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THE SLUMP BRECCIAS OF THE TOQUEPALA PORPHYRY CU(-MO) DEPOSIT, PERU: IMPLICATIONS FOR FRAGMENT ROUNDING IN HYDROTHERMAL BRECCIAS

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Introduction

Intrusive hydrothermal breccias have long attracted interest (e.g., Bastin and Hill, 1917; Farmin, 1934; Bryner, 1961; Mayo, 1976) due, in part, to their widespread occurrence in association with many types of ore deposits. In porphyry copper centers such breccias may host a substantial proportion of the mineralization but, even where barren, they provide critical information on the physical evolution of the (magmatic) hydrothermal environment. Most salient aspects of ore-related breccias are addressed by Sawkins and Sillitoe (1985). Burnham (1985) emphasized the enormous release of energy concomitant with the near-surface intrusion of water-bearing magmas and its role in breccia development, and since the proposals of Reynolds (1954), most workers have accepted an involvement of fluidization processes in the emplacement of the fragmental materials.

Among the more intriguing features of hydrothermal breccias is the occurrence of rounded clasts, particularly in the so-called pebble breccias. These have generally been attributed to shearing, rotation, and attrition of originally angular rock fragments during transport in a particle-charged gaseous stream (see Boothroyd, 1971). Thus, in the Patch breccia pipe, Central City, Colorado, Bastin and Hill (1917) record a correlation between fragment rounding and the juxtaposition of diverse rock types. Extensive downward (e.g., at Leadville, Colorado; Emmons et al., 1927) or upward (e.g., at Tintic, Utah; Farmin, 1934) movement of clasts in breccia pipes has been well documented in several mining districts. In an allied context, Williams (1936) established a correlation between the degree of rounding of fragments and the extent of their upward translation in Pliocene diatremes in Nevada.

Alternative mechanisms proposed for clast rounding include solution, perhaps in an originally overlying crater lake (e.g., Yeatman, 1911), or subsurface chemical corrosion (Butler, 1913); neither model has received wide support. In contrast, Farmin's (1937) concept of "hypogene exfoliation" resulting from abrupt decompression has been advocated by several workers. Sillitoe (1985), in particular, argues that exfoliation would be a predictable outcome of breccia formation, and that its occurrence is evident in the fabrics of numerous breccia systems.

Despite the abundant evidence supporting these mechanisms, the writer considers that processes other than either interfragment attrition or exfoliation may have been responsible for the development of rounded clast forms in some hydrothermal breccia systems. The fabrics of some tectonites in the Toquepala porphyry copper (-molybdenum) deposit of southeastern Peru are interpreted as evidence for the formation of rounded clasts during initial rock fragmentation, possibly under conditions equivalent to, or approaching, those of shock metamorphism, as originally proposed for hydrothermal breccia development by Godwin (1973). In this discussion, the roundness scale developed for sedimentary particles by Powers (1953) is applied. Level altitudes in the Toquepala open pit are expressed in meters above sea level.

Hydrothermal Breccias at Toquepala, Peru

The presence of enormous volumes of hydrothermal breccia of diverse types in the Toquepala deposit (lat 17°14′ S; long 70°36′30″ W) has been recognized since the early geologic work of Richard et al. (1951) and Richard and Courtright (1958). Those authors distinguished a polyphase ore breccia (the "angular breccia" of recent Southern Peru Copper Corporation mapping; Fig. 1) characterized by a tourmaline-quartz-rock flour cement, which was considered to contain inherent chalcopyrite mineralization (but see Zweng and Clark, 1984, and in prep.). Rock fragments in the ore breccia, which would be classified by Sillitoe (1985) as a "magmatic-hydrothermal" system, are overwhelmingly of local derivation and are predominantly angular, but small volumes of tourmaline-cemented breccia, as on the 3,160-m level north (1975)[1] and the 3,160-m level northeast (1982), contain a proportion of rounded to surrounded clasts (Fig. 2a). Some such breccias display a heterolithic clast population (Fig. 2b), a relationship in permissive agreement with models involving clast abrasion during transport. However, some of the rare rounded clasts in the characteristic tourmaline-cemented angular breccia show (Fig. 2a and c); concentric fractures strongly suggestive of exfoliation and spalling during abrupt decompression (cf. Farmin, 1937; Allman-Ward et al., 1982; Sillitoe, 1985, fig. 21; Chârusiri, 1988).

[1] Dates of observations are given in parentheses.

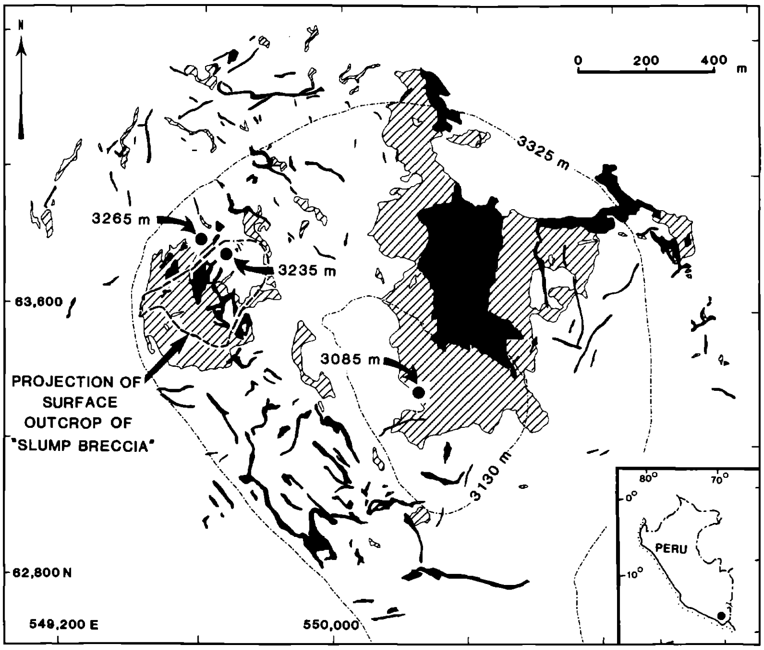

FIG. 1. Simplified geologic map of Toquepala porphyry Cu(-Mo) deposit (after Richard and Courtright (1958) and Southern Peru Copper Corp. Eng. Dept.). Locations of breccia exposures described here are shown, as are selected open-pit levels (in m a.s.l.). Dashed area indicates approximate vertical projection of body of slump breccia mapped on premine surface by Richard et al. (1951); cf. Figure 5. Diagonal ruling = ore or angular breccias; black = pebble- and other rock-flour-cemented breccias.

A minor mineralized breccia facies, the "molybdenite breccia" of Zweng (1984), in which molybdenite constitutes a major component of the matrix, also displays a subordinate proportion of rounded and subrounded clasts, commonly of earlier formed tourmaline-cemented breccia. Such features were observed on the 3,085-m level northwest (1982) of the pit (Figs. 1 and 3). In the same area, molybdenite and chalcopyrite occur abundantly in a stockwork in which the majority of the fractures are markedly curved.

Richard and Courtright (1958) further documented the occurrence of an exceptional development of predominantly rock flour-cemented breccias at Toquepala; these they grouped under the single heading of "pebble breccias" although not all facies exhibit rounded clasts. A wide (avg dia, 300 m) breccia pipe (Fig. 1), dominated by angular to subangular clasts, is surrounded by both radial and crudely concentric inward-dipping dikes of characteristic pebble breccia (Figs. 1 and 4). Richard and Courtright (1958) observed that almost all bodies of such phreatic breccias postdated hypogene Cu and Mo mineralization at Toquepala but overlapped temporally with the emplacement of quartz latite porphyry dikes, a relationship amply confirmed by subsequent workers (e.g., Stevenson and Damiani, 1968, who, however, proposed a breccia classification differing from that of Richard and Courtright). These late breccias conform to the phreatic (hydromagmatic) class of Sillitoe (1985). Zweng (1984) and Zweng and Clark (in prep.) provide additional documentation of the major breccia lithologies in this deposit.

Slump Breccias

In addition to the above hydrothermal breccia classes, a further type was identified in the initial surface geologic mapping at Toquepala (Richard et al., 1951). Two outcrops of "slump breccia," lying to the west and north-northeast, of the surface outcrop of the main mineralized zone, respectively, were delimited (Fig. 5). This descriptive term was probably employed (A. Plazolles V., pers. commun., 1979) because the upper part of the southwestern body coincides with an apparent fault displacement of the volcanic country rocks of the Toquepala intrusive center; the previous existence of a small graben was envisaged. The slump breccias were not subsequently distinguished by Richard and Courtright (1958; they describe the southwesterly zones of the outcrops in question as "ore breccia"), and they are not specifically delimited in recent open-pit maps (see Fig. 1).

The southwest zone of the slump breccia has been informally distinguished by the personnel of Southern Peru Copper Corporation (SPCC) during almost 30 years of operation of the open pit. The breccia zone mapped at surface would overlie the west-central part

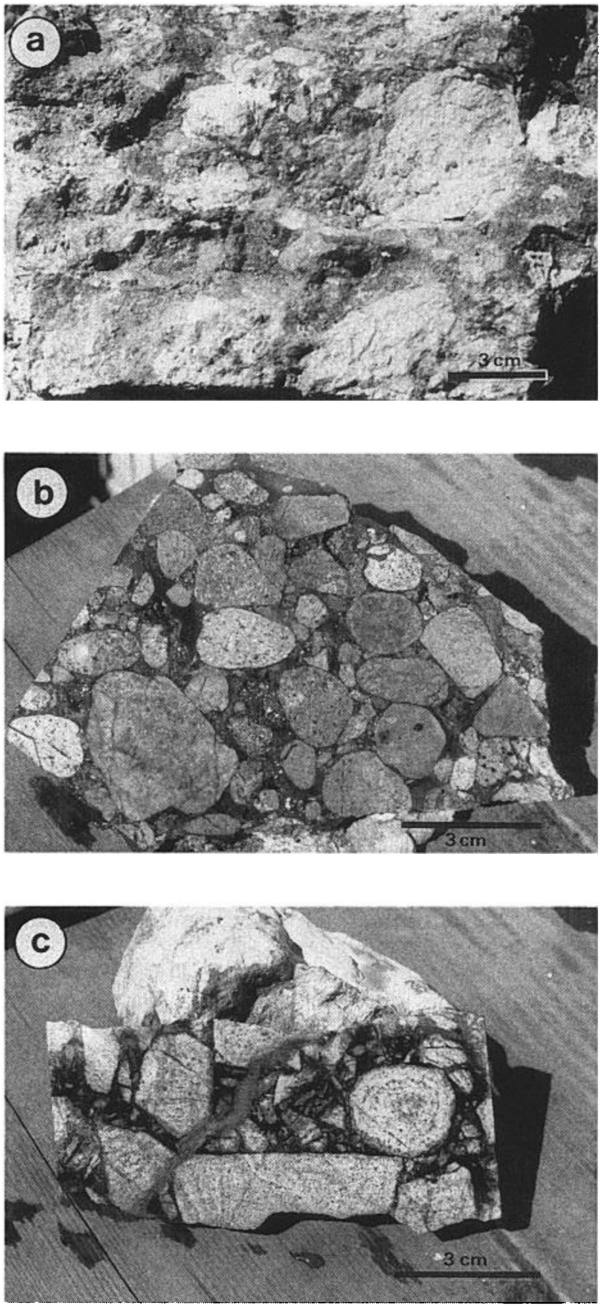

FIG. 2. Tourmaline-cemented breccias, Toquepala deposit. a. Breccia comprising subangular to rounded sericitized clasts. Note crudely concentric fracture-alteration zones in one fragment (top right). 3,160-m level northeast (1982). b. Markedly heterolithic breccia with entirely rounded clasts. Matrix comprises aphanitic tourmaline and euhedral quartz and pyrite. Southern Peru Copper Corporation collections. Precise location unknown. c. Breccia dominated by angular clasts, but with a single well-rounded fragment displaying concentric fracture-alteration zones probably resulting from hypogene exfoliation (see Farmin, 1937; Sillitoe, 1985). Southern Peru Copper Corporation collections. Precise location unknown.

FIG. 3. Molybdenite breccia (see Zweng, 1984). Boundary of excavated clast is in part defined by curving fractures (arrows, top); coating of matrix (gray, at bottom right) comprises chalcopyrite and molybdenite. Breccia is developed in earlier formed tourmaline breccia. 3,085-m level northwest (1982). Length of hammer head, 17.5 cm.

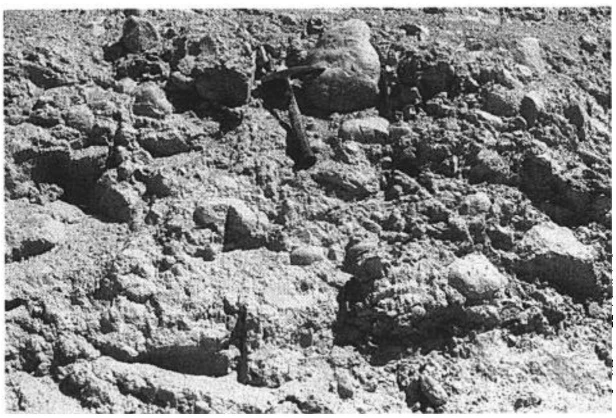

FIG. 4. Characteristic pebble breccia dike, with dominantly subrounded monzodiorite clasts (clearest adjacent to hammer) in a poorly consolidated vuggy matrix rich in kaolinite, montmorillonite, quartz, and pyrite. 3,160-m level west (1976). Proportion of rounded clasts in this dike decreases above this level (Freemark, 1977). Dike has a crudely concentric cone-sheet configuration (see Fig. 1). Hammer for scale.

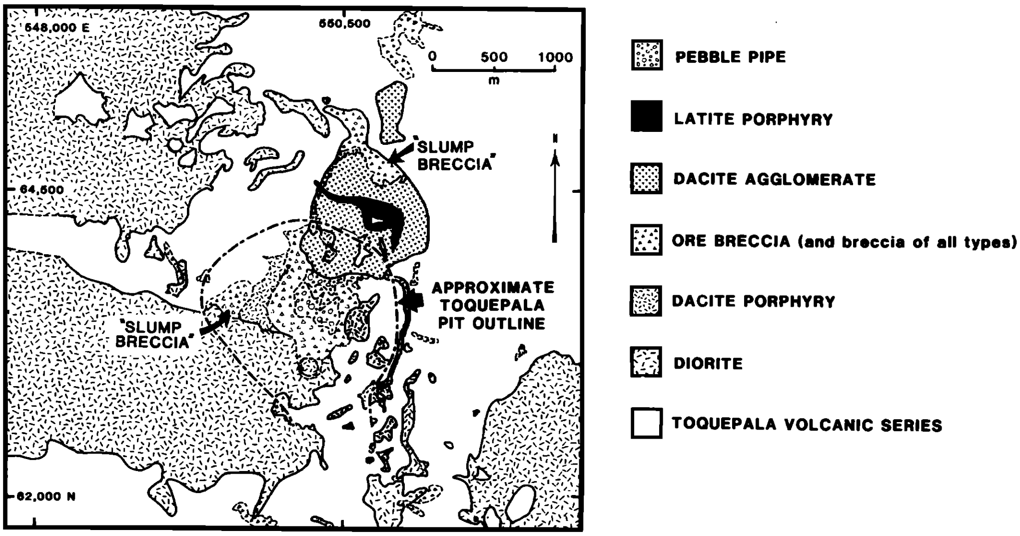

FIG. 5. Premine surface geologic map of Toquepala area (after Richard et al., 1951), showing locations of the two main areas of slump breccia. Approximate vertical projection of the southwestern body in the present open pit is shown in Figure 1. Map units as distinguished by Richard et al. (1951).

of the present open pit (Fig. 1), essentially coinciding with a body of angular breccia. However, in practice the term slump breccia is largely applied to smaller, discontinuous bodies of fragmented rock which trend in a northwest direction across the northwestern quadrant of the pit and which extend at least between the 3,580- and 3,205-m levels. The continued use of this term is prompted by the unusual appearance of the tectonites, although it is a misnomer. Exposures broadly described as slump breccia have been examined in several parts of the open pit, but particularly on the 3,235- (1976 and 1979) and the 3,265-m (1982, 1984) levels northwest (Fig. 1). The rocks affected by the fragmentation under discussion include granodiorite-monzodiorite (Zweng, 1984), dacite porphyry, and locally, earlier formed tourmaline-cemented ore breccia. The slump breccias are closely associated with a crudely radial dike of typical pebble breccia.

It should be emphasized that the fracture systems described herein are not blasting artifacts.

Breccia fabrics

Field relationships indicate that the slump breccia system represents a transition from a stockwork to a clast-supported, matrix-poor, true breccia. The stockwork (Fig. 6a) constitutes a distinctive tectonite, differing markedly from the normal stockworks of this (Fig. 6b) and other porphyry deposits. The intensely, even chaotically, broken appearance of the rocks reflects the close spacing of megascopic fractures (cf. Fig. 6b) and, particularly, the rarity of extended, quasiplanar, and systematically oriented fracture surfaces and the dominance of discontinuous, apparently randomly oriented fractures. The few essentially through-going quasiplanar fractures evident in Figure 6a are associated with weak, pyrite-dominated, late-stage mineralization (Zweng, 1984) and formed demonstrably later than the chaotic stockwork in which the closely separated (avg. spacing, 1-3 cm) megascopic fractures delimit approximately equant rock volumes. Very little mineral precipitation occurred in the majority of the fractures, but minor pyrite and quartz, and rare chalcopyrite, sericite, kaolinite, and montmorillonite have been observed within some fracture segments. Void space in such stockwork does not exceed ca. 1 percent, but irregular cavities up to 0.75 cm across are locally developed.

Although the majority of the coherent blocks in the stockwork are crudely trapezoidal and markedly faceted, many of the fracture surfaces are distinctly curved, delimiting at least partially rounded interfracture domains. These domains are generally broadly comparable in size to associated, more angular bodies (Fig. 7a) but may be considerably larger (Fig. 7b). Bodies with an extensive development of curved surfaces constitute approximately 10 to 20 percent of the stockwork facies of the slump breccia. A body is considered rounded if over one-half of its surface comprises one or more curved elements; many such bodies are in fact rounded on one side and planar or faceted on the other. Examination of 16 blocks partially excavated from their surroundings revealed that three may be described as subrounded, nine as rounded, and four as well rounded.

Whereas the angular interfracture domains in the stockwork are subequant, the rounded bodies are commonly elongate and their long axes are crudely

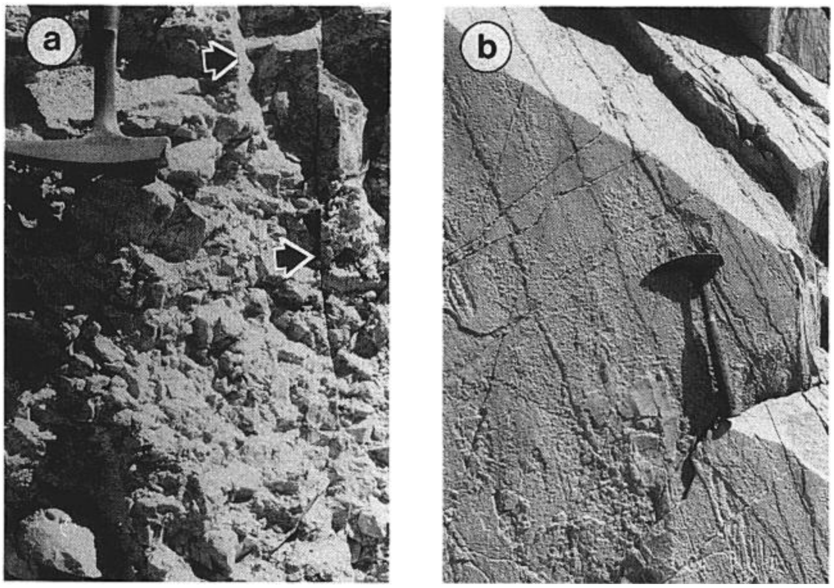

FIG. 6. Contrasting stockwork styles. a. Stockwork facies of slump breccia. Note very close spacing of discontinuous and apparently randomly oriented megascopic fractures. Stockwork is crosscut by more continuous and planar fractures (arrows at right and top) and is developed in monzodiorite (3,265-m level northwest; 1982). Length of hammer head, 17.5 cm. in both views. b. Normal stockwork, developed in monzodiorite, and associated with late-stage pyritic mineralization. Note continuity of the quasiplanar fractures. 3,265-m level southwest (1982). Length of hammer head, 17.5 cm in a and b.

parallel, most plunging at ca. 70° ± 20° to the southeast.

Observations on the 3,265-m level northwest indicate that the chaotic stockwork domains of the slump breccias have sharply defined boundaries with rocks exhibiting structurally normal (i.e. with planar fractures), but unmineralized stockwork fabrics. Internal boundaries between the chaotic stockwork and the breccia facies of the slump breccia system are, in contrast, gradational, involving a progressive increase in the proportion of matrix. Most exposures (e.g., Fig. 7a and b) referred to as slump breccia by mine personnel have, however, only 5 to 20 percent matrix (including void), and the continuity of prebreccia fabrics such as quartz veinlets indicates that little or no displacement of the clasts has taken place. The clasts display a range of forms similar to that of the interfracture domains in the contiguous stockworks, i.e., most are angular or subangular. Some have extremely complex forms with irregularly dentate boundaries. However, overall, about 10 to 25 percent are subrounded to well rounded. The relative abundances of subrounded, rounded, and well-rounded clasts are also comparable to those in the stockwork, i.e., 16:29:3. Clustering of rounded blocks is commonly observed; some exposures are made up predominantly of blocks displaying at least one major curving surface. Measurements of detached blocks which display rounding show that the majority are prolate spheroids in form, either ellipsoids or crude cylinders with rounded extremities (Fig. 7c). A very small proportion is approximately spherical. Aspect ratios of the rounded blocks range from 1.2 to 8, averaging ca. 3 to 4. The breccias are essentially barren. The matrix comprises rock flour, largely of silt size, locally weakly cemented by fine-grained quartz, together with very minor and erratically distributed pyrite and sericite, and generally rare, but locally abundant, chalcopyrite. Small cavities are widespread, some coated by mamillary chalcedony interlayered with montmorillonite. Tourmaline occurs in breccia clasts but not in the matrix. The clasts are intensely sericitized.

Relationships between the slump breccias and normal pebble breccias were clearly observed in only a single exposure on the 3,265-m level. Here, one breccia type grades into the other over a distance of approximately 2 to 3 m; an increase in the volumetric proportion of rock flour matrix (silt and sand size) from <20 to ca. 35 percent is accompanied by an abrupt increase in the occurrence of curving clast surfaces and rounded clast forms (to about 80% of the fragments). In the vicinity of the slump breccia bodies, the clasts in the pebble breccias clearly display rotation. However, the relative proportions of subrounded, rounded, and well-rounded fragments are similar to those of unrotated rounded blocks in the slump breccia; examination of 44 bodies excavated

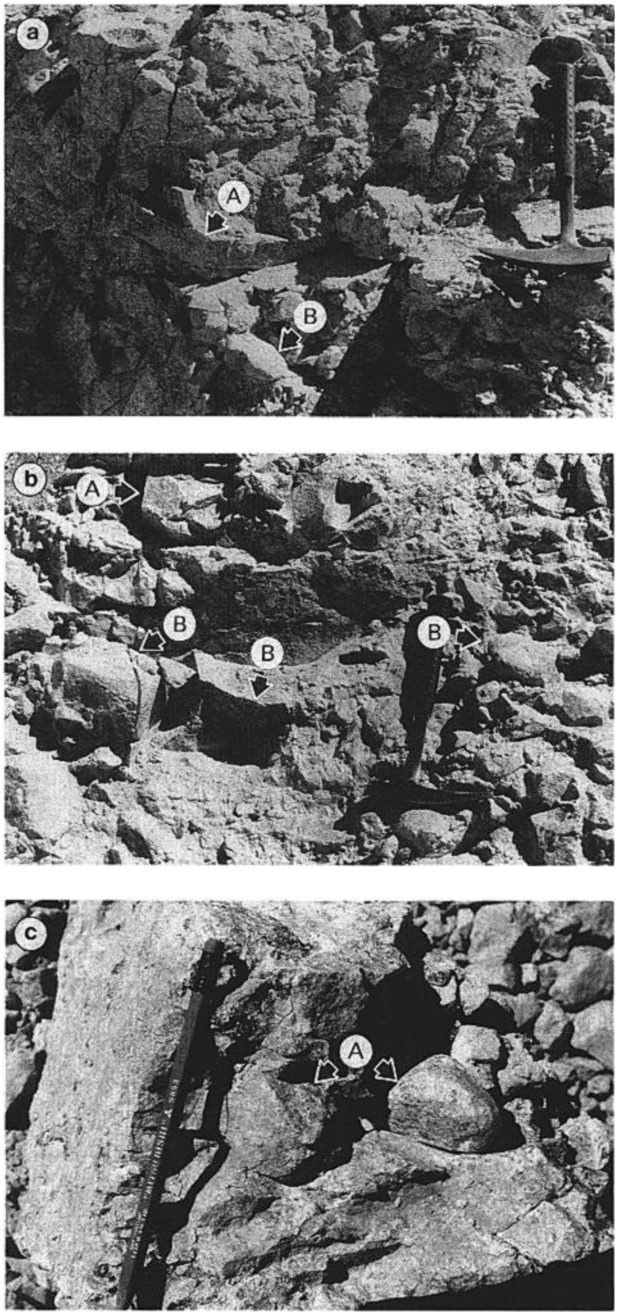

FIG. 7. Characteristic features of slump breccia, 3,265-m level northwest (1982). a. Stockwork with generally irregularly shaped interfracture domains and a small proportion of curviplanar fractures (see **A** at left center). Note projecting body near center bottom (B) with crudely ellipsoidal form; its tapering extremity is defined by curviplanar surfaces with sharp cuspate intersections. Fractures are dominated by void space (to 3 mm wide) or (upper field) by finely mammillary chalcedony and montmorillonite. Looking north-northwest. b. Stockwork facies showing angular (A, top left) and well-rounded (B) blocks. Note extensive curviplanar fractures at center of view. Most fractures, including the curviplanar, are tight, with minimal void and mineral infilling. Looking north-northeast. c. Transitional stockwork breccia facies. Detached block showing two interfracture domains (A) dominated by curviplanar surfaces and with crudely ellipsoidal long sections. These are rooted in intensely fractured monzodiorite (top and left); a volume of clast-supported breccia, with only ca. 10 percent matrix and originally enveloping the rounded blocks, has been detached from the right-hand side of the block. Pencil for scale.

from pebble breccias yielded values of 15, 23, and 6, respectively. Moreover, the clasts show very similar forms in the two breccia types, with ellipsoidal or crudely cylindrical bodies predominating.

Discussion

The relationships documented above are interpreted as pertaining to a single process and environment of rock fragmentation which successively generated the chaotic stockwork, the slump breccia proper, and the pebble breccia. Thus, the stockwork and breccia facies of the tectonites under discussion are considered to constitute both marginal facies of, and precursor stages in the development of, true pebble breccia. Few, if any, descriptions have been presented of the margins or roots of pebble breccias, and it is not clear whether fabrics such as those documented here are widespread in such systems. At Toquepala, weak stockworks displaying some curviplanar fractures occur adjacent to several radial pebble breccia dikes on the western branches of the open pit, but they are absent in the hanging walls and footwalls of the concentric pebble dikes. No other exposures of the slump breccia facies have been observed by the writer. The roots of the pebble breccia dikes are considered to lie at elevations of ca. 2,900 to 3,000 m (Zweng, 1984), i.e., well below the present floor of the pit, and slump breccia fabrics would probably be impossible to discern in drill core. It is thus not clear why such tectonites are concentrated in the area described; certainly no correlation with faulting or actual slumping of the Toquepala Group volcanic host rocks can be established (cf. Richard et al., 1951)

The incidence of curved fractures in stockwork systems associated with porphyry copper and other ore deposits is uncertain. However, Heidrick and Titley (1982) document the occurrence of "J_2" joint sets in southwestern U. S. porphyries; the fractures are uncommon, rough surfaced and curviplanar, are rarely mineralized, and are considered more characteristic of "less structurally isotropic, non-intrusive wall rocks" (Heidrick and Titley, 1982, p. 75). In many respects, this subordinate fracture system is apparently similar to that documented here, but Heidrick and Titley (1982) do not record an association with phreatic breccias and do not discuss the origin of the curved joints. Elsewhere, however, Davies (1988) specifically describes the conjuction of curviplanar fracture sets and phreatic breccia pipes and dikes in association with the Archean gold quartz lodes of the

Timmins camp, Ontario. Moreover, at Khao Soon, southern Thailand, a stockwork system dominated by curviplanar fractures around the margin of a large ferberite-bearing phreatic-phreatomagmatic breccia pipe has been documented (A.H.C. *in* Chârusiri, 1989). Such tectonites may, therefore, be more widespread than is realized in environments of hydrothermal brecciation.

Neither interclast attrition nor hypogene exfoliaton can explain the development of the curved surfaces shown by many blocks in the stockwork facies of the Toquepala tectonites. An alternative mechanism is therefore sought. Enormous and rapid energy release is triggered in environments in which water-bearing magmas are emplaced subvolcanically (Burnham, 1985); the major source of energy is decompression of the aqueous phase, following second boiling. Such processes are presumed to have been responsible for the development of the main planar stockwork and the tourmaline-cemented ore breccia at Toquepala (see also Sillitoe, 1985). It is probable that broadly comparable energy release accompanied the late-stage injection of latitic magma into the core of the porphyry system, which may have already experienced extensive incursion of ground waters. Pebble breccia dikes exposed on the 3,160-m level southwest (1983) of the mine indeed exhibit a transition from an igneous quartz latite cement to one of rock flour, a relationship interpreted as recording the turbulent interaction of magma and water. The crudely concentric and radial arrays (Fig. 1) of pebble breccia dikes in the western part of the open pit, the great size of the main phreatic breccia pipe, and the occurrence of smoothly curving cone sheets of quartz latite in the eastern pit quadrant (not shown in Fig. 1) are considered to have resulted from the intrusion of a substantial volume of high-temperature water-undersaturated magma along the axis of the preexisting orebody, causing an explosive event of unusual magnitude when it encountered fractured rocks containing large volumes of meteoric water.

As noted above, Godwin (1973) first suggested that energy release and strain rates within endogenous hydrothermal breccia systems could be great enough to generate true shock metamorphic fabrics, comparable to those in at least small meteorite impact sites. Indeed, planar quartz deformation lamellae have been documented in the East Tintic, Utah, pebble breccias by Godwin (1973) and Yamamura (1985), as well as in the Slate Island, Ontario, diatreme (Sage, 1978). Johnson (1986) and Clark et al. (1987) record zones of microbrecciation, similar to those generated in astroblemes, underground nuclear explosions, and laboratory shock experiements (e.g., Stöffler, 1974), in rocks adjacent to phreatic breccia dikes in the epithermal Cacachara silver deposit, southeastern Peru.

Microscopic intra- and intergranular textures ascribable to shock metamorphism have not been observed at Toquepala, perhaps because of the large size and heat capacity of the hydrothermal zone and the duration of hydrothermal activity. Certainly, it would be premature to interpret the Toquepala tectonites as the products of stress magnitudes and strain rates equivalent to those in true shock metamorphic environments. However, it is suggested that the development of curviplanar fractures during rock fragmentation, as shown by the slump breccias, may itself be a direct result of the propagation of a shock wave, or series of waves, probably controlled by fracture systems initiated during intrusion of the latitic magma. A similar origin has been proposed for the shatter cones associated with many astroblemes (Dietz, 1968), but the rounded domains in the Toquepala stockwork and breccias have a different form, lacking the simple conical configuration and (horsetailing) striated surfaces of shatter cones. Instead, analogies are drawn with the Hertzian quasioval fracture systems which, in the geologic context, have been most extensively evaluated by Bahat (1978, 1979, 1980). As summarized by Bahat, Hertzian stress differs from the more familiar compressive Hubbertian system in that deformation originates from a point source rather than a broad surface and acts in three rather than two dimensions. In shallow Hertzian stress environments (Hertz 1881; Frank and Lawn, 1967; Lawn and Willshaw, 1975), involving impingement of a point spherical plastic indenter on a brittle solid, a cone-shaped crack forms. Bahat (1977a, 1979) has argued that a similar stress field may be caused by a plastic indenter, such as a liquid or gas. Lawn and Marshall (1977) demonstrate that, under deep and modified Hertzian fracturing, the transition from compression at the (horizontal) indented surface, through horizontal tension and, finally, to horizontal compression with increasing depth within the brittle material, may lead to the development of a closed paraboloidal or three-dimensional quasioval fracture. As Bahat (1977b) has emphasized, such deep fractures are shown by innumerable prehistoric knapped flint and chert tools.

Many of the prolate spheroidal blocks in the Toquepala slump breccia system, as well as the clasts in the contiguous pebble breccias, have long sides wholly or partly of paraboloidal contour and are similar to the deep Hertzian fractures figured by Bahat (1977b, 1980). It is therefore suggested that these rounded domains resulted from local focusing of unusually intense stress transmitted by shock waves associated with the explosive expansion of the phreatic system. A very heterogeneous stress distribution on the outcrop scale would be predicted, but the crude parallelism of the long axes of the rounded domains in the slump breccia stockwork would be in permissive agreement with a broad upward and radial compression. On a broader scale, the unusual characteristics of the associated stockwork (Fig. 6) are tentatively considered to reflect local stress concentrations exceeding those responsible for the main planar stockwork of the deposit. Although the possibility of continued clast rounding through attrition or abrupt decompression in the main pebble breccia channels cannot be ruled out, it is possible that most such fragments obtained their forms prior to or immediately following their entrainment in breccia sheets. This is supported by Freemark's (1977) observation that the extent of fragment rounding decreased upward (between the 3,160- and 3,220-m levels) in a pebble dike exposed in the western quadrant of the pit. Ellipsoidal clasts predominate at the lower level, but many such bodies are truncated or transected by planar fractures at shallower depths.

The hypothesis tentatively advanced here may probably be assessed through more detailed studies of the forms and surface characteristics of rounded bodies in hydrothermal breccias and stockworks, through a careful search for microscopic features indicative of extreme compressive stress and strain rate, and through determination of the incidence of these unusual tectonites.

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