Discovery of abundant arthropod trackways in the ?Lower Devonian Muth Quartzite (Spiti, India): implications for the depositional environment

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Abstract—Arthropod trace fossils are described from the ?Lower Devonian Muth Quartzite (Spiti, India), a sequence virtually devoid of faunal evidence. Trace fossils, which are abundant and often well preserved, mainly consist of arthropod trackways; some burrows are present, too. The ichnogenera of the trackways include numerous Palmichnium and rarer Diplichnites. The first can probably be assigned to eurypterids and the second is probably related to myriapods. Sedimentological observations point to deposition of the Muth Quartzite in a foreshore/backshore environment. This combination of eurypterid and myriapod trackways is a spectacular indication of early terrestrialization. © 1998 Elsevier Science Ltd. All rights reserved

Introduction

Within the Tethyan Zone (Tibetan Zone, Gansser, 1964) sediments along the northern margin of the Indian plate ranging from Precambrian to Eocene, the white Muth Quartzite is one of the most striking marker horizons, and has been traced throughout the whole NW Himalayas, from Kashmir to Nepal (Gansser, 1964). In spite of its considerable importance for correlation in regional mapping, due to its easy recognizability in the field, the age of the Muth Quartzite is poorly constrained and its depositional environment is still under debate. The recent discovery of abundant trace fossils in the Muth Quartzite may prove helpful in the reconstruction of its depositional environment.

In the Spiti area, the Tethyan sediments were deformed during the Himalayan orogeny into largescale upright folds, with axes trending NNW–SSE and wavelengths of approximately 5 km (Fuchs, 1982). The quartzite represents a more competent layer within the pile of Tethyan sediments, thus showing no second order folding as less competent formations do, and as a result, sedimentary structures are well preserved.

Stratigraphical setting

The term ”Muth Series” was first used by Stoliczka (1865), who assigned a probable Silurian age to the unit. Oldham (1888) correlated the Muth Series with the Carboniferous of Kashmir, a correlation also followed by Griesbach (1891). In the definition of Hayden (1904) the Muth System included: (a) Dark coral limestone, (b) Red quartzite, (c) Coral limestone and (d) White Muth quartzite. However, in recent literature, only the white Muth Quartzite of Hayden (1904) is regarded as being the Muth Formation, whereas (a) and (b) belong to the Ordovician Shian Quartzite Formation and (c) to the Silurian Pin dolomite Formation (Srikantia, 1981; Bagati, 1990). Bhargava and Bassi (in press) included only the pure, white quartz arenite in the Muth Formation, from its first appearance above the Pin Dolomite up to the first carbonate bands, which are regarded as lowest Lipak Formation.

In the Pin Valley (Fig. 1) the Muth Formation consists of a lower unit of pure, white, mature quartzarenites, followed by alternating pure quartzarenites and hybrid dolomitic arenites (Fuchs, 1982; Bagati, 1990). The upper unit is similar to the late Devonian dolomites, calcareous quartzites and quartzarenites in western Dolpo, Nepal (Fuchs, 1977; Flügel and Tintori, 1993). Although a littoral to aeolian deposition is assumed for the quartzarenites, the upper unit, with the rare occurrence of coral patch reefs, indicates a shallow marine depositional environment (Garzanti et al., 1996). This succession seems to be invalid for the whole outcropping area of the Muth Formation, since contrasting sedimentary successions have been described, for example by Mukherjee and Dasgupta (1972) and Kumar et al. (1977).

The Muth Formation is conformably underlain by the Silurian Pin Dolomite, which is correlated with the Takche Formation in the Ladakh area (Kumar et al., 1977; Baud et al., 1984) and the Manchap Formation in the Kinnaur region (Bhargava and Bassi, 1986). Bhargava (1997) on the other hand describes a sharp lower contact. The Pin Dolomite comprises an intertidal to littoral, well sorted argillo-arenaceous succession with sporadic small reefal complexes with a gradual contact to the littoral sand deposits of the Muth Quartzite, displaying a shallowing upward
Fig. 1. Geological map of the study area. Arrow indicates the outcrop with trackways.

throughout the whole basin (Bhargava and Bassi, 1986).

In contrast to the transitional lower boundary, the upper contact of the Muth Formation, with the overlying Lipak Formation, is conformable but fairly sharp (Baud et al., 1984). Gaetani et al. (1986) report an intercalation of white quartzarenites (Muth Quartzite) with dark grey arenites (Lipak Formation) in some parts of the contact near Tanze (Zanskar), but also a sudden contact between white microconglomerates with black silty limestones can be found. An conformable, gradual upper contact has been confirmed by own field studies at the type locality near Muth (Pin Valley). The dark limestones, with minor incursions of sandstone and mudstone in the lower part, of the Lipak Formation represent a shallow subtidal carbonate shelf environment (Bagati, 1990).

Age of the Muth Formation

Due to its very limited fossil content, the age of the Muth Quartzite is highly controversial (see Talent et al. (1988) for the special problems of this subject). Commonly the Muth Formation has been dated indirectly by its stratigraphic position. In its type locality the Muth Quartzite gradually passes from underlying fossiliferous Silurian dolomites into limestones of the overlying Lipak Formation containing Mid- to Late Devonian fossils (Chaterji, 1967). Mukherjee and Dasgupta (1972) estimated a Mid Silurian lower age limit and a Mid Devonian upper age limit for the Muth Quartzite. Talent et al. (1988, p. 22) suggest a sedimentation of the Muth Quartzite somewhere in the interval Ashgill–Ludlow.

Lower age limit

Hayden (1904) found the brachiopod Pentamerus oblongus in the Pin Dolomite in beds just below the Muth Quartzite and suggested a Late Silurian to Devonian age. Mukherjee and Dasgupta (1972) mentioned the existence of tabulate corals in grey siliceous limestones below the Muth Formation, near the type locality, and proposed a Mid Silurian age. Fuchs (1982) described the frequent occurrence of Psilophyton princeps from beds just below the Muth Formation, west of Losar (Spiti, Pin Valley). The Early to Mid Silurian age of the reefal buildups within the Pin Dolomite are well established from numerous corals, bryozoans and brachiopods (Bhargava and Bassi 1986). Copper and Brunton (1991) favoured an Early Silurian Age.

Upper age limit

Mukherjee and Dasgupta (1972) describe brachiopods of Mid- to Late Devonian age in greyish fossiliferous limestone-beds of the Lipak Formation, just 7 m above the top of the Muth Formation. Fuchs (1982) found badly preserved Late Devonian brachiopods in the basal beds of the Lipak Formation WNW
Muth. Baud et al. (1984) mentioned a rich fauna of brachiopods and bryozoa north of Sarchu (Zanskar) about 20 m above the bottom of the Lipak Formation, representing an Early Carboniferous age. Bassi (1988) discovered Orthis aff. rustica in the middle part of the Muth Quartzite, 1 km W of Khimukul La, Kinnaur. Conodont dating in carbonates of the upper Muth Formation indicated Late Fammenian age (Garzanti et al., 1996). Recent dating of the Lipak Formation in the Pin valley, near Guling, using conodont fauna, indicate a Devonian age for the whole formation, a sample from 27 m above the Muth Formation at the type locality gave a reliable Mid Devonian age (pers. comm. Krystyn, 1997).

Although there may exist considerable variations of facies and stratigraphic range in its broad extent (Fuchs, 1977), the consensus is that the Muth Formation in the Spiti area was deposited at some time in the Late Silurian to Mid Devonian, the authors believe in an Early Devonian age.

### Facies

Although the appearance of the Muth Formation is quite uniform throughout its whole outcrop, the thickness varies from about 200 m to 444 m (Baud et al., 1984; Bagati, 1990). The formation consists of thick bedded, striking white to light grey, fine to medium grained, submature to supermature, quartz-cemented quartzarenites (Gaetani et al., 1986). Beds of grey carbonaceous quartzites, sandy dolomites and dolomites intercalated with quartzites occur in the uppermost part (Fuchs, 1982; Bagati, 1990).

Several depositional environments have been proposed for the Muth Quartzite: Mukherjee and Dasgupta (1972) discussed a shallow marine re-sedimentation of eolian desert sands. A beach environment was assumed by Banerjee (1974), Ranga Rao et al. (1984), Bhargava and Bassi (1986) and Gaetani and Garzanti (1991). Kumar et al. (1977) and Bagati (1990) considered a shallow marine sand bar/shoal complex, while an aeolian origin is mentioned by Dasgupta (1971) and Garzanti et al. (1996).

Fuchs (1977) emphasised a pronounced facies variation during the Devonian, with a distinct shallowing towards the W. The flyschoid Tilicho Pass Formation of central Nepal grades laterally into the dolomites and calcareous quartzites of western Dolpo, which are probably equivalent to the beach sands of the Muth Quartzite in Spiti (Fuchs, 1977). Flügel and Tintori (1993) suggested that the correlation of the dolomites in central Dolpo with the Muth Formation of Spiti was too poorly constrained and preferred to designate these beds as “fossiliferous Late Devonian Limestone”.

In the Pin Valley east of Mikkim, the white Muth Quartzite crops out in a 2 km long area in an inclined, horizontal, SW-vergent anticline, with a NNW–SSE trending fold axis and a total thickness of about 300 m (Fig. 1). Deformation is related to orthogonal flexure (Twiss and Moores, 1992) accommodated by a microfracture cleavage, extension gashes and pressure solution. Concerning sedimentological sections it is important to note that the orthogonal thickness of the layers remains constant during orthogonal flexure. The quartzite predominantly shows large scale, tabular-planar cross-stratification, with subordinate tangential, concave-up crossbeds, but wedge-shaped-planar sets and horizontal stratification also occur (Fig. 2). Reactivation surfaces are present. Single foresets are about 20 cm thick, display a millimetre to centimetre scale lamination of finer and coarser sand. Some foreset-laminae are reverse graded in the upper part, similar to the aeolian pin-stripe lamination described by Fryberger and Schenk (1988). The angle between foresets and bedding surfaces ranges between 13–30° with a mean angle of 24°.

After restoring the bedding surfaces to the horizontal around the fold axis, the dip of the foresets indicates a bimodal ENE- and WSW-ward paleocurrent direction with a strongly dominating ENE-ward direction, corresponding well with the paleocurrent directions of the Muth Formation in the Malla Johar area, to the ENE (Kumar et al., 1977), and in the Zanskar area, to the E (Gaetani et al., 1986). Asymmetrical ripples on bedding surfaces show a greater variation of directions, but mainly also point to a NE-directed paleocurrent.

Ripples are common, most of them are symmetrical, but slightly asymmetrical ripples are also present. They have average amplitudes of 0.6 cm and 4–6 cm wave-
Sandstone of Kalbarri, Western Australia consists mainly of sand-sized sediments interpreted as a fluvial shore environment. Comparable sedimentary environments with striking similar ichnoassemblages of Takcha and Khar grade laterally into one another, resulting in a complex sedimentary environment roughly the same age are described from Antarctica (Gevers et al., 1971; Trewin and McNamara, 1995 and references cited therein). The sedimentary environment of the Taylor Group of the Beacon Supergroup of southern Victoria, Antarctica was under debate for a long time, in the more recent literature a non-marine in a fluvial to alluvial plain environment is favored (Woolfe, 1990, and references cited therein).

Locality details

In the Pin Valley, at an altitude of about 3640 m, SE of Mikkim, at the river junction of the Pin River and the Parahio River, where the Pin River cuts into the western termination of the Muth Quartzite, river erosion and weathering have exposed the steeply dipping quartzite, producing fresh bedding and forest surfaces, on both of which abundant superbly preserved trackways have been found (Fig. 1). Trackways also occur in other parts of the Muth Quartzite outcrop, but are scarce and often badly preserved. The rock surfaces show a white color when they are relatively fresh, but become progressively darker, from pale yellow to orange to dark brown, when they have been exposed to weathering for a long time. They commonly display dissolved surfaces with small, irregular solution hollows (resembling raindrop impressions), due to chemical weathering under probable weak alkaline rainwater conditions (Dongarrá and Francofonte, 1995). Additionally, rock surfaces are coated with dark brown to black, shiny rock varnish, often veiling the trackways and primary sedimentary structures. Rock surfaces more exposed to the wind show substantial abrasion.

Description of trackways

Several clearly distinct arthropod trackway types have been recorded. The trails vary in their external width from 4–50 cm and comprise circular, elongate, crescent-shaped and scratch-like imprints, forming straight to curved trackways with track lengths of up to 3 m or more. A variety of limb and telson impressions have also been preserved.

Besides the more striking arthropod trackways some burrows have been recorded (Fuchs 1982; Bhargava and Bassi 1988). They consist of gently curved endichniial burrows, usually continuous for about 10 cm, occurring mainly horizontally on bedding surfaces, gradually fading-out across the surface. These burrows generally preserved as open tunnels, circular in cross-section and are 0.9–1 cm in width (Fig. 3(a)). A second distinct group of burrows are only about 0.4 cm in width. These burrows are more strongly curved and show several junctions. They are also endichniial burrows on bedding surfaces, but as a difference they are filled in their whole length (Fig. 3(b)). The interpretation and ichnotaxonomy of the trace-fossils remains preliminary; more observations, which will be carried out during the fieldwork in the Summer of 1997, are required for a complete systematic ichnology.

lengths; the ripple index L/H ranges from 4 to 14. Ripples are typically sub-parallel crested, slightly sinuous and often bifurcated, resembling many attributes of wave ripples. Interference ripples with rounded crests, also recorded in the Muth Quartzite in Lahul by Vannay (1993) can be found. A strong argument for at least temporarily emergent conditions is the occurrence of scour-remnant ridges (Allen, 1965). They occur on upper bedding surfaces, showing a streamlined shape with the steeper side facing windwards and are up to 4 cm long, about 0.2 cm high and up to 0.7 cm wide. This feature, which is wholly erosional in origin, is chiefly related to aeolian deflation and represents a common surface structure on beaches (Allen, 1965). It is important to note that these scour-remnant ridges indicate a paleowind direction to the west, which is exactly the opposite direction indicated by the dip of the foresets. An additional sedimentological feature are desiccation cracks, which have also been observed by Bagati (1990) in the Muth Quartzite near Taka and Khar.

The general mineralogy of the Muth Quartzite in the Pin Valley near Mikkim is strongly dominated by moderately to well sorted quartz grains, with a very low polycrystalline to total quartz ratio (Gaetani et al., 1986). There are hardly any other minerals present in thin section; of the heavy minerals only zircon and well rounded blueish tourmaline occur (Vannay, 1993), which are considered as unstable during sedimentary processes. There is virtually no clay matrix present.

Due to post-depositional alterations of the quartzarenite, including pressure solution and silica overgrowth, grain size analyses are difficult to carry out. The size of quartz grains varies from 0.12–0.75 mm, with two maxima of about 0.13–0.16 mm and 0.35–0.60 mm. This bimodal distribution of grain sizes has been described from the Muth Quartzite in several areas; Spiti (Dasgupta, 1971; Mukherjee and Dasgupta, 1972), Zanskar (Gaetani et al., 1986) and Lahul (Vannay, 1993). Several authors explain this bimodal distribution of grainsizes by grain sorting during aeolian transportation in the Muth Quartzite. However, bimodal grain size distributions are also found in several other depositional environments (Taira and Scholle, 1979).

The nearshore/foreshore/backshore environment shows a huge variety of depositional structures due to the action and interaction of several marine processes driven by wind, waves and currents. Many of these sedimentary structures are quite similar and often grade laterally into one another, resulting in a complex pattern of depositional environments, complicating their interpretation, especially in the fossil record (Davis 1992).

The present authors suggest a deposition of the Muth Quartzite in the Pin Valley in a foreshore/backshore environment. Comparable sedimentary environments with striking similar ichnoassemblages of roughly the same age are described from Antarctica and Australia (Gevers et al., 1971; Trewin and McNamara, 1995). The ?Upper Silurian Tumblagooda Sandstone of Kalbarri, Western Australia consists mainly of sand-size sediments interpreted as a fluvial braided outwash plain in its lower part, a mixed fluvial sandsheet and aeolian dune development in the middle part, containing most of the arthropod traces, and a shallow marine, tidal influenced upper part (Trewin and McNamara, 1995 and references cited therein).
**Palmichnium antarcticum** (Gevers et al., 1971)

Trackways of this type are preserved on both bedding surfaces and foresets, in approximately equal abundance. Trackways display a wide size range; the internal width (Trewin, 1994) varies from 3.9–24.5 cm and the external width from 7.4–49.8 cm. Commonly, trackways are straight to gently curved, and when occurring on foresets they show a surprisingly uniform uphill walking direction. Some of the trackways display a continuous medial impression, this rarely occurs along the mid-line, but more commonly lateral to the median axis of the trackway. The medial impressions vary in thickness varies from 0.2–1.5 cm, with an imprint depth of 0.1–0.4 cm, and are semi-circular in cross-section. Some medial impressions show weak variations in impression depth, indicating the variation in the force that the telson was applied to the substrate, possibly corresponding with the stride.

In most trackways, there are two pairs of tracks on either side of the mid-line. However two excellently preserved trackways show three tracks in a series (Fig. 4(a) and (b)). The outer and middle tracks are variable in their appearance, depending on their level of preservation. In well preserved trackways the outer and middle track are associated with thin, elongate imprints oblique to the mid-line at an angle of about 40°, with distinct ridges, often more than 0.5 cm high, pushed up behind each imprint. Some scratch marks and some abraded tracks, that penetrate to a deeper level, suggest a bifid termination of the outer limb. Where preserved, the inner tracks form shallower circular imprints, which are not in line with the middle and outer track, but offset to lie between the stride of the middle and outer tracks (Fig. 4(a) and (b)).

Usually there is a great regularity in the spacing and arrangement of the tracks, but more irregular track
series have also been found. Sometimes there is a change of stride, symmetry or the angle of the series to the mid-line (Trewin, 1994) along the trackways. The symmetry of these trackways is not always opposite but in places staggered or occasionally alternate (Trewin, 1994). The angle of the "V" ranges from 98-180° apparently depending on the stride and/or foreset slope-angle.

The ichnotaxonomy of these trackways is uncertain at this preliminary stage of analysis. Well preserved
trackways are similar to *Paleohelcera* (*Beaconichnus*) *antarcticum* (Gevers et al., 1971), which was recently transferred to *Palmichnium* by Braddy and Milner (In review).

These type of trackways in the Muth Quartzite were produced by large, heteropodous, hexapodous or octopodous animals. The size of the trackways, the relatively large size, the structure and heteropodous appearance of the tracks favour eurypterids as probable candidates. The wide size range displayed by the trackways possibly indicates a wide range of ontogenetic stages or different genera of the animals responsible.

The broad, deep medial impressions were most likely produced by the animals dragging their telson. The genital appendages of these animals are unlikely to have produced the median drag marks (cf. Hanken and Stormer, 1975), as appendage imprints tend to occur as isolated marks (e.g. Braddy, 1995).

Most of the trackways are surface tracks, often demonstrated by the undisturbed sand laminae directly above them. Although rare undertracks (Goldring and Seilacher, 1971) do occur, it seems that the coarse grain size of the Muth Quartzite did not facilitate the development of undertracks, which tend to occur preferably within laminations of clay and silt sized sediments (Goldring and Seilacher, 1971).

A widely believed general rule for eurypterid trackways is that opposing pairs of tracks "V" in the direction of movement, as in the xiphosuran trackway *Kouphichnium* (but not the scorpion trackway *Paleohelcera*). As eurypterids were so morphologically diverse, it is likely that they also had diverse walking techniques (Selden, 1984). Therefore additional criteria are required to assess the direction of movement. The walking direction is considered to have been in the direction of series divergence, as evidenced by small sand ridges pushed up behind each track, especially when the animal walked uphill on foresets, but this is more difficult to determine for trackways on bedding surfaces.

*Diplichnites gouldi* (Gevers et al., 1971)

The trackways consist of straight to gently curved rows and single trackways can be traced over more than 73 cm on a bedding surface. Imprints define two rows with a relatively constant width of 2.3 cm. Where the trackway is curved, the outer track row is flanked by slightly raised outer ridges. Due to missing posterior ridges the direction of movement cannot be determined unequivocally. Individual tracks commonly show undisturbed, distinct imprints, tending to be circular to ellipsoidal to semi-circular in shape and range in dimensions from c. 0.7–0.8 cm. Tracks tend to be inclined at 65–70° to the trace axis, the angle possibly closing anteriorly (Johnson et al., 1994). Single tracks are spaced c. 0.9 cm apart along the length of the trackway and the symmetry of tracks changes slightly along the trail from opposite to weak staggered (Fig. 5).

Trackways of this type are rare compared with the *Palmichnium* traces. The size and appearance of the trackways imply that these probably originated from myriapods (see the discussion of possible trailmakers in Johnson et al., 1994).

**Discussion**

According to Buatois and Mangano (1993) just about 20 non-marine, Devonian invertebrate ichnogenera are known so far, of which only a small number have been assigned to arthropods. Most of these have been described from marginal marine and lacustrine settings although subaerial environments have been
noted. The depositional setting of the Muth Quartzite is still under debate; this discovery of abundant trace fossils in the Muth Quartzite may prove helpful in the reconstruction of its ancient depositional environment. Another outcrop in the Muth Quartzite with arthropod trackways evident was mentioned by Bhargava and Bassi (1988), who described arthropod trackways possibly produced by chelicerates 4.5 km WSW of Leo, Spiti, lying 15 m below the contact to the overlying Lipak Formation.

The high maturity in its mineral composition and sorting and the lack of any fine grained matrix point to a high energy sedimentary environment for the Muth Quartzite. This raises the question, why have these trackways been preserved in such large numbers? The majority of trackways reported in the literature occur in clay–silt sized sediments, which are often finely laminated, whilst reports of trackways from sandstone are rare. For this reason, it has often been argued that sand, and especially dry sand, does not have the degree of cohesion necessary for the preservation of trackways (McKeever, 1991). A substantial moistening of sand or infiltrating clay minerals were proposed by McKeever (1991) to get a suitable potential of preservation in sand-size sediments. Fornos and Pons-Moya (1982) equally suppose moistened sand conditions during the formation of *Myotragus balearicus* trackways in Pleistocene aeolian dunes. Gevers and Twomey (1982) considered algal slime and saline surf-spray as other possible binding agents. They regard pure water from dew or light rain as insufficient to enable the preservation of trackways.

Another possibility for the preservation of trackways is probably the early cementation of the fine grained part of a pin-stripe lamination, a lamination of fine and coarser grained sand common in aeolian sediments (Fryberger and Schenk 1988). These early cemented layers possibly represent a discontinuity along which the sediment separates, displaying the trace fossils.

Brand (1979, 1996) carried out extensive field studies to investigate the appearance of trackways produced by modern amphibians and reptiles on different substrates, slope angles and moisture contents. The different substrate conditions were found to cause a big variation in the appearance of trackway within one species. Comparison of the trackways considered here with the work of Brand (1979, 1996), reveals an obvious similarity between some uphill trackways found on foresets in the Muth Quartzite and these produced on sloping dry sand in the laboratory studies. There are only a few arthropods known from the Devonian which are big enough to have been the trackway producers. Eurypterids or scorpions are candidates as possible trailmakers (cf. Briggs and Rolfe, 1983 for a discussion of possible arthropods). Besides the size, there are several other arguments favouring eurypterids. Eurypterids are thought to have had an amphibious habit (Briggs and Rolfe, 1983; Selden, 1984; Walter, 1984), which is consistent with the appearance of some trackways, apparently formed under at least temporarily dry conditions. Eurypterids are strongly heteropodous, which corresponds well with the observations on these trackways, where wind abrasion reveals a deeper level of tracks, showing their heteropodous nature.

One important question arises, whether the foreshore/backshore environment of the Muth Quartzite, at least temporarily dry, was the normal habitat of the trailmaker. Interesting observations are two trackways at the same place of exactly the same size and shape, running in the same direction, just separated by two foresets, suggesting that exactly the same animal or two different individuals of exactly the same size walked the same way at least two times. An additional observation is a sharply defined beaten track c. 30 cm wide and more than 1.5 m visible on a bedding surface consisting of more than a dozen individuals trackways of probable eurypterids (Fig. 6).
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Andrews H. E., Brower J. C., Gould S. J. and Reyment R. A. (1974) related much thought on the environment of deposition. Hugh Christine Miller and Gerhard Wiesmayr, who assisted ED and BG in their field studies. The thorough and constructive Palaeozoic terrestrial ichnofaunas awarded to D.E.G. Briggs (University of Bristol). Christa-Charlotte Hofmann stimulated much thought on the environment of deposition. Hugh Rice, Fritz Steininger, Werner Piller, Christian Meyer and Peter Pervesler provided much helpful discussion and support. The drawings were made by Leo Leitner. Thanks to Christine Miller and Gerhard Wiesmayr, who assisted ED and BG in their field studies. The thorough and constructive review by N.H. Trewin was much appreciated and improved both content and style.

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