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and subject to tropical weathering processes [14], we find that the amount of erosion and infill needed to explain its current topographic expression is between 0.06 mm/yr (infill) to 0.13 mm/year (erosion of rim and near-rim ejecta). Of course, the degree of observed erosion at both the ZIF and the BIC assumes that the pre-erosional morphology of these impact structures can be reconstructed using established dimensional scaling relationships, such as those summarized by Ivanov [4] and Melosh 15]. Table 1 summarizes the available observational data on the dimensions of the two structures and all our estimates of parameters that can be derived on the basis of high-resolution topographic data. Model values are listed for comparison on the basis of simple scaling laws [4,5]. A model for terrestrial erosion as a function of geologic environment, rock type, and local to regional relief (ΔZ) is used to compute the expected erosion/infill rates for the regions associated with the ZIF and the BIC [3]. These model erosion rates are integrated throughout geologic time, and as such are upper bounds on the rates that would be operational over a time period as short as ~1 Ma. Thus, the 0.019 mm/yr that would be predicted for the ZIF does not take into account that this region of the central Kazakhstan semidesert has apparently experienced much lower erosion during the Quaternary [2]. Indeed, the geomorphic record of erosion in the ZIF general region has been dominated by eolian redistribution and deposition of loess, with probable maximum accumulation levels in the range of 20–70 m within the interior cavity of the ZIF, based upon unpublished drilling results described by Masaitis and Boiko 12]. Thus, our impression is that it is impossible to reconcile typical erosion rates at the ZIF (in the range of 0.019 to 0.080 mm/yr) with what would be predicted (0.19 to 0.38 mm/yr) given erosion of a typical 10- to 15-km-diameter complex impact crater. While the observed erosion at the BIC appears to be within a factor of 2 of what would be predicted using terrestrial erosion models and pre-erosional crater dimension scaling laws, that for the ZIF disagrees by up to a factor of 20. We believe that the pre-erosional morphology of the initial ZIF cannot be approximated using traditional complex crater scaling relationships, and that the ZIF represents a new class of complex crater form on the Earth that may help to explain the current deficiency of observed craters in the 8- to 16-km-diameter range. Furthermore, we believe that it is possible that there are perhaps tens of ZIF-style complex craters preserved, albeit poorly, within the sedimentary platforms of the continents [13]. Thus, it is important to develop methods for reconstructing ZIF-style cratering events, and for understanding why such events produce crater forms with anomalously mundane topographic expressions [11,12].

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ASTEROIDS AND ARCHAEAN CRUSTAL EVOLUTION: TESTS OF POSSIBLE GENETIC LINKS BETWEEN MAJOR MANTLE/CRUST MELTING EVENTS AND CLUSTERED EXTRATERRESTRIAL BOMBARDMENTS.

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Since the oldest intact terrestrial rocks of ca. 4.0 Ga and oldest zircon xenocrysts of ca. 4.3 Ga measured to date overlap with the lunar late heavy bombardment, the early Precambrian record requires close reexamination vis a vis the effects of megaimpacts. This includes modeling of early megaimpact events [1], examination of the nature and origin of early volcanic activity [2–4], examination of Precambrian structures [5,6], and close examination of the isotopic age evidence [7]. The identification of microtektite-bearing horizons containing spinels of chondritic chemistry and Ir anomalies in 3.5–3.4-Ga greenstone belts [8,9] provides the first direct evidence for large-scale Archaean impacts. The Archaean crustal record contains evidence for several major greenstone-granite-forming episodes where deep upwelling and adiabatic fusion of the mantle was accompanied by contemporaneous crustal anatexis. Isotopic age studies suggest evidence for principal age clusters about 3.5, 3.0, and 2.7 (±0.8) Ga, relics of a ca. 3.8-Ga event, and several less well defined episodes. These peak events were accompanied and followed by protracted thermal fluctuations in intracrustal high-grade metamorphic zones. Interpretations of these events in terms of internal dynamics of the Earth are difficult to reconcile with the thermal behaviour of silicate rheologies in a continuously convecting mantle regime. A triggering of these episodes by mantle rebound response to intermittent extraterrestrial asteroid impacts is supported by (1) identification of major Archaean impacts from microtektite and distal ejecta horizons marked by Ir anomalies; (2) geochemical and experimental evidence for mantle upwelling—possibly from levels as deep as the transition zone; and (3) catastrophic adiabatic melting required to generate peridotitic komatiites. Episodic differentiation/accretion growth of sial conse-

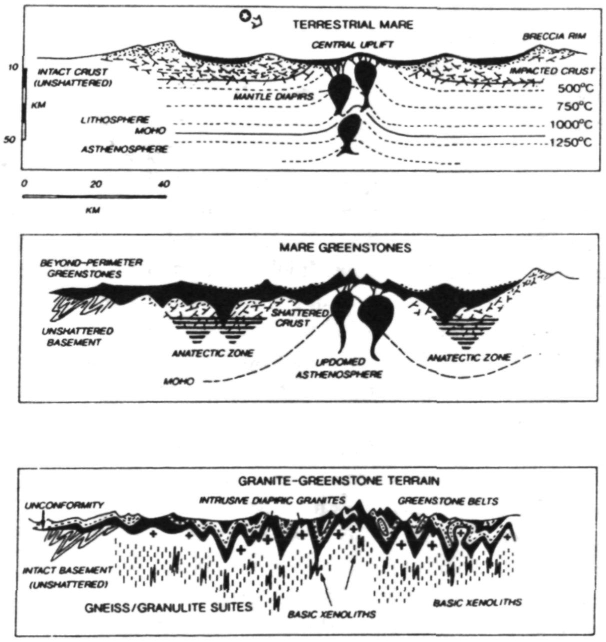

Fig. 1. Schematic model portraying the concept of evolution from terrestrial impact basins to greenstone/granite terranes.

quent on these events is capable of resolving the volume problem that arises from comparisons between modern continental crust and the estimated sial produced by continuous two-stage mantle melting processes. The volume problem is exacerbated by projected high accretion rates under high Archaean geotherms. In accord with the model portrayed in Fig. 1, it is suggested that impact shock effects have been largely obscured by (1) outpouring of voluminous basic/ultrabasic lavas, inundating shock-deformed crust and extending beyond the perimeters of impact excavated basins; (2) gravity subsidence and downfaulting of terrestrial maria, accounting for the burial and anatexis of subgreenstone basement; and (3) extensive shearing and recrystallization at elevated temperatures of impact structures, breccias, and mineral deformation features beneath impact-excavated basins, relics of which may be retained in structural windows in high-grade metamorphic terranes. Isostatic subsidence and anatexis of thick maria-type piles and underlying impacted crust resulted in formation of intracrustal comagmatic plutonic and volcanic suites within periods in the order of 15–30 × 10^6 yr, limited by postimpact mantle convection cooling. Repeated posttectonic thermal/magmatic fluctuations reflect existence of long-term anomalous mantle regions beneath excavated impact basins, and possibly thermal perturbations related to younger distal impacts. The broad age zonation of some Archaean terranes suggests lateral accretion of the maria piles in a convection-driven plate tectonic regime.

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THE ACRAMAN IMPACT AND ITS WIDESPREAD EJECTA, SOUTH AUSTRALIA.

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Discovery of a widespread horizon of shock-deformed volcaniclastic ejecta preserved in Late Proterozoic (~600 Ma) shales in South Australia [2–4,7] and its probable link to the Acraman impact structure in the Middle Proterozoic Gawler Range Volcanics [2,8,9] provide a rare opportunity to study the effects of a major terrestrial impact, including the sedimentology and distribution of an ejecta blanket and its precious-metal signature.

The ejecta horizon occurs in the Bunyeroo Formation at many localities within the Adelaide Geosyncline [2,3], including the Wearing Hills, which are ~350 km northeast of the Acraman impact site. Following a search at the same stratigraphic level in other basins in South Australia, the ejecta has been located within the Lower Rodda beds of the Officer Basin, extending the limits of the ejecta to ~470 km northwest of the Acraman impact structure [4,7]. The ejecta is therefore widely dispersed, and provides an important chronostratigraphic marker enabling precise correlation of Late Proterozoic sequences in southern Australia.

The ~600-Ma Bunyeroo Formation consists of maroon and green shales, with minor concretionary carbonates, deposited in an outer marine-shelf setting. The ejecta horizon comprises mainly angular clasts of acid volcanics ranging from boulder (up to 30 cm diameter) to fine sand size. All large fragments and most sand-grade material were derived from a pink to red porphyritic volcanic rock like that at the Acraman impact site. The ejecta sequence varies in thickness from 0 to 40 cm, and is commonly (from base upward) breccia, sandy mudstone, and graded sand. Such a sequence probably represents the primary ejecta fallout since it (1) is very widespread, (2) displays virtually perfect sorting and normal grading, resulting from its settling through a marine water column, and (3) invariably contains a sandy mudstone layer that directly overlies the basal breccia. Clast size analysis of the primary fallout sequence indicates that two distinct grain size populations are present (gravel and sand sized). These populations may be products of sorting by transport through the atmosphere or fragmentation processes during impact or subsequent transport.

Mass flow and storm reworking processes have been commonly superimposed on, and in places obliterated this primary sequence. To account for various sedimentological features, the following sequence of events probably took place: (1) Initial impact occurs, debris is ejected into the atmosphere, and a massive seismic event takes place with resulting disruption and slumping of muds in adjacent marine basins. (2) Ejecta entered the water column, with gravel-sized material deposited first. (3) Deposition of suspended host muds, together with continued settling of coarse sand, produced the sandy mudstone. (4) Continued hydrodynamic settling of sand-sized material produced the graded sand unit. This occurred several hours after ejecta entered the water column, assuming a 200-m water depth. Storm waves created during massive atmospheric disruption reached the depositional site during latter stages of sand deposition and resulted in hummocky and trough cross-stratification.

Evidence supporting an impact origin for the horizon includes the abundance of shattered mineral grains, the presence of multiple sets of shock lamellae in quartz grains, the presence of small shatter cones on large clasts, the local abundance of altered, tektitelike spherules [6], and anomalous Ir and other PGE values [3]. The correlation of the Bunyeroo ejecta with the Acraman impact structure is further supported by U-Pb ages obtained from severely shocked, euhedral zircons within the ejecta [1]; the dominant age of 1575 ± 11 Ma for the ejecta is consistent with derivation from the Gawler Range Volcanics, which has a U-Pb zircon age of 1592 ± 3 Ma. The geographic distribution of the ejecta and the lateral variation of clast size within the horizon also are consistent with the Acraman impact site as the source.

The Bunyeroo ejecta is enveloped in green shales that are several centimeters thick [2]. These shales and the sandy layers of the ejecta horizon are enriched in Cu carbonates, barites, and Fe oxides, minerals that are widespread in sediments of the Adelaide Geosyncline. Geochemical profiles of the ejecta horizon indicate anomalously high Ir, Au, Pt, Pd, Ru, and Cr relative to the host shales of the Bunyeroo Formation (Ir up to 2.0 ppb, Pt up to 270 ppb). Iridium enrichment up to 100 times the background value for the host shales has been recorded. As Ir values for the volcanic rocks that crop out at the Acraman impact site are <0.005 ppb, the high values for Ir and for other PGEs and Cr in the ejecta horizon strongly suggest derivation from the impactor itself. The marked enrichment in Ir in the Bunyeroo ejecta is similar to that in sediments at the Cretaceous-