The terrestrial Permian-Triassic boundary event bed is a nonevent

Robert A. Gastaldo[1], Johann Neveling[2], C. Kittinger Clark[1], Sophia S. Newbury[1]
[1]Department of Geology, Colby College, Waterville, Maine 04901, USA
[2]Council for Geosciences, Private Bag x112, Silverton, Pretoria 0001, South Africa

ABSTRACT

A unique isochronous interval in the Karoo Basin, South Africa, previously has been interpreted to postdate vertebrate extinction at the Permian-Triassic boundary in the Bethulie area, Lootsberg Pass, and elsewhere. It is demonstrated that the laminated beds, or laminites, in the Bethulie region are stratigraphically indistinct. The heterolithic interval exposed on the Heldenmoed farm is ~8 m below the Bethel farm section, <1 km away. At Lootsberg Pass, the laminated interval is below the Permian-Triassic boundary as defined by vertebrate biostratigraphy, rather than overlying it. Hence, this interval, critical to models of end-Permian mass extinction, is neither isochronous across the basin nor unique. Rather, the lithofacies represents avulsion channel-fill deposits within aggradational landscapes. South African models for the response of terrestrial ecosystems to the perturbation in the marine realm require critical reevaluation.

INTRODUCTION

The response of terrestrial ecosystems to the end-Permian perturbation recorded in the oceans (Erwin, 2006) is based primarily on the vertebrate biostratigraphic record from South Africa (e.g., Ward et al., 2005) and Russia (Benton et al., 2004). In Gondwana, the latest Permian *Dicynodon* assemblage zone is replaced by the Early Triassic *Lystrosaurus* assemblage zone (e.g., Smith, 1995) and linked to changes in Karoo Basin fluvial architecture transitioning from the Balfour to Katberg Formations (Ward et al., 2000). This was interpreted variously as a sedimentological response to orogenic loading in the Cape Fold Belt (Hiller and Stavrakis, 1984; Catuneanu et al., 1998), increasing aridity (Smith, 1995), and the loss of the *Glossopteris* flora (Ward et al., 2000), the last two occurring essentially coeval with the boundary event (Ward et al., 2005). The stratigraphic positions of the vertebrate extinction and transition in fluvial styles are associated with a unique boundary facies described from the Bethulie area, southern Free State Province, South Africa (Ward et al., 2000; Retallack et al., 2003). The interval is reported as regionally correlative across the basin (Ward et al., 2005; Botha and Smith, 2006) and is recognized elsewhere (Australia, Antarctica; Retallack et al., 2003).

The unique boundary facies consists of several meters of laminated sandstone and shale, directly overlain and underlain by sheet sandstone interbedded with siltstone (Smith and Ward, 2001), based on outcrops at Lootsberg Pass, Eastern Cape Province, and near the town of Bethulie (Smith and Ward, 2001, p. 1147). It also is reported from Wapatsberg (sic), Eastern Cape Province, and Tweefontein, Free State. Ward et al. (2000, their Fig. 1) placed the Permian-Triassic boundary either at the base of (i.e., Lootsberg Pass, Bethulie) or within the heterolithic interval (Old Lootsberg W). Smith and Ward (2001, their Fig. 1) designated it as the event bed, due to the presence of a negative $\delta^{13}C$ excursion in the underlying carbonate-nodule bearing siltstone interpreted as the expression of the Chinese marine Permian-Triassic boundary signal (MacLeod et al., 2000). Smith and Ward (2001) considered it as the lifeless zone, although subvertical burrows of moist soil-inhabiting invertebrates occur near the top (Gastaldo and Rolerson, 2008).

This study focuses on the lateral correlatives and stratigraphic relationships of the laminated event bed, or laminites (Retallack et al., 2003), in Bethulie and Lootsberg Pass. It is demonstrated that, across <1 km between the Bethel to Heldenmoed farms (Bethulie District), laminated event beds are neither correlative nor at the same stratigraphic position. At Lootsberg Pass, ~225 km southeast, the laminites are stratigraphically beneath the Permian-Triassic boundary nodules reported as the end-Permian paleosol (Retallack et al., 2003).

GEOLOGIC SETTING

Karoo Basin sedimentation began in the Permian–Carboniferous and continued into the Jurassic (Johnson et al., 1997). The entire stratigraphic section, as much as 12 km thick, is known as the Karoo Supergroup. Most of the continental deposits are grouped in the aerially extensive Beaufort Group (Johnson et al., 1997), subdivided into the Adelaide and Tarkastad Subgroups. The fluvio-lacustrine deposits of the Balfour Formation, the uppermost unit of the Adelaide Subgroup, are dominated by high-sinuosity fluvial regimes (Hiller and Stavrakis, 1984; Smith, 1995). The base of the overlying Katberg Formation, representing braid-plain deposits (Hiller and Stavrakis, 1984), marks the Tarkastad Subgroup boundary (Johnson et al., 1997). The exposures under investigation in the Bethulie area (Fig. 1) and Lootsberg Pass belong to the Palingkloof Member, Balfour Formation, and are overlain by the Katberg Formation (Neveling, 2004).

PREVIOUS EVENT BED DESCRIPTIONS

Only generalized descriptions are available for the laminated (heterolithic) interval in the Bethulie area (Bethel, Heldenmoed, and Fairydale farms; Tussen die Riviere Game Reserve [Caledon; Ward et al., 2000]), starting with Ward et al. (2000), who originally placed the Permian-Triassic boundary within a laminated sandstone-

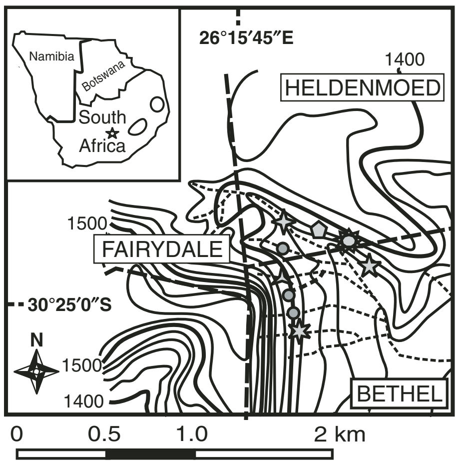

Figure 1. Locality map showing Bethulie region, South Africa, and study sites on the Bethel, Heldenmoed, and Fairydale farms (3026AD TampasFontein 1:50000 1980 Quad map [Pretoria, South Africa, Council for Geosciences]). Dashed lines mark farm boundaries. Stars are discussed laminite intervals and are illustrated in Figures 2 and 3; circles are correlatives not discussed. Contour interval = 20 m.

shale (mudstone) unit. Smith and Ward (2001, p. 1148) described the heterolithic interval as a 3–5 m horizon of "thinly bedded dark red-brown and olive-gray siltstone-mudstone couplets," also referred to as a lifeless zone, interpreted to represent ≤50 k.y. Although they reported no vertebrates from the interval, Retallack et al. (2003) showed the presence of the large therocephalian *Moschorhinus* in concretions at its top, and moved the boundary to this nodular horizon from the underlying maroon concretionary siltstone, from which the last *Dicynodon* is reported (Retallack et al., 2003, their Fig. 4). Herein, the description changes to a 7-m-thick sequence of laminated purple and gray beds with varve-like fining-upward sequences, weakly developed rooted paleosols, crustacean burrows (*Katbergia*; Gastaldo and Rolerson, 2008), and vertebrate footprints (Retallack et al., 2003, p. 1135). The sequence is described as laminites, and the facies are reported to be basin-wide. Ward et al. (2005) recognized it as their Unit II, a 3–5-m-thick, rhythmically bedded laminated mudrock overlying the paleontological boundary.

Smith and Botha (2005) redescribed the so-called laminites from Bethulie and Graaf-Reinet sites as rhythmically bedded, dark red-brown and olive-gray siltstone and mudstone couplets enclosing a single concretionary horizon. Primary structures include small oscillation ripples, crenulated structures previously interpreted as algal mats, and desiccation features. Reports of rare occurrences of vertebrate fossils from Bethulie provide evidence for biogenic activity in addition to the presence of *Katbergia* (Gastaldo and Rolerson, 2008) burrows. Botha and Smith (2006, their Fig. 1) recognized this interval as capping what was considered to be the end-Permian (see the GSA Data Repository[1]) paleosol (Retallack et al., 2003, their Fig. 4) located beneath the heterolithic interval of Ward et al. (2000).

FACIES CHARACTERIZATION

The heterolithic interval is exposed in erosional gullies (dongas) in the Bethulie district and elsewhere. Long stratigraphic donga sections where the interval is found occur on the Bethel and Heldenmoed farms (Gastaldo et al., 2005, their Fig. 9B; Fig. 1 herein), and in a restricted site in Tussen die Riviere Game Park (30°26′671″S, 26°18′028″E; Retallack et al., 2003, their Fig. 3B). The local stratigraphy consists of repetitive aggradational sequences that include green-gray and maroon siltstones with subordinate sheet and lenticular sandstones. This discussion focuses on the farm exposures, because the game-park outcrop is in fault contact with green-gray siltstone in the gully (to the left in Fig. 3B of Retallack et al., 2003), severely limiting its regional stratigraphic usefulness.

On the Bethel farm (Figs. 1 and 2A), the heterolithic unit stratigraphically overlies a concretion-bearing, maroon to brown-gray (5YR 4/1) massive siltstone (see the GSA Data Repository for stratigraphy). Two concretionary horizons occur in the 2 m unit; the majority of concretions is within the lower 1 m. In concretion hand sample and thin sections, starburst structures occur and conform to carbonate replacement of gypsum. Both invertebrate (*Katbergia*; vertical, centimeter diameter) and inclined vertebrate burrows are present, rare slickensides are conserved, and rooting structures are absent. The overlying interbedded unit begins with fining-upward sequences (couplets) of centimeter-scale green-gray (4GY 4/1) very fine sandstone overlain by millimeter-scale gray-red (5R 4/2) siltstone drapes. It is overlain by 0.4 m of weathered red-brown siltstone (Fig. 2A), above which are centimeter-scale beds of green-gray lithic wacke that fine to siltstone, some of which are HCl reactive. Primary structures in sandstone include imbricated planar beds, small-scale contorted and convoluted bedding, and ripples viewed in cross section on the wall exposure. Sandstone-cast *Katbergia* (Gastaldo and Rolerson, 2008) are preserved in green-gray siltstone beneath vertebrate-bearing nodules, ~2.2 m above the laminate base. Thin lenticular sandstone and ball-and-pillow structures, thinning to the northwest, of yellow-gray (5Y 8/2) to very pale orange (10YR 8/2) feldspathic arenite are enveloped within green-gray siltstone 0.5 m above the nodules (Fig. 2A). Planar tabular and rippled bedsets of fine to very fine grained sandstone become more common upsection, whereafter beds become more massive.

The single well-developed heterolithic interval on the Heldenmoed farm (Figs. 1 and 2D) has a higher sand:silt ratio and does not overlie a maroon concretionary-bearing siltstone. Rather, it is in contact with a green-gray (5G 6/1) to light gray (N7), very fine rooted feldspathic wacke. X-ray diffraction (XRD) bulk composition indicates a mix of quartz (39.7% by volume), albite (44.9%), muscovite (7.3%), and clinoclore (8.2%). Subvertically oriented rooting structures are thin (2–5 mm diameter) and dispersed; root segments may be branched. Stratigraphically above the paleosol is an interval of coarse green-gray siltstone and cross-bedded and rippled, centimeter to decimeter beds of feldspathic wacke organized in lenticular bedforms. Approximately 2 m of heterolithic rock occur above the sandstone. Couplets are

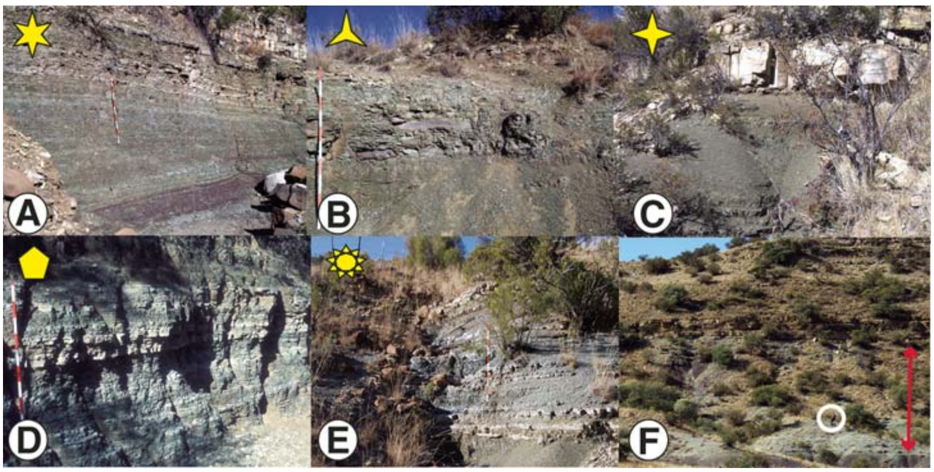

Figure 2. Bethel and Heldenmoed farms heterolithic units. Outcrops are identified by stars in Figures 1 and 3. A: Laminites on Bethel Farm (30°25′321″S, 26°15′918″E) as described by Ward et al. (2000) and Smith and Ward (2001). *Moschorhinos* is reported from the nodule horizon (Retallack et al., 2003). Scale in decimeters. B: Lateral correlative on the Bethel Farm (30°25′105″S, 26°15′859″E), where tabular and low-angle cross-bedded sandstone dominates. Scale in decimeters. C: Lateral correlative on the Heldenmoed farm (30°24′999″S, 26°15′846″E), where green-gray siltstone is heavily weathered and there is no evidence for sandstone-siltstone couplets. D: Laminite interval on the Heldenmoed farm (30°25′003″S, 26°5′875″E). Scale in decimeters. E: Lateral correlative of laminite interval (30°25′062″S, 26°16′006″E) on Heldenmoed farm where medium-grained tabular and planar cross-bedded sandstone are overlain by green-gray coarse siltstone. Scale in decimeters. F: Smith and Botha's (2005, Fig. 3) EPP (End-Permian Paleosol) identified on the Bethel farm that is stratigraphically below the Heldenmoed laminites. Neveling stands within white circle marking stratigraphic position of datum used to correlate across this side of valley. Vertical arrow indicates Early Triassic recovery faunal interval as recognized by Botha and Smith (2006).

[1]GSA Data Repository item 2009056, lithofacies descriptions, high-resolution stratigraphies, and correlation between Bethel and Heldenmoed farms as shown in Figure 3B, is available online at www.geosociety.org/pubs/ft2009.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, USA.

thicker and exhibit interference ripples; crinkle structures, horizontal trails, and infilled burrows are on the upper sandstone contacts (Gray et al., 2004). This is the only site where these structures are exposed. Overall, the interval fines upward from coarse to fine siltstone laminae in which *Katbergia* are preserved. The heterolithic interval is overlain by 1.2 m of fine feldspathic wacke in which small-scale, micro-cross-stratified ripples, trough cross-beds, flute casts, and millimeter-scale angular mudclasts occur. The wacke is yellow-gray (5Y 8/2) to very pale orange (10YR 8/2) and fine grained. XRD data indicate an even mix of quartz (44.7% by volume) and albite (42.0%), with 13.3% laumontite. Point-count data confirm its feldspathic nature (54% quartz, 44% feldspar, 1% lithic).

Attempts at thin-sectioning siltstone from both localities met with failure due to its highly weathered and rubbly nature. Thin sections of better lithified siltstone from the game park locality are structureless and show no evidence of millimeter-scale bedding or brecciation (Gray et al., 2004).

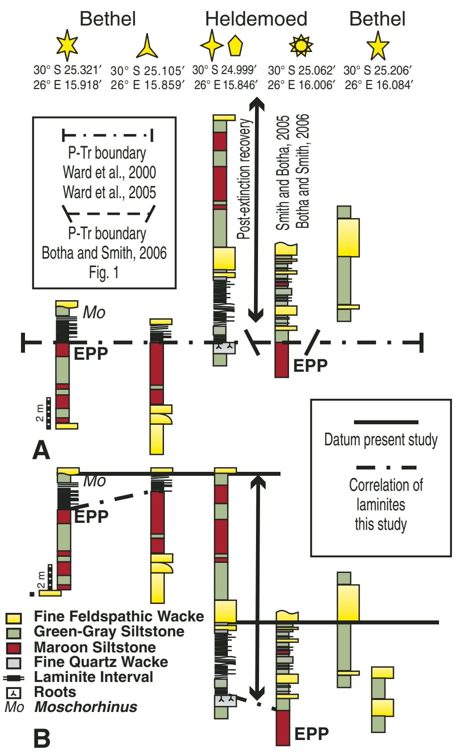

Figure 3. Contrasting correlations of laminite intervals across the Bethel and Heldenmoed farms. EPP—End-Permian Paleosol. A: Correlation proposed by Ward et al. (2000) and subsequent workers with the laminite unit interpreted as unique isochronous, basin-wide event bed deposited in response to the Permian-Triassic extinction. B: Empirical correlation based on facies relationships with respect to traceable bounding surfaces of sandstone datums that overlie the laminites on the Bethel and Heldenmoed farms.

LATERAL FACIES CONTINUITY AND RELATIONSHIPS

The sandstone overlying the heterolithic interval on the Bethel farm (Fig. 2A) was traced as pavement exposures across hill slopes and within dongas (Fig. 1), providing a stratigraphic datum for correlation (see Gastaldo et al., 2005, their Fig. 9B, at 45 m height). The character of the laminated unit changes strikingly from the Bethel to Heldenmoed farms. When traced ~300 m northwest, the interval overlies a thick, concretion-bearing maroon siltstone, the upper 0.3 m of which are more resistant to weathering. This is overlain by (1) a 0.3-m-thick planar bedded, fine to very fine grained, yellow-gray sandstone, and (2) green-gray siltstone with dispersed millimeter-sized angular mud clasts. Thereafter, decimeter-scale, fining-upward couplets of fine sandstone to siltstone are capped by the thick cross-bedded datum sandstone (Fig. 2B). Approximately 300 m north on the Heldenmoed farm (Figs. 1 and 2C) the interval is a green-gray, highly weathered, massive siltstone in which red-gray carbonate concretions occur. The laminated interval reported from the Heldenmoed farm (Ward et al., 2000; Smith and Ward, 2001; Botha and Smith, 2006) does not occur at this stratigraphic horizon. Rather, it begins >10 m stratigraphically below the datum (Fig. 3B; see the Data Repository).

The heterolithic interval and underlying gray paleosol on the Heldenmoed farm also can be traced onto the Bethel farm (Fig. 1). At the barbed wire fence that delineates the farm boundaries (Fig. 2E), the interbedded unit consists of ~3 m of decimeter-scale, very fine sandstone and olive-green siltstone, and overlies a red-gray siltstone. A feldspathic arenite datum is traced to this stratigraphic position (Fig. 3B). Sandstone bed contacts may be rippled, small-scale planar and trough cross-beds occur, and small-scale soft-sediment deformation is present. This heterolithic interval is no longer identifiable farther to the southeast (Fig. 2F) in exposures that extend up to the base of the Katberg Formation. Here, sandstones become thin intercalations within green-gray siltstone, and the datum is traced to a position meters above the rubified concretion-bearing mudrock (Fig. 2F).

LOOTSBERG PASS EVENT BED

Retallack et al. (2003, their Figs. 3A and 4) placed the Permian-Triassic boundary at a nodule horizon above the laminated interval described at Lootsberg Pass. Hence, this seems to be the reason for their basin-wide boundary correlation at the top of the laminites that contradicts prior (Ward et al., 2000; Smith and Ward, 2001) and subsequent (Ward et al., 2005) reports placing the boundary beneath them. The concretion horizon was interpreted as part of the earliest Triassic Kuta paleosol, representing a deep calcareous zone (Retallack et al., 2003). Indeed, the heterolithic unit is stratigraphically beneath the concretions, which are restricted aerially in outcrop (Fig. 4). Here, the heterolithic interval consists of fining-upward, fine-grained quartz wacke overlain by red-gray and green-gray coarse siltstone, or coarse to fine siltstone couplets. In pavement exposures 5 m northwest in the donga, fine- to medium-grained sandstone exhibits ladder ripples (2 cm λ), as well as pustular and soft-sediment flow structures. It

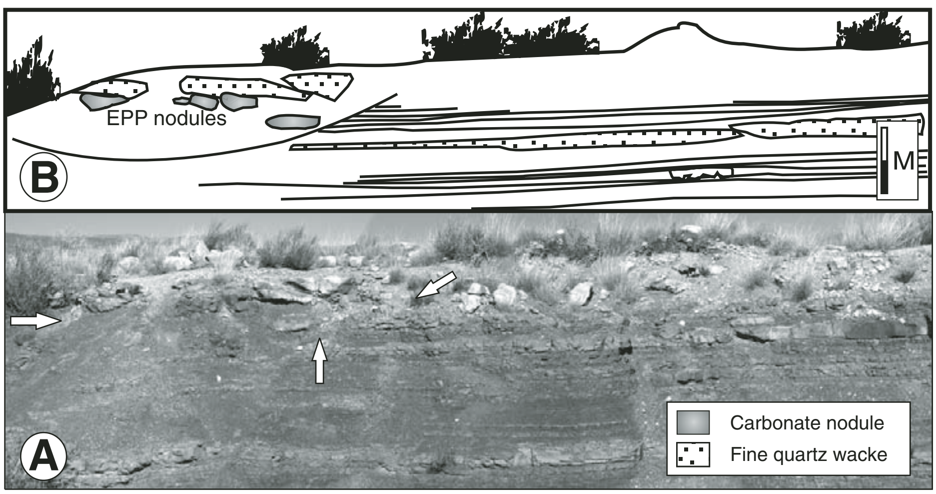

Figure 4. Relationship of End-Permian paleosol (EPP) concretions as reported by Retallack et al. (2003, their Fig. 3A) to the laminite interval at Lootsberg Pass (31°50′952″S, 24°52′525″E). A: Photomosaic of EPP nodules in channel-form siltstone overlying heterolithic unit. Arrows mark erosional contact between units. B: Line illustration of facies relationships in A. Laterally tracing the sandstone overlying the nodules reveals that interbedded sandstone and siltstone couplets are stratigraphically equivalent to nodules rather than overlying them.

is overlain by 0.8 m of red-gray, weathered siltstone, over which are lenticular, cross-bedded sandstone bodies that contain large (≤10 cm), poorly sorted, angular to subangular rip-up mud clasts. The boundary concretions do not occur in a laterally extensive siltstone. Rather, they are restricted to a small erosional cut within the heterolithic interval (Fig. 4). They are overlain by a fine quartz wacke that, when traced laterally, occurs stratigraphically above the laminated interval and is the same bed in which the ladder ripple structures occur.

DISCUSSION

In the Bethulie area and elsewhere, the event bed is used as the criterion for the terrestrial expression of the Permian-Triassic boundary event recorded in the marine realm (Ward et al., 2005). Its unique character and presumed synchroneity within the Bethulie area (Fig. 3A), across the basin (Ward et al., 2000; Smith and Ward, 2001), and in the Southern Hemisphere (Retallack et al., 2003) have resulted in various models of extinction (Ward et al., 2005) and recovery (Smith and Botha, 2005; Botha and Smith, 2006) of the vertebrate fauna in response to climatic aridification. The sedimentological features of the aerially restricted and stratigraphically confined heterolithic units do not support an interpretation of extensive playa lake formation (Smith and Ward, 2001, and others) or an isochronous marker bed that delimits the terrestrial expression of the paleontologically defined boundary. Rather, the field relationships and suite of sedimentological features support deposition within floodplain avulsion channel systems (Slingerland and Smith, 2004), each of which has undergone weak pedogenesis. Our study demonstrates that the laminated (laminite) beds are nonsynchronous (Fig. 3B), not isochronous, as contended by Ward et al. (2005). Approximately 10 m of stratigraphic section separate the exposures of the heterolithic beds on the Bethel and Heldenmoed farms, over a distance of <1 km. In addition, neither laminated interval can be traced laterally for more than a few hundred meters, let alone traced regionally (kilometers) or across the basin. Hence, extrapolation of the laminated interval to other continents as the terrestrial expression of the Permian-Triassic boundary event is imprudent.

The claims of rapid vertebrate recovery within <100 k.y. following the extinction event (Smith and Botha, 2005; Botha and Smith, 2006) also must be called into question (Fig. 3). The interval used to speculate on the recovery is on the eastern side of the valley (Fig. 2F; Botha and Smith, 2006, their Fig. 1) beneath the Permian-Triassic boundary as recognized on the western side of the valley. Hence, the diversification patterns reported by Smith and Botha (2005) and Botha and Smith (2006) are between the two stratigraphically distinct laminated intervals and may reflect Late Permian originations, rather than Early Triassic recovery.

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