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GROUNDWATER MOVEMENT AND MANAGEMENT IN TUBE-FED LAVAS

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ABSTRACT

Sinking surface streams and large springs imply integrated underground drainage systems can sometimes exist within lava flows. Lava tube caves that contain underground streams have been reported from various parts of the world but various other structures are generally more important for groundwater movement. Complex fissured and conduit aquifers may result, but it is unwise to draw too close an analogy with karst environments. Nevertheless, there are some interesting comparisons to be made in relation to aquifer structure and function. Some aquifers in lava provide important water supplies that may be placed at risk of contamination if their potential vulnerability is not taken into account in management. Some field observations from Iceland, South Korea, Mauritius, Hawaii, Samoa and Australia are recorded.

INTRODUCTION

Erupting lava moves forward from some volcanoes as successive sheet-like flow units that are fed by internal tubes of flowing lava that remain insulated and fluid beneath cooled and congealed surface crust. This process of endogenous or tube-fed lava emplacement enables injection of fluid lava under hydrostatic pressure, causing the lava surface to be raised and lowered in response to variations in pressure. Lava inflation and deflation in this manner commonly results in distinctive surface landforms and the presence of large subsurface voids including major fissures and drained lava tube caves (Hon et al; 1994, Self et al, 1996). Conventional cooling contraction cracking is supplemented by brittle fracturing that results from disturbance of congealed lava crust (Walker 1991; Halliday 1998a,b) and such voids provide significant infiltration routes for water (Kiernan et al, 2003). In recent years there has been increasing recognition that this process has been important even for some lava flows that have long been interpreted as having been emplaced by turbulent floods of fluid lava. The implications of tube-fed flow being more important than previously thought, and of the geological structures it produces, have yet to be taken fully into account in developing groundwater models for some lava flows.

Interstitial spaces in clinkery lava at the tops of lava flows have conventionally been suggested to be of most importance for groundwater storage and transmission in lava flows, followed in importance by cavities between lava beds, shrinkage cracks, lava tubes, vesicles, fissures resulting from faulting and cracking after rocks have cooled, and tree moulds (Maxwell and Hacket 1963; Todd 1980). In this paper we reconsider the potential structure of aquifers in lavas that contain lava tube caves, the extent to which analogies can reasonably be drawn between these and karst aquifers, and the potential for groundwater in such lavas to become contaminated.

LAVA AND LIMESTONE AQUIFERS: CONTRASTS AND SIMILARITIES

While few lava tube caves that contain streams, or significant volumes of alluvial sediment, have been reported there are some significant exceptions (Stearns and McDonald 1946; Kambesis 2000; Halliday 2001; Ollier and Zarriello 1979). The existence of streams in lava tube caves suggests that subsurface drainage in some lava flows may loosely resemble a karst drainage system, but it is not appropriate to draw too close an analogy between them. In basalts, the primary fissure system is generally relatively open, whereas fissures in limestone must be widened by solution before significant infiltration and subsurface streamflow is possible. The density of primary fissures is also generally higher in tube-fed basalts than in limestone. By means of such fissures, sinking water quickly reaches the base of a lava mass and generally flows through lava tube caves only as a temporary diversion. In karst environments streams incise progressively downwards, lowering the water table and leaving higher level cave passages that have been abandoned by streams. In contrast, in lavas the youngest voids occur nearer the surface, forming almost instantaneously as successive new lava flows are superimposed. The water table is likely to already lie deep within or beneath the lava sequence without any need for incision by a cave stream. Water flows through basalt therefore tend to be less concentrated and erosive than those in limestone. Indeed, large erosional stream caves have seldom been reported from basalts, although Werner et al (2002) describe one significant exception.

In a recent paper (Kiernan et al, 2003) we suggested that major fissures and lava tubes will always provide important reservoirs and preferred pathways for groundwater flow in the phreatic zone, but that within the vadose zone lava tube caves caves form preferred pathways for groundwater only in a limited range of circumstances. Each of these cases relates to the incapacity of alternative void networks to accommodate the waters. Subjacent voids may be absent or insufficiently developed to accommodate descending water. Not all tube-fed lavas are subject to the same degree of inflation and deflation due to fluctuations in hydrostatic pressure, hence the density of primary fissures varies. This is highlighted by the contrast between the highly fractured Eldhraun lava flow in Iceland, where there were pronounced fluctuations in hydrostatic pressure, and the less fractured lava at Undara in Australia where the effusion rate appears to have been relatively constant. Infiltration may therefore be impeded by dense, unfractured lava, but also by ash beds, or where thin lava overlies relatively impermeable palaeosurfaces. In some cases very considerable water volumes may need to be accommodated more rapidly than the lava can accomplish, such as where major rivers discharge into lava-filled valleys or rainfall is particularly intense. Following further field investigations and reflection, we would now be inclined to fine-tune this list. The fundamental requirement for water flow through lava tube caves remains the incapacity of alternative void networks to accommodate the water, but a few additional causes for this occurring need to be considered.

Our experience with young lava flows has convinced us that lava tube caves may remain open as potential pathways for underground water movement even if their entrances and the surface above them are entirely sealed by sediment. Inspection during rain that was sufficiently heavy to cause severe flooding and loss of life in South Korea in August 2002, revealed that despite massive infiltration through the ceiling of the very large Manjang Cave on Jeju Island, there was generally still rapid infiltration into the cave floor in all but a few very localised areas where potential outlets were sealed by allogenic sediment that had entered the cave through surface collapses. But while insufficient clastic sediment may be able to penetrate underground to block voids, the entry of minerals in solution may be another matter altogether. Water is able to enter spaces of much smaller dimensions than can be penetrated by sediment particles, and if minerals subsequently precipitate out of solution the potential exists for infiltration to be impeded progressively over time. Hence, we would add to our earlier list the situation where secondary minerals accumulate in voids and reduce their capacity to conduct water. Examples of this process are provided by the accumulation in some caves on Jeju Island, including Hyeopjal and Ssangyong, of speleothem carbonate derived from calcareous sands that overlie the lava.

Freezing of groundwater, particularly where there is permafrost, may also block voids. Many lava tube caves occur in cold climates and their morphology is such that they form cold air traps where snow and ice may persist (Halliday 1977), an Australian example being the caves on Azorella Peninsula, Heard Island (Kiernan and McConnell 2000). Hence, the potential exists for alternative void networks in some volcanic areas to be closed by freezing of liquid water, either within them or sealing their openings. Ponding and freezing of water on the floors of such caves as Surtshellir and Vidgelmir, Iceland, are obvious examples, where even when the surface of pools melts in summer, ice that persists at greater depth precludes pools draining.

We would also now add to our list the situation where voids in tube-fed lavas on coasts may be subject to back-flooding by the sea at high tide, thereby inhibiting discharge of groundwater through them, as occurs locally on Jeju near Hallim Park. Similar effects may occur adjacent to any substantial body of standing water with a fluctuating level, and might conceivably have been involved in the deposition of very significant volumes of sediment in lava tube caves immediately upstream of a lake on the edge of the Eldhraun, Iceland, sediment which we previously assumed to have been simply stream-borne (Kiernan et al, 2003).

POTENTIAL FOR GROUNDWATER CONTAMINATION

Despite the differences between the hydrogeology of basalt and that of karst areas there are some significant similarities in terms of groundwater management issues. The open structure of some aquifers in tube-fed lavas implies high potential for groundwater contamination. The potential for pollution risks similar to those that afflict karst aquifers is significantly compounded where streams do flow through lava tube caves, even if only during floods. In both settings, large natural voids may serve as efficient natural pipes that permit rapid long-distance penetration of contaminated water.

A degree of natural purification may occur in some types of aquifer due to interactions between various physical, chemical and biological agents, together with the influence of transport processes and hydrogeological conditions (Matthes and Pekdeger 1981; Golwer 1983; Ford and Williams 1989). However, the opportunities for this to occur in fissured or conduit lava aquifers may be as limited as in some karst aquifers due to relatively little rock surface being available for adsorption, ion exchange and colonisation by microorganisms. Rapid infiltration is likely to limit the potential for evaporative removal of volatile organic compounds and pesticides. Significant sediment transfer through the caves beneath the Eldhraun (Kiernan et al, 2003) demonstrates that physical filtration of groundwater may be limited in such systems, turbulent flow enabling long distance penetration of particulate matter. Transmission times through aquifers of this type are likely to be short, hence pathogenic bacteria and viruses may be able to survive transit in groundwaters, especially given the likelihood of limited adsorption-desorption effects. The direct run-in contribution via sinkholes and point water-sinks can aggravate water quality deterioration in karst (Wheeler et al, 1989). However, even in a karst environment where sinkholes are numerous the largest quantities of nitrates and pesticides appear to be delivered to groundwater by diffuse infiltration (Currens 1995; Halberg 1985). Similar situations may arise in some lava aquifers.

CASE STUDIES

ICELAND

The Eldhraun lava flow in Iceland has been the focus of recent investigations that have emphasised the hydrogeological significance that lava tube caves sometimes assume (Kiernan et al, 2003). At the best studied site, anabranches of a small river sink into collapse depressions in lava, some pour directly into lava caves when in flood and curtains of water also pour continuously through the ceiling of a lava tube cave beneath the edge of a small lake on the lava margin. Large springs that are presumed to be fed by these cave streams occur a few hundred metres further downvalley, but a short distance beyond them the water sinks again, and no evidence of its reappearance on the surface has been detected.

Only those caves closest to the margin of the lava carry streams under base flow conditions, concentrated flows of surface water spilling into other caves only slightly more distant from the lava flow edge even during floods. Alluvial deposits are also confined to only a few caves, but some springs emerge through alluvial deposits that also floor surface ponds and overflow routes from which water temporarily re-emerges from some other parts of the Eldhraun during major floods. The stream caves beside the lake are generally low and labyrinthine, emphasising that it is not necessary for lava tube caves to be of large dimensions for streams to flow through them. Indeed, caves are not really required for predominantly underground drainage to occur, given the presence of fracture systems associated with lava rises, lava rise pits, flat pavements, surface sags, and deflated and collapsed domes.

Further upvalley near the Vatnajökull ice cap, large collapse depressions are filled with wind-deposited sediment but cave passages remain open. The lava remains sufficiently permeable to absorb even major jökulhlaup floods caused by bursting of large subglacial lakes that form occasionally beneath the ice cap due to ice-melting induced by subglacial volcanic activity (Kiernan et al, 2003).

MAURITIUS

The Indian Ocean island of Mauritius is almost entirely volcanic, having been formed by eruptions that commenced undersea about 13 million years ago and ended only 26,000 years ago (Middleton and Halliday 1997). Over 140 lava tube caves have been documented with an aggregate length of over 16.5 km, the largest individual caves being up to 1 km long (Middleton 2000a,b). There are no surface streams, despite an annual rainfall of around 2,000 mm.

The greatest density of lava tube caves and the most obvious underground water resource occurs beneath the Plaine des Roches in the island's north-east, the region of most recent volcanic activity. The documented caves lie in a band that stretches for about 3.5 km with those containing water becoming more frequent towards the coast. Water has been pumped from cave PR16 for domestic use and is pumped from cave PR6 for agricultural use. PR4, "Womens Cave", is still used for washing clothes, even though articulated water is available, and was recently purchased by the government and developed as a park. PR3 is similarly used, to a lesser extent. Domestic waste is dumped in caves higher in the catchment and dead cattle are routinely disposed of into one particular collapse (PR40).

Further south at Camp Thorel, one of the island's longest caves, and its most varied in terms of morphology and lava speleothems, lies beneath an unsewered village and receives direct input from cesspits and septic tanks. Fortunately there does not appear to be any direct tapping of groundwater in the vicinity at present. Early in 2001 it was announced that the Waste Water Authority planned to use lava tube caves at Montagne Jacquot near the west coast for the disposal of part-treated sewage. Dye tracing had shown that caves in that locality carried water offshore beyond a coral reef and the public was assured that the project would be "without great damage to the environment". Nevertheless, in the face of objections (from Bill Halliday, amongst others) the Government sought other expert opinions and in August 2001 announced that the scheme had been abandoned. The reasons given were unacceptable risks to both the groundwater in the region and marine life at the discharge point.

HAWAII

Kaumana Cave, in a county park west of the city of Hilo, rapidly transmits large volumes of water after heavy rains (Kambesis 2000). Some of its collapse entrances have been used as domestic and industrial waste dumps, posing grave threats to groundwater quality. Further north at Honoka'a, stormwater and waste water from a hospital has deliberately been diverted into a lava tube cave which is also used for dumping domestic waste. South of Hilo, on the eastern slopes of Kilauea volcano, lies Kazumura Cave; at around 60km, the world's longest lava tube cave. Sadly, the significance of this cave has been lost on the locals who have used a number of its entrances as convenient dumping sites. Fortunately a campaign by Bill Halliday (2000) has alerted authorities to the risks posed by dump sites and action is now being undertaken to clean them up. But since the entire length of the cave is under freehold subdivisions (which at this stage are unsewered) the future of this cave is far from assured.

SAMOA

The two main islands of the Pacific nation of Samoa, Upolu and Savai'i, are entirely volcanic. Ana Pe'ape'a ('swiftlet cave'), in the south of Upolu, has captured the Pala River and carries it underground for about 500m (Ollier and Zarriello 1979); after heavy rain the cave evidently fills completely. Fluvially-eroded longitudinal grooves occur in its floor. This cave is traversed by tourists in the dry season despite a lack of facilities beyond the access track (Middleton 2003).

Because there are few surface streams, lakes in lava caves have historically been very important sources of fresh water. At Salamumu, one of the longest known caves contains a number of pools from which water has been drawn. Iliffe and Sarbu (1990) investigated these pools but found none of them to be anchialine (salt or brackish and fluctuating with the tide). At Tafatafa, which is somewhat closer to the sea, they dived the terminal lake for 100m before it became too small to follow. However, they believe it extends beneath sea level. At Fagaee in the north of Savai'i, a small cave not far from the sea has long been a reliable freshwater source. Ford (1911) reported that during the Matavanu eruption between 1905 and 1911 rain water caught in tanks was polluted with sulphur but the water in this cave was "always fresh and sweet". He also noted that the water level fluctuated with the tide. Fortunately there appears to have been very little pollution of the water in Samoan lava caves nor, with one major exception, dumping of rubbish into them.

MADAGASCAR

While Madagascar does not possess extensive areas of recent lavas, tube-fed lavas occur west of Montagne d'Ambre (Decary 1923, Middleton 2002). Lavaka Andranomiditra (literally 'cave of running water'), south of Bobakilandy, has captured an entire (seasonal) stream. While there is a clearly eroded channel upstream of the swallet none exists downstream of it, indicating that the capture occurred soon after the cave was formed. The stream passage is 3m high, 8-10m wide and can be followed for over 300 metres to a point where it is flooded to the roof. This water probably flows to a spring 2.5km to the south-west where channels have been excavated to facilitate irrigation. Locals tell of water fountaining a couple of metres into the air at this point in a good wet season. Pollution of groundwaters in this part of Madagascar has not reached a point where there is concern for water quality.

AUSTRALIA

Infiltration occurs just as rapidly into young tube fed lavas in Australia as it does elsewhere. Subantarctic Heard Island in the southern Indian Ocean experiences an average 300 rain-days and precipitation of 1350mm annually, yet its lava tube caves are largely by-passed by infiltration, the aquifers presumably discharging directly into the sea (Kiernan et al, 2003). Elsewhere in Australia, significant volumes of water accumulate in lava tube caves where the necessary preconditions are met. For example, at seasonally-arid Undara in North Queensland (Atkinson and Atkinson 1995) where granite occurs at shallow depth beneath the lava, a semi-permanent lake occurs in one cave, while others nearby become flooded during major rainfall events.

The potential exists for contamination problems to develop in some Australian lava aquifers (Grimes 1999), and indeed there is already some cause for concern. Rubbish dumping on the surface has been recognised as a threat to the lake in Skipton Cave in temperate western Victoria (Webb et al, 1982). Groundwater from within and beneath western Victorian lavas is used for stock watering, irrigation and domestic purposes, and contributes to water supplies for towns. Discharge from one spring used to boost the reservoir for one town was reported by Stanley (1992) to have nitrate (as N) and *E. coli* levels that regularly exceeded the World Health Organisation's recommended limits. Relatively high nitrate levels need not necessarily indicate pollution, but their co-presence with *E. coli* at this spring was considered to be suggestive of contamination. Pollution of basalt aquifers beneath the western suburbs of Melbourne has resulted from percolation from waste disposal sites (Riha 1976, 1978). Tube-fed lava emplacement, at least locally, is suggested by an eroded tumulus on the foreshore in the western suburb of Williamstown.

CONCLUSIONS

Re-evaluation of the likely origin of some lavas that have previously been interpreted as flood basalts remains in its infancy, but there is increasing recognition of the importance of endogenous lava emplacement processes. While most recorded lava tube caves occur in young lava flows, endogenous emplacement mechanisms are likely to have been equally prominent in the emplacement of some older lavas (Self et al, 1996). Structures resulting from lava flow inflation and deflation, including lava tube caves, are important for groundwater storage and transmission. Some may persist even in very old lava flows where visibility is now impeded by burial or the accumulation of weathering residues. While opportunities exist in some other groundwater contexts for a degree of natural purification of contaminated water, the potential for this may be as limited in some lava aquifers as it is in some karst environments. In these circumstances, greater research and careful protective management seems warranted.

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