Regeneration of ancient impact-scars affect regional geology worldwide

John M. Saul,

John.saul@wanadoo.fr

Independent researcher

ORCID 0000-0002-2282-2430

Abstract

The entire Earth was bombarded c.4100-3800 Ma, establishing initial conditions for all later regional geology. Deep impact-fractures have been regenerated upward from the brittle-ductile boundary by the action of convection, outgassing, circulating fluids, the twice-daily earth-tide, and earthquakes throughout all subsequent time. In consequence, many such fractures have never entirely healed or been eliminated. The two-dimensional map-outlines and circular curvature of numerous three-dimensional "craterform" scars can be readily seen, *once the observer has been alerted to the possibility of their existence*. Many other Hadean/EoArchean impact-scars are covered over, as is the case at present, at any given time. These impact features have been regenerated "cold" from below and are fundamentally different from astroblemes, as presently defined, whose rocks were directly subjected to the high temperatures and pressures that accompany hypervelocity extra-terrestrial impacts. Melt rock filled the largest impact sites and produced cratons, with overflow producing platforms. In later times, craton rims buckled during collisions, producing orogens. Crater rims originally entered the Earth at near-vertical angles but after sufficient net erosion following Snowball Earth episodes, deeply exposed rim-zones entered the Earth at lower angles, thereby facilitating deep subduction. Renewed activation of earliest Precambrian fractures *from below* is a recurrent geological phenomenon. The largest scar, approximately 5350 kilometers in diameter, encompasses Asia and has Novaya Zemlya as part of an outer rim. Our vision has greatly improved since 1788 when James Hutton could find “no vestige of a beginning".

KEY POINTS

1. Initial geological conditions were set by the bombardment that also scarred the Moon.
2. Deep 3–D impact-fractures, rejuvenated from below by activity at the brittle-ductile boundary, are still visible at the Earth’s surface.
3. Ancient 3–D bombardment scars cover the entire Earth and provide a framework for plate tectonics and for regional geology everywhere.

KEY WORDS

Initial geological conditions, Late Heavy Bombardment, impact craters, subduction initiation, cratons, brittle-ductile boundary

PLAIN LANGUAGE SUMMARY

The bombardment episode that scarred the face of the Moon also scarred the Earth. On Earth, shallow impact-scars dating to the bombardment were rapidly removed by erosion. But impacts that were sufficiently deep to have passed through the Earth’s entire crust have left scars that have survived worldwide, constantly rejuvenated upward by movements deep in the Earth. The fractured rocks on the rim-zones of these 3–D “craterform” scars were never themselves actually impacted: their fractures were inherited from below. These deep features have controlled mineralizing fluids, drainage systems, and much else throughout geological time. In particular, they also provide *a framework for plate tectonics.* When continents collide, for example, they form mountainous zones called orogens that may follow the curvature of an ancient impact, as in the case of the Himalayas. These circular scars are not easy to see and many are partly or entirely covered by younger rocks through which upward-propagating fractures have not attained the Earth’s surface. If the patterns had been easy to see, they would have been discovered long ago. In addition, their existence is regarded impossible according to a broadly-held but outdated assumption that the geological record includes no vestige of a beginning.

1 Introduction

1.1 Earth and Moon Both Bombarded

The Earth was heavily bombarded c.4100-3800 Ma (Taylor, 2006) and when the first generations of satellite imagery became available, many geologists expected to see a Moon-like pattern of impact scars on the Earth. But the expected scars were not seen. Doubts then arose, which led NASA’s Paul D. Lowman (1976) to warn that “arguing that the Earth had somehow escaped” the bombardment that battered the Moon was tantamount to “invoking magic or divine intervention”.

Impact craters were in fact spotted on Landsat and other imagery, but most were already known or small, and in time a consensus of sorts was reached that the action of water on the

Earth's surface had erased our planet's ancient Moon-like scars. A few scientists and non-scientists nevertheless still thought they could discern large ancient impact-like patterns or scars with circular curvature on certain images and maps (Kelly & Dachille, 1953; Kellaway & Durrance, 1978; Isachsen, 1978), with Hudson Bay, the coastline south of Prince Edward Island (Canada), and the bulge on the east coast of Sweden as favored candidate-structures.

In 1971 or thereabouts, the theory of plate tectonics began to acquire its modern form and thereafter it was assumed that, if not eroded, traces of the bombardment (abbreviated "LHB") had been subducted. This was just an assumption but it was seemingly sealed in a definitive manner when particular criteria characteristic of hypervelocity impact-shock were recognized at younger (post-LHB) meteorite-impact sites. These "diagnostic shock metamorphic features" included shatter cones, planar deformation features, shocked zircons, and the mineral coesite. In the absence of at least one such feature, a proposed site would not be included in the list of "confirmed impact structures" in the *Earth Impact Database*, which had 190 structures as confirmed astroblemes by October 1, 2022.

Absent from the list of diagnostic features was circularity itself. Yet circularity was, and remains, the prime characteristic by which lunar and other extra-terrestrial impact sites are recognized.

2 Survival and Persistence of Ancient Impact-Scars

2.1 Regeneration upward from the Brittle-Ductile Boundary

By the time of the bombardment, which ended approximately 3850-3800 Ma, the Earth already possessed a solid crust, presumed to have been thin and hot, whose existence is attested by still older detrital zircons derived from granites that had crystallized at depth (Maas et al., 1992; Mojzsis et al., 2001; Cavosie et al., 2004). LHB impact-scars that were too small to have penetrated the early crust would have been rapidly eroded out of existence but the fate of deeper impacts is less evident.

Melt-materials at large impacts would gradually solidify. In an ideal case, uncomplicated by nearby circumstances or later tectonic events, this would produce an unfractured 3–D craterform-mass of solidified melt, bounded by rocks that had not quite melted, i.e., that had been maximally shocked. Yet neither the craterform-mass nor its envelope of shocked rocks could have persisted below the brittle-ductile boundary. Below this boundary, rocks flow. Flow involves shear, and shear obliterates original features. Ductile materials have no memory. In consequence, vestiges of large impact craters (above some presently unknown size) do not continue at depth throughout geological time. Instead, they would be truncated at the brittle-ductile boundary, leaving a circular fracture-pattern just above the depth at which rocks flow. The resultant form, in an ideal case, would be a frozen core surrounded by maximally shocked rocks, with the core and its surrounding envelope of shocked rock both truncated at depth.

Many rock-fractures heal, the two sides welded together or reconnected by quartz, carbonate minerals, direct annealing, or otherwise. It is not clear, however, how fractures at the brittle-to-ductile transition might ever entirely heal on a planet as active as ours. Flow, convection, outgassing, circulating fluids, changes in crystal structure and of volume, earthquakes, and the twice-daily earth-tide provide constant, intermittent, periodic, and sporadic movements. (The magnitude of the earth-tide, which can be as great as 55 cm at the Equator these days and was greater in the past, is not affected by the rigidity of rocks.) In consequence, fractures from the surface downward that had attained the brittle-ductile boundary would be activated and repropagated upward ever after.

It is clear, however, that Hadean/EoArchean impact-sites may be covered by younger geological formations. In some instances, overlying formations acquire circular fracture-patterns regenerated from below. In other cases, the ancient fracture-patterns would not attain the Earth's surface as when, for instance, sedimentation was more rapid than the rate at which the fractures were rejuvenated, or where the fractures were covered by recent lava flows. In consequence, the surface expressions of many LHB impact sites are difficult or impossible to see.

James Hutton's *Theory of the Earth* reports that "we find no vestige of a beginning". This was valid in 1788. Here we ask whether this is still the case.

2.2 Absence of Diagnostic Shock Metamorphic Features at LHB Impact-Scars

Circular arcs with sufficiently large diameters may be vestiges of LHB-fracturing despite the lack of diagnostic shock metamorphic features. One reason for this is because shock metamorphic features only form in solid rocks. They do not form in fluids. But large impacts produce *disproportionately great* quantities of melt-fluids (Grieve & Cintala, 1995; French, 1998; Melosh, 2000; Ryder et al., 2000; Manske et al., 2018). In consequence, diagnostic shock metamorphic features may have been immediately swamped by melt or eventually annealed by the heat retained in the molten mass, thermal metamorphism overwhelming shock metamorphism. Alternatively, they may have never been produced at large impact sites.

Furthermore, the 190 recognized post-LHB impact-sites all include rocks that had actually been subjected to the high pressures and temperatures that accompany crater-forming impacts. They are therefore, by definition, potential hosts for shock-metamorphic features. But the far more numerous vestigial fracture-patterns derived from LHB impacts (Saul, 1978; Byler, 1983, 1992) were formed "cold" in younger rocks, *gradually regenerated from below* in circumstances unsuitable for the formation of shock features, *not violently produced from above* as were the astroblemes listed in the *Database*.

Vestiges of the LHB also differ from the scars listed in the *Database* by their size distribution: no site in the *Database* has a diameter exceeding 160 km, which is smaller than many lunar craters and hence far smaller than many expected terrestrial LHB sites. In addition, the oldest site in the *Database* was formed approximately one and a half billion years after the end of the LHB.

Terrestrial vestiges of the LHB are fundamentally different from the impact features listed in the *Database*.

3 Materials and Methods

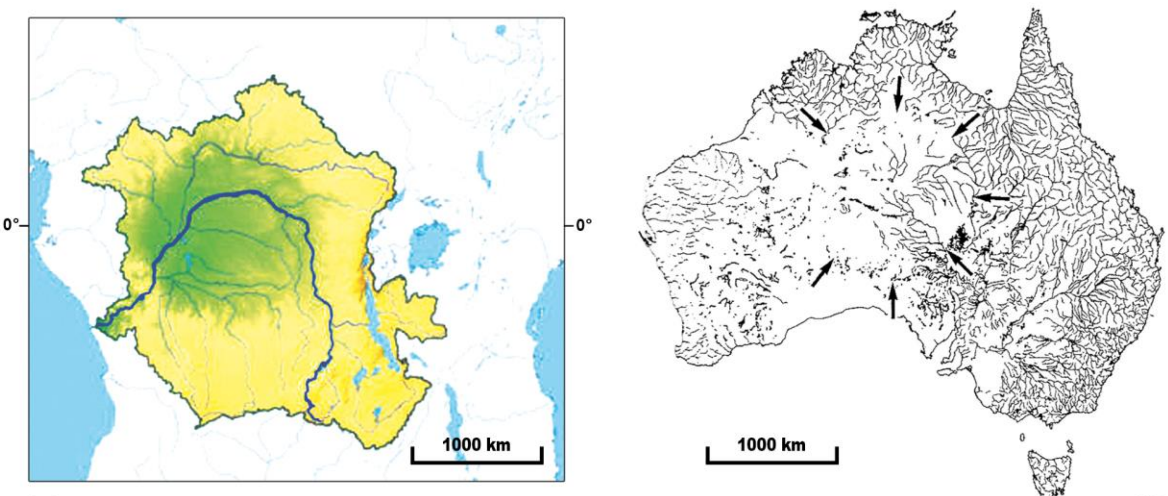
Images of the Earth that show large patterns with circular curvature were collected from sources as varied as satellite imagery, geological maps (old as well as recent), newspaper clippings, flight screens, and snapshots taken at lectures. Such images are *data*, comparable in their imperfections to materials with which scientists in other fields are obliged to work, broadly comparable, for instance, to indistinct photos of animals taken by camera traps or fossils in various states of preservation. In general, LHB patterns are not neatly defined or complete, nor should we expect that they would be, Melosh (1982) referring to “the embarrassing fact that the original rim of very large [lunar] basins such as Orientale cannot be found (or agreed upon)”.

The criteria used in identifying terrestrial LHB impact-sites are similar to the qualitative “no-tech” *observations* that unequivocally signal the bombardment of the Moon.

4 Data with Discussion

4.1 The Congo and Australia: Internal Drainage

A NASA site describes the Congo Basin (Fig. 1a), as “a vast, shallow depression” that “rises to form an almost circular rim of highlands” (NASA-JPL, 2016). The basin has been compared to “the circular lunar maria of impact origin”, with the rocks underlying the basin characterized as possessing “unusual stability and rigidity” (Kochemasov, 1963). A similar pattern (Fig. 1b), with a diameter of approximately 1260 km, was recognized on a continental drainage map of Australia (O’Driscoll & Campbell, 1996).



(a) (b)

Figure 1. Drainage: (a) The watershed of the Congo and Lualaba rivers, indicated with topographic shading. The basin occupies the center of the much larger “Congo Circle”, which extends from near the Atlantic Ocean to the Western Rift Valley (Imagico, http://en.wikipedia.org/wiki/File:CongoLualaba_watershed_topo.png, retrieved 24 March 2020). (b) Central Australian Ring, diameter approximately 1260 km. Base map: Division of National Mapping, Canberra, 1969, on which arrows were added by O'Driscoll & Campbell (1997).

4.2 Wisconsin: Snow and Ice

A circular feature in Wisconsin (Fig. 2) with a diameter of approximately 88 km has been known from before the advent of aerial photography, presumably because the northern half of its perimeter corresponds to the limit of glaciation, with other sections bounded by the Mississippi and other rivers. This scar-pattern went unrecognized on air and satellite photographs until 1977 when recognized by Donna Stetz, a student untroubled by prevailing geological conventions. A search by the Wisconsin Geological and Natural History Survey for features diagnostic of shock metamorphism was not successful. Better-resolution Google Earth images were less informative than newspaper clippings illustrating Stetz’s discovery.

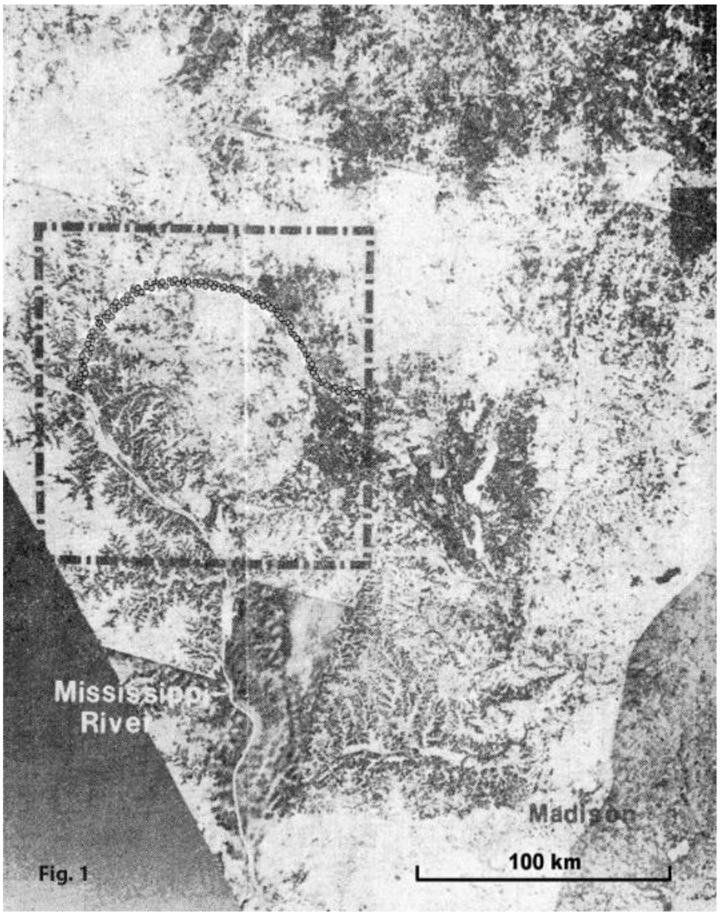


Figure 2. Wisconsin in the snow, late 1977. A string of small circles has been added to indicate the limit of glaciation.

4.3. Mineralization in the Arizona Transition Zone

The thin-crusted Arizona Transition Zone is marked by 19 or more circular features (Saul, 1978); Fig. 3a. Twenty-four economic deposits were registered in the district (Fig. 3b), most of which were polymetallic, with production of Cu, Ag, Au, Mo, V, W, Zn, and Pb (Mardirosian, 1973). Most of the deposits are located within the 9% of the total area covered by the rim-zones of the 19 circles, with all others categorized as “very close” to a rim (Saul, 1978). The deposits include major mines and at least four large porphyry deposits. The blank areas in Fig. 3b are indeed blank, i.e., devoid of known economic mineral occurrences

(Mardirosian, 1973). Many of the mineralized rim-zones are intensely fractured or brecciated, and several deposits are known to have undergone more than one period of mineralization.

Figure 3a is a photograph taken of a relief map with two-fold vertical exaggeration, illuminated at a low angle. Using the same method to detect large circular patterns throughout much of North America, Byler (1983) produced a diameter-distribution plot (Fig. 3c) that showed scaled similarity with the diameter-distribution of impact craters on the Moon and Mars. Byler took this as evidence for a common origin in earliest Precambrian time. He attributed the bend in his data at diameters of ~400 km to the removal of smaller terrestrial scars by erosional processes (Byler, 1983, 1992).

The correlation of mineralization with circular features in the Arizona Transition Zone stands on its own and does not need to be linked to any particular theory.

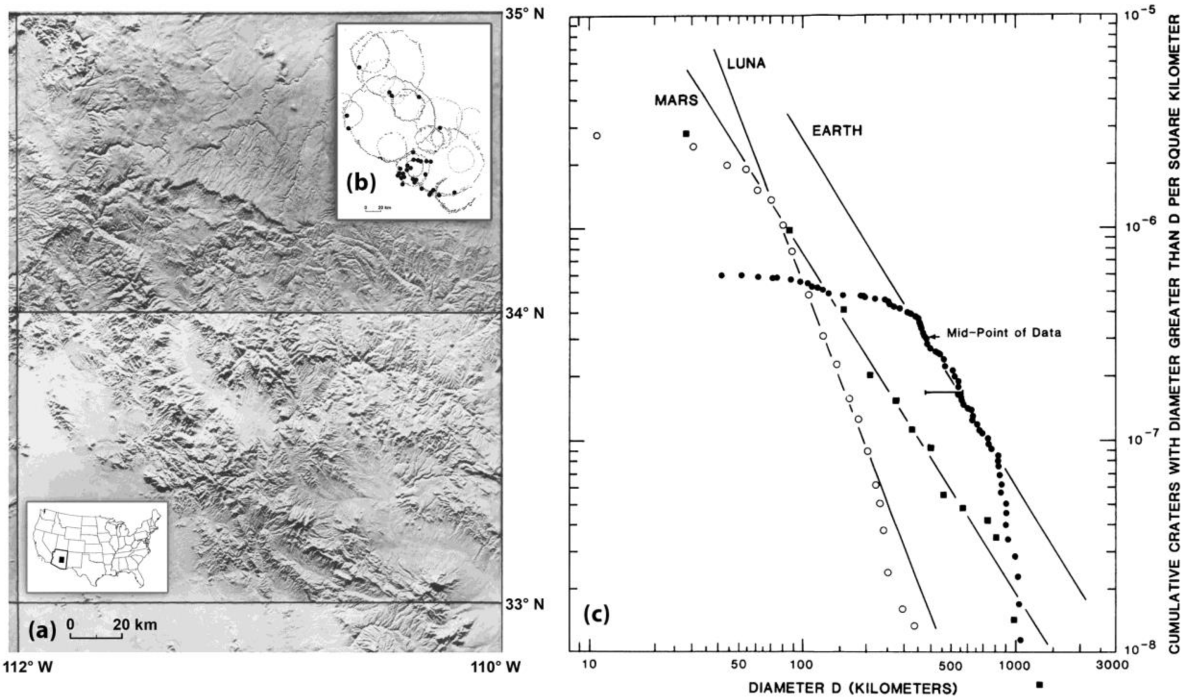


Figure 3. (a) Part of the Arizona Transition Zone of southeast Arizona: image produced by

photographing a relief map with a twofold vertical exaggeration, sprayed white, and illuminated at a low angle. The black dots in the upper inset (b) represent metal mines (Mardirosian, 1973; Saul, 1978). (c) Byler's (1992) plot showing the likelihood the circular patterns he observed in North America were of the same origin as those on the Moon and Mars.

4.4 Continents and Cratons

4.4.1 North America

As recently reconfirmed, established scaling laws “fail to estimate the melt volume” for “giant” impacts (Manske et al., 2018). This failure would be even more severe in estimating the amount of melt produced by large impacts that pierced the thin hot crust of the early Earth (Manske et al., 2018). The disproportionately greater amount of molten material produced by large impacts (Grieve & Cintala, 1995; French, 1998; Melosh, 2000; Ryder et al., 2000; Manske et al., 2018) includes melts produced during long-lived post-impact decompression melting (Jones et al., 2002).

Sufficiently large craters may fill past the point of overflowing which, by one calculation, would occur on today’s Earth in cases where the transient crater (before rebound) had had a diameter of a thousand kilometers or somewhat more (Melosh, 2000). In consequence, terrestrial impacts of sufficient size “may not produce an obvious crater form, as the melt volume … would actually exceed the cavity volume” (Grieve & Cintala, 1992, 1995). See Fig. 4. In times long after a giant impact, (i) solidified crater-fill and (ii) solidified melt-overflow would have appeared much the same, as in Fig. 4, whether viewed from space or as geologically mapped. Figure 5 shows a ~3700-km-diameter circular scar at the heart of the

North American craton.

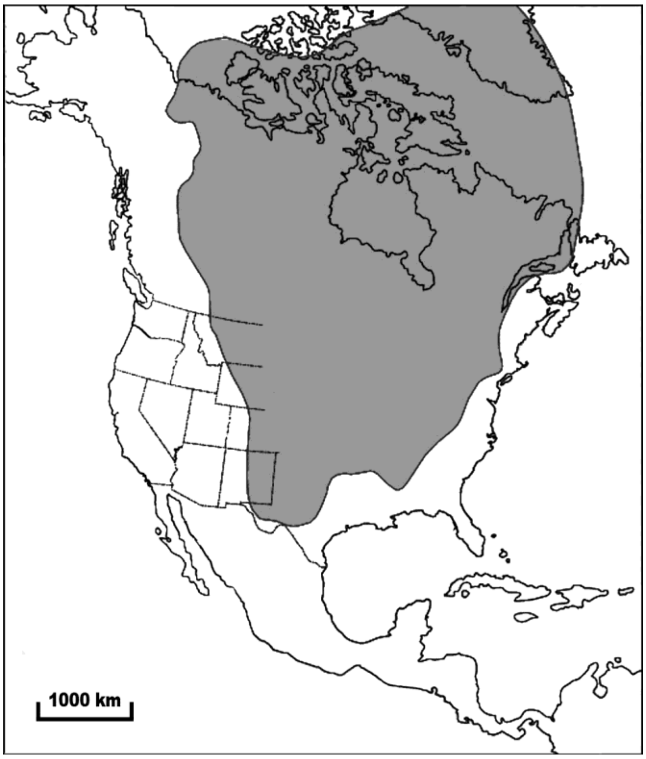


Figure 4. Sketch map showing the approximate present-day extent of cratonic rocks in North America. These are composed of (i) a circular core, for which see Fig. 5, plus (ii) overflow.

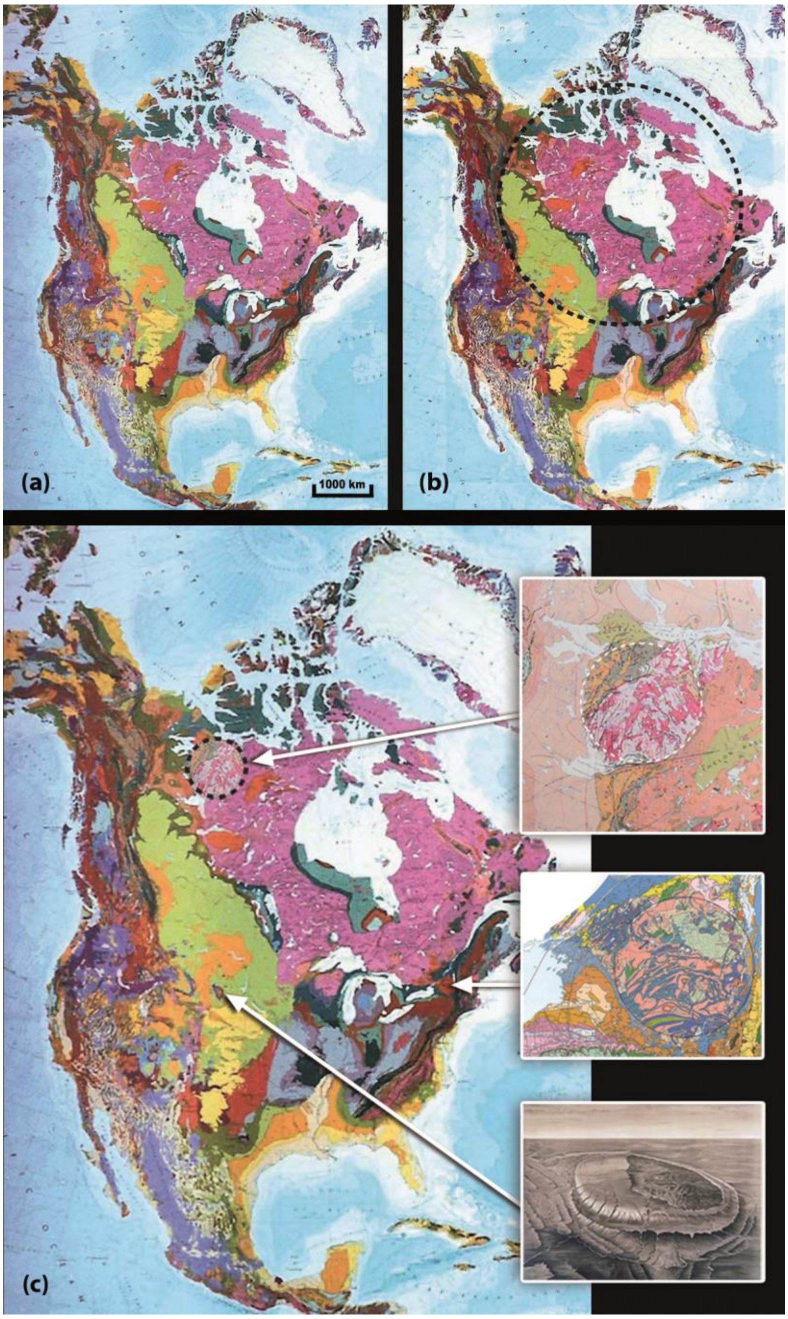


Figure 5. (a) and (b): Geological map of North America, showing the inherent circularity of the craton. The insets in Fig. 5(c), from top to bottom, show a circular feature within the Canadian Shield (a circle within a circle, slightly distorted by the map projection) that hosts the Acasta Gneiss and numerous diamond-bearing kimberlites; the uplifted Adirondack Mountains; and the Black Hills. The Adirondacks and the Black Hills are both situated on the rim zone of the North American craton-circle. Base maps: *Geological World Atlas*,

1:10,000,000, sheets 2 and 3, C.G.M.W.–Unesco (1974); *Tectonic Map, North America*, 1:5,000,000, USGS (1969); *Bedrock Geology of New York*, www.eserc.stonybrook.edu; and *Bird's eye view of the Black Hills to illustrate the Geological Structure* (Newton & Jenney, 1880).

The circular outline of the area within North America (Fig. 5) is the source of the melt-spillover shown in Fig. 4. The circularity of the North American feature would not have become visible until the combination of net erosion from above and net fracture-regeneration from below had allowed fractures along the circumference to reach the Earth's surface.

Materials within the North American craton and other large craton-forming impact-sites remained fluid far longer than at smaller impact sites. Later-arriving (EoArchean) LHB bodies that fell into these great expanses of solidifying melt might have left circular scars – circles within circles (Fig. 5(c), top inset, for one instance) – or they might have *physically* disappeared like raindrops in a puddle. But according to the Nice Model for the dynamic evolution of the solar system, the impacting bodies would have originated at various distances from the Sun. In consequence, they would have been *chemically* variable. Thus, whether they left physical scars or not, the later-arriving impactors would have introduced local variations in the chemistry of the great craton-forming melt-puddles into which they fell. Reheating and re-melting would have subsequently occurred as a consequence of the decay of radioactive isotopes, far more important for the early Earth than now. In two dimensions, the resultant craton would be composed of rock-units of diverse chemical compositions, circular (as in the top inset in Fig. 5(c)) and not, welded together by heat, and subsequently clamped by thermal contraction.

The circular feature shown in Fig. 5(c) hosts both the Acasta Gneiss and a concentration of rich diamond-bearing kimberlites; its diameter is approximately 480 km.

Cratons are coherent and long-lived due to the marked lack of deep fractures in their interiors. Plate collisions barely impinge in their interiors. Instead, collisions produce fold-belts, mountain ranges, and orogens along their perimeters. In North America, parts of the craton-circle are abutted on the southeast by the Appalachian Mountains (formed during the Acadian Orogeny, 375 to 325 million years ago) and on the west by the Canadian Rocky Mountains (formed 70 to 40 million years ago during the Laramide Orogeny).

4.4.2 South America

With no reference to the LHB or to later impacts, Keith Bloomfield, who worked for years as a geologist in Brazil, observed that “when information from drill holes is included, and the younger rocks of the Amazon Basin are ignored, the Guyanan and Brazilian Shields together form a nearly perfect circle” (personal communication, 1980). See Fig. 6. This was independently reported by Burgener (2013) who attributed the circular pattern to a post-LHB impact.

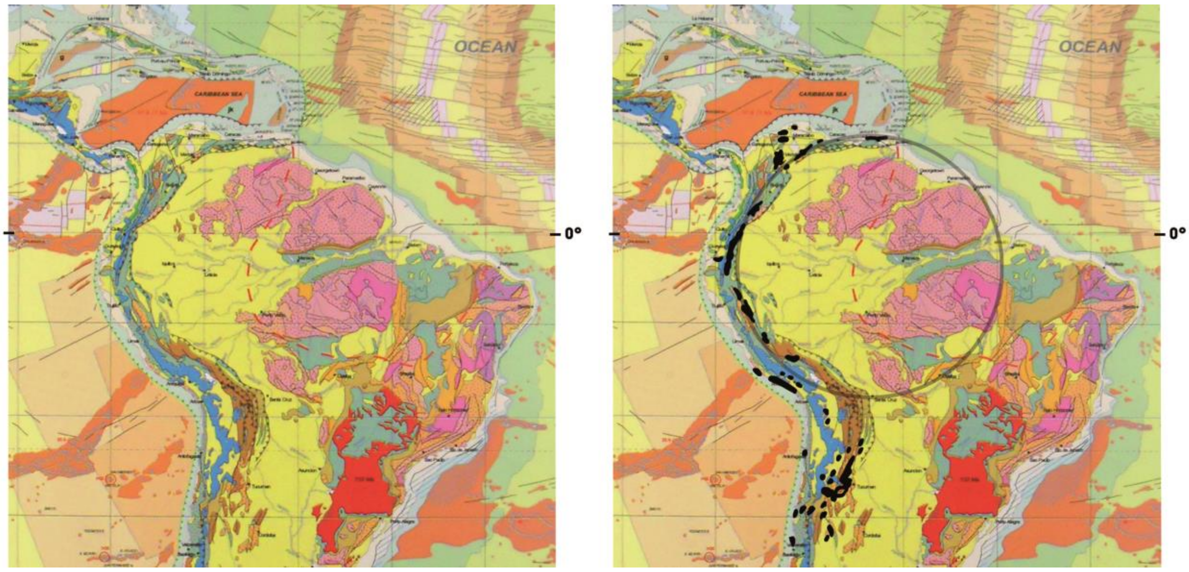


Figure 6. South America with the Guyanan and Brazilian shields shown in violet. Slivers of comparably ancient rocks in the Andes are shown in black, their sizes greatly exaggerated for better visibility. Many of these slivers can be interpreted as fragments of the Guyanan and Brazilian shields that were tectonically uplifted and incorporated in the Andes in the course of the ongoing Andean orogeny (Hoorn et al., 2010). Similarly mapped fragments located to the northwest were uplifted in what appear to have been different circumstances (see Hoorn et al., 2010). Modified from *Seismotectonic Map of the World – Five millennia of earthquakes around the world*, 1:50,000,000, Commission for the Geological Map of the World (2001).

4.4.3 Europe

Much of Europe is also defined by a circle framed by orogenic belts crumpled against its perimeter: the mountains of western Norway (formed during the Caledonian Orogeny 490 to 390 million years ago), the Urals (formed approximately 318 to 252 million years ago, during the Uralian Orogeny), and the Alps–Carpathians–Dinaric Alps–Greek Mountains (formed approximately 55 million to 5 million years ago during the Alpine Orogeny); Fig. 7.

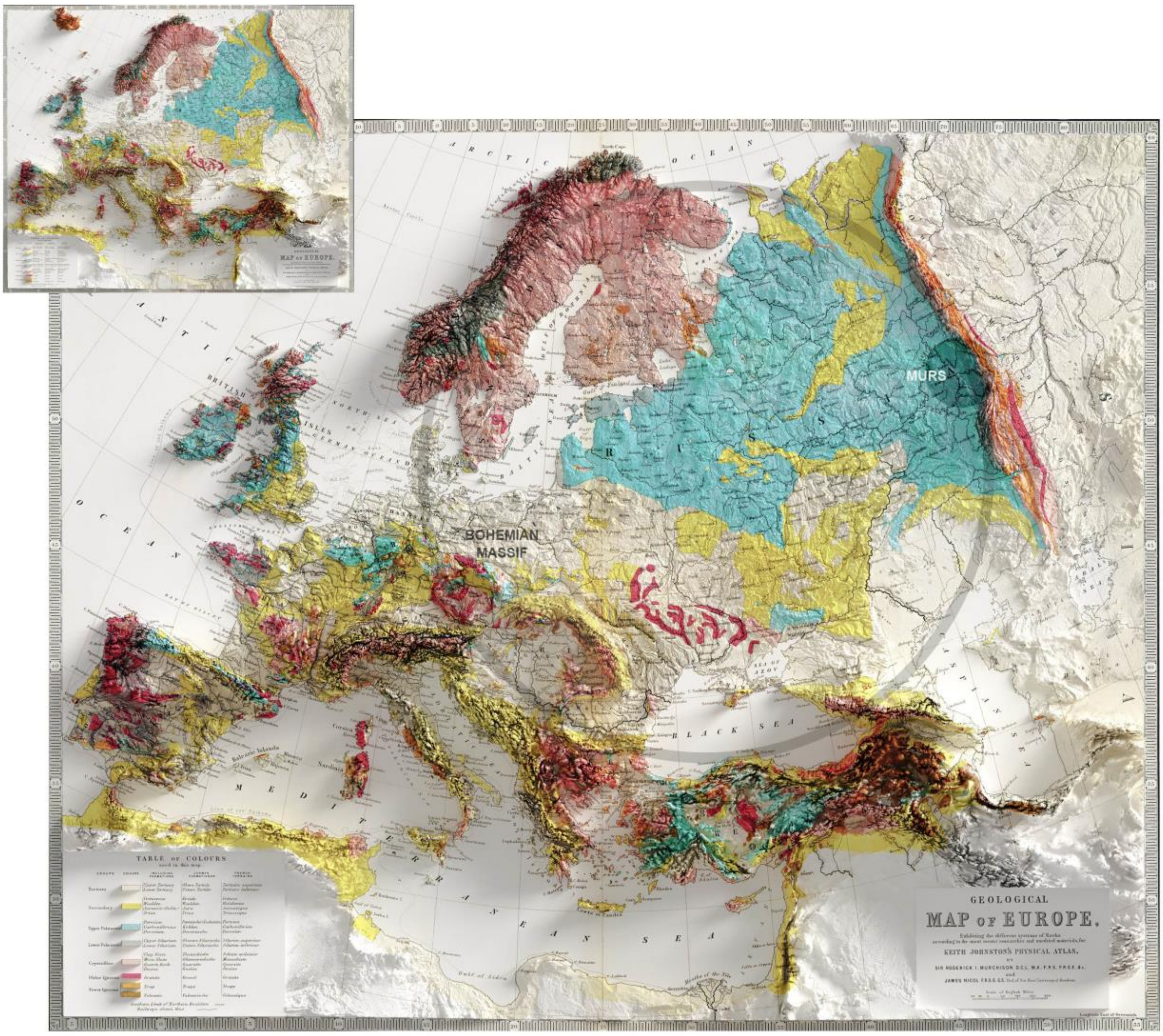


Figure 7. Geological map of Europe showing the positions and shapes of the Middle-Urals Ring Structure (MURS) and of the Bohemian Massif. Satellite imagery led Papagiannis (1989) to argue that “roughly the region called the Bohemian Massif” was a possible impact crater. Turning his argument around, he also reported that the large lunar craters had reminded Galileo “of a region like Bohemia” (Papagiannis (1989), citing Drake (1957) p. 36). Yet the Bohemian site lacks diagnostic shock metamorphic features and is not included in the *Earth Impact Database*.

4.5 Rim Zones, tangents and secants

Despite four billion years of healing and annealing, the rim zones of craton-forming impact-scars would remain fractured and brecciate, and would provide enduring zones of relative weakness. During collisions, rim-zone materials might buckle and fold to produce orogens. In addition, as observed, places along craton rims facilitate the tectonic uplift of coherent rock-units. As proposed here, these coherent rock-units would in particular include plugs of solidified impact-melt, also produced during the LHB, but later than the much larger craton-forming impacts themselves. In North America, two such cases are the uplifted Adirondack Mountains, which itself has a circular core ~160 km in diameter (Fig. 5(c), middle inset), and the uplifted Black Hills, depicted as circular in Newton and Jenney's *Bird's eye view of the Black Hills to illustrate the Geological Structure* (1880); Fig. 5(c), bottom inset. In Europe, Fig. 7, the craton rim-zone is marked by the uplifted ~270-km-diameter Bohemian Massif in the west, and in the east by the partly uplifted >400 km Middle-Urals Ring Structure – MURS (Burba, 1991, 2003), notable for its major commercial deposits of Fe, Mn, Cr, Ni, Cu, Ti, Pb, Au, Pt and transparent colored gemstones (Burba, 2003); Fig. 7. Uplift within cratonic rim-zones appears to be a significant feature of our planet.

According to Burba (1991), the MURS has "a sharp expression in the basement topography". Tangent to the MURS is the ~210-km-diameter Romashkino Dome within which is situated the Romashkino supergiant oilfield. The tangent, along which the two circles "kiss", hosts the elongate Arlan supergiant oilfield (infolded map in Trofimov, 2014); Fig. 8.

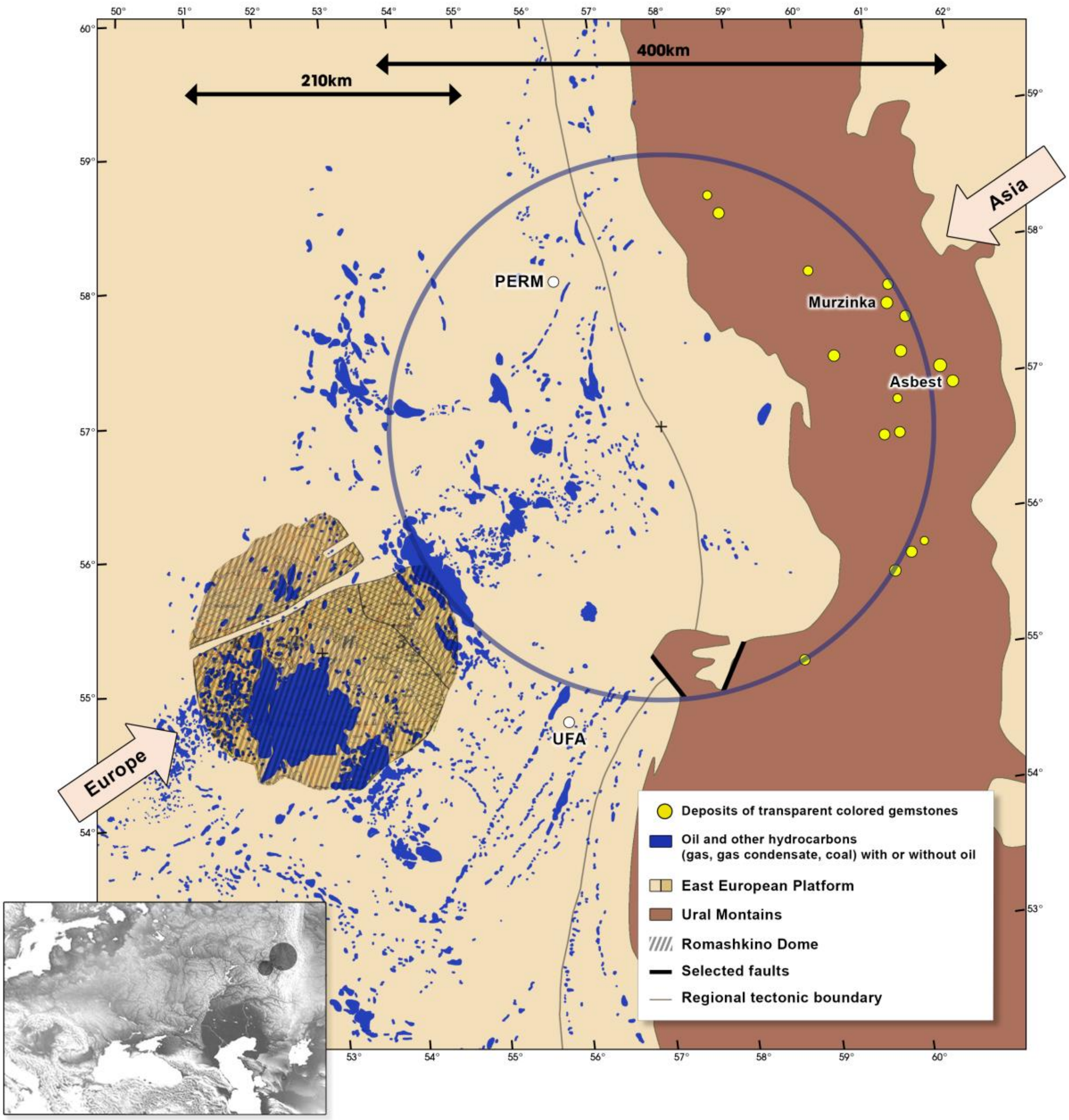


Figure 8. Map showing the Romashkino Dome, the Middle-Urals Ring Structure (MURS), oil and gas fields, occurrences of transparent colored gemstones, part of the Middle Urals, and selected faults. (Some of the gemstone occurrences may be alluvial.) The base map is a 1:2,000,000 oil & gas map of the Volga-Urals region infolded in Trofimov (2014).

In Asia, the arc of the Himalayas forms a quarter-circle that appears to end in the west, blocked by the Pamir Mountains and also perhaps by the Hindu Kush, both of which are uplifted, and both of which have circular cores whose diameters are ~640 km and ~290 km respectively; Fig. 9. In common with the Middle Urals (Figs. 7 and 8), the Pamirs and the Hindu Kush are rich in deposits of transparent colored gemstones, crystallized during the extremely high frictional heating *when and where* one continental plate collided with another (Saul, 2017).

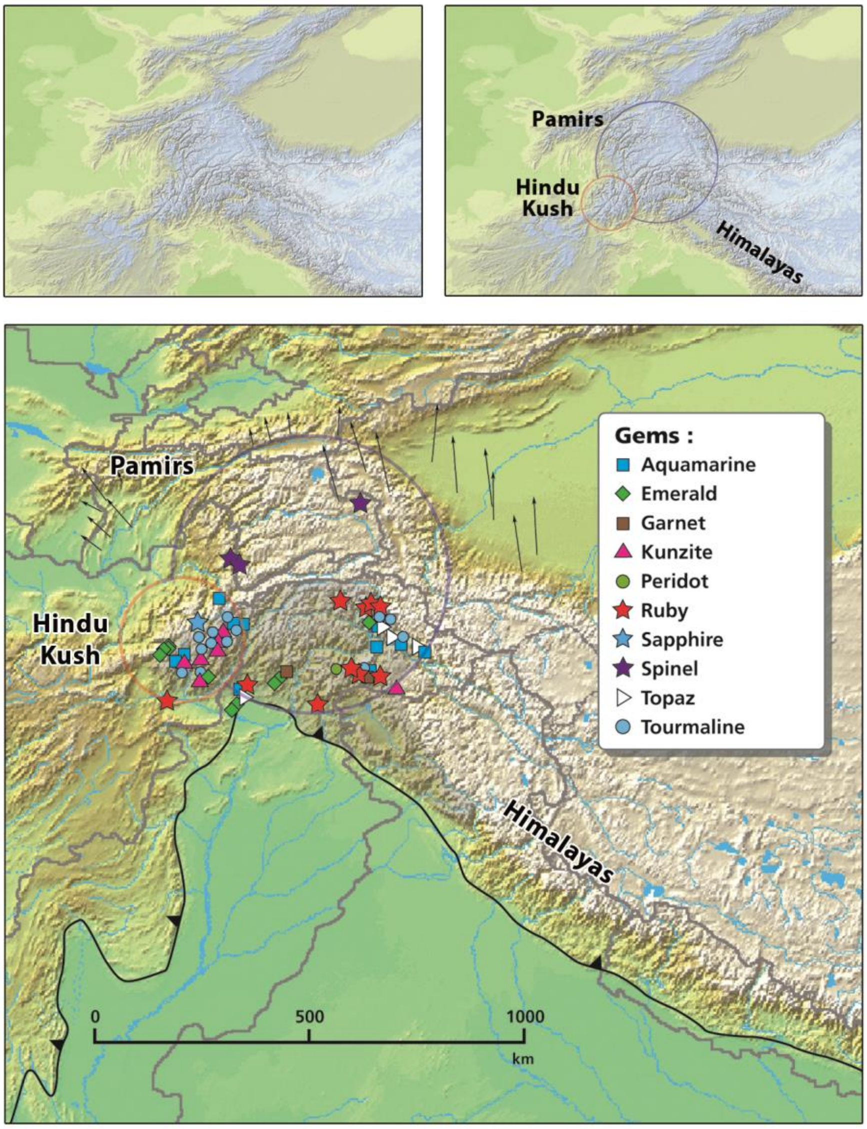


Figure 9. The Pamir Mountains and the Hindu Kush, both of which have circular cores. Both host multiple deposits of transparent colored gemstones formed in conjunction with the

collision of peninsular India with continental Asia (Saul, 2017). GPS velocity field motion vectors relative to fixed Eurasia are from Zubovich et al. (2010). Base map by Geo-Innovations Ltd.

4.6 Asia

A great advance in understanding our planet’s structure might have been achieved c.1896, and again a century later, two occasions when maps were exhibited on which the great circular feature that encompass much of Asia was visible. The older of the two maps was drawn by the geographer T. Ruddiman Johnston for a proposed 84-foot hollow globe to be constructed in Madras (Anon., 1896; Ramaswamy, 2017); Fig. 10(a). The second map was shown in Moscow at the 27th International Geological Congress in August 1984 and captured by a snapshot from the back of the auditorium; Fig. 10(b).

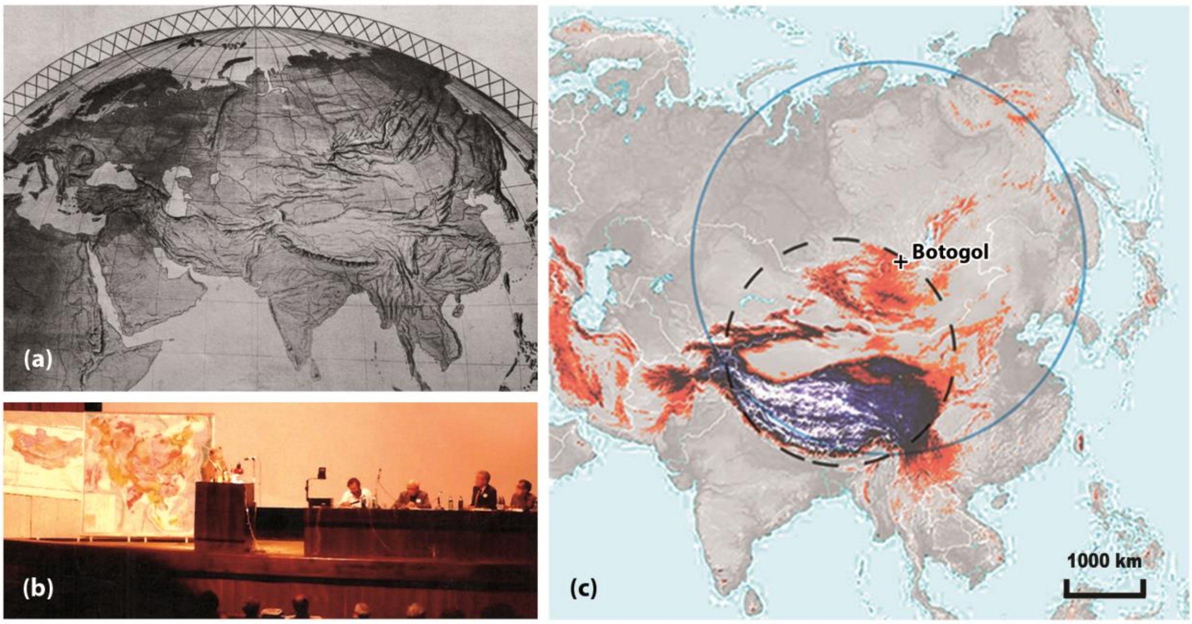


Figure 10. Asian circle. This is the largest recognized terrestrial LHB impact-site. (a) T.

Ruddiman Johnston's proposed 84-foot hollow globe (1 inch = ~8 miles), c.1896 (Anon., 1896, p. 85; Ramaswamy, 2017, p. 86). (b) Unenhanced snapshot taken by the author in a lecture hall at the 27th International Geological Congress, Moscow, August 1984. (c) The Asian and Himalayan circles plotted on a map on which topography is highlighted. The position of the massive Botogol graphite deposit is marked "+". Novaya Zemlya is in a position corresponding to a secondary rim. Note also the change in topography along the SW-NE diameter.

This "Asian Circle" – which is not the same feature as the Himalayan arc – has a diameter of approximately 5350 km, a figure that should be compared to the "approximately 5000 kilometers", twice independently calculated from the lunar cratering record for the diameter of the largest expected terrestrial LHB scar, once by Thomas Gold (personal communication, 1986), and once by Ryder et al. (2000). It is likely that this circle, which encompasses most of Asia, is the largest terrestrial remnant of the LHB.

There are two points where the Asian Circle is intersected by the Himalayan arc (Fig. 10) which, if extended, would form a circle with a diameter of ~3390 km (Bendick & Bilham, 2001). These crossing points, east and west, are places (syntaxes) where the Earth is deeply and doubly weakened (or triply so by the Pamirs in the west; Fig. 9).

Located near the centre of the Asian Circle, and marked "+" in Fig. 10(c), is the historically important Botogol (Batogal, Batagal…) graphite deposit (East Sayan, Buryatia; 52°21'N, 100°46'E). Botogol graphite is uniquely well crystallized (Saul, 2014) and in places contains inclusions of native silicon and native iron, indicative of extreme reducing conditions (Mironov et al., 1998).

4.7 Secondary Rims

In northern Russia, the Asian Circle is manifested by the Polar Urals, with part of a proposed outer secondary rim indicated by Novaya Zemlya (Fig. 10). Figure 11, which shows this region in more detail, includes part of the European Circle, as indicated by the ridges on the Kanin Peninsula, and with Pai-Khoi in the position of a secondary rim. Elsewhere, the Italian peninsular furnishes sections of an outer rim of the European scar, with the Adriatic Sea as an intervening moat (Fig. 7).

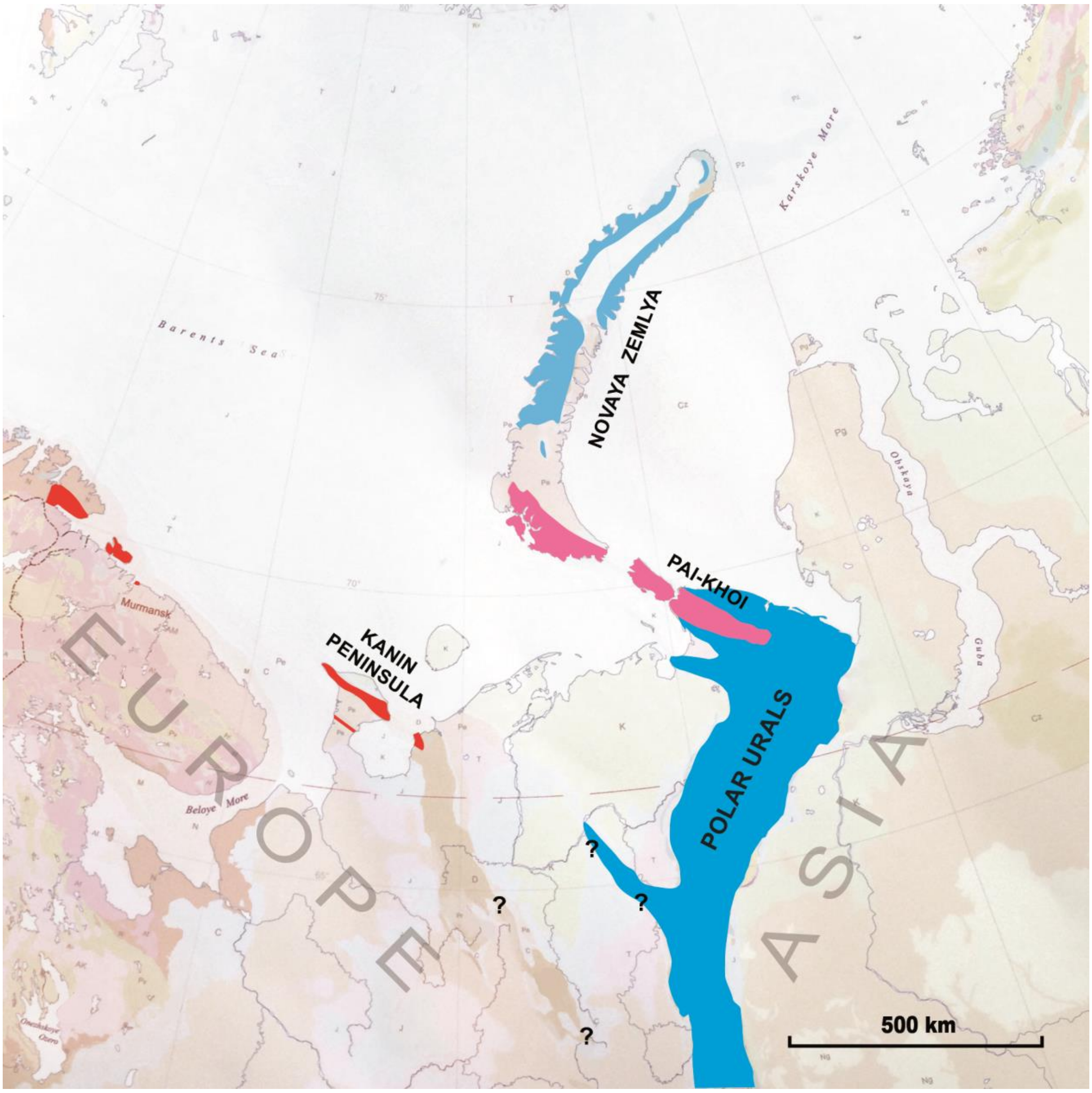


Figure 11. Map showing structures and rock formations in the northern region where the Asian and European circles are not in contact with one another as they are farther south along the Middle Urals. Red and pink indicate sections of the primary and secondary rims of the European scar-circle with two shades of blue indicating parts of the primary and secondary rims of the Asian circle. Base map: Stereographic North Pole Projection, Standard Parallel 70°N, Coordinate System WGS 1984, 1:5,000,000, NGU, Geological Survey of Norway.

5 “Drift units” and rebalancing the Earth’s spin-axis

The European and Asian scars abut, producing a geographical relationship (Figs. 7, 8, 10, 11) that does not date to the LHB. Instead, their present positions are the result of drift and collision during the Uralian Orogeny (~318–252 Ma) during which the two rim-zones coalesced in the straight north-south section of the Middle Urals.

Another feature of our planet that could not have been in existence since the LHB is the alignment along the Earth’s equator (Saul, 2014) that is formed by the South American circle (Fig. 6); the Congo Basin (Fig. 1a); and the “nearly circular” (NASA-JPL, 2016) Lake Victoria basin, which itself cuts into a larger circular scar to its southeast (Sautter et al., 2022), and incorporates smaller-diameter mineralized scars in Kenya and Tanzania (Saul, 2022). This equatorial alignment may be a consequence of gyroscopic rebalancing of the Earth’s spin-axis (by moving dense materials toward the Equator), an effect that minimizes wobble (Yakubchuk, 2008) and may be the prime driving force for drift (Gold, 1955; Yakubchuk, 2008; Saul, 2014).

6 Cratons are Not Forever

Heat trapped below cratons at times when they straddle the Equator causes doming that may lead to deep large-scale fracturing of the cratons themselves. Such fractures may include the valley of the Amazon, the break in topography that extends from the Sea of Okhotsk to the Pamirs and beyond, and the Teisseyre–Tornquist zone in Europe.

7 Deep Subduction

LHB impacts, whatever their diameters, produced crater walls that initially intersected the Earth's surface at steep, near vertical angles. Erosion subsequently exposed the walls at lower levels. At the newly exposed levels, the ancient impact-fractures intersected the Earth's surface at various less-steep angles. At some stage during the erosional process, some of the extremely numerous arcuate crater-wall fracture-zones would have *necessarily* dipped into the Earth at angles geometrically suitable for deep subduction; see Fig. 12.

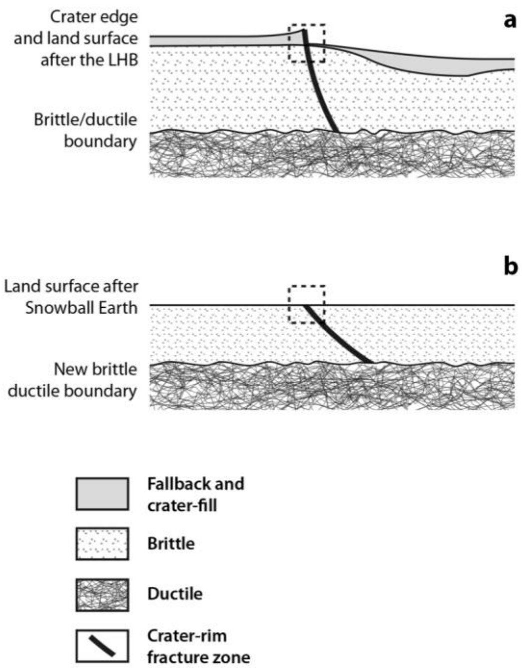


Figure 12. Schematic cross section of the rim zone of a large LHB impact crater. In (a), the square indicates the near-vertical angle at which the crater intersected the Earth shortly after impact ~3800 Ma. In (b), the square indicates the gentle angle at which the crater intersected the Earth after severe glacial scouring, ~640 Ma. (The angle of descent may eventually steepen as a consequence of slab rollback, but this is a later phenomenon, unrelated to the

initiation of subduction.) The diagrams have no scale because each instance depends on the diameter of the scar, the depth of local glacial scouring, and the unknown thickness of the Earth's crust at ~3800 Ma and at ~640 Ma. From Saul (2022) using a base diagram for the cross section from Osinski & Pierazzo, eds. (2013) figure 1.7.

Erosion has been most extreme following Snowball Earth episodes, in particular after c.750 Ma, during the “protracted period of widespread continental denudation” (Peters & Gaines, 2012) that produced the Great Unconformity (and greatly troubled Darwin). Average global erosion during this episode is estimated to have been 3 to 5 vertical kilometers(!) (Keller et al., 2018). This suggests a causal link between Snowball Earth episodes and the initiation of subduction, or of deep modern-style subduction.

A second requirement for the initiation of subduction is the existence of relatively dense material that overlies material that is less dense, a condition fulfilled by the long-term cooling, hence densification, of the lithosphere (Davies, 1992; Stern, 2007; Condie et al., 2016).

A likely third requirement is lubrication furnished by water and soft wet sediment in the down-going slab (Sobolev & Brown, 2019).

8 Subduction Arcs and Mid-oceanic Ridges

The entire Earth was affected by the LHB, necessarily so, but deep scars in areas of oceanic crust are now covered by young basalt, much it unfractured. Subduction arcs develop where and when the basalt covering has been sufficiently fractured *from below*.

The mid-oceanic ridge system is composed of fractures along local paths of least resistance, which, as proposed here, were furnished by LHB rim-sectors and tangents, and by jumps from one to another.

9 Concording views

Arguing from the evidence of “carbonado, ballas and other impact-diamond varieties (*sic*) in placers” in “zones of erosion of early Precambrian rocks”, V. P. Polosukhin (1981) concluded that “the “indestructibility” and active evolution, over a period of over four billion years, of faults formed by explosion-impact processes in structural zones of very different ages and types, and commonly penetrating into the mantle, raise questions about present tectonic concepts, particularly that of Recent global tectonics”. Polosukhin’s thoughts were echoed at the Snowbird Conference seven years later in U. Marvin’s suggestion that “new research programs may prove even more subversive to classical geology if causal links can be found between impacts and plate tectonics” (Marvin, 1988).

10 Concluding remark

Our vision has greatly improved since 1788 when James Hutton could find “no vestige of a beginning". Theory and observation now indicate that the entire Earth was, and remains, affected by the LHB from the surface down to the brittle-ductile boundary. These scars provide a damaged canvass on which later geology has been painted. Plate tectonics is a consequence of the bombardment. Effects of the LHB should be considered in all regional geological studies. This work provides a first step toward establishing a typology of vestigial LHB impact features.

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