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ORE-RELATED BRECCIAS: A REVISED GENETIC CLASSIFICATION, WITH PARTICULAR REFERENCE TO EPITHERMAL DEPOSITS

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Abstract

The processes causing brecciation in epithermal and mesothermal metallic deposits can be intimately related to mineralisation. It is therefore necessary to establish both a genetic and descriptive classification for breccias in this setting. This paper proposes a revision of the genetically-based classification erected by Sillitoe (1985). The most significant innovation is to distinguish between breccias formed by steady-state hydrothermal processes, and those formed by transient disturbances of a hydrothermal system, caused by renewed magmatism. This latter process can be particularly important in mineralisation.

Introduction

The close association between brecciated host rocks and epigenetic precious and base-metal mineralisation in volcanic regions has long been recognised. A frequent tacit assumption has been that the principal significance of brecciation is pre-mineralisation preparation of the host rock, by providing permeable channels for mineralising fluids and a large surface area for fluid-rock interaction (*eg* Huspeni *et al.*; 1984). However, it has become increasingly apparent that the processes causing brecciation are themselves intimately related to mineral deposition. In particular, hydraulic fracturing and associated boiling due to pressure release are a potent means of precious metal deposition. The first objective of this paper is to highlight the importance of these breccia-forming processes. The classification and nomenclature used in this paper are based *closely* on that of Sillitoe (1985). A second objective of this paper is to propose a refinement of Sillitoe's genetic nomenclature, to distinguish between breccias formed by steady-state hydrothermal processes, and those formed by transient disturbances of hydrothermal systems by renewed magmatism.

The subject of breccia description, genesis, classification and nomenclature has been discussed by Laznicka (1988), Baker *et al.* (1986), and Konstantinov (1978). The present paper is principally concerned with the genetic classification of breccias. It is acknowledged that distinction between some of the genetic types of breccias may be difficult in the field at the outcrop scale. A detailed classification of this nature is nevertheless considered to be of value, since it can be used to predict the probable morphology and extent of ore bodies by taking into account their genesis. Criteria for descriptive nomenclature of breccias are outside the scope of this paper and are not discussed in detail: reference should be made to Laznicka *(ibid).*

The discussion concentrates on the various types of "hydrothermal breccias", especially the magmatic-phreatic breccias, since this is where new terminology is proposed. The various "magmatic breccias" are discussed in less detail, since these were thoroughly covered by Sillitoe, and Laznicka *(ibid)*, and no new material has been added to those descriptions. Breccias formed by sedimentary processes, and those in metamorphic terranes, are referred to only briefly, to show how they relate to the proposed genetic classification.

Genetic Classification of Breccias

Seven types of breccia which can occur in epithermal-mesothermal mineral deposits are proposed. Some are divided into sub-types depending on whether they occur on the Earth's surface or subsurface. The types and their genetic relationships are summarised in Table 1 and Figure 1. Correlation with the terminology of other authors is shown in Table 2. The various types of breccia are described below in approximately the order of their Occurrence in the geological cycle: *ie.* the earliest-formed types are described first. This is also more or less in order of decreasing temperature of the mobile phase. The intimate association between certain types of brecciation and mineralisation means that correct recognition of the genesis of breccias in ore deposits is crucial when applying geological reasoning to exploration strategy. Hence the significance of each type of breccia in a typical precious-metal exploration programme in a volcanic terrane is briefly explained. Examples of each type with which economic mineralisation can be associated are given in Table 3.

1. Intrusive Breccias

These are subdivided into three end members, to illustrate the different processes operating in this environment, but a continuum of intergradations between the end members exists.

1a Magmatic-Intrusive Breccias. These are included in the "intrusion breccias" of Sillitoe (1985). They are created during the emplacement of an intrusive body. They consist of clasts comprising xenoliths of country rock, perhaps including previous intrusives, and any fragments of early-crystallised portions of the intrusive disrupted during emplacement, in a matrix of crystalline igneous material. Such breccias frequently occur on the margins of intrusive bodies and typically contain clasts of country rock in a crystalline igneous matrix. They are easily distinguishable from phreatic or magmatic-phreatic breccias by microscopic examination, because of the matrix of crystalline igneous minerals, but may be difficult to distinguish in hand specimen. Because of their high temperature of emplacement, they may show reaction rims around xenoliths.

Mineralisation in such breccias is of direct magmatic origin, with perhaps some modification by reaction with host rocks. A major precious-metal deposit in this setting is unlikely, without some secondary concentration process such as eluvial or alluvial action. In terms of exploration, the ore-hosting breccia can be expected to be closely spatially related to the margins of an intrusive, and these areas should be investigated.

1b. Magmatic-Hydrothermal Breccias. These are equivalent to the "magmatic-hydrothermal breccias" of Sillitoe (1985), or "carapace breccias" (Laznicka; 1988). As an intrusive body cools, the residual melt becomes increasingly concentrated in volatile components, including water. This may exsolve as a separate volatile phase, in a process known as refrograde boiling (Phillips; 1973). Such a hydrous phase is very mobde, because of its high temperature, and, if emplaced at any significant depth, is at lithostatic rather than hydrostatic pressure. It may also be highly mineralised. This solution therefore has a considerable potential for hydraulic fracturing of overlying formations forming breccia pipes and related mineral deposits.

The essential difference between magmatic-hydrothermal breccias and phreatic breccias (as defined below) is that although both have aqueous fluids as the mobile phase, in magmatic-hydrothermal breccias brecciation is initiated by the release of mainly juvenile magmatic volatiles (though these may ultimately have been derived from the partial melting of crustal rocks). The proximal parts of these breccias are formed at a much higher temperature than phreatic fluids, frequently super-critical. They usually contain some evidence of high-temperature, high salinity and volatile content fluids for example minerals such as tourmaline, and fluid inclusions with high homogenisation temperatures (often >400°C), and high salinities (10-25 wt % NaCl). Other identifying features of this type of breccia include a general
pseudomorphs. Breccias of this type may grade downwards into magmatic intrusive breccias with a crystalline matrix, or pegmatites. Their cooler distal sections may grade into phreatic breccias.

Magmatic-hydrothermal breccias are very important in the formation of many porphyry-copper (and molybdenum) deposits. Mineralisation in this case can be expected to occur in a sub-vertical *body* which may be of considerable vertical extent. Lateral zonation of alteration mineralogy around the mineralised zones may be sufficiently distinctive to be useful as a guide to ore. There may be some vertical zonation, but if the level where magmatic-hydrothermal breccias occur within the mineralising system has already been exposed by erosion, gold grades will probably not improve greatly with depth. Any higher-level segment which may have been preserved by down-faulting could be more prospective. The ore-hosting breccia will be spatially related to an intrusive, but may extend some distance away from it.

1c. Magmatic-Tectonic Breccias. These are included within the "intrusion breccias" of Sillitoe (1985). As an intrusive is forcefully emplaced, especially if it is viscous or substantially crystalline, it may cause fracturing of the surrounding formation during emplacement, giving a magmatic-tectonic breccia. The essential feature is that it has been formed by deformation associated with the emplacement of an intrusive, rather than by regional faulting but is of mechanical origin rather than due to hydraulic fracturing. The geological relationships of the breccia to the intrusive body offer the best opportunity to identify magmatic tectonic breccias since texturally they are very similar to other tectonic breccias (see below). Breccias of this type do not usually occur in isolation, but in association with breccias of other types Mineralisation within this type of breccia is not directly related to the brecciation process, but brecciation may provide a suitable preparation of the host rock for later mineralisation. The location of these breccias in an intrusive environment means that they are likely to undergo mineralisation by other magmatic or hydrothermal processes. Tracking the extent of the breccia is important during exploration because of its empirical correlation with ore, but there is a good possibility that mineralisation extends into other formations.

2. Volcanic Breccias

The essential feature of these breccias is that the energy causing brecciation is derived from the release of pressure of magmatic volatiles.

2a. Endogenous Volcanic Breccias (non-eruptive or vent breccias). These are equivalent to the "magmatic breccias" of Sillitoe (1985). They are the sub-surface equivalents of eruptive volcanic breccias, infilling eruptive vents. The degree of comminution of the clasts depends on the violence of eruption, which in turn depends on the volatile content of the magma and the depth of eruption. Very gassy magmas may form diatremes similar to those created by phreatomagmatic processes (described below). The essential difference is that a volcanic breccia in the strict sense is mobilised only by juvenile volatiles, whereas a phreatomagmatic breccia is mobilised by the interaction of magma with surface, ground or connate water. In practical terms, discrimination between these cases may be difficult, and depend on the geological association; for example kimberlite pipes are presumed to be more likely mobilised by juvenile volatiles, because of evidence from their clast composition that they are derived from great depth.

Breccias of this type can be recognised from their geological relations to surrounding formations, in that they occupy identifiable volcanic vents, in roughly vertical bodies. In terms of clast composition, endogenous volcanic breccias are similar to eruptive volcanic breccias, though they may differ in containing a greater proportion of count%-rock lithic clasts, and lacking ballistic clasts. They are distinguisha le from phreatic breccias (as described below) by including uvenile igneous material, which is typically the predominant phase. Clasts may have a reddish, oxidised appearance in near-surface sections. They may grade downward into dikes. The matrix consists of fine igneous vitric and lithic fragments.

The process of brecciation in this case is not directly related to mineralisation, but brecciation may act as a pre-preparation for mineralisation by providing permeability for later mineralising fluids. Although not strictly a causal relationship, magmatic or hydrothermal mineralisation also tends to occur in this setting because of the association with subsequent sub-volcanic intrusions. The occurrence of endogenous volcanic breccias is therefore empirically prospective for mineralisation. During exploration the extent of the breccia body should be determined because of its empirical correlation with ore, but it is not possible to predict the extent of mineralisation with depth on the basis of the association with the breccia alone. Breccia bodies of this nature can be expected to extend over a large vertical interval. Exploration becomes a geostatistical exercise of determining the extent and grade of economic mineralisation.

26. Exogenous (Eruptive) Volcanic Breccias. These breccias are formed by the eruption of fragmental volcanic material. Brecciation may be due to the explosive release of magmatic volatiles, ballistic effects, or collapse during extrusion (crumble breccias). Eruptive breccias generally contain a large proportion of juvenile volcanic clasts, recognisable by their vesicular or glassy nature: They may contain much or little country rock material The matrix consists of volcanic ash, glass shards, or crystal or lithic fragments. Hydrothermally altered (prior to emplacement) material is usually a minor component (though fine- ained and especially vitric tuffs are very prone to post-depositionaralteration. Clasts are angular, or may show aerodynamic shaping if erupted in a plastic state. Near the vents spatter cones may be found. Beds may be massive, or in the case of fine-grained air-fall tuffs may be finely laminated. Even if they are massive and featureless on a small scale, they are deposited in roughly horizontal layers, or at least at less than'their natural angle of repose, though they may mantle topoeraphy. If deposited by base-surges, they may contain dune form; or other cross-bedding. If traceable along strike, changes from proximal to distal facies may be apparent.

Thick silicic pyroclastics may be welded, and form a continuum through to unbrecciated lava flows. If erupted in a subaqueous environment, volcanic breccias may show distinctive features such as clasts of pillow lava, hyaloclastites, chilled margins to clasts. and much deuteric alteration with carbonates, chlorite and hemati' Subdivision of eruptive volcanic breccias according to clast s' morphology and composition can be made. but from the poi' view of genesis such distinctions are unimportant except inso... they permit identification of individual units. Eruptive breccias are transitional to volcaniclastic sediments, and phreatomagmatic breccias, and to non-eruptive vent breccias.

In most cases, the process causing brecciation of this type is not directly related to mineralisation. An important exception, however, is the formation of submarine exhalative deposits of the Kuroko type. Volcanic breccias may also provide good permeability and pre-mineralisation exposure of a large surface area per unit volume, and so can be selectively mineralised later. There may also be a correlation between the Occurrence of volcanic breccias and mineralisation simply because areas with active volcanism are also tectonically favourable for other magmatically-related mineralising processes.

Exploration in this situation can make use of stratigraphic principles to predict the extent and location of the breccia body. Since the mineralisation probably post-dated and was independent of the brecciation process, it is essential to interpret the nature of mineralisation as well as that of brecciation, as mineralisation may not be confined to the breccia unit alone. There may, for example, be mineralised feeder channels at depth, whose location can be estimated by plotting isotherms based on alteration mineralogy.

3. Phreatomagmatic Breccias

These are equivalent to the "phreatomagmatic (hydromagmatic) breccias" of Sillitoe (1985). Phreatomagmatic brecciation occurs when upwelling magma encounters water. This may be groundwater, connate water, or a body of surface water. The mechanisms are sumarised by Sheridan and Wohletz (1983).

3a. Endogenous (non-eruptive) Phreatomagmatic Breccias. These commonly form near-vertical pipes known as diatremes, though this term is also applied to the sub-surface parts of magmatic phreatic breccia bodies (type 4 below), to which these are transitional. They may or may not vent to the surface. Their characteristic features are summarised by Ollier (1974). They are commonly polylithologic, often with a large proportion of wallrock clasts. These breccias are almost always matrix-supported. The matrix is composed of a mixture of comminuted clasts and finely-divided, often tuffaceous juvenile material ("tuffisite"). By definition some of the latter must be present or they would be magmatic-phreatic breccias.

Phreatomagmatic breccia pipes may contain a chaotic mixture of clast types, or there may be identifiable subhorizontal layers representing the stratigraphic sequence of country rocks through which they have passed, often indicating very little net vertical transport despite extensive clast rounding and a high proportion of matrix. However in some phreatomagmatic breccia pipes clasts of distinctive composition are found as much as 1000m below their equivalent stratigraphic position in the surrounding formations. Transport of fragments of wood or lacustrine sediments to great depths is not uncommon. These features are interpreted as due to collapse of a fluidised breccia column. Phreatomagmatic breccia pipes may be multi-generational, with later breccias cutting through earlier-formed deposits. Because of the predominance of water as the mobilising medium in these breccias, temperatures are comparatively low. Wood has been found preserved with only minor charring, even at considerable depth. Gases, especially CO_2, may play a major role as well as steam in the formation of large breccia bodies of this type.

Although the brecciation process is not directly related to mineralisation, phreatomagmatic breccias are prime candidates for selective mineralisation by later hydrothermal fluids. In terms of exploration, the extent of the breccia can only be used empirically as a guide to the location of ore. It is important to separately evaluate the mineralising process.

3b. Exogenous (eruptive) Phreatomagmatic Breccias. These are the eruption products resulting from a phreatomagmatic process venting to the surface. There is an extensive literature describing the features and mode of formation of these breccias, summarised by Wilson and Walker (1982). If only a small quantity of water is present, or there is little mixing with the magma, the resulting breccia may be indistinguishable from eruptive volcanic breccias (*sensu stricto).* If there is much water involved, especially where there is good sub-surface contact of magma with groundwater, violent explosions can occur resulting in vigorous disruption of the magma into fine-grained, often vitric, pyroclastics. The products of an eruption of this type can be distinguished from eruptive volcanic breccias by their finely-divided nature, morphology, and the presence of clasts showing evidence of rapid cooling and interaction with water. There is, however, a complete intergradation between purely volcanic breccias and phreatomagmatic breccias. The essential difference between a phreatomagmatic breccia and an eruptive volcanic breccia is that the mobile phase in the former consists of steam derived from water which did not originally form part of the magma, whereas the latter is fuelled by the expansion of magmatic volatiles (which may include water). The difference between phreatomagmatic eruptive breccias and phreatic eruptive breccias, which are also generated by steam explosions, is that the former include juvenile igneous material, whereas the latter do not.

Mineralisation in breccias of this type is not directly related to the process of brecciation, but they can provide a suitably fractured host-rock for later mineralising fluids. Similarly, they are prone to mineralisation because of their location in areas of active magmatism. This association is stronger than for exogenous volcanic breccias, because a greater proportion of phreatomagmatic breccias are of a silicic or felsic composition. The geologic and tectonic setting in which these magmas tend to occur is more favourable for mineralisation than, for example, areas of plateau basalts. In terms of exploration, application of stratigraphic principles may be useful in predicting the location and extent of the breccia body, but since the process of brecciation was probably not directly related to mineralisation, the mineralising process should be separately evaluated.

4. Magmatic-Phreatic Breccias

By our definition, magmatic-phreatic brecciation occurs through the flashing or expansion of a fluid which is composed of water or steam which may contain a proportion of magmatic volatiles but is predominantly of meteoric, groundwater or connate origin, and which has been directly heated by the intrusion of magma, and where the resulting breccia does not contain juvenile magmatic products. The difference between a phreatomagmatic breccia and a magmatic-phreatic breccia is that the former includes juvenile magma (as distinct from magmatic volatiles), whereas the latter does not. A magmatic-phreatic breccia may be considered as a variation on a phreatomagmatic breccia in which the fuelling mechanism is the contact of magma and water, but where the site of brecciation is remote from the point of contact. They are therefore two end-members of a continuum.

The difference between a magmatic-phreatic breccia and a phreatic breccia is that the heat source for a magmatic-phreatic breccia consists of an intrusive body of hot rock which directly heats water above its flash point, whereas a phreatic breccia is formed by the flashin of a *body* of water which may be heated by an intrusive at depth %ut for which the mechanism transporting energy close enough to the surface for flashing to occur is the convective movement of water, which over a substantial part of its circulating path is single-phase. This is a subtle distinction, and not often drawn, but is vital for understanding the formation of certain mineral deposits. *An* essential feature is that phreatic breccias are the results of small disturbances of a more or less steady-state hydrothermal system, and may therefore *occur* quasi-cyclically over a long period of time, while magmatic-phreatic breccias result from a single profound disturbance of the hydrological regime and are apparently stochastic in occurrence (Lawless, 1988). Magmatic-phreatic brecciation is a much more energetic process, and can result in an eruption with a much deeper focus.

Magmatic-phreatic breccias have not been distinguished as a separate class by previous authors, but have been included either with phreatomagmatic or phreatic breccias (as defined here), or more generally simply referred to as "hydrothermal breccias". It is *clear,*. though, from Laznicka's inclusion (*ibid*; p232) of phreatic eruptions in his discussion of fuel-coolant interactions, that he recognised the mechanism which is presented here.

4a. Endogenous (non-eruptive) Magmatic-Phreatic Breccias. Some of the units described as diatremes are of this nature: the essential point is that this type of breccia lacks juvenile igneous material. Otherwise they share many of the characteristics of endogenous phreatomagmatic breccias, frequently being polymict, having rounded clasts, and being matrix supported. The matrix is clastic though it may be subject to later hydrothermal alteration and therefore apparently crystalline in hand specimen. The distal portions of such a breccia may be indistinguishable from an endogenous phreatic breccia and may grade into hydrofractured breccias. However, since magmatic-phreatic breccias tend to be mobilised by steam and gas, or super-critical fluid, rather than water, there is less opportunity for the transport of dissolved constituents than in hydrofractured breccia formed by a single phase or liquid-dominated fluid. Hence there is little tendency for the deposition of hydrothermal minerals, and so little cementation of the matrix or vein infilling. Gas-phase mobilisation in breccia formation is documented by Konstantinov (1978). These breccias may only be identified because of their geological relations, and place in the geological history of a hydrothermal system. Sillitoe (1985, p1491) describes phreatic or magmatic-phreatic breccia pipes that possess features such as rounded clasts, polymict nature and matrix support, that are indicative of considerable clast transport, but terminate upwards into blind veins and cannot have been eruptive. It would seem possible therefore that breccias of this type can be formed entirely subsurface.

As the magmatic-phreatic breccia is a new classification, a number of examples are cited (see Table 3 for references). A good example of an endogenous magmatic-phreatic breccia (in the opinion of the present authors), which has been extensively explored by drilling, is a unit informally referred to as the "Muddy Breccia" at the Kelian gold deposit, Kalimantan, Indonesia. There is evidence for late-stage injection of magma into the Kelian hydrothermal system, by way of late-stage high temperature/high salinity fluid inclusions and the presence of tourmaline which suggests high temperatures and magmatic volatiles. The deposit in which this unit occurs is described by Van Leeuwen *et al.* (1989), who however present several alternative possibilities for its origin. Other examples of late-stage magmatism into a pre-existing hydrothermal system include the Boulder County gold deposits, Colorado, USA; Cerr Violeta and Cerro Colorado, Chile; late-stage post-mineralisati pebble dikes at El Salvador, Chile; and fluid inclusion evidence for alternating high temperature-high salinity/low temperature-low salinity fluids in the Topia deposit and Fresnillo district, Mexico.

Rapid and prolonged boiling of a hydrothermal fluid, such as occurs when brecciation (and possibly eruption) permits pressure release, is a potent mechanism for gold deposition, as the abrupt loss of H_2S destabilises the bisulphide complexes which are mainly responsible for transporting gold in this chemical regime. Consequently, mineralisation in many epithermal deposits is concentrated within "hydrothermal" breccias. This mechanism applies to both phreatic and to magmatic-phreatic brecciation, but the potential of the latter to cause large-scale, energetic, vigorous flashing means that it can be particularly effective. This is demonstrated in Figure 1, where the area between the temperature profiles and the reference boiling-point for depth curve is proportional to the energy available for brecciation and eruption. This is much greater in the case of the magmatic-phreatic profile, curve 3t, than for the "normal" phreatic profile, curve 2t. The presence of a percentage of magmatic volatiles in magmatic-phreatic fluids, due to the close association with magmatism, can also have a synergistic effect both by providing fluxing elements for metal transport, and a low pH leading to a greater potential for fluid-rock interaction and chemical changes through mixing with a near-neutral pH hydrothermal fluid.

A breccia of this type will be contained within a pre-existing hydrothermal system. The pre-existing hydrothermal system may have produced a pattern of alteration zoning which is effectively unrelated to the economic mineralisation, so targetting what appear to be prospective zones within this pattern may not be successful, and may cause the true ore zones to be overlooked. Alternatively, economic mineralisation in this setting may be associated with higher-temperature mineralogy (such as secondary actinolite, or base metals) than is normally the case in the epithermal environment, *so* recognition of such phases should not be taken as an indication that the system has been eroded to below the level of high-grade mineralisation. Exploration may have to extend to greater depth than is usual in the epithermal setting.

4b. Exogenous (eruptive) Magmatic-Phreatic Breccias. The eruptive deposits of a magmatic-phreatic breccia greatly resemble those of a phreatic eruptive breccia, as described below. Unless the clasts contain fluid inclusions or mineralogy indicative of high temperature or saline fluids, distinction may only be possible by interpreting the geological history, or by recognising that the eruptions were very large or deep-seated.

A well-documented example of a series of historical magmatic-phreatic eruptions is that at Waimangu, New Zealand, following the 1886 volcanic eruption of Mt Tarawera (Keam; 1988). They are interpreted to have resulted from the intrusion of a basaltic dike along a pre-existing zone of structural weakness. This reached the surface in a dry, elevated area at Tarawera, causing the eruption of a volcanic breccia. At Rotomahana it encountered a low-lying area, saturated with warm groundwater, and erupted as a phreatomagmatic breccia. At Waimangu the magma failed to reach the surface, as no juvenile material has been recognised in the eruptive products, but it interacted with the existing hydrothermal system to produce a magmatic-phreatic eruption, followed by continued phreatic activity. The events at Tarawera, Rotomahana and Waimangu are clearly related in time and space. If it was not for the historical record of the Tarawera eruption, it is doubtful that the products of the Waimangu eruptions would be identified as magmatic-phreatic breccias rather than phreatic breccias. Such events are probably more common than has been recognised. One probable example of fossil magmatic-phreatic breccias is at Rotokawa. New Zealand. The largest identifiable single eruptive unit has a volume of 10 Mm^3 (Collar and Browne, 1985). It is difficult to imagine that sufficient energy for an eruption of this magnitude could be stored close enough to the surface within a simple convective hydrothermal system, and an extra addition of energy from a magmatic source seems probable.

Mineralisation within exogenous hydrothermal breccias is similar in origin to that in endogenous magmatic-phreatic breccias, but since it occurs at lower temperature, its true character may be more difficult to recognise than in the sub-surface equivalents. Such breccias have a low potential for preservation in the geological record, since they occur on the surface, more often in areas subject to erosion than sedimentation. In terms of economic mineralisation, the main significance of exogenous magmatic-phreatic breccias may be to indicate the probable presence of mineralised endogenous magmatic-phreatic breccias at depth.

5. Phreatic Breccias

These are equivalent to the "phreatic (hydromagmatic) breccias" of Sillitoe (1985). Our definition is that phreatic breciation is caused by the expansion of steam and gas from a water-dominated fluid, with only a minor component of magmatic volatiles, and that the mechanism of energy transport to the focus of brecciation has to be at some point by a freely-convecting column of sub-critical hydrous fluid, though the process may involve flashing (steam and gas phase separation). It also includes hydraulic fracturing of the containing formations by hydrothermal fluids. The term phreatic breccia includes breccias formed by similar processes in "amagmatic" hydrothermal systems such as those in continental plate collison zones (Henley; 1984; an example in Tibet is documented by Liao et *al.* (1980). The term does not, however, include collapse-breccias formed within a hydrothermal system, whether due to mechanical collapse or chemical solution.

5a Endogenous Phreatic Breccias. These breccias most commonly occur in irregular subvertical pipes. Near-surface, they may form upward-flaring vents and be traceable into eruptive phreatic breccias, or they may terminate as a "blind" breccia pipe. Downwards, they may grade to stockworks and veins. The nature of the resulting breccias varies widely depending on whether flashing occurs and the degree of clast transport. With a single-phase fluid and effectively no clast transport a "jigsaw" breccia may result (hydrofractured breccia). These are monomict and matrix-poor; clasts are angular. With a greater degree of clast transport the breccias become increasingly polymict, clasts are rounded and the proportion of matrix to clasts increases. Clast support rather than matrix support is, however, typical of phreatic breccias. If the transporting medium is a single-phase hydrothermal fluid of typical neutral-chloride composition, a range of typical hydrothermal minerals will be deposited between clasts and in veins. If the fluid boils, minerals such as quartz, bladed carbonates, adularia and wairakite may form. Phreatic brecciation is often multi-stage, giving rise to multiple brecciation textures in the shallower parts of the veins, and banded veins and colloform textures below.

If clast transport is principally by steam and gas, as must occur in the upper part of phreatic breccia pipes which vent to the surface, and perhaps others, then there is little tendency for cementation of the breccia by hydrothermal minerals, as steam does not transport much in the way of mineral solutes at hydrothermal temperatures. There may be very little recrystallisation of the matrix, which will remain clastic (for example, at the 'Golden Wonder gold deposit (Kalliokoski and Rehn; 1987)) unless water-dominated hydrothermal fluids later rise to occupy the spaces in the breccia (implying a rise in fluid pressure). The composition of the clasts in a phreatic breccia depends on the nature of the formations through which it passes. However, since such breccias occur within active hydrothermal systems, most of the clasts are usually hydrothermally altered before brecciation, and in turn may contain different secondary minerals from those in the matrix and veins. Most often, since clasts tend to be transported upwards, alteration in the clasts indicates higher temperatures than do the minerals in the matrix and veins.

The flashing of hydrothermal fluid during brecciation and/or eruption can be a direct cause of precious metal mineralisation, localising economic mineralisation within the breccias. Recognition of a breccia of this type is therefore in itself a prospective indication of mineralisation. Endogenous phreatic breccia bonanza zones can be extremely rich targets;, the corollary of which is that an economic exploration target in this environment can be very small. In particular, fossil boiling zones are prospective, and to a lesser extent zones of fluid mixing. It is therefore necessary to interpret the paleo-hydrology of the hydrothermal system responsible for mineralisation and brecciation, by means of the hydrothermal mineralogy. Once the paleo-hydrology is understood, exploration can be targetted to the most prospective zones.

5b. Exogenous Phreatic Breccias. Breccias of this type are well described and illustrated by Hedenquist and Henley (1985). The eruptive deposits are usually polymict, matrix-supported breccias. Eruptions of this type have a shallow focus, and so the clasts in breccias of this type often have a composition reflecting relatively low temperatures and often a low pH in the upper 100-200m of a hydrothermal system. They are made up of opaline silica, sinters or chalcedony, sulphur, kaolinite, alunite and various other hydrous alumino-silicates. Pre-brecciation mineralisation consists predominantly of pyrite, marcasite or arsenopyrite, with other arsenic, antimony and mercury-bearing minerals.

Eruptive phreatic breccias are deposited in relatively thin layers, rarely exceeding 10m in thickness, but may cover wide areas. They may be crudely sorted and graded but are otherwise featureless. Sags beneath the larger ballistic clasts may be apparent. Since these are by definition deposits formed on the ground surface, hydrothermal alteration after brecciation is limited to low-temperature phases, unless there is subsequent burial followed by continued hydrothermal activity. As for magmatic-phreatic breccias, exogenous phreatic breccias have a low potential for preservation in the geological record.

Active hydrothermal systems commonly contain fluids which are layered in zones of different chemistry. The shallowest zones are frequently acid, and being connected to the source fluid at depth only by way of a vapour-dominated zone, do not contain appreciable gold. The significance of this is that an exogenous phreatic breccia may contain clasts with a composition indicating alteration by acid fluids, and very low gold grades, but still overlie rich boiling-zone deposits at depth. Correct recognition of this situation is therefore essential for successful exploration. The main significance of exogenous phreatic breccias is to indicate the possible existence of mineralised endogenous phreatic breccias and host rocks in the sub-surface. However, mineralisation taking place at the present day in active hydrothermal systems has been noted (eg. Krupp and Seward; 1987), and exogenous phreatic breccias can constitute an important part of an economic deposit, if they contain sufficient mineralised clasts that they constitute ore. In this event, their extent and location can be determined by applying stratigraphic principles.

6. Tectonic Breccias

These are equivalent to the 'tectonic breccias" of Sillitoe (1985). Tectonic breccias are formed by the mechanical disruption of rocks in response to tectonic stress. Mechanical disruption may grind clasts to rock flour forming gouge or mylonite. Tectonic breccias tend to occur in identifiable, usually steeply dipping, fault planes. If a large enough exposure is available, in outcrop or in a drillhole, tectonic breccias may be seen to lie between two different rock types, on either side of the fault (though this can be misleading as phreatic breccias also commonly follow lithologic contacts or fault planes).

Within unmetamorphosed volcano-plutonic terranes, mineralisation in tectonic breccias is generally not directly related to the process of brecciation, although the comments of Sibson (1989) regarding the importance of dilatancy and tectonic processes in the generation and movement of potentially mineralising fluids are significant in this regard. Tectonic breccias on fault zones within an active hydrothermal system do, however, form highly permeable channels for the passage of hydrothermal fluids, and so alteration after brecciation can frequently obscure the effects of tectonic brecciation leaving apparently phreatic breccias. Features such as alignment or imbrication of clasts, slickensides, and fine laminated textures may still reveal their tectonic nature. Under the microscope, undulose extinction indicating strain in quartz crystals may yield a clue, and some evidence of the planar fabric should remain.

Tectonic breccias are of major importance for mineralisation in metamorphic terranes: discussion of these are outside the scope of this paper. Comparisons between the mineralising fluids in this setting, and those in magmatic-related hydrothermal systems, and discussions of the mineralising processes, are provided by McKeag and Craw (1989). If mineralisation is associated with a tectonic breccia in a non-metamorphosed volcanic terrane, it is unlikely that the tectonism caused the mineralisation, and so the function of the breccia is probably just to provide a permeable path for mineralising fluids. Exploration strategy should consist of tracking the extent of the breccia, and separately interpreting the mineralising process. If mineralisation appears to have pre-dated faulting, the possibility of concealed cut-off mineralised zones should be considered.

7. Sedimentary Breccias

These breccias have an extensive literature summarised for example by Laznicka (1988)), and are only included here to show how they relate to the proposed genetic classification scheme. In the typical epithermal/mesothermal environment, they consist principally of volcanic material. Volcaniclastic sediments range from epiclastic deposits such as laharic or avalanche deposits, that have little evidence of sedimentary processes, through to well-sorted volcanogenic sandstones or pumicites. The essential feature of these breccias is that they have been emplaced on the Earth's surface by predominantly sedimentary processes.

Volcanic agglomerates or laharic deposits, which have under one little sedimentary transport can be difficult to distinguish from eruptive breccias. They share the features of forming sub-horizontal layers on a gross scale, but are generally unsorted and featureless on the outcrop scale. With a greater degree of sedimentary transport, clasts become rounded and sorted and may undergo some mineralogical selection, with material such as volcanic glass being rapidly broken down and removed. Features indicative of water transport may be apparent, such as cross bedding. There may be interbedded non-volcanogenic sediments.

Mineralisation in this setting is not directly related to the brecciation process. In terms of exploration, similar comments apply as to an exogenous volcanic breccia. The extent and location of the breccia can be predicted by stratigraphy, but the mineralising process should be separately evaluated.

Conclusions

Since some breccia-forming processes can be responsible for mineralisation, correct recognition of breccia genesis is an important part of the exploration process. Erection of a mineralisation model in terms of genetic processes can be used to guide exploration strategy.

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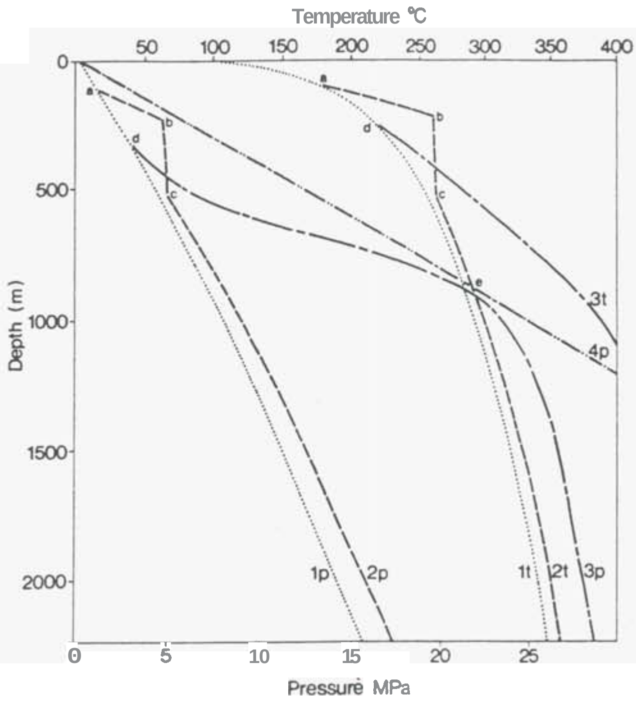

FIGURE 1: Pressure and temperature profiles in hydrothermal systems

Curve 1p: Reference boiling-point-for-depth pressure gradient for pure water.
Curve 1t: Reference boiling-point-for-depth temperature profile for pure water.
Curve 2p: Pressure profile in hydrothermal system just before phreatic brecciation. A low permeability layer exists between a and b. The fluid between c and b consists of a mixture of gas and steam confined below this layer. The focus of the brecciation (and/or eruption) is at b, a depth of 220m from the surface.
Curve 2t: Temperature profile corresponding to curve 2p.
Curve 3p: Pressure profile in a hydrothermal system just before a magmatic-phreatic eruption, as a result of an intrusion of magma at depth (not shown on this scale). The preexisting pressure gradient has been increased from depth up to point d. The focus of brecciation/eruption is most likely to be at e, a depth of 850m from me surface.
Curve 3t: Temperature profile corresponding to curve 3p.
Curve 4p: Reference lithostatic pressure gradient assuming a formation relative density of 2.5.

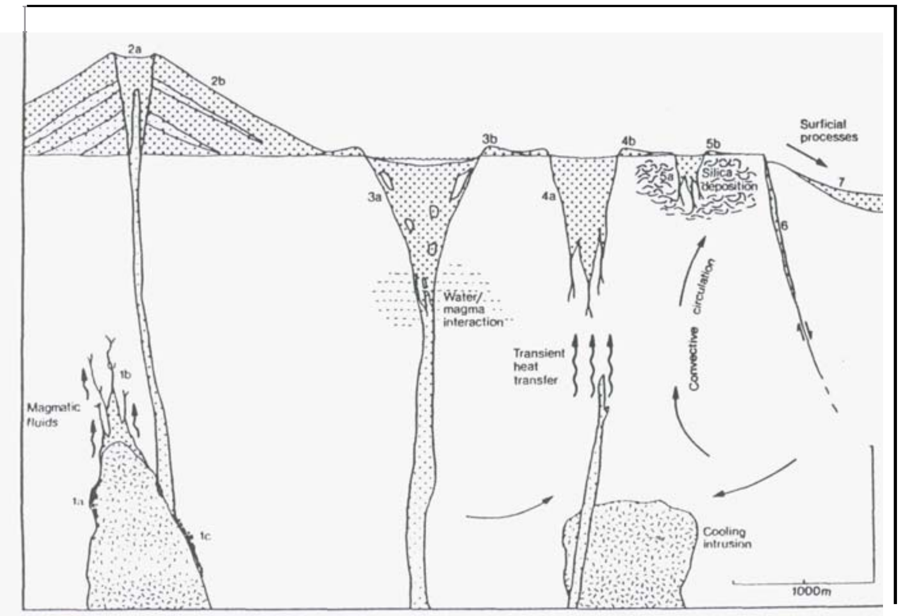

FIGURE 2: Geological environments where each type of breccia could occur. Numbering corresponds to breccia types in text and in tables.

TABLE 1 : Proposed Genetic Classification of Breccias

ENERGY SOURCE	M	
	MAGMA	MAGMATIC VOLATILES
Intrusion		
Magma (directly)	[1a] Magmatic-intrusive breccia {Effusive lava}	[1b] Magmatic (2a) Endogen {2b} Exogenou
Magma, indirectly through water in unstable transient system		
Water in quasi-stable convective system		
Tectonism		
Surficical processes		
	DECREASIN	

Key: [ ] = subsurface (and not necessarily connected to surface)
( ) = subsurface (and connected to surface)
{ } = surface

TABLE 2 : Correlation of Breccia Nomenclature

THIS PAPER	Baker et al. (1986)	Sillitoe (1985)
Magmatic-intrusive breccia Magmatic-hydrothermal breccia Magmatic-tectonic breccia	(not discussed) Hypabyssal breccia/Intrusion breccia (not discussed)	Intrusion breccia Magmatic hydrothermal breccia (not discussed)
Endogenous volcanic breccia Exogenous volcanic breccia	Hypabyssal breccia? Hypabyssal breccia?	Magmatic breccia? (not discussed)
Endogenous phreatomagmatic breccia Exogenous phreatomagmatic breccia	Diatreme breccia* Tuff breccia*	Phreatomagmatic (hydromagmatic) breccia Phreatomagmatic (hydromagmatic) breccia
Endogenous magmatic phreatic breccia Exogenous magmatic phreatic breccia	(not distinguished) (not distinguished)	(not distinguished) (not distinguished)
Endogenous phreatic breccb Exogenous phreatic breccia	Hydrothermal explosion breccia Hydrothermal eruption breccia	Phreatic (hydromagmatic) breccia Phreatic (hydromagmatic) breccia
Tectonic breccb	Fault-related breccia	Tectonic breccia
Sedimentary breccia	(not discussed)	(not discussed)

Noje that some of these terms arc not direct cqwalenls. since they are used Indifferent contexts

* not specifically defined

TABLE 3 : Examples of Mineral Deposits Associated w

BRECCIA TYPE	DEPOSIT	PRIN ECON MINERA
1a Magmatic-intrusive	Redwell Basin Complex, Colorado, USA	Mo
1b Magmatic-hydrothermal	Turmalina, Peru	Cu-
1c Magmatic-tectonic	-	
2a Endogenous volcanic	Toquepala, Peru	Au
2B Exogenous volcanic	Gold Ridge. Guadalcanal	
3a Endogenous phreatomagmatic	Montana Tunnels, USA	Au-
3b Exogenous phreatomagmatic	-	
4a Endogenous magmatic-phreatic	Kelian. Kalimantan, Indonesia	Au
	Boulder County, Colorado, USA	Au
	Cerro Violeta and Cerro Colorado, Chile	Au
4b Exogenous magmatic-phreatic	Wau. PNG	Au
Sa Endogenous phreatic	Golden Cross, NZ	Au-
5b Exogenous phreatic	Wau, PNG McLaughlin, USA	Au Au
6. Tectonic	-	
7. Sedimentary	-	