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Discussion

Reply to the comment by J. R. Ali on "Illawarra Reversal: the fingerprint of a superplume that triggered Pangean breakup and the end-Guadalupian (Permian) mass extinction" by Yukio Isozaki

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ABSTRACT

The following four major questions were raised about my recent proposal for the possible link between the end-Guadalupian extinction and a unique geomagnetic event called the Illawarra Reversal (Isozaki, 2009a); 1) timings of extinction, cooling, and the Illawarra Reversal (end of the Kiaman Superchron), 2) geomagnetic intensity during superchrons, 3) ascent rate of mantle plume, and 4) age constraints of LIP volcanism in east Pangea. The latest research results on the Permian biodiversity change, numerical modeling of plume, and single-crystal measurement of geomagnetism support that the timings of extinction and the Illawarra Reversal, high field intensity during the Kiaman superchron, and ascent rate of plume are reasonably explained in accordance with the integrated "plume winter" scenario (Isozaki, 2009b). The onset ages of LIP volcanism need further refinement for identifying the impingement of a plume head.

1. Extinction timing

Ali (2010-this issue) claims that the Capitanian (late Guadalupian; ca. 266–260 Ma) extinction was too late to be led by the proposed end-Kiaman geomagnetic cooling. By re-evaluating Permian fossil records, however, Clapham et al. (2009) recently demonstrated that shallow marine biodiversity declined not rapidly at the Guadalupian–Lopingian boundary (G–LB; ca. 260 Ma) as previously believed but rather gradually throughout the second half of the Permian. In fact, the extinction of fusulines and algae occurred clearly before the biostratigraphically-defined G–LB (e.g., Isozaki and Ota, 2001; Ota and Isozaki, 2006; Wignall et al., 2009). More interestingly, the mid-latitude brachiopod fauna started to migrate into the tropical zone for the first time in the early Capitanian, ca. 5 million years before the G–LB (Shen and Shi, 2002), suggesting that a global cooling onset approximately when the Kiaman superchron ended (Wardlaw et al., 2004). The selective extinction of tropically adapted fauna and the high productivity Kamura event, as well as the lowest sea level in the Phanerozoic, that occurred during the Capitanian also support the trend of global cooling (Isozaki et al., 2007; Isozaki, 2007, 2009a,b; Aljinovic et al., 2008; Isozaki and Aljinovic, 2009). The threshold temperature effective for survival was likely different among faunas with distinct metabolism, and among areas of different latitude. These varieties likely led an overall gradual and prolonged extinction pattern during the Capitanian. Thus the onset timings of the diversity decline and the cooling have no critical disagreement.

2. Geomagnetic intensity

Ali (2010-this issue) claims that the notion of high geomagnetic intensity during superchrons is not yet generally accepted; however, it is in fact almost proven by numerical modeling and direct measurements. In general, the geodynamo of the outer core generates stable axial dipole magnetic field with occasional and short-term reversals and excursions. The stability of the dipole field is controlled mainly by the heat flux across the core–mantle boundary (CMB) (e.g., Kutzner and Christensen, 2002; Maruyama and Santosh, 2008). As long as the heat flux remains in a certain range, the core dynamo keeps the dipole component of the geomagnetic field steady and dominant. The heat flux may change (mostly increase) by thermal disturbance, either by internal heating from the inner core or external cooling from the mantle. As the heat flux becomes higher than the normal range, the dipole component becomes less stable, starts to repeat polarity change, and eventually yields to a quadropole or higher order components. Kutzner and Christensen (2002) clearly shows in their fig. 3 that mean energy of the dipole magnetic field (proportional to the square of field intensity) drops sharply at a threshold value of Rayleigh number that is proportional to the heat flux at the CMB. Thus, in general, the geomagnetic field intensity likely declines on the Earth's surface when a stable dipole period (in particular, a superchron with stable polarity) ends by the increased heat flux. Biggin and Thomas (2003) explain that the heat flux change can be triggered by the catastrophic avalanching event within mantle in association with the launching of counter-flow plume from the CMB.

On the other hand, a great innovation was recently made in direct measurements of paleointensity, not for bulk rock sample but for single

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crystals (Tarduno et al., 2006). As to the Kiaman Reverse superchron, Cottrell et al. (2008) recently reported extremely high paleointensity by virtue of this new method. Biggin and Thomas (2003) and Tauxe and Yamazaki (2009) demonstrated that high field intensity trend characterized the late Carboniferous to Middle Permian Kiaman Reverse Superchron and the mid-Cretaceous Normal Superchron, respectively. The apparently contradicting results (e.g. Garcia et al., 2006 cited as counter-evidence by Ali, 2010-this issue) needs re-evaluation with the same new technique.

3. Rate of plume ascent

Ali (2010-this issue) questions the rate of plume ascent. By citing several previous articles on plume modeling, he discussed that the travel time of a plume from the CMB to the surface should be at least longer than 10 million years, and he concluded that the 5 million year time gap between the Illawarra Reversal and the plume arrival to the surface is too short. He superficially compared plumes responsible for the Illawarra Reversal to those in the classic models induced by the heat flux from the core (e.g. Campbell and Griffin, 1990; Farnetani and Samuel, 2005; Lin and van Keken, 2006); however, the flow induced by avalanching I am referring to is totally different from the simple plume ascent from the CMB. The mantle convection model that assumes catastrophic avalanching or megalith drop from the 660 km boundary requires much greater space dimension in consideration. As to the late Paleozoic–early Mesozoic Pangean formation/breakup, a large amount of subducted ocean slabs likely played the major role in the megalith drop or avalanching to change the convection pattern of the entire mantle and also to generate an extremely large superplume (e.g., Biggin and Thomas, 2003). In this case, the ascent rate of a plume changes dramatically with the size of a plume according to the Stokes' Law (proportional to the square of size); i.e., the larger a plume becomes, the faster it can ascend. In the case of a superplume over 1000–2000 km in diameter, given the average viscosity of the lower mantle around 5×10^{21} to 1×10^{22} Pa s, the plume head possibly reach to the surface in 2.5–20 m.y. after launching from the CMB. Thus at present, there is no solid basis for limiting the travel time of a plume to "almost certainly over 10 m.y." as Ali (2010-this issue) claimed.

4. Age constraints of LIPs

By checking references of Permian LIPs in eastern Pangea, Ali (2010-this issue) discusses that the LIPs in Oslo, Oman, N. India, and off-shore W. Australia (listed by Isozaki, 2007, 2009a) became activated prior to 265 Ma, thus these are not likely the products of the putative Illawarra superplume. There are two major points to be checked; the precise age of the onset of main plume volcanisms, and the precise age of the Illawarra Reversal. I admire Ali's efforts to get updated references for the possibly relevant volcanic units, and admit that all of these LIPs were not dated in satisfactory resolution. Some of the ages were measured by the old-fashioned bulk K–Ar dating, thus what is definitely needed is more sophisticated dating with modern methods for the listed mid-Permian volcanisms. Ali (2010-this issue) particularly criticized that the volcanism in off-shore W. Australia all belong to Cretaceous; however, he overlooked the rifting along the W. Australian margin that started obviously prior to the Cretaceous. Veevers and Tewari (1995) reported the extensive alkaline volcanism occurred in that domain during the Kazanian (Middle Permian) to early Triassic on the basis of detailed stratigraphic relationships with the Permo-Triassic strata and radiometric ages. Judging from the alkaline nature of the volcanism and its extensive development along the rifting Gondwana margin, the impingement of a plume there was inevitable already in the second half of the Permian.

Although uncertainty still remains in ages of the listed volcanisms, it is noteworthy that major plume-related alkaline igneous complexes in the eastern half of Pangea, e.g., the LIPs of Emeishan, Siberian, Oslo, Oman, N. India, and W. Australia, were emplaced in a limited time interval of the Middle Permian to Early Triassic. These suggest the potential arrival of a swarm of plume beneath E. Pangea.

Mantle plume is not a sharp-bounded geologic entity that exists as a solid exotic block of distinct composition from the rest of the mantle, but is an actively convective center of mantle rocks with diffuse compositional and thermal boundaries within the surrounding mantle. Therefore, minor perturbations upon the outer margin of a plume head occasionally induce small leaking streams composed of relatively lighter material as laboratory and numerical modeling demonstrates (e.g., Davaille, 1999; Ogawa, 2007; Fujita and Ogawa, 2009). From such precursory plumelets, small-scale basaltic volcanisms may occur prior to the arrival of the main plume head. In addition, there are thermal/compositional heterogeneity not necessarily identified as plumes in a convecting mantle, and the heterogeneity sometimes causes local volcanisms. In this regard, the temporal identification of the impingement of the major plume head appears not easy. For example, the minor-scale mid-Capitanian basaltic volcanism reported by Wignall et al. (2009) may represent such a precursory plumelet activity and/or local heterogeneity but not the arrival of a plume head. Such a small volcanism could unlikely trigger the major extinction because it was not merely too small in size but also too late for the early Capitanian biotic response mentioned above.

On the other hand, the age of the Illawarra Reversal needs further refinement. Isozaki (2009a,b) adopted the age assignment at the base of the Capitanian according to Wardlaw et al. (2004), whereas Menning et al. (2005) and Steiner (2006) mentioned that the timing might slightly range down into the Wordian age. Under the circumstances, therefore, we should refrain from further superficial comparison of timing until more reliable age datasets become available.

5. Conclusion

Among the four major points criticized by Ali (2010-this issue), the timing of extinction, high geomagnetic field intensity, and the rate of plume ascent are reasonably explained in accordance with the latest research results without conflict. As to the timing of volcanism, more precise ages are definitely needed; however, it may be too naïve at present to mention simply that the end-Paleozoic extinction events may have been related to the Emeishan and Siberian volcanisms as Ali (2010-this issue) recommended, because the more or less the same message has been frequently repeated since the early 1990s (e.g. Renne and Basu, 1991; Campbell et al., 1992; Chung et al., 1998; Courtillot, 1999). Instead, we need one more step forward to look for extended and/or alternative interpretations that may bring further fruitful discussions/understandings. The integrated "plume winter" scenario (Isozaki, 2009b) intends to explore a *terra incognito* in the extinction-related studies by correlating the unique geophysical event in the core with the most prominent biological event on the planet's surface in terms of mantle plume.

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