Violent rupture of mid-crustal barriers by fluidised breccia (Cloncurry Fe-oxide-Cu-Au district, Australia): implications for Cu-Au mineralization and kimberlites

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Abstract

The source and transport regions of fluidized (transported) breccias outcrop in the Cloncurry Fe-oxide-Cu-Au district, providing insights into the origins of other fluidized magmatic-hydrothermal breccias such as kimberlites. Discordant dikes and pipes with rounded clasts of metasedimentary calc-silicate rocks and minor felsic and mafic intrusions extend several kilometres upwards and outwards from the contact aureole of the 1530 Ma Williams Batholith into overlying schists and amphibolites. The brecciation initiated at depths > 10 km and may have resulted in surface breaching. We used analytical equations for particle transport to estimate clast velocities (e” 20m s^{-1}), approaching volcanic ejecta rates (up to 80m s^{-1}). The wide range of CO_2 fluid inclusion densities (up to 150 MPa), the localisation of the base of the breccias in contact aureoles, and the scale and discordancy of the bodies suggests the breccia transport process was triggered by an abrupt release of overpressured fluid. At these depths, such extreme behaviour may have been achieved by release of dissolved fluids from crystallizing magma, in combination with a strongly fractured and fluid-laden source, sitting under a strong, low permeability barrier, and such parameters may be analogous to the asthenosphere/lithosphere boundary in the case of kimberlite initiation. The relationship of these breccias to the Ernest Henry iron-oxide-Cu-Au deposit suggests they may have been either fertile or “failed” orebody feeders.

Keywords: *fluidization, fragmentation, mineralization, fluid pressure, intrusion, copper, gold*

Introduction

Fluidized flows form as a consequence of entrainment and transport of particles by high velocity fluid (and/or gas), such that the flowing mass can effectively be treated as a single viscous medium. Such flows are generated in the materials–, minerals– and food processing industries by adding particles to a conduit with moving fluid, and the rate of particle transport is optimised by adjusting (amongst several other variables) the conduit size and shape, the particle size and density, and the incoming fluid velocity and viscosity. Evidence for such flows in geological materials was summarized by McCallum (1985), who noted the large transport distances and rounding of clasts, matrix containing finely comminuted rock fragments, and characteristic confinement to pipelike or irregular bodies cutting surrounding rocks. Fluidization has been proposed to explain “neptunian” sandstone dikes, kimberlites and diatremes, and

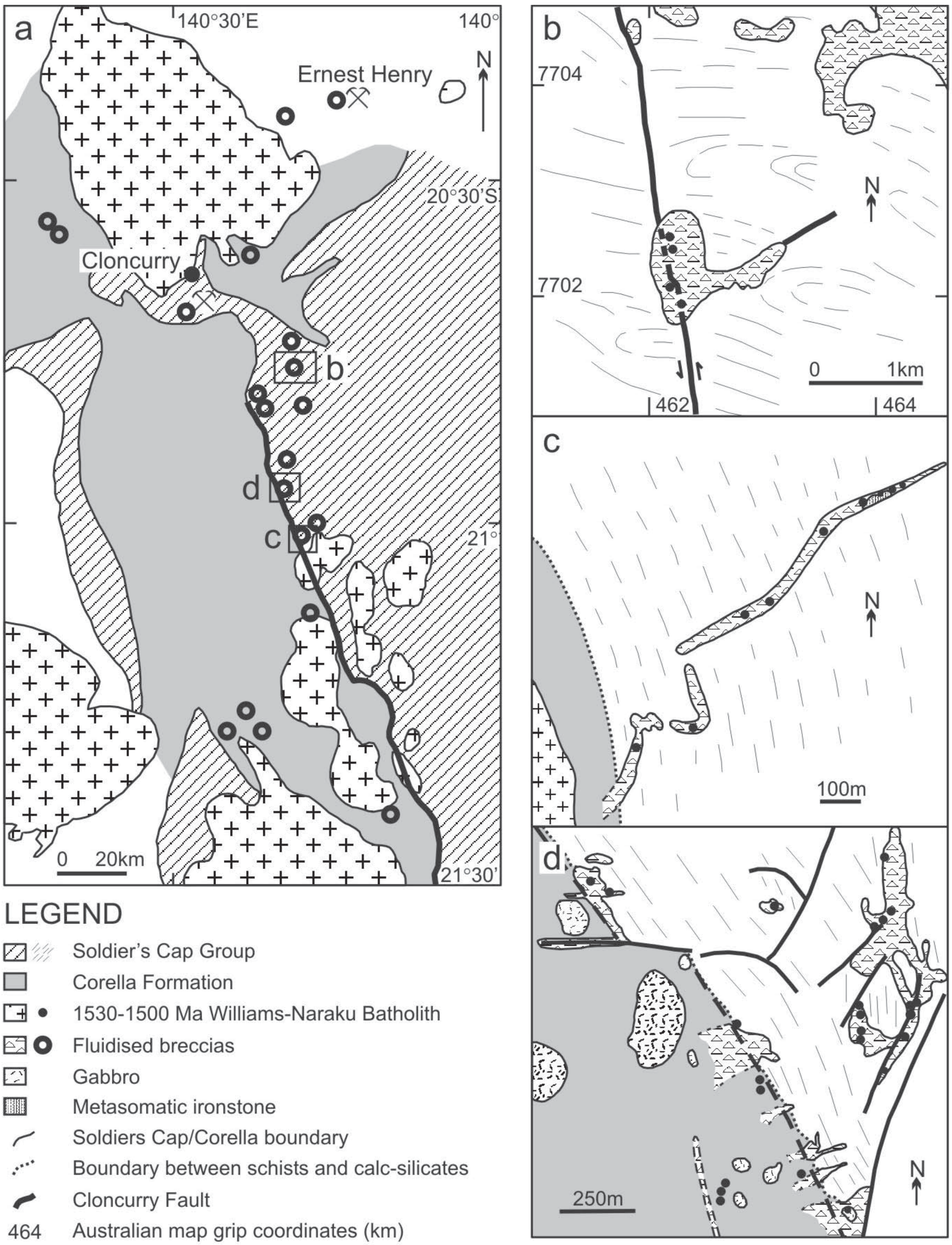

Figure 1: **(a)** Generalized map of the Cloncurry district showing the distribution of fluidized breccias relative to faults and the Corella/Soldiers Cap contact, the granitoids of the 1540 to 1500 Ma Williams-Naraku suite, and breccia-hosted Cu-Au mineral deposits, including Ernest Henry, and the locations of the more detailed locality maps; **(b)** map of the Gilded Rose breccia type locality. The breccia is dominated by clasts of the underlying Corella Fm but cuts (stope-like) through foliated schists of the Soldiers Cap Group. 50m-scale granitoid bodies are localised near the fault intersection that was the likely central point of the upward flow; **(c)** and **(d)** locality maps of other fluidized breccias, in which we infer the breccia initiation is triggered by build-up of magmatic-hydrothermal fluid overpressure under barriers, being the contact aureole of the Mt Angelay Granite and the Cloncurry Fault respectively.

phreatomagmatic volcanic eruptions (e.g. (Cas and Wright, 1987; Wilson and Head, 2004). Observations and experiment demonstrate that short term (minutes to days) volcanic eruption periodicity may be due to cyclical breaching and resealing of carapaces and/or vent plugs above magma chambers otherwise characterized by gentle gas streaming (Fischer et al., 2002). The volume expansions of H_2O-rich fluids separating from crystallizing felsic magma, and of gas released by subsequent phase separation of such fluids (first and second boiling), were proposed by Burnham (1985) to be the main drivers for fluidized brecciation in subvolcanic and porphyry environments. Likewise, volume expansion of CO_2 when released by magma crystallization in the mantle is thought to drive kimberlite initiation and transport (Wilson and Head, 2004).

Spectacular discordant breccia pipes and dykes with metasedimentary clasts cut several kilometres through overlying schists in the Proterozoic Cloncurry Fe-oxide-Cu-Au district of northern Australia, and appear to show characteristics of fluidized flows. Not only are these rocks perplexing from a hydrological and geomechanical perspective, they are very interesting from a mineralization perspective because some of the district's ore deposits are hosted in breccias of similar apparent timing. We use field data, preliminary fluid inclusion data, geothermobarometry, and an analytical fluid mechanics approach to attempt to calculate some parameters pertinent to fluidized transport, including particle velocities and pressure gradients. Implications for other fluidized breccia types are discussed, and the possible connection with the breccia-hosted Fe-oxide–Cu–Au deposits (e.g. Ernest Henry) of the district is also explored.

Field relationships and interpretations

The Mary Kathleen Group, dominated by impure carbonate rocks of the c. 1750 Ma Corella Fm, outcrops over 3000 km^2 south and west of Cloncurry in the eastern Mt Isa Block. More than half of the exposed Corella Fm consists of post-sedimentary breccia (Fig. 1a). Hydrothermal or mechanical brecciation on this scale is unknown elsewhere on Earth. Interest has also increased in the last 15 years upon discovery of breccia-hosted Cu-Au deposits such as Ernest Henry (> 165 Mt at 1.1% Cu and 0.5 g/t Au). However, volumetrically few of these breccias are grossly discordant, with structurally controlled regional metamorphic breccias and most intrusion-related breccias (c. 1600 to 1500 Ma) showing apparent minimal clast transport distances. Discordant breccias in which clasts are dominated by Corella Fm

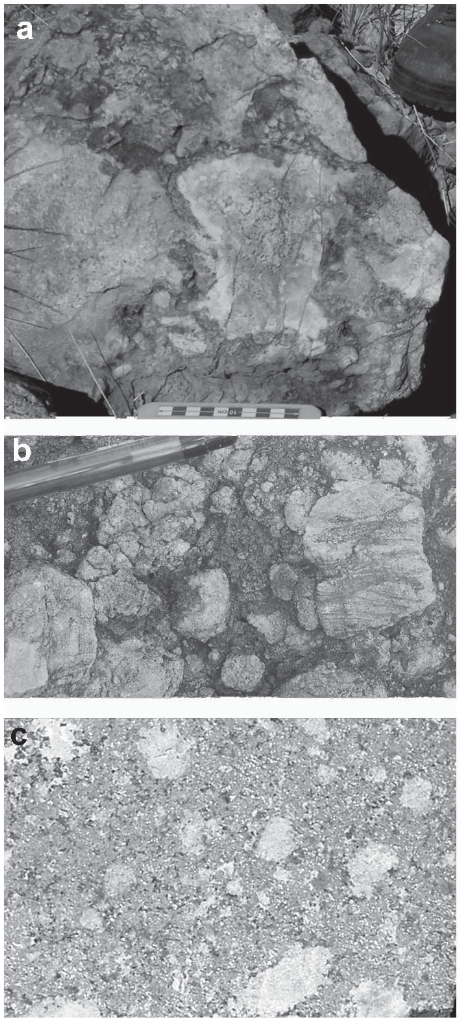

Figure 2: Field photographs of key breccia types. **(a)** breccia proximal to the intrusive source from the locality shown in Fig. 1c, showing a pegmatite-aplite dike with rounded edges suggesting it was not completely crystallized at the commencement of brecciation, cm scale at bottom; **(b)** typical fluidized breccia showing rounded fragments and a wide range of particle sizes – the breccia matrix here comprises microfragments of albitized calc-silicate and granitoid, with hydrothermal infill of albite+magnetite+titanite+apatite+actinolite, pen for scale; **(c)** fluidized breccia from the Ernest Henry iron-oxide-Cu-Au deposit showing rounded clasts of felsic volcanic rocks in a matrix of K-feldspar altered microclasts with hydrothermal infill of magnetite+chalcopyrite+pyrite+calcite±barite±biotite±fluorite, view is 4cm high.

rocks are found in patches and sheets in close proximity to 1520 - 1530 Ma late tectonic granitoids, as irregular bodies abutting against faults, and as pipes (10 to 1000m diameter) and dikes (5 to 100 m across). They commonly exploit pre- to syn-breccia fault arrays as much as 6 km away (in map view) from exposures of unbrecciated source rock material (Fig. 1). They typically crosscut foliated schists and amphibolites of the 1680 to 1650 Ma Soldiers Cap Group rocks, overlying the Corella Fm (Figs 1b-d). We do not know the total vertical paleo-extent of the breccias due to the present erosion level being fairly flat; however, the paleo-depth of the base of the breccias (11 km) is constrained by geothermobarometry on contact metamorphosed pelites around the Williams Batholith (Mt Angelay Granite), exposed within 1 km of the breccia outcrop shown in Figure 1c. The assemblage andalusite + biotite (both replacing cordierite) + K-feldspar + quartz + sillimanite defines a range from 590 to 670°C at 300 MPa, using the phase relationships, andalusite/sillimanite boundary, and biotite Fe/Mg ratio isopleth method defined by Pattison and Spear (2002).

Clasts within the discordant breccia bodies are rounded to sub-rounded, distinct from other breccias in the district. They are uncommonly weakly aligned parallel to the walls of the breccia sheets, but show no obvious size sorting across the width of a pipe or dike. They range in size from mm to 10 m-scales, most commonly between 1cm and 1m (Fig. 2b). The small clasts are intensely albitized; larger clasts may preserve little altered rocks in their core (impure marble, granite). The matrix is a combination of finely comminuted clasts and hydrothermal infill. These characteristics overall suggest the breccias were fluidized during transport. Some of the fluidized breccias have marginal zones typically < 1m wide containing strongly altered clasts of immediately adjacent Soldiers Cap Group schists. The field relationships also require that these schists must have been displaced vertically by, or incorporated into, the breccia bodies at some scale (e.g. Fig. 1b). The infill component of the breccia matrix shows 400 to 600°C assemblages (e.g. albite-magnetite-actinolite±diopside-calcite-quartz-hematite-sulphides) consistent with the general thermal structure around the granitoids (Fig. 2).

All of the fluidized breccias contain m- to 50m-scale bodies of leucocratic granite, aplite, and local pegmatite; some contain m- to 10m-scale gabbro bodies (Fig. 1). The granitoids typically are intensely altered, with quartz vein networks and a bleached appearance due to syn-intrusive albite alteration, similar to the carapaces of bigger intrusions of the same age elsewhere in the district (Mark and Foster, 2000). Although the granitoid outcrop patterns are mostly circular, they may be irregular or elongate, and locally display brecciated, lobate margins from which we infer intrusion was synchronous with brecciation (Fig. 2a). Some breccia dikes contain magnetite, chalcopyrite and pyrite. These observations imply a close connection between Williams Batholith magmatism, brecciation, albitization, and formation of mineralized metasomatic ironstones, as previously inferred from other relationships regionally (Perring et al., 2000; Pollard, 2001).

Crack, fluidization and brecciation dynamics

We can consider three types of depth-dependent behaviours for large, pipe- or sheet-like cracks and related fragmentation processes. Firstly, at a single depth, the process of fluid pressure increase until the point of tensile failure, with a subsequent decrease in fluid pressure as the crack opens, potentially may lead to repeated cycles of veining and local brecciation, as described by several authors (e.g. Cox, 1999). Secondly, if a large fault is formed but the fluid reservoir is limited, initial overpressure at the base of the crack may translate into significant underpressure subsequently as the crack expands and surrounding fluid is drawn towards the fracture at rates too slow to maintain the initial pressure (Fig. 3). Such a scenario may be termed an ‘implosion’ trajectory because the effects of reduced fluid pressure in the crack after expansion have a tendency to spall local wallrocks (Phillips, 1972), leading to potential mineralized breccias with local clasts but potentially exotic chemical precipitates in the matrix. Finally, the formation and migration of very large cracks in rocks at depth requires that the tensile failure criterion (P_f e” ó$_3$ + T) is exceeded over a range of depths and rock types (not just at the point of initiation), and

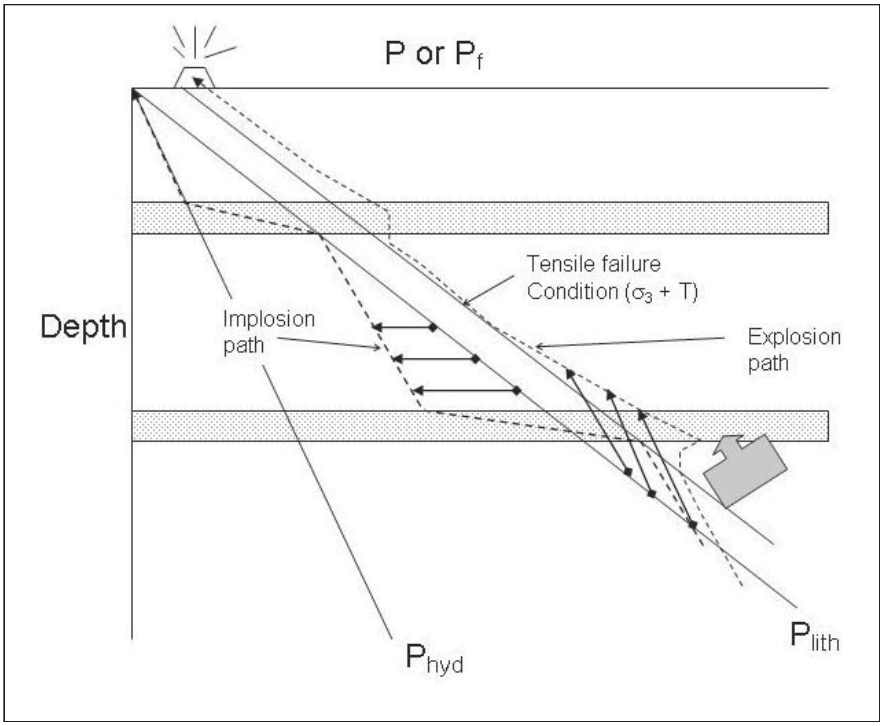

Figure 3: Schematic depth – pressure (P or P_f) diagram showing inferred processes leading to fluidized brecciation and transport. Hydrostatic (P_{hyd}) and lithostatic (P_{lith}) fluid pressures are shown, as well as the contribution from rock tensile strength required for tensile failure. Arrows with dots represent the potential pressure/depth paths of rock fragments during brecciation in two modes. The horizontal bars represent permeability barriers. The implosion path shown (modified from Sibson, 1996) is typical of initially overpressured scenarios at depth in which fluid pressure slowly increases above lithostatic, and failure then results in fluid pressure decrease, particularly near the base of the fault as depicted – limited fluid supply is insufficient to stop the decrease and prevent spalling of local wallrocks. In contrast, a combination of a very rapid pressure build up under a barrier, and a big, overpressured fluid supply at the base (shaded arrow-box), can lead to conditions for explosive brecciation in which rocks are entrained with the rapid, upwards flow. This type of path is required to produce phreatomagmatic eruptions and is also likely to be crucial for kimberlites. Ernest Henry may have formed by interaction of explosive breccia pipes with a dilatant bend in a shear zone involving big pressure changes, as depicted by the horizontal line connecting the two paths.

that fluid supply is sufficient (at least at the base of the crack) to maintain high fluid pressures over the length of the crack (e.g. Secor, 1965; Bons, 2001; Oliver and Bons, 2001). For fast-propagating cracks, pulses of high pressure fluid within them will have the potential to drive the crack over very long distances, because an initial modest overpressure at the crack base may translate into a large overpressure as the fluid (and the crack tip) rises, assuming that the fluid supply is adequate. This can be termed an 'explosion' trajectory (Fig. 3) such that rocks may be entrained from depth (in essence by suction), and spalling of local rocks into the crack is limited because the crack is at a higher pressure. Resultant breccias may show evidence for fluidized particle entrainment, and complex matrix composition with a wide variety of fragment sizes and hydrothermal infill. Such cracks reaching the surface would lead to venting of both fluids and fragments (e.g. a typical phreatomagmatic eruption). Additional factors assisting the generation of very large, long distance cracks include expansions in fluid volumes, such as those due to pressure dependent phase separation.

Explosive pipes or sheets generated at depth might thus be expected to show evidence for upwards particle transport distances and velocities that are comparable to those measured during

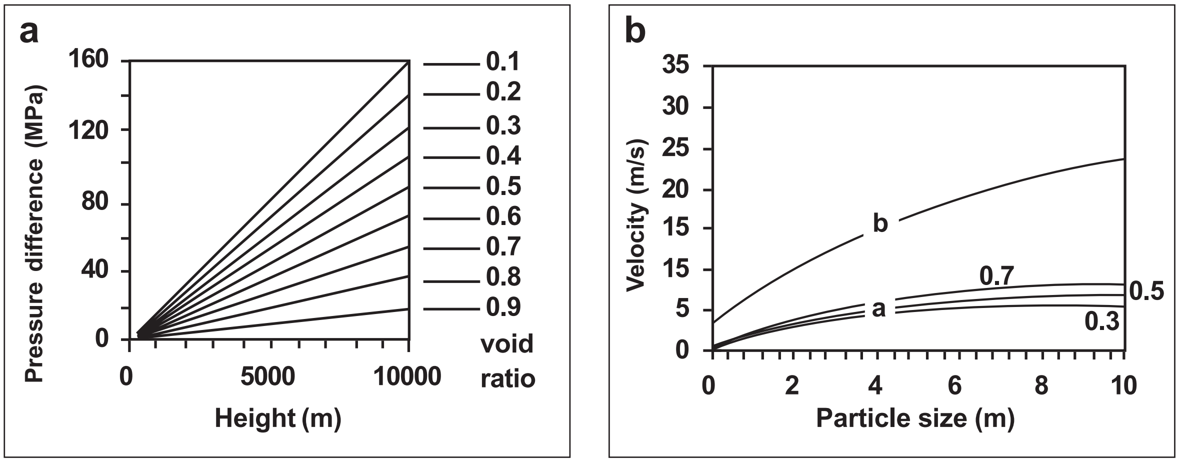

Figure 4: Results of fluidization calculations.
(a) Calculated particle velocities for different particle sizes showing initial conditions required for fluidization of a "bed" of particles at 3 different fractions of voids (fluid) to the total volume, and also upper (but minimum) velocities for transport of clasts not restricted by interaction with other clasts, i.e. buoyed up against the terminal velocity;
(b) Heights to which fluidized conditions would extend for given pressure gradients, calculated for different indicated void ratios, using the minimum fluidization conditions approximated by the Ergun equation (see text).

volcanic eruptions. We can approximate minimum velocities and pressure gradients by treating fragmented materials as permeable media, although more sophisticated approaches are possible with numerical (particle) codes and particle physics. The Ergun equation describes the velocity fields needed to stimulate fluidization under any flow regime, whether it be laminar, transitional or turbulent (Sissom and Pitts, 1972), and incorporates terms for fluid and fragment density, particle spacing, particle diameter and fluid viscosity. Simpler expressions can be used to consider an upper velocity for a single particle suspended in an upwards flow (equivalent to a terminal velocity). Using the field data and assuming initial fluidization affected zones of fractured rocks up to 1000m high, Fig. 4a shows the velocities we calculated from these equations for different particle sizes and void ratios (particle spacings). Particle transport rates of up to several 10's of m/s are suggested from this analysis. These are very rapid rates for subsurface geological processes, but are comparable to volcanic ejecta rates. We then used a differentiation of the Ergun equation to determine the initial fluid pressure gradients acting across the bed of particles at the moment of fluidization (Fig. 4b), for a given height of fluidization and average particle size (Sissom and Pitts, 1972, eq. 20-42, p. 731). If fragments were entrained upwards over a distance of 5 km, for example, and the amount of initial voids (fluid) relative to the total volume (clasts + fluid) was 0.3, a pressure difference of at least 62 MPa would be required from the bottom to the top in order for the minimum fluidization condition to be sustained over that interval. However, the pressure difference may have been much greater than this if we consider the effects of abrasion and comminution – note that the outcrop pattern in Fig. 1b suggests that a large volume of Soldiers Cap schist has been abraded and blasted upwards to be displaced by the present ~ 1km^2 of breccia containing clasts from the underlying Corella Fm in the pipe.

Quartz from the matrix of breccias from the Mt Avarice quarry on the outskirts of Cloncurry township was extracted for fluid inclusion analysis. The density of carbonic fluid inclusions was used to determine entrapment pressures using the equation of state of Holloway (1977). A single population of primary fluid inclusions that we infer from petrographic relationships to be associated with the brecciation shows a range of homogenisation temperatures from -37 to -13.5°C, corresponding to variation in densities from 1.105 to 1.001 g cm^{-3} for the pure CO$_2$ system. At this location, breccias are associated with actinolite – albite – magnetite ± calcite alteration typical of other fluidized breccias in the district that are distal to large granitoid bodies. The pressure calculated for the mean of the CO$_2$ densities is 335 MPa, similar to the 300 MPa pressure determined for the Williams Batholith contact aureole, indicating that the fluids were in a broadly lithostatically pressured regime for at least part of their history. Interestingly, at the likely temperatures of 400 to 450°C, the difference in fluid inclusion densities within the dataset suggests that pressures may have varied by up to 140 MPa during the entrapment history of this fluid. We are unsure whether the densities represent a specific pre- and post-brecciation fluid pressure difference at one crustal level, or whether they might represent different levels at which fluids were trapped within one breccia pipe. In any case, the implied pressure difference appears to indicate either substantial upwards fluid transport distances from an initial lithostatic (or supralithostatic) condition, or else a very large change in fluid pressure at one depth, consistent with a major faulting or breaching event. Elsewhere, overpressure-underpressure cycles (with fluctuations up to 100 MPa or more) have been demonstrated for several fault or magmatic systems by several authors using fluid inclusion densities to determine pressure (Baker and Lang, 2003).

Discussion

We interpret that these breccias formed by rapid upwards emplacement of fluidized masses predominantly composed of fragmented Corella Formation rocks derived from the contact zone of the Williams Batholith. Intrusions of this batholith near the study area, also associated with fluidized breccias, were emplaced at 1527 Ma, an identical age to titanite found in the ore of the Ernest Henry breccia (Mark et al., 2005). Two distinctive locations where breccia bodies are broader and contain the highest abundance of felsic intrusions internally are around the carapaces of the main granite stocks and plutons, and adjacent to long-lived fault zones or major rock contacts such as the Cloncurry Fault (Fig. 1). Overall, these relationships suggest that the present distribution of breccias was a consequence of pooling of volatiles and small igneous intrusions under hornfelsed contact aureoles and major rock type boundaries above the main intrusions, followed by rupture and penetration of the breccias (along with some entrained probably partly solidified igneous rocks) along former minor fault zones in the Soldiers Cap Group (Fig. 3). The source of fluids involved with brecciation was most likely from crystallization of the Williams Batholith (and related gabbros), notable for its association with highly saline brines and abundant CO_2 recorded in fluid inclusions (Perring et al., 2000; Pollard, 2001). In subvolcanic environments, fluidized breccias have been interpreted as the product of rapid degassing from the top of an intrusive body (first boiling), with or without subsequent immiscible fluid phase separation (Burnham, 1985; Tait et al., 1989).

In subvolcanic environments, a high pressure gradient may be established by communication between an overpressured magmatic-hydrothermal fluid, and the surface, in which case the gradient slope may be as much constrained by depth of emplacement as the amount of overpressure generated at the magmatic source. However, in the case of kimberlites, and the case presented here, the starting fluid would not “know” about the low pressure regime at the surface, so the overpressure must be generated largely by the conditions at the deep fluid generation point (Fig. 3). Rapid upwards transport in a highly turbulent flow would then have been possible if a large volume of fluid and rock from underneath these trapping carapaces were entrained. The unusual behaviour, compared with the normal behaviour expected for faults (Fig. 3, implosion path), is inferred to have been a function of a very large, high pressure fluid reservoir (the fractured Corella Fm sitting underneath the barriers), and the possible effects of phase separation, which may have created extra volume to sustain the upwards, explosive path (Fig. 3). This latter effect is proposed for kimberlites (Hawthorne, 1975; Wilson and Head, 2004) such that any rise of the fluidised mass leads to more release of CO_2 from the mass, and hence more volume expansion and greater buoyancy.

Although the Cu-Au mineralized Ernest Henry breccia contains clasts of gangue derived from the local metavolcanic rock package, clast roundness and size distributions are similar to those described here (Fig. 2). Fluidized breccia with calc-silicate dominant clasts are also locally interspersed with the ore breccia at Ernest Henry (D. Johnson, pers. comm.). We speculate that the fluidized, discordant breccias observed in the field were conduits into, and underly Ernest

Henry (Fig. 3). The interaction of the breccia pipes with the Ernest Henry metavolcanic host rocks may have commenced with fragmentation and permeability enhancement, providing pathways for subsequent fluids, or may also have triggered rapid mixing or unmixing of fluids that led to mineralization.

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References

Baker, T. and Lang, J.R., 2003. Reconciling fluid inclusion types, fluid processes, and fluid sources in skarns: an example from the Bismark Deposit, Mexico. Mineralium Deposita 38: 474-495.

Bons, P.D., 2001. The formation of large quartz veins by rapid ascent of fluids in mobile hydrofractures. Tectonophysics 336: 1-17.

Burnham, C.W., 1985. Energy release in subvolcanic environments: implications for breccia formation. Economic Geology 80: 1515-1522.

Cas, R.A.F. and Wright, J.V., 1987. *Volcanic successions: modern and ancient.* Allen and Unwin, London, 518 pp.

Cox, S.F., 1999. Deformational controls on the dynamics of fluid flow in mesothermal gold systems. In *Fractures, Fluid Flow and Mineralization,* K. McCaffrey, K., L. Lonergan, L. and Wilkinson J.J. eds, Geol. Soc. London., Special Publications, pp. 123-139.

Fischer, T.P., Roggensack, K. and Kyle, P.R. 2002. Open and almost shut case for explosive eruptions: vent processes determined by SO2 emission rates as Karymsky volcano, Kamchatka. Geology 30: 1059-1062.

Hawthorne, J.B. 1975. Model of a kimberlite pipe. Physics and Chemistry of the Earth 9: 1-15.

Holloway, J.R., 1977. Fugacity and activity of molecular species in supercritical fluids. In NATO ASI Series. Series C: Mathematical and Physical Sciences, pp. 161-181. Reidel Publishing Company, Dordrecht-Boston.

Mark, G. and Foster, D.R.W. 2000. Magmatic-hydrothermal albite-actinolite-apatite-rich rocks from the Cloncurry district, NW Queensland, Australia. Lithos, 51: 223-245.

Oliver, N.H.S. and Bons, P.D. 2001. Mechanisms of fluid flow and fluid-rock interaction in fossil metamorphic-hydrothermal systems inferred from vein-wallrock patterns, geometry and microstructure. Geofluids, 1: 137-151.

Perring, C.S., Pollard, P.J., Dong, G., Nunn, A.J. and Blake, K.L. 2000. The Lightning Creek sill complex, Cloncurry District, northwest Queensland: a source of fluids for Fe oxide Cu-Au mineralization and sodic-calcic alteration. Economic Geology 95: 1067-1089.

Phillips, W.J. 1972. Hydraulic fracturing and mineralisation. Journal of the Geological Society of. London 128: 337-359.

Pollard, P.J. 2001. Sodic(-calcic) alteration associated with Fe-oxide-Cu-Au deposits: an origin via unmixing of magmatic-derived H2O-CO2-salt fluids. Mineralium Deposita, 36: 93-100.

Secor, D.T. 1965. Role of fluid pressure in jointing. American Journal of Science 265: 633-646.

Sibson, R.H. 1996. Structural permeability of fluid-driven fault-fracture meshes. Journal of Structural Geology 18: 1031-1043.

Sissom, L.E. and Pitts, D.R. 1972. *Elements of transport phenomena.* McGraw-Hill, New York, 814 pp.

Tait, S., Jaupert, C. and Vergniolle, S. 1989. Pressure, gas content and eruption periodicity of a shallow, crystallizing magma chamber. Earth and Planetary Science Letters 92: 197-123.

Wilson, L. and Head, J.W. 2004. Diatremes and kimberlites, 2: an integrated model of the ascent and eruption of kimberlitic magmas and the production of crater, diatreme and hypabyssal facies. Lithos 75, No. 3/4, Abstract 244.

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