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Dinosaur burrows in the Otway Group (Albian) of Victoria, Australia, and their relation to Cretaceous polar environments

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ABSTRACT

Three enigmatic structures in an outcrop of the Otway Group (Albian) of Victoria, Australia, compose the first known evidence suggestive of dinosaur burrows outside of North America and the oldest from the fossil record. The most complete of the Otway structures nearly matches the size and morphology of a burrow attributed to the only known burrowing dinosaur, *Oryctodromeus cubicularis* from the Upper Cretaceous (Cenomanian) of Montana (USA). The suspected burrows cross-cut alluvial facies and overlie nearby strata containing dinosaur tracks. The structures contain identical sand fills in their upper portions, implying a near-synchronous origin and filling; graded bedding in the most complete structure also indicates passive filling of an originally open structure. This probable burrow is a 2.1 m long, gently descending, semi-helical tunnel, with a near-constant diameter (about 30 cm) that connects with an enlarged terminal chamber. The structures are unlikely to have been caused by physical or chemical sedimentary processes, and hence are considered as biogenic structures; moreover, their size and morphology imply tetrapod tracemakers. Burrow allometry indicates tracemakers with a mass of 10–20 kg, matching size estimates for small ornithopods from the Otway Group. Burrowing behavior in hypsilophodontid-grade dinosaurs, which compose most of the dinosaurian assemblage in the Lower Cretaceous of Victoria, was proposed previously as an adaptation for surviving formerly polar conditions in southeastern Australia. This paradigm is explored in detail, particularly through actualistic examples of tetrapod burrowing in cold climates. These structures may provide the first clues of ornithopod burrowing in these extreme environments, while also establishing search images for similar structures in other Lower Cretaceous outcrops in Victoria.

1. Introduction

The recent interpretation of a Lower Cretaceous species of burrowing dinosaur, the basal ornithopod *Oryctodromeus cubicularis* in the Blackleaf Formation (Cenomanian) of Montana (USA), provided an additional explanation for some large, enigmatic sedimentary structures in Mesozoic terrestrial deposits (Varricchio et al., 2007). Just before then, Loope (2006) also proposed that large structures in the Entrada Sandstone (Middle Jurassic) of Utah were tetrapod-made, although he lacked sufficient evidence to attribute these specifically to dinosaurs. Varricchio et al. (2007), in contrast, were fortunate enough to have skeletal remains of *O. cubicularis* and two of its probable offspring entombed in the burrow structure. This circumstance, in addition to anatomical traits in the adult specimen that suggested adaptations for burrowing, composed evidence for the first known burrowing and denning behaviors in dinosaurs. In that study, the authors also proposed that burrowing might have conferred an advantage to small ornithopod dinosaurs living in environments with challenging conditions, such as deserts and polar environments (Varricchio et al., 2007), which had been proposed for large tetrapod burrowing in general (Loope, 2006).

In this report, three closely associated sedimentary structures are described from the Lower Cretaceous (Albian) Otway Group of Victoria, Australia, that are also likely the result of tetrapod burrowing. Moreover, the geometry and size of one structure nearly matches that of the burrow attributed to *Oryctodromeus* (Varricchio et al., 2007) and the other two partially resemble the first; hence these structures are attributed to small dinosaurian tracemakers, such as hypsilophodontid-grade dinosaurs. The Otway Group and slightly older Strzelecki Group (Aptian) of this part of Victoria are well known for their remains of small hypsilophodontids, such as

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Leaellynasaura, *Atlascopsosaurus*, and *Qantassaurus* (Rich et al., 1988; Rich and Rich, 1989; Rich et al., 2002), thus the structures can be linked with potential tracemakers in the same region and strata. The circumpolar setting of this part of Australia during the Early Cretaceous (Veevers et al., 1991; Gregory et al., 1989; Wagstaff and McEwen-Mason, 1989; Constantine et al., 1998) also supports previous suggestions that some small ornithopods burrowed as an adaptation to extreme environments (Varricchio et al., 2007; Bell and Snively, 2008).

Assuming these structures are dinosaur burrows, they would represent the first known outside of North America and the oldest in the geologic record. Regardless of the identity of the Otway structures, a more detailed consideration of dinosaur burrowing as a behavioral strategy for overwintering in polar environments is further explored, including suggested search images for trace fossil evidence that would support such interpretations in the future.

2. Study area and previous research

The Otway Group crop outs in extensive cliff-face and marine-platform exposures along the southern coast of Victoria and west of Melbourne (Fig. 1). The Otway Group is well known for its fossil vertebrates, e.g., fish, amphibians, turtles, dinosaurs, and mammals, most of which were recovered from Dinosaur Cove (Rich et al., 1988; Currie et al., 1996; Rich et al., 1997, 2002, 2005), but also contains a well-documented assemblage of terrestrial plants (Wagstaff and McEwen-Mason, 1989; Cantrill, 1991; Dettmann et al., 1992). Dinosaurs in the Otway Group and nearby Strzelecki Group are dominated by hypsilophodontid-grade ornithopods, which is unusual among dinosaur assemblages worldwide (Rich and Vickers-Rich, 1999; Vickers-Rich et al., 1999; Rich et al., 2002), although a few theropods and representatives of other clades have been identified as well (Rich et al., 1988; Rich and Rich, 1989; Currie et al., 1996; Smith et al., 2008). Invertebrate body fossils in the Otway Group are relatively uncommon, but include parastacid crayfish (also recovered from Dinosaur Cove), the oldest known from the Southern Hemisphere (Martin et al., 2008). Insect body fossils are, however, abundantly represented in the Koonwarra fossil deposit of the Strzelecki Group (Jell and Duncan, 1986). Invertebrate trace fossils in the Otway Group are likewise rarely reported, but burrow systems at several localities have been attributed to crayfish or similar fresh-water decapods (Martin et al., 2008).

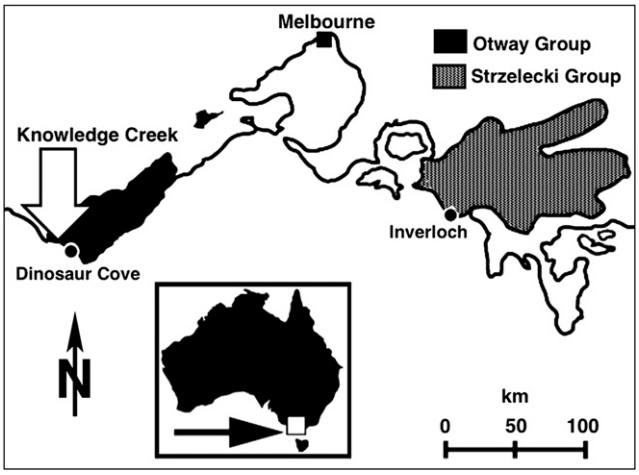

Fig. 1. Location of Knowledge Creek outcrop and structures (this study), Otway Group (Albian), Victoria, Australia;Latitude-longitude coordinates are S38° 45.27′, E143° 20.85′. Location is indicated relative to the two most productive dinosaur sites in Victoria, Dinosaur Cove (Otway Group) and Inverloch ("Dinosaur Dreaming," Strzelecki Group).

Rock types of the Otway Group include mudstones, cross-bedded sandstones, and intraclast conglomerates and breccias; most clastic facies are composed of reworked volcaniclastic sediments (Bryan et al., 1997; Tosolini et al., 1999; Miller et al., 2002). Otway Group sediments were deposited in the Otway Basin, a rift basin that formed with the divergence of Australia and Antarctica in the Early Cretaceous (Tosolini et al., 1999; Miller et al., 2002; Veevers, 2006). Sedimentary environments of the Otway Group were primarily braided fresh-water braided streams, forming multistorey lithic sandstones with coarser-grained channel-fill and finer-grained sheetflow or overbank deposits (Bryan et al., 1997). In the nearby Strzelecki Group, poorly sorted conglomerates are interpreted as braided stream-dominated alluvial-fan deposits (Tosolini et al., 1999); this diagnosis is probably also applicable to coarse-grained lithofacies in the Otway Group. Sediments were derived from nearby volcanic uplands or reworked from within the basin (Rich et al., 1988; Bryan et al., 1997). Flooding associated with spring and summer thaws, as well as occasional pulses of volcaniclastic sediments, likely caused high-energy flow regimes in seasonally active streams or alluvial channels (Rich et al., 1988; Tosolini et al., 1999). Paleolatitudes are estimated to have been $78 \pm 5°$S, and mean annual air temperatures were in the range of $-6°$ to $+8$ °C, based on a combination of paleogeography, oxygen isotopes, paleobotany, cryoturbation structures, and oxygen isotopes (Veevers et al., 1991; Gregory et al., 1989; Wagstaff and McEwen-Mason, 1989; Constantine et al., 1998). As a result, Otway Group strata are assumed to have formed in periglacial environments, with freezing conditions and prolonged periods of darkness during winters (Constantine et al., 1998; Rich and Vickers-Rich, 2000; Rich et al., 2002).

3. Diagnosis of Otway Structures

3.1. Geologic context and description

The three structures of interest in this study are located in a coastal outcrop of conglomeratic sandstone in the Otway Group (Albian) at a locality dubbed Knowledge Creek, named after the drainage within the ravine (hanging valley) that divides the exposure (Rich and Vickers-Rich, 2000). This small cove is about 240 km southwest of Melbourne, Victoria, and 6–6.5 km northwest of Dinosaur Cove (Fig. 1). The stratigraphic sequence at Knowledge Creek has not been measured or otherwise described, although some lithofacies are described here.

Despite numerous finds of vertebrate material in the Otway Group at other localities, no body fossils have been discerned at this site, and the only significant paleontological find reported there previously was a single dinosaur footprint, discovered in 1980 (Rich et al., 1988; Rich and Vickers-Rich, 2000). This footprint was later confirmed as a small ornithopod track; more recently, other partial, poorly preserved dinosaur tracks have been found at this site (Martin et al., 2007). Since 1980, paleontological researchers (including the author of this study) have visited the site three times, in May 2006, July 2007, and May 2009. During the first of those visits, the author observed and photographed the structures, noting the remarkable similarity of one to a Lower Cretaceous dinosaur burrow he had seen in Montana (research that was, at the time, still in process), but he did not describe it in detail. Follow-up visits by the author in 2007 and 2009 provided the opportunity to make a more thorough description and diagnosis of the structures, related further herein.

The outcrop displays significant exposures of Otway Group lithofacies, including planar-bedded mudstones and siltstones,