Fluidization pipes and spring pits in a Gondwanan barrier-island environment: groundwater phenomenon, palaeo-seismicity or a combination of both?

E. DRAGANITS¹, B. GRASEMANN¹ & H. P. SCHMID²

¹Institut für Geologie, Universität Wien, Althanstrasse 14, A-1090 Wien, Austria
(e-mail: Erich.Draganits@univie.ac.at)
²OMV, Exploration & Production, Gerasdorfer Strasse 151, A-1210 Wien, Austria

Abstract: Cylindrical structures, cross-cutting stratification at right angles, occur in the Muth Formation, representing Lower Devonian barrier island arenites of the North Indian Gondwana coast. These structures are up to 1.5 m in height and 0.8 m in diameter, with an internal structure comprising concentric, cylindrical laminae. The pipes, which probably represent water conduits for laminar upward flow of ground water, initiate from relatively thin horizons, with upper terminations formed by spring pits. Thus, the structures in the Muth Formation represent a rarely observed combined occurrence of spring pits and their conduits below. Their formation is explained by rising ground water seepage in a coastal depositional environment that produced a relatively high hydrostatic head, resulting in the formation of springs. The rise in relative sea level might be related to tectonic subsidence caused by tectonic activity linked to the formation of conjugate deformation bands in the Muth Formation. This means, if tectonic activity was involved, it did not form the cylindrical structures by seismic liquefaction directly, but might be responsible indirectly through ground water seepage rise resulting from tectonic subsidence. Due to the little relief in this environment, the sea level rise affected a relatively large area and fluidization structures can be found widespread in distant sections.

Liquidization structures represent important post-depositional modifications of sediments, affecting many lithological parameters at various scales and bearing considerable importance to groundwater flow, oil migration paths and reservoir characteristics. At small scales, liquidization can modify grain size distributions, orientation of clasts, porosity and permeability (Lowe 1975), whilst at larger scales it may alter primary sedimentary structures, bed contacts and even the overall shapes of sedimentary bodies (Lonergan et al. 2000).

According to Allen (1982, pp. 293–295), ‘liquidization’ describes processes that modify loose, grain-supported sediments, reducing their shear strength so that they behave like a viscous liquid. Liquidization processes include ‘liquefaction’, which is the transformation of a loosely packed granular material from a solid state into a liquefied state without any exchange of fluid and neglectable volume change (Youd 1973) and ‘fluidization’, which is liquidization by upward directed flow of externally derived fluid in a granular sediment body, where the fluid drag on the detrital grains exceeds their weight. Liquidization structures are common in clastic sediments and may originate from seismic and non-seismic processes (e.g. Lowe 1975; Allen 1982; Obermeier 1996a).

Cylindrical structures in granular sediments, cross-cutting stratification nearly at right angles, have been mentioned from several depositional environments. Several explanations have been summarized by Dionne & Laverdière (1972), Deynoux et al. (1990), Hunter et al. (1992), Dionne & Pérez-Alberti (2000) and Massari et al. (2001). These include: (i) upward flow of liquidized sediment resulting from liquefaction (triggered by wave action, seismic events and impact shaking (Alvarez et al. 1998), mass movements or rapid sedimentation); (ii) fluid/gas escape resulting from fluidization (e.g. water springs, volcanic exhalation, hydrocarbon gas seeps, boiling water above basaltic sills (Rawlings 1998), gas blow-out pipes or conduits below mud-volcanoes (Kopf 2002, and references cited therein)); (iii) collapse following the removal of underlying material (e.g. evaporite and carbonate dissolution or melting of buried ice); (iv) filling of pipe-shaped cavities (e.g. evorsion holes, Fenninger 2000); (v) vertical, pipe-shaped weathering channels (van Husen 1999); (vi) concretions around an organic core; and (vii) animal burrows. In this context, it is worth mentioning that creationists generally interpret cylindrical liquidization structures as direct evidence for the global Flood of the bible (Cox 1977; Roth 1992; Walker 2000).

Spring pits have been described by Quirke (1930), but hardly anything has been written about these structures since then (Draganits & Janda 2003); therefore relatively little is known about them compared to cylindrical liquidization structures.
According to Quirke (1930) they form near the shoreline, above and below water, by ascending water which rises with sufficient force to sweep out finer sand grains.

In this paper, we describe cylindrical structures developed in quartz arenites of the Lower Devonian Muth Formation (NW Himalayas). These pipes, together with other liquidization structures, like spring pits and slumped beds, have been found in three lithostratigraphical sections with a total restored distance of 31 km normal to the overall facies trend (Figs. 1, 2). The cylindrical structures in the Muth Formation add important new information to those described in the literature, as both the source and termination of the pipes are exposed. The depositional environment of the Muth Formation has been interpreted as a barrier-island system, with the quartz arenites representing sediments deposited from shoreface to coastal dunes (Draganits 2000). In this environment, liquefaction by wave action and tectonic activity (Öbermeier 1996b) or fluidization by ground water table variations controlled by relative sea-level fluctuations (Massari et al. 2001) seem the most probable mechanisms behind liquidization.

The liquidization features in the Muth Formation are associated with conjugate deformation bands (Aydin 1978) and conjugate brittle faults in the uppermost part of the broadly upper Ordovician to lower Silurian Pin Formation below. Both deformation structures show identical orientations and document E–W directed shortening in a transcurrent tectonic setting; they are interpreted to belong to the same process and represent a previously unknown pre-Himalayan deformation stage in the NW Himalayas (Draganits 2000). Cashman & Cashman (2000) have shown that deformation bands may develop at near-surface conditions and that the formation of deformation bands can be related to seismic slip events on nearby faults. Due to the existence of deformation bands, palaeo-seismicity is a possible trigger mechanism for liquefaction in the Muth Formation.

**Geological setting**

The Muth Formation belongs to the Tethyan Zone of the Higher Himalaya tectonic unit, which records an almost continuous stratigraphic sequence from the Neoproterozoic up to the Eocene, deposited at the northern Indian continental margin. In the Pin Valley (Fig. 1), the Tethyan sediments were deformed during the Himalayan orogeny into large-scale SW-vergent folds, with maximum wavelengths of approximately 5 km (Fuchs 1982; Wiesmayr & Grasemann 2002). Crustal thickening related to folding resulted in metamorphic conditions ranging from diagenetic zone in the Mikkim and Muth sections to anchizone in the Baba La (‘La’ is the Tibetan word for pass) section (Wiesmayr & Grasemann 2002).

The Muth Formation is underlain by the yellow-brown weathering Pin Formation of upper Ordovician to lower Silurian age (Bhargava & Bassi 1998; Talent pers. comm. 2001). At the type section, the Pin Formation reaches a thickness of some 290 m and consists of variable lithologies. The contact to the white quartz arenites of the Muth Formation above represents a disconformity in all three sections (Fig. 2).

The Muth Formation is devoid of age-diagnostic fossils, but well constrained middle Devonian conodont faunas in the lower parts of the overlying Lipak Formation and the arthropod ichnofauna of the Muth Formation broadly indicate an early Devonian age (Draganits et al. 2001; Draganits et al. 2001).
2002). The formation comprises monotonous white, fine- to medium-grained, extremely pure quartz arenites with high textural, as well as compositional, maturity; the only exceptions are thin horizons of sandy and silty dolomites in higher levels of the formation (Fig. 2). The Muth Formation represents a relatively 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 (Wiesmayr & Grasemann 2002).

In the Pin Valley, based on different, diagnostic sedimentary structures, the Muth Formation has been divided into four facies associations (FA 1 to FA 4, Fig. 2). The basal facies association (FA 1) is dominated by relatively thin-bedded, horizontally laminated arenites, with an increase in tabular cross-bedding at higher levels. This association is followed by thick, large-scale tabular and tangential cross-bedded beds with steep foreset angles (FA 2). The third association (FA 3) forms a conspicuous, sharp-based horizon comprising orange to brick red, highly oxidized very fine-grained dolomite, clay-, silt- and sandstone. The uppermost part (FA 4) of the Muth Formation consists mainly of horizontally bedded quartz arenite, which shows a gradual increase in impurity towards higher levels.

In general, the depositional environment of the Muth Formation is interpreted as a barrier island system; arguments leading to this interpretation are discussed in detail by Draganits (2000). FA 1 is interpreted as transgressive sequence with beach sediments at the base and upper shoreface to upper foreshore deposits in the upper part. FA 2 is considered to represent shallowest foreshore, backshore, and coastal dune sediments. Sedimentary structures such as flat-topped ripples, adhesion ripples, tear-shaped ridges (McKee 1957) and desiccated biofilms indicate at least temporally emergent conditions. The fine-grained, fine-laminated sediments of FA 3 are interpreted as lagoonal deposits. The final facies association probably comprises foreshore to lower shoreface and displays a transgressive trend with a gradational contact to the inner shelf deposits of the overlying Lipak Formation (Draganits 2000). Cylindrical structures are found in the uppermost beds of FA 2 and within FA 3; spring pits occur in the upper part of FA 2 and in the uppermost part of FA 4 (Fig. 2, 3).

**Liquidization structures**

The lithostratigraphical sections of the Muth Formation in Figure 2 represent simplified bed-by-bed sections. Peculiar cylindrical structures and spring pits represent the most eye-catching liquidization structures in the Muth Formation of the Pin Valley. However, a slumped bed occurs in the Mikkim section, some 220 m above the base of the formation (i.e. in the lower part of FA 2) and dish – and pillar structures (Lowe 1975) have been found rarely in some levels of the section. Both structures are of relative small-scale and do not seem to exceed water escape structures, which might be expected in the coastal depositional environment of the Muth Formation. They probably formed by de-watering induced by common processes in this environment such as storm waves or sedimentary overloading, which are different from the processes that formed the much larger cylindrical structures and spring pits.

**Cylindrical structures**

Among the liquidization structures of the Muth Formation, the cylindrical structures are by far the most spectacular ones (Fig. 4). In both size and internal structure, they are very similar to the cylindrical structures described by Hawley & Hart (1934) and Dionne (1973), although their closest analogues are the cylinders described by Deynoux et al. (1990). Two small cylindrical structures appear in an arenaceous bed in FA 3 (Fig. 2) in the Baba La section, c. 2 km to the north of the Baba La (Figs. 1, 2), a pass connecting the Pin and Baba Valleys (section G-G’; N31°40’05”; E78°00’14”; 4520 m).

With the exception of the two pipes in the Baba La section, all cylindrical structures have been found in the type section (Fig. 2), 1.3 km to the south of village Muth (section E-E’; N31°56’44”; E78°02’05”; 3860 m). There, relatively small and rare pipes are found 12 m below the top of FA 2. In the uppermost three beds of FA 2 (aeolian dunes), pipes are large and abundant and some small pipes also occur in arenaceous beds within the fine-grained dolomites in the upper part of FA 3, interpreted as lagoonal sediments (Figs 2, 3). Although both sections have a restored distance of 18 km (Wiesmayr & Grasemann 2002), these structures occur at similar levels in FA 3.

The cylindrical structures in the uppermost beds of FA 2 in the type section at Muth have been investigated in detail; there these structures are abundant and best exposed (Fig. 4). Bed numbers refer to beds of the bed-by-bed section in Fig. 3. Most pipes are found in the uppermost three beds of FA 2 (beds M438–M440 in Fig. 3); rare pipes are found in bed M436 too. The contact of the uppermost bed of FA 2 (M440) to the first bed of FA 3 above is a very sharp lithological break of quartz arenite to fine-grained dolomite (Fig. 3).

All bar one of these beds comprise white to slightly greenish, pure quartz arenite with a high textural and compositional maturity, cemented by quartz. The
exception is bed Me437, which consists of dark green quartz arenite with a mixed chlorite/quartz matrix, showing a texture of pore-filling infiltrated clays (Price 1996). Grain size in all the beds is consistently in the medium sand range. Beds Me438 and Me440 show large-scale, high-angle, concave-up tangential cross bedding. Bed Me437 shows no internal structure and the rest of the concerned beds are horizontally laminated (Figs. 3, 4e, 4f). Outside the pipes, the beds have preserved their primary sedimentary structures and bed boundaries very well; only beds Me435–Me437 show slightly wavy bedding surfaces with varying bed thickness.

The pipes crosscut bedding surfaces at right angles and generally comprise straight, nearly perfect cylindrical shapes (Fig. 4e, f). A few funnel-shaped structures have been found, which always taper downwards; generally, they are much smaller compared to cylindrical-shaped pipes and have been found only in the lowermost part of bed Me438. Pipes range in height from 5 to 155 cm with diameters from 2 to 80 cm; longer cylinders tend to have larger diameters than smaller ones, but no correlation is evident. The contact of the pipes to the completely undisturbed rest of the beds is a sharp boundary (Fig. 4e, f) and thus contrasts strongly from fluidization pipes surrounded by fluidization halos described by Mount (1993). Where the lamination of the host rock is truncated abruptly, the cylinder shape is regular and smooth. No clay enrichment at the contact between pipe and the rest of the bed as described by Mount (1993) has been observed. Analogous to observations by Best (1989), the sediment in the pipe-interior is slightly depleted in the finest sand fraction and especially in clay. Apart from this depletion of fines, grain size, composition and cement are nearly identical within cylindrical structures and host sediment.

Fig. 2 left. (a) Lithostratigraphical sections of the Muth Formation from the Pin Valley showing the correlation of the facies associations and the levels with cylindrical structures. The restored distances between the Mikkim and Muth sections and the Muth and Baba La sections are 13 km and 18 km, respectively. FA = facies association. (b) Overview of the Palaeozoic stratigraphy in the upper Pin Valley; view from the ravine NW of Muth village towards the SE; up-section to the left. Arrow indicates the location of the cylindrical structures at the contact between FA 2 and FA 3. S = Shian Formation, P = Pin Formation, M = Muth Formation, L = Lipak Formation.

Fig. 3 right. Detail of the lithostratigraphical section E-E’ at the level of the cylindrical structures. For lithological index and abbreviations see Fig. 2. Bed numbers represent numbers of the bed-by-bed section. FA 2 – mainly aeolian arenites; FA 3 – lagoonal dolomites and sandy dolomites; FA 4 – shallow marine arenites.
The internal structures of the pipes vary between two end members, which are similar to the two types of cylindrical structures described by Deynoux et al. (1990). Most of the structures are somewhere in between these two extremes and therefore no separate types are classified in this paper. No differences in size have been found between these two end members; both types occur next to each other. One end member, identical to type 2 of Deynoux et al. (1990, fig. 7), comprises just a single, thin cylindrical-shaped lamina, representing the boundary of the structure, with more or less undisturbed primary sedimentary structures preserved inside; the primary sedimentary lamination commonly shows downward bending and/or normal faulting to variable extend.

Fig. 4. (a) Lower bedding surface view of several circular and spindle shaped liquidization structures at the base of bed M₄,438 (Lens cap diameter 53 mm). (b) Lower bedding surface view of an empty, spherical shaped liquidization structure at the base of bed M₄,438, connected to the beginning of concentric laminations of a pipe above. (c) Lower bedding surface view of axial sections of cylindrical structures at the base of bed M₄,438, partly obscured by lichens. (d) Lower bedding surface view of two, small cylindrical structures, some 12 cm apart within a larger, elliptical shaped liquidization pipe. (e) Sectional view of a large pipe crosscutting tangential cross-beds; up-section to the left. Note slightly darker bed M₄,438 at the base of the cylindrical structure. See geological compass for scale. (f) Slightly oblique, near-axial section of a cylindrical structure crosscutting bedding at nearly right angles; up-section to the left. Note the sharp boundary to the host sediment and the thin, well-developed concentric laminae at the rim and the thicker, concave upward laminae in the central part.
In the other end member, which is similar to type 1 of Deynoux et al. (1990, fig. 5b), in axial sections the internal structures show several, regular, vertical, concentric (in rare cases slightly eccentric), some few mm thick laminae across the complete diameter of the cylinders (Fig. 4c). In contrast to type 1 of Deynoux et al. (1990) they rarely show a cone-in-cone arrangement in longitudinal sections, but this might just reflect which part of the internal structures of pipes actually are exposed, because conical laminae tend to become cylindrical shaped in higher parts.

The concentric laminae in the pipes are formed by subtle grain size variations; there is no trend of grain size variations visible across the pipe diameter. Concentric laminae may occupy the complete diameter of the cylinder, or just parts of it (Fig. 4c, f). In the latter case, without exception, the lamination is always found at the rim but the core appears to be relatively structureless or the lamination is thicker, further found continuing into the fine-grained, red, well-oxidized dolomite bed (M441); therefore, the upper surface of M440 is regarded as the top of the liquidization pipes. At the upper surface of M440, there is no sign of any extruded sand material; on the contrary, the filling has sunk, as already indicated by the previously described internal structures of downward bending of sedimentary lamination and normal faulting. In one case, a c. 3 cm long, fine-grained sediment clast was found in the uppermost part of a pipe, possible indicating some backfilling from above. Thin, planar sand fissures occur (compare with Deynoux et al. 1990, fig. 5C), oriented perpendicular to the bedding, but they do not show radial orientation to the pits; in some cases they seem to cross-cut the rim of the spring pits (Fig. 5b).

Other possible spring pits are found in the uppermost part of the Muth Formation at the type locality. There a prominent upper bedding surface that can be traced for several km is completely covered with abundant, randomly distributed circular pits (Fig. 5c). The bowl-shaped depressions are up to c. 80 cm in diameter and resemble spring pits (Quirke 1930), but no cylindrical structures have been found in the beds below them.

Enigmatic donut-shaped structures on upper bedding surfaces of horizontal well-laminated beds have been found SE of village Mikkim. These structures have a striking circular, donut-shaped raised ring with a bowl-shaped, central depression; they might be confused with spring pits, but represent microbial gas domes (Noffke pers. comm. 2002).

Deformation bands

Another group of post-depositional structures in the Muth Formation are deformation bands (Aydin 1978). They represent conjugate shear fractures that develop cluster zones rather than discrete fault zones. They show evidence of effective porosity reduction and compaction by cataclastic processes, as well as reorganisation of quartz grains. The final appearance of the microstructure is controlled by porosity, effective pressure, fluid content and amount of displacement (Antonellini et al. 1993).

They have been observed SE of Mikkim (section A-A’) throughout the entire Muth Formation. Deformation bands are concentrated at c. 120 m and 180 m above the base of the Muth Formation, but they are most common between 200–240 m, in

Spring pits

Several liquidization pipes have been described in the literature, but their upper terminations have hardly ever been exposed or preserved. The upper bedding surface of bed M440 shows numerous, virtually circular, randomly distributed deep pits, some more than 80 cm in diameter and several tens of centimetres deep (Fig. 5a). In a closer view, the rims of the pits are smooth and slightly raised and show concentric laminae; the uppermost filling has been partly weathered out (Fig. 5b). No pipe has been found continuing into the fine-grained, red, well-oxidized dolomite bed (M441); therefore, the upper surface of M440 is regarded as the top of the liquidization pipes. At the upper surface of M440, there is no sign of any extruded sand material; on the contrary, the filling has sunk, as already indicated by the previously described internal structures of downward bending of sedimentary lamination and normal faulting. In one case, a c. 3 cm long, fine-grained sediment clast was found in the uppermost part of a pipe, possible indicating some backfilling from above. Thin, planar sand fissures occur (compare with Deynoux et al. 1990, fig. 5C), oriented perpendicular to the bedding, but they do not show radial orientation to the pits; in some cases they seem to cross-cut the rim of the spring pits (Fig. 5b).

Other possible spring pits are found in the uppermost part of the Muth Formation at the type locality. There a prominent upper bedding surface that can be traced for several km is completely covered with abundant, randomly distributed circular pits (Fig. 5c). The bowl-shaped depressions are up to c. 80 cm in diameter and resemble spring pits (Quirke 1930), but no cylindrical structures have been found in the beds below them.

Enigmatic donut-shaped structures on upper bedding surfaces of horizontal well-laminated beds have been found SE of village Mikkim. These structures have a striking circular, donut-shaped raised ring with a bowl-shaped, central depression; they might be confused with spring pits, but represent microbial gas domes (Noffke pers. comm. 2002).
the lower part of FA 2, in coastal aeolian deposits (Fig. 2).

Deformation bands in the Muth Formation are mm thin, planar, slightly undulating features that can be traced for some cm to several m. They hardly ever occur alone, but usually occur in ‘zones of deformation bands’ (Aydin & Johnson 1983) that constitute many closely spaced deformation bands. Although deformation bands comprise the same mineralogy as the host rock they are raised slightly above the average rock surface due to higher weathering resistance; in contrast brittle faults of fully cemented quartzite show reduced weathering resistance. The boundary to the host rock is well defined, but not as distinct as in brittle faults.

The orientation of the deformation bands does not fit reasonably to any of the orientations of brittle faults related to Himalayan deformation in the Pin Valley (Wiesmayr & Grasemann 2002). Consequently, the deformation bands are not related to Himalayan deformation and therefore early Himalayan large-scale folding has been restored by back-rotation of the bedding surfaces to horizontal orientation together with the deformation bands. In the restored orientation, deformation bands show consistent orientations throughout the complete Muth Formation, forming conjugate sets of dominant WNW–ESE and less pronounced ENE–WSW trending faults, nearly perpendicular to stratification (Fig. 6).

Discussion

Occurrence of the cylindrical structures

Pipe-shaped structures with concentric internal lamination, cross-cutting stratification at right angles have been found in Lower Devonian quartz arenites of the Muth Formation. Several similar structures have been described in the literature (e.g. Deynoux et al. 1990; Hunter et al. 1992; Massari et al. 2001); two features seem to be common with the occurrence of cylindrical structures. The first characteristic is the frequent occurrence in mature, arenaceous sediments, e.g. shallow marine reworked aeolian sand (Hawley & Hart 1934) or aeolian sand (Deynoux et al. 1990). There, high porosity and permeability seem to support the formation of pipes. The second frequent feature is the common link of cylindrical structures and/or spring pits with the transition of marine/limnic/fluvial and terrestrial environments, where high water saturation occurs and water table variations are frequent (Quirke 1930; Hawley & Hart 1934; Gabelman 1955; Plint 1983; Deynoux et al. 1990; Guhman & Pederson 1992; Massari et al. 2001; Netoff & Shroba 2001; Draganits & Janda 2003). Both characteristics are also found in the Muth Formation. From this point of view, the restriction of the cylindrical structures in the Muth Formation to certain levels might thus
reflect the control of the depositional environment; the effects of repeated seismic events might also explain it.

With only few exceptions, the pipes in section E–E’ near Muth are restricted to beds Me438–Me440 (Figs 2, 3). From the observations, it seems that the initiation horizon of nearly all cylindrical structures is at the top of bed Me437, as indicated by tiny funnel-shaped pipes starting at the interface of beds Me437/Me438 and by small liquidization cells below the cylindrical structures (Fig. 4b); there are only a few pipes originating from below. A similar relatively narrow defined horizon of pipes initiation is also mentioned by Gabelman (1955). Compared with other beds of the Muth Formation, bed Me437 shows very high contents of chlorite in the inter-granular space, which might have originated from infiltrated clays (Price 1996). Lowe (1975) mentioned that many of his ‘Type B pillars’ originate at the bases of sand units that overlie mud or clay layers. Whether the increased clay content of bed Me437 is a result of high groundwater activity, or the clay content affected the movements of the fluids is a kind of chicken and egg problem.

Relationship between cylindrical structures and spring pits

The upper bedding surface of bed Me440 forms the boundary between FA 2 and FA 3 (Fig. 3); from its appearance, it even may represent a short period of non-deposition. This boundary is also the upper termination of all cylindrical structures at this level of the Muth Formation. No single continuation of pipes has been found above this surface and hence the formation of the pipes is interpreted to have happened before the sedimentation of the fine-grained dolomite above bed Me440. Consequently, there was no layer with reduced permeability (e.g. Plint 1983; Nichols et al. 1994; Obermeier 1996b) above the cylindrical structures during their formation, although the strength of the upper bed surface of Me440 might have been increased by microbial activity, observed in comparable levels of the Muth Formation in sections near Mikkim (Draganits 2000).

The upper bedding surface of bed Me440 is covered with irregularly spaced pits (Fig. 5a, b) resembling spring pits (Quirke 1930), but also earthquake induced circular settlements in sand (Galli 2000). Thus, the liquidization structures in the Muth Formation represent a rare combined occurrence of spring pits and their conduits below. Pit diameters are surprisingly similar; bearing in mind that most of the pipes seem to originate from the same depth near bed Me437, this possibly implies that the final pipe height controls the diameter. The lack of small erosion channels leading away from pit centres indicates that they formed under water (compare with Quirke 1930). This setting additionally implies fully water-saturated pore spaces during pipe formation. The good preservation of the spring pits also excludes strong erosion of the bedding surface after their formation. The fine-grained dolomite covered the spring pits with slow sedimentation rates and protected it from erosion; today the dolomite weathers much more rapidly than the quartz arenite of bed Me440 below, therefore the pits are very well exposed (Fig. 5a, b).
Common explanations of vertical cylindrical structures

The upward flow of the water is controlled by two mechanisms; relief of a high pore-water pressure and reconsolidation of the sediment grains. The rims of the spring pits show only a thin cover of sand rising only slightly above the bed surface with a smooth contact to the bed, indicating that the upward water flow was not competent enough to carry much sand.

Several different explanations of cylindrical structures in arenaceous sediments have been discussed extensively by Deynoux et al. (1990), Hunter et al. (1992) and Massari et al. (2001).

Following their arguments, many of the possible formation mechanisms can be ruled out. The coastal barrier island depositional environment makes liquefaction by slumping or overpressure by very rapid sedimentation unlikely. The position of the pipes in aeolian sand dunes (FA 2) below lagoonal sediments (FA 3) additionally reduces the probability of strong wave action. Collapse following dissolution or melting of underlying material is excluded by the lack of suitable sediments or former ice below the pipes; the lack of organic material also argues against a formation by hydrocarbon gas escapes. Hot water (Rawlings 1998) or volcanic exhalation is disqualified by the total lack of indication for volcanic activity. Filling of pipe-shaped cavities is improbable, as suitable cavities did not exist; concretions around organic cores like tree trunks or plant roots look different and there are also no indications for former organic material. Animal burrows are unlikely considering the size of the pipes, their regular shape and the lack of any other trace fossils at this outcrop of the Muth Formation.

Two explanations remain: liquefaction by earthquake shaking and fluidization by water springs. Both explanations concern an upwards-directed flow of a water/sand mixture, but differ in the reason behind liquefaction. However, distinguishing between seismic and non-seismic liquefaction structures can be difficult (Holzer & Clark 1993; Obermeier 1996a, b; Li et al. 1996).

Relationship between cylindrical structures and deformation bands

Earthquakes with magnitudes of five or more are thought capable of causing liquefaction, and magnitudes of about 5.5–6 are given in the literature for seismic events at which liquefaction effects become relatively common (Obermeier 1996a). Liquefaction of seismic origin, which is mainly caused by a cyclic shaking of the ground, is most common in sand, silty sand and rarely in gravel, but is very unusual in sediment with more than 15% clay content (Obermeier 1996a). Liquefaction takes place only where the sediment is completely saturated, strongly affecting sediments from a few to about ten meters depth; the susceptibility to liquefaction decreases nearly to nil at greater depths (Obermeier 1996a).

If the liquidization structures of the Muth Formation were caused by seismic activity, then the existence of deformation structures would support this model. Deformation bands, which have been found in the Muth Formation, are suitable candidates for such deformation structures. Seismic events during their formation can trigger liquefaction, but deformation bands do not channel upward-directed fluid flow, because they show reduced permeability compared with the host sediment due to grain size reduction and compaction (Aydn 2000). The orientation of the acute bisectrix of these conjugate deformation bands indicates E–W directed palaeo-strain direction, identical with the palaeo-strain direction of brittle faults in the underlying Pin Formation. These structures indicate seismic oblique contraction in a transcurrent tectonic setting and document a previously unknown pre-Himalayan deformation stage at the northern passive margin of the Indian continent during the Early Devonian.

In recent publications, it has been shown that deformation bands typically form in porous sandstone (Aydn & Johnson 1983; Antonellini et al. 1994; Mair et al. 2000). Thus their older age limit is constrained by the depositional age of the sediment and the younger age limit by the timing of thorough cementation. Quartz grains of the Muth Formation rarely show fractures or pressure solution, indicating relatively early diagenetic cementation. Cashman & Cashman (2000) have shown from Pleistocene marine terraces in California that deformation bands can develop at ‘essentially surface conditions’ and that their formation can be related to seismic slip events on nearby faults. Therefore, the age of deformation bands probably is close to the age of sediment deposition and the seismic events responsible for them might also have triggered liquefaction.

However, there are also several arguments against a seismic explanation of the cylindrical structures. In the Muth Formation near bed M,437, although the bedding surfaces show some undulation, there is no indication of severe liquefaction. The vertical settlement caused by sediment densification is commonly only some 3% of the liquefied sediment thickness (Obermeier 1996a). Therefore, a single seismic event is regarded incapable to produce enough water to form the cylindrical structures and spring pits of the Muth Formation, bearing in mind the multitude of large pipes within unliquefied host sediments.
and the well-developed concentric lamination of several pipes that argue for considerable fluid flow through the pipes. Furthermore, this hypothesis is supported by the depth of spring pits that may give indications for a combination of volume loss due to compaction and by selective out-wash of finer grain sizes (Best 1989; Draganits & Janda 2003). More persistent and less vigorous flow of water than expected from short-lived liquefaction processes may explain the size, shape and internal structures of the liquidization structures of the Muth Formation.

Additionally, the regular cylindrical pipes from the Muth Formation look quite different from liquefaction structures of unequivocal seismic origin, which usually are much more irregular (Obermeier 1996a). No evidence of fracturing or indications of rapid, short-lived, vigorous expulsion, as might be expected with seismic liquefaction (Obermeier 1996a, b; Takahama et al. 2000) has been found.

Formation of the cylindrical structures in the Muth Formation

The cylindrical structures of the Muth Formation are interpreted as fluidization pipes formed by channelled ascending ground water, while the surrounding sediment remained largely unfluidized; possible other explanations have been discussed in the previous section. Similar cylindrical structures in sandstone have commonly been attributed to non-seismic origin, often to up-welling of ground water (e.g. Hawley & Hart 1934; Gabelman 1955; Dionne 1973; Deynoux et al. 1990; Li et al. 1996; Dionne & Pérez Alberti 2000; Massari et al. 2001).

Accepting a possible ground water spring explanation for the cylindrical structures, what are the possible reasons for up-welling water in the barrier island depositional environment of the Muth Formation? During deposition of the Muth Formation in early Devonian time, the climate is generally regarded as having been relatively arid. Additionally the high maturity, surprising consistency of the quartz arenites of the formation and the thorough oxidation of the fine-grained dolomite above the pipes reduces the probability of a major fluvial or precipitation influence. Therefore, freshwater, which can rise upwards in a marine phreatic zone due to gravity differences as suggested by Hawley & Hart (1934) and Deynoux et al. (1990) is regarded unlikely to have formed the pipes in the Muth Formation, but cannot be ruled out completely.

The sharp lithological break on top of bed M4,440 from quartz arenite to very fine-grained dolomite indicates a major change in the depositional environment of the Muth Formation. Rapid rise in relative sea level indicated by the deposition of lagoonal sediments above barrier island dunes possibly also triggered a rapid rise in ground water seepage that produced a relatively high hydrostatic head, resulting in the formation of springs. Subtle grain-size variations probably caused small inhomogeneities in fluid flow, which initiate self-accelerating channelling of the vertical upward movement of fluid (Couderc 1985), that resulted in randomly distributed pipes and related spring pits (Fig. 5a). The observation that only small amounts of sand have been extruded on top of the pipes in the Muth Formation probably argues for a relatively slow but persistent upward flow of water (seepage of Lowe (1975), compare with Guhman & Pederson (1992)), although a penecontemporaneous erosion of possible sand volcano deposits cannot be ruled out completely. Natural examples by Guhman & Pederson (1992) and Deynoux et al. (1990) and experiments by Hawley & Hart (1934) indicate the formation of cylindrical water up-welling structures in loose sand without an aquiclude on top of the sand. Quirke (1930) observed fresh spring pits in lake shore sands which formed after heavy rainfalls just by rising ground water seepage; in his example there was also no low permeable layer involved.

The rise in relative sea level might be related to tectonic subsidence caused by tectonic activity linked to the formation of deformation bands in the Muth Formation. This means, if tectonic activity was involved, it did not form the cylindrical structures by seismic liquefaction directly, but might be responsible indirectly through ground water seepage rise resulting from tectonic subsidence. Due to the little relief in this environment, the sea-level rise affected a relatively large area, thus pipes are found in widely separated sections. The existence of rare cylindrical structures some metres higher up in FA 3 (Fig. 3) possibly indicates some repetitions of tectonic activity, or that their formation was just linked with frequent sea-level fluctuations common in shallow marine environments.

Conclusions

Numerous cylindrical structures cross-cutting stratification perpendicularly in Lower Devonian barrier island arenites from the NW Himalayas represent channels for upward flow of ground water. Pipes initiated from a relative thin horizon; their upper termination formed spring pits. These structures thus represent very rare examples of the preservation of fossil spring pits and their conduits below; their formation is explained by variations in ground water seepage in a coastal depositional environment.

Rapid rise in relative sea level, indicated by the deposition of lagoonal sediments above barrier island dunes, possibly caused a rapid rise in ground water seepage that produced a relatively high
hydrostatic head, resulting in the formation of springs. Due to the minor relief in this environment, the sea level rise affected a relatively large area and cylindrical structures can be found in widely separated sections.

The occurrence of conjugate deformation bands in the Muth Formation with east to west directed palaeo-strain direction documents a previously unknown pre-Himalayan deformation stage at the northern passive margin of the Indian continent during the Early Devonian. Rapid relative sea level variations might have been triggered by tectonic activity related to the formation of deformation bands. This means, if tectonic activity was involved, it did not form the cylindrical structures by seismic liquefaction directly, but might be responsible indirectly through ground water seepage rise resulting from tectonic subsidence.

Many thanks to U. Exner, S. Gier, R. Thiede and G. Wiesmayr with whom we shared unique experiences in these mountains. We are grateful to D. Banerjee for productive collaboration as well as K. Dorje and his family for immense hospitality during several field seasons. Many thanks also to H. Rice who improved both contents and style of this paper. Our paper benefited greatly from thorough reviews by Geraint Owen and Massimo Moretti. The financial support by Fonds zur Förderung der wissenschaftlichen Forschung (P-14129-Geo) and Hochschul jubiläumsstiftung der Stadt Wien (H-32/2001) is acknowledged.

References


OBERMEIER, S.F. 1996b. Use of liquefaction-induced features for paleoseismic analysis – An overview of how seismic liquefaction features can be distinguished from other features and how their regional distribution and properties of source sediment can be used to infer the location and strength of Holocene paleo-earthquakes. Engineering Geology, 44, 1–76.


