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Response to Comment on "Impact Ejecta Layer from the Mid-Devonian: Possible Connection to Global Mass Extinctions"

New international efforts to define global boundary stratotypes (GSSPs) and resolve biostratigraphic uncertainties should make it possible to test key questions in geology and biostratigraphy. Our study (*1*) contributed toward an answer to one such question: whether, and how often, bolide impacts have had a significant effect in changing life on Earth. The comment by Racki and Koeberl (*2*) raises several issues concerning our work, to which space restrictions here allow only limited responses.

First, we agree with Racki and Koeberl (*2*) that our work requires further confirmation, and we are working toward that end. Some new data from the Mech Irdane section (*1*) are reported here (Figs. 1 and 2). In addition, we have identified a new Eifelian-Givetian (E-G) section, Jebel Rich Haroun, to the east of the town of Rissani, Morocco, at the same biostratigraphic level as identified within the E-G GSSP (*1*); the new section contains shocked quartz at that level. And ongoing studies have identified shocked quartz at the E-G boundary in a core in the United States and in a Spanish section. Other workers are also now active in this search.

The Moroccan sections we have studied contain conodonts that are black, an indication of heating to ~300°C or more. These temperatures in rocks from nearly 380 million years ago (Ma) would have an annealing effect on quartz planar deformation features (PDFs). Nevertheless, we have recovered, from very small samples (<2 g residues), relatively large numbers of quartz grains with PDF orientations consistent with shock metamorphism (*1*). Our new data (Fig. 1) show two PDF levels within GSSP Bed 117, a possible indication of two impacts. On the question of possible elemental anomalies, questioned by Racki and Koberl (*2*), we note that As and V anomalies, as well as other elements we reported (*1*), are also typically reported from K-T impact levels. Ir may or may not be associated with bolide impacts. We have not found sulfides in the E-G impact levels.

Racki and Koeberl (*2*) also take issue with our characterization of the E-G boundary extinctions as major global extinction events. In raising this point, they would have us use an estimate from the work of Sepkoski (*3*) different from the estimate we actually used (*1*). Sepkoski's work is very useful, but there are problems. His paper (*3*) was submitted for publication in 1993, before ratification of the E-G GSSP (*4*) and before much of the careful biostratigraphic work was performed and published, and therefore does not include more than 10 years of activity. Further, Sepkoski clustered his biostratigraphic data using a 1986 time scale, then later recalibrated his data to conform to a 1990 time scale; both of these time scales are now out of date. He divided the Devonian into substages, none of which are formally defined; even the E-G GSSP had not been defined. These clear biostratigraphic uncertainties, introduced by Sepkoski (*3*), are evident in figure 1 of the comment by Racki and Koeberl (*2*), which is modified from the figure by Sepkoski (*3*). In that figure, the extinction points (filled dots) are placed well above and well below the E-G GSSP—clearly a broad range that does not show the Kacák/*otomari* extinctions known to occur just below the boundary (*4*–*6*). This has resulted in an incorrect placement of the

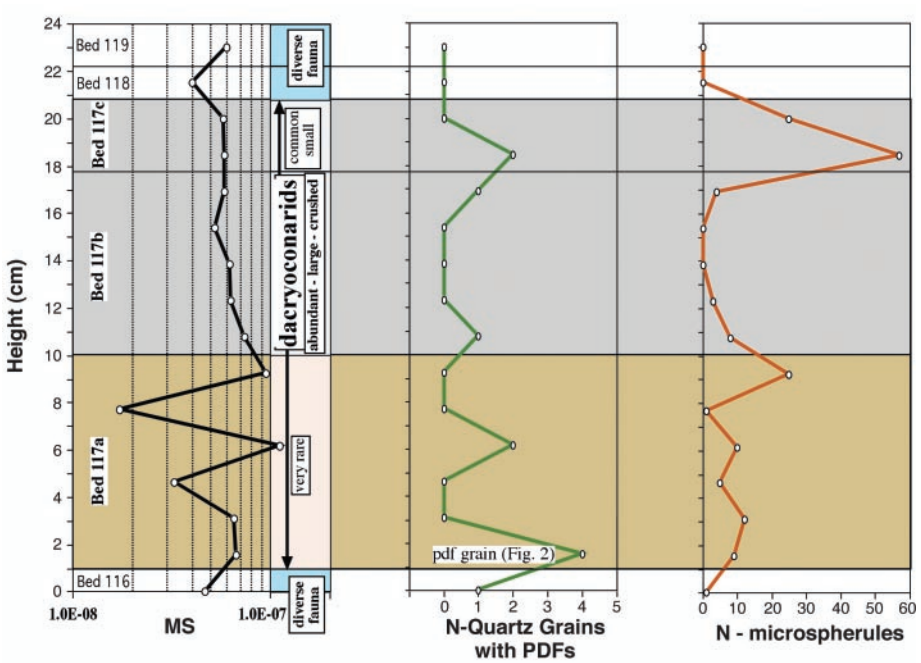


Fig. 1. Multiphase Bed 117 (0.2 m) in the Mech Irdane GSSP (*1*). Magnetic susceptibility (MS; m^3/kg), number of quartz grains with shock deformation features (PDFs), and number of microspherules from small samples collected in 2003. Bed numbers from Walliser *et al.* (*4*). We have modified numbering in Bed 117 to include a brown marl (25 to 30% $CaCO_3$) containing impact evidence and very rare dacryoconarid fragments, with some biotrubation (Bed 117a); a gray, rapidly deposited marl with abundant, large and crushed dacryoconarids and very few impact indicators (Bed 117b); and a gray marl with reduced abundance and size of dacryoconarids and a large increase in impact-related evidence similar to that reported in (*1*) (Bed 117c).

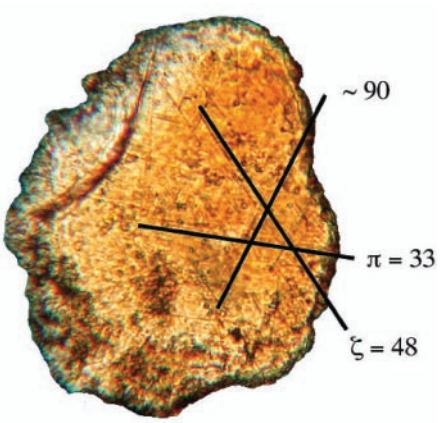


Fig. 2. Example of a quartz grain exhibiting shock-metamorphic PDF orientations; grain is from base of Bed 117a in Fig. 1. Symbols and numbers represent known PDF orientations for shock metamorphism in quartz (*1*).

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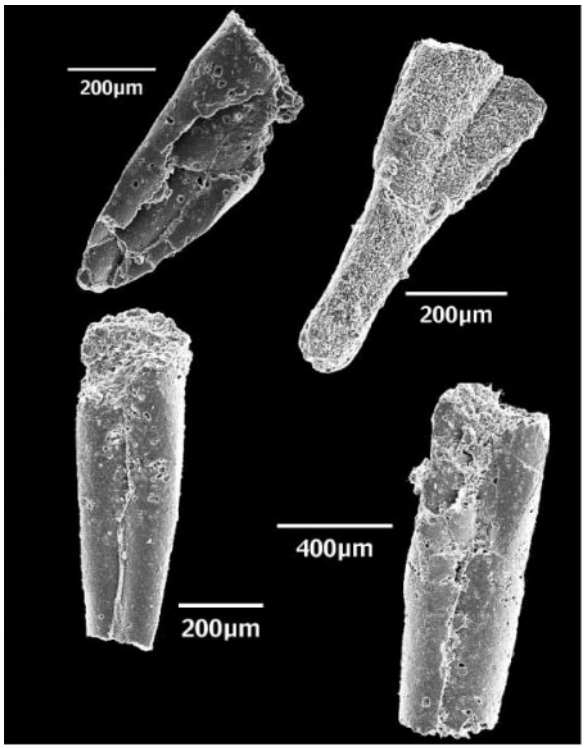


Fig. 3. Examples of crushed dacryoconarids from Bed 117b in Fig. 1.

E-G GSSP impact event on figure 1 of Racki and Koeberl (*2*). Biostratigraphic uncertainties are also clear from the fact that the marine genera extinction magnitudes of Sepkoski (*3*) range from ~40% (our choice as reasonable, given the uncertainties) to as low as ~15% (the choice of Racki and Koeberl), depending on which Sepkoski diagram (assumption) is chosen (*3*). In any case, these extinctions represent a global event (*4*–*6*), and those extinctions shown within the E-G GSSP (*4*) correspond to ejecta levels (Fig. 1).

The Kacák/*otomari* event, the focus of much of the comment by Racki and Koeberl (*2*), is one event within which are two extinction levels, both just below the E-G boundary (*4*, *6*). The precise timing of this event is unknown. Racki and Koeberl (*2*) argue that the event represents widespread anoxia and black-shale deposition lasting approximately 1 million years. We are aware of no supporting isotopic ages, however, and believe that this estimate is wrong. We continue careful examination of the Kacák/*otomari* level within the formally defined E-G GSSP (*4*). Although we have previously shown that a long-term transgressive pattern exists toward the end of the Eifelian (*7*), the Kacák/*otomari* event only occurs at the end of this event. Bed 117, the ~0.2 m bed bracketing the Kacák/*otomari* event (*4*, *5*), represents three phases (Fig. 1), none of which contain obvious evidence of anoxia. Bed 117a contains a large negative carbon isotope anomaly (*1*) and shocked quartz (Fig. 2). Bed 117b contains abundant, relatively large, crushed dacryoconarids (Fig. 3), an indication of rapid sediment deposition. Thus dacryoconarid living chambers were crushed before sediment infill.

We have examined a number of other E-G boundary sections, including sections in the United States, Spain, France, and Morocco (*7*, *8*). In these sections we find no significant anoxic event within the E-G boundary interval, suggesting that evidence of anoxia elsewhere is a local or regional phenomenon.

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