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HYDROVOLCANIC BRECCIA PIPE STRUCTURES - GENERAL FEATURES AND GENETIC CRITERIA - I. PHREATOMAGMATIC BRECCIAS

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ABSTRACT. Two types of hydrovolcanic breccias are generally accepted: phreatomagmatic and phreatic. Due to their specific characteristics generated during the brecciation, characteristics that control the ore deposition, these breccias represent favourable hosts for mineralization. The depth of formation, the general form and dimensions, the breccia - host rock contact, as well as fragments, matrix, and open spaces altogether control the position and the size of the breccia hosted ore bodies and contribute in different degrees to the rise of the ore grades in phreatomagmatic and phreatic structures. Consequently, the recognition of the genetic type of breccia allows an appropriate strategy in mineral exploration.

Describing a breccia necessarily implies a check of its general features, such as environment/depth of formation, general form/geometry, dimensions, breccia-host rock contact, fragments, matrix, alteration, mineralization, surface connection, as well as of its additional features, namely fluidization and facies changes (see Table 2). There are several characteristics with high genetic significance among the abundant descriptive features regarding breccia structures. To point out such evidences means to find out the keys for the genetic intrepretation. A complete list of genetic criteria is proposed for phreatomagmatic breccias (see Table 3).

Key words: hydrovolcanism, phreatomagmatic breccias, descriptive breccia features, and genetic criteria.

INTRODUCTION

A great number of breccia pipe structures to which epithermal ore deposits are frequently related represent the underground/subsurface result of hydromagmatic/ hydrovolcanic activity. As a general rule, volcanologists only pay attention to the surface reflections of hydrovolcanism/hydromagmatism, granting little or no attention to the equivalent subsurface manifestations, i.e. breccia pipe genesis. Our purpose is to examine the hidden subsurface manifestations of the same hydromagmatic/hydrovolcanic processes and to discuss about hydrovolcanic breccia pipe structures (i.e. phreatomagmatic structures). In addition to this, new markers in describing phreatomagmatic breccias and several other criteria with genetic significance will be emphasised.

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Breccia structures have always attracted the interest of miners and geologists due to their high metallic potential. An accurate approach to breccias is possible only if their characteristics are known in detail. One possibility towards a better understanding of a breccia structure is to find out the genetic mechanisms of brecciation responsible for its genesis. A wide spectrum of descriptive and genetic breccia items flourished during the 20th century. Synthetic and quite necessary approaches to this subject and to breccia classification were realised during the ‘80s and the ‘90s. Among the most representative of them we may quote several contributions such as those of Sillitoe (1985), Baker et al. (1986), Laznicka (1988), Taylor and Pollard (1993), Corbett and Leach (1996), Mârza and Tămaş (1997), Tămaş (2002) (see Table 1).

A series of two articles (this one being the first of them) aims at emphasising general descriptive features and genetic criteria of the hydrovolcanic breccia pipe structures. Before penetrating into the "core" of this subject, several aspects should be clarified.

The approach to hydrovolcanism/hydromagmatism greatly benefited by the works of Sheridan and Wohletz (1981, 1983) who stated that "hydrovolcanism refers to volcanic phenomena produced by the interaction of magma or magmatic heat with an external source of water, such as a surface body or an aquifer".

Two end member styles of hydrovolcanic breccias are widely accepted: phreatomagmatic and phreatic ones (Lorenz, 1973, Nairn and Wiradiradja, 1980, Sheridan and Wohletz 1981, 1983, Sillitoe, 1985, Baker et al., 1986, McPhie et al., 1993, Cas and Wright, 1995, Corbett and Leach, 1996, etc.). For this purpose, 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 both cases the explosive phase transition of the available water supply is responsible for brecciation, and of course for pyroclastic ejecta. Specific features define phreatomagmatic and phreatic breccia structures. These characteristics occur as a result of different and particularly intimate relationships between the magma body and/or magmatic heat and the external water supply, which together contribute to the genesis of the breccia pipes.

The exploration and the mining activities on breccia pipe centred ore deposits often highly benefited by recognition of the genetic type of the breccia structure (Taylor and Pollard, 1993). For this purpose, early genetic interpretation without an accurate field study often led to misinterpretation. To merely give a breccia pipe structure a name is not our most important goal. Keeping in mind that the styles of mineralization and the spatial distribution of the ore bodies in a breccia hosted epithermal ore deposit are always controlled by the genetic type of the breccia involved entirely justify the efforts to decipher the genetic mechanism of brecciation. A list of the general features of phreatomagmatic breccias related to environment/depth of formation, general form/geometry, dimensions, breccia-host rock contact, fragments, matrix, alteration, mineralization, surface connection, is presented below, with an emphasis on peculiarities that hold high genetic significance.

Table 1

Genetic classification of breccia pipe structures, based on the genetic mechanism involved in brecciation (Tă maş, 2002).

<table>
<tr><td rowspan="4">Magmatic breccias (proto- and histero-magmatic)</td><td rowspan="3"></td><td rowspan="2">Breccias generated by the mechanical effect of intrusions</td><td>Contact breccias</td></tr>
<tr><td>Injection breccias</td></tr>
<tr><td colspan="2">Breccias generated by the magmatic fluids</td></tr>
<tr><td rowspan="2">Hydrovolcanic breccias</td><td colspan="2">Phreatomagmatic breccias</td></tr>
<tr><td rowspan="3">Post-magmatic breccias</td><td colspan="2">Phreatic breccias</td></tr>
<tr><td rowspan="2"></td><td colspan="2">Solution collapse breccias</td></tr>
<tr><td colspan="2">Tectonic breccias</td></tr>
</table>

GENERAL FEATURES OF PHREATOMAGMATIC BRECCIA PIPE STRUCTURES

Phreatomagmatic breccia pipes represent complex petrologic and metallogenetic structures. Such barren or mineralised entities could be characterised like other geological bodies, taking into account the geologic environment of formation, the external features of the breccia body considered as a whole unit (morphology, dimensions), its relationships with the host rock, and the intrinsic peculiarities regarding its components – fragments, matrix, and open spaces. In addition, other significant aspects are to be checked: surface connection, fluidization, alteration, mineralization, and facies changes. Each of the above mentioned descriptive parameters, alone or obviously combined, may more or less give the key to the understanding of a breccia pipe structure, and, furthermore, facilitates the definition of the breccia structure's affiliation to a genetic type (i.e. phreatomagmatic).

1. *Environment/Depth of formation*

Phreatomagmatic breccia pipe structures usually occur within the transition zone between sub-volcanic and volcanic levels (at least 1 km), but it is not unusual to be found at deeper levels (up to 2500 m, Lorenz, 1986). These structures are intimately related to high-level magmatic (porphyry) intrusions, their apophysis or feeder dykes (Lorenz, 1986, Corbett and Leach, 1996). Sheridan and Wohletz (1983) considered that "hydromagmatic process could even occur within deep (a few km) hydrothermal zones related to plutonic bodies." Over certain areas, towards the deeper levels of the breccias, there is a close transition between phreatomagmatic and magmatic breccias.

As shown by field evidence and confirmed by experiments (Sheridan and Wohletz, 1981, 1983, Wohletz, 1983, 1986, Kokelaar, 1986, Zimanowski et al., 1991, Kurszlaukis et al., 1998, etc.) phreatomagmatic explosive manifestations are controlled by the release of a direct interaction between a magma body and an external source of water, and, in a minor extent, by the composition of the magma involved (silicic, neutral, mafic, or ultramafic). As a consequence, phreatomagmatic breccias are related to subvolcanic and volcanic manifestations of various compositions which range from ultramafic (kimberlite pipes) (Hawthorne, 1975), and mafic (basaltic) (Lorenz, 1973, 1975, 1986, Kokelaar, 1983), to neutral and/or silicic (Wilson, 1980, Self, 1983, Sillitoe et al., 1984, etc.).

2. General form/Geometry

Phreatomagmatic breccia pipes usually breached the paleosurface and thus came to possess a surface expression and a subterraneous one as well. So far, we have only mentioned that the surface expression of a phreatomagmatic breccia pipe is called *maar*, while its underground segment (the breccia pipe body) is known as the *diatreme* (Lorenz, 1973, Baker et al., 1986).

Phreatomagmatic diatremes are characterised by their regular morphology with an inverted cone shaped - like profile. In the upper levels, towards the surface (if preserved) these structures present an accentuated funnel-like appearance with more or less flatly dipping walls. For the middle and lower levels, the walls of the breccia body become steeply dipping, often almost vertical, and the shape of the diatremes is similar to a cylinder. This is the reason why phreatomagmatic breccias are also commonly called chimneys, columns, or pipes.

Leaving our idealised representation of phreatomagmatic breccias – of which the kimberlitic ones are highly suggestive (Hawthorne, 1975, fig. 1) – aside, these breccias do not always have such a regular geometry. The dip of the breccia walls varies with the height of the structure and they often shown protuberances (Hawthorne, 1975, fig. 2) or even branching. Furthermore, the horizontal sections range from circular and/or elliptic to irregular contours.

3. Dimensions

Phreatomagmatic breccias could be considered giants in the breccia community. The sizes of diatremes can reach impressive values, both on vertical and on horizontal scales. Commonly, their height overtop 1000 m (Sillitoe, 1985), but often they have greater vertical development, up to 2500 – 3000 m (Lorenz, 1975, 1986, Sillitoe, 1985). As regards the horizontal dimensions we may state that the diameters of phreatomagmatic diatremes usually exceed several hundreds of meters (i.e. Roşia Montană , Romania, 875 x 375 m, Tă maş, 2002) but may range up to over 1 km. Among the biggest values for horizontal dimensions of phreatomagmatic breccias we may quote several extreme examples like Wau (Papua New Guinea) - 1.4 x 1.4 km (Sillitoe et al., 1984), and Montana Tunnels (Montana, USA) – 2.1 x 0.6 km (Sillitoe et al., 1985). Obviously, the most impressive one is the amazing Guinaoang breccia pipe from Philippine (Sillitoe and Angels, fide Sillitoe et al., 1985) with 8.5 x 3.5 km diameters!

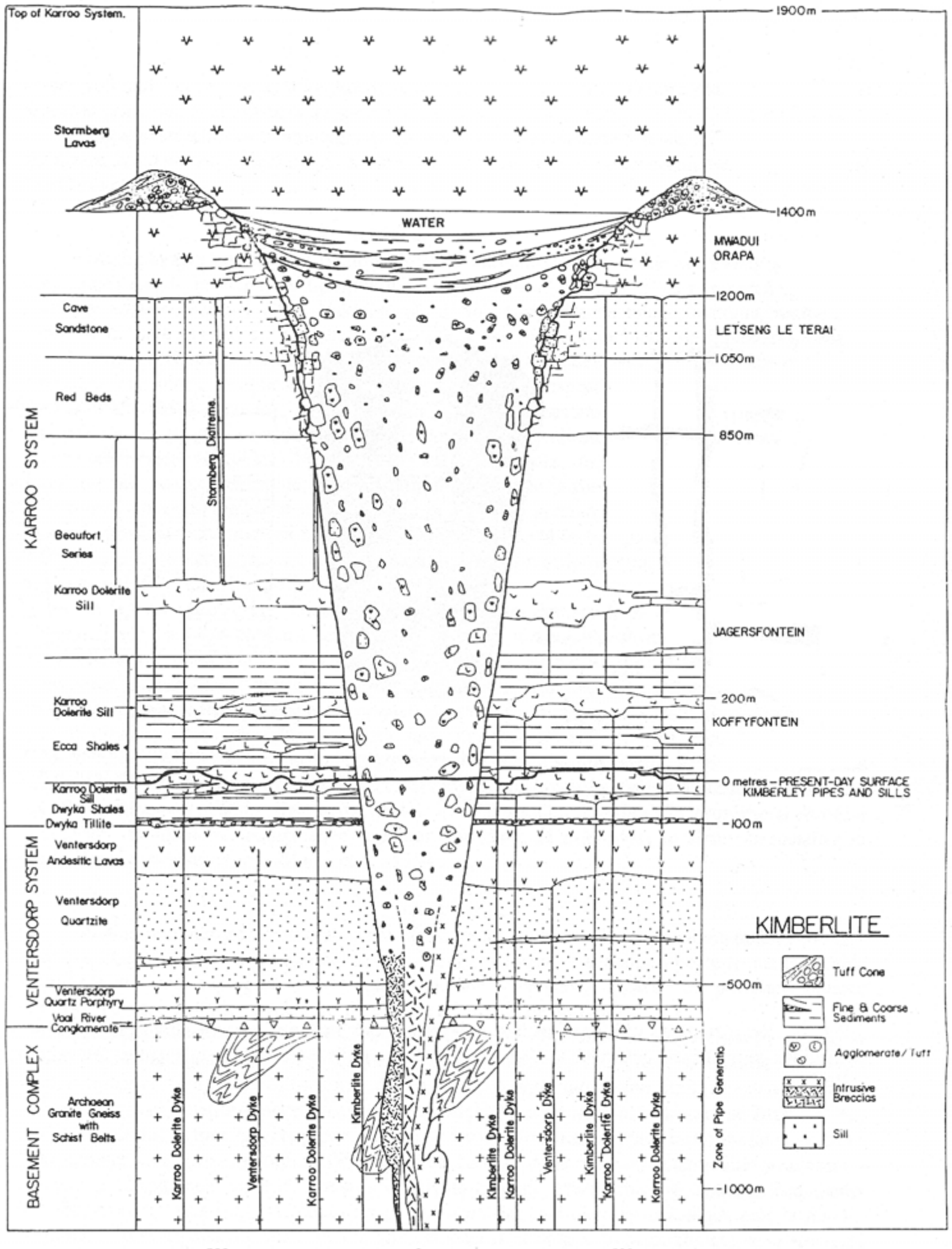

Fig. 1 – The idealised representation of a kimberlite breccia pipe (in Hawthorne, 1975).

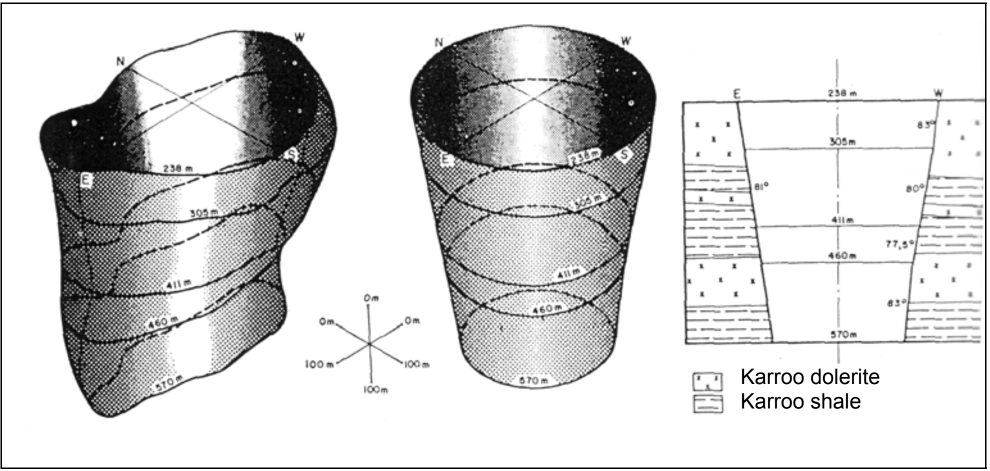

Fig. 2 – The isometric projections of Jagersfontein kimberlite pipe and its idealised equivalent (in Hawthorne, 1975).

4. Breccia – host rock contact features

The contact of phreatomagmatic breccias to their host rocks is sharp, sometimes underlined by ring faults (Sillitoe, 1985, Sillitoe et al., 1985, Baker et al., 1986). The rocks that confined a pipe could be affected in different degrees by the nearby brecciation process. Additional processes involved in brecciation and in growing up of the breccia pipe structure (i.e. fluidization, reiterated brecciation events, or injection breccias) contribute to the final intermingled relationships between the breccia body and the host rocks. The rocks which are close to the breccia contacts are often crosscut by sheeted fissure systems controlled by the ring faults adjoining the pipe, or they may have been transformed into crackle breccias. The aggressive interaction of the breccia body with the host rocks during its formation may lead to fragment generation along breccia margins. The dimensions of those new fragments range from centimetres up to several hundreds of meters diameters, and, obviously enough, after their detachment they gradually subside into the pipe towards the root zone along the breccia walls. In this case, depending on the intensity of the subsiding processes, collapsed breccia may be generated. The abundance of the rock fragments along the borders of the diatremes generates a particular breccia facies enriched in rock fragments, which is called annuli breccia. Within this marginal facies, the fragments are very abundant and exceed the matrix participation. Moreover, the rock fragments within annuli breccias are commonly more angular (due to their incipient set within the structure) than the fragments from the rest of the structure, which passed almost entirely through a fluidization process and underwent a more important processing.

Instead of the sharp contact with the host rocks that usually define a phreatomagmatic breccia, a clear outward transition from the main breccia body towards the marginal areas is obvious for the injection breccias that accompany diatremes (Corbett and Leach, 1996). Near the breccia edges there is a clear transition from fluidised and rotational breccias towards jigsaw and crackle breccias. Furthermore, a generalised system of injection breccias, which radiate outward of the main breccia body, through the adjoining rocks, could be present. Tă maș (1998) pointed out this sort of additional satellite brecciation manifestations for Cetate breccia pipe (Roșia Montană , Romania). Within the injection breccias which radiate outwards of the main Cetate breccia body towards the confined rocks, the following transition was revealed: rotational breccias → jigsaw breccias → fluidised crackle breccias → crackle breccias → unbrecciated host rock.

The downward transition zone of a phreatomagmatic breccia pipe towards the host rock genetically not involved in assessing the breccia formation or even towards the magma body responsible for its genesis is often only assumed. In the root zone of a diatreme the breccia may grade into a feeder dyke, sill or a magmatic apophysis (Lorenz, 1975, Baker et al., 1986, Corbett and Leach, 1996, etc.) or into a magmatic breccia.

5. Fragments

The clasts (rock fragments) in a phreatomagmatic breccia underwent an intense mixing. Furthermore, diatremes show heterogeneous fragment characteristics from different points of view: form, dimension, composition, alteration, direction and distance of transport.

The clasts within phreatomagmatic breccias range from angular to well rounded, but those with a more rounded shape commonly prevail (Sillitoe, 1985, Baker et al., 1986, Tă maș, 2002). The generalised rounded shape is the result of the intense working (milling and abrasion) of the fragments during breccia genesis. As a general rule, the smaller clasts are commonly well rounded and better polished, except for the juvenile fragments which could be excessively angular, while the larger fragments are usually more angular. Large spheroidal clasts displaying hypogene exfoliation and consequently well rounded shapes were also reported (Sillitoe, 1985). Well rounded clasts occur within pebble breccia dykes, which sometimes may accompany phreatomagmatic structures. Apparently unlikely association of well milled hard intrusive fragments reflecting considerable vertical transport which may occur near angular, softer, locally derived rocks were often reported.

The size of the rock fragments within a diatreme covers a great dimensional interval. Fragments up to hundreds of meters in diameter were cited by Sillitoe (1985), Sillitoe et al. (1985). The common fragment size ranges from several meters to tens of centimetres or even less. The smaller clasts (less than a few centimetres) frequently occur, mainly in the fluidised areas of the breccias where there is always a natural grading from small clasts to coarse grain size matrix (rock flour). The juvenile fragments, habitual components of phreatomagmatic breccias, are mainly angular and show blocky equant shapes.

Different rock source areas could be involved in fragment generation in the case of phreatomagmatic structures. As noted above, the juvenile fragments (shards, pumice, rimmed chill fragmented clasts with perlitic cracks, and tuffaceous components) are present. The rocks that host the breccia column as well as those from the rooted zone and below represent another important source area. All the lithologies of the rock column involved in brecciation, as well as fragments of its own extracraterial formation occur within the breccia body. Among the exotic sort of fragments we mention fluviolacustrine sediments, rich in organic material, or even carbonised wood. All the organic traces represent remnants of the lacustrine environment from the maar crater lake, which could be invaded by vegetation during the ceased intervals of the hydrovolcanic eruptions. Other specific clasts which indicate a phreatomagmatic structure are the accretionary lappilli, which can be found within diatremes as well as within extracraterial formation (base surge). These accretionary lappillis suggest an intense and widespread fluidization process.

The study of fragments composition may reveal information regarding the direction and the amplitude of the movement inside the breccia body. In many cases, fragments may show ascending and/or descending displacements of hundreds or even thousands of meters away from their source area.

6. Matrix

Phreatomagmatic breccia pipes are largely matrix supported (50 – 90 %) (Sillitoe, 1985), being thus matrix dominated (Baker et al., 1986). The matrix is a comminuted rock flour with a composition reflecting those of the rock fragments and of the host rocks at the same time. Matrix may also contain input from extracraterial formations, as well as unlithified materials (sediments) washed out from the rocks abutting the breccia pipe.

The matrix of phreatomagmatic breccia pipes is generally generated during reiterated active pulses of the breccia formation. The examination of diatremes always proved the multiple phases of matrix generation which were "frozen in" later on, as the fluidization process for each brecciation interval ceased. Located in the "heart" of hydrovolcanic manifestations, and due to the main role of fluid drainage played later by the breccia structure, the matrix is usually altered, the most common alteration mineral assemblage being clay minerals – pyrite alteration. Generally, the rock flour matrix may be massive but a layering of the matrix may sometimes be present.

The abundance of matrix within diatremes commonly determines the lack of open spaces. At the level of the whole phreatomagmatic breccia body there is an obvious diminution of matrix participation towards the breccia margins where the fragments usually prevail. The decrease of matrix participation correlated with the angular character of the rock fragments along the breccia margins induce an increased participation and development of the open spaces.

Fluidization and related processes are, in our opinion, the main mechanisms of matrix generation. This assertion was clearly validated by the field evidences (for active and fossil phreatomagmatic manifestations) as well as by experiments (McCallum, 1985).

7. Alteration

Barren or mineralised phreatomagmatic breccia pipe structures show intensive and extensive alterations of the fragments and of the matrix. Breccia columns commonly represent a main conduit of the paleofluids flow due to their increased porosity induced by brecciation. As a general rule breccia pipes are able to focus the flow of the fluids involved in alteration and mineralization. As a consequence, the alteration zonation and the pervasive character of the newly created mineral assemblages are centred on the breccia pipe body. Vertical and lateral zonality of the alteration products are extremely possible (Roșia Montană , Mârza et al., 1997).

The alteration of the breccias could be hypogene, predating the ore deposition, or it could be a later supergene process, which may overprint the primary alteration products and may also affect the primary mineralization. Epithermal (high–, and low– sulfidation) and porphyry copper ore deposits are usually hosted by phreatomagmatic breccias, and thus the accompanying alterations may selectively touch the breccia components – matrix, rock fragments – as well as the host rocks.

8. Mineralization

Epithermal systems (high–, and low– sulfidation), and in a lesser extent porphyry copper/molybdenum deposits are the most frequent types of ore deposits related to phreatomagmatic breccia pipes. These structures are mainly composed of fine-grained rock flour matrix (fluidization channel). The high degree of comminution and the abundance of clays within the fluidization channel induced low porosity and permeability constraints that inhibit the flow of mineralised fluids. In these conditions the ore bearing fluids will migrate towards the areas with greater/induced porosity along/around the marginal sectors of these breccias (Baker et al., 1986) (fig. 3).

Different areas of mineralization related to phreatomagmatic breccias are to be emphasised within and outside of the breccia body. Within breccia structure the mineralization may occur as replacement of the fragments and/or the matrix. Probably the most common style is the impregnation within breccia matrix, but it represents a low-grade ore. More important metal concentrations occur as infillings of the vugs within rude matrix, and especially in the open spaces among rock fragments. In this case, adjacent to breccia pipe margin and conspicuously towards the upper levels, high-grade mineralization occurs (fig. 3), which may form an ore ring related to the collapse breccias (annuli breccia) rich in open spaces. Outside of the main breccia pipe body the mineralization consists of replacements in extracraterial formations where mineralising fluids were entrapped beneath impermeable layers. The host rock – breccia contact is also of major interest for the ore concentration. The enrichment along breccia contacts could be related to ring fault structures that bound the pipe and usually indicate a multiphase brecciation history. Around the breccia body, steeply dipping veins hosted by the sheeted fissure systems induced by brecciation, or flatly dipping veins induced by the subsidence of the host rock into the diatreme may both occur. The intersection zone between overprinting veins and breccia body usually holds important ore shoots. Higher ore grades of this type could be hosted by the breccia body, but the veins also commonly show an important enrichment (see fig. 4). Briefly, we may note, in agreement with Sillitoe (1985), that the concentration of the richest ore bodies towards the marginal zones of the diatremes, along the breccia contacts, characterises the phreatomagmatic breccias. Furthermore, the upper levels of these structures are particularly high-grade ore zones.

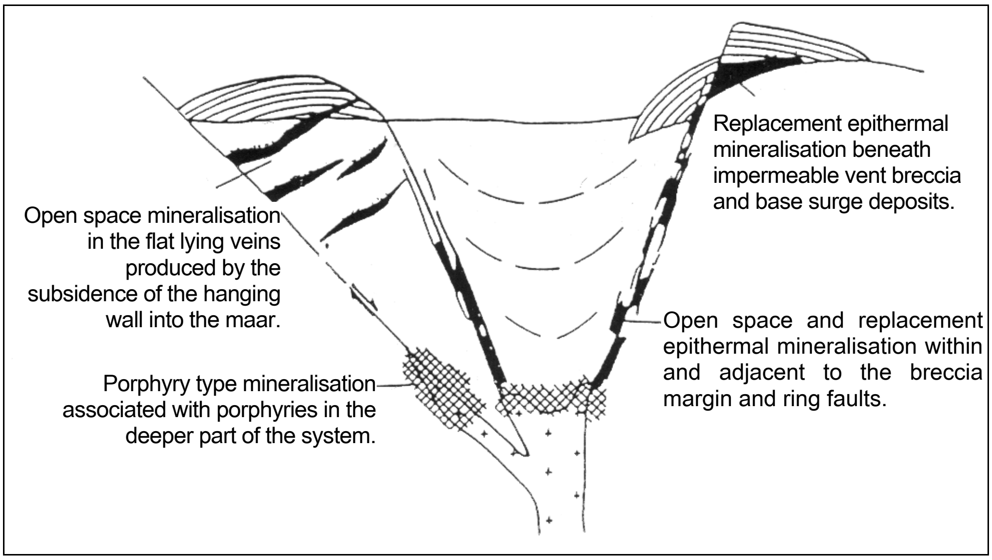

Fig. 3 – The ore control induced by phreatomagmatic breccia pipe structures (in Baker et al., 1986).

Brecciation – ore deposition age relationships are to be stressed. Pre-, sin-, and post- brecciation mineralization may occur. The ore may be represented by ore clasts, for instance in the case of a prebrecciation mineralization event. Impregnations, infillings of the open spaces, and replacement of the matrix and/or rock fragments characterised sin-, and post-brecciation mineralised systems. Late overprinting events may be present, increasing the general ore grade of the breccia system. This is the case of late vein type mineralization that overprint the breccias at Cripple Creek (Thompson et al., 1985), or the vein swarms that cut the fluidisation channel of Cetate breccia pipe (Roșia Montană , Tă maș, 2002). The phreatomagmatic activity may be prolonged by phreatic eruptions (phreatic breccias), which could rework the diatreme edifice and may also induce an additional input of metals. This case is peculiar for Roșia Montană precious metal diatreme hosted ore deposits, with pipe-like narrow phreatic chimney within the main Cetate phreatomagmatic breccia pipe body (Tă maș, 2002). Last but not least, supergene enrichment could be also important in some cases.

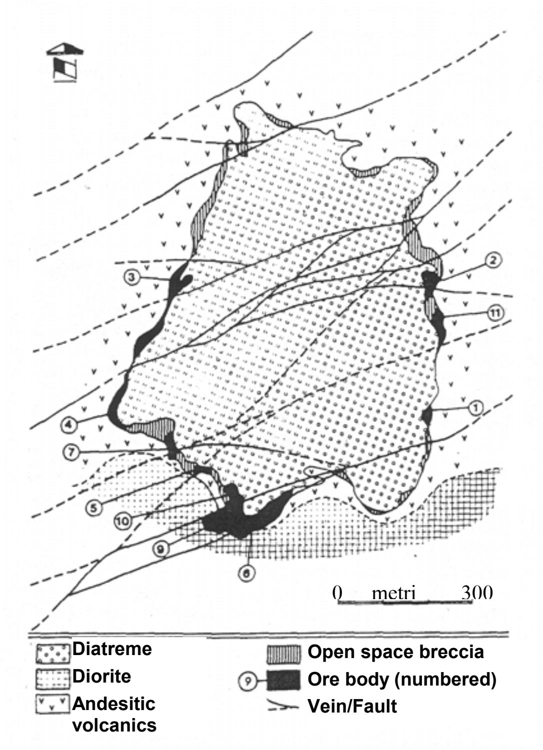

Fig. 4 – Ore bodies located towards breccia margins and selectively in the enrichment zones of the veins that crosscut Acupan breccia body, Philippine (in Damasco and de Guzman, 1977, fide Berger and Morrison, 1990).

Placer deposits could be considered as indirectly related to breccia mineralization; they represent ubiquitous traces of primary precious metal ore deposits (i.e. breccia hosted). In some cases even the primary ore deposits hosted by breccias were identified by panning their spatially and genetically related alluvial gold and placers (i. e. Kelian, Hedenquist et al., 1996).

9. Surface connection/extracraterial formation

Phreatomagmatic breccias that breached the paleosurface always induced multiple changes of the paleorelief and of the surface geology, due as well to the associated pyroclastic formation. These formations include several genetic and spatial units (McPhie et al., 1993): pyroclastic flows, pyroclastic surge deposits (commonly called base surge deposits), and, of course, pyroclastic fall deposits. Close to the vent, two separate types of pyroclastic deposits were identified: tuff cone, and tuff ring (Heiken, 1971). A tuff ring is a low-lying circular vent with a low topographic profile (height – width ratio 1:10 – 1:30) and gentle external slopes constructed from "dry" ash. As opposed to this, a tuff ring is a low-lying circular vent with a high topographic profile (height – width ratio 1:9 – 1:11) and steep external slopes constructed from "wet" cohesive ash.

Phreatomagmatic derived extracraterial products are composed of well stratified tuff beds interbedded with massive breccias. These pyroclast sequences may contain juvenile fragments (poorly vesicular, angular or pumiceous scoriaceous pyroclasts, and bubble wall shards), accretionary lappilli, and often show bomb sag structures (McPhie et al., 1993). The fine-grained tuff beds characteristically contain accretionary lappilli and posses low angle dune form cross bedding. Close to the pipe (vent) pyroclast beds dip inwards, but further out they dip gently away from the vent. Where the surface pyroclast formations have been deposited under water, they lack bedding, accretionary lappilli, dune form cross bedding and bomb sag craters. The pyroclast formations that accompany phreatomagmatic explosions are well developed and may cover several km^2 around the vent, up to 10 – 15 km away from the venting area.

Prospecting phreatomagmatic breccias in the field often reveal the similarity of the breccias in the pipe with those expelled from the vent (surge deposits). Both of them are composed of the same matrix that cemented similar rock fragments, which show the same composition, shape, and dimension. Intra– and extra– pipe breccias could be differentiated taking into consideration the discordant or the concordant character of the respective breccia structure.

10. Additional features

10.1. Fluidization

Genesis of phreatomagmatic breccias is directly related to a magma body (intrusion, apophysis, and dyke) which together with a water source contribute to the initiating of the explosive phreatomagmatic activity and brecciation. Taking into account these intrinsic aspects of phreatomagmatic breccia genesis frequently has been found that there is a transition from a phreatomagmatic breccia towards a magmatic breccia or towards a xenoliths enriched magmatic rock. On the other hand, the ubiquitous presence of water during phreatomagmatic events certifies that the fluidization process is highly involved. There is no doubt that the initial magma – water interaction started the explosive and brecciation activity, but the fluidization is responsible for most of the finishing touches of those structures. We may also enumerate several peculiarities induced by fluidization, leaving apart its role in the spatial development of the pipe: pebble breccia dykes, matrix dykes, accretionary lappilli, fragment mixing, rock flour matrix, etc.

10.2 Facies changes

Important facies changes occur within a phreatomagmatic breccia pipe. Variations concerning rock fragments (shape, size, composition, and spatial distribution), matrix (composition, dimension, structure, and participation), open spaces (frequency, dimensions), and interrlationships among the above cited items are always present. Consequently, various types of descriptive breccias and facies transition are common (Fig. 5).

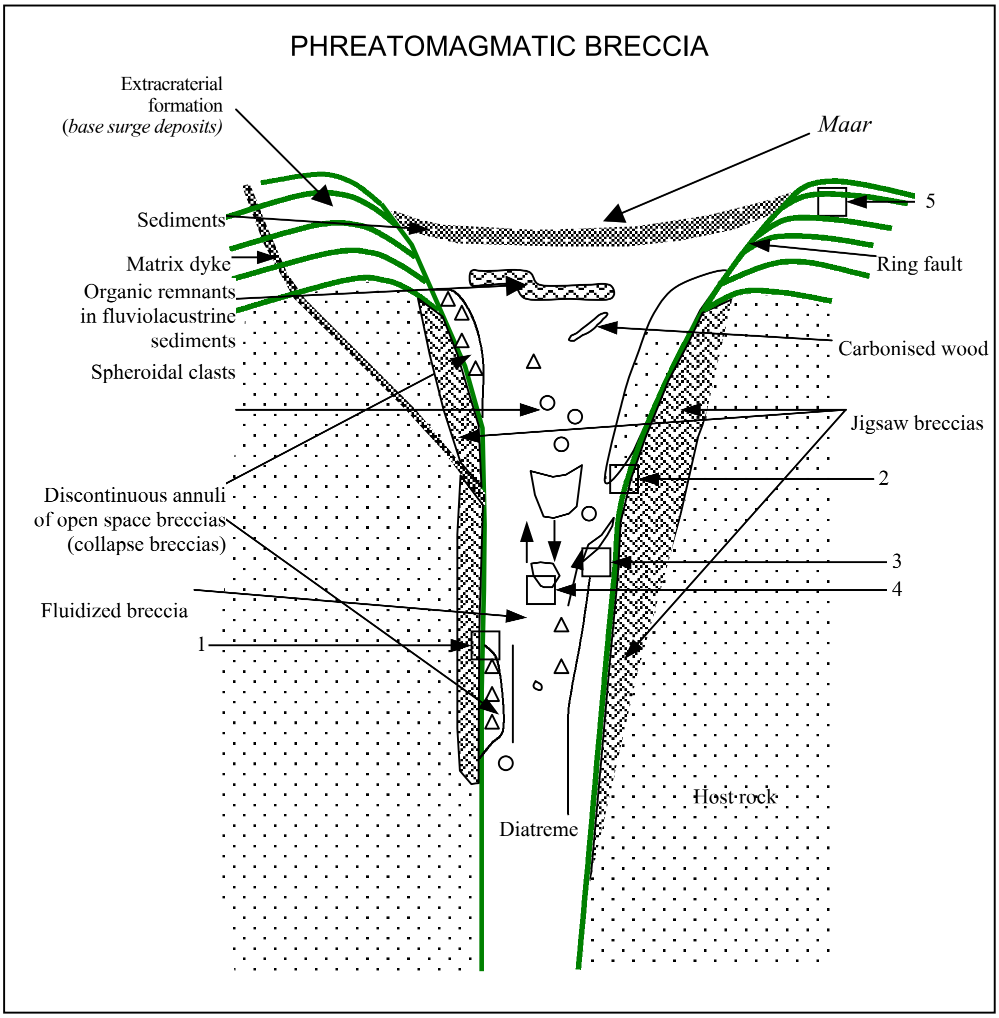

Fig. 5 – Idealised representation of a phreatomagmatic breccia pipe structure. Different types of breccias and theirs area of distribution are noted (in Tămaș, 2002).

Towards the marginal area of diatremes a coarser facies occurs. The fragments are bigger and more angular, while the matrix is less important quantitatively. The open spaces, often filled with ore and gangue minerals, are widespread. Discontinuous annuli of open space breccia adjoin diatremes. In this marginal zone of the diatremes clast supported and open spaces breccias prevail, as well as normal transitions towards mosaic or jigsaw breccias, shingle breccias, and crackle breccias. Along the walls (marginal rim) of the breccia column the descending movement of the rock fragments is more obvious (collapse breccias). Furthermore, large rock fragments of tens to hundreds of metres diameter often occur along breccia walls. These blocks were detached, either from surface pyroclastic formations, either from the walls of the breccia pipe, and they gradually sank towards the root zone. On the contrary, the central zone of a phreatomagmatic pipe mainly consists of matrix with minor clasts only. The clasts from this zone are more rounded, but their size has considerably diminished. The rock fragments prove a longer term processing within the pipe because they were brought about into the fluidization cell (McCallum, 1985). The fluidization channel is usually located on the axial part of the pipe, but there are also field evidences that suggest that it could be also eccentrically situated (Roşia Montană , Romania, Tă maş, 2002). For the central zone of a phreatomagmatic diatreme matrix supported facies with mill breccias are most present. The movement in this area is mixed: the flux of matrix with the smaller clasts is pushed up and it ascends, while the bigger fragments, accidentally fallen into the fluidization channel, are moving down especially during the periods of relaxation of the fluidization process.

Facies changes are occurring not only at horizontal scale, but also on the vertical. The vertical variations were stressed by Baker et al. (1986), who identified two main levels of interest, as follows: middle to lower vent, and the upper vent. Summarising Baker's statements, we may note that the upper vent is characterised by the extreme mixing of the rock fragments with various origins. Fragments from deep seated levels (hundreds to thousands metres depth) may be found together with fragments from pyroclastic sequences or with remnants of organic components which one time were abundant within the maar. The middle to lower vent is represented by a chaotic mélange of matrix (rock flour) and rock fragments. The horizontal variations above mentioned are still present, with fragment concentration along the walls of the pipe. Towards the deepest level (root zone) the fluidization gives all the main characters of the breccia body and the dimensions of the breccia body gradually decrease.

Tă maş (1997, and 2002) analysed the above mentioned vertical and lateral changes, as well as additional facies variation, also providing several graphic representations of different types of breccias and of their area of occurrence within a phreatomagmatic breccia pipe body (fig. 5 and 6).

Injection breccia dykes (hydraulic breccias) may be present around the pipes. These structures usually radiate outward of the main breccia body into the host rock. Dyke-like bodies, composed of fluidised breccia matrix (tuffisite) sometimes with abundant small-sized well rounded clasts (the so-called pebble breccia dykes) are also present.

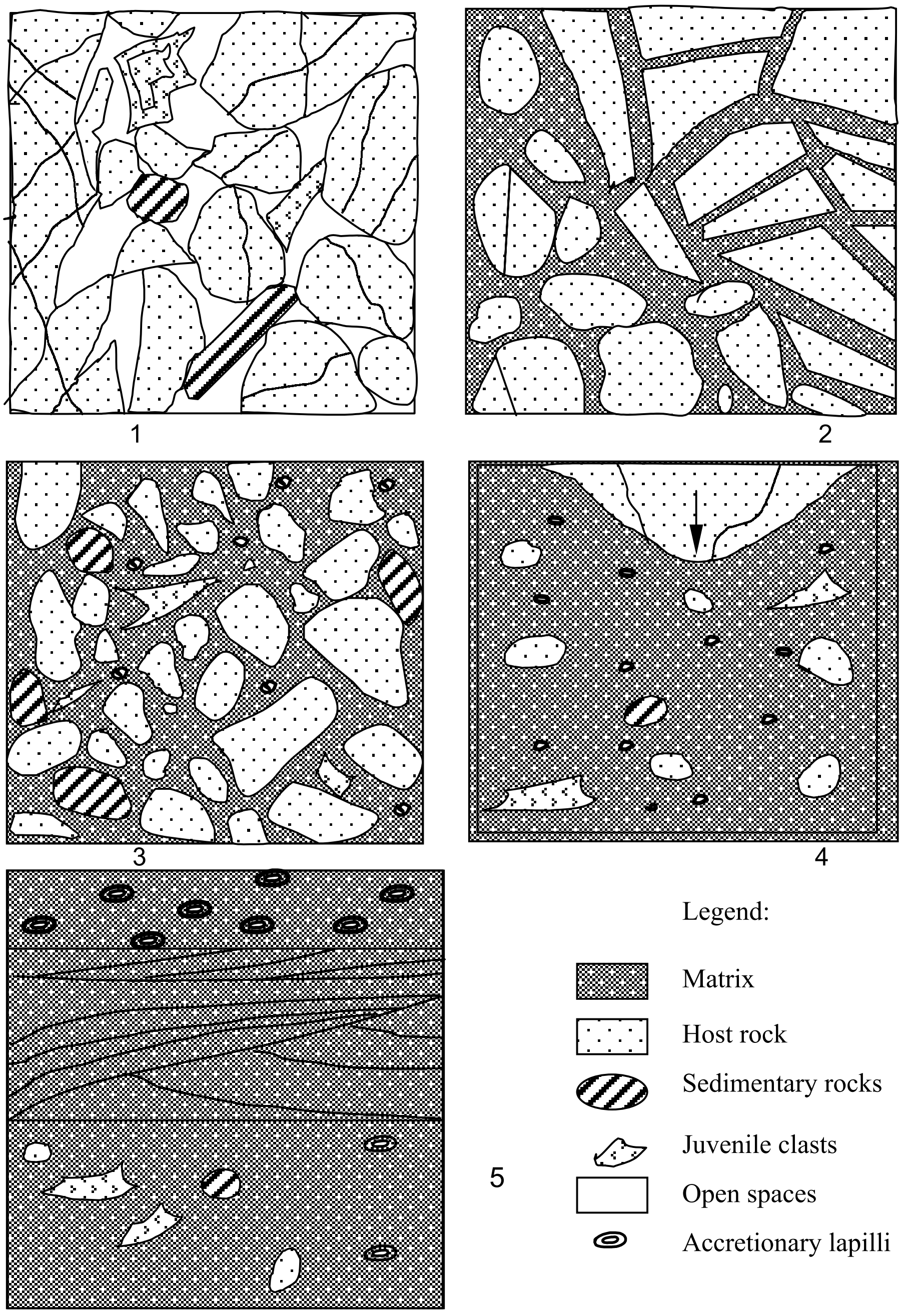

Fig. 6 (1-5) - A series of sketches showing several "insights" into the breccia body and also some genetic criteria (1-open space breccias and crackle breccias; 2-jigsaw breccias and rotational breccias; 3-coarse breccia fragment dominated; 4-large matrix supported breccias; 5-base surge deposits) (in Tămaș, 2002).

GENETIC CRITERIA

The abundance of descriptive features usually hinders the exploration of breccia structures. A list of the general features of phreatomagmatic breccias is given (Table 2), in order to emphasise the multitude of the aspects involved.

Table 2

General features of phreatomagmatic breccia pipes

Items	**Description**
Environment/Depth of formation	**In relation to high level magmatic (porphyry) intrusion**; volcanic/subvolcanic (at least 1 km in depth). In certain places there is a **close relationships between phreatomagmatic and magmatic breccias.**
General form/Geometry	Inverted cone, mostly circular, becoming cylindrical at depth; **maar**, **diatreme**
Dimensions	**Horizontal dimensions**: hundreds of metres to over 1 km in diameter; usually **1000 – 3000 m.** **Vertical dimensions**: up to 3000 m; usually greater than **1500 m.**
Breccia – host rock contact features	The contacts are generally abrupt and defined by **ring faults.** The wall rocks abutting the ring faults are shattered and in some cases brecciated (crackle breccias). **Margins often contain large fractured blocks of host rocks as collapse breccias.** Injection breccias with distinct outward facies changes may be present.
Fragments	Fragments mixed. <u>Shape</u>: - sub-angular to rounded, generally **more rounded (pebble dykes)**; - smaller clasts are commonly rounded and better polished; - large spheroidal clasts displaying hypogene exfoliation may be present; **- very large rock fragments** (tens to hundreds of metres in diameter). Fragments within the pipe usually indicate a long distance transport. <u>Composition</u>: **- juvenile fragments present** (shards, pumice, rimmed chill fragments with perlitic cracks, tuffaceous component); **- fragments from tuff ring**; **- fluviolacustrine sediments** rich in organic remnants; **- carbonised wood.** Well milled hard intrusive fragments reflecting considerable vertical transport may occur near angular, softer, locally derived rocks. <u>Alteration</u>: usually present.
Matrix	**- largely matrix supported (50 – 90 %) – matrix dominated**; - rock flour ± tuffaceous component; - matrix generally displays **clay mineral – pyrite alteration**; **- commonly lack of open spaces**; **- matrix participation decrease towards the marginal part of the pipe**; - layering of the matrix may be present.
Alteration	- ubiquitous; - lateral and vertical zonation of the alteration assemblages; - alteration may affect matrix, rock fragments and host rocks.

Items	**Description**
Mineralization	**- impregnations, vugs infilling, replacement**; - replacement of the fragments and the matrix in the upper levels; - mineralization in breccia matrix, **within and adjacent to the breccia margin and the ring faults**; - vugs infilling within the matrix and among breccia fragments; - overprinting veins and phreatic brecciations.
Surface connection	**Tuff ring/Tuff cone, Surge deposits** **- juvenile fragments present** (poorly vesicular, angular or pumiceous scoriaceous pyroclasts, and bubble wall shards); **- well stratified tuff beds interbedded with massive breccias**; **- bomb sag structures**; - the fine-grained tuff beds characteristically contain **accretionary lappilli** and posses **low angle dune form cross bedding**; - thick, well indurate, near vent deposits (tuff cone); - beds – generally thick, with indistinct stratification (tuff cone); **- close to the pipe beds dip inward but further out they dip gently away from the vent**; **Tuff rings/tuff cones deposited under water** are characterised by tuff breccias, which lack bedding, accretionary lappilli, dune form cross bedding and bomb sag crater. **Development** – several km away from the vent (up to 10 – 15 km).
Fluidization	**Very important.**
Facies changes	Outward and downward facies changes. Coarser breccias typically occur along the marginal parts of the diatreme. Discontinuous annuli of open space breccia adjoin diatremes (collapse breccias). Matrix participation and degree of fragment rounding decrease towards the margins of the pipe. Large blocks, up to several hundred metres, detached from the walls, usually occur along the marginal parts of the breccias. In the middle to lower vent often a coarse layering is present with a discrete grading. The presence of dyke-like bodies of fluidised breccia matrix (tuffisite) sometimes with abundant small-sized well rounded clasts – pebble dykes. Commonly the bottoms of the pipe pass downward into the intrusive body, which is responsible for brecciation. The central zone of the breccia is commonly characterised by better sorted, smaller, more rounded fragments as opposite to the larger, more crowded, less rounded fragments typically found in the outer zone (annular) breccias.

During early stages of breccia exploration it is impossible to check all the earlier mentioned characteristics. Including a breccia pipe structure in a certain genetic mechanism does not necessarily mean taking into account an exhaustive list of the peculiarities. Our attention was focused on delineating several genetic criteria that give striking evidence about the genesis of a breccia body. More than once, one of those key features of undoubted genetic significance have allowed us to infer the brecciation mechanism. After discovering such a "first signal", additional criteria are then more easily revealed to an already prepared "eye". Consequently, it is always important to find these key genetic criteria in the field, because afterwards they allow an accurate genetic interpretation.

A synthetic list of descriptive features with high genetic significance is highlighted in Table 3. Early recognition of these genetic characteristics in the field will facilitate an accurate recognition of breccias from a genetic point of view and, of course, an appropriate mineral exploration.

CONCLUSIONS

Hydrovolcanism covers a large spectrum of explosive manifestations. Among them, phreatomagmatic and phreatic explosions are very good examples, due to their particular characteristics regarding genesis, surface and underground products (surge deposits and breccia pipes). Our purpose was to reveal descriptive and genetic features of phreatomagmatic breccias.

Phreatomagmatic breccias always show specific descriptive features. An exhaustive list of descriptive peculiarities was also provided. Our approach was focused on the following criteria: environment/depth of formation, general form/geometry, dimensions, breccia – host rock contact features, fragment characteristics, matrix, alteration, mineralization, surface connection, fluidization, facies changes. Furthermore, specific genetic criteria were underlined in order to allow an accurate genetic interpretation of breccias. Several specific criteria with genetic significance for phreatomagmatic breccia pipes were suggestively presented in a series of idealised representations (fig. 5 and 6). Summarising, the main genetic criteria are stressed in Table 3.

Table 3

Genetic criteria for phreatomagmatic breccia pipes.

Items	**Description**
Environment/Depth of formation	Single or multiple columnar structures related to porphyry intrusions. Volcanic to sub-volcanic level of formation; maar and diatreme.
General form/Geometry	Funnel-like bodies in the upper levels and pipe-like (cylindrical) towards the middle and lower levels. Horizontal cross-section ranges from circular to elliptic; branching of the structures towards the surface is not uncommon.
Dimensions	Horizontal: hundreds to thousands of metres, but usually around 1000-2000 m. Vertical: well developed, usually greater than 1500 m, up to 3 km.
Breccia – host rock contact features	Sharp contacts, well defined, frequently delineated by ring fractures. Annuli breccias (collapse breccias) around the margins of the diatremes. Host rocks are usually shattered and brecciated (crackle breccias).

Items	**Description**
Fragment characteristics	Juvenile clasts and accretionary lappilli; Rounded and sub-rounded fragments prevail, but angular and sub-angular clasts may also occur. Clasts dimensions range from metres to tens of metres (sometimes bigger – over 100m), to cm and dm. There is an obvious concentration of bigger fragments along the marginal area of the diatremes.
Matrix	Matrix dominated (50 – 90 %); specific matrix supported breccias.
Alteration	Phillic, potassium silicate, argillic, silicification.
Mineralization	- high grade ore bodies; - widespread within the breccia body, especially along the contacts; - infillings of the open spaces, impregnation, replacements; - overprinting veins and phreatic breccias.
Surface connection	- surface clues: surge deposits, maar, tuff ring, tuff cone; - juvenile clasts, accretionary lappilli, bomb sag structures.
Fluidization	Very important (fluidization cell)
Facies changes	- vertical and lateral zonality; - upper levels: collapse breccias, ring faults; - middle to lower levels: mill breccias with prevailing peculiarities induced by fluidization.

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REFERENCES

Baker, E.M., Kirwin, D.J., Taylor, R.G. (1986) - Hydrothermal breccia pipes. E.G.R.U. Contribution 12, James Cook University of North Queensland, Australia, 45 p.

Berger, B.R., Morrison, G.W. (1990) - Gold bearing breccias: characteristics, genesis and exploration. Course manual, 22nd-23rd March, C.C.E, Univ. Southampton, 74 p.

Cas, R.A.F., Wright, J.W. (1995) - Volcanic successions - modern and ancient. A geological approach to processes, products and successions. University Press, Cambridge, Great Britain, p. 528 p.

Corbett, G.J., Leach, T.M. (1996) - Southwest Pacific Rim gold - copper systems: structure, alteration and mineralization. Workshop manual, 185 p.

Hawthorne, J.B. (1975) – Model of a kimberlite pipe. Phys. Chem. of the Earth, v. 9, p. 1-16

Hedenquist, J.W., Izawa, E., Arribas, A., White, N.C. (1996) – Epithermal gold deposits: Styles, characteristics and exploration. Soc. Resource Geology, Special Publication 1, 16 p., Japan.

Heiken, G.H. (1971) - Tuff rings: examples from the Fort Rock-Christmas Lake Valley Basin, south - central Oregon. Journ. Geophys. Res., v. 76, no. 23, p. 5615-5626

Kokelaar, B.P. (1983) - The mechanism of Surtseyan volcanism. J. Geol. Soc. London, v. 180, p. 939-944

Kokelaar, P. (1986) - Magma - water interactions in subaqueous and emergent basaltic volcanism. Bull. Volcanol., v. 48, p. 275-289

Kurszlaukis, S., Buttner, R., Zimanowski, B., Lorenz, V. (1998) - On the first experimental phreatomagmatic explosion of a kimberlite melt. Journ. Volcanol. Geotherm. Res., v. 80, p. 323-326

Laznicka, P. (1988) - Breccias and coarse fragmentites: petrology, environments, associations, ores. Elsevier, Amsterdam, 832 p.

Lorenz, V. (1973) - On the formation of maars. Bull. Volcanol., v. 37, no. 2, p. 183-204

Lorenz, V. (1975) - Formation of phreatomagmatic maar-diatreme volcanoes and its relevance to kimberlite diatremes. In Ahrens, L.H., Dawson, J.B., Duncan, A.R., Erlank, A.J. (eds.) - Physics and Chemistry of the Earth, v. 9, p. 17-27

Lorenz, V. (1986) – On the growth of maars and diatremes and its relevance to the formation of tuff rings. Bull. Volcanol., v. 48, p. 265-274

Mârza, I., Tă maş, C.G. (1997) - Structuri de brecii mineralizate. Studia Univ. "Babeş-Bolyai", Geol, XLII, 1, p. 49-79

McCallum, M.E. (1985) – Experimental evidence for fluidization processes in breccia pipe formation. Econ. Geol., v; 80, p. 1523-1543

McPhie, J., Doyle, M., Allen, R. (1993) - Volcanic textures. A guide to the interpretation of textures in volcanic rocks. Centre for ore deposits and Exploration studies, University of Tasmania, 189 p.

Nairn, I.A., Wiradiradja, Solia (1980) - Late Quaternary hydrothermal explosion breccias at Kawerau geothermal field, New Zealand. Bull. Volcanol., v. 43, 1-14

Self, S. (1983) – Large scale phreatomagmatic silicic volcanism: a case study from New Zealand. Journ. Volcanol. Geoth. Res., v. 17, p. 433-469

Sheridan, M.F., Wohletz, K.H. (1981) - Hydrovolcanic explosions: the systematics of water - pyroclast equilibration. Science, v. 212, 1387-1389

Sheridan, M.F., Wohletz, K.H. (1983) - Hydrovolcanism: basic consideration and review. Journ. Volcanol. Geotherm. Res., v. 17, 1-29

Sillitoe, R.H. (1985) - Ore-related breccias in vulcanoplutonic arcs. Econ. Geol., v. 80, p. 1467-1515

Sillitoe, R.H., Baker, E.M., Brook, W.A. (1984) - Gold deposits and hydrothermal eruption breccias associated with a maar volcano at Wau, Papua New Guinea. Econ. Geol., v. 79, p. 638-655

Sillitoe, R.H., Grauberger, G.L., Elliot, J.E. (1985) – A diatreme-hosted gold deposit at Montana Tunnels, Montana. Econ. Geol., v. 80, p. 1707 - 1721

Taylor, R.G., Pollard, P.J. (1993) - Mineralized breccia systems. Method of recognition and interpretation. E.G.R.U. Contribution 46, James Cook Univ., North Queensland, Australia, 31 p.

Tă maș, C. G. (1997) – Advances in ore deposits study – breccia pipe structures, fluid inclusions and microprobe analyses. Rapport DR/MGG/NT97/021, B.R.G.M., Orléans, 35 p.

Tă maș, C. G. (1999) – Structuri *breccia pipe* – mecanisme genetice, tipologie și importanț a economică . Ref. doctorat (unpubl.), Univ. Babeș-Bolyai, Cluj-Napoca, 118 p.

Tă maș, C.G. (2002) – Structuri de “breccia pipeî asociate unor ză că minte hidrotermale din România. Univ. Babeș-Bolyai, Cluj-Napoca, (unpubl. PhD thesis), 336p.

Thompson, T.B., Trippel, A.D., Dwelley, P.C. (1985) – Mineralized veins and breccias of the Cripple Creek District, Colorado. Econ. Geol., v. 80, p. 1669-1688

Wilson, L. (1980) – Relationships between pressure, volatile content and ejecta velocity in three types of volcanic explosion. Journ. Volcanol. Geoth. Res., v. 8, p. 297 - 313

Wohletz, K.H. (1983) - Mechanisms of hydrovolcanic pyroclast formation: grain-size, scanning electron microscopy, and experimental studies. Jour. Volcanol. Geotherm. Res., v. 17, p. 31-63

Wohletz, K.H. (1986) - Explosive magma-water interactions: thermodynamics, explosion mechanisms, and field studies. Bull. Volcanol. v. 48, p. 245-264

Zimanowski, B., Fröhlich, G., Lorenz, V. (1991) - Quantitative experiments on phreatomagmatic explosions. Journ. Volcanol. Geotherm. Res., v. 48, p. 341-358