FORUM

Magnetic anomaly near the center of the Vredefort structure: Implications for impact-related magnetic signatures: Comment and Reply

COMMENT

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Hart et al. (1995) postulated that large meteorite impacts may generate characteristic magnetic signatures due to thermal resetting of remanent magnetism, as a consequence of the impact process. Their postulation is based on the results of a study of the ca. 2 Ga Vredefort structure which shows that the remanent magnetism of rocks from the core of the structure was reset penecontemporaneously with the formation of the structure. While we agree with Hart et al. (1995) that the Vredefort structure is the product of a large meteorite impact at ca. 2 Ga and that the reset remanent magnetism in the rocks is consistent with the 2 Ga paleopole orientation for the region, we believe that Hart et al. failed to satisfactorily discount an alternative possibility: that the postimpact thermal event manifested by the reset magnetism reflects high, preimpact, ambient rock temperatures that are related to an earlier regional metamorphic event. Hart et al. (1995, p. 279) mentioned this possibility briefly but discarded it on the grounds that (1) the magnetic anomaly and thermal metamorphism are centered on the Vredefort structure, and (2) there is no evidence of any ca. 2 Ga metamorphism predating the formation of the structure.

In order to address the first point, it is necessary to establish what is meant by the term "Vredefort structure." Hart et al. (1995, p. 277) stated that the Vredefort structure is "a large complex crater . . . [with] an original diameter of ~300 km." However, their Figure 1, described as a geologic map of the Vredefort structure, shows only the central, ~70–80-km-wide Vredefort *dome*, which, according to Therriault et al. (1993), corresponds to the central uplift of the impact structure. We propose that the term "Vredefort structure" be reserved for the originally wider, now deeply eroded, *impact basin*, and that the central uplift be designated as the Vredefort dome. In this context, it is not clear whether Hart et al.'s (1995) statement, that the magnetic anomaly and thermal metamorphism are centered on the structure, refers to the wider impact basin or only to the dome. Because the metamorphism has most typically been described as centered on the dome (e.g., Schreyer, 1983), we assume that this is their implication. Evidence exists, however, for regional magnetic resetting at 2 Ga, as follows. (1) Layer et al. (1988) established that remanent magnetism *throughout the Witwatersrand basin* was reset to a ca. 2 Ga paleopole; (2) Morgan (1985) established a similar paleopole for rocks in the Limpopo Belt, some 500 km to the north of the Vredefort structure.

The striking similarity of these paleopole orientations to the paleopole obtained from the 2.06 Ga (Walraven et al., 1990) Bushveld Complex gabbros led Layer et al. (1988) to propose that a regional thermal event affecting the crust of the Kaapvaal craton accompanied the Bushveld magmatic event. The *P-T* path inferred for the mid-amphibolite facies metasedimentary rocks in the collar of the Vredefort dome is consistent with such timing (Gibson and Wallmach, 1995), and the high-grade metamorphism observed in the core of the dome (Schreyer, 1983) could also be reconciled with the intrusion of voluminous mafic magmas into the lower crust and upper mantle during the Bushveld event. On the basis of an estimated peak geothermal gradient of ~40 °C/km (Gibson and Wallmach, 1995), much of the middle to lower crust in the region is likely to have undergone temperatures above the Curie point for magnetite (~550 °C; Telford et al., 1990) during this event, leading to remagnetization. According to Hart et al. (1995), however, the remagnetization that they describe occurred after the impact event, which postdated the Bushveld event by ~35 m.y. (Kamo et al., 1995; Spray et al., 1995). If during this interval the rocks cooled rapidly, the magnetic anomaly described by Hart et al. (1995) might be attributable to the impact event. We believe, however, that sufficient evidence exists to suggest that postpeak cooling was slow prior to the impact event and, thus, that large parts of the crust were still above the magnetite Curie point temperature at the time of impact. (1) Clinoeulite (magnesian clinoferrosilite) grains in granulite facies meta-ironstones from the core of the dome contain narrow Fe-augite exsolution lamellae indicative of rapid cooling from temperatures above the lower stability limit of pigeonite (~800 °C; Schreyer et al., 1978). This texture is consistent with rapid exhumation of still-hot granulites. (2) Schreyer and Abraham (1978) linked granulite facies decompression textures in garnet paragneisses from the core of the dome to pseudotachylite development. Hart et al. (1991) challenged this interpretation and suggested a 3.5 Ga age for the decompression event; however, a reappraisal of the textures in these rocks (G. Stevens, 1995, personal commun.) supports Schreyer and Abraham's (1978) findings. (3) Metamorphic textures compatible with pseudotachylite-related decompression under lower amphibolite facies conditions also occur in the mid–amphibolite facies metapelitic collar rocks (Gibson and Wallmach, 1995).

The temperatures indicated by these textures are consistent with a regional crustal geothermal gradient of >25 °C/km immediately prior to the impact-related exhumation event. Rapid cooling following exhumation of these rocks associated with the impact event could thus "freeze in" a 2 Ga paleopole orientation in the upturned lower crustal rocks. We are in no way implying that the Vredefort event did not cause a significant temperature rise in the rocks as a consequence of impact processes. Instead, we believe that, owing to the unusual coincidence of the Vredefort impact event with a regional metamorphic event, the magnetic signature of the rocks described by Hart et al. (1995) cannot be regarded as a characteristic feature of large impacts, as they suggest. Given the complex interaction of a variety of processes that affect the magnetic signatures in other impact sites (Pilkington and Grieve, 1992), it is imperative that detailed petrographic analysis be performed on the rocks discussed by Hart et al. (1995) to identify the magnetic minerals responsible for the observed signature and their mode of occurrence.

Finally, we point out that as yet no published structural data exist to substantiate Hart et al.'s (1995, p. 277) assertion that the so-called Vredefort discontinuity is a major tectonic boundary. A similar problem exists with the inferred "southeast boundary fault" (Hart et al., 1995, Fig. 1) and the statement (p. 277) that "the rim strata and the basement rocks all dip steeply inward toward the center." Fundamental geological, structural, and mineralogical data remain to be collected from the core and collar of the Vredefort dome—the central part of a uniquely exposed deeper level of a large multiring impact basin.

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REPLY

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We thank Gibson and Reimold for their Comment and the chance to expand the discussion on the relation between the petrophysical properties of rocks and impact processes. Our article (Hart et al., 1995) deals specifically with the magnetic anomaly above the exposed basement rocks near the center of the Vredefort impact crater. The rocks associated with the anomaly are Archean gneisses and granulites with highly unusual petrophysical properties; in particular, they have extremely high Q ratios (intensity of remanent magnetism/susceptibility). Gibson and Reimold's Comment restates the old belief that the thermal metamorphism in the core of the Vredefort structure is caused by a regional metamorphic event related to the intrusion of mafic magmas into the lower crust and upper mantle during the Bushveld event (Schreyer, 1983); Gibson and Reimold would have it that the high Q ratios in the basement rocks also relate to this event.

Their claim of an ongoing regional metamorphic event at the time of impact is based on their interpretation of the sequence and timing of the metamorphic reactions observed in the collar and basement rocks of the Vredefort structure (Gibson and Wallmach, 1995). Specifically they conclude that retrograde reactions associated with injection of pseudotachylite and the drop in pressure resulting from uplift and exhumation must have occurred soon after peak metamorphic conditions. In the absence of definitive radiometric dating of this peak metamorphism, we do not find their argument in any way compelling.

By far the most overwhelming evidence of a thermal event in the core region of the structure is the presence of recrystallized quartz and feldspar, and the local development of orthopyroxene-bearing granophyric veins (Schreyer, 1983; Hart et al., 1991). Both of these phenomena, which occur only in the Vredefort basement, clearly postdate the shock event and are consistent with a single heat pulse possibly related to impact (Hart et al., 1991). It is our premise that the same heat pulse remagnetized the basement rocks in the core of the structure at ~2.0 Ga (Hart et al., 1995). The observation that the intensity of the recrystallization of the quartz and feldspar (Bisschoff, 1982; Schreyer, 1983) increased toward the center of the structure led those authors to suggest that the metamorphism was caused by a local heat source (possibly the intrusion of Bushveld magmas) located near the center. A 40 mgal positive gravity anomaly in the central region, indicative of dense (mafic) material beneath the surface, was thought to provide support for this claim (Bisschoff, 1982). A borehole located close to the peak of the gravity anomaly (Hart et al., 1990a) indicates that the central region of the structure is underlain by ultramafic rocks (harzburgites), which bear no resemblance to the Bushveld magmas. Isotopic evidence suggests that these ultramafic rocks are Archean in age, and would not supply a ca. 2.0 Ga heat source required for a thermal metamorphic event in this region.

The suggestion that the high Q ratios in the core of the Vredefort structure may be due to the intrusion of the Bushveld Complex has no basis, in our opinion. The Q ratios from Vredefort are commonly several orders of magnitude greater than published data for granitic rocks worldwide (see Clark and Emerson, 1991), and are not generally seen in contact metamorphic aureoles. As yet, similar rocks with high Q ratios have not been described elsewhere in the Kaapvaal craton; rather, it would appear that these rocks are unique to the core of the Vredefort impact structure.

Gibson and Reimold have raised an important issue, which we well recognize, concerning the need for detailed petrographic analysis to determine the cause of the unusual magnetic properties of the gneisses and in particular the origin of the magnetic minerals. However, apart from the intense shock deformation (Hart et al., 1991), these rocks appear to be unremarkable compared to other granite gneisses of similar composition. A possible consequence of the shock event is the occurrence of an unusual amount of very fine grained magnetite which we believe could be the cause of the high Q ratios.

Finally, Gibson and Reimold challenge the existence of various structural and tectonic features (e.g., the Vredefort discontinuity) in

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the Vredefort basement. However, we point out that these issues are discussed in detail in various publications (e.g., Hart et al., 1990b).

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Hot-side-up aureole in southwest Yukon and limits on terrane assembly of the northern Canadian Cordillera: Comment and Reply

COMMENT

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Johnston and Erdmer (1995) presented data supporting the connection of the continental Nisling terrane and the Stikinia arc terrane by early Middle Jurassic time, a hypothesis previously proposed by numerous workers. Recognition of an Early Jurassic pluton in the Nisling terrane, although significant, does not differentiate among tectonic models for the northern Canadian Cordillera, as Johnston and Erdmer implied. In addition, they perpetuated two major misconceptions concerning regional geologic relations.

Johnston and Erdmer (1995) began and ended their paper by stating that Hansen (1990) interpreted the Nisling terrane, which is outboard of Stikinia, as largely autochthonous to North America. Hansen's unfortunate choice of terms has led to confusion. The main point of Hansen (1990) is that the previously defined Yukon-Tanana terrane is divisible into two structurally distinct tectonic packages, a lower package that is parautochthonous to North America and a higher allochthonous package. The two packages were juxtaposed in early Middle Jurassic time. Unfortunately, Hansen (1990) referred to the lower package as "Nisling," thereby associating these rocks with the displaced continental Nisling terrane of Wheeler and McFeeley (1987), which is west of the "Yukon Tanana terrane." Hansen regrets any confusion caused by her choice of terminology. However, this issue was corrected in subsequent papers in which the term "Nisling" was applied only to rocks of continental affinity outboard of Stikinia (Hansen et al., 1991; Hansen, 1992; Dusel-Bacon and Hansen, 1992; Dusel-Bacon et al., 1995).

Johnston and Erdmer (1995), following Mortensen (1992), also stated that Triassic to Jurassic plutons intrude the "Yukon-Tanana terrane." However, these workers have used "Yukon-Tanana terrane" too broadly, disregarding a host of field and laboratory data that indicate that not all "Yukon-Tanana terrane" tectonites have the same geologic history (e.g., Hansen et al., 1991; Hansen, 1992; Dusel-Bacon and Hansen, 1992; Dusel-Bacon et al., 1995). Structurally high, arc-oceanic rocks (Teslin–Taylor Mountain tectonites) record high-pressure metamorphism, dominantly orogen-normal

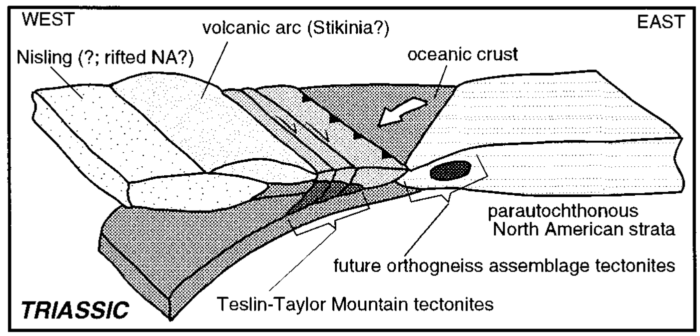

Figure 1. Cartoon illustrating tectonic environment and evolution of "YTT" tectonites. Dark gray oval represents Devonian and Mississippian orthogneiss bodies. Modified from Hansen et al. (1991).

ductile shear, and intrusion by Triassic to Jurassic plutons. Structurally low continental rocks (orthogneiss assemblage) are characterized by peraluminous Devonian and Mississippian orthogneiss and pelitic host rocks, and lack Triassic to Jurassic intrusions. By ignoring these fundamental differences within what has been called the "Yukon-Tanana terrane," Johnston and Erdmer disregard that part of the terrane is allochthonous and part is parautochthonous. This point is key to tectonic models of the northern Canadian Cordillera.

In an illustration of the tectonic environment and evolution of the divisions of the "Yukon-Tanana terrane" tectonites, (Fig. 1, from Hansen et al., 1991) a volcanic arc (Stikinia?), partially built on continental crust (Nisling?), lies outboard of western North America in Triassic time. The upper-plate tectonic package (arc and accretionary complex) was thrust over the lower-plate package (parautochthonous North American continental margin hosting Devonian and Mississippian orthogneiss) by early Middle Jurassic time along low-angle east-vergent ductile thrust faults in Yukon, and along northwest-vergent ductile thrust zones in Alaska; Alaskan and Yukon tectonites were subsequently modified by Cretaceous extension and dextral shear, respectively (Hansen, 1989, 1992; Dusel-Bacon and Hansen, 1992; Pavlis et al., 1993; Dusel-Bacon et al., 1995).

Contrary to the statements by Johnston and Erdmer (1995), this model does *not* assume that the Nisling lacks Triassic to Early Jurassic igneous rocks; instead, it predicts intrusion of Nisling by

Triassic to Early Jurassic plutons associated with Stikinia. Johnston and Erdmer's conclusion is equally as supportive of the model shown in Figure 1 here as it is of the Cache Creek enclosure model (Nelson and Mihalynuk, 1993), the only model they mention. Thus, although Johnston and Erdmer's data provide additional support for a post–Early Jurassic tie between Nisling and Stikinia, a hypothesis supported by a variety of geologic data (which they summarize), it does not differentiate among current tectonic models that propose just such a link.

One might disagree with the model shown in Figure 1, but the data on which it is based should not be ignored. Treatment of "Yukon-Tanana terrane" tectonites as a single tectonic entity disregards key geologic relations, including documented differences in lithology, age of plutonism, isotopic signature (references in Hansen, 1990), and extensive integrated kinematic, thermobarometric, and thermochronometric constraints (cited above).

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REPLY

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Hansen et al. state that our data do not allow for differentiation of tectonic models of the northern Cordillera and suggest that, contrary to our statements, intrusion of the Nisling terrane in the Early Jurassic is predicted by their model, in which Nisling is depicted as the basement to the Triassic Lewes River arc of Stikinia.

Geologic and tectonic maps are the fundamental starting points for any tectonic model of an orogen. We considered it significant that on recent maps of the northern Cordillera, including the one used by Hansen et al. (1991) in their tectonic model, Stikinia encompasses the Early Jurassic intrusions that border on Nisling, including the Aishihik batholith. Nisling had until now been considered as being separated from these intrusions by terrane-bounding faults. Our data demonstrated that these plutonic bodies intrude Nisling and that they can no longer be used to distinguish Nisling from Stikinia.

Hansen et al. state that we ignore a "host of field and laboratory data" indicating that the Yukon-Tanana terrane is divisible into allochthonous and autochthonous parts. Some existing field and laboratory data can indeed be interpreted to indicate that the Yukon-Tanana terrane consists of two originally disparate assemblages that have been tectonically juxtaposed (references in Comment). However, other interpretations of these data are possible, including ones that treat the Yukon-Tanana terrane as a tectonized yet coherent crustal block, (i.e., Mortensen, 1992; Johnston et al., 1994; Johnston, 1995a). In addition, not all existing data are consistent with the model of Hansen et al. (1991). Locally, rocks of the autochthonous orthogneiss assemblage show Early Jurassic cooling ages similar to that of the allochthonous assemblage (see Wilson et al., 1985, sample 4, Table 1). This is in conflict with the conclusion of Hansen et al. (1991) that Cretaceous cooling ages characterize the autochthonous assemblage. Devonian-Mississippian augen orthogneiss, interpreted as diagnostic of the autochthonous assemblage (Hansen et al., 1991), is intimately interfoliated with schist included in the allochthon in central Yukon (Johnston and Hachey, 1993; Johnston, 1995b).

Interpretation of the Yukon-Tanana terrane as a composite crustal domain with allochthonous and autochthonous components (references in Comment) is thought-provoking and may help guide further investigations. Because only a small proportion of the exposed rocks of the Yukon-Tanana terrane have been studied in any detail, amounting to at most a few percent of exposed bedrock, it is premature to consider any interpretation definitive. In order to avoid the pitfalls of model-driven field study, we encourage all workers to gather data with the view that the story is yet far from satisfactorily told.

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