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Paleomagnetic Constraints on the Permian-Triassic Boundary in Terrestrial Strata of the Karoo Supergroup, South Africa: Implications for Causes of the End-Permian Extinction Event

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Abstract

The closure of the Palaeozoic witnessed the greatest biotic crisis in earth history. Surprisingly little is known about the effects and timing of the terrestrial counterpart of the well-described End-Permian mass extinction from known marine successions worldwide. In the present study, reliable paleomagnetic results were obtained from a PT boundary section in the terrestrial Karoo Basin of South Africa. Permo-Triassic aged mudstones from a locality in the Eastern Cape Province yielded two magnetic chrons, reverse followed by normal (with the boundary possibly close to the reversal). This extends to results from a previous study: thereby jointly identifying a R/N/R polarity pattern for this boundary interval. The PTB interval is constrained below the red mudstones of the Beaufort Group at the present locality and within reverse-magnetised green mudstone, implying a diachronic relation between the marine and terrestrial End-Permian mass extinction events.

Keywords: Permian-Triassic boundary, extinction, paleomagnetism, Karoo Supergroup, South Africa.

Introduction

The end of the Permian Period is marked by the greatest mass extinction in the history of life (Erwin, 1993). It is estimated that there was a species-level extinction in the marine environment of between 75% (Hoffman, 1985) and 96% (Raup, 1979). Our knowledge of the Permian-Triassic boundary (PTB) is almost exclusively based on the study of marine successions in Europe and Asia. Although it has been suggested that a similar extinction event took place in the terrestrial environment (Retallack, 1995; Hallam and Wignall, 1997), its extent and whether it was exactly synchronous with the extinction event in the marine environment is not yet proven. Solving this problem is critical, as it could help narrow down the field of possible causes of the extinction.

Arguably one of the best-preserved terrestrial successions spanning the PTB is represented by the Beaufort Group of the Karoo Basin in South Africa (Fig. 1). This basin had no connection to the open ocean during the Late Permian (Hancox, 2000). The Beaufort Group is world renowned for its abundance of Late Palaeozoic and Early Mesozoic vertebrate fossils, providing a means of biostratigraphic subdivision (Rubidge, 1995). At present the PTB is taken at the last appearance datum (Smith, 1995; MacLeod et al., 2000) of vertebrate fossils of the *Dicynodon* Assemblage Zone followed by the continued (Smith 1995; Ward et al., 2000) presence of the synapsid reptiles and amphibians of the *Lystrosaurus* Assemblage Zone. The *Lystrosaurus* Assemblage Zone has been proposed as a standard for the correlation of the non-marine Latest Permian and Early Triassic (Lucas, 1998). *Lystrosaurus? sp.* (Shishkin et al., 1986) has been reported form the lower Norilskian basalts of the Tungusska Basin, Siberia (A proposed candidate for the continental GSSP of the Permian-Triassic boundary (Lozovsky, 1998)). The Norilsky region intrusions are correlated to the Mokulaevskyi basalt (248±4 Ma; Campbell et al., 1992). If this occurrence of *Lystrosaurus* can be confirmed it would imply a Late Permian-Early Triassic age for the first occurrence of *Lystrosaurus* within these strata.

The PTB interval in the Karoo Basin is also marked by negative excursions in $\delta^{13}C_{carbonate}$ values (Thackery et al., 1990; McLeod et al., 2000), similar to that observed in marine successions (Musashi et al., 2001). It is not clear at present which negative spike correlates with which event. In the Karoo Basin, the boundary interval is thought to occur in the Palingkloof Member of the Balfour Formation of the Beaufort Group (Hiller and Stravakis, 1984). However, the exact placement of the PTB in the succession is not constrained because of the sporadic stratigraphic distribution of macrofossils and carbonate concretions for isotopic analysis, overlap of biostratigraphic units and the lack of suitable ash layers for radiometric dating. These problems have been addressed by Smith (1995), who indicated the extinction of Permian dicynodonts to be associated with a facies transition, suggested to be the result of a change in fluvial style from meandering to low sinuosity channels. Smith and Ward (2002) indicated the presence of a "lifeless" event bed coinciding with this facies transition. However, it has not been proven that this horizon can be correlated to the chronostratigraphic PTB.

Due to this inaptness of the above mentioned stratigraphic methods to establish the exact position of the chronostratigraphic PTB in terrestrial successions, the synchronicity of the mass extinction events in the marine and non-marine environments has not been discussed in much detail. Paleomagnetic studies might hold the answer to both the problems of stratigraphic placement and correlation of the chronostratigraphic PTB in time and space. An earlier study of folded Late Permian Beaufort strata adjacent to the Cape Fold Belt suggested pervasive remagnetisation associated with Jurassic deformation and intrusion of numerous dolerite dykes and sills (Ballard et al., 1986). Subsequently Kirschvink and Ward (1998) sampled two profiles well away from the Cape Fold Belt, but results also indicated partial or complete remagnetisation by Jurassic dolerite intrusions. In the present study the Permian-Triassic boundary interval was sampled in flat lying strata of the Palingkloof Member at Komandodrifdam (Fig. 1) in an area with sparse dolerite intrusions. Fossil bone fragments at Komandodrifdam are light coloured, indicating low thermal maturity (Smith, 1995). Results show a polarity chron pattern that constrains the approximate Permian-Triassic boundary interval in the succession more accurately and allows for comparison with the End-Permian mass extinction events as seen in marine successions worldwide.

Stratigraphy

The profile (Fig. 2) is characterised by massive greenish-grey mudstone and siltstone containing abundant vertebrate fossils and isolated carbonate concretions. Fine-grained greenish-grey stacked, lenticular and sheetlike sandstone bodies grade upwards into drab mudstone or siltstone. These sandstones are for the most part massive

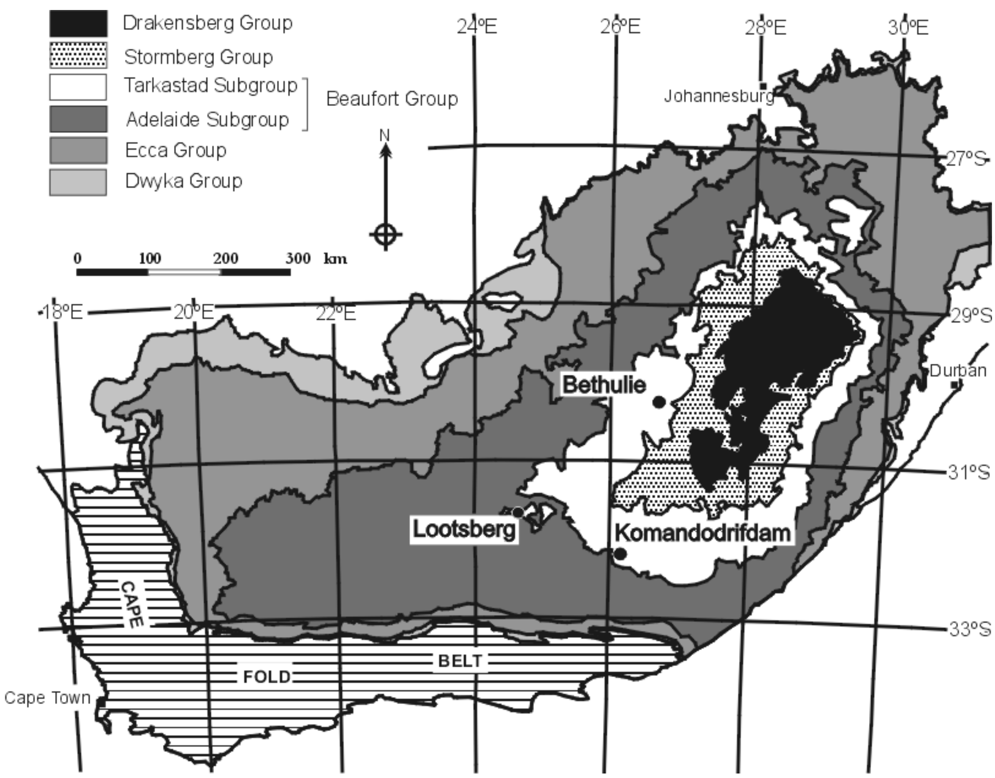

Fig. 1. An overview map of the Karoo Basin of South Africa, with the location of profiles discussed in the text.

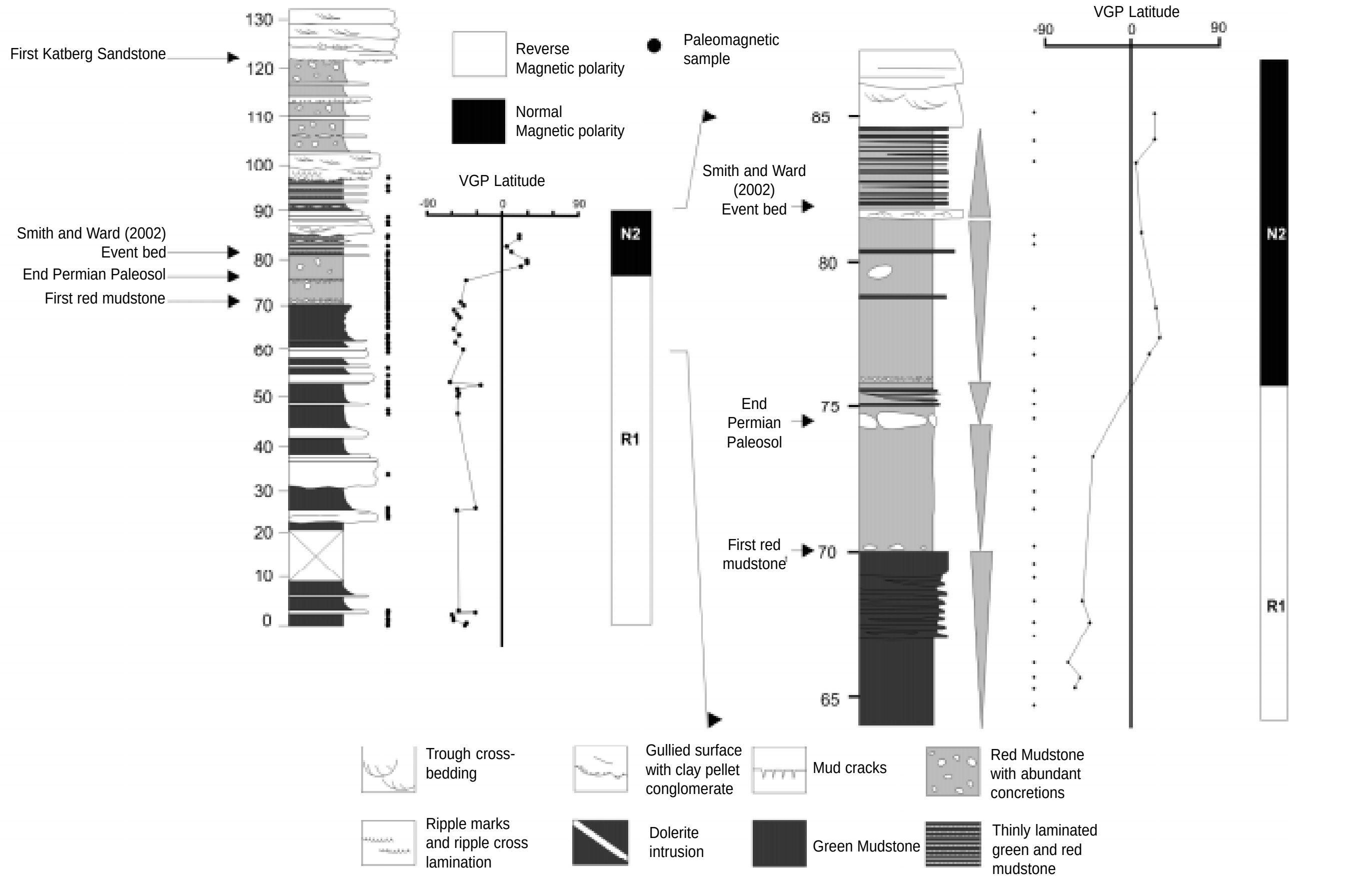

Fig. 2. Magnetostratigraphic results from Komandodrifdam. The stratigraphic profile of the PTB interval is given with detailed lithostratigraphy for the interval in which a change in magnetic polarity occurs. Paleomagnetic sample positions are indicated and those that yielded significant results are plotted as VGP's (virtual geographic poles) against the stratigraphic height. An interpretation of magnetic polarity is given.

with sharp basal contacts. A layer, at 73 m, of small irregular grey carbonate concretions foregoes a rapid change in lithology from green mudstone to red mudstone. Roughly six metres above this level a prominent concretionary layer of brown-weathering calcareous nodules is developed in reddish mudstone. This is the first occurrence of brown-weathering calcareous nodules and is the horizon that is taken as a lithological expression of the last appearance datum (LAD) of *Dicynodon* assemblage animals (Smith 1995; Smith and Ward, 2002). It is referred to here as the End-Permian Paleosol or EPP, and is well developed throughout the Karoo basin and serves as a good marker bed for lithological correlation (Rubidge 1995). Roughly six metres above the EPP a laminated horizon of red and green mudstone of 2.6 m is developed. This is the horizon proposed by Smith and Ward (2002) as the PTB event bed. At Komandodrifdam it occurs 12 m above the first occurrence of red mudstone.

Sandstones above the 73 m level are fine-grained stacked lenticular sand bodies with irregular bottom surfaces, characterised by intraformational clay-pellet conglomerates and bone fragments. The sandstones also exhibit trough cross-bedding and ripple marked surfaces in places and grade upward into red mudstone. Medium-grained stacked sheetlike sandstone bodies of the Katberg Formation conformably cap this succession of reddish mudstone and fine-grained sandstones.

Sixty-three closely spaced (see Fig. 2 for sampling positions) and individually orientated core samples of fine-grained lithologies were collected from the profile using standard sampling techniques (Butler, 1992).

Method

All paleomagnetic analyses were completed at the California Institute of Technology paleomagnetics laboratory, using a 3-axis DC-SQuID moment magnetometer with an 80-specimen automatic sample changer. AF demagnetisation of samples was performed with a computer-controlled, three-axis coil system in line with the SQuID magnetometer, while thermal demagnetisation was performed in a magnetically shielded furnace. All samples were subjected to a series of low AF demagnetisation steps of 2 mT up to 10 mT to remove any viscous components of magnetisation introduced during the field sampling and transportation. Samples were then treated to approximately 30 steps of thermal demagnetisation. Starting from 100°C up to 325°C in 25°C steps, in 15°C increments to 415°C and in 10°C or 15°C steps up to 675°C or until the samples became unstable. Approximately 2600 measurements, each of which was based on 24 independent readings of magnetisation in two orientations (up and down), were performed on 70 samples. Demagnetisation data were obtained using principle component analysis (Kirschvink, 1980), including both line and plane analyses. Analyses were performed in the computer programs PaleoMac 5.4 (Cogné, 2003) and Paleomag 3.1 (Jones, 2002). Only demagnetisation lines with maximum angular deviation (MAD) angle values ≤ 10°, and planes ≤ 15° were included in the subsequent analysis. For the purpose of polarity stratigraphy, demagnetisation lines with MAD values ≤ 15°, and planes ≤ 15° were accepted. Rockmagnetic experiments were carried out on typical greenish- and red mudstone samples.

Results

The average magnetic moment of the greenish mudstones and red mudstones of the Palingkloof Member is relatively low to moderate and generally consists of two stable vector components (A present field component is separated from what is inferred to be the Permian-Triassic component, which is more stable against demagnetisation). The greenish mudstones (Fig. 3A) are characterised by a north-northwest directed, steep normal direction (present field direction, removed at weaker demagnetisation levels) that overprints clear great circle arcs in the temperature range from 350°C to 550° towards the Permian-Triassic reverse direction. Demagnetisation planes representative of the ChRM (chemical remanent magnetisation) were isolated in 21 samples and were included in the final pole analysis. The same steep present field overprint direction was present in the red mudstones (Fig. 3B). At higher temperatures, a secondary, shallower direction, towards the Permian-Triassic normal direction, unblocked.

The acquisition and AF demagnetisation of isothermal remanent magnetisation suggest that only magnetic phases of low coercive force are present in the greenish mudstone as the samples reach saturation at 300mT. The normalised thermal demagnetisation curve exhibits blocking temperatures at 350°C and ca. 550°C, probably corresponding to maghemite and magnetite respectively (McElhinny and McFadden, 2000). The overprint direction also unblocks at 350°C, suggesting that maghemite is the

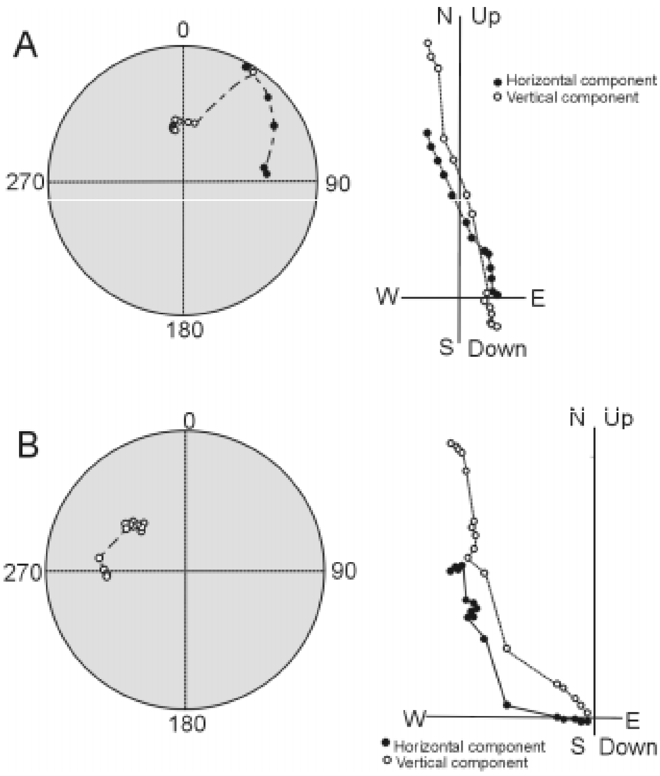

Fig. 3. Demagnetisation data for representative samples. A. Equal area diagram and orthogonal projection showing the demagnetisation behaviour of a representative green mudstone sample. B. Equal area diagram and orthogonal projection showing the demagnetisation behaviour of a representative red mudstone sample. On equal area diagrams solid (open) symbols indicate downward (upward) directions and on orthogonal projections solid symbols represent the horizontal component of remanance vector, open symbols represent the remanance vector in the east/west vertical plane.

magnetic carrier for this direction. The present field overprint is, therefore, thought to be in part a chemical remanent magnetisation (ChRM) due to the oxidisation of magnetite to maghemite in the modern near-surface environment. Magnetite could also be a carrier of the overprint direction, and the direction, in such cases, would be a viscous remanent magnetisation (VRM). The AF demagnetisation curve of the isothermal remanent magnetisation acquisition is below the saturation IRM curve for the greenish sample and constitutes a positive Lowrie-Fuller test (McElhinny and McFadden, 2000) for single domain grains of magnetite. The ChRM corresponds to the higher unblocking temperatures of magnetite in all of the samples, thus implicating single domain magnetite as the carrier of the remanence.

The acquisition and AF demagnetisation of IRM suggest that magnetic phases of low and high coercive force are present in the red mudstone, as the sample does not reach complete saturation at 300mT. Samples are completely demagnetised by ca. 650°C, which corresponds to the unblocking temperature of fine-grained hematite (McElhinny and McFadden, 2000). The overprint direction in the red mudstone, like in the greenish mudstone, is interpreted to be a VRM. The main carrier of ChRM in the red mudstone is hematite.

For the P-Tr normal direction (Fig. 4A), both demagnetisation planes and lines were available, and an average direction was easily calculated using the method of McFadden and McElhinny (1988).

For the P-Tr reverse directions (observed in the greenish mudstone and red mudstone), only demagnetisation planes were available for analysis and the method of McFadden and McElhinny (1988) gave a pole direction (Fig. 4B) that is highly suspect. The calculated pole is situated at a position (Fig. 4B) that demands demagnetisation in a westerly direction. This was not the case. The bias in the method, when using only plane data, can be bypassed by making use of arc constraints (McFadden and McElhinny, 1988). Sector constraints (the last stable data point on the arc and the direction that is located 180° along the arc from its starting point) restrict analysis to those parts of the great circle arcs outside of which the true direction is unlikely to lie. The introduction of these constraints visibly and statistically improves the result (Fig. 4B).

It is obvious that a clear stratigraphic distinction exists in the section (Fig. 2). With samples above about 80 level (Fig. 2) being of normal polarity and samples below being reverse. Although the ChRM directions from Komandodrifdam are clearly split into normal and reverse (Fig. 4A and B), strict antipodality could not be achieved as a result of secondary overprint components, which are present in nearly all of the samples. A few samples yielded dubious polarities and these were discarded. The first normal polarity is recorded in red mudstone above the so-called EPP. All of the strata sampled at Komandodrifdam above this horizon yielded normal polarities, including the finely interbedded red mudstone and green silt-/mudstone of the proposed event bed of Smith and Ward (2001). This normal polarity association of the event bed of Smith and Ward (2001) is consistent with data obtained from the same interval at Lootsberg Pass (Kirschvink and Ward, 1998), situated approximately 125 km to the northwest of Komandodrifdam. This serves as a positive consistency test for magnetic polarity within the Karoo Basin.

At Lootsberg Pass, Kirschvink and Ward (1998) were able to demonstrate a positive baked contact test, thereby establishing that their inferred Permian-Triassic direction is primary and that this direction was later overprinted only by a dolerite intrusion. This remagnetisation, however, is narrowly associated (in space) with the intrusion and not widespread as suggested by Ballard et al. (1986).

Mean pole directions (Table 1) were obtained using Fisher statistics and the method of McFadden and McElhinny (1988) for combining demagnetisation planes and lines. The mean PT direction for Komandodrifdam is in excellent agreement with the PT pole of Kirschvink and Ward (1998) for the Palingkloof Member at Lootsberg Pass with $\gamma_0 = 1.4°$ and $\gamma_c = 6.4°$. The two directions also pass the test for common k (McFadden and McElhinny, 1990) at the 99% confidence level. The upper normal polarity interval identified in this study is correlative with the basal normal polarity interval of Kirschvink and Ward (1998) based on the position of the EPP in both sections. The presence of layer-bound magnetic polarity zones in combination with the field tests for stability (baked contact test and test for magnetic polarity stability) strongly suggests that the magnetisation was acquired shortly after deposition during Late Permian-Early Triassic times. The PT mean direction scores a perfect 7 on the "Q" reliability criteria scale of Van der Voo (McElhinny and McFadden, 2000).

Discussion

Two magnetic chrons, reverse (R1) followed by normal (N2) were identified at Komandodrifdam in the present study. This extends to the results from a previous study (Kirschvink and Ward, 1998), which had identified an N/R pattern. The upper reverse magnetic chron identified by Kirschvink and Ward (1998) at Lootsberg was not sampled at Komandodrifdam, but can be assumed.

The first normally magnetised sample of the N2 normal polarity interval at Komandodrifdam is situated within an increment of red mudstone (Fig. 2), which is stratigraphically constrained by a mature alluvial paleosol at its base. Samples from the increments immediately below this paleosol (red mudstone as well as green mudstone) yielded reversed polarities. The flip in magnetic polarity from R1 to N2 can accordingly be placed at the stratigraphic level immediately at the paleosol horizon developed above the prominent concretionary horizon known as the End Permian paleosol or EPP (Fig. 2).

The Permian-Triassic boundary (PTB) is positioned at or very near to the end of a reverse polarity zone within marine strata (Heller et al., 1995), but within the Karoo the mass extinction of mammal-like reptiles occurred during a time of normal polarity (Fig. 5). It follows that the extinction of mammal-like reptiles in the Karoo Basin (and as such the extinction in the terrestrial environment) cannot be correlated with the inferred PTB as observed in marine successions worldwide. This conclusion is, however, very much dependent on the exact placement of the end of the *Dicynodon* Assemblage Zone. Currently this is placed about 12 m above the flip in polarity

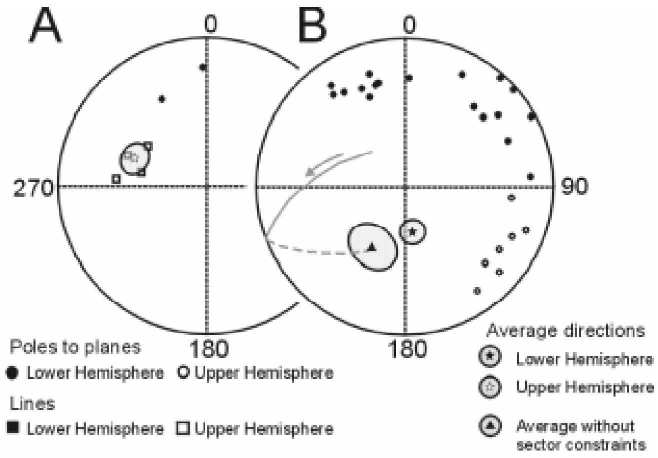

Fig. 4. Mean pole directions from demagnetisation data. A. Equal area plot showing demagnetisation planes (plotted as poles to planes) and lines for the normal ChRM as observed in samples from Komandodrifdam, and the average normal direction obtained from them. B Equal area plot showing the average reverse direction obtained from demagnetisation planes (plotted as poles to planes) for the reverse ChRM seen at Komandodrifdam. Both the direction calculated without sector constraints (triangle symbol) and its required demagnetisation path by definition as well as the improved direction calculated with the use of sector constraints is shown (star symbol)

(R1 to N2) seen at Komandodrifdam and correlated to Lootsberg Pass (the type locality for the *Lystrosaurus* Assemblage Zone (Rubidge, 1995) and the Lootsbergian land-vertebrate faunachron of Lucas (1998)), and about 100 m below the flip in polarity (N2 to R2) indicated at Lootsberg Pass (Kirschvink and Ward, 1998). This paleontological placement of the extinction at Lootsberg Pass is unlikely to be wrong, due to the long history of vertebrate fossil collecting in this area. It is also a possibility that there initially was an additional reverse polarity interval present in the Permian-Triassic boundary interval in the southern main Karoo Basin, but the reported overlap (Smith, 1995; MacLeod et al., 2000; Ward et al., 2000) between the occurrences of *Dicynodon* and *Lystrosaurus* during the latest Permian argues for continuous sedimentation across this boundary interval. It follows that for the global marine extinction to take place during an interval of reverse polarity it may either precede (placed within the R1 reverse interval) or follow (placed in the R2 reverse interval) the terrestrial extinction as observed in the main Karoo Basin. Thus it can either be assumed that at least 12 m of older normally magnetised strata, or a minimum of a 100 m of younger normally magnetised strata separates the extinction of mammal-like reptiles from the mass extinction event as seen in the marine realm. The first possibility is favoured, as age constraints imposed by the biostratigraphy would be much better approximated.

As previously mentioned the Permian-Triassic boundary is marked by mirrored multiple negative stable carbon isotopic anomalies in $\delta^{13}C_{carbonate}$ and $\delta^{13}C_{organic}$ values (Musashi et al., 2001, Holser et al., 1989). In the uppermost part of the Permian $\delta^{13}C_{carbonate}$ values decline continuously to a minimum near the boundary only to return to more normal values in the Upper Griesbachian, 1-3 million years after the extinction (Holser et al., 1989). The presence of a mirrored negative anomaly or anomalies in $\delta^{13}C_{carbonate}$ and $\delta^{13}C_{organic}$ values within the Karoo Basin has been indicated by Thackery et al. (1990), MacLeod et al. (2000) and more recently by De Wit et al. (2002). De Wit et al. (2002) showed large oscillations in the $\delta^{13}C_{organic}$ values occurring before and after the Permian-Triassic transition. It is at present not yet clear which of these negative spikes correlates with which event (marine or terrestrial extinction), in fact it is presently unknown just how many negative anomalies there are recorded within the Karoo sedimentary rocks and how, and if, these are related to any extinction event at all. What can be established from carbon isotopic data at present is those stratigraphic intervals that are characterised by a "quiet" isotopic signature and those that are characterized by an oscillating or "noisy" isotopic signature (Fig. 5). Within the Karoo Basin the commencement of "noisy" isotopic signatures roughly corresponds to the interval of overlap between the *Lystrosaurus* and the *Dicynodon* assemblage zones (MacLeod et al., 2000). The limitations of their (MacLeod et al., 2000) data set should, however, be kept in mind, most important of which is possibly the sporadic stratigraphic occurrence of carbonate concretions (especially within green mudstone). From marine successions it is clear that the marine extinction event and as such the PT boundary *senso stricto* coincides with a large negative anomaly in carbon isotopic values and as such occurs during a time of a "noisy" isotopic signature as well as within a period of reverse magnetic polarity. These associations of the boundary with reverse magnetic polarity and a "noisy" carbon isotopic signature occur within the Karoo Permian-Triassic interval only more than 12 m stratigraphically below the biological event bed of Smith and Ward (2001), and as such the terrestrial extinction event at the Komandodrifdam locality (Fig. 5).

The interval of reversely magnetised rock and coinciding occurrence of both *Dicynodon* and *Lystrosaurus* Assemblage Zone animals is apparently narrowly associated with a sudden change in lithology from predominately green mudstone to red mudstone (Fig. 5). Recently this change in lithology was interpreted (Smith, 1995; Ward et al., 2000) as the expression of a changing fluvial style from predominantly meandering in the Late Permian to braided in the Early Triassic. The first occurrence of red mudstone at Komandodrifdam is part

Table 1. Paleomagnetic results from the Komandodrifdam PTB interval.

Directions	N (L,C)	Dec	Inc	k	α95	VGPLat	VGPLong
Komandodrifdam (KDPT)							
Overprints:							
Present field	52 (52,0)	334.6	-61.8	56.1	2.8	N 67.3	W 99.7
Primary Directions:							
All Reverse	26 (0,26)	168.7	65.1	41.8	6.6	S 72.7	W 127.2
All Normal	9 (7,2)	290.2	-56.8	12.3	16.5	N 33.7	W 90.2
Combined	35 (7,28)	311.9	-61.6	17.8	7.6	N 50.9	W 93.7

of a whole increment of sedimentation capped by a paleosol, the EPP. The EPP occurs six metres above the lithological transition. Red mudstone does not cut into the increment directly underneath, which is also capped by a paleosol, developed at the 73 m level (Fig. 5). It can be concluded that the occurrence of red mudstone is depositionally constrained and not cross-cutting diagenetic. This change from predominantly green mudstone to red mudstone must accordingly be explained by a change in diagenetic conditions and a change to more oxidizing conditions at that. One way to achieve this is by a drop in the ground water table brought about by a sudden drying out of climate. Another way is by lowering the amount of organic carbon in the system and forcing reducing conditions to become more oxidizing. Either of these options calls for a dramatic environmental change. Dramatic environmental change can be expected from an event that was responsible for the extinction of 96% of marine organisms. It is therefore argued with much reserve that if the chronostratigraphic PTB is to be placed anywhere in the terrestrial boundary interval, it is more likely to coincide with the lithological change and the first appearance of red mudstone in the sequence (Fig. 5).

When the magnetostratigraphic section from the southern main Karoo Basin is compared to the already published magnetostratigraphic sections in marine strata from China (Heller et al., 1995; Heller et al., 1988; Steiner et al., 1989), Pakistan (Haag and Heller, 1991) and Europe

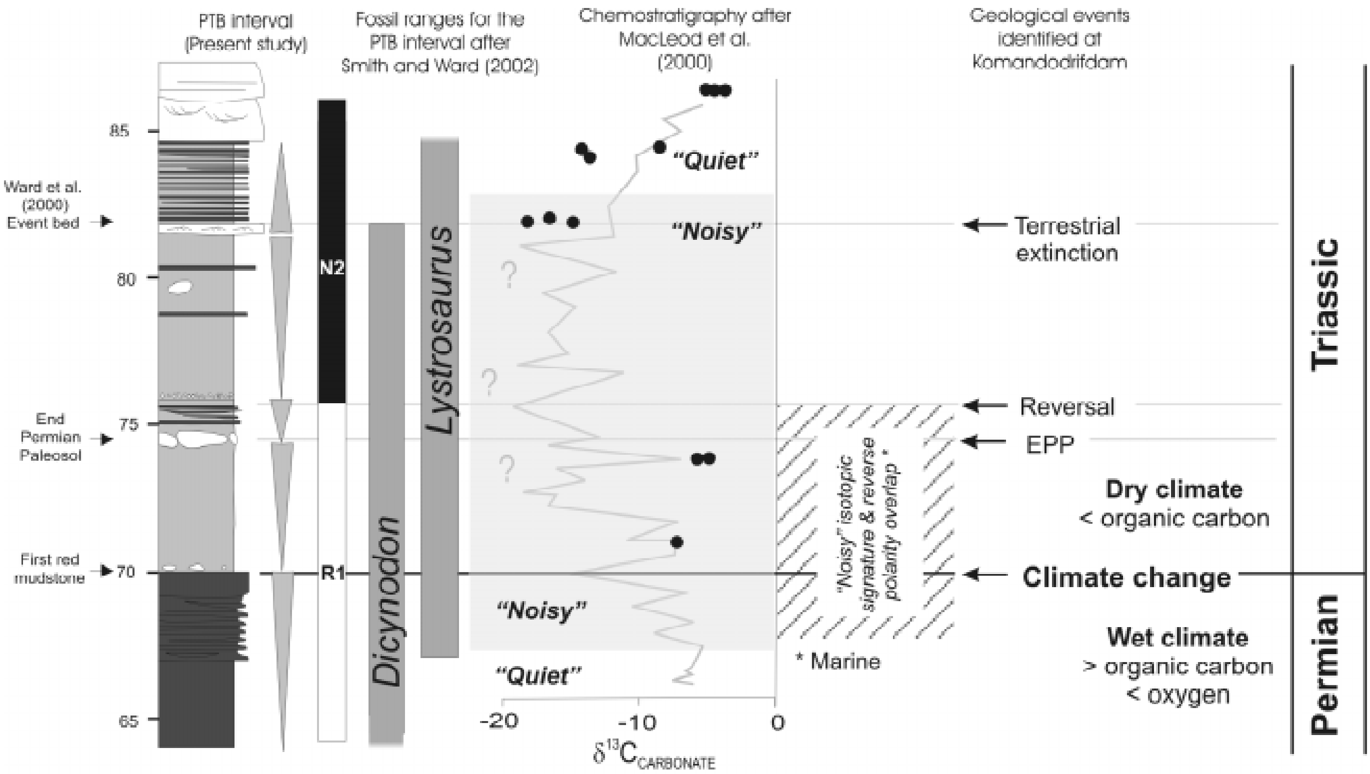

Fig. 5. Placement of the Permian-Triassic boundary based on lithostratigraphy and magnetostratigraphy results from Komandodrifdam and biostratigraphy and stable isotope geochemistry in the Karoo Basin across the assumed PTB interval.

(Mørk et al., 1999; Scholger et al., 2000), some common features become apparent. A reverse polarity interval is observed in the Upper Permian. The lower proportion of the Early Triassic is characterized by a normal polarity interval; this is followed again by a reverse polarity. The Permian as a whole is characterized by a main R-N-R-N-R sequence (Heller et al., 1995). Of this polarity sequence only the last reverse polarity interval, R-N-R-N-R, could be retrieved from the main Karoo Basin (if the age constraints provided by biostratigraphic units are to be believed), but this reverse polarity was followed by a N-R pattern, thus yielding a R-N-R pattern in the main Karoo Basin.

Conclusions

The PTB is thought to be situated along the contact between green- and red mudstone, associated with a reverse magnetic polarity chron and a "noisy" isotopic signature (Fig. 5). This position of the PTB is stratigraphically lower than previously suggested and well below the extinction of mammal-like reptiles of the *Dicynodon* Assemblage Zone.

Data show that that the terrestrial extinction, as currently defined, postdates the marine extinction event observed globally. The two events are thus diachronous. This illustrates that the events could not have been catastrophic, although the marine event and terrestrial event as a separate entities may well have been catastrophic. The following question now begs answering: was the terrestrial extinction a real extinction? And if "yes", was it linked to the marine extinction event? The PTB as defined in marine successions is correlated with the change from green to red mudstone in the terrestrial succession at Komandodrifdam, which represents a change in climatic conditions from a wet to dry. *Dicynodon* survived for some time after the drying of the climate set in and *Lystrosaurus* appeared before it. Is the appearance of *Lystrosaurus* and the disappearance of *Dicynodon* linked to the Permian-Triassic change? This does not appear to be the case and it is argued that fossils from the *Dicynodon* and *Lystrosaurus* assemblage zones (as defined at present) are not good index fossils for the PTB.

These data present two alternatives when evaluating possible causes for the extinction event(s). If it is assumed that the mass extinctions (observed in the marine and terrestrial environments), though diachronous, can have a causal relationship: when evaluating primary causes for the End-Permian event this relationship between marine and terrestrial extinctions should be taken into account, as it eliminates hypotheses that predict synchronous extinction in both environmental settings as well as hypotheses that predict extinction in one type of environmental setting, but not the other. This pattern of thought eliminates possible extinction hypotheses like extraterrestrial impact or cosmic radiation. It also eliminates possibilities that would only be responsible for extinction in marine settings, like salinity change, etc. It does, however, leave possibilities such as flood basalt volcanism, clathrate/methane release and climatic change open for debate.

On the other hand it could also be assumed that the extinction in the marine environment and the extinction on land are unrelated. This opens those mechanisms that would exclusively affect the marine setting once again as possible causes for the End-Permian event. Extraterrestrial impact or cosmic radiation is, however, still outside the field of possible causes.

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