ABSTRACT

Thin sedimentary interbeds within the Kirkpatrick Basalt (Jurassic) of Antarctica harbor exquisitely preserved ‘soft-bodied’ organisms that lived in and around shallow freshwater lakes of the time, some of which were hydrothermally influenced. In the hottest pools, associated with magmatic vents, unusual carbonates were apparently precipitated by Archaea extremophiles adapted to living near active lava flows. In cooler lakes more distant to the vents, fine siliciclastic sediments record other communities of spinicaudatan (“conchostracan”) and notostracan crustaceans, larval insects, fishes, and ostracodes much of which may have been sustained by microbial mats, which are also well preserved in the deposits. Along the lake-edge, carbonized leaves, peat or coal, and silicified logs are often found in association with paleosols. Notably, evidence of carnivory, a primary taphonomic filter, is essentially lacking in these sediments. Exceptional preservation of non-biomineralized or lightly skeletonized organisms, therefore, reflects the original diversity of non-biomineralized or lightly skeletonized organisms present.

INTRODUCTION

One of the most striking and paradoxical observations about the evolutionary record is that the most numerous and diverse animals on Earth are represented by a weak fossil record - among them, insects, spiders, scorpions, mites, myriapods, shrimp, nematodes, “worms” of various kinds, and countless other species lacking hard skeletal parts. Conversely, groups best represented in the fossil record constitute a relatively small fraction of total species diversity, including mollusks, brachiopods, corals, echinoderms, vertebrates, and other animals having hard (biomineralized) shells, bones, or teeth, which today constitute less than 20% of animal species. Compensating for this “preservation paradox,” in which the most abundant and diverse forms on Earth have a weak fossil record, usually involves the discovery of deposits where both biomineralized fossils and non-biomineralized fossils have been preserved. Such deposits are variously referred to as Devonian, Scottish, and African basaltic deposits (Beardmore and Shackleton Glacier areas; Elliot et al., 1979; Borkow and Babcock, 2003; Briggs, 2003). Two of these sedimentary horizons can be correlated widely and indicate brief periods of relative cessation of extrusive magmatism. The Kirkpatrick Basalt itself forms the cap sequence on tholeiitic rocks (Cambrian of Yunnan, China), the Burgess Shale (Cambrian of British Columbia), the Rhynie Chert (Devonian of Scotland), the Mazon Creek deposit (Carboniferous of Illinois), the Solnhofen Limestone (Jurassic of Germany), and the Green River Formation (Eocene of Wyoming, Colorado, and Utah). Studying fossils from these and similar deposits provide rare snapshots of organisms and ecosystems otherwise not preserved in the fossil record.

Here, we describe such an instance of exceptional preservation, and an unusual process of carbonate sedimentation, from the Jurassic of Antarctica. The unusual carbonates were precipitated near a strong hydrothermal source, and nearby cooler and silica-rich hydrothermal waters apparently worked to fossilize organic remains rapidly and produce a “freeze-frame” of macroscopic and microscopic life forms. Microbes seem to have played a vital role in both processes. This example provides an unusual perspective on the fossilization process, and suggests that further insight into taphonomic processes and occurrences of microbial fossils may be gained through expansion of our search strategies, even to igneous-dominated environments.

LOCATION AND STRATIGRAPHY

This paper focuses on thin sedimentary deposits interbedded within lava flows of the Kirkpatrick Basalt (Ferrar Group; Jurassic) of Antarctica, which is exposed in South Victoria Land (Carapace Nunatak) and isolated peaks in the central Transantarctic Mountains (Beardmore and Shackleton Glacier areas; Fig. 1) (Ball et al., 1979; Tasch, 1977, 1987; Barrett et al., 1986; Bradshaw, 1987; Elliot et al., 1991). Two of these sedimentary horizons can be correlated widely and indicate brief periods of relative cessation of extrusive magmatism. The Kirkpatrick Basalt itself forms the cap sequence on tholeiitic rocks of the Ferrar Large Igneous Province (FLIP), which occur in a 3,500 km linear belt along the Transantarctic Mountains from the Weddell Sea region to North Victoria Land (Elliot and Fleming, 2000, 2004). The FLIP was emplaced about 180±3.5 Ma during initial breakup of Gondwana in the Early Jurassic (Toarcian Epoch), from a source
thought to be a triple junction in the proto-
Weddell Sea (Elliot and Fleming, 2000,
2004). Radioisotopic dating constrains the
duration of FLIP emplacement to a brief
interval, less than 1 million years (Heiman et
al., 1994). This extrusive magmatism ends
with the capping iron-rich lavas of the
Kirkpatrick Basalt, which comprises less than
1% of the FLIP rocks that locally exceed 2 km
in thickness (Elliot and Fleming, 2004).

SEDIMENTARY INTERBEDS
IN THE KIRKPATRICK
BASALT

The interbeds of the Kirkpatrick Basalt
record sedimentary and biotic processes in re-
latively shallow lakes and ponds, and in sur-
rrounding wetlands to upland areas, during
two brief intervals when active magmatic
activity had slowed along an expanding rift
system in high latitude Pangaea. Among these
sedimentary interbeds are two dominant types
of subaqueous origin: (1) fine-grained, thinly
laminated siliciclastic deposits (Fig. 2) and (2)
unusual carbonate deposits rimming and fill-
ing spaces between basalt pillows (Fig. 3).

Both of these subaqueous deposits transition
laterally into thin paleosols and poorly consol-
ated peat deposits, where large permineral-
ized (silicified) logs occur locally in the
Beardmore Glacier region (Taylor and Taylor,
1990).

The siliciclastics were evidently deposited in
small, relatively shallow, freshwater lakes and
pools (Tasch, 1977, 1987). In many places,
synsedimentary deformation of the laminations is associated with igneous extrusions. At
Carapace Nunatak, for example, large clasts of
lithified or semilithified sediment appear to
have been rafted by hot magma (Bradshaw,
1987) (Fig. 2b). Elsewhere, numerous thin
dark brown to black laminae and crinkled lay-
ers with clotted textures are interpreted as
microbial mat communities of photosynthetic
bacteria and possibly algae (compare Schieber,
1999; Noffke et al., 2001). The fossil assem-
blage in these environments is dominated by
small (1-2 cm) bivalved spinicaudatan (“con-
chostracan”) arthropods that are today most
typical of ephemeral, alkaline pond settings (Fig. 4a) (Tasch, 1987). Other macrofossils
include fishes (mostly Oreochima), notostracan
branchiopods, ostracodes, insect nymphs and
wings, and plant leaves (Fig. 4), but macro-
scopic trace fossils are extremely rare. The
animal body fossils are preserved with miner-
alogies that mimic their original skeletal com-
position (i.e., spinicaudatan carapaces are pre-
served as calcium phosphate, while those of
ostracods are preserved as calcium carbonate),
though portions of spinicaudatan carapaces
are silicified (Stigall Rode et al., 2005) (Fig.
5). Overall, the preservation of original skele-
tal composition and the preservation of cara-
pace layers in spinicaudatan specimens indi-
cate rapid burial and preservation of speci-
mens with little or no alteration of regions of
their exoskeleton. The silicification of regions
within spinicaudatan carapaces (Fig. 5) may
have been microbiologically mediated.

Weak to distinct laminae in the carbonate
beds are aligned subhorizontally to concentri-
cally around basalt pillows (Fig. 3b). The car-
bonates appear to lack the macroscopic body
fossils common in the siliciclastic beds.

Backscatter SEM-EDS analyses, however,
reveal minute, irregular, organic morphologies
preserved with a high concentration of carbon.
These organic structures are rimmed by thin
silica-rich carbonate “halos”, and the surround-
ing carbonate mud lacks needles or other indi-
cators of precipitation by macroscopic organ-
isms. Thermoacidophilic microbes likely
occurred in this type of setting and may have
mediated carbonate, and perhaps also silica,
precipitation in pools closely associated with
hydrothermal vents and basaltic extrusion.
Another untested possibility is that microbial
consortia on the surface of cooler basalt pil-
lops created an alkaline chemical microenvi-
the Kirkpatrick Basalt. Spinicaudatans (dominated by *Carapaciesstheria*, Fig. 4a) are densely packed in many thin layers at localities in both South Victoria Land and the Central Transantarctic Mountains. Their enormous numbers and nearly uniform lengths presumably reflect a high reproductive (and presumably rapid maturation) rate in pools where they had few predators. The growth lines in the carapaces of *Carapaciesstheria* in the Kirkpatrick beds indicate that specimens in the individual layers were all of the same age at death. This suggests that each bedding plane represents a single generation of spinicaudatans that hatched simultaneously during the initial spring flooding of the pond, a pattern mimicking that of modern spinicaudatans (Weeks et al., 1997). Carapaces of the freshwater ostracod, *Darwinula* (Fig. 4e), commonly occur on slabs with spinicaudatans.

In South Victoria Land, nymphs of ephemeropteran insects (Fig. 4b) are present in certain thin horizons, apparently confined to narrow time intervals, on Carapace Nunatak. Some localities in the Central Transantarctic Mountains yield abundant remains of fishes (Fig 4c) (mostly *Oreochima*) most of them fully or largely articulated. This again suggests that predaceous and scavenging activity in the Kirkpatrick lakes was minimal. Likewise there is little evidence of bioturbation of benthic muds in the siliciclastic-dominated lakes. Lack of an active infauna may have provided an opportunity for microbial mat communities to flourish.

In numerous other instances of exceptional...
preservation in the Phanerozoic, biodegradation, including predation and scavenging, is minimal and sediment bioturbation largely absent. Non-biomineralized remains often survived long enough in the Kirkpatrick lakes to undergo early diagenesis, especially if it were mediated by microbial decay agents within a few weeks (compare Briggs et al., 1993; Wilby et al., 1996; Borkow and Babcock, 2003). Microbial mediation of silicification likely occurred in the siliciclastic interbeds of the Kirkpatrick Basalt. Microbial influence is suggested by differential replacement along zones of weakness between carapace layers as well the increased silicification of carapaces preserved within microbial-mat influenced versus other sediments (Fig. 5).

Plant remains, including bennettitalean leaves, silicified trunks of gymnosperms, and peat (or low grade coal), are another important constituent of the fossil assemblage in the siliciclastic interbeds of the Kirkpatrick Basalt. Most of the plants lived in wetlands surrounding relatively cool water lakes, or somewhat upland from them. The sizes of the tree trunks, often 50 cm or more in diameter, provide a minimum duration between lava flows. The large diameter of these trunks suggests that some of the trees were several decades to perhaps a hundred years or more in age. Leaves and peat are preserved as hydrocarbons, whereas the logs are permineralized with silica (Taylor and Taylor, 1990) presumably sourced from Si-rich waters derived from nearby volcanic sources.

Silicification of plant material associated with igneous sources is not uncommon (e.g., Chinle Formation, see Sigleo, 1979 and Creber and Ash, 2004; Rhynie Chert, see Rice et al., 2002 and Trewin et al., 2003), but instances where a nearby hydrothermal source for magmatophreatic interactions can be identified are unusual. The Rhynie Chert (Devonian of Scotland) is perhaps the best-known example (Trewin et al., 2003). Silicification of woody material in the Kirkpatrick Basalt provides a window into paleoenvironments and climate of high-latitude Gondwana during the Jurassic (see Taylor and Taylor, 1990; Parrish, 1990).

CONCLUSIONS

Sedimentary interbeds deposited over lava flows of the Kirkpatrick Basalt during the Early Jurassic splitting of Gondwana represent unusual freshwater paleoenvironments. They illustrate an important means of solving some of the issues related to the “preservation paradox” for a critical paleo-environmental setting: high latitude Gondwana during the early Mesozoic. Hot lakes associated with hydrothermal vents were likely home to thermophilic microbes (archeans) capable of withstanding not only high temperature, but also sulfidic water. They promoted the precipitation of carbonate laminae even around basaltic pillows that extruded into the water. Other freshwater lakes away from direct contact with hydrothermal vents, where water temperatures were cooler, were home to low diversity faunas and microbial mat communities. Vascular plants were rooted beyond the margins of the water. Carnivory was limited, and exceptional preservation of non-biomineralized or lightly mineralized organisms became commonplace. Microbial decay agents contributed to rapid diagenesis.

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