Search for evidence of impact at the Permian-Triassic boundary in Antarctica and Australia

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ABSTRACT

Life on Earth was almost destroyed some 250 m.y. ago in the most profound of all known mass extinction events. We investigated the possible role of impact by an extraterrestrial bolide through chemical and mineralogical characterization of boundary breccias, search for shocked quartz, and analysis for iridium in Permian-Triassic boundary sections at Graphite Peak and Mount Crean, Antarctica, and Wybung Head, Australia. Thin claystone breccias at the isotopically and paleobotanically defined boundary at all three locations are interpreted as redeposited soil rather than impact ejecta. The breccias at all three locations also yielded shocked quartz, but it is an order of magnitude less abundant (0.2 vol%) and smaller (only as much as 176 μm diameter) than shocked quartz at some Cretaceous-Tertiary boundary sites. Faint iridium "anomalies" were detected (up to 134 $pg \cdot g^{-1}$). These values are an order of magnitude less than iridium anomalies at some Cretaceous-Tertiary boundary sites. Furthermore, peak iridium values are as much as 1 m below the isotopically and paleobotanically defined boundary. The idea that impact caused the extinctions thus remains to be demonstrated convincingly.

INTRODUCTION

The Permian-Triassic life crisis has long been appreciated as the greatest of all extinctions in the ocean, and recently it was found to have been equally devastating for plants and animals on land (Retallack, 1995, 1996a). Explanations for this great midlife crisis include oceanic anoxia, oceanic CO_2 overturn, and eruption of flood basalts of the Siberian Traps (Hallam and Wignall, 1997). Although microspherules, spinels, and iridium anomalies were reported from the Permian-Triassic boundary (Xu and Yan, 1993; Yang et al., 1995), all have been disputed (Zhou and Kyte, 1988; Holser et al., 1991). Candidate impact craters remain either incompletely documented (Gorter, 1996) or not quite the right age (Hammerschmidt and Engelhardt, 1995). We have extended the search for evidence of impact to nonmarine sequences of Australia and Antarctica, where the Permian-Triassic boundary can now be recognized using isotopic chemostratigraphy (Morante, 1996; Krull et al., 1996) and chronostratigraphy (Retallack, 1995).

MATERIALS AND METHODS

Field sections and colors were measured (by Retallack and Krull) with tape and Munsell color chart. The names Wybung, Birdie, and others are distinct pedotypes recognized in the field (Retallack, 1998; Retallack et al., 1997, 1998). Point counts (by Retallack) of 500 grains per slide were made with a Swift automated counter. Clay minerals were determined (by Ambers) on a Rigaku Miniflex X-ray diffractometer using Cu radiation. Clay mineral abundance was estimated with the computer program NEWMOD (Reynolds, 1985). Abundance of shocked quartz includes the number of grains per slide divided by area of that thin section (by Retallack). One grain per square centimeter is 0.3 vol% at the grain size of these samples. The molar ratio of alumina/bases $[Al_2O_3/(CaO + MgO + K_2O + Na_2O)]$ was calculated from major element chemical analysis using inductively coupled plasma fusion by Bondar Clegg Inc.

Shocked quartz was studied with a JEOL scanning electron microscope (SEM) with EDX, CL, and BSE capability (by Seyedolali). Isolated grains were separated by immersion of claystone breccia in deionized water for 24 h, then 16 h in 50% HCl, then 1 h in 50% HF, followed by rinsing in 5% Na_2CO_3. Grains showing grooves after HF etching were glued to needles on a detent spindle stage (Bloss, 1981) and refractive index oils used to determine optical axes (by Retallack and Holser).

Samples for iridium analysis were ground and heated to 300 °C overnight before sealing in quartz tubes. They were irradiated at the University of Missouri Research Reactor for 60 h at a neutron flux of 7×10^{13} $n \cdot cm^{-2} \cdot s^{-1}$. Radiochemical purification of iridium followed procedures of Kyte et al. (1992) prior to counting (by Kyte).

PERMIAN-TRIASSIC BOUNDARY IN AUSTRALIA AND ANTARCTICA

The most likely marine stratotype level for the Permian-Triassic boundary is at the first appearance of the conodont *Hindeodus parvus* in sections near Meishan, China (Fig. 1, Yang et al., 1995). The boundary there and in other marine sequences worldwide is marked by a pronounced excursion toward decreasing values of $\delta^{13}C$ in both carbonate and organic matter (Holser et al., 1991). This $\delta^{13}C$ decrease in organic carbon has been used to locate the Permian-Triassic boundary in nonmarine sequences of Australia, Antarctica, and South Africa (Morante, 1996; Krull et al., 1996; MacLeod et al., 1997). The isotopically located boundary also coincides with (1) abrupt global cessation of coal formation (Retallack et al., 1996); (2) extinction of the coal-forming *Glossopteris* megaflora and its distinctive *Vertebraria* roots

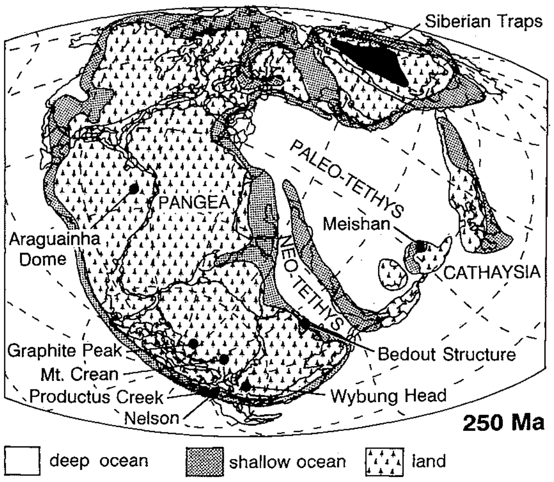

Figure 1. Localities for shocked quartz and iridium at Permian-Triassic boundary in Australia and Antarctica, likely boundary-stratotype locality near Meishan in China, and candidate impact craters, Araguainha in Brazil and Bedout in offshore Western Australia, on 250 Ma reconstruction using computer program *Terra mobilis* by C. Scotese.

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(Retallack, 1995; Retallack, et al., 1997, 1998); (3) global proliferation of fungal spores (Visscher et al., 1996); (4) appearance of *Dicroidium callipteroides* megaflora (Retallack, 1995); (5) appearance of *Lystrosaurus* therapsid fauna (Retallack, 1996a; Retallack et al., 1998). Interpolation from recent radiometric dating in Australia confirms the age of the last Permian coal at about 250 Ma (Retallack, 1995, 1998), the same age determined for the Permian-Triassic boundary in China and Siberia (Bowring et al., 1998).

In southeastern Australia, the isotopically, radiometrically, and paleobotanically determined Permian-Triassic boundary is in the basal Dooralong Shale at Wybung Head and basal Coal Cliff Sandstone at Coalcliff (Retallack, 1995, 1998; Morante, 1996). In Antarctica, the isotopic and paleobotanical boundary is also above the last coal: 2 m below the top of the Weller Coal Measures on Mount Crean, and at the base of the Fremouw Formation at Graphite Peak (Krull et al., 1996; Retallack et al., 1997, 1998).

BOUNDARY BRECCIAS

There are remarkable lithological similarities in boundary beds at these Antarctic and Australian localities, despite their separation by at least 2600 km during the Permian-Triassic transition (Fig. 1). In each place, the boundary beds are 6–15 cm of claystone breccia (Fig. 2). The claystone breccias have been thoroughly leached of alkalis and alkaline earths compared with clastic partings in underlying coal measures or overlying fluvial sediments and paleosols, as indicated by molar ratios of alumina/bases (Fig. 2).

We interpret claystone breccias at the Permian-Triassic boundary in Antarctica and southeastern Australia as redeposited soils (pedoliths), because many claystone clasts include microfabrics typical of soils and of Permian and Triassic paleosols in these sections (Retallack, 1998). The earliest Triassic pedolithic breccias may reflect soil erosion following deforestation implied by the plant extinction and global proliferation of fungi at the Permian-Triassic boundary (Retallack, 1995, 1998; Visscher et al., 1996).

We have not been able to find suevite, spherules, or other indicators of an impact ejecta layer in these claystone breccias, like those known from the Cretaceous-Tertiary boundary (Izett, 1990). The claystone breccia at Wybung Head was leached to an extent comparable to Cretaceous-Tertiary boundary beds taken as evidence for acid rain (Retallack, 1996b), but the Antarctic claystone breccias were not. Mineralogical and petrographic differences between the claystone breccias (Fig. 2) preclude interpretation as a single layer of impact ejecta. The rare shocked quartz grains and iridium in and around these Permian-Triassic boundary beds were thus not direct fallout from a distant impact, but rather were redeposited with destabilized local soils.

SHOCKED QUARTZ

Claystone breccias at the Permian-Triassic boundary in Antarctica and Australia contain rare grains of shocked quartz. The grains have two to four intersecting sets of planar deformation features that are straight and parallel (Fig. 3). Within the claystone breccia at Graphite Peak, shocked quartz grains show maximum abundance of 1 in every 125 separated quartz grains, or 0.2 vol% in thin section (Fig. 2). None was found below the Permian-Triassic boundary (99 thin sections examined). Some shocked quartz was redeposited into overlying strata, but none was seen more than 1 m above

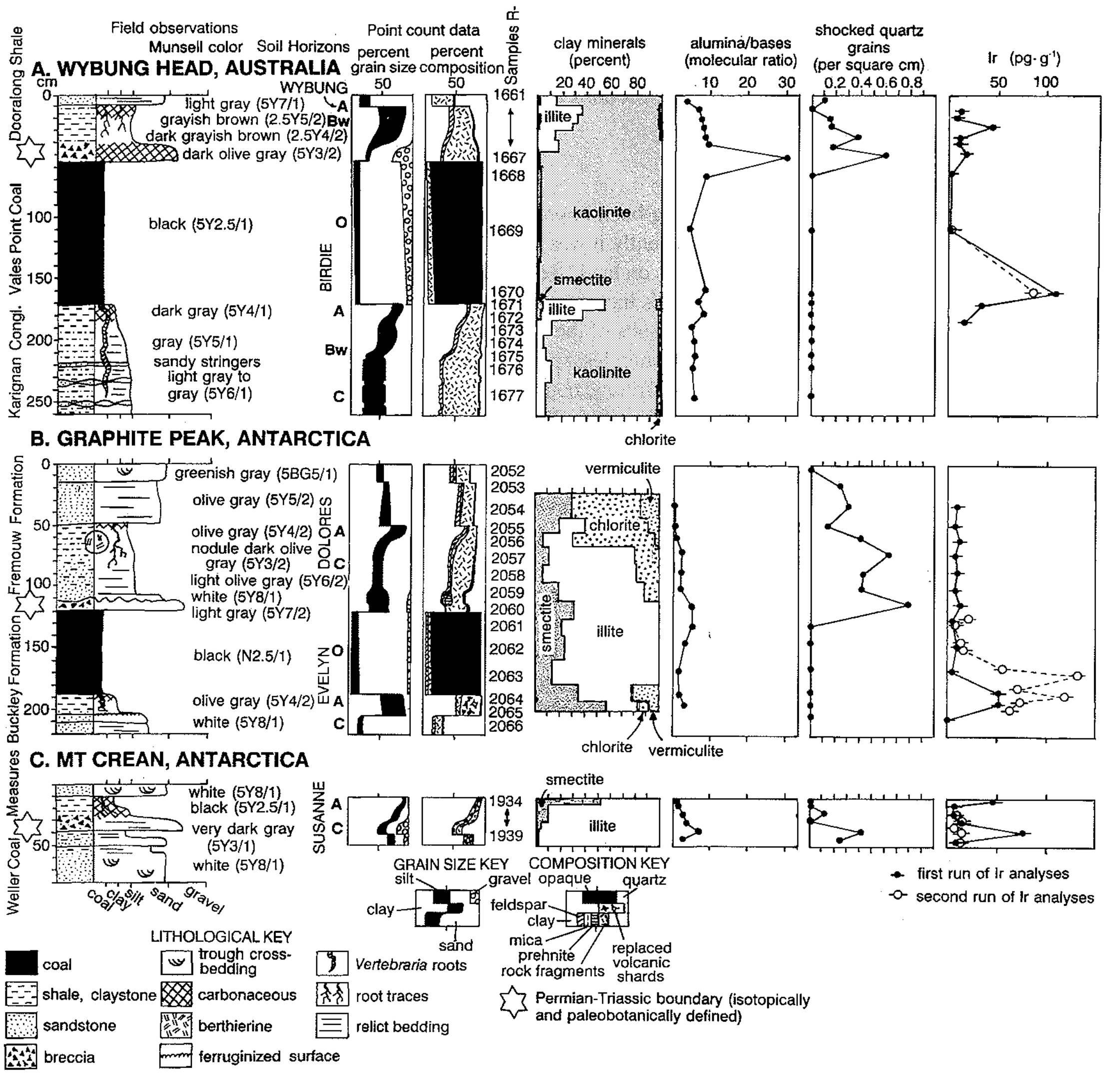

Figure 2. Sequences of paleosols with Permian-Triassic boundary breccias, their grain size, mineral composition, shocked quartz content, degree of weathering, and iridium content in three Gondwanan localities: (A) Wybung Head, north of Sydney, Australia, (B) Graphite Peak near Beardmore Glacier, central Transantarctic Mountains, and (C) Mount Crean, southern Victoria Land, Antarctica. Sand and granule grains in coal seams are mainly opaque coal macerals.

the Permian-Triassic boundary (196 thin sections examined). The maximum observed diameters of shocked quartz grains were 176 μm at Mount Crean, 168 μm at Graphite Peak, and 150 μm at Wybung Head. These grains are both smaller and less common than shocked quartz known from the Cretaceous-Tertiary boundary (Bostwick and Kyte, 1996) and late Precambrian (Gostin et al., 1986), but within the size range and abundance for shocked quartz reported from other Cretaceous-Tertiary boundary beds (Izett, 1990), as well as from the Late Devonian (Warme and Sandberg, 1996), latest Triassic (Bice et al., 1992), latest Jurassic (Dypvik et al., 1996), and late Eocene (Clymer et al., 1996).

The Permian-Triassic planar deformation features are 1 μm thick and spaced 1–20 μm apart (Fig. 3), comparable to shocked quartz from the Cretaceous-Tertiary boundary beds (Bostwick and Kyte, 1996) and numerous impact craters (Grieve et al., 1996). Identification of these shocked grains as quartz without inclusions was verified by energy-dispersive X-ray spectrometry and backscattered-electron images. Secondary SEM images of HF-etched grains showed numerous straight intersecting grooves where planar deformation features had partially dissolved (Fig. 3D). Despite the different orientations of the grooves, pillars within the deep grooves are oriented in the same direction, often at a high angle to the groove (Fig. 3D). The pillars may represent an additional planar deformation direction (Gratz et al., 1996). These Permian-Triassic shocked quartz grains are petrographically similar to those we have studied from known impact beds of Miocene to Precambrian age in Germany (Engelhardt and Bertsch, 1969), the Barents Sea (Dypvik et al., 1996), Montana (Izett, 1990; Retallack, 1996b), and South Australia (Gostin et al., 1986).

Orientation of planar features can also be indicators of shocked quartz. Spindle stage measurements showed preferred orientation of the planar features (Fig. 4). Quartz grains with two or more intersecting sets of planar deformation features oriented preferentially at 23° and 32° to the *c*-axis are formed by transient pressures of 25–28 GPa and are characteristic of meteorite or comet impacts (Grieve et al., 1996).

The three boundary sequences studied also have quartz grains from other sources. Tectonically and volcanically deformed quartz grains were distinguished from shocked grains by twins, cracks, fractures, and planar features in single sets, rather than multiple sets oriented in different directions (Lyons et al., 1993; Seyedolali et al., 1997). Tectonic and volcanic planar features in quartz grains are also curved, branching, unpillared when etched, nonparallel, discontinuous, diffuse, or en echelon (Lyons et al., 1993; Grieve et al., 1996). Also seen were unshocked HF-resistant, euhedral hexagonal-bipyramids of volcanic quartz (Fig. 3E). In some grains, planar features similar to those produced by shocking are intersected by wide, tapering, and curved features like those produced by tectonic deformation and microspherulitic, authigenic quartz overgrowths (Kerr, 1996). Glassy parts of shocked grains would have annealed and recrystallized in the 250 m.y. since they were redeposited with destabilized soil debris, deeply buried (~2 km), and heated by local dikes and sills (~200 °C; Retallack, 1995, 1998; Retallack et al., 1997, 1998).

IRIDIUM ANOMALIES

Iridium analyses of the three boundary sections showed peak values of only 134 pg·g^{-1} (i.e., 134 parts per trillion) and background levels of about 15 pg·g^{-1} (Fig. 2). A peak value of 80 pg·g^{-1} at Mount Crean is within the claystone breccia bed, but a second run (open symbols in Fig. 2) gave only 15 pg·g^{-1} for the same sample. At both Wybung Head and Graphite Peak, there was no anomaly in the claystone breccia, and peak values of iridium were about 1 m lower, in the base of the last coal of the latest Permian (Fig. 2). Peak values varied from 81 to 120 pg·g^{-1} in different runs for Wybung Head and 60 to 134 pg·g^{-1} for Graphite Peak. Such variations within the same samples may reflect dispersed iridium-bearing nuggets, like those observed in Archean impact deposits (Kyte et al., 1992). Even so, these iridium values are barely significant (Wybung Head, Graphite Peak) to insignificant (Mount Crean).

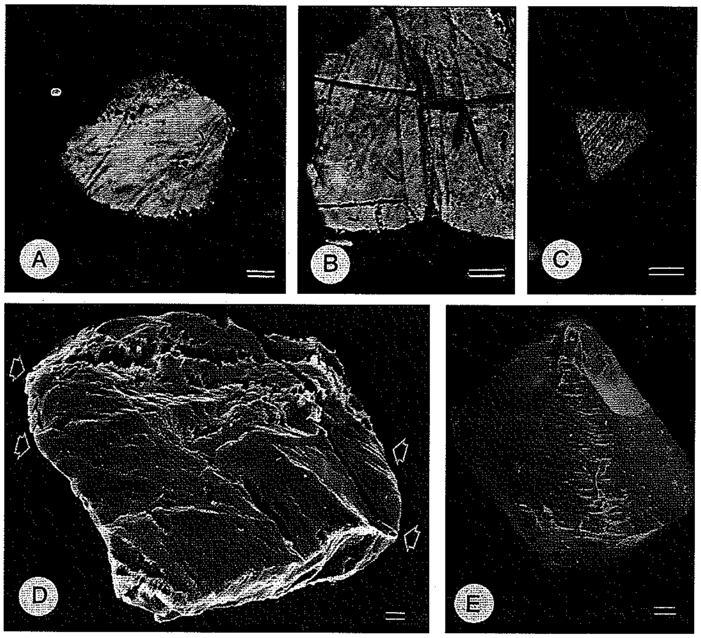

Figure 3. A–C: Photomicrographs of shocked quartz viewed in petrographic thin sections under cross-polarized light, showing dark planar deformation features. D–E: SEM photomicrographs of quartz etched by HF. Shocked quartz grain (D) shows grooves of preferentially etched planar deformation features (especially the fine set between arrows), whereas unshocked volcanic quartz (E) remains little etched. Grains are from claystone breccias at Permian-Triassic boundary at Graphite Peak (A, D, E) and Mount Crean (B), both in Antarctica, and Wybung Head (C) in southeastern Australia. Bar scales all represent 10 μm.

Our iridium values are similar to those previously reported at the Permian-Triassic boundary in Italy, Austria, Armenia, India, and China (Holser et al., 1991; Bhandari et al., 1992; Xu and Yan, 1993). These values are at least an order of magnitude weaker than those at the Cretaceous-Tertiary boundary, and some analyses could not be replicated (Zhou and Kyte, 1988). Peak values of iridium as low as ours have also been reported from some Cretaceous-Tertiary boundary sequences of paleosols (Retallack, 1996b), as well as the late Eocene (Clymer et al., 1996) and Late Devonian (Warme and Sandberg, 1996).

These data leave more questions than answers. Iridium observed at the Permian-Triassic boundary could reflect impacts too small to have been the cause of the extinctions. Another possibility comes from modeling studies. Comets or asteroids more than 10^{17} kg, or more than 50 km in diameter,

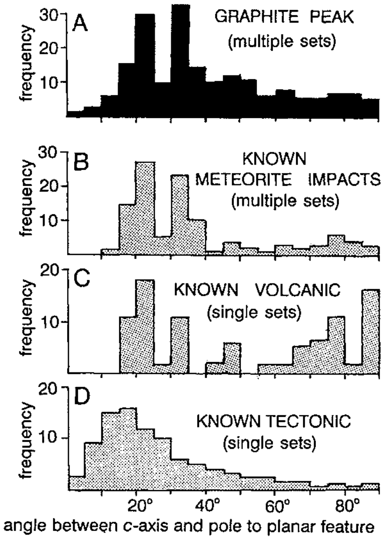

Figure 4. Spindle-stage measurements of (A) orientation of 207 sets of planar features in 100 isolated quartz grains from Graphite Peak, Antarctica (sample R2060 of Fig. 2). For comparison are published data (Lyons et al., 1993) on orientation of planar features in quartz from (B) Canadian meteorite-impact craters, (C) Toba volcanics, and (D) tectonically deformed rocks, Dry Creek Ridge, Montana.

impact with such energy that they blow off most of their own mass and shocked atmosphere beyond Earth's gravity. Such an impact would leave little iridium (Vickery and Melosh, 1990) and also little life. Alternatively, the impactor may have been iridium poor (Bhandari et al., 1992). Iridium anomalies can be weakened by leaching in strong acids that are generated by impact shocking of the atmosphere and evaporites (Retallack, 1996b). Iridium may also be dispersed by microbial activity (Dyer et al., 1989). This is an appealing explanation for our peak iridium values at the base rather than the top of the coal at Graphite Peak and Wybung Head.

CONCLUSION

Unlike the Cretaceous-Tertiary boundary with abundant evidence of a major impact in Yucatan and globally broadcast ejecta (Izett, 1990; Bostwick and Kyte, 1996), the Permian-Triassic boundary yields only the scent of an impact. Yet, the much more severe extinction at the Permian-Triassic boundary demands evidence of a much larger impact if that were its primary cause. The magnitude and location of impacts at the Permian-Triassic boundary remain uncertain, so their role in Permian-Triassic extinctions remains to be demonstrated. Nevertheless, there are nonmarine Cretaceous-Tertiary sections such as Bug Creek, Montana, where iridium and shocked quartz are rare or lacking (Retallack, 1996b). The search should continue for more complete Gondwanan Permian-Triassic boundary sections, comparable to Cretaceous-Tertiary boundary beds at Brownie Butte, Montana (Izett, 1990).

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