Subaqueous artesian springs and associated spring pits in a Himalayan pond

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Subaqueous, bowl-shaped depressions found in a Himalayan pond formed in an abandoned river channel in the Lingti Valley (Spiti, NW India) are spring pits (Quirke 1930). The occurrence of the spring pits is restricted to the western end of the pond, where coarse-grained, highly permeable alluvial fan material continues below lacustrine mud deposits. The spring pits formed by active vertical discharge of ground water from an underlying artesian alluvial fan aquifer, confined by the overlying fine-grained lacustrine sediments. The aquifer is continuously recharged by down-slope ground-water flow in the alluvial fan. These small artesian springs are comparable with much larger artesian springs described in the literature and a similar mechanism of formation is proposed. Some similarities in their shapes and mechanisms of formation may indicate that spring pits represent small, nearshore examples of pockmarks. The differences of these features, formed by persistent fluidization from short-lived seismic liquefaction processes, are discussed and the utility of the structures for palaeo-environmental and palaeo-ground-water interpretation is evaluated.

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In the example presented here, upwelling ground water has produced shallow, circular, some decimetres in diameter depressions in muddy sediments in a high-alpine Himalayan pond. Similar structures were first described from sandy beaches at Maple Lake (Canada) by Quirke (1930), who called them ‘spring pits’. According to Quirke (1930), they formed near the shoreline, both above and below water, by upwelling ground water after heavy rains which rose with sufficient force to sweep out finer sand grains. With the exception of spring pits in Early Devonian coastal arenites in the Northwestern Himalayas (Draganits *et al.* in press), these structures seemed to be extremely rare.

However, contemporary side-scan sonar and multi-beam surveys have demonstrated that similar, but much larger structures, are common features on continental shelves and continental slopes, where they can form huge pockmark fields (e.g. Hovland & Judd 1988; Hasiotis *et al.* 1996; Paull *et al.* 2002). These ‘pockmarks’ (King & MacLean 1970) are usually circular, up to 300 m in diameter and usually less than 12 m deep, with steep sides and relatively flat-floored centres, but may also be cone-shaped (Paull *et al.* 2002). While pockmarks are generally attributed to some form of fluid and/or gas discharge (Hovland & MacLean 1988), the actual nature of venting is undocumented for most pockmarks (Paull *et al.* 2002). Because of their diverse occurrence, size and morphologies, pockmarks are probably formed by a variety of mechanisms. Hasiotis *et al.* (1996) has proofed the formation of pockmarks in the Patras Gulf by gas venting, while ground-water discharge is responsible for the formation of pockmarks in the western Baltic Sea (Kaleris et al. 2002). Some similarities in their shapes and mechanisms of formation may indicate that spring pits represent small, nearshore examples of pockmarks.

Although the term ‘spring pits’ has been defined for structures formed by upwelling ground water in arenaceous lake sediments (Quirke 1930), contrasting with the mud in our example, the similar size, shape and identical mechanism of formation recommends the use of ‘spring pits’ for the Indian structures. Differences in the size and shape of the pits are a function of the flow rate and the strength of the materials in which the structures formed (Christiansen *et al.* 1982).

The investigation of the surface structures and hydrogeological background of small artesian subaqueous springs in a high-alpine lacustrine shore environment may be used as a small-scale example of similar, but much larger, artesian springs (Christiansen *et al.* 1982; Habermehl 1982; Guhman & Pederson 1992). The direct observation of active formation of these features and their detailed documentation can facilitate the recognition of similar structures in the fossil record and their use for palaeo-environmental interpretation. Additionally, our observations contribute to the discussion of seismic/non-seismic origin of similar fluidization features and their distinction in the fossil record (Obermeier 1996; Li *et al.* 1996; Galli 2000).

Circular depressions, formed by artesian springs, are described from several places and at various scales. The Great Artesian Basin of Australia, which covers *c.* 22% of the continent, is famous for its springs, having great ecological, scientific and economic significance. These

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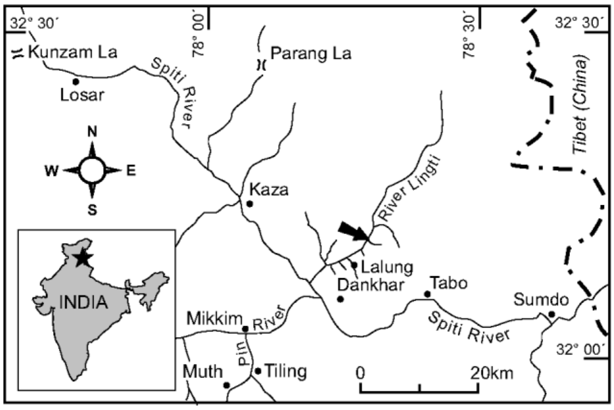

Fig. 1. The Lingti Valley in relation to the Spiti Valley and adjoining regions of Himachal Pradesh, NW India. Arrow indicates the location of the investigated pond with spring pits.

artesian springs can form large circular depressions, but also 'mound springs' when upwelling water has built a mound by the accumulation and cementation of clastic material around the springs (Habermehl 1982; Mudd 2000).

Several depressions, up to some hundreds of metres in diameter, have been found on the plain of the former glacial Lake Agassiz in eastern North Dakota (e.g. Lake Howe, Kelly Slough and Lake Ardoch), caused by artesian upwelling of ground water during glaciation, especially at about the time the area was being deglaciated (Christiansen *et al.* 1982; Bluemle 1993).

Guhman & Pederson (1992) describe active, circular springs next to the Dismal River (Nebraska), fed by ground water moving upwards along cylindrical conduits; depths measured with plummets indicate a conduit depth greater than 44 m. Upward flowing ground water within these vertical fluidization pipes reaches velocities capable of holding sand-sized particles in suspension (Guhman & Pederson 1992).

Close analogues, and of similar size to the depressions of this investigation, are spring pits and their underlying cylindrical conduits from barrier island arenites in the early Devonian Muth Formation, NW India (Draganits *et al.* in press). Their formation is explained by spring formation by a rising ground-water table related to sea-level changes in a coastal depositional environment.

Geological setting

In its middle and lower parts, the Lingti River forms a roughly NE–SW trending valley, cutting through the Carboniferous to lower Cretaceous sediments of the Tethyan Zone of the Higher Himalayan tectonic unit, Spiti, NW India (Bhargava & Basssi 1998). The valley is a relatively narrow gorge, which only widens out where tributaries join the Lingti River. Owing to its location to the north of the Main Himalayan Range, the area is protected from heavy monsoon rains and may be classified as an alpine desert, with an annual precipitation rarely exceeding 300 mm (Bhargava & Bassi 1998). During summer, river discharge originates nearly exclusively as meltwater from large glaciers to the north with a diurnal maximum around noon.

A pond has been formed at the level of the modern floodplain on the left bank of the Lingti River, upstream of an alluvial fan of a left-side ravine (Figs 1, 2A; N32°10′54″, E78°17′07″, 3780 m above sea level); the

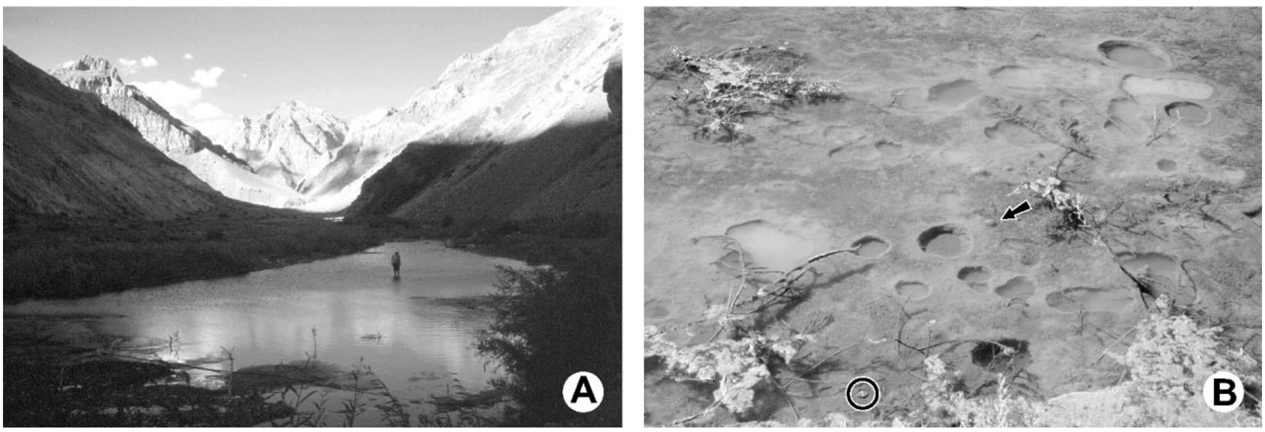

Fig. 2. A. General view of the pond in the Lingti Valley; view upstream towards the northeast. Spring pits occur in the right foreground of the photo. In the left foreground, prograding sediments of the alluvial fan are visible. Note the shallowness of the pond; note the figure of a man for scale. B. Overview of the spring pits close to the shore, formed by the alluvial fan showing their appearance and their distribution on the pond bottom; view towards the north. Springs show broadly similar characteristics; two spring pits filled with suspended mud are caused by footprints (see Fig. 3C). Arrow points to a small pimple-shaped dome shown in detail in Fig. 3D. Encircled lens cap is 5.3 cm in diameter.

pond is some 50 m long and some 10 m wide, with a depth not exceeding *c*. 40 cm (Fig. 2). The pond is interpreted as an abandoned river channel of the Lingti River, dammed by sediments of the alluvial fan.

The bottom of the pond shows thin microbial mats on the surface of the mud (Fig. 3A, D), which is partly rich in rotting organic material and shows synaeresis cracks in places. The thickness of the mud exposed within the spring pits is *c*. 30 cm. The sediments below the lacustrine mud are not exposed, but the pond is small and the subsurface may be reconstructed from the local geological outcrop around. The northwestern shore comprises fluvial gravel; the opposite southeastern shore consists of rock debris from nearby cliffs and alluvial fan material at the southwestern termination of the pond (Fig. 2A); the best interpretation of the subsurface geology is an interfingering of fluvial gravel and alluvial fan sediments overlain by lacustrine mud (Fig. 4).

Spring pits

Spring pits are randomly distributed subaqueous depressions in the lacustrine mud at the southwestern part of the pond in an area within some 5 m of the shore made by the alluvial fan (Fig. 2B); they have not been found in other parts of the pond. Generally, their shape is circular to slightly elliptical with relatively smooth outlines, but some examples of more irregular-shaped spring pits also occur (Figs 2B, 3A). Spring pits are usually separated from each other by variable distances up to *c*. 60 cm (Fig. 2B), but in several cases two pits have joined to form elongate, elliptical depressions (Figs 2B, 3B). The pits range in diameter from about 10 cm to 30 cm, although composite pits may reach up to 40 cm in diameter.

Spring pits are found in lacustrine mud at some 15 cm water depths, where they form depressions up to *c*. 25 cm deep below the pond water surface (Figs 2A, 3A).

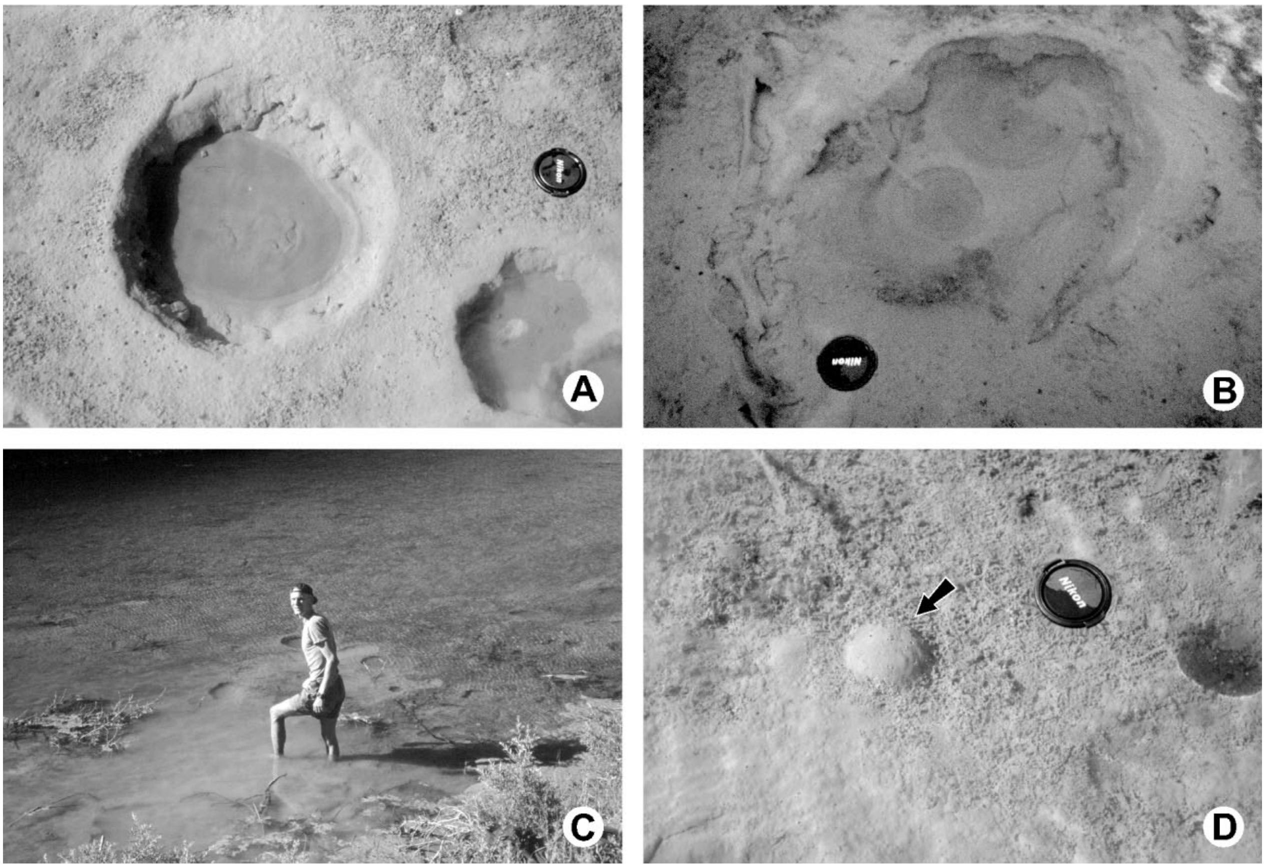

Fig. 3. A. Detail of a representative spring pit. Note the appearance of boiling-like fluidized sediment at the bottom, the tapering walls and the more cohesive, microbial-rich upper part with photosynthetically produced oxygen bubbles on the pond floor. A smaller, irregular-shaped spring pit is seen in the lower right corner. Lens cap is 5.3 cm in diameter. B. Detail of an elongate spring pit formed by the joining of two springs, with still visible separate fluidization centres. C. First author standing with his right foot in a spring pit and the left foot on the pond floor, demonstrating the shallow depth of the pond and the complete depth of the spring pits. Note the proximity of the shore in the lower right. D. Details of a small pimple-shaped dome, raised *c*. 3 cm above the pond bottom. Dark circle on right side is the shadow of the floating lens cap on the pond floor.

The complete bottom of the depressions is formed by fluidized mud, the sediment being kept in suspension by ascending spring water; solid ground inside the spring pits is reached 45 cm below the pond water surface (Fig. 3C). This means that the spring pits have some 20 cm of fluidized mud at their base.

Spring pit walls are steep to nearly vertical, slightly tapering downwards (Fig. 3A). Usually, the uppermost centimetres narrow downwards at about 50° inclination with relatively even surfaces. Fray-out mud from the upper part, rich in microbial activity that increases sediment cohesion, commonly hangs downwards, partly overhanging steeper parts of the spring pit walls (Fig. 3A). Below there follows a steeper lower part with more irregular surfaces compared to the smooth upper part (Fig. 3A).

At the time of our study, all the pits showed spring activity, indicated by fast, irregular movements of fluidized sediment at the spring pit bottoms (Fig. 3A, B) and trails of mud suspended into the water column (Fig. 2B). The orientation of the mud trails indicates weak drift of pond water towards the east, away from the alluvial fan. No gas bubbles ascending from the spring pits have been observed, and there was no marked difference in temperature between pond water and spring water.

In one place a group of three small, pimple-shaped domes was found on the bottom of the pond in an area with relatively rare spring pits (Figs 2B, 3D). They are perfectly circular in plan view with diameters ranging between *c*. 4 and 8 cm and not more than some 3 cm high (Fig. 3D).

Results and discussion

The pond in the Lingti Valley in the northwestern Himalayas is interpreted as an abandoned river channel of the Lingti River (Fig. 2A). Its base is formed mainly by fluvial gravel overlain by 30 cm of fine mud. Towards the west, the pond is dammed by sediment of an alluvial fan (Fig. 2A), which partly continues below the pond (Fig. 4); the occurrence of subaqueous springs is restricted to this area. These springs clearly meet one of the earliest technical definitions of springs ‘a place where, without the agency of man, water flows from a rock or soil upon the land or into a body of surface water’ (Meinzer 1923). Although the discharge is moderate, their surface features clearly differentiate them from seeps, which are defined as discharge of water ‘that oozes out of the soil or rock over a certain area without distinct trickles or rivulets’ (Bouwer 1978). Considering the boiling-like movements of fluidized sediment at the bottom of the spring pits (Fig. 3A, B), they might be classified as ‘boiling sand springs’ (Bryan 1919). Some similarities in their shapes and mechanisms of formation may indicate that spring pits represent small, nearshore examples of pockmarks (King & MacLean 1970).

In a broad sense, the spring features described here

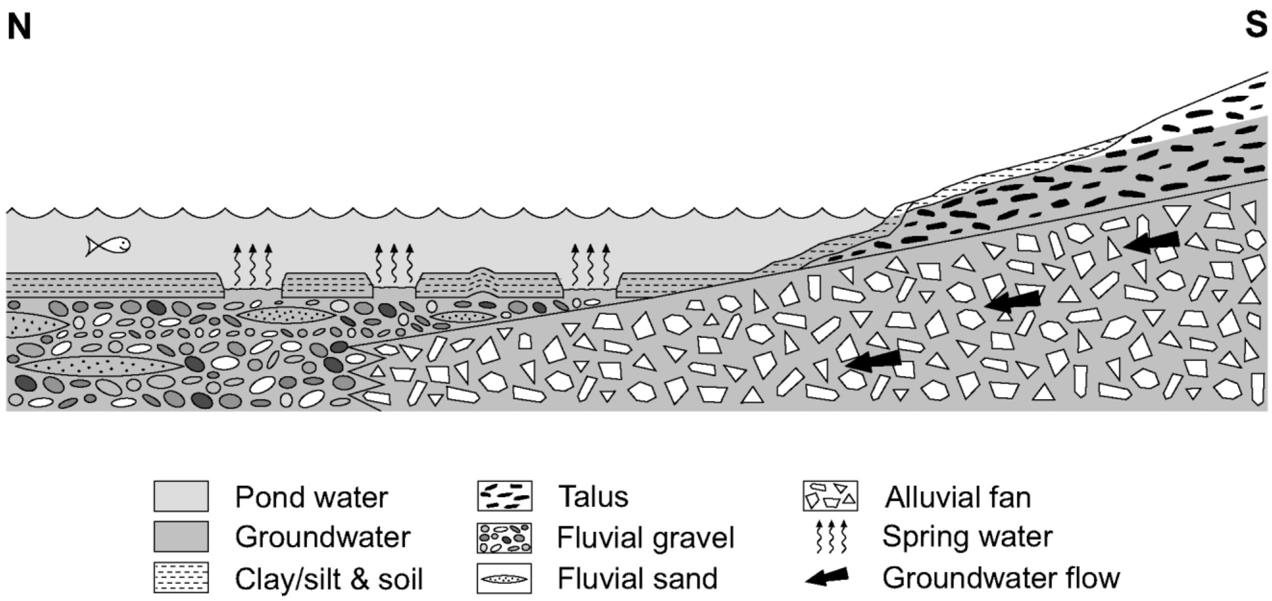

Fig. 4. Schematic diagram illustrating a conceptual hydrogeologic model of the formation of spring pits. Lacustrine mud and soil above fluvial gravel and alluvial fan sediments form a local aquiclude for the ground-water flow in coarse-grained, highly permeable alluvial fan sediments towards the valley axis. These conditions result in pressurizing of the aquifer and formation of pimple-shaped updoming of microbial pond mud and circular springs when artesian springs break through the mud. Not to scale; details are discussed in the text.

might be categorized as liquidization structures in general. According to Allen (1982: p. 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 as a consequence of increased hydrostatic pressure 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.

Could spring pits have been formed by seismic liquefaction?

The study area is close to active faults in the Himalayan orogen and some Quaternary lake deposits show seismic liquefaction features (Mohindra & Bagati 1996; Bhargava & Bassi 1998; Janda *et al.* 2002). Structures caused by seismic induced liquefaction or by non-seismic fluidization are usually difficult to separate in the fossil record (Holzer & Clark 1993; Obermeier 1996; Li *et al.* 1996). Additionally, Galli (2000: figs 3, 4) shows circular, water-filled depressions closely resembling spring pits of this study. There is therefore a theoretical possibility that the spring formed by seismic liquefaction processes. Earthquakes with magnitudes of 4.5 or more are thought to be capable of causing liquefaction (Obermeier 1996) within a 50 km radius of the epicentre (Galli 2000).

During the period 3 days before and inclusive of the day of our observations (25th of July 1999), the closest magnitude 4 earthquakes to the Lingti Valley were reported about 310 km to the west, in the Hindukush area, and 3 other events with magnitudes ranging from 1.7 to 3, at about 400–420 km distance to the south and southeast (International Seismological Centre 2001). In seismic catalogues from the National Earthquake Information Center (2001) and the Incorporated Research Institutions for Seismology (2001) no earthquakes have been found which were closer than 750 km to the spring pits in the Lingti valley. A seismic origin of the spring pits can therefore be excluded by the lack of earthquakes strong and close enough to the pond (Obermeier 1996; Galli 2000) at the relevant time. Additionally, a persistent but less vigorous water flow than expected from short-lived seismic liquefaction processes may better explain the regular shape of the spring pits and the lack of extruded sediment around their rims (Obermeier 1996).

Artesian spring formation of the spring pits

Still ongoing spring activity within the spring pits is indicated by the fast movement of fluidized sediment at the base of the pits. This water/sediment mixture represents liquidized granular sediment, kept in this state by the continuous upward directed fluid flow. During this process, upward flow of water is controlled by the hydrostatic head and reconsolidation of the sediment grains. In contrast to ‘Monroe structures’ (Dionne 1973b), which are eye-catching build-ups in tidal-flat mud and similar mud volcanoes (Dionne 1976), both formed by ascending gas/water/sediment mixtures, the rims of the spring pits show hardly any deposition of sediments around them (Figs 2B, 3A). This indicates that the upward directed water jet from the springs was not competent enough to carry sand-sized sediment (Allen 1982). Spring activity only caused suspension of fine-grained sediment which is distributed more evenly, over greater distances from the pits by the weak water currents.

The lack of ascending gas bubbles contradicts a formation of the spring pits by gas escapes; the lack of increased water temperatures in the springs also excludes thermal spring activity. However, the restricted occurrence of spring pits close to the south-western shore, which is made up of alluvial fan material, strongly suggests a genetic link between the springs and ground-water discharge from the alluvial fan. The random distribution of the pits argues against outflow of ground water controlled by faults.

In our model, ground water within the highly permeable alluvial fan material flows down slope towards the northwest. In its lower reaches, this aquifer is confined by an aquiclude of lacustrine mud (Fig. 4). These conditions result in a local increased hydrostatic head in the alluvial fan aquifer below the pond, resulting in spring formation and related spring pits at the bottom of the pond. Pimple-shaped structures represent areas of up-domed lacustrine mud (Figs 2B, 3D), where cohesive forces of mud increased by microbial activity just allowed up-doming, but prevented rupture of the mud and spring formation. In places where artesian ground water was able to break through the pond mud, artesian springs and later spring pits formed.

The *c.* 30 cm thick mud at the pond bottom represents an aquiclude, strongly contrasting with the coarse-grained, highly permeable aquifers of the fluvial and alluvial fan sediments. Nichols *et al.* (1994) carried out fluidization experiments with a two-layered system, both layers containing the same granular material, but the top layer with additional variable clay contents. Increasing the high hydrostatic head resulted in channeled fluid flow forming pipe-shaped conduits through the upper layer. In their experiments, a minimum clay content of 15 wt% was critical to guarantee sufficient bonding of granular material to inhibit erosion and break-up of the top layer (Nichols *et al.* 1994).

The formation of the springs modifies the hydraulic gradient in the aquifer below, resulting in a channelized upwards flow of water (Mount 1993). The discharge of spring water is just capable of fluidizing mud at the bottom of the spring pits, but not strong enough to produce a forceful water jet to move sand-sized sediment upwards and deposit it around the spring. In contrast to processes forming mud volcanoes (e.g. Dionne 1973b, 1976) by extrusion of liquidized material with high sediment/water ratios, upwelling ground water in the Spiti example only caused suspension of fine-grained sediment with low sediment/water ratios which is distributed more evenly, over greater distances from the pits by the weak water currents. Similarly, King & MacLean (1970) describe pockmarks from the Scotian Shelf with sharply defined, steeply sloping rims, without sediment accumulations around the depressions. These processes formed the spring pits by selective outwash of finer grain sizes and possibly by volume loss due to compaction (Best 1989; Draganits *et al.* in press). The longevity of artesian springs and their related structures has been noted by Habermehl (1982) and by Guhman & Pederson (1992).

Possible fluidization structures underneath the spring pits

The subsurface structure of ground-water conduits underneath the spring pits is speculative, but comparison with similar springs may indicate subvertical cylindrical feeder pipes. Vertical, cylindrical structures in sandstone have commonly been attributed to upwelling of ground water (e.g. Hawley & Hart 1934; Gabelman 1955; Dionne 1973a; Gangloff 1974; Deynoux *et al.* 1990; Dionne & Pérez Alberti 2000; Massari *et al.* 2001; Kaleris *et al.* 2002), although their occurrence together with spring pits has only recently been demonstrated (Draganits *et al.* in press). Guhman & Pederson (1992) suggest cylindrical fluidization pipes up to 10 m in diameter and up to 44 m in depth below active boiling sand springs in Nebraska, whilst Christiansen *et al.* (1982) and Bluemle (1993) described a vertical fluidization pipe, some 50 m in diameter and at least 138 m deep, below the circular Lake Howe in Saskatchewan.

Occurrence of spring pits in relation to sedimentary environments

Most of the cylindrical structures and/or spring pits mentioned in the literature have been found at the transition of marine/limnic/fluviatile and terrestrial environments, where high water saturation occurs and water-table variations are frequent (Quirke 1930; Hawley & Hart 1934; Gabelman 1955; Dionne 1973a; Plint 1983; Deynoux *et al.* 1990; Guhman & Pederson 1992; Massari *et al.* 2001; Draganits *et al.* in press). The subaqueous spring pits, close to the shore of the pond in the Lingti Valley, further strengthen this observation. The existence or lack of small erosion channels leading away from pit centres additionally shows whether the spring pits formed subaqueous (no erosion channel) or subaerial (erosion channel) (Quirke 1930; Guhman & Pederson 1992; Draganits *et al.* in press). Thus, spring pits may represent a tool for palaeo-environmental interpretation and possibly even for reconstruction of palaeo-ground-water conditions.

Conclusions

Circular depressions found at the bottom of a Himalayan pond represent spring pits (Quirke 1930) formed by active vertical discharge of ground water from an artesian alluvial fan aquifer, confined by an aquiclude of fine-grained lacustrine sediments. The aquifer is continuously recharged by downslope groundwater flow into the alluvial fan.

The spring pits represent persistent features generated by the regional ground-water flow system and are small-scale analogues of processes in much larger artesian systems (Habermehl 1982; Guhman & Pederson 1992; Christiansen 1982). Any origin of the spring pits from short-lived seismic liquefaction is excluded by the lack of earthquakes, strong and close enough to the area at the relevant time.

Spring pits have commonly been found at the transition of marine/limnic/fluviatile and terrestrial environments, where high water saturation occurs and water table variations are frequent. Thus, spring pits may give indication for palaeo-environmental interpretation of the fossil record.

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References

Allen, J. R. L. 1982: *Sedimentary Structures: Their Character and Physical Basis. Developments in Sedimentology, 30B*, 663 pp. Elsevier, Amsterdam.

Best, J. L. 1989: Fluidization pipes in volcaniclastic mass flows, Volcan Hudson, Southern Chile. *Terra Nova 1*, 203–208.

Bhargava, O. N. & Bassi, U. K. 1998: Geology of Spiti-Kinnaur, Himachal Himalaya. *Geological Survey of India Memoirs 124*, 1–210.

Bluemle, J. P. 1993: Hydrodynamic blowouts in South Dakota. *In* Aber, J. S. (ed.): *Glaciotectonics and Mapping Glacial Deposits.* Proceedings of the INQUA Commission on Formation and Properties of Glacial Deposits, Canadian Plains Research Center, 259–266 pp. University of Regina, Regina.

Bouwer, H. 1978: *Groundwater Hydrology*. 480 pp. McGraw-Hill, New York.

Bryan, K. 1919: Classification of springs. *Journal of Geology 27*, 522–561.

Christiansen, E. A., Gendzwill, D. J. & Meneley, W. A. 1982: Howe

lake: a hydrodynamic blowout structure. *Canadian Journal of Earth Sciences 19*, 1122–1139.
Deynoux, M., Proust, J. N., Durand, J. & Merino, E. 1990: Water-transfer cylindrical structures in the Late Proterozoic eolian sandstones in the Taoudeni Basin, West Africa. *Sedimentary Geology 66*, 227–242.
Dionne, J.-C. 1973a: Structures cylindriques verticales dans du quaternaire a Arthabaska, Quebec. *Sedimentary Geology 9*, 53–63.
Dionne, J.-C. 1973b: Monroes: a type of so-called mud volcanoes in tidal flats. *Journal of Sedimentary Petrology 43*, 848–856.
Dionne, J.-C. 1976: Miniature mud volcanoes and other injection feature in tidal flats, James Bay, Québec. *Canadian Journal of Earth Sciences 13*, 422–428.
Dionne, J.-C. & Pérez Alberti, A. 2000: Structures cylindriques verticales dans un dépôt meuble quaternaire, en Galice (Espagne). *Géographie physique et Quaternaire 54*, 343–349.
Draganits, E., Grasemann, B. & Schmid, H. P. In press: Fluidization pipes and spring pits in a Gondwanan barrier-island environment: groundwater phenomenon, palaeo-seismicity or a combination of both? *Geological Society Special Publications*.
Gabelman, J. W. 1955: Cylindrical structures in Permian(?) siltstone, Eagle County, Colorado. *Journal of Geology 63*, 214–227.
Galli, P. 2000: New empirical relationships between magnitude and distance for liquefaction. *Tectonophysics 324*, 169–187.
Gangloff, P. 1974: Les structures cylindriques et l'évolution géomorphologiques d'une plage tardiglaciaire à Saint-Jérôme, Québec. *Revue de Géographie de Montréal 28*, 357–373.
Guhman, A. I. & Pederson, D. T. 1992: Boiling sand springs, Dismal River, Nebraska: agents for formation of vertical cylindrical structures and geomorphic change. *Geology 20*, 8–10.
Habermehl, M. A. 1982: *Springs in the Great Artesian Basin, Australia: Their Origin and Nature*. *Geology and Geophysics Australia Report 235*, 50 pp. Bureau of Mineral Resources, Canberra.
Hasiotis, T., Papatheodorou, G., Kastanos, N. & Ferentinos, G. 1996: A pockmark field in the Patras Gulf (Greece) and its activation during the 14/7/93 seismic event. *Marine Geology 130*, 333–344.
Hawley, J. E. & Hart, R. C. 1934: Cylindrical structures in sandstone. *Geological Society of America Bulletin 45*, 1017–1034.
Holzer, T. L. & Clark, M. M. 1993: Sand boils without earthquakes. *Geology 21*, 873–876.
Hovland, M. & Judd, A. G. 1988: *Seabed Pockmarks and Seepages*. 293 pp. Graham and Trotman, London.
Incorporated Research Institutions for Seismology 2001: *Seismi Query*. Washington, D.C., http://www.iris.washington.edu/SeismiQuery.
International Seismological Centre 2001: *On-line Bulletin International Seismological Centre*, Thatcham, UK, 2001: http://www.isc.ac.uk/Bull.
Janda, C., Hager, C., Grasemann, B., Draganits, E., Vannay, J.-C., Bookhagen, B. & Thiede, R. 2002: The Karcham Normal Fault: implications for an active extruding wedge Sutlej Valley, NW-Himalaya. *Journal of Asian Earth Sciences 20/4/S1*, 19–20.
Kaleris, V., Lagas, G., Marczinek, S. & Piotrowski, J. A. 2002: Modelling submarine groundwater discharge: an example from the western Baltic Sea. *Journal of Hydrology 265*, 76–99.
King, L. H. & MacLean, B. 1970: Pockmarks on the Scotian Shelf. *Geological Society of America Bulletin 81*, 3141–3148.
Li, Y., Craven, J., Schweig, E. S. & Obermeier, S. F. 1996: Sand boils induced by the 1993 Mississippi River flood: Could they one day be misinterpreted as earthquake-induced liquefaction? *Geology 24*, 171–174.
Massari, F., Ghibaudo, G., D'Alessandro, A. & Davaud, E. 2001: Water-upwelling pipes and soft-sediment-deformation structures in lower Pleistocene calcarenites (Salento, southern Italy). *Geological Society of America Bulletin 113*, 545–560.
Meinzer, O. E. 1923: Outline of ground-water hydrology, with definitions. *United States Geological Survey Water-Supply Paper 494*, 48–59.
Mohindra, R. & Bagati, T. N. 1996: Seismically induced soft-sediment deformation structures (seismites) around Sumdo in the lower Spiti valley (Tethys Himalaya). *Sedimentary Geology 101*, 69–83.
Mount, J. F. 1993: Formation of fluidization pipes during liquefaction: examples from the Uratanna Formation (Lower Cambrian), South Australia. *Sedimentology 40*, 1027–1037.
Mudd, G. M. 2000: Mound springs of the Great Artesian Basin in South Australia: a case study from Olympic Dam. *Environmental Geology 39*, 463–476.
National Earthquake Information Center, U.S. Geological Survey 2001: *Preliminary Determination of Epicenters Catalogue.* Denver, http://neic.usgs.gov/neis/epic/epic.html.
Nichols, R. J., Sparks, R. S. J. & Wilson, C. J. N. 1994: Experimental studies of the fluidization of layered sediments and the formation of fluid escape structures. *Sedimentology 41*, 233–253.
Obermeier, S. F. 1996: 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.
Paull, C., Ussler, W., Mahar, N., Greene, H. G., Rehder, G., Lorensen, T. & Lee, H. 2002: Pockmarks off Big Sur, California. *Marine Geology 181*, 323–335.
Plint, A. G. 1983: Liquefaction, fluidization and erosional structures associated with bituminous sands of the Bracklesham Formation (Middle Eocene) of Dorset, England. *Sedimentology 30*, 525–535.
Quirke, T. T. 1930: Spring pits; sedimentation phenomena. *Journal of Geology 38*, 88–91.
Youd, T. L. 1973: Liquefaction, flow, and associated ground failure. *United States Geological Survey Circular 688*, 1–12.