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Cockade breccia: product of mineralisation along dilational faults

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Abstract

Cockade breccias are a type of fault fills in which individual clasts are completely surrounded by concentric layers of cement. They occur particularly in low-temperature near-surface hydrothermal veins. At least six mechanisms have been proposed for the formation of cockade breccia-like textures, but only two – repeated rotation-accretion, and partial metasomatic replacement of clast minerals – have been supported by detailed evidence. A typical example of cockade breccia from the Gower Peninsula (South Wales) shows clear evidence for the rotation-accretion mechanism: in particular, overgrown breakage points in cement layers – where cockades were previously touching each other – and rotated geopetal infills of haematitic sediment. Based on the available evidence, it is proposed that cockade textures result from low rates of cement growth compared to high rates of dilational fault slip. Seven criteria are given for the correct identification of cockade breccias.

1. Introduction

Fault zones are important in controlling fluid flow in the upper crust. Depending on the permeability of the fault core and surrounding damage zone, an individual fault zone can act either as a barrier or a conduit for fluids (Caine et al., 1996; Faulkner et al., 2010). Most fluids alter the permeability of fault zones over time by deposition of mineral cements and reaction with the wallrocks (e.g. Woodcock et al., 2007). Critical to understanding fault zones is the identification and interpretation of fault rocks, particularly fault breccias: coarse fault rocks with potentially high permeability.

Recent classification schemes for fault breccias (Mort and Woodcock, 2008; Woodcock and Mort, 2008) are non-genetic and easily applicable in the field. However, they do not deal satisfactorily with fault rocks dominated by crystalline cement. Rocks with less than 30% large (> 2mm) clasts and less than 30% fine matrix are classified as ‘fault veins’ (Woodcock and Mort, 2008, Fig. 5b). However, these cement-rich fault rocks include a puzzling type of ‘breccia’ in which clasts appear to be completely surrounded by cement: a geometry which has no simple genetic explanation. These cement-supported breccias are commonly termed ‘cockade breccias’.

The term cockade breccia (also: cockade ore, cockade texture) refers specifically to hydrothermal fault fills in which centimetre- to decimetre-sized clasts appear to be completely enclosed by concentric bands of cement (Bastin, 1950; Kutina and Sedlackova, 1961; Genna et al., 1996; Leroy et al., 2000). Cockade breccias are of considerable interest in the study of vein-type mineral deposits because they may record much of a vein’s mineralisation sequence (Leroy et al., 2000) and provide evidence for syntectonic mineralisation (Van Alstine, 1944; Genna et al., 1996), allowing correlation of mineralisation with deformation. Yet, there is no consensus on the exact origin of cockade breccias, and some confusion exists in the literature about nomenclature and identification. This paper therefore aims a) to summarise research on the formation of cockade breccias, b) to present new evidence for the syntectonic formation of cockade textures in carbonate vein fills on the Gower Peninsula, Wales, and c) to review nomenclature and classification of cockade breccias, particularly to help their correct identification in the field and the laboratory.

2. History and usage of the term *cockade*

Cockade breccias were first described from Pb-Zn-Ag veins in the German part of the Erzgebirge Mountains as *Sphärengestein* (German *sphere rock*; Weissenbach, 1836), although this term apparently included varieties with only one generation of columnar cement. The terms *Kokardenerz* (*cockade ore*) and *Ringelerz* (*ring ore*) used by Cotta (1859) and other authors (Pošepný, 1895;

Beck, 1903) to describe similar ore-bearing fissure fills refer to the concentric banding around individual clasts seen in sections.[1] It is from the translation of Cotta's work on ore deposits that this terminology seems to have entered English geological nomenclature (Cotta, 1870). Variants such as *cocarde ore* also appear (Pošepný, 1895) but have not stood the test of time. Sperling (1973) gives separate but overlapping definitions of the terms ring ore and cockade ore. He defines ring ore as an end member of the transition from banded veins with straight bands to those with wavy, and finally concentric bands, when overgrowing single wall rock fragments (calcite, sphalerite, galena). Cockade ore, on the other hand, is defined by fine-grained, layered intergrowths of galena and quartz overgrowing host-rock fragments. This distinction seems superficial since the resulting textures are symmetrically and genetically equivalent. Cockade ores have also been called *orbicular* or *nodular* ores by some authors (Spurr, 1926; Van Alstine, 1944; Penczak and Mason, 1997).

In a number of publications, mis-applications of the terms cockade breccia or cockade texture deviating significantly from the original definition were encountered. For instance, breccias where only a single generation of cement surrounds individual fragments are sometimes called cockade breccias (Feitzinger and Paar, 1991; Hagemann et al., 1992; Feitzinger et al. 1995; Kontak et al., 1999; Yilmaz et al., 2010), probably due to confusion with the earlier term *Sphärengestein*. Because of their superficially similar appearance in section, colloform cavity fills have also occasionally been called cockade breccias, particularly with reference to Mississippi-Valley-Type mineral deposits (Clar, 1929; Jicha, 1951; Kalliokoski, 1965; Schneider et al., 2002; Okrusch et al., 2007; Patrier et al., 2013). Other non-canonical applications include the use for oolites (Ilavsky et al., 1991), peloids (Kucha et al., 1990), microscopic overgrowths of one mineral on another (Genkin et al., 1998), tourmaline sprays in aplite dikes (Boriani et al., 1988), vugs (Suh and Dada, 1997; Vishiti et al., 2013), and normal columnar or laminar cements growing on vein walls (Hodgson, 1989; Byrne and Harris, 1993; Fusswinkel et al., 2013, 2014).

Historically, the term cockade breccia or cockade texture was intended exclusively for hydrothermal breccias in which individual clasts are surrounded by several generations of cement and, to avoid confusion, its meaning should be restricted accordingly. A set of textural criteria which should be met by any true cockade breccia is presented below.

3. Mode of occurrence

A summary of 106 reported occurrences of cockade breccias in different types of deposits (Table

[1] A cockade (French *cocarde*) is a symbol consisting of differently coloured concentric rings, used for recognition by many, particularly military, organisations around the world. In the past, they were also used to show the allegiance of the wearer to a political faction, most prominently during the French Revolution with the creation of the *cocarde tricolor*, now a popular symbol of France and the basis for the current French national flag.

1) shows that they are most often reported from low- to mid-temperature (typical formation temperatures between 50 – 350°C), vein-style mineralisation thought to have formed in near-surface environments. However, the clear prevalence of reports from ore-bearing veins is probably due to a significant sampling bias towards the well-exposed occurrences encountered in mines. Sampling bias might also be responsible for the apparent relative abundance in different types of mineral deposits.

The presence of cockade breccias is often used to indicate space-filling processes – rather than replacement – during mineralisation (e.g. Perelló, 1994; Liu et al., 2011). However, this interpretation has been challenged in some cases where ore minerals replaced specific cement generations or formed along the contacts between cement and clasts (Kutina and Sedlackova, 1961; Rieder, 1969), leading to an appearance similar to that of cockades sensu stricto.

4. Proposed formation mechanisms

4.1. Six possible mechanisms

Successive deposition of several cement generations is required for the formation of cockade breccias. The resultant volume of cement means that clasts seem not to touch each other and appear to be suspended within the cement. This was already noted by Weissenbach (1836), and a number of explanations have been put forward for this phenomenon since his first description:

1) *The cut effect* (Fig. 1a). Pošepný (1895) noted as early as 1895 that a lack of contact points between clasts in any 2D section does not preclude contacts in 3D. Pošepný showed this for a few specific cases by preparing serial sections of specimens showing no contact points at their surface. Later experiments by Talmage (1929) also showed that there is a high probability for sections through random, self-supporting structures to contain abundant seemingly unsupported fragments.

2) *Crystallisation pressure* (Fig. 1b). The earliest explanation for a true suspension of clasts within the cement was put forward by Weissenbach (1836) himself. He proposed that fragments were pushed apart by the crystallisation pressure exerted on the clasts by minerals precipitating between them. Many authors have repeated this hypothesis (Cotta, 1859; Beck, 1903; Taber, 1918; Lindgren, 1919; Bastin, 1950).

3) *Suspension in fluid* (Fig. 1c). Another early hypothesis was that clasts were suspended in a fluid during the growth of the cements, either because of the high viscosity or density of that

fluid (Spurr, 1926), or due to its fast speed of ascent (Farmin, 1938). Recently, the hypothesis of highly viscous and dense mineralising fluids was re-invoked by Dill and Weber (2010), while Jobson et al. (1994) re-introduced the hypothesis of a violently ascending fluid to explain the occurrence of cockade breccias.

4) *Partial metasomatic replacement of clast minerals* (Fig. 1d). Partial inward replacement/alteration of clasts might result in a lack of contact points between the residual cores of the clasts (e.g. Bateman, 1924; Bastin, 1925). Later deposition of another mineral around the clasts might give the (superficial) appearance of concentric layers of cement. Kutina and Sedlackova (1961) as well as Rieder (1969) present evidence for such processes contributing to the formation of some cockade breccia-like textures.

5) *Infall of clasts during cementation* (Fig. 1e). Kutina and Sedlackova (1961) pointed out that an apparent suspension of clasts within the cement might also be achieved by the gradual accumulation of rock fragments in a fissure simultaneous with mineral deposition.

6) *Repeated rotation and accretion* (Fig. 1f). Van Alstine (1944) proposed that cockades form by repeated fracturing of a partially cemented breccia, mostly along the boundaries between individual clasts, in an extending fissure followed by growth of a partial layer of new cement. Although individual layers never completely enclose the clasts, the low spatial density of contact points leads to the appearance of complete concentric layers of cement, and to the suspension of clasts within the cement. Genna et al. (1996) recently presented evidence for the same mechanism, but without citing Van Alstine (1944). Van Alstine's contribution was also omitted by Kutina and Sedlackova (1961) in the most comprehensive review of cockade formation to date.

While the cut effect (1) clearly explains some cockade-like textures, there are many breccias where clasts are demonstrably *not* in contact with each other. In such cases, detailed evidence has only been presented for the partial metasomatic replacement mechanism (4) (Kutina and Sedlackova 1961) and the rotation-accretion mechanism (6) (Van Alstine, 1944; Genna et al., 1996). However, a detailed discussion of the textural implications of all of the above possibilities is usually lacking. Therefore, such a discussion follows in the subsequent paragraphs.

4.2. Crystallisation pressure hypothesis

If cockade breccias were formed by the action of crystallisation pressure on loose granular aggregates (2), the resulting textures would depend on the surface energies of the minerals involved. If the cockades and cement are composed of minerals with very similar surface energy and surface energy anisotropy, faces on individual crystallites would not develop, except in the first generation of cement that grew into open spaces. Successive cement generations would be expected to show only anhedral textures, similar to those developed in crack-seal veins. By contrast, cements containing minerals with significantly higher surface energy and surface energy anisotropy (e.g. pyrite in quartz; cf. Spry 1969), should develop crystal faces projecting into *all* directions, except where grains of the same mineral impinge on one another. The minerals with the lower surface energy should again not show developed crystal faces (Spry, 1969). Although veins have been described in which such textures are observed, and which might therefore have formed through the action of crystallisation pressure (Wiltschko and Morse, 2001; Hilgers and Urai, 2005; Philipp, 2008; Noriel et al., 2010), cockades generally lack such textures. They instead show rims of crystals with well-developed growth faces projecting outward from the central clasts (e.g. Spurr, 1926; Leroy et al., 2000). This indicates formation by growth into open spaces. The crystallisation pressure hypothesis can therefore be dismissed on textural grounds.

4.3. Fluid suspension hypothesis

Two distinct cases require separate consideration: a) involvement of a highly viscous and dense (drilling fluid-like) fluid agitated by fault movement (shear fluidisation) and b) involvement of a low viscosity fluid at high flow speeds.

If indeed highly viscous drilling-fluid like suspensions were involved in the formation of cockade breccias (as proposed by Dill and Weber, 2010), large amounts of fine-grained sediment should be associated with the cockades – at least 20 vol.%. Although Dill and Weber (2010) do report the occurrence of argillaceous material in normal breccia units, they fail to show its association with the cockade material. Virtually all other occurrences of cockade breccias reported in the literature show no association to fine-grained material, and the spaces between clasts are usually filled by cement (e.g. Spurr, 1926; Buerger and Maury, 1927). Another reason to reject this model is based on its implication that clasts remain suspended in the fluid for the entire duration of cement growth. This is an unrealistic scenario, since the seismic agitation required to sustain the drilling-fluid like suspension is intermittent and clasts should settle during interseismic periods. Compaction and cementation would likely follow and result in a material difficult or impossible to resuspend. Therefore, the drilling-fluid model is neither strongly supported by field evidence, nor by general considerations of fault dynamics.

To evaluate rapidly ascending, low-viscosity aqueous fluids, analysis is needed of the hydrodynamic conditions required to suspend cockades of typical sizes, as well as the physical constraints on maximum flow rates in hydrothermal systems. As an example, we will consider an aqueous fluid at 150°C with a salinity of 20 wt.% NaCl (3.4 mol/kg). This salinity is fairly high (Roedder, 1984; Shepherd et al., 1985), resulting in comparatively high density and viscosity. Based on the relations presented by Haas (1970), Kestin et al. (1978) and Mao and Duan (2009), this fluid would have a density of 1.0 g/cm^3, and a viscosity of 4.0 mPas. The flow threshold for fluidisation of a loosely packed granular aggregate (voidage = 0.5) of quartz or calcite (ρ = 2.7 g/cm^3) pebbles with an equivalent hydraulic diameter of 5 cm (a fairly typical size for cockades, e.g. Leroy et al., 2000), can be estimated from the relations given by Eichhubl and Boles (2000) to be 0.24 m/s. This velocity value is reasonably robust against changes in salinity or temperature of the fluid, and represents the absolute minimum for fluidisation to occur.

On the other hand, the minimum flow speeds needed for suspension of clasts in the fluid are equal to their terminal settling velocity. The relevant relations for cube-shaped particles are given by Gaskell (1992) and Pettyjohn and Christiansen (1948), and the result for the case described above is 0.88 m/s. Minimum fluid ascent velocities on the order of 10^{-1} to 10^{0} m/s are therefore necessary, if the formation of cockade breccias is to be explained by bed fluidisation or suspension.

The critical question is now whether such high flow velocities can be attained and also *sustained* in fault-related hydrothermal systems. Unfortunately, there is virtually no data on fluid flow velocities in terrestrial systems and no easy way to infer them from field evidence. Eichhubl and Boles (2000) used fluid inclusion thermometry and oxygen isotope data to assess the temperature anomaly associated with a carbonate vein along a strike-slip fault in California, which in turn yielded an estimate of upward fluid flow velocities in the fault. Due to parameter uncertainties, they arrived at a wide range of 10^{-4} to 10^{0} m/s for the velocity of *pulses* of hot fluid moving up the fault (Eichhubl and Boles, 2000). This just includes the required minimum velocities calculated above, but represents episodic and not sustained flow. Fluid flow in natural fault-related hydrothermal systems is probably intermittent, due to the operation of seal-fracture and fault-valve processes linked to seismic activity (Sibson, 1981; Cathles and Smith, 1983; Sibson et al., 1988; Boullier and Robert, 1992; Eichhubl and Boles, 2000). Release of fluids from over-pressured reservoirs is thought to be triggered when fluid pressures approach lithostatic pressure (Sibson, 1990). Thus the maximum pressure gradient along a fault discharging fluids will be given by the difference between the lithostatic and hydrostatic pressure gradients. If the shape of the fault conduit and the fluid properties are known, the maximum (transient) flow velocity can be estimated. Approximating a typical cockade-bearing fault cavity by a conduit with a rectangular cross section 100 m long and 0.5 m wide, using the same fluid as above (aqueous solution of NaCl, 20 wt.%, at 150°C), and assuming the relative roughness of the fault walls to be on the order of 0.1 (i.e. that the short-wavelength deviations of the fault walls from flat surfaces amount to about 10% of the total width of the conduit), we arrive at a maximum velocity of ~20 m/s using the Darcy-Weisbach equation (assuming an average rock density of 3.0 g/cm^3; De Nevers, 1970). This value is well above the minimum requirement for clast fluidisation or suspension derived above. Consequently, this mechanism cannot be ruled out as the driver for cockade rotation. However, it will probably only occur for short periods of time when flow velocities peak due to the release of over-pressured fluids during seismic events. The calculation of maximum flow rate assumes that the fault is fed by a reservoir with no internal flow resistance, and discharges into a similar reservoir. Actual maximum flow rates will probably be lower because the fluid reservoirs in natural systems are typically porous rocks with a much lower permeability than large open fractures. Another consequence is that high flow rates are probably not sustainable over extended periods of time. Measurements of natural fluid flow velocities have been made at black smokers, where fluids have steady state exit velocities of 0.5 – 5 m/s (RISE, 1980; Macdonald et al., 1980; Converse et al., 1984; Hekinian et al., 1983, 1984). However, these high velocities are probably due to highly focussed flow at the exiting point (cf. Strens and Cann, 1986), with each black smoker field fed by a large fracture network (Strens and Cann, 1986). The high thermal gradients present around the centres of mid-ocean ridges may also contribute to these high flow velocities. Additionally, mass flow rates of black smoker fields are typically small compared to the expected discharge rate of the fault zone in our model calculation. For fluid velocities of 0.2 to 0.9 m/s, a fault fracture 100 m long and 0.5 m wide would discharge 10 to 45 m^3/s, while a black smoker field typically only discharges 150 kg/s of fluid (Hekinian et al., 1984). Consequently, steady-state fluid flow velocities in the fracture system associated with a black smoker field must be much smaller than the discharge velocities cited above. Another argument for low steady-state flow velocities is the significantly smaller pressure gradient resulting from temperature induced density differences, compared to the maximum pressure gradient assumed above.

It is clear from the foregoing discussion that *intermittent* fluidisation and cementation of clasts cannot be ruled out as a mechanism for the formation of cockade breccias. However, the calculations indicate that *sustained* suspension of cockades over extended periods of time is highly unlikely: the required flow velocities and volume flow rates would be too large. Sustained suspension (or fluidisation) and simultaneous cementation in a rapidly ascending low-viscosity aqueous fluid can therefore be discounted as a realistic formation mechanism for cockade breccias.

4.4. Rotation-accretion hypothesis

Intermittent fluidisation or suspension and subsequent partial cementation essentially describe the rotation-accretion mechanism (6). The hypothesis specifies no specific mechanism for the re-fracturing of the partially cemented breccia and the subsequent rotation of clasts. However, the re-fracturing that would have to precede re-suspension or re-fluidisation can probably only be achieved by the mechanical action of moving fault walls and not the moving fluid alone. Cementation is expected to occur mostly in interseismic periods (cf. Eichhubl and Boles, 2000), and significantly higher flow rates would be required to dislodge partially cemented clasts than to fluidise or suspend non-cemented ones.

Identification of the primary driver for clast agitation might be possible from textural relationships, specifically grading relations. While a cockade breccia unit formed from fluidisation of individual cockades would be expected to show normal grading of cockade sizes, due to the faster settling velocities of larger particles, one formed primarily through the action of fault wall movement and associated agitation (shaking) without fluidisation should show reverse grading because of the Brazil-nut effect, that is, the tendency of larger particles in an agitated self-supporting mass of non-equigranular particles to migrate towards the top (Möbius et al., 2001). The frustrating result this effect can have on the distribution of nuts and dried fruit in packages of breakfast cereal should be familiar to most readers. In the only case of cockades where grading relationships have actually been reported, reverse grading is observed (Genna et al., 1996), indicating the dominance of seismic shaking or fault shear for the re-fracturing and rotation of the breccia unit.

4.5. Other hypotheses

Replacement processes (4) will result in their own characteristic set of textures which are easily distinguishable from the space-filling growth of minerals (Bastin, 1950), while the infall of clasts during cementation (5) would not yield cement crusts completely enclosing the fragments and would result in a distinctive asymmetric overall texture (Fig. 1e) which is not usually observed.

Considering the evidence available from the literature, the rotation-accretion mechanism of formation (6), the textural implications of which are discussed in section 5, may be regarded as being the most likely to explain all of the observed features, although different mechanisms might be responsible for the necessary re-fracturing and rotation. Replacement processes might contribute to the formation of some cockade-like textures.

5. Textural evidence for the rotation-accretion mechanism of cockade breccia formation

If repeated rotation and accretion is the most likely mechanism for the formation of cockade breccias, the following textures would be expected on the macro- to microscale:

1) Open space-filling cement textures, e.g. colloform or columnar growths, well-developed

crystal faces;

2) Lack of contact-points between clasts in 3D;
3) Lack of extensive replacements;
4) Points of breakage or missing sections in the cement layers where clasts formerly touched each other and thus hindered the development of complete encrustations;
5) Rotated geopetal ('way up') indicators, such as sediment deposited on and around the clasts.

In addition to these essential textures, the following are expected to be developed depending on the primary driver for breccia re-fracturing and clast rotation:

6) Reverse grading of cockades within individual breccia units – resulting from the Brazil Nut or Muesli Effect in an agitated non-equigranular material (Möbius et al., 2001), which might be accompanied by an upward-increasing cement to clasts ratio. This will result if seismic shaking is the dominant mechanism for re-fracturing of the breccia and rotation of clasts.
7) Normal grading of cockades within individual breccia units – resulting from the faster settling velocities of larger clasts, if intermittent fluidisation or suspension is the dominant mechanism for re-fracturing and rotation of clasts.

The most thorough study of rotation-accretion cockade breccias (Genna et al., 1996) detailed only the reverse grading of cockades (6) and mentioned their mechanical attrition (4). Van Alstine (1944) described evidence that clasts do not touch in 3D (2). Neither study involved detailed microscopic analyses of the textures. The necessity for a more comprehensive study of well-exposed cockade breccias is indicated by this lack of published data. Material found by the authors during an investigation of low-temperature, near-surface veins on the Gower peninsula, South Wales, will serve to illustrate a few more of the textural aspects described above.

6. Geological setting of Gower veins, Gower peninsula, Wales

Abundant calcite-haematite veins outcrop within the Pembroke Limestone Group (Mississippian, lower Carboniferous) along the southern coast of the Gower Peninsula, South Wales (Fig. 2a). They occur along dilational strike-slip faults active late in the tectonic history of the Gower (George, 1940; Roberts, 1979), towards the end of the Variscan orogeny (Wright et al. 2009) and probably during Mesozoic rifting of the Bristol Channel Basin (Woodcock et al., in press; Ault, personal communication). Wright et al. (2009) documented a range of syndeformational open-void filling textures including the occurrence of cockade breccias. Formerly economic haematite mineralisation is present in some veins and might be related to the iron deposits of the Taff's Well/Llanharry ore field east of Swansea. The general nature of the fills, their simple mineralogy, and similarity to other deposits for which reasonable temperature constraints can be given (Dunham, 1984; Rankin and Criddle, 1985) indicates that formation probably occurred below 150°C.

Material for the present study was collected from the central part of the eastern vein at Oxwich (Fig. 8a of Wright et al., 2009). Cockades only make up a small part of the East Oxwich vein, occurring as the latest fill in a 20 to 50 cm wide zone cutting across the boundaries of all previous fills (Fig. 2b). They range from about 2 – 10 cm in diameter and consist almost entirely of several generations of columnar ferroan calcite cement, overgrowing clasts of previous calcite vein fills or of limestone. Later alteration processes including the partial leaching of ferrous iron from the calcite, oxidation and precipitation of finely disseminated ferric hydroxide caused the orange-brown colour of the haematite-free calcite now observed in the outcrop.

7. Textural evidence from the Gower cockades

While much of the cockade breccia unit is massive, some parts still show remnant porosity (Fig. 3). Sampling was from one of these parts, and was aided by the fact that individual cockades tended to break off along the sutures between the last generation of cement growing on adjacent clasts. This also demonstrated the lack of contact-points between clasts – individual fragments were found to be completely and evenly surrounded by cement on all sides. This was confirmed by the preparation of serial horizontal sections cut from several cockades. Figures 4 and 5 show detailed line drawings and the corresponding photographs of three parallel sections through one of the larger examples. The central sparry calcite clast is evidently not supported by other clasts on its lower side, parts of which would be expected to be seen in the last section.

The cement itself is exclusively columnar to blocky, with most individual crystals showing well-developed growth faces. These are picked out by layers of fine-grained haematite inclusions which appear to have coated the cockade at irregular intervals during its formation. The haematitic material probably originated from the comminution of massive haematite during fault movements within higher parts of the vein or as a direct precipitate from the solutions, and behaves as an internal sediment. This behaviour is illustrated by its tendency to coat individual calcite crystals only on their upward pointing faces in other parts of the vein system (Fig. 6a), as well as forming characteristic drapings which are thinnest at the tips of the crystals and become thicker in the spaces between crystals (Fig 6b). Such differences in thickness are only expected from sedimentation. A third characteristic illustrating the primarily sedimentary nature of the haematite coatings is the embedding of some larger fragments (up to a few millimetres in size) in these layers (Fig. 6c).

Finally, similar material present in other parts of the vein shows normal grading (Fig. 6d). Notably, the thickest layers of the haematitic sediment occur towards different sides of the cockades within different cement generations, and sometimes even on what is now the lower surface of the central clast (Figs. 4 and 5). It can also be seen from Fig. 4 that breakage points are occasionally present within the haematite and cement layers. Similar textures are present in all of the material collected.

The five essential textural characteristics expected for cockades formed by the rotation-accretion mechanism (see above) are therefore met by the Gower material. Unfortunately, the extent of the cockade breccia unit and the nature of the exposure (horizontal section) did not allow for the observation of any grading relationships and the dominant agitation mechanism could therefore not be assessed. The sedimentary behaviour of the very fine-grained haematitic material indicates that maximum fluid velocities must have been very low during the formation and subsequent cementation of the haematitic layers. Obviously, a fluid velocity in which material with an average grain size of < 100 μm can settle is much too low to fluidise much coarser material (cm-sized cockades), though the intermittent occurrence of high-flow events cannot be ruled out. Intervals evidently occurred in which no sedimentation of haematitic material took place (Figs. 4 and 5). If high-velocity flow did occur, it must have alternated with periods of low-velocity flow. It is difficult to assess the exact number of rotation and accretion cycles which occurred during the formation of the Gower cockades, since this would require the identification of all or most breakage points in the cement layers surrounding the cockades. However, from the points identifiable in the sections shown, there must have been at least two events after the initial formation of the central clast. If the occurrence of the thick layers of haematitic sediment is related to individual slip events, then at least four such events can be counted.

In conclusion, the evidence from the Gower strongly supports the rotation-accretion mechanism for cockade breccia formation as envisaged by Van Alstine (1944) and to an extent Genna et al. (1996). Although the dominant agitation mechanism (fault wall movement or high-flow events) could not be assessed, the above description considerably complements their observations.

8. Cockade breccias as indicators for relative cementation rates

Persistent void space between cockades throughout their formation is evidenced by a) the rarity of contact points, b) the abundance of nicely developed calcite crystal terminations (Fig. 4), and c) the incomplete infill between cockades at the present outcrop (Fig. 3). Similar observations were made by Genna et al. (1996) on the cockade breccias in the Cirotan gold mine, Indonesia. Incomplete cementation between bursts of tectonic activity is probably one of the key requirements for the formation of cockade textures, since it allows for relatively easy breakage along the cemented sutures between adjacent cockades. Such fracture sites in turn ensure that individual cockades remain mostly intact through each fracturing event and can slowly accumulate their successive cement coatings (Fig. 7a). This tendency to break between rather than across clasts was observed during sampling, particularly in the poorly cemented parts of the unit, supporting the notion that it also occurred during fault displacement. If cementation had been complete before every fault-slip episode, specific points of weakness would have been lacking. Fracture would have occurred across clasts, resulting in different generations of cross-cutting fracture fills (Fig. 7b).

Since fracturing by either movement of the fault walls or rapidly ascending fluids will always be related to fault slip (as discussed earlier) it is proposed that cockade breccias form along dilational faults where the rate of hydrothermal cementation is slow compared to the rate of fault slip. An abundance of cockades relative to other kinds of breccia vein fills therefore provides a proxy for either low cementation rate or high fault slip rate. In Gower, the abundance of cockade breccias is relatively low compared to other types of breccia, while in the Cirotan gold-mine it appears to be relatively high (Genna et al., 1996). However, calibrating absolute rates of either cementation or fault-slip on ancient faults remains problematic.

9. Random packing of granular materials and (cockade) breccia classification

There is a nomenclatural problem with many cockade breccias: the ratio of original clasts to crystalline cement is generally so low (< 30 %, cf. Table 2) that they would be classified as ‘vein fills’ rather than ‘breccia’ on the scheme of Woodcock and Mort (2008, Fig. 5b). This section addresses this issue.

Random packing of similarly sized grains of different shapes results in maximum porosities of about 50 % (Wyllie and Gregory, 1953). Random packing of non-equigranular materials results in lower porosity, because spaces between the larger grains are filled by some of the smaller grains. Therefore, in a cement-rich breccia resulting from a single fracturing event followed by cementation, the percentage of clasts should not be less than 50 %, well above the 30% threshold chosen by Woodcock and Mort (2008). However, where fragmentation results in a high proportion of small clasts (< 2 mm, Woodcock and Mort, 2008) and matrix (< 0.1 mm), the proportion of large clasts in fault rocks is commonly lower than 30 %, beyond which threshold the rocks are classified as cataclasites or mylonites (Woodcock and Mort, 2008, Fig. 5b).

Table 2 shows the proportion of cement (and minor matrix) present in photographs of seven published occurrences of cockade breccias. These examples mostly have negligible fine-grained matrix but an average of over 70 % cement. Clearly, clasts in these breccias cannot and do not form a self-supporting framework. It also means that many cockade breccias are not strictly breccias according to Figure 5b of Woodcock and Mort (2008). They have less than 30 % large clasts, and therefore classify as vein-fills.

The genetic explanation for the difficulty in classifying cockade breccias lies in their formation by repeated fracturing and cementation events. Mechanically, the 'clasts' produced by later fracturing events are composites of the original clasts and the early cement. Having recognised this nomenclatural difficulty, we do not propose to pursue it. There are many geometric problems in classifying the spectrum from vein-fills to cement-rich breccias, which lie beyond the scope of this paper. Whilst the purist may want to use the term *cockade texture* for examples with a low clast percentage, we suggest that *cockade breccia* is a pragmatic choice unlikely to be misunderstood.

10. Correct identification of cockade breccias

Criteria are listed below to help in the correct identification of proper cockade breccias, particularly in the field. The following five criteria should be observable in any cockade breccia (also see Fig. 8):

1) Concentric banding around clasts,
2) Columnar cement and, or, other space-filling textures;
3) Sharp boundaries between clasts and the first cement generation (i.e. no evidence for replacement, although this might not be detectable on the macro-scale);
4) Volume proportion of cement significantly higher than 50%;
5) Clasts not touching. This might be demonstrated either by extracting single cockades from the outcrop (such as was done for this work) or by serial sectioning of samples containing at least one or two whole clasts.

Two further criteria might be evident from lab-based investigations:

6) Points of breakage in cement layers where cockades were previously touching each other;
7) Rotated geopetal indicators (such as the haematitic sediment in the present case).

Of particular significance, especially for the distinction between cockade breccias and single-phase breccias cemented by multiple cement generations are criteria (4) to (7). The volume proportion (4) provides the strongest clue, and should be observable in the field. It should also be preserved if later overprinting or alteration of the breccia has removed some or most of the other textural evidence such as columnar cement textures (2) or clast/cement contacts (3).

Two different mechanisms are expected to contribute to the mechanical agitation necessary for cockade formation: fault wall movement and fault slip-induced rapid fluid flow. If cockade breccia units are of a sufficient size to show grading relationships, the dominant agitation mechanism might be identified. In particular, reverse grading is expected if fault wall movement was dominant, while normal grading is expected if a rapidly ascending fluid was dominant.

It will be noted that the criteria given above specifically limit the definition of the term *cockade breccia* to those structures formed by the rotation-accretion mechanism. For the superficially similar structures formed by partial metasomatic replacement of clast minerals, a different term should be used. The genetic implications of their occurrence are quite different to that of cockade breccias.

11. Conclusions

- Cockade textures have been recognised in mineral veins since 1836, with the term *cockade* being used since 1859 for concentric banding of mineral cements around breccia clasts.
- A review of 106 published descriptions of cockade breccias shows that about half of the examples come from epithermal Au-(Ag, Cu) veins, a quarter from mainly epithermal Pb-Zn-(Cu, Ag, Sn) veins, and the remainder from other parageneses.
- At least six mechanisms have been proposed for the formation of cockade breccia-like textures, but only two – repeated rotation-accretion, and partial metasomatic replacement of clast minerals – have been supported by detailed evidence.
- A new example of cockade breccia, from the East Oxwich fault on the Gower Peninsula (South Wales), shows clear evidence for the rotation-accretion mechanism, particularly overgrown breakage points in cement layers, where cockades were previously touching each other, and rotated geopetal infills of hematitic sediment.
- Cockade textures probably result from low rates of cement growth compared to high rates of dilational fault slip. Seven criteria are given for the correct identification of cockade breccia.
- Grading relationships can be used to identify the driver mechanism for re-fracturing and cockade rotation. This is relevant since such cases where rapid fluid flow can be demonstrated to have been the dominant driver mechanism might be used to constrain maximum fluid flow velocities.
- Due to their different genetic implications, cockade breccia-like textures resulting from partial metasomatic replacement of clast minerals should not be called cockade breccias. The criteria defined above may be used to distinguish them from cockade breccias *sensu stricto*.

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Figure Captions

Fig. 1: Illustrations of the six main hypotheses for the formation of cockade breccias: (a) cut-effect, (b) crystallisation pressure, (c) suspension in fluid, (d) partial metasomatic replacement of clast minerals, (e) infall of clasts during cementation and (f) repeated rotation and accretion. For detailed explanations see main text.

Fig. 2: Maps showing the exact location of the cockade breccia occurrence on the Gower peninsula: (a) Regional geological overview, with the Oxwich faults marked in; (b) map of the East Oxwich fault as it outcrops on the foreshore. The sequence of the major fill generations is: (1) white calcite, (2) breccia with red matrix, (3) breccia with orange matrix, (4) cockade breccia. Note that the term 'matrix' in this case is used to refer to all the material between individual clasts, since the distinction between cement and fine-grained material is difficult in the field. Coordinates provided on (a) refer to the UK ordnance survey grid. Ovals with radiating lines towards the eastern side of the vein represent wall rock fragments overgrown by the first cement generation.

Fig. 3: Field photographs showing the cockade breccia unit: (a) sampling location, with sample material still in place (the arrow marks the cockade shown in detail in Fig. 4), and (b) view to the right of (a), showing the continuity of the unit. Hammer for scale. Red bands correspond to haematite inclusion-rich zones.

Fig. 4: Line drawings of horizontal, serial sections through one cockade, taken at vertical distances of c. 1 cm, with (a) being on top, and (c) at the bottom. All black lines and areas mark zones rich in haematite inclusions. Sections are shown in the same orientation as the cockade was found, seen from above (cf. Fig. 3a). The subdivision into cement generations I to IV followed the occurrence of pronounced zones of inclusion-rich material. Shading does not reflect real variations in colour. Arrows indicate small breaks in the cement layers. The photographs corresponding to these drawings are shown in Fig. 5.

Fig. 5: Photographs corresponding to the line drawings in Fig. 4; (d) shows a schematic sketch of the exact locations of the sections within the original cockade, seen from the side.

Fig. 6: Sedimentary nature of fine-grained haematitic material: (a) preferential coating of upward directed crystal faces of cement on fault walls, (b) varying thickness across crystal tips which were probably coated from above, due to sediment slumping (detail of Fig. 5b), (c) larger fragments of

various vein fills embedded in haematitic sediment, (d) normal grading of fragments in haematitic sediment. All samples shown were taken from the East Oxwich fault, except for the one shown in (a) which was taken at Limeslade Bay. Similar textures occur ubiquitously throughout the Gower veins.

Fig. 7: Illustration of the two textural end-members resulting from multiple refracturing and recementation events of a breccia body depending on the relative speed of cementation: (a) formation of a cockade breccia at low relative cementation speed where fracturing of clasts is mostly along cement sutures between clasts, and (b) formation of a multiphase crackle breccia, where relative cementation speed is fast, resulting in the complete cementation of the clasts between fracturing events. The apparent proportion of cement in the lower two thirds of the two breccia bodies at stage III are 58.3% and 63.2 % for the cockade and crackle breccias, respectively.

Fig. 8: Schematic illustrations of eight criteria for the correct identification of cockade breccias *sensu stricto*, (a) identifiable on outcrop scale, (b) identifiable on hand-specimen scale. Verification of some criteria might necessitate microscopic examination. For details see main text.

Table 1 – Occurrence of cockade breccias

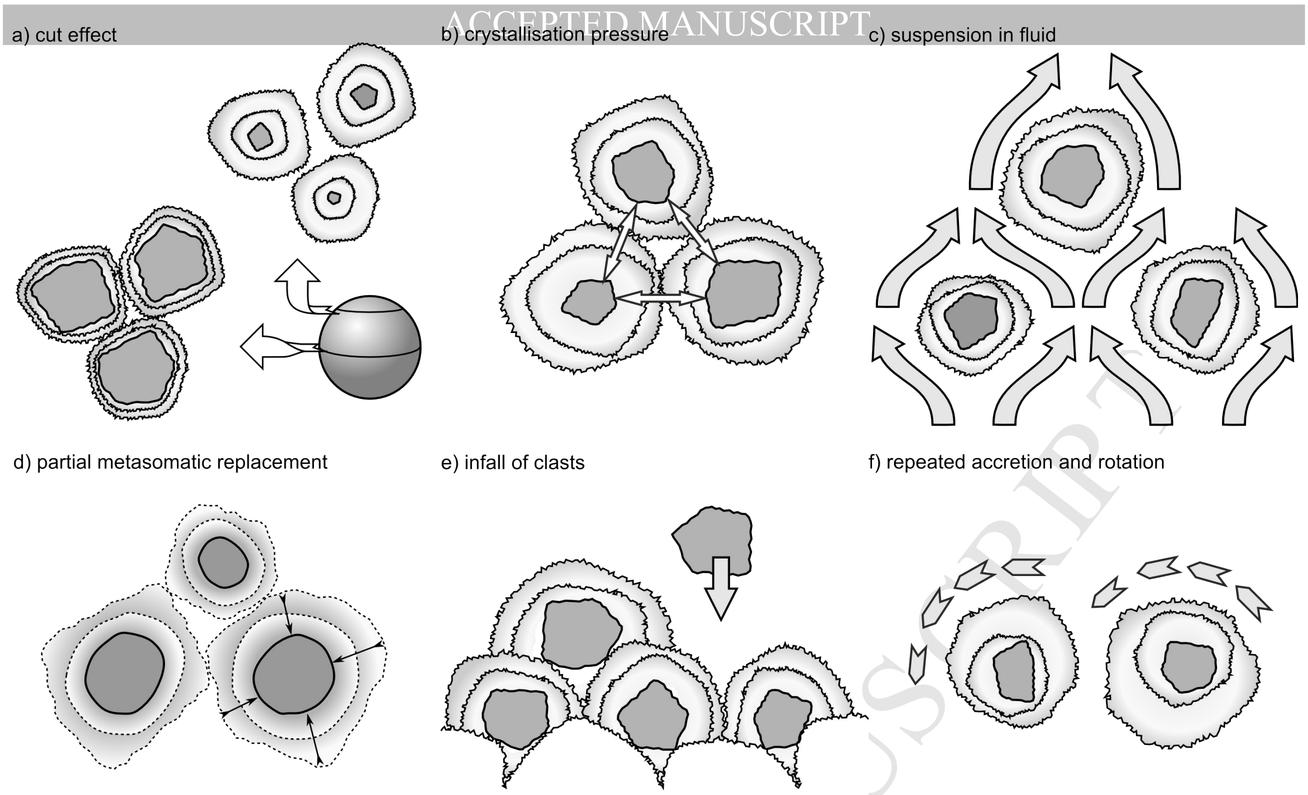
Type	No. of well documented occurrences[1]	Total no. of reported occurrences	Main references (well documented occurrences)
Epithermal Au-(Ag,Cu) veins	5	52	Gibson et al., 1990; Jobson et al., 1994; Genna et al., 1996; Leroy et al., 2000; Grancea et al., 2002; Squires, 2005
(Epithermal) Pb-Zn-(Cu,Ag,Sn) veins	11	25	Weissenbach, 1836; Spurr, 1926; Buerger and Maury, 1927; Ingham, 1940; Watson, 1943; Kutina and Sedlackova, 1961; Rieder, 1969; Sperling, 1973; Laznicka, 1988; Munoz et al., 1994, 1999; Bélissont et al., 2014
Fluorite-(Baryte) veins	1	10	Van Alstine, 1944
Low-T Calcite veins	1	2	Wright et al., 2009
Mesothermal veins (various)	-	2	-
Other	-	15	-

[1]Containing at least either pictures of proper cockade breccias or an accurate and detailed description.
Note: A complete list of all occurrences and the references used for the compilation of this table may be found in Appendix A, in the online supplementary material.

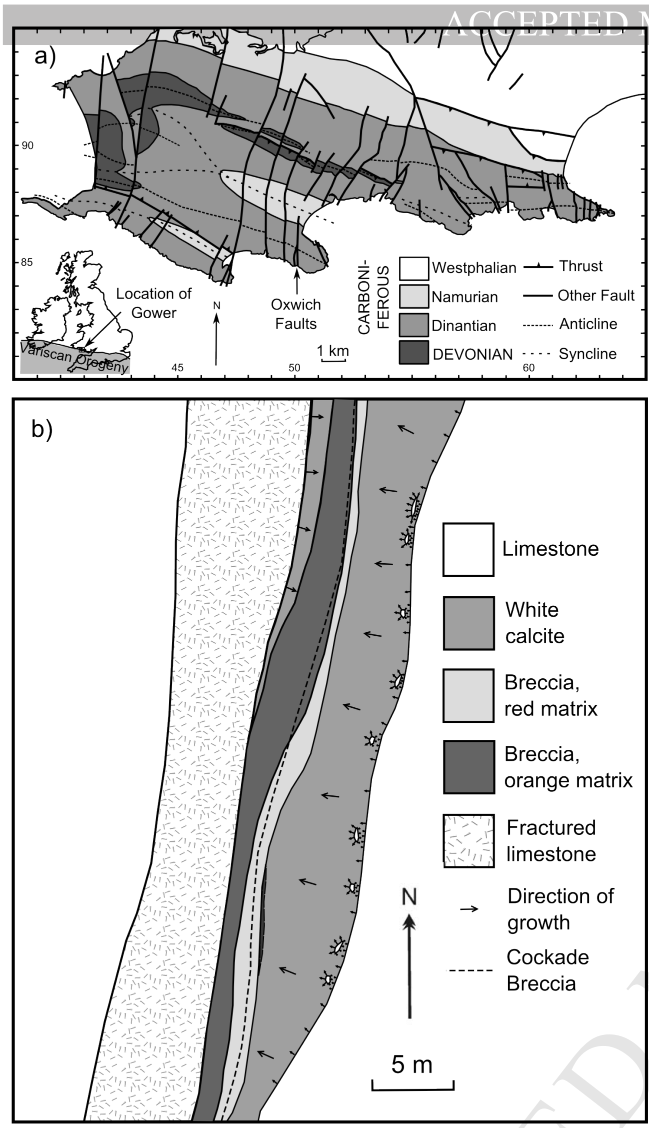
Table 2 – Cement proportion of (true) cockade breccias

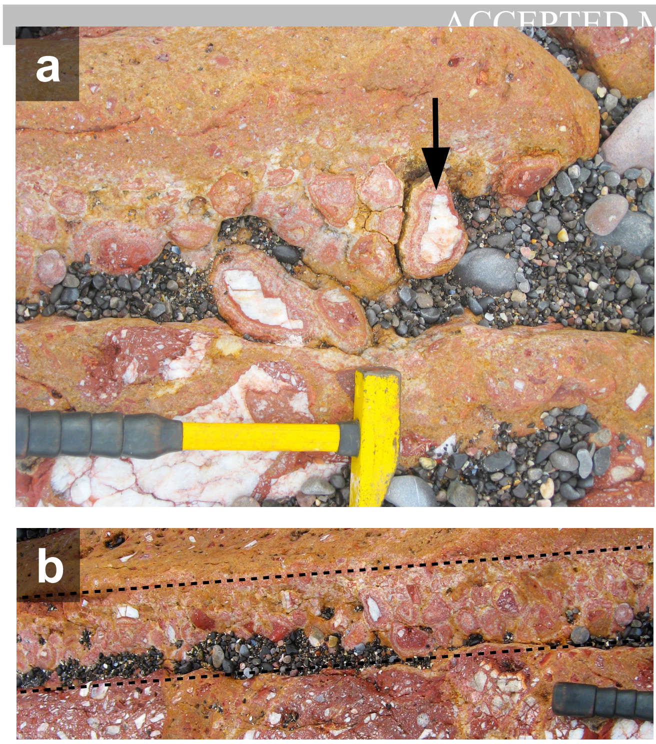
Locality	Type	Clasts touching in section?	Apparent porosity[1]	No. of clasts in sections (No. of figures)	Reference(s)
Chocaya, Bolivia	Sn-Ag veins	No	0.71	12 (1)	Buerger and Maury, 1927
Grund mine, Germany	Pb-Zn-Ag veins	No	0.65 – 0.78 (0.71)	29 (2)	Sperling 1973
Lebong Tandai mine, Indonesia	Epithermal Au veins	No	0.72	16 (1)	Jobson et al., 1994
Pribram, Czech Republic	Pn-Zn-Ag veins	No	0.75 – 0.85 (0.80)	44 (2)	Kutina and Sedlackova, 1961
Alacrán Mine, Mexico	Ag-Pb-Zn vein	No	0.72 – 0.85 (0.80)	18 (3)	Spurr, 1926
Akshiiryak deposit, Kirghizia	Pb-Zn veins	No	0.81	16 (1)	Laznicka, 1988
Cirotan, Indonesia	Epithermal Au veins	No	0.57 – 0.89 (0.79)	88 (6)	Genna et al., 1996; Leroy et al., 2000

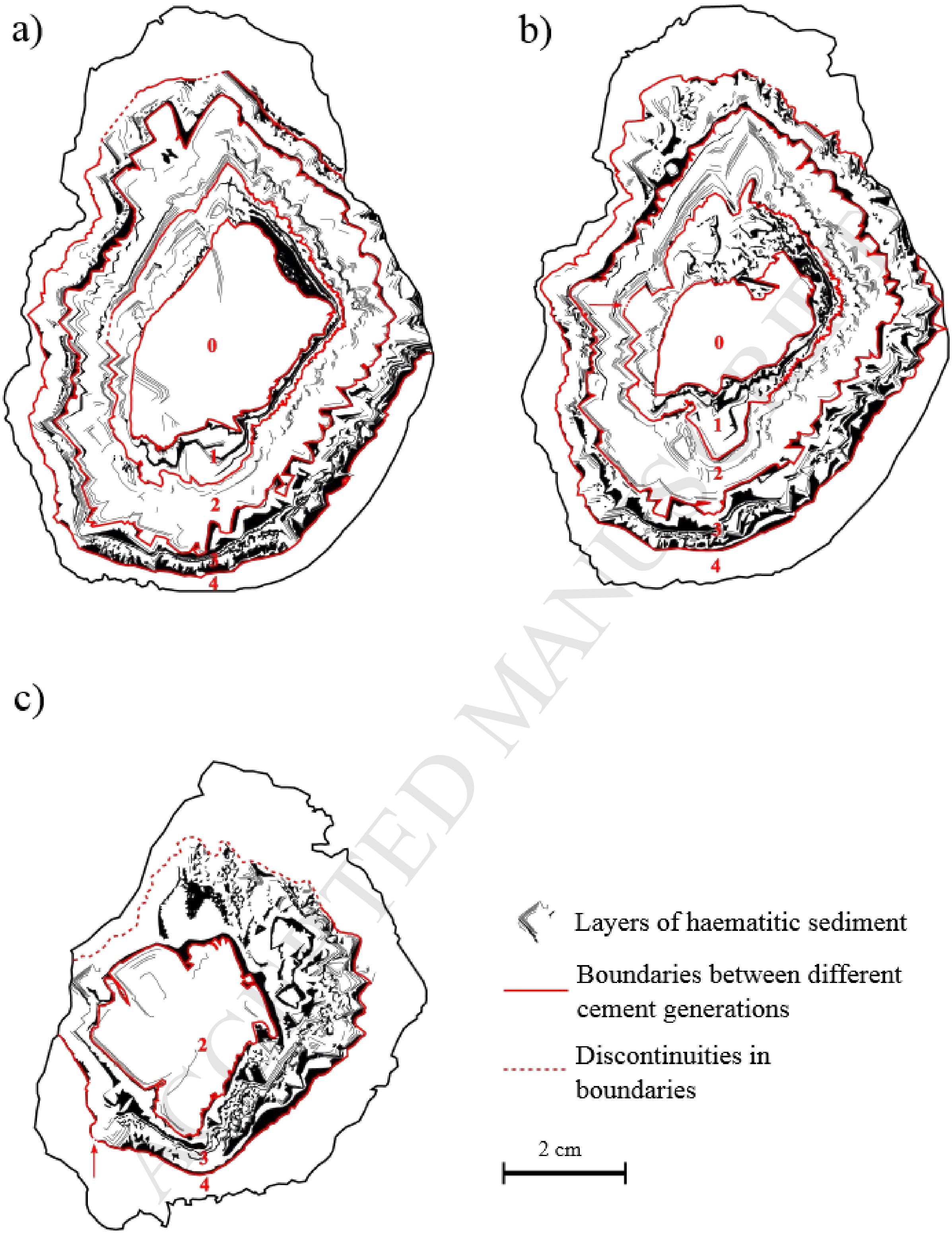
[1]Ranges are given, where several figures were analysed. The number in parantheses below the range gives the average apparent porosity of all figures.

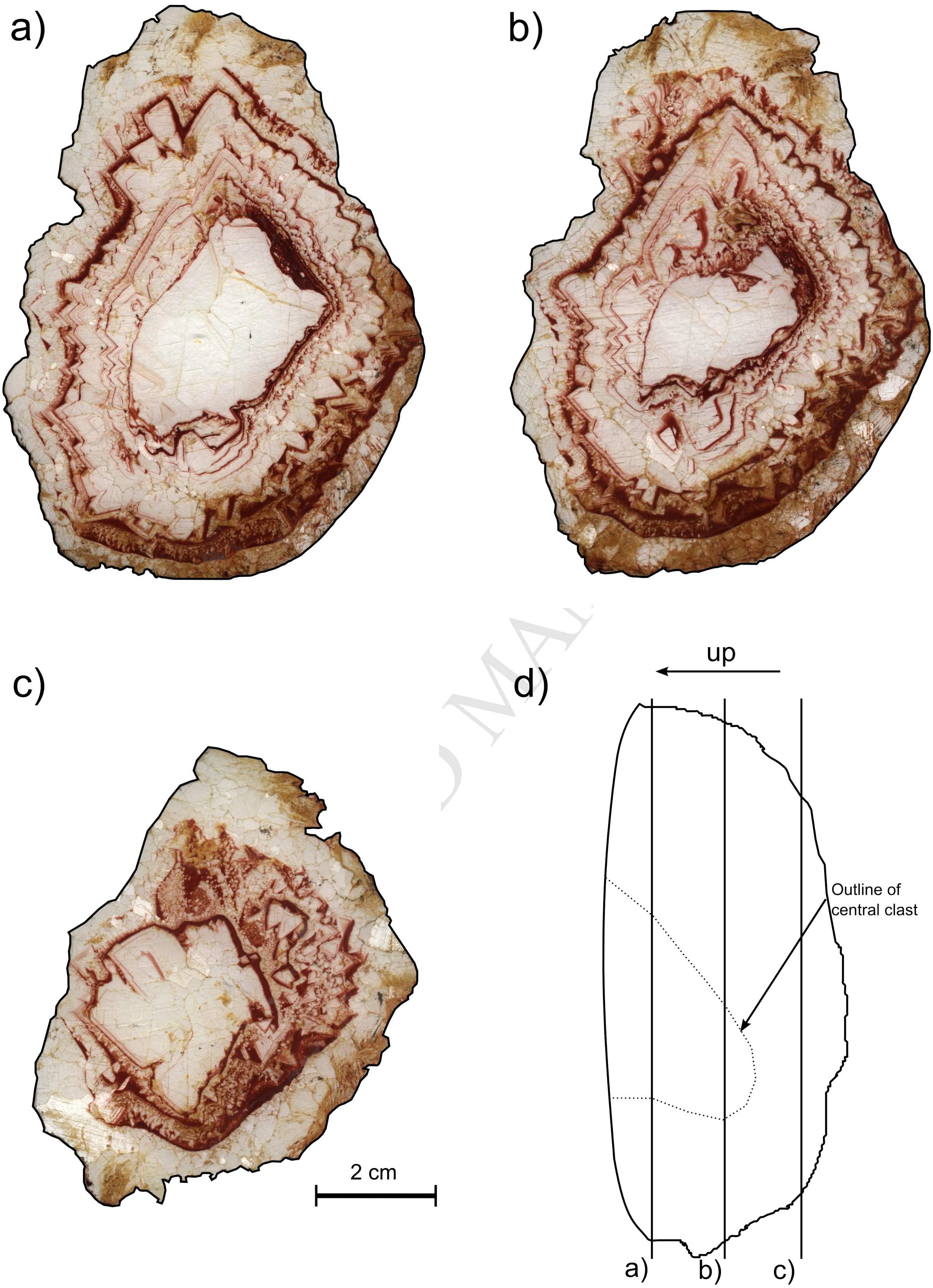


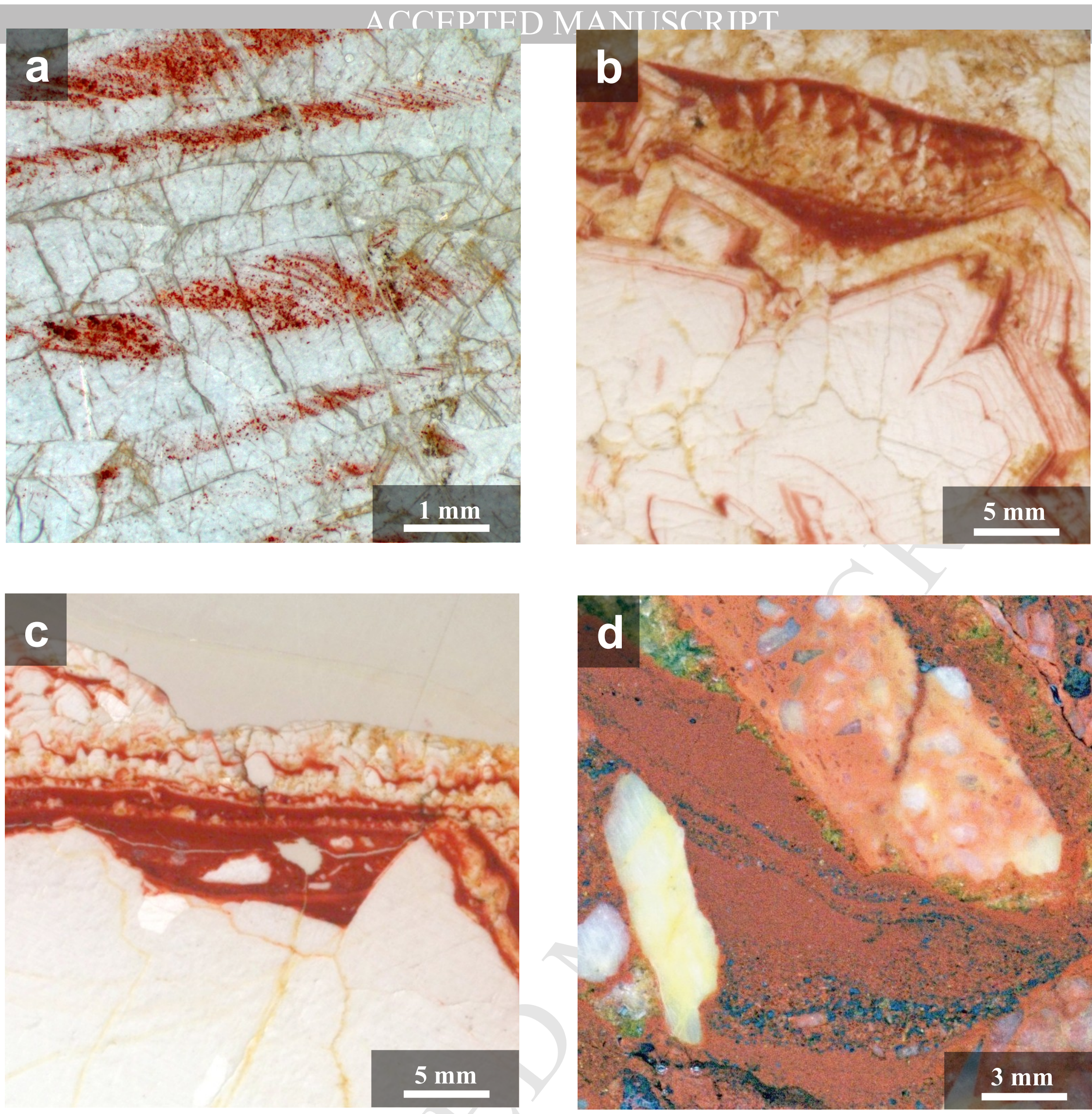
a) cut effect
b) crystallisation pressure
c) suspension in fluid
d) partial metasomatic replacement
e) infall of clasts
f) repeated accretion and rotation

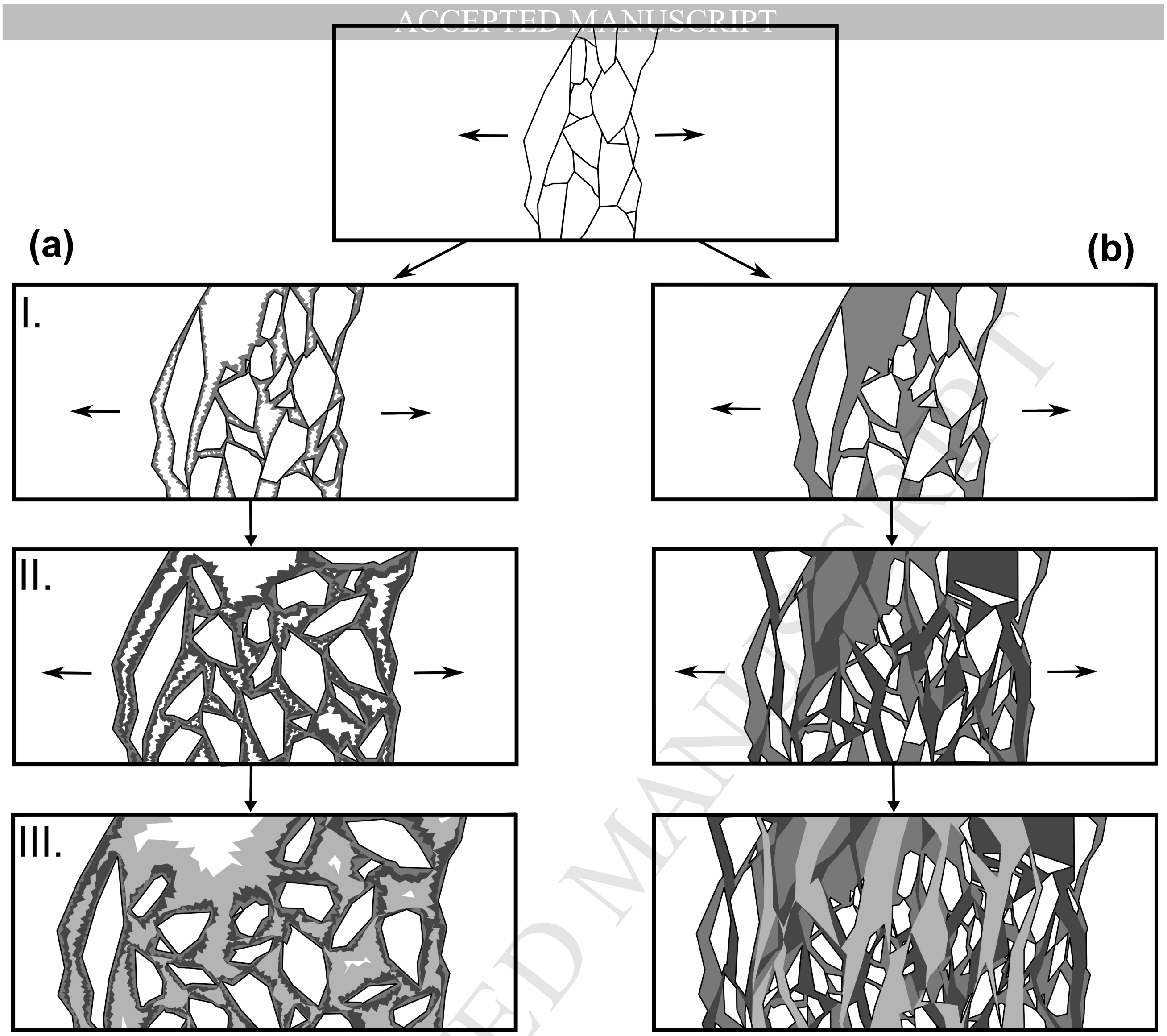

a)
90
85
Location of Gower
Variscan Orogeny
N
Oxwich Faults
45
50
60
1 km
CARBONI-FEROUS
Westphalian
Namurian
Dinantian
DEVONIAN
Thrust
Other Fault
Anticline
Syncline
b)
Limestone
White calcite
Breccia, red matrix
Breccia, orange matrix
Fractured limestone
N
Direction of growth
Cockade Breccia
5 m

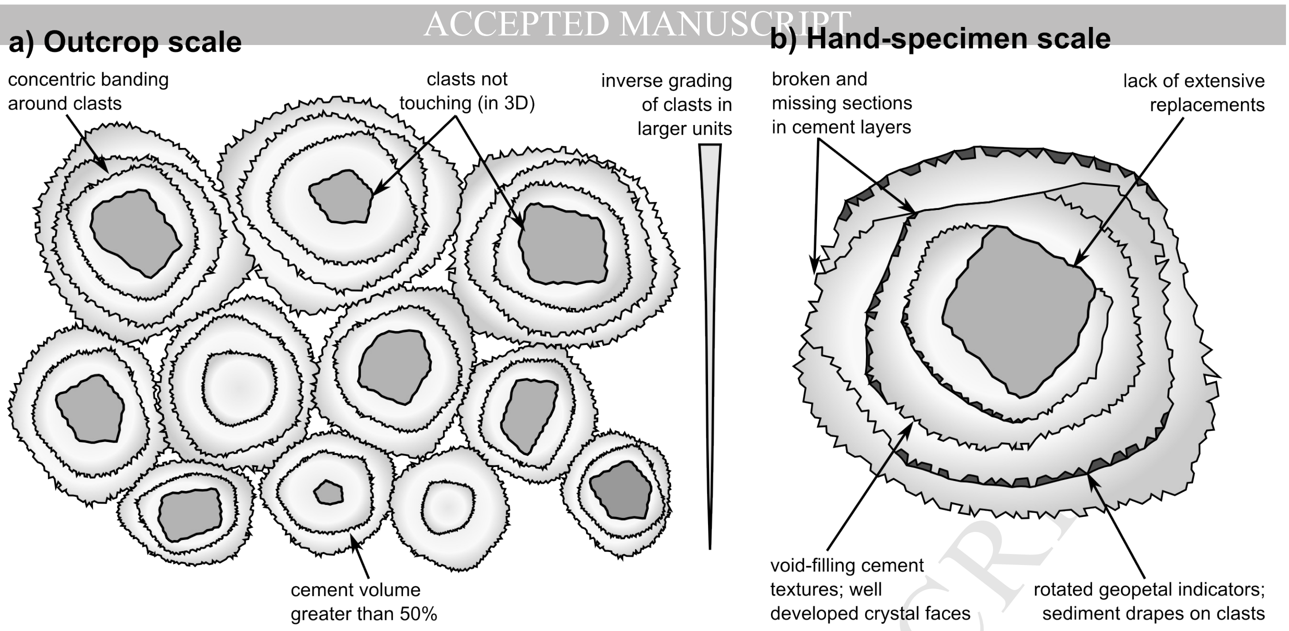

a
b


a)
0
1
2
4
b)
0
1
2
4
c)
2
3
4
Layers of haematitic sediment
Boundaries between different cement generations
Discontinuities in boundaries
2 cm


a)
b)
c)
d)
up
Outline of
central clast
2 cm
a)
b)
c)


a
1 mm
b
5 mm
c
5 mm
d
3 mm


(a)
(b)
I.
II.
III.



a) Outcrop scale
concentric banding around clasts
clasts not touching (in 3D)
inverse grading of clasts in larger units
cement volume greater than 50%
b) Hand-specimen scale
broken and missing sections in cement layers
lack of extensive replacements
void-filling cement textures; well developed crystal faces
rotated geopetal indicators; sediment drapes on clasts

Appendix A – Occurrences of cockade breccias

Table A1 – Well documented occurrences

Type	Locality	Reference(s)
Epithermal Au-(Ag,Cu) veins	Calera, Oropampa district, Peru	Gibson et al., 1990
	Baia Mare, Romania	Grancea et al., 2002
	Exploits subzone and Gander zone, Newfoundland	Squires, 2005
	Cirotan mine, Indonesia	Genna et al., 1996; Leroy et al., 2000
	Lebong Tandai mine, Indonesia	Jobson et al., 1994
Epithermal Pb-Zn-(Cu,Ag,Au,Sn) veins	Saint-Salvy/Noailhac deposit, France	Munoz et al., 1994; Bélissont et al., 2013
	Peyrebrunne, France	Munoz et al., 1997
	Chocaya, Bolivia	Buerger and Maury, 1927
	Shawangunk Mts., New York State, USA	Ingham, 1940; Sims and Hotz, 1951; Wilbur et al., 1990; Friedman et al., 1994
	Pribram, Czech Republic	Kutina and Sedlackova, 1961
	Bad Grund, Harz Mts., Germany	Lang, 1973
	Akshiiryak, Khirgizia	Laznicka, 1988
	Bianska Stavnica, Slovakia	Rieder, 1969
	Alacran mines, Mexico	Spurr, 1926
	Port au Port Peninsula, Newfoundland, Canada	Watson, 1943
	Erzgebirge Mts., Germany	Weissenbach, 1836
Fluorite-Baryte veins	St. Lawrence, Newfoundland, Canada	Van Alstine, 1944
Low-T calcite veins	Gower Peninsula, Wales	Wright et al., 2009

Table A2 – Reported occurrences

Type	Locality	Reference(s)
Epithermal Au-(Ag,Cu) veins	Efemcukuru, Izmir, Turkey	Baba and Güngör, 2002; Oyman et al., 2003
	Golden Cross, New Zealand	Bebgie et al., 2007
	Pajingo, Queensland, Australia	Bobis et al., 1995
	Waihi, New Zealand	Braithwaite and Fauré, 2002
	Shila Cordillera, Peru	Cassard et al., 2000; Chauvet et al., 2006
	South Korea	Choi et al., 2005a,b
	Hauraki goldfield, New Zealand	Christie and Robinson, 1992
	Acupan, Baguio District, Philippines	Cooke and Bloom, 1990
	Cracow vein system, Queensland, Australia	Dong and Morrison, 1995; Dong and Zhou, 1996
	Eastern Dunnage zone, Newfoundland, Canada	Evans, 1993
	Qaleh-Zari deposit, Iran	Hassan-Nezhad and Moore, 2006
	Yatani deposit, Japan	Hattori, 1975
	Tonopah mine, Nevada, USA	Henley and Berger, 2000

Type	Locality	Reference(s)
	Comstock district, Nevada, USA	Hudson, 2003
	Ikuno mine, Japan	Jensen, 1957
	Lalab, Sibutad, Zamboanga del Norte, Philippines	Jimenez et al., 2002a,b, 2007
	Sunshin, South Korea	Kim et al., 2012
	Haenam-Jindo area, South Korea	Kim and Choi, 2009
	Ducat and Lunny orefields, Russia	Konstantinov et al., 1993
	Chah Zar deposit, Iran	Kouhestani et al., 2012, 2013
	Ozernovskoe and Praslovskoe deposits, Kuril, Kamchatka, Russia	Kovalenker and Plotinskaya, 2005
	Jinxi-Yelmand, Tianshan, Xinjiang, China	Long et al., 2005
	Guanajuato, Mexico	Mango et al., 2013
	Steep Nap prospect, Newfoundland, Canada	Mills et al., 1999
	Kiena Mine, Val D'Or, Quebec, Canada	Morasse et al., 1995
	Don Sixto deposit, Mendoza, Argentina	Mugas Lobos and Marques Zavalia, 2013
	Ohio and Mt. Baldy districts, Piute Cty., Utah, USA	Nuelle et al., 1985
	Holyrood Horst, Newfoundland, Canada	O'Brien, 2002
	Bahia Laura, Deseado Massif, Argentina	Paez et al., 2010
	Taebaeksan district, Korea	Pak et al., 2004
	El Dorado district, El Salvador	Richer et al., 2009
	Victoria deposit, Mankayan district, Luzon, Philippines	Sajona et al., 2002
	Tuvatu deposit, Fiji	Scherbarth and Spry, 2006
	Tongyoung deposits, Korea	Shelton et al., 1990
	Seigoshi district, Izu Peninsula, Japan	Shikazono, 1985
	Koryu mine, Hokkaido, Japan	Shimizu et al., 1998
	Mt. Muro Prospect, Borneo, Indonesia	Simmons and Browne, 1990
	Sierras Pampeanas, Argentina	Skirrow et al., 2000
	Esquel deposit, Argentina	Soechting et al., 2008
	Major's Creek, New South Wales, Australia	Wake and Taylor, 1988
	Hurd Peninsula, South Shetlands	Willan, 1992, 1994; Willan and Spiro, 1996
	Wadi Abu Khuhsayba, Jordan	Al-Hwaiti et al., 2010
	Gunung Pongkor deposit, West Java, Indonesia	Basuki et al., 1994
	Chahnali prospect, Baman volcano, Iran	Daliran et al., 2005
	Caylloma district, Peru	Echavarria et al., 2006
	Tombulilato district, North Sulawesi, Indonesia	Perello, 1994

Type	Locality	Reference(s)
	Promezhutochnoe deposit, Central Chukchi, Russia	Volkov and Prokofev, 2011
Epithermal Pb-Zn-(Cu,Ag,Au,Sn) veins	Milos Island, Greece	Alfieris et al., 2013
	Santo Nino Vein, Fresnillo Distr., Zacatecas, Mexico	Simmons et al., 1988; Gemmell et al., 1989
	Yatanideposit, Japan	Hattori, 1975
	Pingüino vein system, Deseado Massif, Patagonia, Argentina	Jovic et al., 2011a,b,c
	Nigadoo vein deposit, New Brunswick, Canada	Kalliokoski, 1961
	Dunbrack deposit, Musquodoboit batholith, southern Nova Scotia	Kontak et al., 1999
	Hiendelencina district, Guadalajara, Spain	Martinez Frias, 1992
	Alcudia valley, Eastern Sierra Morena, Spain	Palero-Fernandez et al., 2003; Palero Fernandez and Martin Izard, 2005
	San Vicente, Peru	Schütfort, 2001
	Sambo deposit, Korea	So et al., 1984
	Plaka Ore-System, Lavrion, Greece	Voudouris et al., 2008
	Castrovirreyana District, Central Peru	Wise, 2005
	Minas Capillitas	Marquez Zavalia, 2002; Putz et al., 2006; Paar et al., 2008; Putz et al., 2009
	Kolyma-Verkhoyansk fold belt, Russia	Anikina et al., 2003
	Assif El Mal, High Atlas, Morocco	Bouabdellah et al., 2009
Fluorite-Baryte veins	Cerro Aspero, Cordoba prov. , Argentina	Coniglio et al., 2000
	Nabburg-Wölsendorf district, SE Germany	Dill and Weber, 2010; Dill et al., 2011
	Regensburg, SE Germany	Dill et al., 2012
	Speewah, Kimberley, Australia	Gwalani et al., 2010
	Southeastern Alps, Europe	Hein et al., 1990
	Southwestern Massif Central, Albigeois, France	Munoz et al., 1999
	Valle de Tena, Pyrenees, Spain	Subias et al., 1998
	La Azul deposit, Taxco district, Mexico	Tritlla and Levresse, 2006
	Santa Catarina State, Brazil	Jelinek et al., 1999
Low-T calcite veins	Southern Arizona	Davis et al., 1979
Mesothermal veins (various)	Salsigne deposit, France	Demange et al., 2006
	Bilimoia, Kainantu region, Papua New Guinea	Espi et al., 2007
Orogenic/Epizonal gold deposits	Red-Lake/Campbell mine, Canada	Penczak and Mason, 1997; Tarnocai et al., 1998; Penczak and Mason, 1999; Dubé et al., 2004; Chi et al., 2009
	Donlin Creek, Alaska, USA	Goldfarb et al., 2004

Type	Locality	Reference(s)
	Yilgarn Craton, Western Australia	Groves, 1993; Groves et al., 1998; Bateman and Hagemann, 2004
	Wiluna, Western Australia	Hagemann and Lüders, 2003
	Kalgoorlie district, Western Australia	Mueller et al., 1988, 2013
MVT	*Zawar, India*	*Mookherjee, 1964*
	County Tipperary, Ireland	*Wilkinson and Lee, 2003*
	Southwestern Sardinia, Italy	*Boni and Malafronte, 1983; Boni, 1986; Boni et al., 1988*
	Howell, Jefferson County, USA	*Ludlum, 1955*
	Bleiberg	*Schroll et al., 1983*
IOCG	Oak Dam East, Galwer Craton, Australia	Davidson et al., 2007
	Contact Lake Belt, Northwestern Territories, Canada	Mumin et al., 2007
Calcite cemented calamine breccia	High Atlas, Morocco	Choulet et al., 2014
U-Ni-Co-As-Ag/Bi veins	Zalesi deposit, Czech Republic	Dolnicek et al., 2009
Low-T quartz-fluorite-pyrite-chlorite-siderite veins	South Crofty mine, Cornwall, UK	Dominy et al., 1994
Cassiterite veins	Rosevale Mine, Zennor, West Cornwall	Dominy et al., 1995
Karst collapse breccias	*Egypt*	*El-Aref et al., 1986; El-Sharkawi et al., 1990*
Hydrothermal Mn/Fe-Mn deposits	Baft, Kerman, Iran	Heshmatbehzadi and Shahabpour, 2010
Quartz veins in granite	Southwest Avalon zone, Newfoundland, Canada	O'Driscoll and Strong, 1979
Phreatic breccias	*Southern Alps, Italy*	*Servida et al., 2010*
	-	*Tamas and Milesi, 2003*
Au-Sb veins	Loddiswell, Devon, UK	Stanley et al., 1990
Unmineralised epithermal veins	Ixtacamaxtitlan, Puebla State, Mexico	Tritlla et al., 2004

Note: Occurrences in italics were not included with the counts in Table 1, since it was thought that they did likely not represent proper cockade breccias.

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