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BRECCIA-FILLED PIPES: DISTINGUISHING BETWEEN VOLCANIC AND NON-VOLCANIC ORIGINS

ABSTRACT: OLLIER C.D., *Breccia-filled pipes: distinguishing between volcanic and non-volcanic origins*. (IT ISSN 1724-4757, 2007).

Some vertical cylindrical bodies of breccia are breccia-filled volcanic pipes, some may form when caves collapse, some result from solution of evaporite pipes, and some are produced by various other mechanisms. Convergent landforms are those formed by different processes but with the same surface expression: an example is the surface expression of breccia pipes. We can also think of convergent structures, for breccia pipes have section and plans that may be very similar, yet formed by completely different mechanisms. There is a spectrum from obvious volcanic phenomena to obvious collapse phenomena, but some breccia-pipes are difficult to interpret. Besides volcanism and collapse, many different origins have been proposed. Hydrothermal alteration, closely related to volcanic gas eruption, is associated with many breccia pipes that are thought to form in the first place by collapse into limestone caves, which seems a remarkable coincidence. The rock mechanics and mechanisms of collapse seem incapable of producing the largest breccia pipes, which are over a kilometre deep.

KEY WORDS: Breccia, Pipe, Diatreme, Sinkhole, Collapse, Eruption, Hydrothermal.

INTRODUCTION

Breccia pipes are vertical cylindrical bodies of breccia ranging in width from about a metre to about 100 m, and in depth from tens of metres to over a kilometre. They give rise to landforms such as craters, lakes, or hills, and some are planated and hard to see on the ground. Exposures are found in coastal sections and quarries, and further information comes from drilling and mining in those instances where economic minerals are associated with the pipes. They can be produced by several quite different mechanisms: some are volcanic explosion breccias, some are breccia fill in collapsed caves; some are formed by intrusion of evaporate pipes followed by later solution, some are formed by hydrothermal intrusions, and several other explanations have been proposed. Quite different explanations have been offered for the same pipes in some places, and they remain controversial. Sometimes composite methods are proposed, such as cave collapse followed by hydrothermal activity on the same site. Breccia pipes provide excellent examples of convergent landforms and structures. In some instances theoretical considerations suggest that the proposed mechanism is unlikely. In others the repeated association of two very different mechanisms seems to be beyond reasonable coincidence. Here I present a brief review and attempt to provide criteria for distinguishing breccia pipes of different origins. I present a large number of examples to show the range of breccia pipes, and many descriptions are necessarily rather brief, and read rather like a catalogue of pipes. Others get a fuller treatment, especially the debatable and controversial examples.

VOLCANIC BRECCIA PIPES

Volcanic pipes are roughly cylindrical feeders of volcanoes that may be filled with solidified lava, tuff-breccia or agglomerate, depending on the nature of the original eruption and magma type. The agglomerates may contain varying amounts of bedrock. Volcanic rock usually rises from a magma chamber through wall-like dikes, but as they approach the surface the dikes divide into individual pipes that rise to the ground surface (a few blind pipes stop short of the surface). Volcanic pipes range in size from a few tens of metres to hundreds of metres. Here I am deal-

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ing with pipes usually a few tens to a few hundred metres across. Pipes are usually vertical. Towards the surface some flare out, giving an inverted cone or trumpet shaped pipe. The composition of pipe infill varies from all volcanic, to mainly volcanic with a few fragments of bedrock, to mainly bedrock with a few volcanic components, and possibly to all bedrock fragments.

It is useful at this stage to discuss the mechanism of intrusion of pipes, as several features are important in diagnosing the mode of breccia formation. A mixture of solid particles suspended in a gas can behave in many ways like a liquid, and occurs naturally in volcanic eruptions when finely divided pyroclastics are suspended in volcanic gas. Holmes (1965) described the mechanism. Explosive energy in a rising pipe gives rise to blast waves that shatter the adjoining rock, and heat that increases both the temperature and pressure of gases. The rock is cracked and rising streams of high-pressure gas, expanding as they go, force their way towards the surface through passageways which they widen by abrasion, at the same time arming themselves with dust that adds teeth to their erosive powers. Dust-laden gas streaming through a crack widens it, and liberates bigger fragments. Smaller particles are carried upwards but the largest ones tend to sink. All fragments are rounded by abrasion.

Fluidisation can account for many things: the fineness of the first-erupted ash, the structures seen within some volcanic pipes, and possibly the formation of pipes with breccia but no volcanic rocks, the subject of this paper. Holmes (1965, p. 271) says that fluidisation-erosion is probably the chief mechanism responsible for the chimney-like form of volcanic pipes, and that however irregular the initial passageway may be, its widening will tend to produce a cylindrical form.

Kimberlite pipes are the best studied of all volcanic pipes, as they have been mined for diamonds. They are vertical cylindrical pipes that possibly flared out near the surface. Their original surface expression was possibly like a maar. Blind kimberlite pipes are also known. Besides volcanic components, they contain rocks from well above the present ground surface, and rocks brought up from below. One Transvaal pipe contained unmetamorphosed blocks of coal weighing many tonnes, 200 to 300 m below the coal seams from which they were derived. The matrix of serpentine and calcite suggest an immense amount of gas that was available when the pipes were being drilled to the surface.

Mitchell (1986) wrote «Pipe development is initiated by subsurface brecciation processes». And «Diatremes appear to be secondary processes formed by subsequent modification of the underlying root zone embryonic pipe». Kimberlite pipes bring diamonds to the surface of the Earth. If kimberlite ascended slowly the diamond would be converted to graphite: to retain the diamond structure the pipes must ascent very quickly. This may account for anomalies - for example, it is sometimes noted that the pipes do not convey enough of heat to alter the surrounding rocks.

Carbonatite Pipes are full of an igneous rock consisting largely of calcium carbonate, and in some ways are related to kimberlites. Heinrich (1966) covered the subject and devoted a chapter to Explosion Pipes. He wrote: «The conclusion that many widespread explosion breccias and diatremes owe their fragmented nature to CO_2 - rich gas explosions is unavoidable». Maars are a variety of volcano consisting of a ring or pyroclastic material around a crater that is below the neighbouring ground surface, and often contain lakes. The classic examples are the Eifel maars, where "maar" means lake. The composition of ejecta varies from dominantly volcanic to dominantly comminuted bedrock, and some possibly erupted gas only.

There is much debate about hydrovolcanic breccia pipes and their classification into phreatic and hreatomagmatic types. According to Tamas and Milesi (2002) «phreatomagmatic structures are the result of direct interaction between a magma body and an external source of water, while phreatic structures are derived only by the effects of magmatic heat flux upon an external body of water, without any direct interaction/ contact between the magma body and the water supply». In this and a later reference (Tamas and Milesi, 2003) they list genetic criteria to distinguish the two.

In some situations scoria cones are formed where eruptions came through solid bedrock, and maars were formed where it came through water-saturated sediments. In this case fragmentation would be confined to the upper part of the pipe. Lorenz (1985) believes that maars are formed by phreatomagmatic eruptions, where lava reacts with groundwater. He claims maars are «not the result of explosive… juvenile volatile phases from magmas…». His fig. 11 shows a funnel shaped diatreme down to 2000m. This, of course, is well below most feasible groundwater, and he suggests that the water works its way down *during* the eruption. It seems improbable to me that liquid water could work its way down a hot volcanic pipe. The time scale involved is also strange. Groundwater flow takes months or years, and the short-lived maar eruption would be over before groundwater could be replenished. How fast could water percolate down? Ollier (1967) suggests that maars result from short-lived eruptions - perhaps hours to a few days.

Elsewhere it is possible that the initial volcanic pipe was so charged with gas that breccia could be found in much of the pipe. In some pipes distinctive clasts are found (Ollier & Joyce, 1974), such as the "golf-balls" - abraded and rounded fragments of limestone dimpled by lapilli which still lie in the dents. In volcanoes of Western Victoria, Australia, a maar eruption may be followed by a lava flow and finally a scoria cone. The rock of the maar, apart from bedrock fragments, has only basaltic lapilli. Rock in the final scoria cone may contain bombs of lherzolite derived from the mantle, suggesting that the eruption brings rock from deeper sources as the eruption progresses.

The Swabian pipes are volcanic necks filled with breccia and tuffisite (intrusive tuff) described in detail by Cloos (1941). Earlier ideas of volcanic breccia were that the explosive material thrown out of the volcano simply fell back into the neck, but Cloos showed that the intrusion was largely by gas, carrying tuff and lapilli. The lapilli were probably already solid when they reached the level of the tuffisite now exposed to view. Large blocks of bedrock actually sink relative to the equivalent rocks outside the pipe (fig. 1). This is a significant observation so far as breccia pipes are concerned, because derivation of clasts from above is sometimes used as proof of collapse, but clasts can move downwards even in a volcanic pipe when emplacement is by fluidisation.

In Donegal there are about fourteen known breccia pipes, cut through Precambrian metamorphic rocks, including Dalradian dolomite. They are related in space and time to the Caledonian pluton of Ardara, so have long been accepted as volcanic in origin (French, 1977). Breccia fragments make up well over half the total volume and consist of marble, quartzite and metadolerite in a sparse igneous matrix. All stages of disruption, comminution and alteration can be observed. The pipes are vertical and have elliptical outcrops not over 300 m across.

There is considerable variation amongst the breccia pipes. The Birroge Pipe consists of closely packed rounded fragments of calc-silicate and quartzite rocks set in a dioritic matrix. The xenoliths have been abraded, as by fluidisation, the removed grains being added to the matrix.

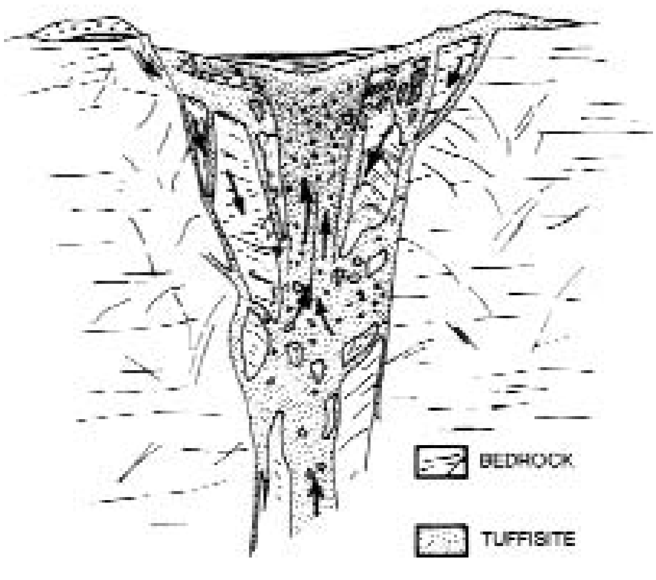

FIG. 1 - Swabian pipes (after Cloos, 1941). As the tuffisite rises, driven by volcanic gases, the larger blocks of bedrock sink. The illustration is diagrammatic and there is no scale on the original.

The intrusive rock against the contact is extremely altered. Cavities along the contact and in the igneous rock are often lined with dog-toothed calcite. The pebbles are often almost touching one another and the amount of matrix is minimal - it sounds like a clast-supported conglomerate. Calcareous xenoliths are metasomatised in contact with the amphibolic material of the matrix. The Kilkenny School pipe is a small breccia-pipe 300 m diameter with a fine-grained friable igneous matrix. The breccia mass has no sharp contact but grades through veined into normal metadolerite.

In the Dunmore pipe the limestone was intensely shattered with no dilation of the country rocks and there is very little matrix material. This, together with other mineralogical evidence «suggests that the brecciating agent was extremely tenuous and possibly gaseous». However, within the breccia proper the scanty matrix is rich in igneous minerals, microcline and oligoclase.

At Crannogboys pipe most of the xenoliths are of local derivation including limestone, quartzite and mica-schist (fig. 2). They are unsorted and in blocks up to 3 m across. «Some initially large blocks are now represented by a multitude of fragments which have not moved far apart».

In all examples space was made by comminution and transport of the metamorphic bedrock. «Flow of volatiles from the melt into the opening rocks could have led to the comminution of the metamorphics in advance of magma injection». «The magma may then have been confined to preferred channels, amplifying the brecciation and entraining smaller fragments». «Gases, therefore, evidently played an important part in the production of the breccias» (French, 1977).

Bowes and Wright (1967) described about twenty breccia pipes near Kentallen, Scotland, that cut varied Dalradian (Proterozoic) rocks. The pipes are structurally located by cleavage and steeply plunging fold axes, and the breccias are volcanic, with some inclusions of quartzite derived from the roof of 300 m of Appin Quartzite. They wrote: «Explosive activity took place on the sudden release of gas when the gas-charged basic magma moved into the dome-shaped interference structures with their pipe-shaped zone of much fractured and brittle rock».

In the Rudha Mor Pipe the country rock surrounding the pipe was also shattered and brecciated. «Where the diapir transgresses the brecciated areas, it is generally by fingering along cleavage or bedding planes, preceded by gases causing pockets of intrusive breccia at the tips of these fingers. Other effects of gas action and high gas concentration are widespread». The Back Settlement Pipe never reached the surface. «The much more rounded nature of the boulders and the steep and sharp margins of the Back Settlement main pipe on its northern side indicate considerable transport of blocks and erosion of the pipe walls». A generalised sequence of events (somewhat simplified here) includes: (1) Explosive activity with shattering and brecciation of country rocks; (2) Emplacement

FIG. 2 - Crannogboy Pipe, Donegal, Ireland. An undoubted volcanic breccia pipe cutting through Dalradian limestone, which provides most of the clasts (photo C.D. Ollier).

of mafic rocks with included quartzite blocks; (3) Emplacement of diorites; (4) Emplacement of granodiorites in small masses. In other words, the breccia phase is the first formed, in a gas rich environment, as a precursor for normal volcanic neck intrusion.

Evidence is presented that the breccia pipes were formed at a depth of 2 - 2.5 km. They compare their pipes with the Irish pipes, and conclude that the latter are shallower and may have broken through to the surface. Large numbers of breccia-filled diatremes occur in the desert east of Cairo. Here the country rock consists of Eocene limestone but the breccia in the vent consists of quartzite, otherwise unrepresented in the region. Rittmann (1962) described them as follows: «Some initial perforations produce nothing but gaseous materials. If the explosions are sufficiently powerful, broken pieces of the rocks penetrated will be thrown out and deposited around the point of eruption as a vent-opening breccia. In this way so-called *gas Maars* are formed».

Rittmann proposes the following sequence of events to explain the gas maars: (1) A powerful gas blast blew the pipe clear; (2) It was filled from above by loose Oligocene quartz sand; (3) The sands were consolidated by recrystallization under the influence of hydrothermal solutions; (4) A second, much weaker, phreatic explosion broke up the quartzite without ejecting it; (5) Finally the resulting breccia was cemented once again, this time by ferruginous hydrothermal deposits.

Unfortunately Rittmann's book has no references, and he provides no details of how the story was derived. Rittmann believes the vast majority of gas volcanoes result from essentially phreatic outbreaks, where igneous intrusion merely provided the necessary heat energy, but the same mechanisms could easily be associated with deep-seated gas eruptions.

West of Cairns in NE Australia there is a group of maars as well as other Quaternary volcanic features. The most remarkable is Hypipamee Crater. This crater was blasted through granite, with very little volcanic debris around the edge or inside the crater. The granite walls plunge about 60 m, and the crater lake is 80 m deep. It appears to be a purely gas explosion, and solid granite is not likely to have held enough water for this to be a phreatic eruption, or to be formed in the way Rittmann proposed for the Egyptian gas maars. Other maars in the region have tuff rings consisting of comminuted bedrock together with some volcanic component.

Endersbee (2005) has collected evidence that the water in the Great Artesian Basin of Australia (GAB) is not artesian at all, but comes from fractured bedrock below the sedimentary basin. Until 1914 no drilling for water in the Great Artesian Basin brought water without reaching the bedrock base of the GAB sediments. Furthermore, the water contains dissolved gases including methane and helium that are difficult to explain. Dams have been built on the alleged intake areas and hold water, so the rocks are not as porous as suggested in the artesian model. Endersbee suggests that, before it was bored by people, some gases escaped naturally through "blowouts". He wrote: «It is my view that the groundwaters in the Basin are derived from deep within the Earth. They have a similar source to the steam that explodes from volcanoes, and the hot acid waters that gush from the deep ocean vents. They are part of the original constitution of the Earth». It is relevant to note that the gases in the groundwater of the Great Artesian Basin include helium (Lehmann & *alii*, 2003), including ^{3}He, which is generally assumed to be primordial. Helium is not recycled, but lost to space, though Lehmann & *alii*, claim that it is somehow stored in the Bulldog Shale bedrock.

On the edge of the basin lies Lightning Ridge, an opal field with abundant exposures. In the opal diggings there are many vertical, cylindrical bodies of breccia, known locally as blowouts (usually about 1 m across). At the ground surface some blowouts may be represented by mound springs, hills up to 10 m high built of carbonate sinter around emerging springs, or by box-hollows', slight depressions about 10 m across, often rimmed by box trees.

There is anecdotal and field evidence that some Australian mound springs erupt explosively, ejecting gravel and boulders 60 cm across from a formation 150 m below, as near Malpas, Queensland (Grimes, 1973) and Eulo (Read, 2002). Pebbles and boulders of exotic rock have been noted on many opal fields. Boulders of basement rock with Devonian fossils were reported to be common near White Cliffs, NSW (Kenny, 1934). Boulders of granite have been reported around mound springs SW of Coober Pedy (Keith-Ward, 1921), where basement (granite) is over 1000m deep.

NON-VOLCANIC BRECCIA PIPES

I now consider a group of breccia pipes that have been explained without any reference to volcanic activity. It is difficult to organize this section because the same features have often been explained in different ways, so the headings used are not completely systematic. When brecciated rocks have the form of a vertical cylinder they have most commonly been explained by either: collapse into a cave in underlying limestone, or formation in evaporate pipes where the evaporate is later dissolved away, but some pipes have been given quite different explanations.

Cave collapse

Although solution of limestone is often invoked to explain breccia pipes, few good examples of breccia pipes entirely in limestone are known. The gash breccias of Pembroke were interpreted as breccia pipes formed by cave collapse (Dixon, 1921), but Thomas (1971) challenged this and proposed a tectonic origin. A recent investigation by P. Walsh, J. Hepworth, Y. Battiau-Queney and me found that some of the pipes did not have even roughly circular cross sections, so may not strictly belong in the set of breccia "pipes" (fig. 3). Waltham & *alii* (2005) maintain that breccia-pipes entirely in limestone are very rare.

Many breccia pipes in non-carbonate rock have been attributed to collapse into underlying caves that were formed in limestone. These pipes may have a crater or depression, sometimes called subjacent dolines. One good example is the Big Hole at Braidwood, NSW, Australia. The hole is cylindrical, twice as deep as wide, with vertical walls 115 m high. Silurian limestone is inferred to underlie the Devonian sandstone of the walls (Jennings, 1985). There is no certainty that the Big Hole is underlain by the Silurian limestone, and its location is quite distant from any outcrops of Silurian limestone. On the basis of calculations described later, the original cave height (and therefore the original limestone thickness) would have to be half a kilometre.

A similar big hole called Montlake (fig. 4) occurs on the Cumberland Plateau in Tennessee. 25 km north of Chattanooga (Stockdale, 1936). It is in horizontal Pensylvanian sandstone. The hole is elliptical, with greatest diameter of 90 m and minor axis 75 m. An estimated 240 m of sandstone underlie the pit. Beneath this are thick Upper Mississippian limestones. The hole is located only 120 m from the steep Cumberland Escarpment, almost 300 m high. A spring emerges on the escarpment, in a position about 150 m lower than the water level in Montlake. Possibly seepage from Mortlake contributes to this and other springs. There are no limestone caves in the vicinity and the nearest large caverns are perhaps 20 km distant. Stockdale proposes that the hole was formed by collapse into a limestone cave 250 m below the ground surface.

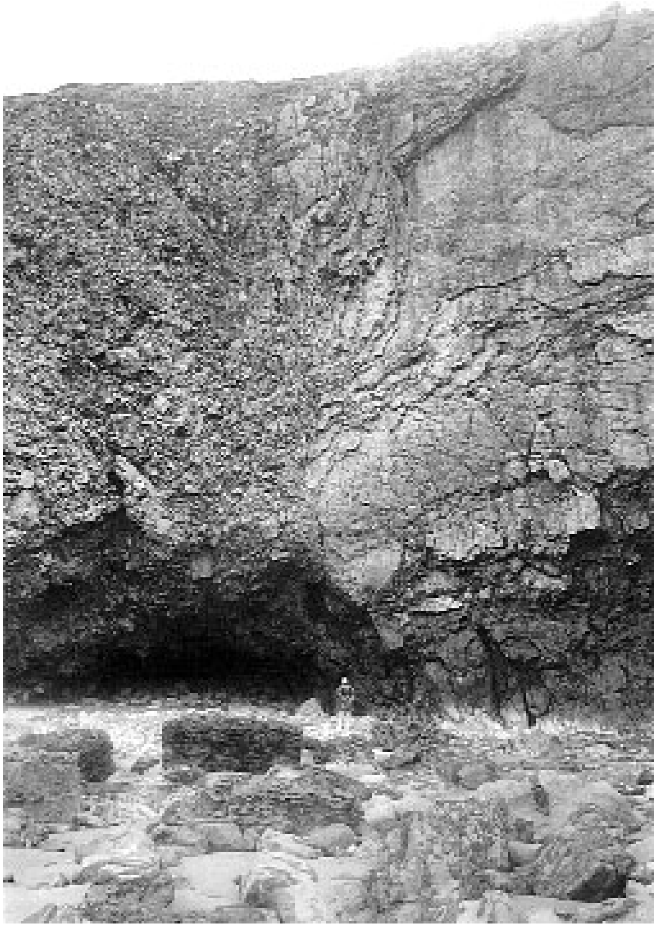

FIG. 3 - Gash breccia, Pembroke, Wales. The Pembroke breccia pipes were interpreted as cave collapse breccia pipes (Dixon, 1921) and as structural breccias (Thomas, 1971). Other possibilities include fault-breccias (since faults are sometimes present), brecciation associated with bedding-plane slip (since some boundaries coincide with vertical bedding planes), and brecciation by gas is not impossible. Note how the edge of the breccia pipe is oblique to the steeply dipping bedding planes (photo C.D. Ollier).

In Italy there are some «big holes» too. On the boundary between Latium and Campania lies a cylindrical shaped sinkhole about 40 meters deep and 170 m in diameter. The outcropping rock is pyroclastic deposits and a borehole down to 130 meters below the ground surface did not encounter any limestone. Any hypothetical limestone cave to cause collapse would be very deep and very wide (Stefania Nisio pers. comm.)

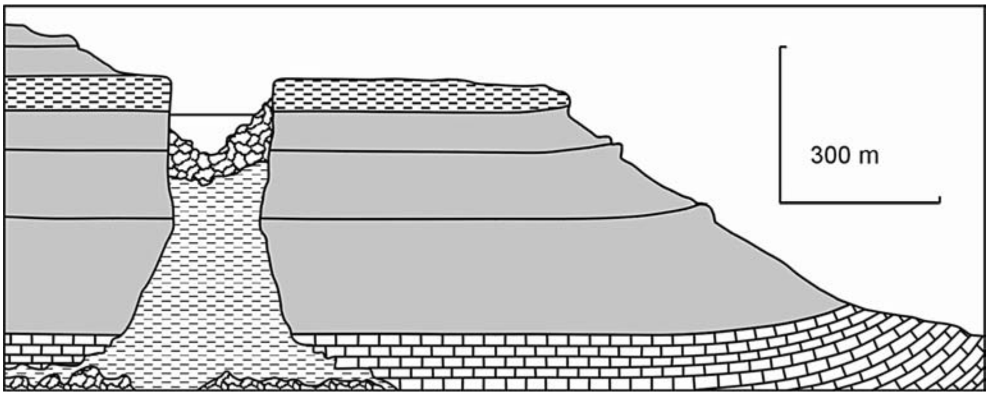

FIG. 4 - Montlake cross section, largely speculative (after Stockdale, 1936). This is the simplest kind of breccia pipe, attributed to collapse of overlying beds into a cave formed in limestone.

In the Hainaut Coalfield of Belgium there are many vertical cylinders of brecciated rock in the Carboniferous coal measures (fig. 5). Since they cut through mined coal seams their distribution is very well known. Most of the pipes are close to cylindrical, and diameters range between 50 and 700m. They are locally described as "crans". and over 300 crans have been identified. They are covered by Mesozoic and Tertiary sediments. Some fail to reach the ground surface and are said to be blind. Quinif (1995) considers that the crans were formed by upward stoping from caves in the underlying Carboniferous Limestone, to a stage where they breached a Wealdean ground surface. But the cylinders are up to 1200m high! Quinif (1995) describes them as «the deepest endokarstic structures in the world». As with the earlier examples, there seems to be a problem with the size of the original cave. Furthermore, is it possible for collapse to continue by roof fall stoping for such a distance, and maintain the constant width of the cylinder? Can collapse work its way upwards for over a thousand metres through varying strata and structures with so little change in diameter? And how to make caves at such depths? Deep phreatic caves are known, but hardly on this scale.

As an aside it is useful to discuss fossils in pipes at this point. Although many caves contain rich fossil assemblages, fossils are very rare in pipes even in limestone regions. This suggests that, however they may form, they were not open to the surface for very long. The one major exception is the «Cran du Midi» at Bernissart in the Hainaut Coalfield of Belgium which contains huge piles of *Iguanodon* (denoting a Lower Cretaceous age). These were recovered in the 1870s in coal mining operations at a level 300 m below the top of the breccia pipe. The surrounding rocks are mainly argillaceous Westphalian coal measures. The bones cannot have been washed into the pipe through 300 m of brecciated argillaceous and arenaceous sediment. Nor does it seem likely that a herd of *Iguanodons* fell into a 300 m-deep «alligator hole» in the swamp where they grazed. The presence of vast numbers of *Iguanodon* bones suggests the simultaneous death of a large herd, which might conceivably be due to them being killed by emanations of noxious gases from the pipe which now preserved them, though this still leaves many unanswered questions.

Whatever the mechanism of subidence here, it was either continuous or spasmodic throughout a greater part of the lower Cretaceous and the Upper Cretaceous up to the Middle Turonian. Upper Turonian strata pass over the cran without deflection into it. Quinif (1995) regarded this as a karstic process, related to deep-seated solution in Dinantian limestones and evaporites many hectometres below the level at which the bone breccias are preserved. The minimum discrepancy between stratigraphic levels in the walls and fill in the Hainaut crans is 400 m.

Returning to the difficulty of forming pipes, the problems of the mechanics and geometry of collapse into an underlying cave can be simply illustrated by a calculation. A collapse breccia always has void space, and it is impossible for such a process to continue indefinitely. Suppose an initial cave is 10m high above a base at 0m elevation. Suppose a slab of roof 2 m thick falls into it as a breccia with 50% void space. The cave roof will now be 12 m above the original base, the cave floor 3 m above, so the cave height is now 9m above the floor. The next 2 m rockfall produces 3 m of fill and the cave height is reduced to 8 m above the floor. After only ten falls of 2 m of solid rock the cave will be completely full. The cave roof will have stoped up only 20 m. The height of the blind breccia pipe is three times the height of the original cave. If we reverse the argument, then a breccia pipe of 1000 m requires an original cave of 333 m. Such caves are unknown.

The theory of cave roof stability is summarised by Waltham (2005). According to him there are no such things as limestone cave roof collapses where the limestones are thick-bedded and well-crystallised. There are simply no historical records of major cave systems collapsing. Only where the limestone is very weak and thin-bedded can upwards stoping take place, possibly to reach the ground surface above. Indeed, except for the most freakish geomorphological circumstances, the roofs of cave chambers formed in phreatic conditions are completely stable except for a small tensional zone below the arch that carries the superincumbent load - the so-called Voussoir arch. Waltham comments that, to all intents and purposes, if the roof of a cavity is at least 5 m thick, it may be

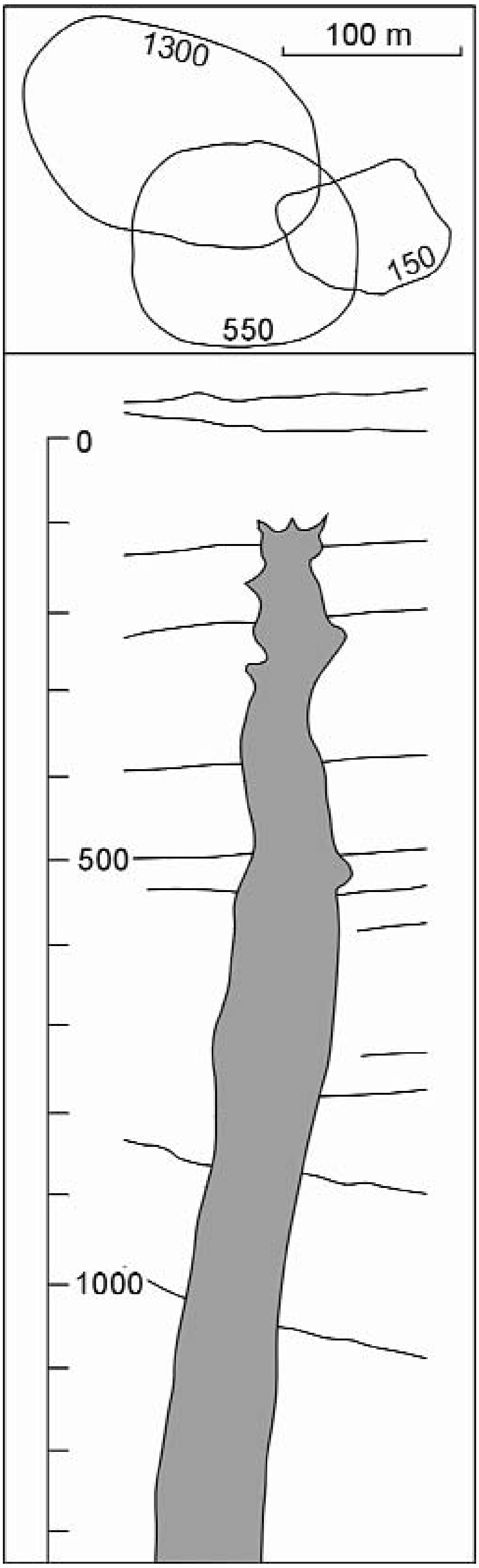

FIG. 5 - Breccia pipe from the Hainaut province, Belgium (after Quinif, 1995). The pipe is interpreted as a collapse into an underlying limestone cave, and stoping eventually reached the surface.

regarded as completely stable for all except the most stressful or concentrated of engineering operations.

Roof collapse is commonly observed inside karstic caves. It makes a pile of debris in the middle that usually contains some very large, angular slabs that cannot be readily matched with the side walls: indeed their affinity is with the roof. Furthermore they have a lot of flowstone, quite unlike the debris found in any of the breccia pipes described in this paper. We never find these large, debris filled caves in the geological record.

Evaporite pipes

We now come to breccia pipes formed by evaporite intrusion and solution. Evaporites, especially salt but also gypsum and anhydrite, have a great ability to flow and sometimes erupt as salt domes and related phenomena. These can include vertical pipes of evaporates that may contain fragments of country rock (often limestone). Gravitational instability is the prime motivating cause. If the evaporate is later dissolved out, a breccia filled pipe remains. Waltham (2005, p. 81) wrote that nearly all very deep breccia pipes originate from dissolution of gypsum or salt. The most spectacular assemblage is in China, where some 2,875 breccia pipes are known. They have excellent exposures in coal mines and boreholes, and all seem to have been formed as evaporate pipes.

The crans of Belgium have been described earlier, and Quinif (1995) attributed them to collapse into underground caves. A totally different explanation was offered for the cran of Saint-Ghislain, Belgium by Delmer & *alii*, 1982. A deep borehole revealed a heavily brecciated zone of Visean carbonates and anhydrite at depths of 2,100 - 2,728 m below ground level. Delmer & *alii* show the pipe from 300 to 1,800, so pipe is 1,500 m high (fig. 6). In the figure the pipe appears to be interpreted as a result of solution of an anhydrite pipe. To make the problem even more complicated, breccia pipes that appear to be very similar to the Belgian ones occur over the border in France, but they have wolfram mineralization, so appear to be akin to the hydrothermal pipes described later (Weppe, 1956).

Bowles and Braddock (1963) describe solution features in Dakota and Wyoming where up to 80 m of anhydrite and gypsum has been dissolved in Pennsylvanian and Permian strata. Some resulting debris is irregular, but some is in pipes up to 70 m high and from a few m to perhaps 100 m across. Some are funnel shaped. «The breccia pipes are cylindrical masses of blocks and fragments derived from overlying beds and are firmly cemented by calcite. Intense cementation causes the pipes to weather out in relief along the canyon walls or to form free-standing masses of breccia…». Some collapsed in Oligocene times, but two sinkholes formed in Recent times, the biggest being 80 m in diameter and 20 m deep.

Neal (2002) described a group of about 50 individual sinkholes within a 3 km wide depression called McCauley Sinks in Arizona. They range up to 100 m wide and 50 m deep. The surface rock is Kaibab limestone, but this has

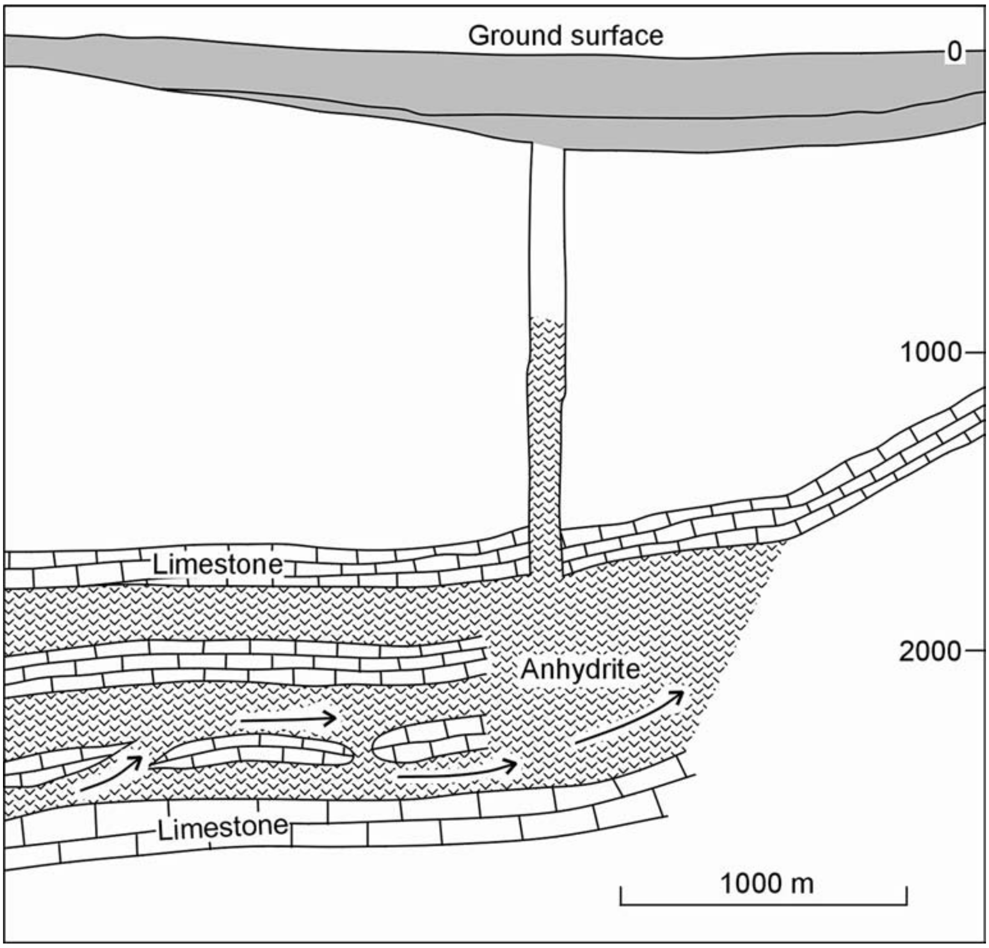

FIG. 6 - Breccia pipe from the Hainaut province, Belgium (after Delmer & *alii,* 1982). The pipe appears to be interpreted here as an evaporate pipe that was later dissolved.

only minor solution features and is less than 15 m thick. It was essentially a passive unit that collapsed into solution cavities in the underlying salt. The structure suggests a compound breccia pipe with multiple sinks contributing to the inward-dipping major depression. A solitary sinkhole of the same general form, Richards Lake, occurs 5 km southeast of McCauley Sinks.

Piping

Many Italian sinkholes appear to result from piping, but they are mixed with some of other origins. Stefania Nisio (pers. comm., 2003) has collated a large amount of information on over 200 Italian sinkholes in thick alluvium. Diameters range from a few metres to 200m, and depths up to 50m, but the majority are small and water-filled. Bedrock occurs at a depth of over 100m. This has led her to distinguish the following two main types:

Cover collapse sinkhole. This requires:the presence of a cohesive cover sediment over bedrock. A cavity forms in the sedimentary cover (not the bedrock) and propogates upwards. When the cover is reduced to a thickness that cannot support acting shear stresses it collapses quickly, and causes catastrophic damage.

Piping sinkhole. This type of sinkhole is characterised by mineralised water, elevated concentration of dissolved gases, and bubbling, and high pore pressure. The process finds a flow path in which high velocities are maintained, with erosion of material and formation of channels. Fault and fracture systems, if present, enhance the migration of deep acidic fluids such as mineral springs or gases such as CO_2 and H_2S. The cover of alluvium may be up to 200 m, often over a karst bedrock. The sinkholes are not caused by collapse into a deep hole, and no signs of water flow from the surface to underground drainage has been found.

These sinkholes do not relate closely to the pipe breccias, being in unconsolidated material, but the association with high water pressures and gases suggests a possible, if tenuous, relationship to the blow-outs of Australia and perhaps other pipe phenomena such as fluid escape structures.

The role of thermal waters in karst is further discussed by Forti (2002). Sauro (2002) gives an account of collapse dolines in the Venetian fore-Alps where processes seem to be exceptionally rapid.

Blowouts of gas and perhaps water provide a link to the next section.

Fluid escape structures

Ogilvie & *alii* (2000) described deformational structures in the Triassic sandstones of Morayshire, Scotland, that have the form of vertical pipes that rise from sea level to the clifftops 20 m higher. They are thought «to have resulted from escape of air through rain-dampened dune sand». «The air was trapped within pores in the dune's core and compressed by the fluvial flood water outside, coupled with the penetrating effects of capillarity». «Concertina folding of its west flank implies collapse following initial uplift, presumably as the air escaped. Some boulders on the foreshore exhibit brittle fracture of presumed moist sand». The explanation seems to be based on an earlier description of the same area by Glennie and Buller (1983) in which the structures are called "fluid-escape structures", which seems to be assuming the mechanism we are trying to determine.

The proposed mechanism sounds rather weak, and we seem to have the sand being unconsolidated or consolidated to explain different effects. I consider it rather dubious that the small-scale phenomenon of capillarity could affect a structure at least tens of metres in size.

Schlee (1963) described sandstone pipes in the Laguna area, New Mexico. They are up to 50 m wide and 100+m high, but have distinct tops and bottoms at different levels. They are filled with material found at the top of the pipe, sometimes in coherent clasts. The wall rocks sag downwards around the pipes. He write that the «pipes are in sharp contact with little-deformed underlying stock». He considers that solution played a subordinate role in pipe formation as some pipes were not underlain by evaporates and in others the evaporate layer was too thin to provide enough space for the creation of sandstone pipes. He considers the «Pipes originated during deposition of the uppermost sandstones that contain them». They probably formed by gravitational foundering of sand into the underlying water-saturated mud, although underlying gypsum may have been a contributing factor. The pipes are all above the Entrada sandstone, which is unaffected.

The same pipes were described by Hunter & *alii* (1992), who came to a different conclusion. They agree that the pipes are all above the undisturbed, horizontal Entrada Sandstone and the Tedilto Limestone member, but they illustrate evaporate being deformed, and the base of the pipes is rather splayed. This does not match the figure of Schlee which shows the bases occurring at quite different levels. They believe, in brief, that solution of underlying evaporates caused the collapse of the pipes: if it is totally dissolved there will, of course, be no trace of it. Neither are they interested in arguments about height to width ratios, a topic discussed later in this paper.

Netoff (2002) describes clastic pipes as wide as 75m and as high as 100m in Jurassic rocks of Utah. They are cylindrical structures with sharp contacts with cross-bedded host sandstones. They extend downwards into the underlying Carmel redbeds. The pipes are cored with homogenous sandstone, but there are also breccia blocks (his fig. 8). He notes that «… abundant breccia blocks in many pipes suggest that at least some of the host rock was already somewhat cohesive during the injection of fluidised sands».

Some pipes are blind (his fig. 5). Some pipe edges are said to be bent down, though the illustrating figure is not very clear and any bend is rather small. Some of the pipes have weathered out into giant weathering pits up to 15 m deep.

The Carmel rock consists of «consolidated mudstone: alternating with deformed gypsum layers». At two sites the Carmel beds dip away from the pipes, and the upturned beds of mudstone and gypsum are only weakly convoluted.

The pipes are thought by Netoff to result from «liquefaction and fluidisation» though he clearly understands the problems of such an interpretation. He wrote «Just how fluidised pipe sands were able to penetrate downwards into the underlying Carmel mudstone and evaporates is puzzling, especially as other evidence implies forcible intrusion of fluidised sands from below». He further suggested that fluidisation was initiated by seismic vibration.

The structures were formed soon after the deposition of the upper beds of the Lower Member of the Entrada Sandstone, as no pipes penetrate younger strata. These are therefore fossil breccia pipes.

In brief, we have a series of breccia pipes in sandstone, but extending into underlying red beds with evaporates. Seismic-induced fluidisation is the suggested origin, but on the face of it gas fluidisation (as in Morayshire) or evaporite diapirism seem equally possible.

HYDROTHERMAL BRECCIA PIPES

Some pipes do not fit into a volcanic - non-volcanic system because there are several processes involved in their formation, even if they are synchronous. Since many of the breccia pipes of Arizona, Mexico, Honduras and elsewhere are associated with mineral deposits normally attributed to hydrothermal deposition (and supported by high temperatures determined from fluid inclusions), it is not surprising that some writers attribute the breccia and the mineralization to the same event. For example, Heylmun (2001) wrote: «The origin of breccia pipes has been kicked around for years. The most commonly accepted idea is that they formed at the intersections of fractures, where hydrothermal solutions forced their way, sometimes explosively, towards the surface». The story is complicated by the additional fact that some mineralised breccia pipes are associated with cave collapse and stoping, and others have volcanic associations.

The Copper Creek mining district of Arizona, about 70 km NE of Tucson, hosts more than 500 mineralised breccia pipes. The pipes are confined to the Copper Creek Granodiorite and the Glory Hole volcanic rocks. Anderson (2003) describes one example, Mammoth Breccia Pipe.

The unexposed pipe was discovered by drilling and has a vertical extent of 915 m and maximum width of 180 m.

The angular clasts are of granodiorite, cemented by quartz, anhydrite, and calcite besides ore minerals. Dates suggest the granodiorite is not younger than 60 Ma, and mineralization lasted 4-5 Ma. Other studies suggest temperatures of the boiling mineralization were as high as 376°C. Oxygen and hydrogen isotope studies indicate a dominant magmatic component within the hydrothermal fluids responsible for mineralization.

Hundreds of breccia pipes are known from northern Arizona (Wenrich & *alii*, 1992), and as they bear uranium and copper mineralisation they have been extensively studied. Finch (2004) describes them as near-vertical cylindrical solution-collapse breccia pipes, 30-175 m in diameter and 1,000 m in length. They occur in flat-lying upper Palaeozoic and Triassic rocks restricted to the Grand Canyon region in the southwest part of the Colorado Plateau. The pipes apparently originated at intersections of joint or fracture sets. Wenrich & *alii* (1992) wrote: «They are not classic breccia pipes in that there is no volcanic rock associated with them in time or space». «They are the result of solution collapse into the Redwall Limestone and stoping of the overlying strata». «The collapse hypothesis is supported by two main observations: (1) No pipes have been observed… in rock below the base… of the Redwall Limestone» (p. 1722); (2) No pipes have been found to contain rocks from underlying formations. Their figure 2 (here fig. 7) depicts a clear base to the pipe in the Redwall Limestone. Their figure 4 shows four types of solution collapse features in NW Arizona: (1) Breccia pipe that bottoms in Redwall Limestone; (2) Collapse due to solution of gypsum bedrock in the higher strata; (3) Collapse in the (higher still) gypsum of the Harrisburg Member); (4) Collapse of a recent sinkhole in Kaibab Limestone (very shallow and vertical sided. The mineralization occurred between 260 and 200 Ma ago.

Finch (2004) summarises the modern view of their formation like this. Breccia pipes developed from solution collapse within the thick Mississippian Redwall Limestone (0-210m) beginning in the Late Mississippian and propagated upward into overlying strata of carbonate-cemented sandstone, siltstone, limestone, and conglomerate for at least 1,000 m, apparently only where the Redwall is >15 m thick. «Stoping was intermittently active and reached the lower members of the Chinle formation in Late Triassic time». Van Gosen and Wenrick (1988) depict the same cross section as above, showing the base of the breccia pipe in the Redwall Limestone, and the caption says «Schematic section based on cliff exposures in the Grand Canyon of Arizona». The Grand Canyon is an intensely studied region. This is a very critical region, because the pipes apparently have clear bases, yet extend for perhaps a thousand metres. It does not match theoretical limits to collapse, but the evidence seems incontrovertible.

Although everyone is apparently agreed on the formation of the breccia pipes, there are many theories of the mineralization (which occurred about 200 Ma ago) including rising fluids, descending fluids, groundwater and hydrothermal fluids. They do not seem to think it remarkable that the mineralization should be associated with the

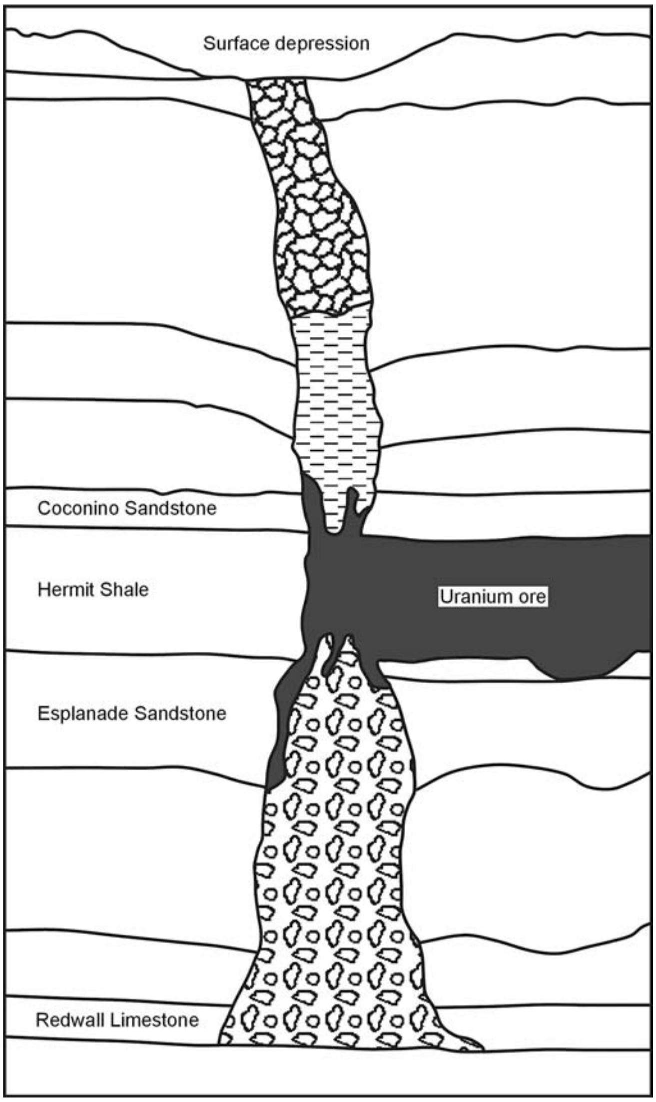

FIG. 7 - Mineralised breccia pipe in Arizona (after Finch, 2004). The breccia pipe is attributed to collapse into a cave in the Redwall Limestone, which appears to be too small for the job. Note that the Coconino Sandstone, Hermit Shale and Esplanade Sandstone appear to be essentially horizontal, though the strata above and below are bent down. Mineralisation is essentially confined to the Hermit Shale, with extensions into underlying and overlying beds.

pipes, apparently in a one-to-one relationship, and yet the two phenomena are not related to a single cause.

The Pascua-Lama region is on the Chile-Argentine border 150 km SE of Vallenar, Chile (Pascua-Lama, 2005). At the surface, breccia pipe outcrops range up to several hundred metres across, and the main one extends at least 700m below surface. The breccia pipe is evidence of an explosive hydrothermal event related to the formation of the Quebrada de Pascua ore deposits. Rather strangely they report «Breccia Oeste and Breccia Sur are the two large post-mineralization breccia pipe complexes located in the mine area». It is unusual to consider the breccia pipes formed after the mineralization. The El Ocote deposit in Honduras is another mineralised breccia pipe, rich in silver, that makes a topographic high, and has substantial supergene enrichment; in other words there is a considerable geomorphic history after the formation of the breccia pipe (Silver Crest Mines, 2005). The deposit is an elliptical breccia pipe 160 m by 90 m and extends to a depth of at least 100 m. Significantly this breccia pipe has a Tuff Cap, also mineralised, that is seen as an upward extension of the breccia pipe, so this breccia pipe sounds like a typical volcanic pipe with some maar deposits preserved at the top.

Cripple Creek, Colorado, is a mining district built on a nested complex of breccia pipes, such as the Cresson Blowout, up to 150 m wide and exceeding 700 m deep. Mineralization is around the margin in the upper part, and in the centre lower down.

The term breccia pipe is used even when the bodies in question are not vertical, like the Golden Sunlight breccia pipe in Montana, which is 100 to 220 m across and appears to slope at about 45% with a quite irregular cross section, and is not particularly circular. (De Witt & *alii* 1996). This is a mineralised pipe of late Cretaceous age cutting Archaean sediments and rhyolite sills. Rock fragments all moved downward during the intrusion.

Yates and Thompson (1959) present an excellent review of the breccia pipe problem as well as describing very complex pipes in the Terlingua District, Texas. They have components of volcanic, hydrothermal and collapse origin. Some breccia pipes extend over 300 m vertically, and were even bigger at the time of formation. The pipes are in the area of the Terlingua uplift, an irregular dome believed to be formed by igneous uplift. One pipe, Maggie Sink Pipe, is elliptical, 180x70 m. Breccia fragments are of all sizes, randomly arranged, and all move downwards. Debris in one circular pipe, 80 m across, indicated downward movement of over 500 m. Hot water was found by deep drilling and was utilised for domestic purposes. Chisos Mine Pipe with a diameter of 25 m did not reach the surface and was only discovered by mining. As the overlying rock is undisturbed they assume rock collapse continues until debris filled the void entirely. They basically attribute the pipes to collapse, and write: «The nature of the breccia and its walls indicate that the pipes were formed by collapse of bedded rocks into solution caverns» and «As the underlying rocks are undisturbed, material must have been removed from below. This suggests solution of the Devils River limestone and contemporaneous collapse-stoping, which advanced upwards until brecciation increased the volume of the rock enough to support the roof». They are well aware that they need a very big cave to start with.

The volcanic association is clear, as volcanic sills were intruded later than pipe formation. One volcanic sill is reported that lifted the bounding sediments yet had little effect on the form of the breccia pipe (the Two-Forty-Eight Pipe), but interfingers with and bakes the breccia. The hydrothermal connection is indicated not only by the still hot groundwaters, but also by the massive mineralization, especially in mercury. They write «The quicksilver deposits were formed from hydrothermal solutions of igneous origin at temperatures below 300 °C, pressures locally as high as 30 atmospheres». «Mineralising solutions ascended breccia pipes and fractures and the ore minerals were deposited in parts of these channels lying less than 2000 ft [700 m] below the surface». In contrast, Emmons (1938) assembled comparative data on a large number of pipes in the same region, and interprets most of them as diatremes, blown through the rock by gas.

DISCUSSION

Breccia pipes are common geological features, and often produce distinctive landforms, usually as craters but sometimes as positive hills. Their mode of origin is varied, but not always clear. Numerous examples have been attributed to different mechanisms by different authors, and many examples have evidence of several different mechanisms in the same place.

Collapse into limestone caves is frequently invoked as a cause of breccia pipes. Since breccia has a larger volume than the original rock from which it is derived, this presents problems of the size of pipes (and some pipes are over 1000 m high). The strength of massive limestone is another problem.

Many breccia pipes are associated with evaporate deposits, as pipe-like equivalents of the better-known salt domes. So long as there are evaporites in the vicinity there is no problem, but since the evaporate matrix is commonly dissolved away they may be interpreted in alternative ways, like the crans of Belgium. Volcanic pipes grade from those filled with volcanic rock, through those filled with breccia with variable content of volcanic and bedrock clasts, possibly to pipes formed by volcanic gas that have no volcanic component at all in the breccia. The speed of formation of breccia pipes, according to different authors, ranges from intrusion at the speed of sound (kimberlite pipes), to slow upward stoping over several geological periods (Arizona pipes). The longer time scale is apparently related to mineralised pipes, though in other circumstances mineralization is often thought to occur faster.

Mineralized breccia pipes are attributed to rising hydrothermal solutions, which are presumed to make the breccia pipes and convey mineralising fluids. More complex scenarios are devised when necessary. The collapse hypothesis is associated with many mineralised breccia pipes, where the pipe seems to be based in a specific limestone horizon. Temperatures and pressures determined from minerals, isotopes and fluid inclusions are often high, even though other indications may suggest the breccia pipes were not formed at great depth. It is rather strange that mineralization should occur only above a certain stratum, and still be confined to breccia pipes. It is hard to see how hydrothermal solutions manage to affect upper strata but have no effect on underlying strata.

Breccia pipes in Pembrokeshire have been attributed to cave collapse and to structural deformation. Breccia pipes of Belgium have been attributed to both collapse and to evaporate solution, and over the border in France similar features have been attributed to hydrothermal injection. Perhaps several mechanisms can combine to produce the features observed, but sometimes the coincidences involved appear extraordinary.

CRITERIA FOR DETERMINING THE GENESIS OF BRECCIA PIPES

In view of the complex explanations summarised above, it is worth summarising the criteria that may help to determine the origin of breccia pipes:

Features that prove nothing

Vertical contacts: vertical crosscutting contacts can be produced naturally by many different processes.

Circular cross sections: these can be made by several different processes in nature. A circular profile makes a tectonic origin less likely, though not impossible (cf. Thomas, 1971).

Blind pipes: can be produced by igneous intrusion, evaporite intrusion and, through stoping, by karstic collapse.

Downward-falling clasts: can be produced by volcanic fluidisation (as in kimberlite pipes), by fragments falling or being washed into dolines, by cave roof collapse and by other mechanisms.

Large (house sized) fragments: are found in collapse pipes, volcanic pipes and salt diapirs.

Positive proofs

Original igneous rock fragments: Ash and lapilli (tuffisite) in the pipe-fill are proof of a volcanic origin.

Fragments of mantle rock: Peridotite and Iherzolite are found only in volcanic pipes.

A distinct base to the pipe: As volcanic pipes rise from deep in the Earth, a distinct floor to the pipe theoretically disproves any volcanic origin. In limestone the existence of a base may be difficult to identify, because it is impossible to enter a cave that has been filled up with collapsed roof material. A side view in a vertical exposure is one way to recognise such a base (as in the exposures in the Grand Canyon). Mining and drilling could also find a base to pipes.

Partial proofs

Flowstone: Recent cave collapses in caves which may still be entered are often seen to have deposits of flowstone in association with the collapse piles. If flowstone is present in the breccia pipe in a limestone host, it is a fairly clear indication of cave roof collapse. On the other hand, absence of flowstone does not mean that it cannot be a cave roof collapse. Very few accounts of flowstone, broken stalactites and stalagmites etc appear in the literature of breccia pipes. Dixon (1921) described stalagmite in the Pembrokeshire breccia pipes, but in my opinion they are not stalagmites at all.

Fossils: the presence of fossils in the matrix of a pipe breccia is fairly sound evidence that it is not of volcanic origin. The general absence of fossils in pipes, compared with the abundant fossils in many caves, is generally against a karstic origin of pipes, but not conclusive.

Upward moving clasts: rock masses can be brought from below in pipes by both volcanic and halokinetic processes. Some of these may actually reach the ground surface, as in the Great Artesian Basin of Australia where fragments of igneous rocks such as granite near supposed blow-outs in sedimentary rock kilometres thick indicates quite violent gas eruptions, or high pressure water/steam vents.

Related igneous phenomena: Related igneous phenomena support a volcanic interpretation (e.g. supposed volcanic pipes in Donegal and Argylshire are directly associated with granite plutons).

Related tectonic structures: Many pipes of proven volcanic origins are clearly associated with major tectonic structures. Examples of such phenomena are the Swabian pipes, which lie on the margins of the Rhine Graben and some Victorian maars, which follow a synclinal axis. Joint control for the development of pipes has been described for the Arizona mineralised pipes, and suggested by Thomas (1971) for the Pembroke Gash Breccias.

Height/width ratio: There is evidence that most thick-bedded, well-crystallised limestones are perfectly stable if the roof thickness of a cave is more than 0.4 its width. Where the thickness of the putative cave roof is of the order of hectometres (or kilometres in the case of some of the Belgian crans) prodigious widths of caves are implied - the deepest of the Belgian crans would imply that the supposed cave which collapsed is over 2 km in width! Such supposed deep karst must be regarded as suspect and an alternative explanation sought.

Thickness of limestone: As a generalisation, one might suppose that very tall pipes could only be produced by thick limestone hosts. This is contradicted by the supposed karstic origins of the 1,000 m - high pipes in Northern Arizona. Finch (2004) considered that the karstic stoping in these instances was initiated in a host limestone over 15 m thick, which seems a remarkably small limit.

The presence of gases: The presence of volcanic gases in modern sinkholes in alluvium in Central Italy and in boreholes in the Great Artesian Basin of Australia suggests that cryptovolcanic gas activity may play a part in creating breccia columns.

Temparature of mineral formation: despite the evidence that some of the kimberlite pipes of South Africa were created by fluidisation processes involving volcanic gases at no great temperature (volatile hydrocarbons survived the brecciation process unaltered), pipes of volcanic origins might normally be expected to show some evidence of a high temperature origin. Fluid inclusions in minerals associated with the Arizona mineralised breccia pipes indicate an ambient temperature of 80-173°C, which is much too high for a pipe generated anywhere near ground surface.

Negative evidence

While negative evidence may cast doubt on any interpretation of the origin of breccia pipes, it should not automatically disqualify an interpretation from being made. For instance, if gas blasts are acceptable as cryptovolcanic features, then a breccia pipe formed by volcanic agency need not necessarily contain igneous clasts at exposure levels; in a covered karst subsidence, absence of limestone clasts at exposure levels investigated does not preclude a karstic origin in a limestone host below those exposure levels; evaporite diapirs may have created breccia columns without the evaporite rock being preserved.

CONCLUSIONS

It is clear that several different processes can give rise to breccia filled pipes. It is also evident that several current explanations are somewhat lacking in support. Some pipes have been explained by very different mechanisms. Some pipes require peculiar combinations of events that seem unlikely. Modern ideas on rock mechanics suggest that the commonly invoked collapse into limestone caves may be in error. The role of gas is well documented in the definite volcanic breccia pipes, but the concept of purely gas eruptions seems to be more important than generally recognized. The mineralization of breccia pipes present many anomalies, incorporating problems of collapse pipes with the problems of hydrothermal mineralization within a kilometre or so of the ground surface. Breccia pipes are almost extreme examples of convergent landforms and convergent structures. In many instances we are still seeking firm criteria to determine the actual mode of formation.

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