unsustainable. The authors are highly selective with their observations. The sample with data closest to chondritic PGE ratios (710–720 m) occurs 250 m above that with the most chondritic Ni/Cr, Co/Cr, Ni/Ir, Ni/Pt and Cu/Pd ratios (970–980 m). The conclusion that these signatures "accompany" one another (and by implication support one another) is fundamentally incorrect.

CONCLUSION

In conclusion, Fohn-1 might be considered an interesting structure, which deserves more detailed work to unravel its origin and the nature of the glassy component in the carbonate breccia zone. We feel, however, that the first step has to be a detailed petrographical study, designed to document any characteristic shock features in a quantitative way. Presenting PGE data without documentation of accuracy, precision and reagent blanks simply makes those data subject to great uncertainty. Replicate analyses in a dedicated low-level PGE laboratory are a prerequisite for this type of study (*e.g.*, Koeberl *et al.*, 2000; Huber *et al.*, 2000). Geophysical surveys, especially combined seismic reflection/refraction and gravity data, can indeed aid in the identification of possible impact structures. However, the results must be used with caution.

Proper assessment of regional geophysics and detailed correlation between borehole samples and geophysical logs are essential.

In our view, the data presented by Gorter and Glikson (2000) do not support the interpretation that Fohn-1 is an impact structure or that meteoritic material is present within the breccia. For this reason, to refer to Fohn-1 as a "probable impact structure" is presently unjustified.

Acknowledgment–This is University of the Witwatersrand Impact Cratering Research Group Contribution No. 23. Supported by the Austrian FWF, Start-Y58.

Wolf U. Reimold[1]*, Christian Koeberl[2], Cedric Wright[3], and Iain McDonald[4]
[1]Impact Cratering Research Group, Department of Geology, University of the Witwatersrand, Private Bag 3, P.O. Wits 2050, Johannesburg, South Africa.
[2]Institute for Geochemistry, University of Vienna, Althanstrasse 14, A-1090 Vienna, Austria.
[3]Bernard Price Institute for Geophysical Research, University of the Witwatersrand, Private Bag 3, P.O. Wits 2050, Johannesburg, South Africa.
[4]School of Earth and Environmental Sciences, University of Greenwich, Chatham Maritime, Kent ME4 4TB, U.K.
*065wur@cosmos.wits.ac.za

Authors' Reply

(Received 2000 December 5; accepted 2001 February 5)

Abstract–Reimold *et al.* question our interpreted impact origin of the Fohn structure, Timor Sea, and criticise methodological aspects of the seismic reflection survey of Fohn structure and chemical analytical techniques. Our impact interpretation resulted from (1) remarkable analogies between the seismic structures of massive core–annular trough structure of volcanic diatremes, and the syncline-ringed central uplift of impact structures; (2) occurrence of Cretaceous microfossils in the drill chips, which suggested deep excavation; (3) lack of seismic evidence for volcanic feeders or conduits, and (4) the ultramafic chemistry of drill chips (Ni < 428 ppm; Co < 51 ppm; Cr <518 ppm). Here we indicate that, since publication of our paper, we have uncovered in Fohn-1 drill cuttings rare apatite-rich lamproite mineral assemblages consisting of pseudomorphs of analcite after leucite, nontronite-altered olivine, diopside, alkali pyroxene, Ti-phlogopite, apatite, Mg-ilmenite, priderite, rutile, and secondary barite. The new data explain the high gamma ray log anomalies in Fohn-1 well and shed new light on the origin of the Fohn structure. Our error serves to clarify criteria for distinguishing between buried diatremes and impact structures.

SEISMIC METHODOLOGY

Reimold *et al.* state that the "anticlinal" feature may be a processing artifact from inadequate velocity resolution and that the synclinal feature could be the result of gas escape or tectonic slumping. In our paper (Gorter and Glikson, 2000) we describe domal rather than "anticlinal" features. Push-down of reflectors below the 500 ms horizon is subtle, occurring to about 650 ms to the southeast of the time high and barely apparent to the northwest. Pull-up features of seismic reflectors below the 500 ms horizon are apparent down to but not below about 1200 ms at Fohn-1. This is in marked contrast to hydrocarbon-related gas escape features in the region where disturbance commonly extends down almost to the reservoir levels at 1500–2500 ms. Whereas, superficially, there may be some resemblance between the Fohn structure and such hydrocarbon-related diagenetic zones (HRDZs), inspection of published examples (O'Brien and Woods, 1995; O'Brien *et al.*, 1996, 1998) shows that these zones are discrete and unrelated to the features developed at the Hibernia Formation/basal Oliver Sandstone Member interface. Specifically, these HRDZs are associated with older, Eocene sandstones, they are usually associated with major faults at Callovian level and their reactivated extensions, and they are rarely circular.

The six seismic lines critical to the interpretation of Fohn structure are spaced at 1 km apart on a regular grid pattern. The latter defines a localised time-high and a surrounding annular depression at about the 500 ms level, which is not part of any through-going channel system at the top Eocene pre-Miocene unconformity. Line ZPW92-1145—the only line that passes directly through the Fohn-1 well intersection—shows that Fohn-1 was drilled just off the time high at the top Eocene unconformity. Between 500 ms and about 200 ms the section contains broken up seismic reflectors, but none of the reflectors above 200 ms appear to offer any reason to cause the time high. The 200 ms reflector forms a slight time depression over the 500 ms time high. There are no sea bottom anomalies over the Fohn structure that may cause seismic anomalies. Near Fohn-1, the regional seismic and well data indicate that the top Eocene horizon is an erosional surface, but there is no suggestion of peneplanation over the Fohn region. It is highly likely that the overlying younger marine strata would show some drape over preexisting topographic features on the Eocene erosion surface.

Attempts at determining lateral velocity variations from the stacking data provided in velocity panels annotated on the seismic sections are frustrated by the insufficiency of data points in the 0–1000 ms interval. Velocity data derived from Fohn-1 well, including check shot data, are too broadly spaced to show any perturbation from the regional trends seen in offsetting wells. Consequently, there is no evidence either for lateral or vertical velocity variations on the current data set.

Instrumentation and data collection evaluation procedures are described in detail in Appendix 1 (ZARASEIS) available from the authors. To summarise, the survey used the LRS-16A Marine Telemetry System—a multi-channel seismic data acquisition system using closely spaced hydrophone groups for high-resolution surveying. The system samples 240 channels of seismic data plus 20 waterbreak channels, 20 depth transducers and 4 general purpose auxiliary channels at 1 ms sample rate. The shipboard system processes and records the data in raw channel format and in demultiplexed array format with programmable array sets up to 240 channels. During a seismic recording, 1000 streams of data are received by the shipboard electronics every second. Each 1 ms data stream includes a burst of data from each channel of each streamer module in the cable. An individual data burst contains 20 bits and represents one sample of one channel. These data are telemetered in high speed serial form over one coaxial cable data transmission line.

Reimold *et al.* raised the possibility that the disturbances seen on the illustrated seismic line may be the result of tectonic slumping. Gravity sliding in strata near the large reefs of the Karmt Shoal (early Pleistocene to present) is probably related to collapse of the reef fronts (Bishop and O'Brien, 1998). The uppermost strata below the sea floor is often disturbed, sometime showing buckling and chevron folding, thrust faulting away from the reef front and detachment surfaces. However, the broad zones of disturbed seismic associated with these features are not circular in outline and the disturbance does not appear to extend more than a few hundred milliseconds below the detachment surfaces. These features are again quite unlike the Fohn structure where reefs are absent.

GEOCHEMISTRY AND PETROLOGY

Reimold *et al.* state "The PGE and other chemical data fail to meet the most basic criteria of analytical geochemistry, lacking information on the analytical procedures, sample size, standards, accuracy, precision, or blank concentration." This information was not included in our paper because of space constraints and is included here. Reimold *et al.* also use a few errors to question the results: (1) a typographical error in the abundance of Ru at the 1070–1080 m level (in Table 2a, Gorter and Glikson, 2000)—which should be 62 ppb not 623 ppb), and (2) errors in calculation of average PGE ratios (Pt/Ir, Ru/Ir) (Table 2c). These errors, however, did not affect our discussion, which was based on trends plotted in Figs. 7 and 8.

The analyses were conducted by Analabs Pty Ltd., Perth, Western Australia, including specifications of analytical methods, accuracy and precision, which were not included in our original paper for space reasons. No pre-analysis de-volatilisation was conducted. Cr and S were dissolved by total acid digestion (HF, HCl, HNO_3, $HClO_4$) and analysed by inductively-coupled plasma atomic emission (ICP-AE) spectrometry. Ni, Co and Cu were dissolved by total acid digestion (HF, HCl, HNO_3, $HClO_4$) and analysed by inductively-coupled plasma-mass spectrometry (ICP-MS). Ir, Os, Pd, Pt, Rh, Ru were analysed by ICP-MS following nickel sulphide fire assay collection from 20 g samples, followed by Aqua Regia digestion. Accuracy and precision were monitored using standards of felsic composition (std SO4 = International soil standard developed in Canada) and mafic composition (std GS2 = Internal Analabs standard on sample from Garnet Holdings Pty Ltd.). Analytical batches are run with one standard per six samples of unknown compositions, a blank and 8% duplicate and replicate analyses. The compositions of standards and blanks, not listed here for space limitations, are available on request. Precision/reproducibility is evaluated as $\pm 10\%$ for base metals and $\pm 15\%$ for the PGE elements collected by fire essay. Accuracy for PGE analyses near detection limits (0.5 ppb) are evaluated at ± 1.5 ppb. In this regard, the PGE data are indeed of little meaning, especially where attempts at calculating ratios are concerned.

We consider the variations in absolute abundances of the siderophile elements—Ni, Cr and Co—significant. Siderophile element levels at the 710–720 m interval of the breccia section (Ni = 428 ppm; Cr = 518 ppm; Co = 50.9 ppm) are high by a factor of 5 to two orders of magnitude as compared to lower levels of the breccia section (1200–1210 m: Ni = 4 ppm; Cr = 39 ppm; Co = 2 ppm), and at high levels of the breccia (650–660 m: Ni = 10 ppm; Cr = 104 ppm; Co = 4.7 ppm) (Table 2b; Fig. 8, Gorter and Glikson, 2000).

Our petrological studies of drill chips from Fohn, conducted later than final submission of our paper (Gorter and Glikson, 2000), documented rare altered apatite-rich leucite-olivine-phlogopite lamproite fragments, shedding a new light on the nature of Fohn structure. The drill cuttings were subject to (1) scanning electron microscopy (SEM) and coupled energy dispersive spectrometric (EDS) analysis, x-ray mapping, small-area whole-rock scanning analyses, and (2) whole-rock analyses by x-ray fluorescence for major and trace elements and by ICP-MS and ICP-AE for siderophile trace elements, including PGE by Ni-sulphide collection/ICP-MS analysis. The fragments consist of euhedral pseudomorphs of analcite after leucite and nontronite-montmorillonite clay minerals after olivine, set in a groundmass dominated by clay minerals (?altered glass), Ti-rich phlogopite, abundant needles of apatite, laths of diopside and amphibole, Mg-ilmenite, priderite, rutile and secondary barite. On this basis, we now regard Fohn as a lamproite diatreme cored by a massive volcanic plug, which forms a palaeo-morphological high.

We now interpret the saucer-type downward-narrowing seismic structure in terms of the "champagne glass" morphology of lamproite diatremes (Lorenz, 1986). The occurrence of lamproites explains (1) the high siderophile element abundance observed earlier, including anomalously high Cr, Co, Ni, Cu, S and PGE abundances (Gorter and Glikson, 2000); (2) the occurrence of barite in the drill cuttings, and (3) high gamma ray counts between 710–1050 m at Fohn-1 are accounted for by the high K levels of the lamproites and their alteration products. Insofar as the large cluster of similar crater-form and bulge-form structures associated with Fohn, which intrude the late Eocene and are truncated by the basal Miocene strata, may have the same origin as Fohn—an identification of a lamproite field similar to the Early Miocene lamproite field of the West Kimberley (Jaques *et al.*, 1986) may be implied.

CRITERIA FOR RECOGNISING IMPACT STRUCTURES

Although we have withdrawn the impact model for Fohn, Reimold *et al.*'s points regarding recognition of impact structures require a response. Reimold (1995) proposed a two-fold classification of glass or meta-glass-bearing micro-breccia veins referred to colloquially in the literature as "pseudotachylite", in the following terms (1) pseudotachylite *sensu stricto* formed purely by friction melting is compositionally akin to the host rocks, and forms along fractures and faults due to either tectonic or impact events; (2) impact melts form by shock melting, commonly containing siderophile and PGE contamination derived from the bolide, and may be injected as veins into the crater floor. However, transitional situations may occur which render the above scheme restrictive.

Reimold *et al.* state "Glikson (*e.g.* 1996) has previously taken the view that the presence of pseudotachylite is equivalent to shock metamorphic effects and, by implication, is diagnostic for impact structures". This constitutes a misrepresentation of Glikson's (1996) paper in which the term "pseudotachylite" was used strictly in the context of the listing of the possible consequences of impact (pp. 587, 599). Nowhere in this paper, or elsewhere, is it suggested by us that, in itself, the occurrence of pseudotachylite is diagnostic of extraterrestrial impact. The contrary is true—Glikson and Mernagh (1995) document and interpret pseudotachylite-breccia networks from the Giles Complex, Western Australia, strictly in terms of friction melting related to tectonic faulting.

The Fohn study highlights the close analogies between impact structures and volcanic diatremes on seismic profiles. Where a diatreme has been exposed and eroded, a central topographic high can form over the massive feeder pipe through differential erosion of the surrounding more friable fragmented volcanics—leading to the classical "sombrero-like" cross section. The "Champagne-glass-like" structure of the diatreme (*e.g.,* Lorenz, 1986) narrows with increasing depth and may be lost in background seismic noise in the two-dimensional and three-dimensional profiles. This may result in the masking of evidence of deep-seated feeders and in a close analogy to excavated complex impact crater containing a central uplift.

CONCLUSIONS

Definitive evidence for an extraterrestrial impact origin of buried impact structures depends on identification of shock metamorphic features. Whereas initial studies of candidate impact structures may not encounter diagnostic features, it is important to document and report these structures in order to encourage further tests. Where close analogies occur between different classes of buried circular structures, errors are inevitable, and the questions need to be pursued further, as we have done in our study. The present discussion serves to illustrate the remarkable analogies between, and helps to clarify criteria for discrimination of, buried volcanic diatremes and impact structures.

J. D. Gorter[1]* and A. Y. Glikson[2]*
[1]Agip Australia Limited, P.O. Box 1265, West Perth, Western Australia, Australia
[2]Research School of Earth Science, Australian National University, Australian Capital Territory, Australia
*john.gorter@agipenergy.com.au,
*Andrew.Glikson@anu.edu.au

Editorial handling: D. M. Shaw

REFERENCES

BISHOP D. J. AND O'BRIEN G. W. (1998) A multi-disciplinary approach to definition and characterisation of carbonate shoals, shallow gas accumulations and related near-surface sedimentary structures in the Timor Sea. *The APPEA J.* **38**, 93–113.

EVANS N. J., GREGOIRE D. C., GOODFELLOW W. D., MCINNES B. I., MILES N. AND VEIZER J. (1993) Ru/Ir ratios at the Cretaceous-Tertiary boundary: Implications for PGE source and fractionation within the ejecta cloud. *Geochim. Cosmochim. Acta* **57**, 3149–3158.

FRENCH B. M. (1998) *Traces of Catastrophe*. Lunar and Planetary Institute, Houston, Texas, USA. 120 pp.

GLIKSON A. Y. (1996) Mega-impacts and mantle melting episodes: Tests of possible correlations. *Austral. Geol. Survey Org. J.* **16**, 587–608.

GLIKSON A. Y. AND MERNAGH T. (1990) Major pseudotachylite breccia-vein networks, Giles layered basic-ultrabasic complex, western Musgrave Block, central Australia. *BMR J. Austral. Geol. Geophys.* **11**, 509–519.

GORTER J. D. AND GLIKSON A. Y. (2000) Origin of a late Eocene to pre-Miocene buried crater and breccia lens at Fohn-1, North Bonaparte Basin, Timor Sea: A probable extraterrestrial connection. *Meteorit. Planet. Sci.* **35**, 381–392.

GRIEVE R. A. F., SHARPTON V. L. AND STÖFFLER D. (1990) Shocked minerals and the K/T controversy. *EOS Trans. Am. Geophys. Union* **71**, 1792–1793.

HUBER H., KOEBERL C., MCDONALD I. AND REIMOLD W. U. (2000) Use of γ–γ spectrometry in the geochemical study of diamictites from South Africa. *J. Radioanalyt. Nucl. Chem.* **244**, 603–607.

JAQUES L. A., LEWIS J. D. AND SMITH C. B. (1986) *The Kimberlites and Lamproites of Western Australia*. Geol. Surv. W. Aust. Bull. **132**, 268 pp.

KOEBERL C. (1998) Identification of meteoritical components in impactites. In *Meteorites: Flux with Time and Impact Effects* (eds. M. M. Grady, R. Hutchison, G. J. H. McCall and D. A. Rothery), pp. 133–152. Geological Society of London, Special Publication **140**, London, U.K.

KOEBERL C., REIMOLD W. U., MCDONALD I. AND ROSING M. (2000) The search for petrographical and geochemical evidence for the Late

Heavy Bombardment on Earth in early Archean rocks from Isua, Greenland. In *Impacts and the Early Earth* (eds. I. Gilmour and C. Koeberl), pp. 73–96. Springer-Verlag, Heidelberg, Germany.

LORENZ V. (1986) On the growth of maars and diatremes and its relevance to the formation of tuff rings. *Bull. Volcan.* **48**, 265–274.

MCDONALD I. (1998) The need for a common framework for collection and interpretation of data in platinum-group element geochemistry. *Geostand. Newslett.* **22**, 85–91.

MCDONALD I., HART R. J. AND TREDOUX M. (1994) The analysis of the platinum-group elements in South African kimberlites by nickel sulphide fire assay and neutron activation analysis. *Anal. Chim. Acta* **289**, 237–247.

O'BRIEN G. W. AND WOODS E. P. (1995) Hydrocarbon-related diagenetic zones (HRDZs) in the Vulcan Sub-basin, Timor Sea: Recognition and exploration implications. *The APEA J.* **35**, 220–252.

O'BRIEN G. W., LISK M., DUDDY I., EADINGTON P. J., CADMAN S. AND FELLOWS M. (1996) Late Tertiary fluid migration in the Timor Sea: A key control on thermal and diagenetic histories? *The APPEA J.* **36**, 399–427.

O'BRIEN G. W., QUAIFE Q. P., COWLEY R., MORSE M., WILSON W. D., FELLOWS M. AND LISK M. (1998) Evaluating trap integrity in the Vulcan Sub-basin, Timor Sea, Australia, using integrated remote-sensing geochemical technologies. In *The Sedimentary Basins of Western Australia 2* (eds. P. G. Purcell and R. R. Purcell), pp. 237–254. Proc. Petrol. Explor. Soc. Aust. Symp., Perth, Western Australia, Australia.

REIMOLD W. U. (1995) Pseudotachylite—Generation by friction melting and shock brecciation? A review and discussion. *Earth Sci. Rev.* **39**, 247–264.

REIMOLD W. U. (1998) Exogenic and endogenic breccias: A discussion of major problematics. *Earth-Sci. Rev.* **43**, 25–47.

Forward

Back

Table of Contents