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Did the Indo-Asian collision alone create theTibetan plateau?: Reply

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Argument supporting explosive igneous activity for the origin of “cryptoexplosion” structures in the midcontinent, United States: Comments and Reply

COMMENT

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In the Rampino and Volk (1996) study of the eight structures in the central U.S. chain, we reviewed all previous work and concluded that the ages of all are very poorly constrained, based as they are on perfunctory geologic mapping and crude radiometric dating (mostly K/Ar and Rb/Sr) of uncertain materials; most were published more than 30 years ago. This early work was done before impact was a respectable alternative to endogenous processes, and thus prior to the many studies that have determined the diagnostic characteristics of impact-induced deformation, impact breccias, impact melts, and pseudotachylites (e.g., French, 1990).

We also noted that shock features unique to hypervelocity impact (shocked quartz and shatter cones) were known from Decaturville and Crooked Creek (e.g., Short and Bunch, 1968; Offield and Pohn, 1977), but careful searches for such features have never been attempted for the other six structures. We did not mean to imply that other features (e.g., shattered quartz grains, breccia dikes) found at these structures were *diagnostic* evidence of impact, only that they were suggestive. Detailed mapping of the structures and breccia distribution, a search for diagnostic shock features, and reliable radiometric dating would be useful. Luczaj (1998), however, presented no new data, and reviewed the same largely pre-1970s literature that we used in the Rampino and Volk (1996) paper.

Luczaj referenced French (1990) to imply that a controversy still exists with regard to the process that produces “cryptoexplosion” structures. The reality is just the opposite. To quote French’s conclusion, “During the last 25 years of this debate, numerous studies have reinforced the view that shock-metamorphic features uniquely indicate shock pressures of from about 5 to >50 GPa (50 to 500 kbar); no generally accepted shock-metamorphic features have been found in unquestionable volcanic structures; and no internal process has been demonstrated to produce the required shock pressures. This history therefore supports an impact origin for . . . cryptoexplosion structures.” Experimental studies have shown that shocked quartz showing various planar deformation features requires at least 5 GPa (more commonly >20 GPa) (Grieve et al., 1996), and shatter cones >4.75 GPa (Schneider and Wagner, 1976). Gibson and Spray (1998) have shown that some shatter cone surfaces display evidence of shock-induced melting and vaporization, indicating localized shock pressures in excess of 60 GPa.

These shock pressures contrast markedly with the conditions during volcanism or “cryptoexplosion,” where the main control on the maximum overpressures is the tensile strength of the rock surrounding the magma chamber-conduit system (de Silva et al., 1990). This limits maximum explosion pressures to less than 0.05 Gpa (0.5 kbar), orders of magnitude less than the experimentally determined pressures required to form shocked quartz and shatter cones.

Luczaj (1998) argued that if the structures are shown to be of various ages, then the impact chain theory is ruled out and *none* of these structures can be impact-related; therefore the characteristic features of shatter cones and shocked quartz (as found at Decaturville and Crooked Creek) can be produced by internal processes. The situation instead is simply this: Crooked Creek and Decaturville are unequivocally known to be impact structures, on the basis of shock criteria. If it turns out that the other structures were formed at different times (and Luczaj provided no new absolute dating to support this conclusion), then some other mechanism besides an impactor string must be found to explain why the structures occur in a straight line. If any of the other six structures are non–impact-related in origin, then there are several possibilities, including localization of stresses by the two known craters, tectonic effects of impacts (including igneous intrusions that might be associated with impact deformation or impact-induced faulting), and of course possible coincidences. If they are all impact structures, but really of different ages, then the apparent alignment could be a result of an unlikely coincidence, a repetitive capture process, or some still unknown mechanism.

Some of Luczaj’s (1998) interpretations of age constraints are not supported, in my view, even by the poorly known geology. For example, the Decaturville structure was first dated within narrow limits as latest Cambrian to early Ordovician by Bucher (1936), on the basis of supposed constraints in the internal stratigraphy, and then revised to post-Silurian when Silurian blocks were discovered within the breccias (Snyder and Gerdemann, 1965). Because undeformed Pennsylvanian cover rocks are found in the vicinity, the event can most likely be bracketed between the Silurian and Pennsylvanian, not (as Luczaj concluded) younger than Pennsylvanian (for an impact origin) or younger than Silurian (for a volcanic origin), with no lower age limit given in either case.

Luczaj (1998) also suggested that origin of a 700-km-long crater line through breakup of a parent object by terrestrial or lunar tidal forces or from bodies in orbit around the earth is unlikely. However, the recent discovery of a 4500-km-long row of Late Triassic impact craters (Spray et al., 1998), has led to a reconsideration of the probability of asteroid fragmentation and capture into Earth orbit through aerobraking in the upper atmosphere.

The published age determinations, geologic mapping, and search for shock effects are still insufficient to rule out the contemporaneous impact or impact-related origin of all eight structures (Rampino, 1997). In any case, whatever the outcome of future studies, the Decaturville and Crooked Creek structures clearly contain shock features unequivocally linked to the enormous pressures created only by hypervelocity impact; Luczaj’s (1998) arguments provide no reason to question shatter cones or shocked minerals as clear indicators of impact. On the other hand, numerous studies argue against “cryptoexplosion” as a real phenomenon capable of producing the kinds of features seen in hypervelocity impact structures.

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COMMENT

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The juxtaposition of eight structural and/or igneous features along a lineament straddling the 38°N parallel in the midcontinent United States, including the Decaturville and Crooked Creek structures associated with shatter cones and penetrative deformation lamellae (PDFs) in quartz, was interpreted by Rampino and Volk (1996) and Rampino (1997) in terms of impact by a string of bolides. By contrast, Luczaj (1998) viewed these features as the product of tectonically controlled explosive igneous activity, proceeding to suggest that the shock metamorphic features of the Decaturville and Crooked Creek structures may be genetically related to these igneous events—which casts doubt on the diagnostic criteria used for the identification of extraterrestrial impacts (French and Short, 1968; Grieve and Pilkington, 1996). However, reexamination of the stratigraphic relationships of these features suggests that the interpreted ages are at best circumstantial. The data indicate that older age limits of the Decaturville and Crooked Creek structures are broadly contemporaneous with the oldest igneous events along the lineament, which lends itself to an interpretation in terms of an impact-triggered deep crustal fault zone that formed the loci for repeated younger igneous activity during the Paleozoic and part of the Mesozoic. I suggest here that, pending isotopic age studies, no conclusions can be drawn from the relationships along the 38°N lineament with regard to the origin of the shock metamorphic features of the Decaturville and Crooked Creek structures.

Four alternative views can be advanced regarding the origin of the structural and/or igneous features along the 38°N lineament: (1) Selective preservation and exposure of igneous units throughout the region, resulting in a sampling bias and an apparent rather than real alignment of unrelated features; (2) impact by a bolide string, comparable to the SL9 impacts on Jupiter and to crater strings on Mars, as suggested by Rampino and Volk (1996) and Rampino (1997); (3) structurally controlled mafic and ultramafic igneous activity juxtaposed with fault intersections of the lineament; (4) formation of a deep crustal fault zone by multiple impacts, accompanied and followed by repeated long-term reactivation and intrusion of mafic and ultramafic magma.

The occurrence of shock metamorphic features and igneous units is exclusive; of the eight aligned structures, two are associated with shatter cones and PDFs (Decaturville, Crooked Creek) and no igneous rocks, whereas the other six are associated with igneous units but display no shock metamorphic features (Rose Dome, Weaubleau, Hazel Green, Furnace Creek. Avon, and Hicks Dome).

Unless complete data sets for the regional distribution of structural and igneous features throughout the U.S. midcontinent in depth and in unexposed areas are available, possibility 1 cannot be discounted. However, in this Comment, I tentatively assume exclusive linear loci of structural and igneous features in the region.

As correctly pointed out by Luczaj (1998), the difference in ages between the structural and igneous features militates against an origin related to simultaneous effects by impacts (model 2). The suggested time for the igneous activity ranges from Cambrian to Cretaceous, including (1) Rose Dome—post-Pennsylvanian, pre-Cretaceous; (2) Weaubleau—post–Early Mississipian, pre-Pennsylvanian; (3) Hazel Green—pre-Ordovician; (4) Furnace Creek volcanism—Cambrian; (5) Avon—Devonian; (6) Hicks Dome—Permian. According to Luczaj (1998) some of these igneous events predate the Decaturville and Crooked Creek structures, in which case accidental superposition of two impact structures on the linear loci of older magmatic-structural domes is considered unlikely.

Examination of the age limits placed by Luczaj (1998; Fig. 2) on the structures and igneous units associated with the 38°N lineament suggests that the evidence is at best circumstantial and amenable to different interpretations.

Of the two structures associated with shock metamorphic features, the older age limit for the Crooked Creek structure is defined by the deformed Lower Ordovician sediments. The older age limit for the Decaturville structure, however, is less clear. Luczaj (1998, p. 296) based his argument for a post-Pennsylvanian age of this structure on the work of Offield and Pohn (1977), who suggested that “the structure may be as young as post-Pennsylvanian because, although Pennsylvanian rocks are present in the surrounding areas, none have been found in the structure, as would be expected if it was involved in the deformation or if rocks were deposited in topographic lows after the structure formed.” However, this does not take into account that central uplifts of impact structures may form long-surviving positive morphological features where they consist of resistant lithological units, and that the entire impact aureole may in some instances rise further due to long-term isostatic uplift of the low-density fractured and brecciated crater and subcrater lens. Such positive morphological features may restrict sedimentation to outer zones of the impact structure. Examples of morphologically high-standing impact structures are Gosses Bluff (central Australia; Milton et al., 1996), Vredefort ring (Transvaal; Henkel and Reimold, 1996), Shoemaker Impact Structure (formerly Teague ring; Pirajno and Glikson, 1998) and several Australian impact structures documented by Shoemaker and Shoemaker (1996). Thus, a post-Pennsylvanian age for the Decaturville structure appears to be far from a foregone conclusion.

From the above, the older age limits of the Crooked Creek and Decaturville structures are defined by deformed Lower Ordovician and deformed Cambrian-Ordovician rocks, respectively. The only igneous units that *may* predate the formation of these structures along the 38°N lineament are the Upper Cambrian Hazel Green volcanic rocks and Furnace Creek igneous rocks—the latter including redeposited lapilli and intrusive and extrusive ultramafic rocks. It is not clear whether the Hazel Green volcanic rocks are associated with a “cryptoexplosion” structure, as the location of their source is only inferred (Luczaj, 1998, p. 296). The poorly defined overlap between the older age limits of the Crooked Creek and Decaturville structures on the one hand and the Upper Cambrian Hazel Green and Furnace Creek volcanic rocks on the other hand lends itself to an interpretation in terms of model 4—i.e., formation of an impact-triggered deep crustal fracture accompanied and succeeded intermittently by long-term mafic and ultramafic activity.

It is not clear whether the volcanic events represented by the Hazel Green and Furnace Creek volcanics were focused on the 38°N lineament or were more widely distributed through the midcontinent. Melosh (1998) indicated that exposure of structural and igneous features in the Kansas-Ohio region is at least in part controlled by glacial cover. This factor, coupled with the poor stratigraphic controls on the ages of the tectonic and igneous events juxtaposed with the lineament, hardly allows elucidation of their temporal and spatial relationships, at least pending isotopic age studies. Despite these uncertainties, Luczaj (1998, p. 297) applied stratigraphic age interpretations in terms of model 3 as a basis for questioning the significance of shatter cones and PDFs vis-à-vis extraterrestrial impacts.

The criteria for identification of meteoritic impacts were discussed by French (1990). It may help to point out that deformation lamellae associated with explosive felsic volcanism (Carter et al., 1990) differ fundamentally from PDFs associated with hypervelocity impacts (Alexopoulos et al., 1988).

Luczaj's (1998) reference to the Reimold (1995) paper regarding the significance of pseudotachylites does not help the volcanic explosion cause, as it has long been known that pseudotachylites can occur in a variety of tectonic environments—cf. Glikson and Mernagh (1990)—and are not restricted to impact structures. Studies of shatter cone orientations indicate that the explosions that created the Vredefort and Gosses Bluff structures occurred at relatively shallow crustal foci (Manton, 1965; Milton et al., 1996). A build-up of magmatically derived volatile pressures on the order of >75 kbar (where incipient PDF generation occurs; Stöffler and Langenhorst, 1994) at shallow crustal levels must be constrained by the lithostatic pressure gradient and the mechanical properties of overlying crust. Mechanical failure of overlying crust would result in venting out of volatiles before pressures of this magnitude can be reached. Thus, no shatter cones and/or PDFs were observed around a volcanic diatreme or igneous plug, nor are explosive igneous units known to be associated with the 160 or so impact structures documented to date (Grieve and Pesonen, 1992; Grieve and Pilkington, 1996).

Pending more precise definition of the spatial relationships and isotopic ages of deformation and igneous events along the 38°N lineament as well as the surrounding region, all that can be said is that the formation of the shock metamorphic events that produced the Crooked Creek and Decaturville structures may have been accompanied and intermittently succeeded by igneous events that were, in part, linearly juxtaposed with these structures. Possibly, but not necessarily, such co-linearity represents a deep crustal fracture zone triggered by the impacts.

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COMMENT

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Luczaj (1998) discussed eight "cryptoexplosion" structures in Kansas, Missouri, and Illinois, and discounted the hypothesis of Rampino and Volk (1996), who suggested that these structures represent the remnant of a crater chain formed by the impact of a string of bolides. Rampino and Volk (1996) based their suggestion on the observation that two of the eight structures had previously proven to be impact structures, and on the similarity of this chain of structures to crater chains found on the Moon or on Jovian satellites (e.g., Melosh and Whittaker, 1994). Luczaj (1998) criticized Rampino and Volk's hypothesis, concluded that these eight structures are of internal (i.e., explosive igneous) origin, and asserted that shock metamorphic features "can be produced by explosive ultramafic igneous activity."

Whereas we find it difficult to defend the hypothesis of Rampino and Volk (1996), as the ages of the structures are poorly constrained and only two of eight structures contain shock metamorphic features (and can thus reliably be identified as impact structures), we strongly object to the unsupported assertion that shock metamorphic features can result from endogenic terrestrial processes. It is unfortunate that incomplete understanding of shock metamorphism persists in the geological community. In contrast to some assertions (many of which are outdated—e.g., Amstutz, 1965; or ignore the experimental evidence—e.g., Lyons et al., 1993), the existence of definite shock metamorphic features in volcanic rocks has never been substantiated (see, e.g., de Silva et al., 1990; Gratz et al., 1992). Shock compression is a nonequilibrium process. Most of the structural and phase changes in mineral crystals and rocks are uniquely characteristic of the high pressures (5–>50 GPa) and extreme strain rates (10^6–10^8/s) associated with impact.

Static compression, as well as volcanic or tectonic processes, yields different products because of lower peak pressures and strain rates that are different by more than 11 orders of magnitude. The study of the response of materials to shock is not a recent development; it has been the subject of thorough investigations over several decades. Numerous controlled shock-wave experiments, which allow the collection of the shocked samples, have been performed for decades and have led to a good understanding of the conditions for formation of shock metamorphic products and a pressure-temperature calibration of the effects of shock pressures up to about 100 GPa (see, e.g., French and Short, 1968; Stöffler, 1972, 1974; Huffman et al., 1993; Stöffler and Langenhorst, 1994; Huffman and Reimold, 1996; and references therein).

Microscopic features diagnostic for shock metamorphism include: planar deformation features (PDFs), optical mosaicism, changes in refractive index, birefringence, and optical axis angle, isotropization, and phase changes. PDFs in rock-forming minerals (e.g., quartz, feldspar, or olivine) have been shown to be diagnostic evidence for shock deformation (see, e.g., French and Short, 1968; Stöffler, 1972, 1974; Stöffler and Langenhorst, 1994). Best studied in quartz, PDFs are ≤1–3 µm thick, highly parallel zones filled with amorphous silica that are spaced about 2–10 µm apart. With increasing shock pressure, the distances between the planes decrease, and the PDFs become more closely spaced and more homogeneously distributed over the grain, until at about 35 GPa complete isotropization has been achieved. PDFs occur in planes corresponding to specific rational crystallographic orientations (cf. Stöffler and Langenhorst, 1994, and references therein). Depending on the peak pressure, PDFs are observed in 2 to 10

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(maximum 18) orientations per grain, and relative frequencies of the crystallographic orientations of PDFs can be used to calibrate shock pressure regimes (see, e.g., Stöffler and Langenhorst, 1994; Grieve et al., 1996). Such shock-characteristic features (including multiple sets of PDFs in quartz) were found at the Crooked Creek and Decaturville structures, both in Missouri (cf. Koeberl and Anderson, 1996). Thus, these two structures are, so far, the only ones among the eight listed by Rampino and Volk (1996) for which an impact origin has been demonstrated. We therefore urge Luczaj (1998) to restrict his critical discussion to Rampino and Volk's interpretation. Furthermore, to use poorly constrained age data to reject Rampino and Volk's hypothesis, while using the same poor data in favor of internal processes and implying that shock metamorphism may have internal causes, represents subjective interpretation and generalization. We reaffirm that the experimentally well understood conditions of pressure, temperature, and strain rate, which lead to the formation of shock metamorphic features, do not occur in explosive igneous activity, and there is no cause for rejecting decades worth of experimental data by asserting that shock pressures in excess of a few GPa can be generated by endogenic processes.

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REPLY

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The main purpose of my paper (Luczaj, 1998) was to show that eight cryptoexplosion structures in a linear array in the midcontinental United States have different ages, and therefore the meteorite impact-string hypothesis of Rampino and Volk (1996) for this set of structures is invalid. My purpose was not to evaluate which of the two existing hypotheses regarding the formation of shock-metamorphic features was “correct.” Rather, it was my intention to present a simple argument to support the *possibility* of an alternative hypothesis that might explain the shock-metamorphic features found in two of the structures.

Comments by Rampino, Glikson, and Koeberl and Reimold focus on two aspects of my paper. They have challenged (1) the accuracy of the age constraints for the structures, and (2) the possibility that shock-metamorphic features could result from explosive volcanism. In addition, Glikson argues in support of Rampino's original idea of impact-triggered volcanism along the linear array of structures, but suggests that the impacts may have occurred much earlier during the Cambrian or Early Ordovician. These three topics are dealt with separately below.

CONSTRAINTS ON THE AGES OF THE STRUCTURES

Rampino challenges the accuracy of the age constraints I provided (Luczaj, 1998), but only those for the Decaturville structure are used to support his challenge. Glikson challenges the accuracy of the age constraints for both the Decaturville and Crooked Creek structures. Although Glikson correctly notes that there are deformed Lower Ordovician rocks in the Crooked Creek structure, I dispute his suggestion that the older age limit for the Decaturville structure is Cambrian-Ordovician. Offield and Pohn (1979, p. 35) stated that “the Bainbridge Limestone is involved in the deformation, so the Decaturville structure is clearly younger than Middle Silurian.” Glikson correctly notes that the absence of Pennsylvanian rocks in the structure is not necessarily evidence that the structure existed during the Pennsylvanian, even though Pennsylvanian sediments exist nearby, because the structure may have had a high-standing morphology that did not allow for net sediment accumulation at the time. However, the post-Pennsylvanian age for the Decaturville structure given in Luczaj (1998) is further supported by evidence from the Pb-Zn-Fe sulfide mineralization in the region, which occurs in rocks as young as Pennsylvanian, and has been isotopically dated as Permian elsewhere in the region (Brannon et al., 1996). The Decaturville structure *postdates* this regional mineralization, while the Crooked Creek structure *predates* the regional mineralization, which also suggests that the structures are of different ages and are separated in time by this regional Permian Mississippi Valley–type mineralization event (e.g., Offield and Pohn, 1979). While it is true that the age constraints are not very precise for the Decaturville structure, for most of the other structures they are very good. For example, the Furnace Creek and Hazel Green structures have volcanic material and basement rock fragments interbedded with Upper Cambrian sedimentary rocks (Snyder and Gerdemann, 1965). This is one of the best arguments that could be made to show that this igneous material is Late Cambrian in age, because it is constrained by the Law of Superposition. In any event, the age constraints for any one of the eight structures could be excluded and it would still be clear that the structures are of several different ages.

Rampino also argues that the radiometric ages used in Luczaj (1998) were unreliable because they were based on “crude radiometric dating of uncertain materials, most published more than 30 years ago” (i.e., Zartman et al., 1967). However, recent work on Permian igneous material from the Hicks dome (Reynolds et al., 1997) has confirmed the reliability of Zartman et al.'s (1967) isotopic dates for igneous material in this structure. Rampino also challenges the interpretation of the igneous material in the structures and suggests it may be a product of shock-induced melting. The ultramafic igneous material in the structures (e.g., Zartman et al., 1967; Cullers et al., 1996; Reynolds et al., 1997) is chemically and physically unlike what would be expected from shock-induced melting of Paleozoic limestone, dolomite, and sandstone target rocks in the region.

Rampino, Glikson, and Koeberl and Reimold correctly point out that the ages of some of the structures are not precise. It is a crucial point that while high-precision ages are necessary to support the impact-string hypothesis (the craters must all be the *same* age), far less precise age constraints can be used to show that the structures are of *different* ages. This is true because age constraints based upon crosscutting geologic relationships have absolute boundaries. Although some of the stratigraphic age constraints for these structures span more than one geologic period, or in some cases are only one-sided, they are still successful at showing that most of the structures are of different ages (see Luczaj, 1998, Fig. 2). Some age constraints are excellent, such as those cited above for the Cambrian volcanics, and delimit the age of volcanism to within part of a geologic period, *without the need for isotopic dating*. This alone rules out the hypothesis of Rampino and Volk (1996) that all the structures are from impact of a string of meteorites.

HYPOTHESIS OF IMPACT-TRIGGERED VOLCANISM

Rampino and Volk (1996) argued for a Mississippian–Early Pennsylvanian age for the impact chain. Rampino (1997, and Comment here) also suggested that if the six structures other than Decaturville and Crooked Creek are igneous, the magmatism may have been triggered by impact deformation from the two "proven" impact craters. However, the two igneous structures closest to Decaturville and Crooked Creek are Late Cambrian in age (see above) and cannot have been related to Mississippian–Early Pennsylvanian impacts.

I am pleased to see that Glikson recognizes that the linearity of the array of structures provides an important constraint on their origin. Glikson supports Rampino's general idea of impact-triggered volcanism, but suggests that "older age limits of the Decaturville and Crooked Creek structures are broadly contemporaneous with the oldest igneous events along the lineament, which lends itself to an interpretation in terms of an impact-triggered deep crustal fault zone that formed the loci for repeated younger igneous activity during the Paleozoic and part of the Mesozoic."

I see several flaws in Glikson's idea of impact-triggered volcanism for the structures in the array. (1) The youngest deformed rocks defining the older age limits for the Decaturville and Crooked Creek structures, as described above, are post–Middle Silurian and post–Lower Ordovician, respectively. The volcanism at Hazel Green and Furnace Creek is clearly Late Cambrian, constrained by the Law of Superposition, and is not, as suggested by Glikson, "broadly contemporaneous" with the older age limits of the Decaturville and Crooked Creek structures. (2) The age of the Weaubleau structure is very well constrained as Late Mississippian to Early Pennsylvanian (Snyder and Gerdemann, 1965; Rampino and Volk, 1996; Luczaj, 1998). Glikson suggests that the Weaubleau structure may be volcanic in origin, related to an Early Paleozoic impact event, although no igneous rocks have been found in the structure. (3) Impact craters in similar geologic settings that are significantly larger than the Decaturville and Crooked Creek structures (e.g., Ries crater) do not contain impact-triggered igneous rocks (e.g., Luczaj, 1998). Indeed, Glikson notes that no explosive igneous units are "known to be associated with the 160 or so impact structures documented to date." (4) The igneous centers at Avon, Rose Dome, and Hicks Dome are at least 115 km, 265 km, and 290 km, respectively, away from either the Decaturville or Crooked Creek structures. It seems very unlikely that meteorite impacts that would have produced these two relatively small impact craters could induce "an impact-triggered deep crustal fault zone that formed the loci for repeated younger igneous activity," but not cause volcanism within or near the impact craters themselves. (5) Glikson states that "the only igneous units that *may* predate the formation of . . . [the Decaturville and Crooked Creek structures] along the 38°N lineament are the Upper Cambrian Hazel Green volcanic rocks and Furnace Creek igneous rocks. . . ." But the older age limits presented for the Decaturville and Crooked Creek structures are only one side of the age constraints and thus do not preclude the possibility that some of the other igneous units might predate one or both of these structures.

SHOCK METAMORPHISM

Rampino and Koeberl and Reimold criticize my paper (Luczaj, 1998) for suggesting that shock-metamorphic features could be produced by endogenic terrestrial processes. Rampino and Koeberl and Reimold cite literature showing that shock-metamorphic features such as complete isotropization of quartz grains or shock-induced melting along shatter cones require very high stresses (>35–60 GPa) to form and thus must be produced by meteorite impacts. However, at Decaturville and Crooked Creek, in the two structures Rampino claims to be "unequivocally known to be impact structures based on shock criteria," such high-pressure shock features are not found. For example, the Crooked Creek structure contains shatter cones that are small, of only fair quality, and found only in the center of the central uplift (Dietz, 1968). In rare shocked-sandstone float samples of the Lamotte Formation, which does not crop out in the structure, Dietz and Lambert (1980) found that "all grains reveal a strong undulose extinction and are highly fractured—the fractures often radiating from contact points" while "decorated planar elements in quartz are locally present, but only among those which are in point-point contact." In the Decaturville structure, Offield and Pohn (1979) observed in "clusters of small angular grains within a single small core sample of mixed breccia" from the center of the Decaturville structure "planar elements in quartz [which] include open 'cleavage' fractures, closely spaced parallel planes called 'planar features,' and possible deformation lamellae." They noted that "these closely spaced planes . . . are reasonably good examples of what Carter (1968) defined as 'planar features,' but are much less common and are in fewer sets per grain than are reported in studies of several other . . . impact structures." They stated that "even rarer are grains . . . [containing features that] seem to be rather poorly developed examples of what Carter (1968) has called deformation lamellae" (Offield and Pohn, 1979, p. 31–32). Offield and Pohn (1977, p. 333) concluded that the planar features and "possible" deformation lamellae "are not common and are rather poorly developed, but they likely indicate deformation under pressures of about 100 kb [i.e., ~10 GPa] or somewhat less. . . ." These descriptions of shock-metamorphic features from the Decaturville and Crooked Creek structures suggest that the rocks in the structures may have experienced pressures only in the lower part of the realm of shock metamorphism and possibly within the range of pressures experienced in explosive volcanism (c.f. Carter et al., 1986). In this regard, Huffman and Reimold (1996) stated that some phase changes in magmatic systems could theoretically drive a shock wave that would propagate through the system. Nicolaysen and Ferguson (1990), whose paper provided the principal background for the explosive volcanic hypothesis in Luczaj (1998), suggested that certain volatile-rich ultramafic magmas may contain large percentages of volatiles under high pressure, and that if an expansive transition of venting volatiles was sufficiently fast, a detonation might drive a shock wave that could cause a cataclysmic disruption of the surrounding rock mass. Under experimental conditions, peak shock pressures of at least 15 GPa are required at high or low temperatures to form single PDFs and shock mosaicism similar to those found in the Toba caldera (Carter et al., 1986), at Mt. St. Helens, and at Yellowstone Caldera, while multiple PDFs require about 18 GPa (Huffman and Reimold, 1996, Fig. 10). Huffman and Reimold (1996, p. 212) concluded that ". . . weak shock events at high temperatures and strain rates from 10^2 to 10^6 s^{-1} in volcanic systems are probably constrained to pressures below 10 GPa, and will produce fracture, mosaicism, rare single sets of PDF's, amorphization, and melting." Carter et al. (1986) suggested that pressures in the Toba caldera that produced PDFs and shock mosaicism in quartz and feldspar may have reached well over 10 GPa.

Glikson considers "deformation lamellae associated with explosive felsic volcanism [to] differ fundamentally from PDF associated with hypervelocity impacts." Two main sets of criteria have been used to differentiate between quartz grains from known explosive volcanic settings and known hypervelocity impact craters. The two criteria are the number of sets of deformation lamellae found in each quartz grain and the overall character of the deformation lamellae, including their curvature, orientation, continuity, spacing, and width. Koeberl and Reimold suggest that the presence of two or more PDF orientations per quartz grain is characteristic of shock-metamorphism from hypervelocity impact. However, in quartz grains from the Toba caldera, Alexopoulos et al. (1988, Fig. 2E) reported that "eleven sets of lamellar features were observed in seven quartz grains from one sample from Toba." This implies that either the majority of grains (four of seven) had two sets of deformation lamellae, or fewer grains had three or more sets of deformation lamellae. With regard to the character of PDFs, comparison of photomicrographs of deformation lamellae from the Toba caldera ignimbrite and various known meteorite impacts seems to show only slight differences in character rather than the fundamental differences suggested by Glikson. For example, Alexopoulos et al. (1988) compared PDFs in quartz from the Toba caldera and the Mistastin impact crater (their Fig. 1, A and B) in order to demonstrate the difference between the poorly defined discontinuous PDFs found in volcanic environments from the sharp, well-defined PDFs found in impact craters. However, photomicrographs of the type shocked quartz grains from the Toba caldera presented by Carter et al. (1986, Fig. 1, A and B) demonstrate sharp, well-defined continuous PDFs in the volcanic quartz. The deformation lamellae reported by Carter et al. (1986) have a closer resemblance to shocked quartz that Alexopoulos et al. (1988) reported from the Mistastin impact crater (their Fig. 1A) than the volcanic quartz they reported from the Toba caldera (Alexopoulos et al., 1988, Fig. 1B). Indeed, Lyons et al. (1993) suggested that the "spacing, morphology, multiplicity, and orientation information for lamellar substructures in quartz do not independently reveal the nature or source of the stresses responsible for them."

Some authors have proposed additional criteria regarding the orientation of microscopic deformation features in quartz (PDFs). For example, Alexopoulos et al. (1988, App. 1) suggested that for microscopic lamellar features to be considered diagnostic of impact, the microscopic deformation features must have orientations in which at least 80% of the measured features have c, ω, or π orientations (±3°). Others have suggested that at least 95% of deformation lamellae in quartz should correspond to rational crystallographic directions to be considered diagnostic of impact shock deformation (Bevan French, 1998, personal communication). The histogram data presented by Offield and Pohn (1979) indicate that the shocked quartz in the Decaturville structure does not satisfy this criterion. Offield and Pohn's histogram (their Fig. 23A) shows that only about 42% of the measured deformation lamellae are within 3° of c, ω, or π. No histogram data have been published for the Crooked Creek structure, so the orientation criterion of Alexopoulos et al. for shock lamellae cannot be evaluated there. Histogram data for shock lamellae from the Toba caldera were presented by Alexopoulos et al. (1988), who observed that "~40% of their orientations are within 5° of ω or π . . .", a proportion similar to that recognized in the Decaturville structure.

Clearly, more work needs to be done with regard to the existence and character of deformation lamellae in quartz from explosive volcanic settings, especially explosive ultramafic settings, which may differ substantially due to the large percentage of volatiles that may be present in such eruptions. It should be pointed out that the volume of erupted material does not necessarily correlate to the peak pressures reached in a particular eruption. I suggest that there might be an overlap between (1) the pressures generated in certain explosive igneous systems (e.g., Nicolaysen and Ferguson, 1990; Huffman and Reimold, 1996) and (2) those pressures predicted to form the poorly developed shock-metamorphic features that were found in the Decaturville and Crooked Creek structures (Offield and Pohn, 1979). If such an overlap does exist, then a terrestrial origin for the Decaturville and Crooked Creek structures cannot be ruled out in light of the arguments presented in Luczaj (1998).

COINCIDENCE HYPOTHESIS

What Koeberl and Reimold may really be suggesting is a fourth hypothesis: the lining up of two or more meteorite impacts with a linear array of terrestrial volcanic centers is the result of sheer coincidence (see also Melosh, 1998). Although such a coincidence is possible, the likelihood that it would occur is remote. I discussed (Luczaj, 1998) why this hypothesis is difficult to defend. The linearity of the array of structures places an important constraint on the origin of the structures. The probability of a linear array of explosive volcanic centers (i.e., Hicks Dome, Avon, Furnace Creek, Hazel Green, Rose Dome, and Weaubleau?) being superimposed upon a line of impact craters (i.e., Decaturville, Crooked Creek, Weaubleau?) must be extremely small. The argument I presented (Luczaj, 1998) is quite different from many previous arguments regarding coincidence of a single impact crater with tectonic features, because it deals with a well-defined linear array of structures, in which each structure in the array is at or near intersections of local and regional tectonic features. Probability arguments are further constrained because no other cryptoexplosion disturbances are known in southeastern Kansas, Missouri, or southern Illinois. This is one of the best explored regions of the eastern half of the United States, owing to the extensive Pb-Zn mining that has existed in the region for almost two centuries, with much of the exploration activity and mining occurring on both sides of the linear array over the entire region.

While the presence of shock-metamorphic features in the Decaturville and Crooked Creek structures is suggestive of impact phenomena, the linearity of the array of eight structures also provides an important constraint that must be addressed before the hypothesis involving coincidence can be fully accepted. Koeberl and Reimold do not adequately address these arguments regarding the linearity, and Rampino offers only unsupported suggestions of repetitive capture, impact-induced magmatism over great distances, or merely coincidence. Glikson suggests that there may be other structures off axis that have not been identified, which is an important concern, but he does not further support his suggestion. Although Rampino and Volk (1996) used the linearity argument in support of the impact-string hypothesis, Rampino discounts a similar probability argument when used to support the alternative hypothesis (Luczaj, 1998). Given the current known linear distribution of cryptoexplosion structures in the midcontinent array, in my view, the sheer coincidence hypothesis seems unreasonable.

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Did the Indo-Asian collision alone create the Tibetan plateau?: Reply

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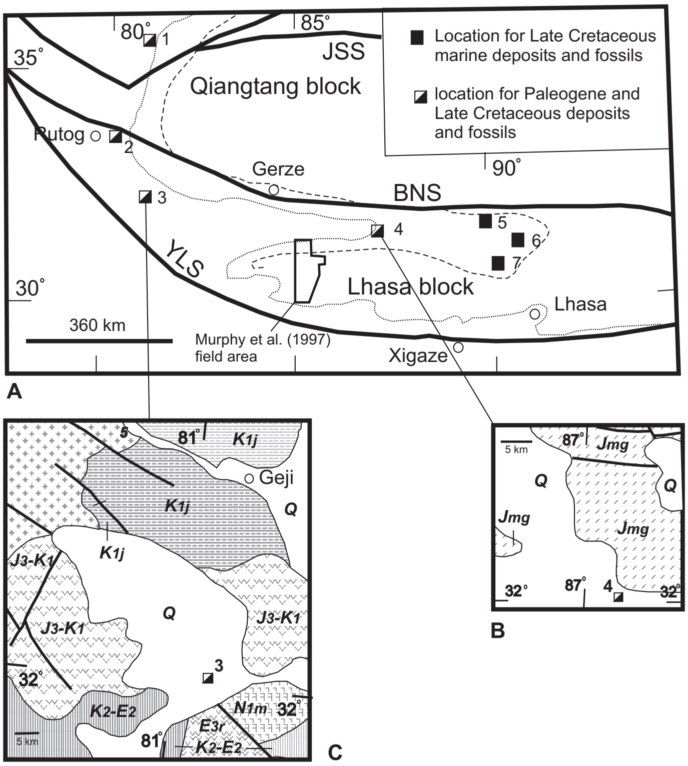

Figure 1. A: Paleogeographic map, as published in Zhang et al. (1998), showing their interpreted distribution of Late Cretaceous to Early Tertiary marine deposits in Tibet. BNS—Bangong-Nujiang suture, JSS—Jinsajiang suture, YLS—Yaluzanbu suture. Dashed and dotted lines indicate eastern limit of Late Cretaceous and early Tertiary marine deposits, respectively. We have plotted on their interpretation limits of field area from Murphy et al. (1997). B: Geologic map, as published in Xizang Geological Survey (1986) of region encompassing fossil locality 4 cited in Zhang et al. (1998). As presented in Zhang et al., locality 4 is location of Late Cretaceous and Eocene fossils reported by Xizang Geological Survey (1986). Q—undifferentiated Quaternary deposits, Jmg—Jurassic slightly metamorphosed sandstones interbedded with shale and chert. C: Geologic map, as published by Xizang Bureau of Geology and Mineral Resources (1993) of region surrounding fossil locality 3 cited in Zhang et al. (1998). At locality 3 (81°05′E, 32°01′N), Zhang et al. reported presence of Late Cretaceous and Paleogene age fossils referenced by Xizang Bureau of Geology and Mineral Resources (1993). Q—undifferentiated Quaternary deposits, N1m—Neogene intermediate volcanic rocks, E3r—Paleogene volcanic and pyroclastic rocks, K2-E2—Upper Cretaceous to Eocene interbedded sandstone and limestone, K1j—Lower Cretaceous limestone, sandstone, and shale, J3-K1—Upper Jurassic to Lower Cretaceous intermediate volcanic rocks, γδ5—Late Cretaceous granodiorite.

Zhang et al. (1998) disputed our interpretation that the Lhasa block attained significant elevation (3–4 km) beginning as early as the Early Cretaceous. They claimed that our interpretation neglects the presence of Upper Cretaceous and Paleogene marine deposits in the northern and western rims of the Lhasa block, which suggest that the Lhasa block was at or near sea level between ~100 and 25 Ma. We have three comments regarding their contention.

1. We are aware of the possible presence of Cretaceous marine strata along the western and northern rim of the Lhasa block. In fact, Yin et al. (1994) have addressed this issue and their possible tectonic implications; they interpret these marine strata to have been deposited in a narrow seaway induced by thrust loading along the Bangong-Nujiang suture zone during convergence between the Qiangtang and Lhasa blocks. Several geological investigations (Allègre et al., 1984; Chang et al., 1986; Leeder et al., 1988; Smith and Xu, 1988) support this suggestion and show that the Cretaceous shallow marine strata in the northern Lhasa block are in fact interbedded with fluvial red beds. The great thickness of these shallow marine Upper Cretaceous strata (locally >3 km thick) and their unique spatial association with the suture zone are also consistent with the development of a flexurally loaded basin. Thus, the presence of marine strata in the northern and western rims of the Lhasa block merely reflects a narrow topographic depression associated with thrusting in the Cretaceous. It does not suggest in any way that the entire Lhasa block was at or near sea level.

2. We cannot verify the validity of all their data points, as all of them are in Chinese literature that is not immediately available to us. However, we do have two key references cited by Zhang et al. (1998) which allow us to examine the accuracy of their age assignment. Their data point 4 for the “Late Cretaceous fossils” is located at 87°05′E and 32°01′N (Fig. 1A). Using their own cited reference (Xizang Geological Survey, 1986), we found that this point is plotted in a Quaternary unit (Fig. 1B). We are also able to locate their data point 3 (81°05′E, 32°01′N) for the “early Tertiary fossils” on the Xizang Bureau of Geology and Mineral Resources (1993) map referenced by Zhang et al. (1998). Again, we find that the location of the data point is plotted on a Quaternary unit (Fig. 1C).

3. Even if we accept their data set at face value, the combination of the two independent data sets by Murphy et al. (1997) and Zhang et al. (1998) implies that high relief (3–4 km elevation over 100 km distance) existed between the interior of the Lhasa block and its northern and western rims. This is not an unusual geomorphologic setting for a region that is being actively thickened. For example, the Tian Shan (Bogda Peak 5445 m) and the Turpan basin (–154 m) are separated about 125 km, and the Elburz Range (Mt. Damavand, 5601 m) and the South Caspian Sea (–28 m) are separated by ~100 km. Both areas are experiencing active crustal thickening due to horizontal compression and exhibit extreme topographic relief. Another example is the formation of the Cretaceous seaway in the North American Cordillera which extended from Alaska to the Gulf of Mexico at the peak of development of the Sevier orogenic belt (e.g., Eaton and Nation, 1991).

In conclusion, we find that the data sets presented by Zhang et al. are unreliable, and thus we question their interpretation. Even if we take their age assignment at face value, Late Cretaceous marine strata along the northern and western rim of the Lhasa block at most may suggest the presence of a narrow seaway created by thrust loading as discussed in Yin et al. (1994).

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Evidence for rapid displacement on Himalayan normal faults and the importance of tectonic denudation in the evolution of mountain ranges: Comment and Reply

COMMENT

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In their description of the Qomolangma detachment as exposed along the walls of the Rongbuk Valley, north of Mount Everest, Hodges et al. (1998) summarized the increasing intensity, in 500 m of structurally upward succession, of northeast-dipping schistosity in the older gneisses, culminating in strong mylonitization beneath the fault breccia zone of the detachment itself. Extrapolating southward toward Mount Everest beyond their mapping in the lower part of the Rongbuk Valley, they cited binocular reconnaissance, aerial photographs, and space shuttle radar imagery to support their contention that “the detachment extends to the Everest massif itself” (Hodges et al., 1998, p. 484).

Those interested in the geology around Mount Everest might find it intriguing that a historical record dating from the third expedition to Mount Everest in the early part of this century seems to strongly support Hodges et al.’s contention: The first *direct* observation relating to this structure was made by a member of the British 1924 expedition. On June 4 of that year, T. H. Somervell took what was then the highest photograph on Earth’s surface, on the north face of Everest, approximately 100 ft below a theodolite-determined altitude of 28,100 ft (8565 m) that shows (Fig. 1), in a view looking northward, and almost directly down dip, very pronounced layering across the southwestern and southeastern faces of Changtse (Bei Peak) (Norton et al., 1925, facing p. 114). The onset of this layering from the darker, more massive-appearing rock below, lies at approximately 7250 m elevation where it crosses the crest of the ridge facing Everest south of Changtse (cf. map of Washburn et al., 1991). Somervell’s photograph, therefore, leads to the simplest estimate that the up-dip projection of a strongly schistose or mylonitic zone below the detachment on Everest’s north face lies at an elevation somewhat above where Somervell stood at that time.

On June 3, 1924, N. E. Odell, a fellow high climber and geologist on the expedition, is reported to have found the first fossil on Everest at ~25,000 ft (7620 m) (Norton et al., 1925, p. 109). It is not recorded whether the fossil was found in place or, more likely, might have come from higher upslope.

The question arises from these observations as to whether the 30° north-dipping layering on Everest’s north face between ~24,000 ft (~7300 m) and ~28,200 ft (~8,600 m) (Odell, in Norton et al., 1925, p. 129) represents relict(?) bedding of the Ordovician rocks, or schistosity imposed on these or presumably older rocks, as described in the Rongbuk Valley by Hodges et al. (1998).

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Figure 1. Changtse (Bei Peak) and Chang La (North Col) from north face of Mount Everest, at approximately 28,000 ft (Norton et al., 1925, p. 114). Planar layering nearly down dip conforms well with location of base of Qomolangma detachment, as extrapolated by Hodges et al. (1998). Photograph by T. Howard Somervell, June 4, 1924; used with permission of Royal Geographical Society, London.

tonic denudation in the evolution of mountain ranges: Geology, v. 26, p. 483–486.

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REPLY

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We appreciate Gary Boone's comments on the geology of the Everest and Bei Peak massifs, as well as his reminder of the intellectual debt we owe to geologists who participated in some of the great exploratory expeditions of the past. While none of the geologist-climbers who tackled Everest in the first half of the 20th century left descriptions of geologic structures high on the mountain, their accounts of the distribution of rock types along Tibetan climbing routes help constrain the likely position of the Qomolangma detachment, which places essentially unmetamorphosed limestones on a metamorphic substrate of impure marbles and calcareous metapsammitic rocks. We have been able to augment their observations by examining samples collected for us by modern climbers. As Somervell's photograph (Boone's Comment, Fig. 1) shows, the detachment is an obvious structural discontinuity, such that surface photographs taken by climbing parties yield further constraints on the fault's position. The most useful resource of all, however, is a spectacular series of low-altitude color aerial photographs taken in 1984 as part of the cartographic work of Washburn et al. (1991). Using all of these tools, scientists from MIT, the Boston Museum of Science, and Oxford University are collaborating to produce the first detailed geologic map of Everest.

Our observations thus far place the brittle Qomolangma detachment at an elevation of 8720–8760 m on the southeastern ridge of Everest, just below a landmark known to climbers as the South Summit. On the north side of the mountain, the fault is exposed near the head of the Hornbein Couloir, at an elevation of about 8600 m. The detachment appears to project down-dip northward, through the air, to the south face of Bei Peak, where it is spectacularly exposed in the strike-parallel section shown in Somervell's photograph at about 7100–7200 m. To specifically answer Boone's question, the north-dipping foliation between 7300–8600 m on the north slope of Everest probably represents compositional layering in metamorphic rocks of the detachment footwall or, alternatively, a mylonitic foliation. We hope that the collection of samples during future expeditions will help us to distinguish between these two possibilities.

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Washburn, B., et al., 1991, The National Geographic map of Mount Everest: Boston, Museum of Science, and Zurich, Swiss Foundation for Alpine Research, scale 1:50,000 and 1:25,000 (second edition).

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