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LETTERS TO THE EDITORS

Tectonic effects of old very large meteoric impacts

Dr. W. B. Jones writes:

The recent paper by Norman (1984) is useful in drawing attention to the possibility of large circular features visible on satellite imagery being manifestations of ancient meteorite impacts. However, it is in some ways misleading. This discussion will concentrate on two particular misconceptions, the reality of 'astrons' and the likelihood of impact sites being focuses of heat and metallic ore deposits.

An 'astron' is envisaged as a large circular cratonic area with a clearly defined margin surrounded by a circular graben. The rocks of the 'astron' are supposed to have been welded into a hard disk by the heat and pressure of a meteorite impact, producing effects similar to regional metamorphism. In reality the conditions obtaining during an impact are quite different from those in regional metamorphism. Pressures are much higher, up to 10^3 kb and act over very much shorter timespans, a few seconds at the most. The products are consequently quite different. The characteristics of shock metamorphism are unusual crystal fracture patterns, traces of very high pressure minerals and solid phase vitrification on a microscopic scale as well as shatter cones, melting and intense fracturing on an outcrop scale (Robertson & Grieve 1977). These are the features described at Manicouagan by Murtaugh (1972).

The degree of shock metamorphism falls off continuously from the point of impact. The crater rim, determined initially by the radius at which the peak pressure falls below the strength of the rocks, and subsequently modified by inward slumping, can be used to define the edge of a young impact site but there is no simple way of identifying the limit of one which is strongly eroded. Thus impact features do not have the clearly defined margins that the examples of West Africa and the Amazon Basin would imply. The analogy with lunar maria, 'astron'-like with their flat circular plains surrounded by rings of mountains, is also misleading. It is well established that the formation of the mare basins and their infilling by lavas are separated by several 10^8 years (Taylor 1975) and are therefore not causally related. The Orientale Basin is not infilled with lavas and shows three rings of mountains, making it quite un'astron'-like.

The rocks beneath a crater floor are strongly fractured and the crater itself is partially filled by a fall-back breccia. The shattered rocks in and beneath the crater would tend to be less competent and more prone to erosion than the unaffected rocks. Impact sites are therefore probably less, rather than more resistant than adjacent areas as Norman claims. This is illustrated by the Cretaceous Gosses Bluff structure in Australia. This was formed 133 Ma ago with a crater originally about 20 km in diameter and shows vertical uplift of up to 3 km at the centre (Milton *et al.* 1972). Erosion has reduced the whole area to a flat plain at about the level of the crater floor. The only remaining topographic relief is a ring of sandstone hills about 5 km in diameter and 200 m high.

Circumferential grabens were reported by Price (1975) as having formed around large chemical test explosions on alluvium. However, a more detailed account of the tests (Jones 1977) described only circumferential fissures with no mention of vertical displacement across them. Inward-dipping fault planes due to slumping of the crater walls are a common feature of impact craters (Dence *et al.* 1977) but outward-downthrowing faults, presumably required by definition in a ring graben, have not been reported from any crater, so far as I am aware. Circular depressions, sometimes referred to as ring synclines, do occur at impact craters alternating with circular ridges but there are no 'peripheral grabens'.

Norman envisages meteorites as shattering on impact or penetrating deep into the Earth. For a meteorite to become the focus of a hot spot it would have to penetrate the Earth to depths of several tens of km where magmas are generated and the surface would have to heal above it. In fact the fate of large meteorites is quite different. Bodies of less than about 100 tonnes are slowed down by the atmosphere but above this figure they arrive at the surface of the Earth with their cosmic velocity, between the theoretical limits of 12 and 70 km s^{-1} (Mason 1962), undiminished. Under these circumstances a meteorite has more than ten times the energy required for its own vapourisation (Heide 1964). Large meteorites are melted and vapourized along with a greater volume of target rock and the great majority of the original meteorite material is dispersed well away from the crater (Dence 1982).

The inadequacy of meteorites as precursors of economic mineral deposits was explained in a discussion of a previous paper (Norman 1980, Jones 1981). Norman now proposes that meteorites with a suitably exotic chemistry could have arrived from outside the solar system. This may be possible but it is highly implausible. In particular his highly radioactive meteorites, proposed as a possible source of thermal anomalies, would have to reach the Earth within a few million years of their formation from supernova debris.

About 20% of the energy of a meteorite is converted into heat (Dence *et al.* 1977) and most of this is probably lost from the immediate impact site with the ejected molten and vapourized rock. The residual heat at the crater would be concentrated just below the floor and quickly lost to the atmosphere by radiation and convection. It is therefore unlikely that impact craters would constitute significant thermal anomalies for long.

'Astrons' and large meteoritic remains probably do not exist. Nevertheless large circular features do occur in the continental crust and a good case can be made for their impact origin (Saul 1978). On the other hand no part of the ocean floor is older than the Mesozoic so impacts on a scale large enough to produce features like island arcs would have to form in the comparatively recent geological past which is most unlikely.

Phillips Petroleum Company, Europe–Africa W. B. JONES
The Adelphi
John Adam Street
London WC2N 6BW
U.K.

Dr. J. W. Norman replies:

Jones mentions that the initial impact pulse is brief, but the pressures at large impacts can be in excess of his 10^3 kb and their effect will extend far beyond, as exemplified by the fractures shown by the radial strain pattern in Nevada (Norman 1984, fig. 5). While I agree that the visual crater rim can be used to describe the edge of a young impact site, it in no way shows the limit of the stresses causing fractures and heating, let alone the surrounding heap of debris which can be several diameters larger. Grieve (1982) has suggested that as much as one billion years may elapse before thermal and tectonic stability is achieved. In most cases the remaining evidence of old large impacts is now obscure and even may have to be sensed by geophysics as in the case of the massive ringed bouguer anomaly reported by Klasner & Schultz (1982) which seems to be a terrestrial version of Orientale and the third type of impact site described in Norman (1984). Grieve's (1982) estimate is broadly in accord with this and that given by Norman for Imbrium. In view of this and the frequent reporting of melt in various quantities from accepted terrestrial impact sites and so many craters on the moon and planets, I cannot believe that they "are not causally related" though whether they are the result of impact-generated heat or upward leakage of molten mantle material from below seems uncertain. The long duration of molten rock in an unstable environment must surely create conditions for extensive grouting of the remaining locality, leaving a round cemented and resistant block on cooling. It is difficult to generalize and produce a model for all situations as there are so many variables such as the amount, type of material and velocity of an impacting body and the target area which create a variety of results. Both Manicouagan and Gosses Bluff which Jones cites are less than the 50 km radius, too small to be included as 'large' impacts, but Manicouagan is surrounded by an annular reservoir. In the words of Dence (1977) . . . "The basic structure of the reservoir filled peripheral trough has been established by ground observations made before flooding began. The trough is essential a graben bounded on the outside by steeply dipping normal faults." Patches of formerly molten rock on high ground indicate past extensive flooding of the area with this material. Dence's (1977) paper also mentions a fractured depression extending beyond the former crater, exceeding the 50 km limit. Gosses Bluff is also surrounded by a concentric ring of alluvium but the main structure is only 5 km wide with local distances up to 11 km, so it is probably insignificant; but most of Poroshin's concentric circular structures (Norman 1984, fig. 1) are probably grabens. A ground photograph (Norman 1980) shows the two concentric fractures of the Canadian dried lake test. The graben drop (about 2 m) was measured from a ground photograph of the excavated feature, using as scale the reported crater measurement and checking roughly with the size of a nearby man on the image. Incidentally, I did not mention outward downthrowing faults—they are his creation, not mine.

Whilst it is agreed that parts, if not all of some bodies may shatter and be dispersed at impact, fig. 9 of Norman (1984) showed that the distribution of chemical elements is not wide in a regional context. This approach was repeated in a different geological environment (the foothills of the Andes) with similar grouped results. The irregular and patchy dispersion of ore-fields of some elements has long puzzled mining geologists as well as those concerned with mantle heterogeneity, but how does one explain that 98% of the world production of the platinum group of elements appears to be from the U.S.S.R. and South Africa? I do not agree that the subject was adequately dealt with in the quoted previous discussion. Some hydrothermal deposits indicate that parts of some arriving bodies penetrated the crust and were melted before being remobilized and moving upwards. Presumably, the fall-back breccia would include some remains of the impacting body.

The possibility of radio-active meteorites was only mentioned in the discussion of Norman (1984) as a possible explanation of uneven distribution of thermal anomalies, but I did not accept this as the major cause, and only considered heat generated by impact. It is agreed that the surface heat is lost to the atmosphere, but this soon forms a thermal insulation. Even now we still have only a thin skin of solid lithosphere (after about 4 billion years) over an interior that is still above melting point at normal pressures. Many have attributed the cause of the Earth's heat to radioactivity, but Jacobs' (1974) calculations have shown that "radioactive isotopes can account for part of the initial heating up of the Earth, but other sources are needed as well".

Finally, the age of the ocean floor is not a criterion of the date of formation of the original fractures locating island arcs for these can be propagated upwards from lower in the lithosphere by later stresses (e.g. earth tides). An example of this process was shown in fig. 3 of Norman (1984) where arcuate fractures seen in the old basement rocks of Saudi Arabia continue into the younger Phanerozoic rocks.

11 *Riverside* J. W. Norman
Forest Row
East Sussex RH18 5HB
U.K.

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