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Archean spherule beds: Impact or terrestrial origin? Reply to the comment by A. Glikson

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We agree with Glikson [1] that the identification of Precambrian impact deposits is an important and largely unresolved problem, and thank him for providing us with an opportunity to further discuss our mineralogical and geochemical results [2] on the enigmatic spherule layers in the Barberton Mountain Land of South Africa. We note, however, that unfortunately Glikson has not been able to name definitive criteria for the identification of such Archean impact deposits either, and, thus, has also been unable to establish an impact origin for the Barberton spherule layers with any degree of certainty. We also would like to note that we [2] did not categorically exclude an impact origin. Rather, we found the arguments in favour of such an origin, as presented by Lowe et al. [e.g., 3–5], inconsistent, unconvincing, and incomplete.

Before summarizing our arguments against an impact origin, we would like to comment on some of Glikson's observations. He comments that it is pertinent to compare the Barberton spherule layers with the Bunyerroo ejecta in Australia, which are connected with the Precambrian Acraman impact structure, and lists the occurrence of "shatter coned volcanic fragments, planar defor-

mation features in quartz grains, tektite-like spherules and Ir anomalies..." in these ejecta. The application of the term 'tektite-like' may be somewhat confusing, as tektites are impact glasses (not pseudomorphs or recrystallization products thereof) that are found to be associated with four Cenozoic strewn fields [e.g., 6]. Nevertheless, if the Acraman ejecta are to be used for comparison with the Barberton spherule beds, we note the complete absence of any evidence of shock metamorphism in the Barberton spherule layers (e.g., shatter cones or, in particular, planar deformation features (PDFs) in the rock-forming minerals [e.g., 7]—the commonly accepted definitive criteria for an origin by impact). The absence of any evidence of shock metamorphic effects in the Barberton spherule layers has already led French [8] and Buick [9] to doubt that these layers were produced in an impact event. We have examined a large number of samples [2,10] and have not found even circumstantial evidence of shock effects, which is, in this respect, in agreement with Lowe et al. It should be pointed out that even in 2 Ga old impact structures, such as Vredefort and Sudbury, abundant evidence of shock metamorphism has been found [e.g., 11–13]. There is no logical reason why such evidence should be completely missing from the Barberton spherule layers—if they were of impact origin.

[UC]

Glikson [1] discusses whether the high concentrations of Ir and other platinum group elements (PGEs) in samples from the Barberton spherule layers could reflect primary chondritic values, and concedes that the extremely high PGE abundances may reflect reconcentration in secondary sulphides. We would like once again to draw attention to the fact that we have found Ir concentrations of up to about 2700 ppb in Barberton spherule samples [2], which, compared to an average chondritic Ir abundance of about 600 ppb, constitutes a 450% meteoritic contribution (in stark contrast to known impact deposits, (including those from Acraman), which usually show a $\ll 1\%$ meteoritic contribution). Clearly, it is impossible to view these abundances as primary chondritic signatures. As the high abundances of siderophile elements are correlated with the occurrence of secondary pyrite, arsenopyrite and other sulphides, it is obvious that the PGEs were redistributed. Consequently, it is not possible to use the high abundances of Ir and other PGEs as an argument for an impact origin. Furthermore, the redistribution of the PGEs during the formation of secondary sulphides will, as Glikson [1] points out, result in a change in the PGE interelement ratios. As a consequence of the different mobilities of the PGEs, any interelement ratio (e.g., Pd/Ir) observed in Barberton spherule samples today does not reflect the values of the source material, as the high present-day concentrations are the result of remobilization. Thus, the PGE ratios are of no consequence for the identification of the PGE source.

Glikson uses the average Ir/Au ratio of eight of our samples in comparison with chondritic values. However, this is exactly one of the points we wished to emphasize: it is not permissible to use ratios obtained from bulk values, if individual subunits (separate shale and spherule layers) have extremely different ratios (note that the variation in elemental abundances in the shale samples was found to be as large as that of the spherule samples). Glikson [1] also suggests that the oxidation state of Cr-spinels, which are found in Barberton samples, and which show an oxidation state that is incompatible with a meteoritic source [10,14], might be altered during weathering. This

seems extremely implausible, considering that none of the spinels of known extraterrestrial provenance [e.g., 15] show any such alteration. The oxidation state of the spinels merely reflects the oxygen fugacity during their formation.

In summary, we would like to reiterate our objections [2,10,14] to an impact origin model for the Barberton spherule beds. Mineralogically and petrographically the Barberton spherule beds are characterized by the absence of any primary minerals (with the possible exception of Cr-spinels), and the total lack of any evidence of shock metamorphism. The textures of the spherules that were previously interpreted as quench textures are in fact growth patterns. Very high PGE abundances (e.g., up to 2700 ppb Ir) cannot be primary, because this would require a 450% chondritic component, which is clearly impossible. If, then, the high PGE concentrations are due to alteration and formation of secondary sulphide mineralization, the PGE interelement ratios cannot be primary either, as the individual PGEs have different mobilities. The iron oxidation state of the Ni-rich Cr-spinels found in samples from the Barberton spherule layers are incompatible with an extraterrestrial origin, assuming that the spinels are primary. If they are secondary, there is no need to assume that the Ni is initially of meteoritic origin. Glikson [1] notes that the spherule beds may have been deposited far from the impact location(s), which is supposed to explain the absence of shock features. However, it is difficult to understand why, then, such massive deposits of supposedly impact-derived spherules would be present. Similar deposits are not present at any of the more than 140 known impact craters on Earth, including the Chicxulub–K/T boundary association. In the latter case, some rare spherule deposits are present (although never as massive as at Barberton), but these deposits are never associated with extremely high PGE anomalies (see [10] for a more detailed discussion). Furthermore, shocked minerals (e.g., quartz with PDFs) at the K/T boundary are distributed worldwide, and are not absent further away from the impact locality. To conclude, we fail to find any convincing evidence for an impact origin for the Barberton spherule layers. However, we agree

with Glikson [1] that Archean impact deposits must exist, and, like Glikson, we would very much like to be able to define criteria for the identification of such deposits.

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