Synchrony between Early Jurassic extinction, oceanic anoxic event, and the Karoo-Ferrar flood basalt volcanism

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ABSTRACT

A well-known second-order mass extinction took place during the Pliensbachian and Toarcian Stages of the Early Jurassic. First recognized as a minor Pliensbachian peak in the global extinction rate, it has alternatively been interpreted as a regional response to the early Toarcian oceanic anoxic event. Detailed studies established it as a global long-term event spanning five successive ammonoid zones. Here we present a revised time scale based on high-precision U-Pb ages resolved to the zone level, which suggests that elevated extinction rates were sustained for about 4 m.y. and peak extinction occurred at 183 Ma. Recent isotopic dating of flood basalts from the southern Gondwanan Karoo and Ferrar provinces documents a culmination in volcanic activity ca. 183 Ma. The onset of volcanism is recorded as an inflection and start of a rapid rise of the seawater ^{87}Sr/^{86}Sr curve. The synchrony of voluminous flood basalt eruptions and biotic crises, as already noted for three of the major mass extinctions, permits a causal relationship, which in this case may be mediated by widespread oceanic anoxia.

Keywords: extinction, Toarcian, flood basalt, oceanic anoxic event, time scale.

INTRODUCTION

The ultimate causes or chain of events triggering mass extinctions are difficult to study but of fundamental scientific interest. Extraterrestrial impacts, climate changes, sea-level changes, oceanic anoxia, and flood basalt volcanism are some of the most often cited possible triggers for elevated extinction rates or wholesale ecosystem collapse. In all instances, hypotheses can be properly tested only if precise timing and correlation of events are possible. A second-order extinction event involving several marine groups occurred in Early Jurassic time (Hallam, 1986). There is a well-established connection between this extinction and a period of oceanic anoxia, which in turn appears to be related to a significant sea-level rise (Jenkyns, 1988; Hallam, 1997). However, some workers argue that either extraterrestrial impacts or flood basalt volcanism were the prime causes of many or all extinctions, on the basis of their mutual periodicity and some well-established cases of synchrony (Raup and Sepkoski, 1984; Rampino and Stothers, 1988; Stothers, 1993).

Herein we discuss the temporal relationship between the Early Jurassic extinction and volcanism in the Karoo and Ferrar large igneous provinces of southern Gondwana. A possible causal link has been tentatively proposed before, but large uncertainties in the Early Jurassic time scale and inaccuracies in dating the magmatism hindered the testing of this hypothesis (Courtillot, 1994). We review paleontological data pertaining to the Early Jurassic extinction, summarize recent advances in dating the Karoo and Ferrar igneous rocks, assess the temporal relationship between extinction and volcanism in the context of a newly revised, zonally resolved time scale for the critical Pliensbachian-Toarcian interval, examine the geochemical evidence for the oceanic anoxic event and environmental change, and discuss some possible extinction scenarios and relationships of the Early Jurassic events.

EARLY JURASSIC EXTINCTION

An Early Jurassic (Pliensbachian) extinction event was recognized from a global database of the stratigraphic ranges of marine animal families and genera. Of lesser scale than the celebrated “Big Five” (i.e., the five greatest extinction events recognized), this extinction, in which about 5% of families were lost, was nonetheless a significant event (Raup and Sepkoski, 1984). An independent compilation of fossil families detected as much as 5% marine extinction in both the Pliensbachian and Toarcian, and 2.4%–12.8% extinction among continental organisms in the Toarcian (Benton, 1995). On the basis of detailed analysis of the fossil record of northwest European epicontinental seas, Hallam (1986, 1996) regarded the extinction as a regional event, the later phase of which coincided with widespread anoxia in the early Toarcian (Fig. 1D). The recognition of an oceanic anoxic event in the Falciferum Zone (Jenkyns, 1988) provided an extinction mechanism that could inflict losses on marine biota by the spread of the oxygen-deficient bottom waters. Little and Benton (1995) analyzed the time distribution of global family extinctions and found that a protracted interval of five zones spanning the Pliensbachian-Toarcian stage boundary showed elevated extinction levels (Fig. 1C). However, outcrop-scale studies of the most fossiliferous sections in England and Germany displayed a clear species extinction peak correlating with the anoxic event in the Falciferum Zone (Little, 1996). The global extent of the Pliensbachian-Toarcian extinction event was established through detailed studies in the Andean basin (Aberhan and Fürsich, 1997) and deep-water facies of the western Tethys (Vörös, 1993) and Japan (Hori, 1993).

AGE OF KAROO AND FERRAR IGNEOUS PROVINCES

The Karoo province in South Africa and the Ferrar province in Antarctica are disjunct parts of a once contiguous large igneous province of Jurassic age in Gondwana. It ranks among the most voluminous flood basalt provinces of the Phanerozoic (Rampino and Stothers, 1988). Early radiometric dating, relying on the K-Ar method, was plagued with problems. A suite of whole-rock ages for the Karoo Group is distributed between 135 and 225 Ma, with apparent peaks of volcanic intensity at 193 ± 5 and 178 ± 5 Ma (Fitch and Miller, 1984). The K-Ar chronometer often yields anomalously young or old ages in disturbed systems, due to Ar loss or uptake of excess Ar, respectively. The use of ^{40}Ar-^{39}Ar and U-Pb dating, however, permits reliable determination of the true crystallization age of mafic igneous rocks. For valid comparison between dates recently obtained using different isotopic methods, we recalculated the published ages to reflect external errors (i.e., including decay constant uncertainty) at the 2σ level and the currently accepted ages of standards for ^{40}Ar-^{39}Ar dating (Renne et al., 1998).[1]

Duncan et al. (1997) reported 28 precise ^{40}Ar-^{39}Ar plateau ages from Karoo Group basalts and dolerites in South Africa and Namibia. The ages range between 179 and 186 Ma, the majority being at 183 ± 2 Ma (Fig. 1E). A U-Pb age of 183.7 ± 1.9 Ma obtained by Encarnación et al. (1996) from a tholeiitic sheet in South Africa is in good agreement with the ^{40}Ar-^{39}Ar results (Fig. 1E).

Various units within the Ferrar Group in Antarctica have also been dated (Fig. 1F). From the Kirkpatrick Basalt, Foland et al. (1993)

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[1] GSA Data Repository item 200080, Table 2, Recalculation of published radiometric ages for Karoo and Ferrar Groups, is available on request from Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301-9140, editing@geosociety.org, or at www.geosociety.org/pubs/ft2000.htm.

Data Repository item 200080 contains additional material related to this article.

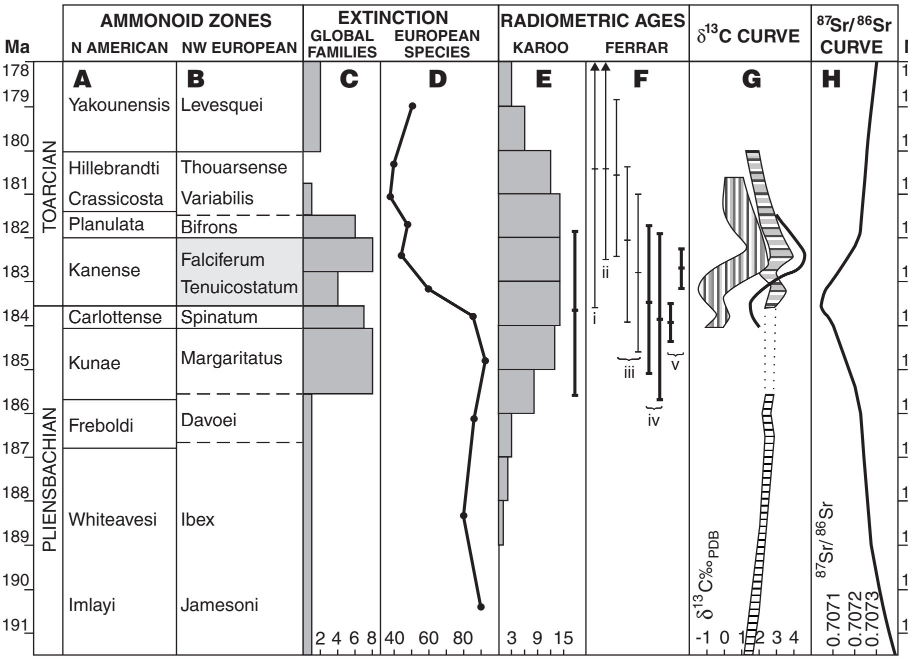

Figure 1. Correlation of marine extinction event, Karoo and Ferrar flood basalt volcanism, and carbon and strontium isotope stratigraphy in numerically calibrated ammonoid zonal chronostratigraphic framework. A: North American regional standard ammonoid zonation (Pliensbachian, Smith et al., 1988; Toarcian, Jakobs et al., 1994); lack of horizontal line between zones indicates that no numeric estimate is available for zone boundary. B: Northwest European standard ammonoid zonation; shading indicates extent of organic-rich deposits in Tenuicostatum and Falciferum zones in western Tethys and northwest Europe. C: Number of global family extinctions by zone (Little and Benton, 1995). D: Cumulative species diversity per zone, expressed in number of species of bivalves, ammonoids, rhynchonellid brachiopods, crinoids, foraminifera, and ostracods from Britain (Hallam, 1996). E: Radiometric ages from Karoo Group (recalculated from published sources with corrected standard ages for ^{40}Ar-^{39}Ar geochronology and 2 σ external errors, unless indicated otherwise) for valid comparison (Renne et al., 1998); age spectrum histogram of 28 ^{40}Ar-^{39}Ar dates with 1 σ internal errors (Duncan et al., 1997) and error bar of U-Pb age (Encarnación et al., 1996). F: ^{40}Ar-^{39}Ar and U-Pb (heavy lines) ages from Ferrar Group (recalculated from published sources with corrected standard ages for ^{40}Ar-^{39}Ar geochronology and 2 σ external errors for valid comparison (Renne et al., 1998). Error bars from left to right: i, composite of 11 ^{40}Ar-^{39}Ar ages by Heimann et al. (1994); ii, composite of two ^{40}Ar-^{39}Ar ages by Foland et al. (1993); iii, three ^{40}Ar-^{39}Ar ages by Duncan et al. (1997); iv, two U-Pb ages by Encarnación et al. (1996); and v, two U-Pb ages by Minor and Mukasa (1997). G: Carbon isotope profiles: horizontal rule—composite profile from Central Apennines, Italy (E. Morettini, 1999, personal commun.); vertical rule—Dorset, England (Jenkyns and Clayton, 1997); solid line—composite curve from Tethyan sections (Jenkyns et al., 1991). H: Seawater ^{87}Sr/^{86}Sr curve simplified from Jones et al. (1994); monotonous decline of curve starts in Hettangian from values >0.7077.

reported two nearly identical incremental heating ^{40}Ar-^{39}Ar ages of 180.4 ± 2.1 Ma. Heimann et al. (1994) reported 11 ^{40}Ar-^{39}Ar plateau ages from the Kirkpatrick Basalt that form a tight cluster and permit a composite age determination of 180.3 ± 3.6 Ma. Basalts from the Kirwan Mountains, East Antarctica, yielded ^{40}Ar-^{39}Ar plateau ages of 180.6 ± 1.8, 182.7 ± 1.8, and 182.8 ± 1.8 Ma (Duncan et al., 1997). Concordant U-Pb ages of 183.4 ± 1.9 and 183.8 ± 1.9 were obtained by Encarnación et al. (1996) from sills within the Ferrar Group. Minor and Mukasa (1997) dated (U-Pb) two samples from the Dufek intrusion (which forms part of the Ferrar Group) as 183.9 ± 0.4 and 182.7 ± 0.5 Ma.

These radiometric ages suggest a short-lived magmatic episode, represented by coeval rocks of the Karoo and Ferrar Groups. Such brevity of volcanism is typical of most other large flood basalt provinces of the world (Coffin and Eldholm, 1994). The cluster of ages around 183 ± 2 Ma is interpreted as the peak of magmatic activity. Additional support for a short-lived magmatic episode is provided by paleomagnetic results. Hargraves et al. (1997) demonstrated that the bulk of basalts in the Karoo province erupted during a single polarity epoch.

REVISED TIME SCALE FOR PLIENSBACHIAN-TOARCIAN TRANSITION WITHIN THE EARLY JURASSIC

The Early Jurassic part of the most widely used time scales is poorly constrained. Previous best estimates for the Pliensbachian-Toarcian boundary are 187.0 ± 15 Ma (Harland et al., 1990) and 189.6 ± 4.0 (Gradstein et al., 1994). We constructed a revised Jurassic time scale, using several recently obtained U-Pb ages from volcanic layers that are also dated by ammonoid biochronology in the North American Cordillera, and additional U-Pb dates compiled from recent reports (Pálfy et al., 2000b). The density and biochronologic resolution of the isotopic age database across the Pliensbachian-Toarcian transition allows, for the first time, the estimation of zonal boundary ages for six consecutive zones. None of the 14 relevant isotopic ages listed in Table 1 were used in earlier time scales. Zonal boundary ages are calculated using the chronogram method (Harland et al., 1990), except for the base of the Crassicosta Zone, which is directly dated in the Queen Charlotte Islands (Pálfy et al., 1997). Ammonoid provinciality warrants the use of the North American regional ammonoid zonal scale (Fig. 1A), which is correlated with the northwest European standard chronostratigraphy following Smith et al. (1988) and Jakobs et al. (1994) (Fig. 1B). Calculated best estimates for initial zonal boundaries are as follows (Fig. 1A): Kunae Zone (early-late Pliensbachian boundary), 185.7 +0.5/–0.6; Carlottense Zone, 184.1 +1.2/–1.6 Ma; Kanense Zone (Pliensbachian-Toarcian boundary), 183.6 +1.7/–1.1 Ma; Planulata Zone, 182.0 +3.3/–1.8 Ma; Crassicosta Zone, 181.4 ± 1.2 Ma.

TOARCIAN STABLE ISOTOPE STRATIGRAPHY

Recognition of a prominent positive δ^{13}C excursion in the Falciferum Zone, along with widespread organic-rich facies, is the basis for defining an early Toarcian oceanic anoxic event (Jenkyns, 1988). Originally the δ^{13}C maximum was thought to be restricted to the Falciferum Zone, but in several Tethyan sections, the rise of δ^{13}C begins in the Tenuicostatum Zone (Jenkyns et al., 1991; Jiménez et al., 1996; E. Morettini, 1999, personal commun.) (Fig. 1G). Organic-rich black shale deposition is also known in the Tenuicostatum Zone in Spain and Italy (Jiménez et al., 1996; E. Morettini, 1999, personal commun.), and manganese-rich deposits are widespread in the Tenuicostatum to Falciferum zones (Jenkyns et al., 1991). Jenkyns and Clayton (1997) argued that such temporal differences stemmed from correlation problems of the ammonoid biochronology, but it is feasible that environmental changes leading to the widespread oceanic anoxia were gradually developing during the first two chrons of the Toarcian.

A δ^{18}O minimum in the Falciferum Zone records a paleotemperature maximum for the Toarcian (Jenkyns and Clayton, 1997). Those authors considered that a correlation with increased CO$_2$ level is a strong possibility supported by low levels of δ^{13}C of organic matter. We note that the CO$_2$ in voluminous volcanic outgassing is a possible cause of greenhouse warming.

TABLE 1. U–Pb ZIRCON DATES FROM BRITISH COLUMBIA USED IN ESTIMATING AGE OF PLIENSBACHIAN AND TOARCIAN ZONAL BOUNDARIES

Dated rock	Locality	U–Pb age (Ma)*	Biochronologic age (zone or *stage*)	
			Maximum	Minimum
Chuchi intrusion	BP Chuchi property	188.5 ± 2.5	Whiteavesi	Kunae
Tuff in Laberge Group	Atlin Lake (East shore)	187.5 ± 1.0	Whiteavesi	Whiteavesi
Tuff in Hazelton Group	Todagin Mtn., Spatsizi area	185.6 +7.3/–0.6	Freboldi	Freboldi
Granitoid boulder in Laberge Gr.	Atlin Lake (Sloko Island)	186.6 +0.5/–1.0[†]	*Sinemurian*	Kunae
Tuff in Laberge Group	Atlin Lake (Copper Island)	185.8 ± 0.7	Kunae	Kunae
Tuff in Hazelton Group	Skinhead Lake	184.7 ± 0.9	Kunae	Kunae
Tuff ("Nordenskiold volcanics")	Whitehorse	184.1 +5.8/–1.6	Kunae	Kunae
Eskay porphyry	Eskay Creek, Iskut River area	184 +6/–1	Carlottense	*Aalenian*
McEwan Creek pluton	McEwan Creek, Spatsizi area	183.2 ± 0.7	Kanense	Planulata
Tuff in Hazelton Group	Mt. Brock range, Spatsizi area	180.4+11.2/–0.4	Kanense	Planulata
Tuff in Whiteaves Formation	Yakoun River, Queen Charlotte Is.	181.4 ± 1.2	Crassicosta	Crassicosta
Tuff in Hazelton Group	Julian Lake	178 ± 1	Yakounensis	*Aalenian*
Eskay rhyolite	Eskay Creek anticline, west limb	175.1 ± 4.7	Yakounensis	*Aalenian*
Eskay rhyolite	Eskay Creek anticline, east limb	174.1 +4.5/–1.1	Yakounensis	*Aalenian*

Note: References to sources of isotopic ages and their biochronologic constraints are given in Pálfy et al. (2000b). See Figure 1 for ammonoid zones.

* External error quoted at 2 σ level.

[†] Maximum age.

PLIENSBACHIAN-TOARCIAN STRONTIUM ISOTOPE STRATIGRAPHY

Temporal variations in the ^{87}Sr/^{86}Sr ratio of the Early Jurassic oceans were measured by Jones et al. (1994) (Fig. 1H) and refined by McArthur et al. (2000). Following a nearly continuous decline from the Hettangian to the Pliensbachian, the curve reaches a minimum at the Pliensbachian-Toarcian boundary and rises in the Toarcian; the steepest slope is recorded for the Falciferum Zone. It is notable that the major Early Jurassic inflection appears to coincide with the inception of Karoo-Ferrar volcanism. The early Toarcian rise can be related to increased humidity and continental weathering, possibly enhanced by acid rain, under escalating greenhouse conditions triggered by volcanic emissions.

DISCUSSION

Synchrony and possible causal links between mass extinctions and continental flood basalts have been postulated by several authors (e.g., Rampino and Stothers, 1988; Stothers, 1993; Courtillot, 1994). However, evidence for precise and reliable correlation was tenuous in many cases. A proposed link between the South African flood basalts and the Pliensbachian extinction (Rampino and Stothers, 1988; Stothers, 1993) was based on a fortuitous coincidence near 190 Ma of the anomalously old K-Ar ages and the overestimate of the Pliensbachian-Toarcian boundary age in older time scales. Duncan et al. (1997) compared their ^{40}Ar-^{39}Ar dating results with the time scale of Gradstein et al. (1994), and suggested that the Karoo volcanism may have contributed to the Toarcian-Aalenian faunal turnover, although the latter does not correspond to an extinction peak. Rampino and Stothers (1988) and Stothers (1993) suggested that the Antarctic flood basalts played a role in a purported Bajocian extinction, but this correlation was based on anomalously young K-Ar ages. Moreover, the Bajocian is not a time of significant extinction (e.g., Benton, 1995).

The two major impediments to establishing synchrony, namely inaccurate dating of mafic igneous rocks and inadequate numeric time scales, are being removed by improved isotopic dating methods, chiefly the U-Pb and ^{40}Ar-^{39}Ar techniques. Now there is a strong case for a temporal relationship between three of the major mass extinctions and magmatic activity associated with large igneous provinces. Eruption of the Siberian Traps coincided with the end-Permian mass extinction at 251 Ma (e.g., Renne et al., 1995), a volcanic spasm of the Central Atlantic Magmatic Province at 200 Ma (Marzoli et al., 1999), and is coeval with the end-Triassic crisis (Pálfy et al., 2000a), whereas the end-Cretaceous mass extinction occurred at 65 Ma during paroxysmal volcanism of the Deccan Traps (Baksi and Farrar, 1991). As demonstrated here, the synchrony of the Pliensbachian-Toarcian extinction and volcanism of the Karoo-Ferrar large igneous province is now well established at 184–182 Ma. Such temporal coincidence requires consideration of a possible causal linkage.

The end-Pliensbachian reversal and Toarcian increase of the Sr isotope ratio is suggested to record the onset of Karoo-Ferrar volcanism. A similar inflection occurs in the Late Permian, although it appears to predate slightly the Siberian Traps (Martin and Macdougall, 1995). The formation of the Central Atlantic Magmatic Province around the Triassic-Jurassic boundary coincides with a downturn of the Sr curve. Modeling results suggest that continental flood basalt volcanism could alter seawater chemistry via enhanced weathering and increase of riverine flux (Martin and Macdougall, 1995). We speculate that changes of opposite sense across the Triassic-Jurassic boundary may reflect the equatorial latitude of the Central Atlantic Magmatic Province (vs. the middle- to high-latitude Siberian Traps and Karoo-Ferrar province), whereby basalt weathering exerts greater influence on the oceanic Sr budget and explains a shift toward less radiogenic values (Taylor and Lasaga, 1999).

The sudden climate and other environmental changes associated with the Karoo-Ferrar volcanism could have triggered the end-Pliensbachian extinction. The early Toarcian sea-level rise may or may not be related to the mantle plume under southern Gondwana and associated tectonic processes, but it would have had significant environmental impact. With intense volcanism sustained for 1–2 m.y., further climate warming occurred (as recorded in the δ^{18}O curve). Oceanographic changes induced by coupled effects of warming, transgression, and increased nutrient availability via more intensive weathering generated an oceanic anoxic event that started in the Tenuicostatum Zone. Indication of increasing productivity during the early Toarcian (Vető et al., 1997), clearly a factor in black shale formation, raises the possibility of volcanically derived iron fertilization of the world ocean (Coale et al., 1996). Peak extinction of marine benthos, observed at the species level in the Falciferum Zone, coincided with maximum spread of anoxic bottom waters. The pulse of flood basalt volcanism likely waned by the time of the end of the Bifrons Zone. Despite several parallels with the end-Permian mass extinction (linked to flood basalt eruption, climate warming, anoxia, and isotopic trends), the Pliensbachian-Toarcian extinction is clearly of much lesser magnitude. Besides the smaller size of the Karoo-Ferrar igneous province, its position at high southern latitude might also explain its less severe effect on the biota.

Future research should test the possible role of Karoo-Ferrar volcanism in triggering environmental change and concomitant mass extinction by quantitatively modeling the scenarios outlined herein, i.e., the possible effects of volcanic output on the biogeochemical cycles, climate, and seawater Sr isotope evolution.

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