How will we recognize buried impact craters in terrestrial sedimentary basins?

S.A. Stewart BP plc, Chertsey Road, Sunbury on Thames, Middlesex TW16 7LN, UK

ABSTRACT

Criteria that are deemed critical for recognition of terrestrial impact craters include features from hand specimens such as shock metamorphic structures. Although these criteria have been selected because they are unique physical products of bolide impact, strict adherence to these criteria means that we cannot positively identify buried astroblemes that are tomographically imaged on three-dimensional seismic data, but are undrilled. Because many of Earth's deeply buried structures may never be drilled because of prohibitive cost and lack of commercial incentive, a large proportion of as yet-undiscovered terrestrial astroblemes, including the best-preserved examples, may remain unclassified and be excluded from impact-structure research. A framework for the identification of impact structures imaged on three-dimensional seismic data is proposed, on the basis of geometrical criteria plus additional image-quality and preservation criteria that assign a level of confidence to the assessment.

Keywords: impact structures, seismic data, sedimentary basins, cryptoexplosion structures.

INTRODUCTION

The inventory of known bolide impact structures on Earth is currently >160 (PASSC, 2002); 70% of these are exposed at the surface and have been discovered by field geologists. The preservation potential of impact structures over geologic time scales, however, like fossils, is highest in sedimentary basins. Cratering-rate statistics indicate that if all craters were preserved, 1% of the surface area of Earth would become cratered per 200 m.y. (Ward, 2002). If 10% of Earth's surface is assumed to have preservation potential for craters at any one time (an estimate of the area of continental shelves plus other nonoceanic basins), the statistics translate on a global basis into several hundred impact craters >1 km in diameter per 10 m.y. of strata (Ward, 2002). Even if erosion or exhumation subsequently destroyed a large proportion of Phanerozoic astroblemes, the number yet to be found could be several times greater than the number currently in the inventory.

In recent decades, proliferation of three-dimensional seismic data in pursuit of hydrocarbons has produced unprecedented high-resolution subsurface images in many sedimentary basins. But the criteria deemed critical for recognition of impact structures on Earth include dynamic metamorphic and geochemical effects that require access to specimens from outcrop or drill core (Rondot, 1994; Norton, 2002). These criteria are different from those routinely applied elsewhere in the solar system. On other planets, the Moon, and asteroids, identification of impact craters is based on morphometric criteria applied to remotely sensed photographic imagery. These morphometric criteria describe basic crater characteristics—excavated basin with raised rim—plus secondary structures such as secondary craters and distal ejecta (e.g., Pike, 1974). The criteria that are currently used for identification of terrestrial impact structures have been chosen principally because they are dynamic metamorphic effects uniquely associated with the high energies that result from asteroid or comet impact (e.g., Stoffler and Langenhorst, 1994). However, the development of these criteria also reflects a history of largely field-based exploration of structures that can be poorly preserved and difficult to recognize on the basis of large-scale structure (Rondot, 1994).

Buried astroblemes imaged on high-quality three-dimensional seismic data can differ from field examples in two key respects. First, they may be extremely well imaged, not only in terms of the cratered paleosurface, but also tomographically in three dimensions, including the internal, adjacent, underlying, and overlying strata, allowing alternative interpretations to be dismissed. Second, many buried structures may never yield rock specimens because of lack of commercial drilling incentive and prohibitive expense of noncommercial drilling. This paper presents a set of geometrical criteria designed to distinguish astroblemes from other types of circular structures on seismic data. The intent of this approach is to allow buried astroblemes that have no surface expression and have not been penetrated by drilling, but are clearly imaged on seismic data, to take their place alongside those already identified on Earth by other means and those imaged elsewhere in the solar system.

CHARACTERISTICS OF BURIED CIRCULAR STRUCTURES

Debate about the origin of candidate astroblemes buried in terrestrial basins usually centers on whether they are volcanic or impact in origin, echoing early twentieth-century discussion on the origin of lunar circular structures (see review by Schultz, 1998). If the buried structure has been identified by three-dimensional seismic data, there is opportunity to constrain the most plausible mode of origin on the basis of three-dimensional geometrical characteristics of the feature and its surroundings. However, ~20 different geologic processes in addition to volcanism and impact can give rise to structures that are circular in plan view. A few of these processes create structures that are unlikely to be confused with astroblemes, but without drilled samples to provide direct proof, all these alternatives should be excluded to demonstrate impact origin. Collation of three-dimensional geometrical characteristics of circular structures shows that many criteria can be defined that uniquely identify impact structures based on three-dimensional mapping alone (Table 1).

Some of the geologic possibilities listed in Table 1 are likely to be easily ruled out; e.g., tectonic pull-aparts have plan-view aspect ratios >1 and are related to strike-slip fault trends. Other possibilities could be more difficult to disprove; e.g., glacial kettle holes share many geometrical characteristics with small astroblemes, but they are restricted to specific stratigraphic intervals and geologic settings and do not contain central peak structures. One of the more obvious alternatives to the interpretation of an astrobleme based on geometry alone is an igneous caldera. A depth-to-diameter aspect ratio of <0.3, however, and lack of relationship to deeper, underlying structure would indicate that an interpretation of an astrobleme was a more likely interpretation than that of a caldera.

Figure 1 illustrates some of these geometrical criteria. The first example, shown in map view (Fig. 1A) and cross section (Fig. 1B), is a positive topographic feature with a large depth-to-width aspect ratio—an interpreter could be confident this is not an impact crater. Figure 1C is a cube showing a set of six crater structures. The number of these features, their small size (each <0.5 km diameter), and their large depth-to-diameter ratios (>1) indicate that they are not associated with impact. Figure 1D shows a crater structure that is surrounded by a number of concentric rings. A cross section from the three-dimensional seismic volume (Fig. 1E) shows that a differential

TABLE 1. GEOMETRICAL CHARACTERISTICS OF CIRCULAR STRUCTURES IN SEDIMENTARY BASINS

Family	Member	Scale: typical diameter (km)	Circular or elliptical (vs. irregular) in plan view?	Shape: typical maximum/minimum diameter ratio*	Crateriform? (vs. dome)	Central peak within crater?	Overturned peripheral strata?	Inward-facing, peripheral extensional fault terraces	Overlying differential subsidence basin	Shape: typical depth/diameter aspect ratio†	Genetic requirement to form linked arrays?	Related to regional trends?	Characterize specific geologic setting?	Related structure in deep underlying strata?	Restricted stratigraphic occurrence?	Reference
Intrusions	Salt diapir	1–5	Y	1	**N**	**N**	~	~	~	**1–5+**	N	~	N	**Y**	N	Price & Cosgrove (1990)
	Mud or shale diapir	0.1–5	Y	1	**N**	**N**	~	~	**N**	**1–5+**	N	~	N	**Y**	N	Van Rensbergen et al. (1999)
	Igneous diapir	1–10	~	1+	**N**	**N**	~	~	**N**	**1–5+**	N	~	N	**Y**	N	Clemens (1998)
	Sand cone sheet	0.1–3	Y	1	Y	**N**	**N**	**N**	**N**	0.1–0.2	N	~	~	N	N	Molyneaux et al. (2002)
Pillows	Salt	1–10	~	1+	**N**	**N**	**N**	**N**	**N**	0.01–1	N	~	N	N	N	Hughes & Davison (1993)
	Sand	1–10	~	1+	**N**	**N**	**N**	**N**	**N**	0.01–1	N	~	N	N	N	Brooke et al. (1995)
	Mud or shale	1–10	~	1+	**N**	**N**	**N**	**N**	**N**	0.01–1	N	~	N	N	N	Wiltschko & Chapple (1977)
Volcanoes	Igneous	1–50	Y	1	**N**	**N**	**N**	**N**	**N**	0.1–0.5	N	~	N	**Y**	N	Thouret (1999)
	Mud or shale	1–5	Y	1	**N**	**N**	**N**	**N**	**N**	0.1–0.5	N	~	N	**Y**	N	Graue (2000)
Fluid expulsion	Diatreme or maar	0.01–3	Y	1	Y	**N**	**N**	~	~	**2+**	N	N	N	**Y**	N	Lorenz (1986)
	Phreatomagmatic explosion	0.01–1	Y	1	Y	**N**	~	~	~	0.01–2	N	N	**Y**	N	N	Lorenz (1987)
	Gas pockmark	**0.01–0.7**	Y	1	Y	**N**	~	~	**N**	0.01–0.2	**Y**	N	**Y**	~	N	Hovland et al. (2002)
	Freshwater rafting	0–1?	**N**	~	Y	**N**	~	~	**N**	–	N	N	**Y**	~	N	Paull et al. (1999)
Withdrawal basin	Igneous (caldera)	2–50	Y	1	Y	~	**N**	~	~	**0.5–1**	N	~	N	**Y**	N	Branney (1995)
	Karst (carbonate & evaporite)	**0.01–1**	Y	1	Y	**N**	**N**	**N**	~	0–10	**Y**	~	**Y**	N	N	Dias & Cabral (2002)
	Salt deflation	2–15	~	1+	Y	**N**	**N**	~	~	**0.5–1**	N	~	N	N	N	Ge & Jackson (1998)
Tectonic	Pull-aparts	0–40	**N**	**2-5**	Y	**N**	**N**	~	~	0–1	N	**Y**	N	**Y**	N	Aydin & Nur (1982)
	Drape fold (dome)	1–100	Y	1+	**N**	**N**	**N**	**N**	**N**	0.2–2	N	~	N	**Y**	N	Davison et al. (2000)
	Interference folds	0–100	Y	1+	**N**	**N**	**N**	**N**	**N**	0.2–2	N	**Y**	N	~	N	Grujic et al. (2002)
	Polygonal faults	0.3–2	**N**	1	**N**	**N**	**N**	**N**	**N**	**0.5–3**	**Y**	~	**Y**	N	N	Cartwright & Dewhurst (1998)
Bioherms	Reefs and carbonate mounds	0.01–2	~	1+	**N**	**N**	**N**	**N**	**N**	0.1–0.5	N	~	**Y**	N	**Y**	James & Bourque (1992)
Glacial	Kettle holes	0.01–5	Y	1+	Y	**N**	**N**	~	~	0.01–0.1	N	N	**Y**	N	**Y**	Olszewski & Weckwerth (1999)
	Drumlins	0.1–2	Y	**2+**	**N**	**N**	**N**	**N**	**N**	0.01–0.1	N	N	**Y**	~	**Y**	Smalley & Warburton (1994)
Impact craters	Simple and complex	1–100+	Y	1	Y	~	~	~	Y	0.05–0.3	N	N	N	N	N	Pike (1974); Melosh (1989)

Note: Geometrical characteristics are after Stewart (1999). Shaded boxes with bold text show unequivocal discrimination against astrobleme interpretation. Criteria are labeled "equivocal" (indicated by ~) if they may or may not be met by that geologic process, for example, carbonate mounds could be, but are not necessarily related to, regional trends.

*A small proportion of impact craters (<1%) are elongate in plan view because of very low angle impact.

†Depth-to-diameter aspect ratio for impact craters takes into account range of geometries spanned by transient to final forms of simple and complex craters.

subsidence basin overlies the central crater and that there is a prominent central peak buried within the crater, whereas there is no link to deep structure. This structure appears to satisfy the geometrical criteria for an astrobleme. Some of these examples are revisited in the discussion of Table 2.

DEGREE OF CONFIDENCE

A degree of confidence can be assigned to any seismic interpretation. The profile of yes, no, or equivocal categorizations using the criteria of Table 1 gives an indication of the level of confidence resulting from this interpretation method. The interpretation should be further qualified by criteria that address seismic image quality and degree of preservation of the structure—three are suggested here. A spatial data-coverage criterion controls the degree of confidence that the entire structure is circular; this criterion can be quantified as the proportion of imaged arc relative to 360°.

Data quality is more awkward to assign, because any structurally complex feature is likely to generate a poorly imaged seismic shadow zone in the underlying strata, even in otherwise good-quality data. Because the absence of related structure in the underlying section is a geometrical criterion (Table 1), assessment of data quality should be based on the seismic image in this area. Data quality can be qualitatively bracketed as good, intermediate, or poor. Figure 2 illustrates this criterion—the data adjacent to the mud diapir are good quality, but the image of the root zone below the diapir is not so clear and could be classified as intermediate quality. A faulted root zone linking the diapir to deeper structural levels is, nonetheless, fairly clear and is one of several criteria indicating that this is not an impact structure (see also Table 2).

A third criterion affecting the confidence in interpretation is how much of the structure is preserved. In practice the degree of erosion, either prior to burial or due to exhumation, will probably be difficult to quantify, but a loose classification along the lines of uneroded, slightly eroded, or deeply eroded should be straightforward. Rondot (1994) discussed how impact structures, like most of the other circular structure types listed in Table 1, vary in appearance with depth of exposure and mechanism of erosion.

EXAMPLES OF A REFLECTION SEISMIC APPROACH TO ASTROBLEME IDENTIFICATION

Table 2 collates results of applying this approach to a number of structures that are circular in plan view. These interpretations are used to show how this method can be applied, and thus they are illustrative rather than definitive, because each criterion merits thorough discussion that is beyond the scope of this paper. Example 1 is the structure shown in Figures 1A and 1B and was discussed earlier in this paper. Several criteria strongly indicate that this is not an astrobleme, with a high confidence level. Example 2, shown in Figure 2, has a high level of confidence in the interpretation, which has several criteria siding strongly against astrobleme interpretation.

Example 3 considers Murshid crater in Oman (Levell et al., 2002). Murshid crater meets many criteria in favor of an astrobleme interpretation, and none unequivocally indicates an alternative interpretation. Several criteria are equivocal; e.g., the carbonate-platform setting requires regional geologic knowledge to rule out dissolution collapse, and the relatively poor quality of the published seismic image below the structure obscures the depth-to-diameter ratio and underlying structure (Levell et al., 2002). In the framework discussed in this paper, Murshid crater can be interpreted as an astrobleme with a moderate degree of confidence. Example 4 categorizes Silverpit crater (Stewart and Allen, 2002), illustrated here in Figures 1D and 1E. As discussed earlier in this paper, most of the

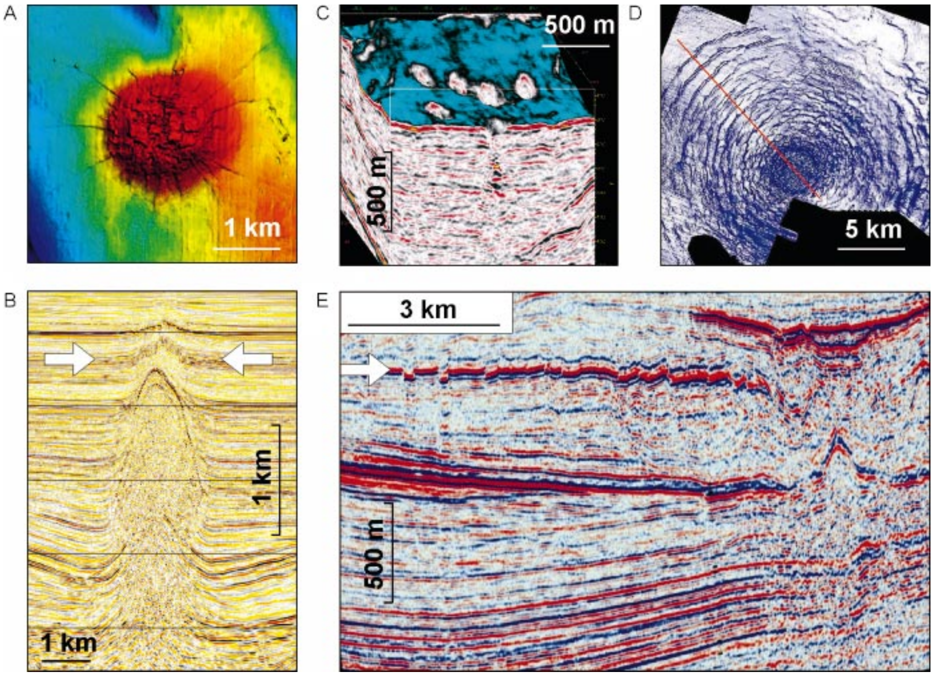

Figure 1. Comparison of some circular features and surrounding strata in three-dimensional seismic images. A: Map view of domal drape fold (North Sea), color shaded according to depth (red high, blue low). Overlies B. B: Cross section through salt diapir; arrows indicate horizon mapped in A. Vertical scale is approximate in all seismic sections. C: Three-dimensional seismic cube showing set of six circular crater features. One is cut in cross section on front face of cube. These are collapse features related to dissolution of underlying salt (Clark et al., 1999). D: Map shows surface shaded according to short-wavelength structure (steeper dips darker), with concentric rings surrounding central crater. Line shows location of section E. E: Cross section through structure D (Stewart and Allen, 2002). Arrow shows surface mapped in D.

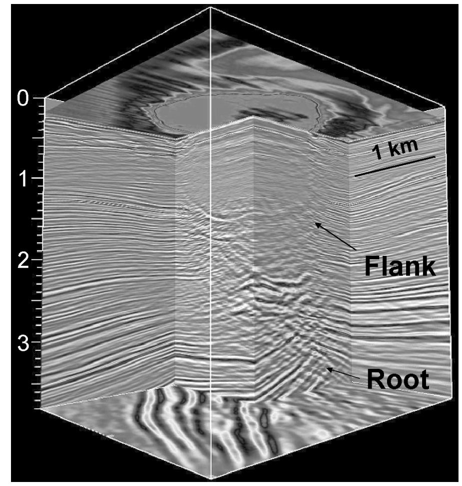

Figure 2. Three-dimensional seismic cube cut to show internal, adjacent, and underlying structure of mud diapir from south Caspian Sea. Seismic data are of good quality adjacent to diapir (flank), but of intermediate quality in root zone below structure (root). Vertical scale is in seismic two-way traveltime (s). Vertical depth exaggeration is ~×1.5.

criteria in Table 1 indicate that this structure is an astrobleme. Stewart and Allen (2002) argued that dissolution and salt tectonics had no primary role in creating this structure. The interpretation is supported by good-quality seismic data, even below the structure, so the level of confidence in astrobleme interpretation is high.

Example 5 is Upheaval Dome, Utah. It is exposed at the present-day land surface, but the degree of subsurface imaging is very limited (Kanbur et al., 2000). As such, it is included here by way of comparison. The few unequivocal criteria support astrobleme interpretation, but the overall level of confidence is very low. In this case, outcrop-based evidence is necessary to support the interpretation. These trials show that, rather than using the criteria presented in this paper as a check list or truth table, the criteria represent a framework for detailed analysis and discussion of a given structure.

CONCLUSIONS

A geometrical approach to identifying astroblemes imaged on seismic data is proposed here. Rather than devaluing the requirement to produce physical evidence of dynamic metamorphism where possible, the geometrical approach is intended to provide an alternative for cases where an excellent three-dimensional tomographic image is available but rock specimens are not. The geometrical criteria set out here appear to be sufficient to uniquely identify an astrobleme imaged via three-dimensional seismic data. Screening criteria for image quality have also been offered to qualify any interpretation. It is suggested that only those structures that meet the criteria outlined in Table 1, combined with a high level of confidence, be accepted as impact structures. It is acknowledged that the geometrical scheme shown on Table 1 should be viewed as a basis for discussion rather than a fully comprehensive tool in its present form. Nonetheless, a method for geometrical identification of astroblemes will potentially be a significant research resource and bring alignment with approaches to identifying impact structures on other planets and satellites in the solar system.

ACKNOWLEDGMENTS

I thank P.H. Schultz and R.J. Davies for suggesting significant improvements. The mapping shown in Figure 1D is by P.J. Allen. The opinions expressed here are solely those of the author and not necessarily those of BP plc.

REFERENCES CITED

Aydin, A., and Nur, A., 1982, Evolution of pull-apart basins and their scale independence: Tectonics, v. 1, p. 91–105.

Branney, M.J., 1995, Downsag and extension at calderas: New perspectives on collapse geometries from ice-melt, mining and volcanic subsidence: Bulletin of Volcanology, v. 57, p. 303–318.

Brooke, C.M., Trimble, T.J., and MacKay, T.A., 1995, Mounded shallow gas sands from the Quaternary of the North Sea: Analogues for the formation of sand mounds in deep water Tertiary systems?, *in* Hartley, A.J., and Prosser, D.J., eds., Characterisation of deep marine clastic systems: Geological Society [London] Special Publication 94, p. 95–101.

Cartwright, J.A., and Dewhurst, D.N., 1998, Layer-bound compaction faults in fine-grained sediments: Geological Society of America Bulletin, v. 110, p. 1242–1257.

Clark, J.A., Cartwright, J.A., and Stewart, S.A., 1999, Mesozoic dissolution tectonics on the West Central Shelf, UK Central North Sea: Marine and Petroleum Geology, v. 16, p. 283–300.

Clemens, J.D., 1998, Observations on the origins and ascent mechanisms of granitic magmas: Geological Society [London] Journal, v. 155, p. 843–851.

Davison, I., Alsop, G.I., Evans, N.G., and Safaricz, M., 2000, Overburden deformation patterns and mechanisms of salt diapir penetration in the Central graben, North Sea: Marine and Petroleum Geology, v. 17, p. 601–618.

Dias, R.P., and Cabral, J., 2002, Interpretation of recent structures in an area of cryptokarst evolution—Neotectonic versus subsidence genesis: Geodinamica Acta, v. 15, p. 233–248.

Ge, H., and Jackson, M.P.A., 1998, Physical modelling of structures formed by salt withdrawal: Implications for deformation caused by salt dissolution: American Association of Petroleum Geologists Bulletin, v. 81, p. 228–250.

Graue, K., 2000, Mud volcanoes in deepwater Nigeria: Marine and Petroleum Geology, v. 17, p. 959–974.

Grujic, D., Walter, T.R., and Gartner, H., 2002, Shape and structure of (analogue models of)

TABLE 2. CRITERIA OF TABLE 1 APPLIED TO SEVERAL EXAMPLES OF STRUCTURES THAT ARE CIRCULAR IN PLAN VIEW

	Example 1. Figure 1A & 1B (this paper)		Example 2. Figure 2 (this paper)		Example 3. Murshid crater Levell et al. (2002)		Example 4. Silverpit crater Stewart & Allen (2002)		Example 5. Upheaval dome Kanbur et al. (2000)	
Geometrical and geological criteria										
Scale: diameter (km)	1.5	Y	2	Y	2.5	Y	3	Y	>2.5	Y
Circular or elliptical (vs. irregular) in plan view?	Circular	Y	Circular	Y	Slightly irregular circle	~	Circular	Y	~	~
Shape: max/min diameter ratio	1	Y	1	Y	1	Y	1	Y	~	~
Craterform? (vs. dome)	dome	N	dome	N	crater	Y	crater	Y	~	~
Central peak within crater?	N	~	N	~	Y	Y	Y	Y	~	~
Overturned peripheral strata?	N	~	N	~	~	~	~	~	N	~
Inward-facing peripheral fault terraces?	N	~	N	~	Y	Y	Y	Y	Y	Y
Overlying differential subsidence basin	N	N	top structure outcrops	n/a	~	~	Y	Y	top structure eroded	n/a
Shape: depth/diameter aspect ratio	1.3	N	3	N	~	~	0.1	Y	~	~
Adjacent or nearby structures with same form and scale?	One of a group of six similar structures	N	linear trend of similar structures	N	N	Y	N	Y	N	Y
Related to regional trends?	N	Y	Y	N	N	Y	~	~	N	Y
Free from issues due to geologic setting?	Siliciclastic basin	Y	Siliciclastic basin	Y	Carbonate platform	~	Carbonate platform, deep underlying salt	Y	Siliciclastic basin, salt close below structure	~
Related structure in deep underlying strata?	~	~	Y	N	~	~	N	Y	~	~
Imaging and preservation										
Data coverage (seismic data area/structure area)	100%		100%		100%		95%		5%*	
Seismic quality below structure	Poor		Intermediate		Poor		Good		Poor	
Preservation of structure	No erosion		No erosion		No erosion		No erosion		Deeply eroded	
Interpretation using this method:	Not an impact crater (probably a salt diapir) High confidence		Not an impact crater (probably a mud diapir) High confidence		Impact crater Moderate confidence		Impact crater High confidence		Impact crater Low confidence	

Note: Examples 1, 2, and 4 are illustrated in this paper. Equivocal indicated by ~. Shaded criteria show unequivocal discrimination against astrobleme interpretation.
*Coverage from a single two-dimensional seismic line.

refolded layers: Journal of Structural Geology, v. 24, p. 1313–1326.

Hovland, M., Gardner, J.V., and Judd, A.G., 2002, The significance of pockmarks to understanding fluid flow processes and geohazards: Geofluids, v. 2, p. 127–136.

Hughes, M., and Davison, I., 1993, Geometry and growth kinematics of salt pillows in the southern North Sea: Tectonophysics, v. 228, p. 239–254.

James, N.P., and Bourque, P.-A., 1992, Reefs and mounds, *in* Walker, R.G., and James, N.P., eds., Facies models: Response to sea level change: Geologists Association of Canada, p. 323–347.

Kanbur, Z., Louie, J.N., Chávez-Pérez, S., Plank, G., and Morey, D., 2000, Seismic reflection study of Upheaval Dome, Canyonlands National Park, Utah: Journal of Geophysical Research, v. 105 p. 9489–9505.

Levell, B., Richard, P., and Hoogendijk, F., 2002, A possible Albian impact crater at Murshid, southern Oman: Geoarabia, v. 7, p. 721–730.

Lorenz, V., 1986, On the growth of maars and diatremes and its relevance to the formation of tuff rings: Bulletin of Volcanology, v. 48, p. 265–274.

Lorenz, V., 1987, Phreatomagmatism and its relevance: Chemical Geology, v. 62, p. 149–156.

Melosh, H.J., 1989, Impact cratering: A geologic process: New York, Oxford University Press, 245 p.

Molyneux, S., Cartwright, J., and Lonergan, L., 2002, Conical sandstone injection structures imaged by 3D seismic in the central North Sea, UK: First Break, v. 20, p. 383–393.

Norton, R.O., 2002, The Cambridge encyclopedia of meteorites: Cambridge, Cambridge University Press, 354 p.

Olszewski, A., and Weckwerth, P., 1999, The morphogenesis of kettles in the Höfabrekkujökull forefield, Mýrdalssandur, Iceland: Jökull, v. 47, p. 71–88.

PASSC, 2002, Earth impact database: http://www.unb.ca/passc/ImpactDatabase/ (accessed 16 April 2002).

Paull, C.K., Ussler, W., and Borowski, W.S., 1999, Freshwater ice rafting: An additional mechanism for the formation of some high-latitude submarine pockmarks: Geo-Marine Letters, v. 19, p. 164–168.

Pike, R.J., 1974, Craters on Earth, Moon and Mars: Multivariate classification and mode of origin: Earth and Planetary Science Letters, v. 22, p. 245–255.

Price, N.J., and Cosgrove, J.W., 1990, Analysis of geological structures: Cambridge, Cambridge University Press, 502 p.

Rondot, J., 1994, Recognition of eroded astroblemes: Earth-Science Reviews, v. 35, p. 331–365.

Schultz, P.H., 1998, Shooting the Moon: Understanding the history of lunar impact theories: Earth Sciences History, v. 17, p. 92–110.

Smalley, I., and Warburton, J., 1994, The shape of drumlins, their distribution in drumlin fields, and the nature of the subice shaping forces: Sedimentary Geology, v. 91, p. 241–252.

Stewart, S.A., 1999, Seismic interpretation of circular geological structures: Petroleum Geoscience, v. 5, p. 273–285.

Stewart, S.A., and Allen, P.J., 2002, A 20-km-diameter multiringed impact structure in the North Sea: Nature, v. 418, p. 520–523.

Stoffler, D., and Langenhorst, F., 1994, Shock metamorphism of quartz in nature and experiment: 1. Basic observation and theory: Meteoritics, v. 29, p. 155–181.

Thouret, J.C., 1999, Volcanic geomorphology—An overview: Earth-Science Reviews, v. 47, p. 95–131.

Van Rensbergen, P., Morley, C.K., Ang, D.W., Hoan, T.Q., and Lam, N.T., 1999, Structural evolution of shale diapirs from reactive rise to mud volcanism: 3D seismic data from the Baram delta, offshore Brunei Darussalam: Geological Society [London] Journal, v. 156, p. 633–650.

Ward, S.N., 2002, Planetary cratering: A probabilistic approach: Journal of Geophysical Research, v. 107, no. 5023, DOI 10.1029/2000JE001343.

Wiltschko, D.V., and Chapple, W.M., 1977, Flow of weak rocks in Appalachian Plateau folds: American Association of Petroleum Geologists Bulletin, v. 61, p. 653–670.

Manuscript received 23 May 2003
Revised manuscript received 15 July 2003
Manuscript accepted 17 July 2003

Printed in USA