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Tectonic effects of old very large meteoritic impacts on Earth showing on satellite imagery: a review and speculations

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Abstract—Examples are given of circular features over 100 km diameter on the Earth's surface. It is suggested that some of these are the eroded remains of the effects of very large impacts after a brittle crust had developed. Some of the tectonic effects of major impact events are reviewed using experimental evidence and established ground examples, and the resulting geological patterns to be anticipated are described. Such past events may have had a widespread influence on our present geology, and speculative suggestions are made of the types of existing phenomena that could be attributed to this cause in some local cases of such features as regional metamorphism, cratons, island arcs, arcuate ophiolites and greenstone belts, large rotational movements, thermal anomalies, introduction of new materials to our planet, biological and magnetic effects.

INTRODUCTION

IN THE last decade or so, satellite imagery has given regional geologists a new view of the world denied to previous generations. The continuous improvement in computer processing of the images is increasing our ability to interpret the information. The previous largest area images consisted of mosaics of air photographs, and these invariably had distracting tonal boundaries, or some photographs had to be debased in an attempt at matching the tonal values. The mosaic's area tended to become so large that the eye could not absorb all the data to make regional generalizations. One Landsat image, covering some two orders of area more than an air photograph shows up the regional relationships.

One of the interesting new features to emerge is the large number of arcuate (i.e. parts of circles) fracture patterns of immense dimensions. Figure 1 (Poroshin 1981) shows ring structures based on interpretation of satellite imagery of Russia, and Fig. 2 shows an arcuate zone of volcanoes, gas and oil occurrences in the East Indies (Gold & Soter 1982), with apparent deep structural control. Figure 3 shows a study of Saudi Arabia in which the search was for those arcuate fractures implying circular features extending under the sedimentary cover of the basement rocks, showing on a mosaic of early standard Landsat images (Norman 1980a,b). The selection was confined to those at least 50 km in radius, and many more of smaller radius were detectable, especially on images processed with a high-pass box filter. However, smaller features could be explained by other causes, such as collapse, igneous intrusion, blind salt

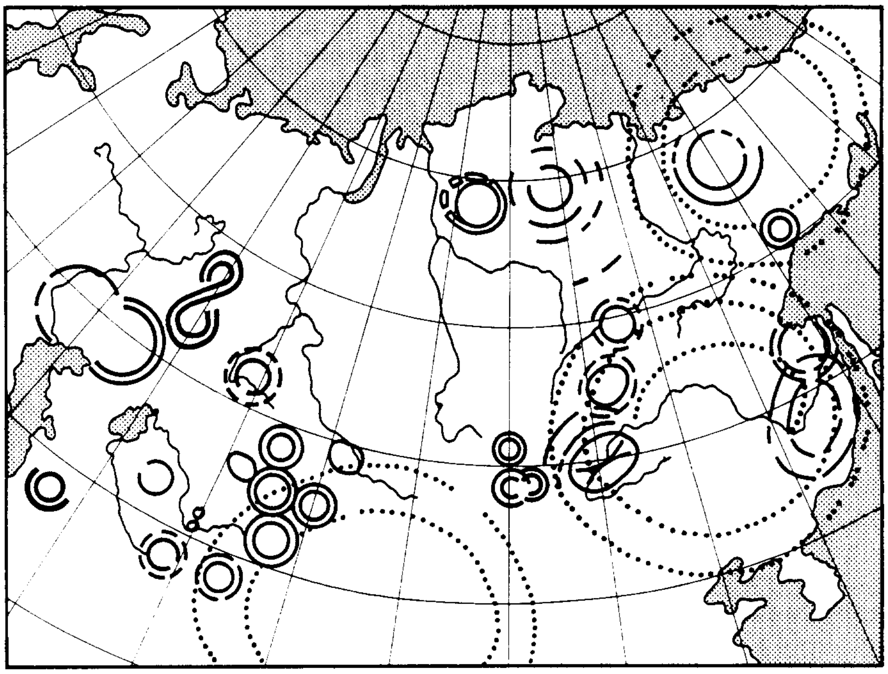

Fig. 1. 'Giant ring structures' from interpretation of Meteor and Salut 4 imagery, after Poroshin (1981).

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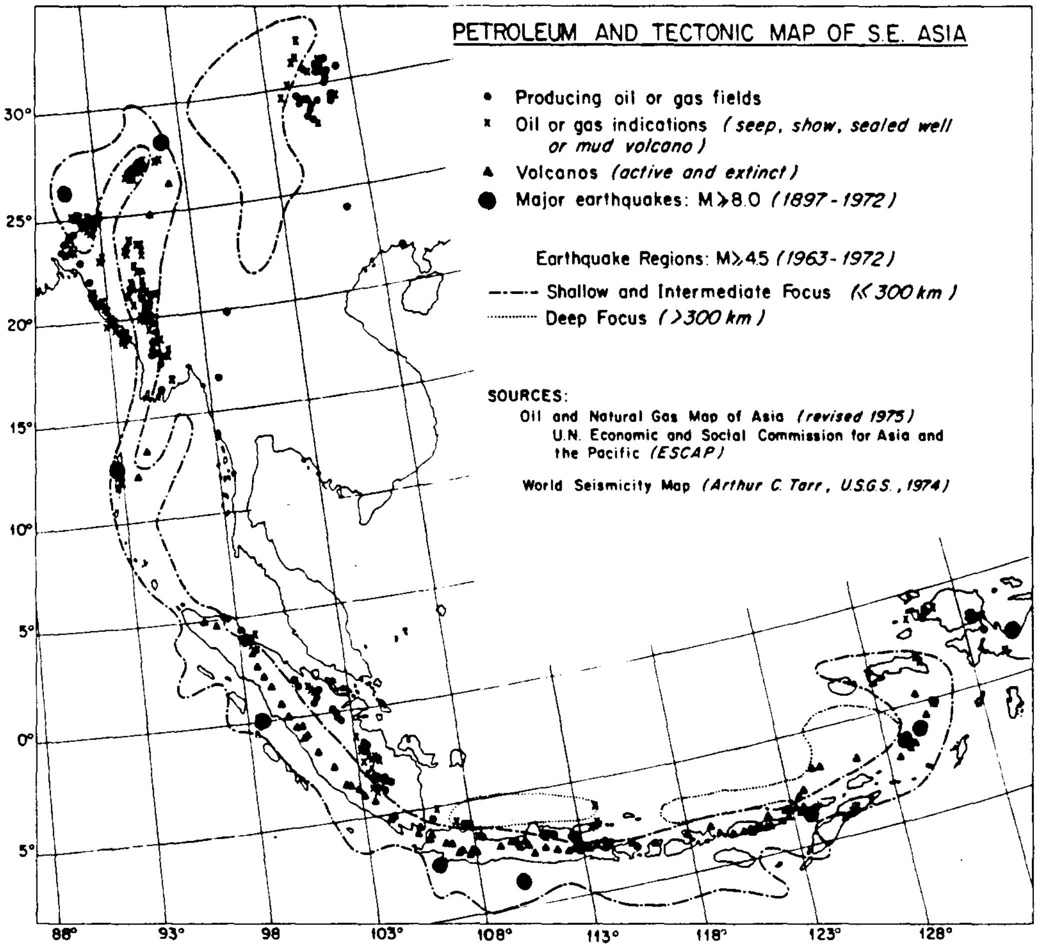

Fig. 2. A very large arcuate zone of apparently structurally controlled phenomena in the East Indies (Gold & Soter 1982).

diapirs, water heave, doming over sills, etc. A concentrically patterned gravity anomaly of three zones of about 2800 km diameter has been reported in North America by Klasner & Schulz (1982).

Many of these features are parts of perfect circles in spite of their size, and there only appears to be one phenomenon that can provide the energy of the right amount and type to create them, namely the impact of large meteoritic bodies, for the shapes shown are in accordance with experimental models, theoretical calculations, and the effects seen on our neighbouring bodies in space. Indeed, Shoemaker (1977) considered the "impact of solid bodies is the most fundamental process that has taken place on the terrestrial planets. The terrestrial planets were formed by this process: the last stage of accretion is still proceeding at a very slow rate". It would be surprising if the Earth had not suffered the same early history of extensive impact events over time in view of its superior gravitational attraction. A small amount of material is still arriving, but judging from the dating of Moon craters, it appears that the bulk of 'fresh' large arrivals occurred before the end of the Archaean, and only relatively small new craters are seen at present.

MECHANISM OF IMPACT

The Earth's orbit is still being crossed by bodies (known as the Apollo asteroids). Of these, 'Hermes' passed at a distance of 780,000 km in 1937. In 1982 a body, '1982 DV', with a diameter of 3 km passed through the orbit within 22,000,000 km of the Earth, and a second, '1982 DB', passed even closer (Anon 1982). Some 40 earth-crossing 'asteroids' are known and there could be a total of over 1000. The frequency and present probability of impact is dealt with by Shoemaker (1983).

The mean velocity of impacting bodies over 1 tonne is around 25 km s^{-1}, and a body with a diameter of 0.7 km can give rise to structures with a diameter of about 10 km. Ceres in the asteroid belt is some three orders larger in diameter, so it is not surprising that there should have been many structures formed early in the Earth's history when most of the large bodies were being swept up in the Solar System. The arrival of these must have extended well into the period after the formation of a brittle crust on Earth. A very small body may be slowed down by the atmosphere, and even disintegrated owing to the heating effect before impact.

The shock of a large impact resulting from the virtually instantaneous dispersion of the kinetic energy has been described by Short (1966), and the geological results seem to have been nicely modelled by a series of test explosions of up to 500 tons of TNT on a series of sediments of a dried-up lake bed (Jones 1977). The experiments showed a gradation in the crater shape from simple bowl-shaped craters produced by charges less than 5 tons TNT through craters with an increasing degree of central uplift, culminating in the SnowBall 500

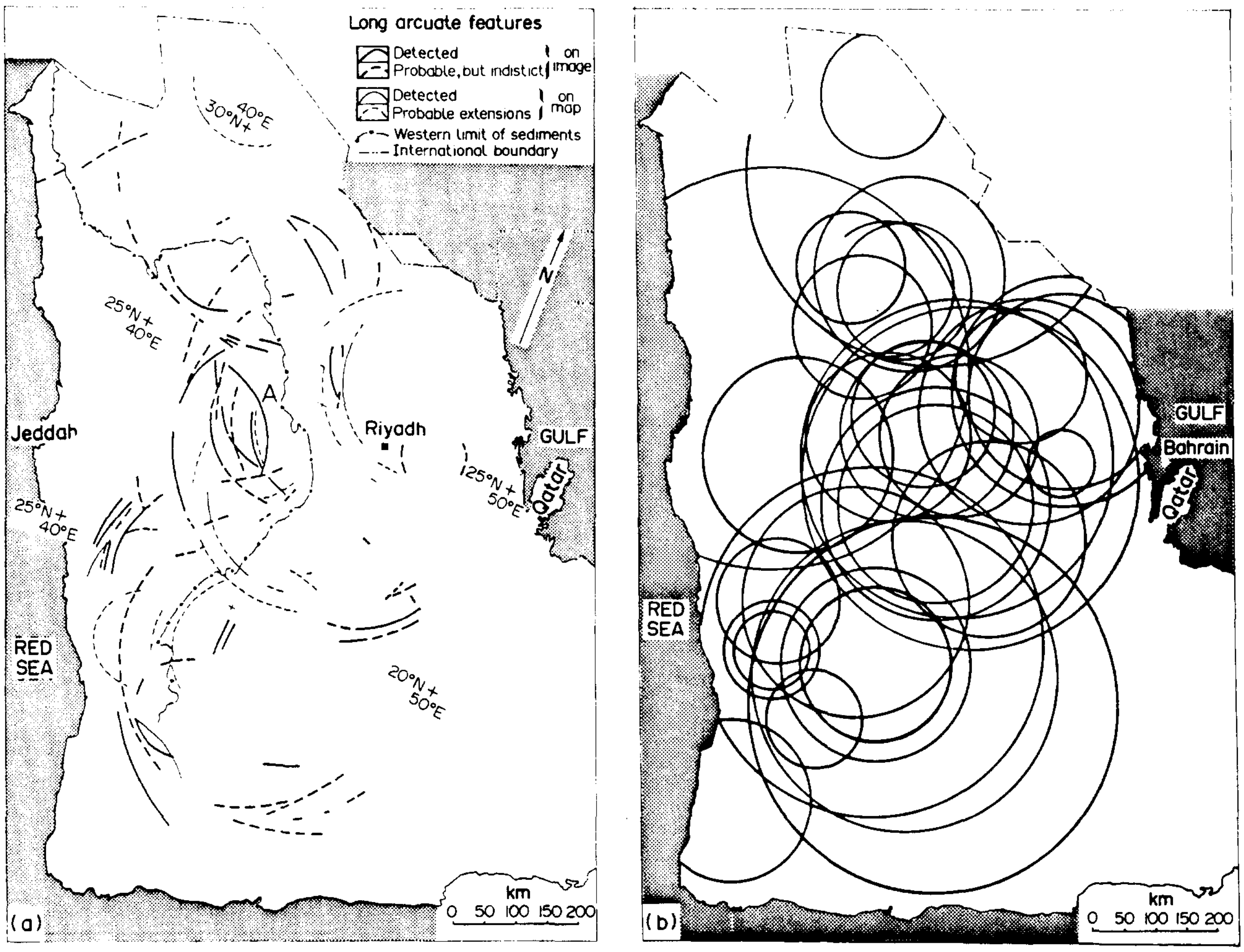

Fig. 3.(a) Arcuate failure lines, visible on Landsat, that extrapolate under the sediments of Saudi Arabia (Norman 1980a). (b) The arcuate features geometrically completed showing extensive overlapping.

ton crater. A second 500 ton trial, called Prairie Flat, produced a ringed structure with a comparatively flat floor very similar in appearance to the very large ring structures seen on the Moon and other bodies in the Solar System. In the Snowball crater there was a large central uplift, debris mounds outside around the rim, and a peripheral graben; in the other case a concentric series of ring structures. After the lake bed test explosion, a fuller investigation of the central uplift type structure showed effects illustrated in Fig. 4. Outside the crater (about 70 m in diameter) there was a zone of inverted 'strata' followed by the peripheral graben. The graben was bounded by fractures which were several metres deep but there was relatively little downthrow of the graben floor initially, though the entire area in the vicinity of the graben was depressed well below the pre-trial surface level. There are of course problems in scaling up the results of such an experiment (Holsapple & Schmidt 1982), but if one extrapolates these results to the size of the large circular features, it is easy to realize that originally some impact structures considered here may have had grabens which were a number of kilometres in depth. Some of these would have had marginal fractures right through the crust giving upward flow routes for hot mantle material which would be later coated with sediments and material collapsing from the steep sides of the graben. In the central area the rebound effect would form features of mountain size initially, and at depth there appear to be features in the experiment resembling ring dykes and cone sheets (Fig. 4). Extending beyond the graben are a series of radial fractures, and in the case of the old lake bed experiment, these were the site of a series of small sand volcanoes derived from a buried sand layer in the dried lake sediments.

In practice, at the larger sizes discussed here there is

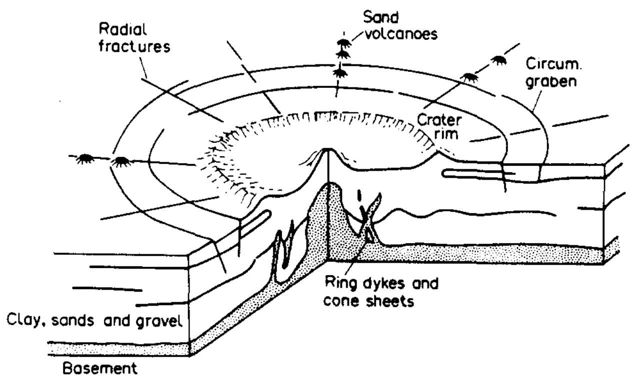

Fig. 4. Result of excavating an explosion site on a dried-out lake (Price 1975, Jones 1977). Note rebound feature at centre, peripheral graben and radial fractures.

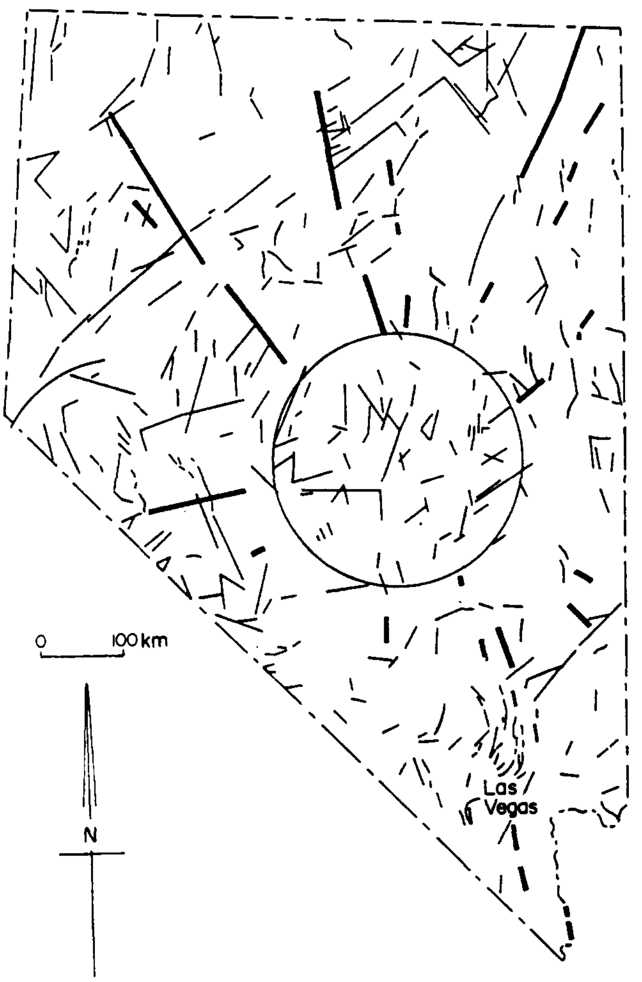

Fig. 5. A circular feature interpreted by Rowan (1975) in Nevada. Radial lineaments have been emphasized. Many lineaments coincide with faults at the surface, or show zones of failure over deep faults.

often evidence of radial stress (e.g. Fig. 5) and these fractures indicate the outward passage of the maximum principal stress which also appeared to cause shear fractures set obliquely to the direction of the radial fractures. The results of the impact pulse are remarkably arcuate and symmetrical (Fig. 6), and do not reflect the directional path of the arriving body unless the trajectory was substantially less than 10° to horizontal, in which case the results may be more akin to a deflection leaving a large furrow. Immediately after impact, gravity starts to affect the unstable steep sides of the crater in the presence of seismic and acoustically fluidized material (Melosh 1982). There will also be a tendency for isostatic forces to readjust the surface level by causing the crater floor to rise and the rim to sink (Baldwin 1970) with a similar tendency in the graben vicinity. About 20% of the kinetic energy of the arriving body is converted into heat (Dence *et al.* 1977). The heat generated by the passage of the impact pulse would be added to the Earth's normal temperature, which increases with depth. Thus the radius of molten material could increase with depth (Price 1981), undermining and adding to the instability of the crater rim. In the case of large impacts, the amount of fluidized rock will be large, as seen in the case of the maria on the Moon. The fluidization of the impact effect, assisted by the considerable heat developed, may be responsible for the central peak of many craters, which indicate rebound effects. This may be likened to the fluidized rock being caused to flow in the manner seen in the central small jet that rises after the dropping of a large object into water. The fluidization of the impacted surface has additional effects, making an easier passage for surviving parts of the impacting body downwards, and providing instant melt material which is jetted out of the crater, together with fractured debris (Phinney & Simonds 1976), by the rarefication effects following the impact pulse (e.g. causing Suevite). On Earth, presumably this material may now resemble volcanics or meta-volcanics.

Simultaneously a second pulse also enters the impacting body, and is reflected back from the rear of the body in a form that causes disintegration (Short 1966). The speed of this pulse in some types of meteorites can be considerably lower than in the Earth's crust, and at arrival speeds averaging 25 km per second it is not surprising that substantial parts of some large impacting bodies can survive through the crust, later become melted, and the lighter fractions rise through the easiest channels to the surface (Norman 1980b).

The third variety of impact structure consists of a series of concentric ring structures, one side of each ring commonly being formed by a fault scarp, and is modelled by the Prairie Flat structure illustrated by Jones (1977). This type of structure seems to be related to a large energy source, and very few features fitting this description have been reported on Earth, although at least 43 ringed basins are known on the Moon (Taylor 1975). Guest & Greeley (1977) found that on the Moon ringed structures were usually the dominant type in the structures greater than 150–300 km in diameter. A possible local terrestrial candidate has been described by R. McQuillin (pers. comm.):

> "The Great Glen Fault is well defined as a major rotational dislocation describing a small circle of the globe with pole of rotation approximately 61°30′N, 17°W. A study of other major fault lines indicates that a suite of similar deep crustal faults may exist with approximately the same pole of rotation. These deep structures of ancient (probably late Caledonian) origin now control many of the important structural elements of the geology of Britain and the adjacent continental shelf, including the margins of a number of Mesozoic basins extending from the Celtic Sea area through into the North Sea."

The marine extensions of the Great Glen Fault from northwest of Ireland to north of the Shetlands appears as a continuous arc approaching 1000 km in length.

There has been considerable past discussion about whether large circular structures were caused by impacts or crypto-explosions although there seems no reason why both should not exist. If a high-velocity body struck water-logged sediment and instantly generated steam, there could be problems in assigning either cause.

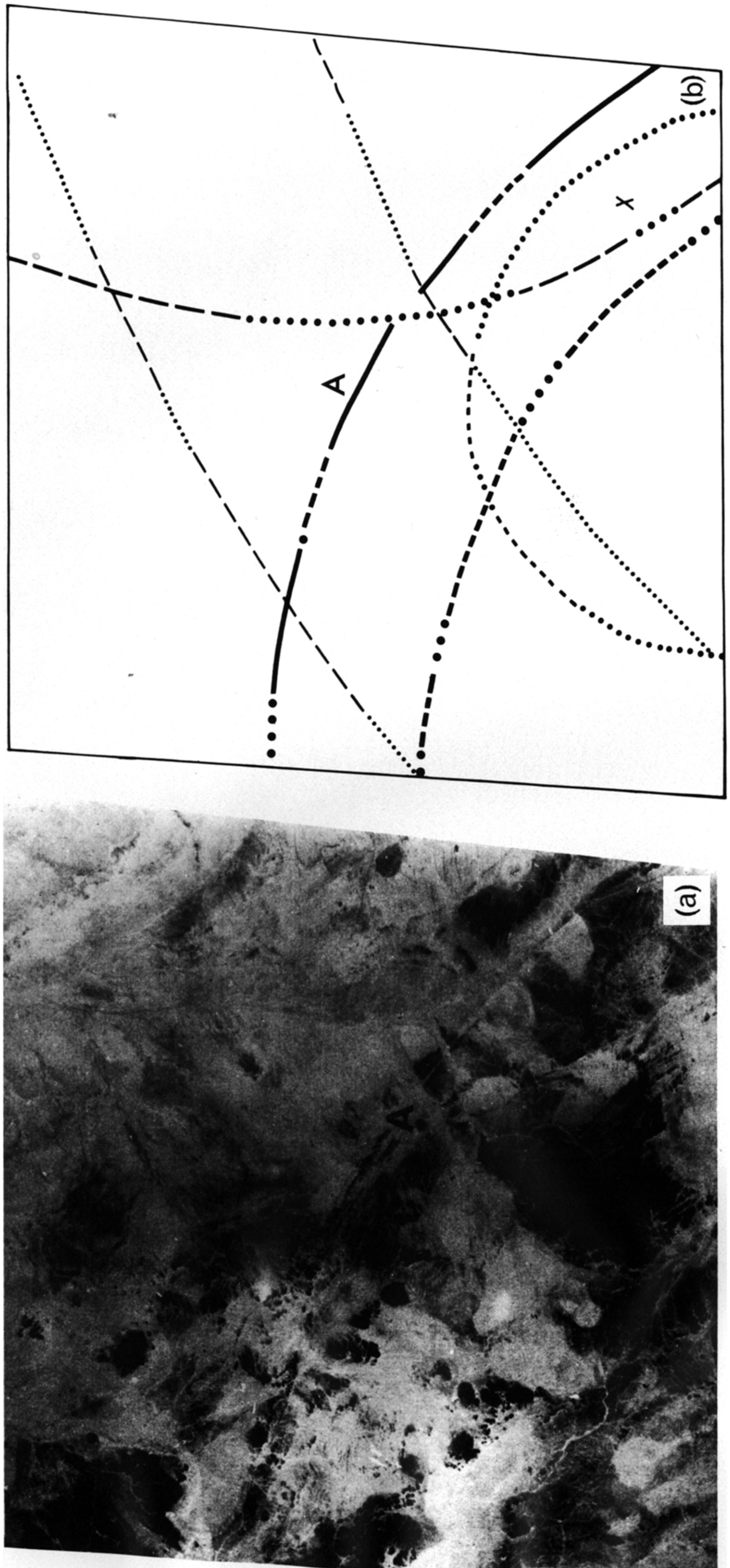

Fig. 6. (a) Landsat (band 7) image of the curved lineament marked A on Fig. 3(a). Length of the side is 185 km. (b) Arcuate features over 50 km radius detected on original image processed with a high-pass filter.

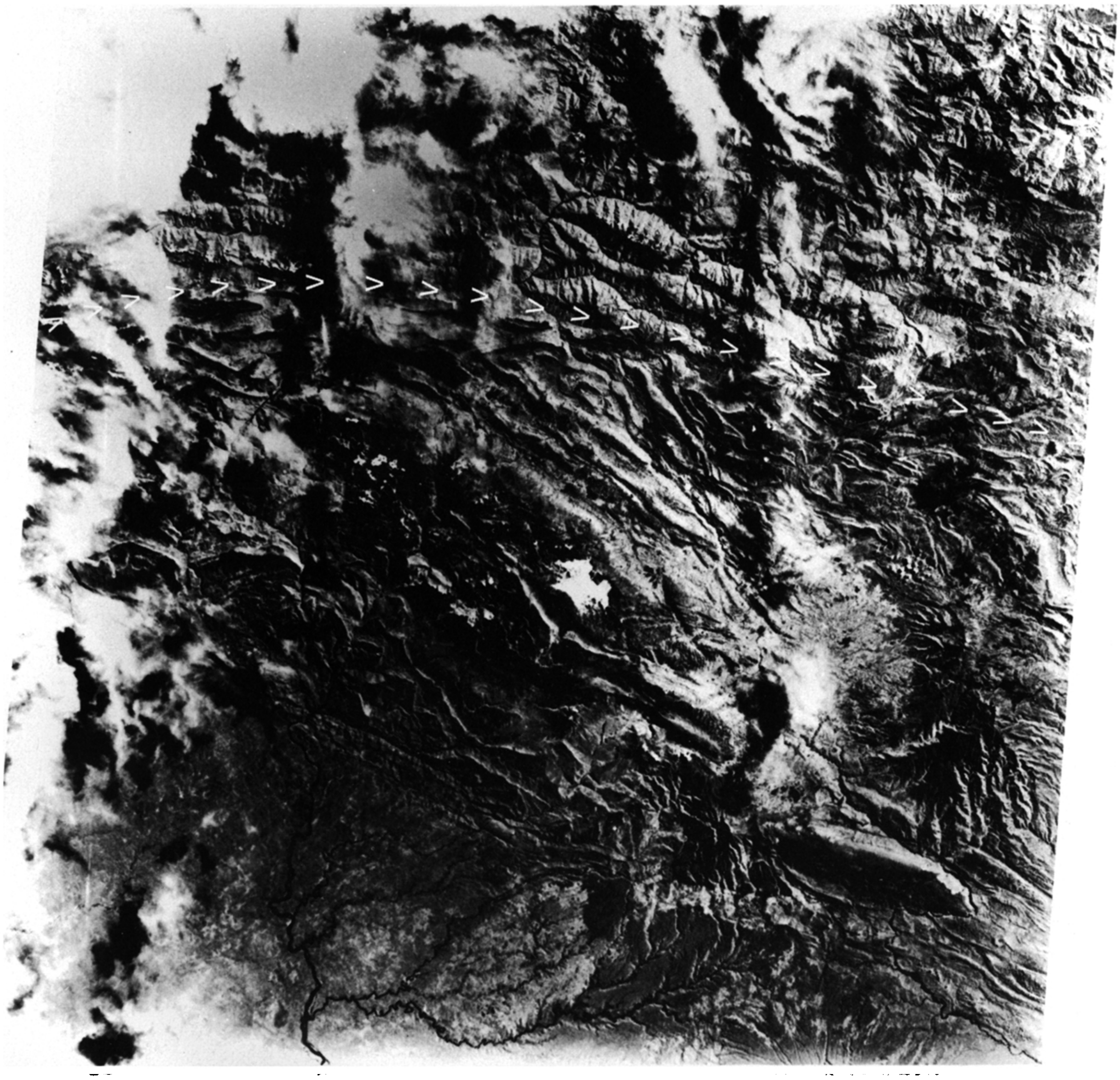

Fig. 8. Landsat image 106/64 showing a gently curved failure line possibly marking the edge of a tilted block and a resulting detached fold belt that has slid southeast (Jenkins 1974). Image sides about 185 km long on the ground.

SOME POSSIBLE GEOLOGICAL IMPLICATIONS

So far, some of the immediate physical effects of a large impact have been described, but possibly there are extensive geological implications resulting from the nature of the effects, and the author's following speculations need widespread investigation before acceptance. It is not suggested that impacts are entirely responsible for all examples of the phenomena to be dealt with in this section, but it is suggested that some individual examples within the various classes might need to be considered in case their initial cause should be attributed to meteoritic impact.

Erosion has removed some kilometres of rock from many areas since the Archaean. Uniformitarian concepts cannot be invoked as no very large impact has occurred in anyone's lifetime. Much of the remaining evidence of impact consists of old deep features on which later forms of tectonism have been superimposed.

Indeed, rarely does one see obvious evidence of very large old impacts, for at medium and large scales the portion of the features seen are easily assumed to be straight. The best approach seems to be to examine small-scale large-area Landsat image mosaics and look for curved features. Then with a sheet of acetate and a template of concentric circles, the radius of the arc can be matched, and its geometrical extrapolation be sought among other remaining parts of the original circle. These features seem remarkably symmetrical, and if an initial examination of the curve does not prove it to be a part of a circle of consistent radius, then the cause is likely to be different. However, some curves are caused by a late regional stress, and may appear as a straight failure along part of their length before exploiting a convenient part of an old circular failure, or it may even be parts of two separate circles of differing radii where late stresses have exploited parts of the perimeters of two adjacent features.

REGIONAL METAMORPHISM

The earlier descriptions discuss effects causing pressures of the order of megabars, and temperatures capable of melting and even vapourizing rock, a possible source of tektites (Jones & Sandford 1977). Inevitably there has been some metamorphism associated with large impacts, and as our planetary system has had sufficient arrivals for the term 'saturation impacting' to be used, the metamorphism must have been extensive. Overlapping of the effects of the features shown in Fig. 3 will be seen if the circles are completed geometrically. Note that some features which have been detected in the sediments probably as fracture zones, have been propagated upward from the underlying basement structures. A later examination of some of the interpreted images, now processed by modern digital techniques, shows that there must be many more arcuate features detectable, but probably the early examples are so overprinted that they defy recognition. It is difficult to avoid the conclusion that here is some of the evidence of past impact saturation that is still visible on neighbouring planets which lack our wet atmosphere and its erosive effects.

Fieldwork on the Lake Manicougan impact structure showed metamorphism inside the peripheral graben which increases in grade towards the centre. Murtaugh (1972) reported the presence of shock metamorphism.

In Fig. 6 it will be seen that the area marked X comes within four large circular features, and by the use of surrounding images it can be seen that a further six have overprinted the same area. Each feature is over 100 km radius, and will have contributed something to the grade of the resulting metamorphic rocks. Some of the arcuate features shown in Fig. 3 are over 500 km radius, reflecting the release of a formidable amount of energy. It seems that the custom of invoking the pressures and temperatures in a zone beneath past mountain chains as being the cause of metamorphism is often overextending a local possible mechanism, and that it is likely that much early regional metamorphism is the result of old impact effects. To this end it is felt desirable that before crediting orogeny with being a local cause of the regional metamorphism, one should first attempt to reconstruct the former mountain chain in relation to the current geology. The correlating and linking together of groups of pre-plate tectonic strain systems on a broad age range as being caused by one widespread tectonic event could be a dubious practice without this approach, especially since local 'atomic clocks' may be re-set in some impact events.

CRATONS

The large welded and thermally fused central area made at an impact is likely to form a hardened disc shape (Norman *et al.* 1977), possibly resembling the mascons on the Moon. The rocks, on cooling, will tend to remain as a single strong unit (an astrobleme-craton, or astron), with a segregation of the lighter minerals to the top. These can in turn be concealed or altered by later events, but nevertheless the interplay of subsequent erosion, sedimentation and tectonism may cause some parts to be exposed. All circular, or sections of disc-shaped cratons need examination with this possible cause in mind, but the large number of major impacts is likely to have caused overlapping and fusing of similar adjacent features. Many areas described as cratons may well be the relics of a number of such units welded together by overprinting impact effects. One of the Earth's largest impact features appears to be West Africa. This has parts of other phenomena adhering to it (e.g. North Morocco) destroying the circularity of the outline. After a large impact event, the rim mountains of jetted debris around the crater will tend to erode and be transported into the depressed centre or outwards into a graben. Some features now known as intra-cratonic belts may be the results of crater debris or sediments from them being later overprinted by adjacent impact events, or they may even be parts of fold belts related to the original impact-generated radial stress.

PLATE TECTONICS

It seems from current opinion that plate tectonic movement did not commence until relatively late in our planet's life, some 1000 Ma (Tarling 1980). Before that time meteoritic impact tectonics were probably a major feature of the Earth's geological development, but ocean spreading will have removed or obscured much of the evidence over large areas. Once the thickness of the cooling crust was sufficient for large plate movements, a mechanism of convection appears to have provided the motive force, and whilst this seems to be generally ascribed to radiogenic heating, there is still a problem in explaining the isolated local heat anomalies and convection cells in a cooling, rotating, spherical body. Perhaps in some instances the possibility should be considered of either a localized concentration of radioactive elements brought by late arrivals from outside the Solar System, or even the driving motor for plate movement being initially related to the enormous residual heat from a major impact. In the case of the largest bodies arriving in the later stages of the Earth's history, the deeper part of the thermal anomalies must last an extremely long time.

While it seems that the vast majority of large impacts took place prior to the commencement of plate tectonics, there are several aspects of the results of very large meteorite impacts which could affect plate movement and shape. The major failure lines left by the impacts still seem to exist, possibly even into the upper mantle, and in places these lines appear to have been exploited in the later plate movement, probably assisted by a resistant block of old metamorphics and melt. The Amazon Basin would appear to be a large astron that has influenced the shape of the Peruvian part of the Andes, although the west coast of South America further south has been influenced by a different cause. Around the western edge of the Amazon craton, subduction probably destroyed any peripheral graben that may have existed and is forcing up material from the edge of the astron. The arcuate shape of the Himalayas may possibly indicate a similar cause on the tectonic impact of India on the main Asian plate.

ARCUATE GREENSTONE BELTS

Where a peripheral graben is created by a large impact, the base of the feature usually seems to be filled at an early stage with basic and ultrabasic material upon which is progressively sedimented material from the rim mountains, together with further volcanic flows. Any subsequent nearby large impact tends to overprint all this material, which commonly forms an arcuate greenstone belt. There are, of course, a number of other possible causes of greenstone belts, but those which are part of circular features are worth looking at in the light of this possible origin.

Many of these features will have been over-filled with material and their original arcuate shape become blurred or destroyed, but rejuvenation occasionally produces clear concentric failures around parts of the edges of the old graben detectable on Landsat images. Commonly they are seen as arcuate anomalies on regional airborne magnetic results. If, however, the lower contents of the graben are raised and exposed, they could now be classed as ophiolites.

ISLAND ARCS

Large island arcs such as the Aleutians inevitably suggests a possible connection with large impact phenomena. While it is felt that the shape and dimensions are likely to be controlled by former impact events, there seem several possible relationships that need to be tested against individual arcs including the local shape being subduction controlled by the rim of an underlying astron, or intrusion controlled by peripheral faults possibly exploited by post-cratering isostatic adjustments. For example, Borsuk & Tsvetkov (1982) in considering the igneous rocks of the Aleutians consider that "it is extremely likely that the primary deep-seated fault that became the conduit for the magmatic melts was formed earlier". Arcuate features inside an arc may be due to a 'ringed uplift' impact feature (in which case the arcs should be concentric), or due to an impacting plate displacing an astron horizontally—in which case the arcs should have the same radius.

The cause of island arcs has been sometimes attributed to inclined flat surfaces intersecting the curved surface of the Earth. A calculation shows that such a surface must be dipping so slightly that its outcrop would be virtually a contour, whereas most features of the arcuate perimeters appear to be controlled by a steeper structure. On the other hand, if a plane dipping at the angles most workers accept for subduction is considered, the arc of intersection with the Earth's surface is of such large radius as to eliminate most island arcs. If the Moon had an ocean, numbers of crater rim mountain chains would become island arcs.

THERMAL ANOMALIES

The immediate dispersal of a body's kinetic energy on impact results in the transposing of some 20% of the energy into heat (Gault & Heitowit 1963). This is generated during the passage of the impact pulse outwards and downwards, and calculation of thermal effects of large impacts shows tremendous amounts of heat that would take an extremely long time to disperse. Some of the thermal anomalies associated with island arcs could be due to this cause. In the case of the largest masses the "thermal anomalies in the Earth's mantle could last for a billion years or more" (Anderson 1975). They are likely

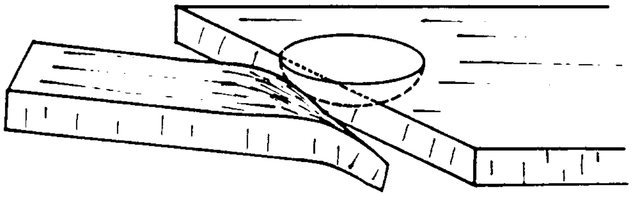

Fig. 7. A resistant block inside free circular faults may rotate and/or tilt when disturbed by a subducting plate.

to form plumes and convection cells, with all the currently associated phenomena. The resulting slow upward flow may dome areas, and in the crater basin, any young mantling sediments may experience residual metamorphosing heat. It has been noted that obliquely illuminated crater flood basalts on the Moon show numerous examples of doming.

Guest *et al.* (1979) showed that the flood material of Imbrium on the Moon was still available 600 Ma later to fill Archimedes and Plato craters, indicating the slow rate of cooling.

It is suggested that the heat-flow maps of large areas be considered in the light of some hot areas having been generated by late major impacts. This would seem to be more frequently a possible cause compared with the generation of anomalous heat in specific but randomly situated localities when considering a cooling Earth that is spherical and has had time to differentiate.

LARGE ARCUATE MOVEMENT

There is evidence of some astrons having experienced partial rotation, although later overprinting events may tend to lock them and prevent free movement around the formerly circular external failure. A potential cause of rotation could be the oblique impact of a plate on part of such a feature, especially an advancing subducting edge (Fig. 7). Three reported movements along curved surfaces in the coastal zone of western North America are possible examples: (1) on part of the San Andreas fault (Woodford & McIntyre 1976); (2) in Oregon where Cox & Simpson (1976) reported a clockwise rotation of 55°, shown to have been in the last 40 Ma by palaeomagnetic methods and (3) in California where Kistler & Peterson (1978) showed a curved movement of about 800 km in the last 1250 Ma using Sr isotope dating. Palaeomagnetism has shown rotation in the Western Transverse Ranges of California (Kamerling & Luyendyk 1979), and further north, in western Canada, Hicken & Irving (1977) showed that at least part of the Queen Charlotte Islands of British Columbia "had rotated at least 25° clockwise since the Palaeocene". In Alaska, local seismic events along a continuation of the Aleutian arc indicates that this feature may be rotating, and the structure is not confined to the marine environment.

In the East Indies, by palaeomagnetic studies "considerable rotations have been demonstrated" (Haile 1981). It is also conceivable that a tilting effect may occur in some instances. An example of a fold belt bounded at its upper end by an extensive arcuate failure is shown in Fig. 8. This could mark the upper limit of a tilted unit causing the sediment detachment and sliding reported by Jenkins (1974). After seeing arcuate segments of old blocks above subduction zones in South America, the impression has been gained that astrons do not always survive the stresses of tilting as a unit.

MAGNETIC AND BIOLOGICAL EFFECTS

Major impacts are likely to have produced at least local magnetic effects (Fuller 1974). This needs bearing in mind in 'polar wandering' studies. A number of the effects of the traumatic large impact events in the Earth's history could also cause widespread biological disasters by the mere shock, the effects on the climate, etc. A number of writers have commented on the coincidence of magnetic changes and destruction of living species, and it is interesting to note that this has been noted to coincide with 'volcanic' activity in some cases. Information available at present indicates reversals take place at random.

A possible impact example at the end of the Cretaceous causing destruction of species including the Dinosaurs has been recently suggested (Norman *et al.* 1977, Alvarez *et al.* 1980). Widespread extinctions of marine life have been linked to impact phenomena by Ganapathy (1982) and Hsü *et al.* (1982), and numerous studies of large impact effects on the atmosphere and life are reported in Silver & Schultz (1982).

REGIONAL STRAIN PATTERNS

Strain patterns related to old impacts may be detected in basement rocks (e.g. Fig. 5), or even after propagation into overlying sediments. For example, Hancock & Kadhi (1978) showed what appears to be the results of a radial stress crossing the arcuate western part of the central Arabian graben system. However, the large number of impacting bodies that have arrived in the time since the brittle crust developed has left a chaotic pattern of crustal fractures from which it is now difficult to isolate individual radial systems. The pattern is further confused by strain caused by other regional systems from such causes as colliding plates or even stresses due to the Moon's gravitational pull as seems possible in an extensive parallel system reported by Al Khatieb & Norman (1982).

INTRODUCTION OF NEW MATERIAL

The arrival of large impacting bodies means the accretion of new material to the planet. Bodies arriving from the Solar System will have dominantly the same chemistry, but cosmic arrivals [especially those including some of the element products of high energy events such as a supernova (Clark 1979)] may have introduced uncommon elements and played a part in crustal and upper mantle heterogeneity. These would be dispersed in several ways.

Of particular interest are the minerals which may survive to a considerable depth on impact; the lighter material would come up to the surface as intrusives. Such magma might bear some of the products of the extremely high pressures at impact, and these might be erroneously attributed to the depth of burial. Much effort concentrates on studying the possibility of the contents of the crust differentiating from the mantle, but some mantle material may originate from accretion.

ECONOMIC ASPECTS

Although most large impacts are pre-Phanerozoic, the fact that they cause extensive brecciation of both *in situ* rocks and ejected material makes them potential petroleum rerservoir rocks, providing the relevant fluids can enter them. These implications were shown by Donofrio (1981), who discussed a number of oilfields that are likely to have this origin. He stated "that if geological or geophysical evidence suggests the presence of a subsurface impact crater in crystalline (or sedimentary) rock, it should be drilled regardless of the presence, absence, or position of source beds". However, it seems likely that in the case of the craters of very large impacts decribed here, the fracturing of the rocks at the crater base is usually likely to be sealed or grouted by fluidized rock. Of more interest might be the ejected breccia if capped and sealed by later sediments. The structures in the sediments, inside and outside the crater, may also play a role. For example, the Nigerian main oifield appears to result from sedimentation into an old peripheral depression around the West African astron. There is also a remarkable coincidence of the earthquake, volcanoes, gas and oil occurrences of a large arcuate zone including most of Sumatra, and around to Papua (Gold & Soter 1982) (Fig. 2).

The material arriving from space after the formation of a crust and particularly from outside the Solar System, can be of interest. Many of our economic metals need the energy of a super-nova for their creation from the fundamental element, hydrogen (Clark 1979). The distribution of metals in Saudi Arabia (Fig. 9) suggests a distribution of concentrations that could be caused by impact sources (Norman 1980b). Alvarez *et al.* (1980) have suggested that an extensive concentration of iridium reached the Earth with an impacting body at the end of the Cretaceous. Some bodies may shatter completely on impact, and distribute their contents widely. Thus around old impact sites some metals may now be found in former superficial deposits, possibly with local quantities of old melt that could now resemble volcanics, for example, as described by Lambert in Silver & Schultz (1982).

The major fractures of the crust caused by large impacts can provide easy routes for rising mineralized intrusives. Saul (1978) described examples of circular structures apparently influencing the position of ore deposits, and one is tempted to consider the possible role of very high pressures at impact in the early history of the formation of the economic polymorph of carbon, diamond. Trofimov (1982) has shown that at least some diamonds have originated in the upper few kilometres of the crust.

Finally, it seems that there is scope for a re-examination of some individual features that have been classified in the past as large circular or arcuate phenomena (e.g. crypto-volcanic explosions, calderas, cauldron subsidence) in the light of our improving understanding of meteoritic impact tectonics.

Fig. 9. Isopleths of the commonest metals resulting from a moving average treatment of Van Daalhoff's (1974) map of metal occurrences in Saudi Arabia. The dot–dash line shows the sediment/basement contact. (a) lead, (b) zinc, (c) copper, (d) silver and (e) gold. The northern part of the area was not included in the statistics (Norman 1980a).

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