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Structure and age of the Cerro de Pasco Cu-Zn-Pb-Ag deposit, Peru

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Abstract. The world-famous Cu-Zn-Pb-Ag deposit at Cerro de Pasco, Peru, consists of texturally massive pyrite, texturally massive sphalerite-galena-pyrite, and veins containing pyrite and enargite. Historically the deposit has been considered to be the hydrothermal product of the adjacent Miocene volcanic and intrusive complex (locally known as the "Vent"). However, both the texturally massive sulfides of the deposit and the pre-Miocene strata are cut by the Longitudinal fault, one of the largest faults in the district, but the Vent is not. Imbrication by the Longitudinal fault zone (duplex structures) has thickened the deposit so that it is amenable to open-pit mining. Dikes and pyrite-enargite veins pass from the Vent into the massive sulfides; fragments of massive pyrite occur in the Vent. Thus, no matter what their origin, the texturally massive sulfides are older and, therefore, genetically unrelated to the Vent.

The Cerro de Pasco Cu-Zn-Pb-Ag deposit of central Peru (Fig. 1) has long been genetically linked to the adjacent Miocene volcanic and intrusive center known as "the Vent" (Graton and Bowditch 1936; Cerro de Pasco Copper Corp., Geological Staff 1950 – hereafter abbreviated CdP 1950; Petersen 1965; Einaudi 1977, 1982; Silberman and Noble 1977; Rodgers 1983). The three major hypogene sulfide assemblages at Cerro de Pasco are: massive pyrite (with associated smaller pipe-like bodies of enargite and luzonite and of pyrite that yields payable silver), massive sphalerite-galena-pyrite (with pipes of pyrrhotite), and volumetrically smaller pyrite-enargite veins that cut the massive pyrite. Lacy (1949), Petersen (1965), and Einaudi (1977) described the detailed mineralogy of these assemblages.

The purpose of the present paper is to present evidence that, contrary to the prevailing viewpoint, the massive sulfide portions of Cerro de Pasco (no matter what their origin) are older than and, therefore, unlikely to be related to the Vent. The pyrite-enargite veins may well be related to the Vent and are not the focus of this paper.

The plate tectonic history of Peru is described by Dalziel and Forsythe (1985), Pardo-Casas and Molnar (1987), and Sébrier et al. (1988). However, only the features of the district and deposit that are germane to the structure and age of the deposit will be discussed here. This description is based on 1:2000 mapping of the McCune pit conducted in 1987 and on some oft-ignored observations of previous authors.

Modern mining at Cerro de Pasco, which began in 1906, has not promoted an understanding of the texturally massive sulfide bodies. Mining from 1906 to 1976 concentrated on the pyrite-enargite veins, supergene copper deposits developed on massive sphalerite-pyrite-galena (and to a lesser extent on massive pyrite), and copper- and silver-bearing veins and pipes in massive pyrite. Mining of the massive argentiferous sphalerite-galena ores did not begin until 1955. The original company was nationalized in 1974 and now operates as Empresa Minera del Centro del Peru, S.A., or Centromin.

At present, virtually all mining is restricted to the Zn-Pb-Ag ores. Present annual capacity is about 1.4 million tonnes of ore from the McCune open pit and approx-

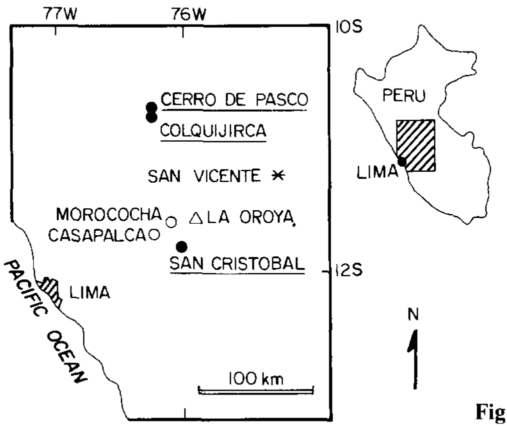

Fig. 1. Index map

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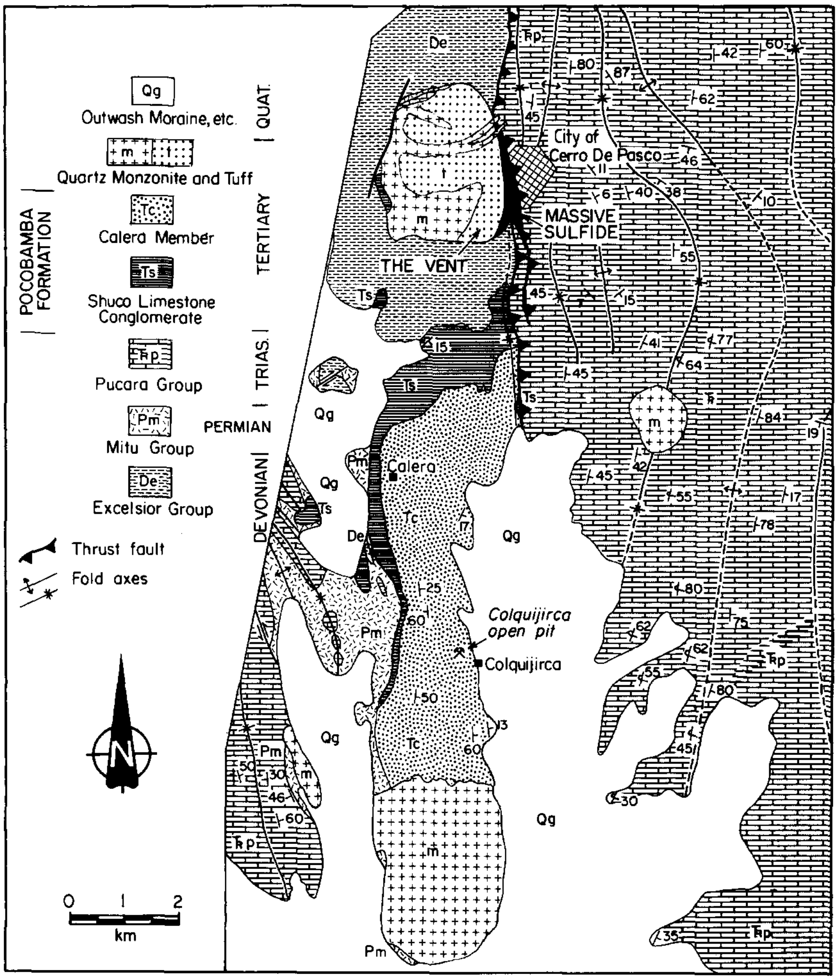

Fig. 2. Geologic map of the Cerro de Pasco district. Sources of data are Bowditch (1935, Fig. 4), Jenks (1951, Plate 1), Petersen (1965, Figs. 6 and 7), and Figs. 3 and 6 of this paper

imately 0.9 million tonnes from underground. Mined ore and reserves total about 80 million metric tonnes and average 9.2% Zn, 3.5% Pb, and 101 g/t Ag (Cheney et al., 1991, Table 1).

Regional geology

Paleozoic to Tertiary strata in the Cerro de Pasco district define large, northerly striking folds (Fig. 2). The oldest strata are biotitic phyllites and fine-grained quartzites of the Devonian Excelsior Formation. The large area of Excelsior Formation west of the city of Cerro de Pasco defines the core of one of the anticlines. A regional north trending thrust, the Longitudinal fault (or Cerro de Pasco fault), dips 30° to 60° eastward (Bowditch 1935, p. 38; Jenks 1951, Plate 1) and places the Triassic-Jurassic Pucará limestone over the Excelsior and the Tertiary Pocobamba Formation (Fig. 2).

A Miocene intrusive and volcanic complex, the “Vent”, intrudes the Excelsior Formation along the west side of the body of massive pyrite (CdP 1950; Petersen 1965; Rodgers 1983). The Vent, about 2.5 km in diameter, may be a diatreme or filled caldera (Graton and Bowditch 1936; Rodgers 1983). Intrusive rocks of the Vent have K-Ar dates of 14 to 15 Ma (Silberman and Noble 1977).

Mine geology

On the eastern side of the McCune pit the Pucará limestone is extensively brecciated and cut by gougy fault zones (Fig. 3 and 4). Due to the lack of descriptions of bedded chert in the Pucará (Jenks, 1951), the discovery of bedded, black cherty rock on the eastern side of the McCune pit (Fig. 3) was unexpected. The black cherty rock appears to conformably overlie brecciated limestone, is ≥300 m thick, and locally is more brecciated than the limestone. The age and significance of this cherty rock are obvious topics for future research, especially as this rock locally contains low-grade Pb-Zn-Ag ore.

Massive pyrite and massive sphalerite-galena-pyrite constitute a northward striking body that on surface is 1800 m long and 300 m wide. Overall, this body dips about 70° westward (Petersen 1965, Fig. 8). The sphalerite-galena-pyrite ores generally occur east of the pyritic assemblage (Figs. 3 and 4; CdP 1950, Fig. 43; Petersen 1965, Fig. 7; Einaudi 1977, Figs. 2 and 3). Orebodies persist to a depth of about 550 m (1800 level of the underground mine), but massive pyrite continues to 820 m.

Pyrrhotite pipes up to 60 × 180 m in plan view (Petersen 1965) cut massive pyrite and massive sphalerite-pyrite-galena (CdP 1950; Petersen 1965; Einaudi 1977). These were not encountered in the present mapping be-

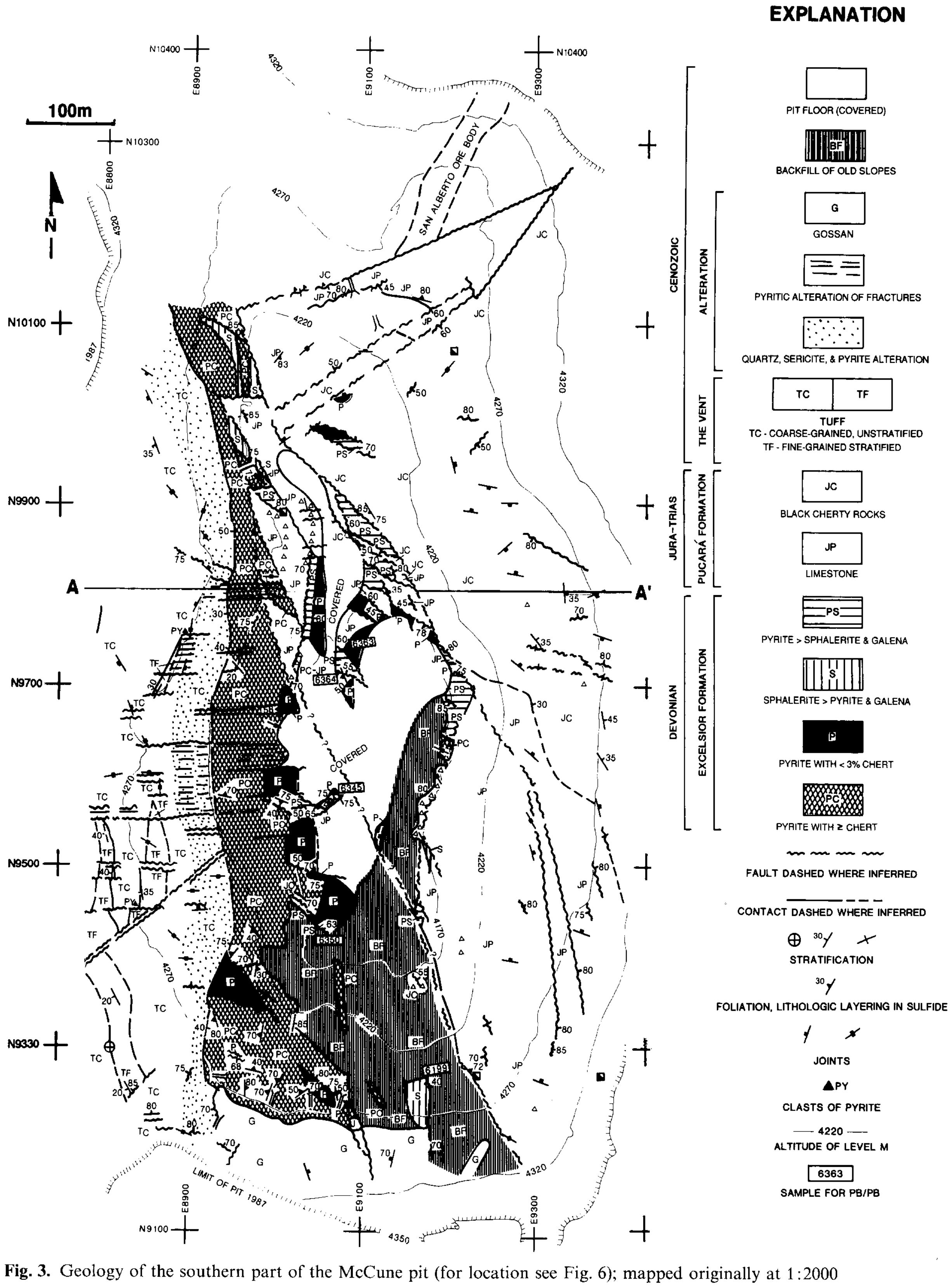

Fig. 3. Geology of the southern part of the McCune pit (for location see Fig. 6); mapped originally at 1:2000

cause most are below the 600 level of the underground mine (CdP 1950), that is, below the 1987 bottom of the McCune pit; furthermore, most of the floor of the pit is obscured by roadways and much of the ore was mined and backfilled prior to open-pit mining.

More than 90% of the pyritic assemblage contains similar amounts of pyrite and quartz. Pyrite occurs predominantly as anhedra with many irregular, hairline cracks (Lacy 1949, p. 52–53, Fig. 7). Some quartz occurs as chert-like, irregular, 0.3 to 10 mm aggregates with un-

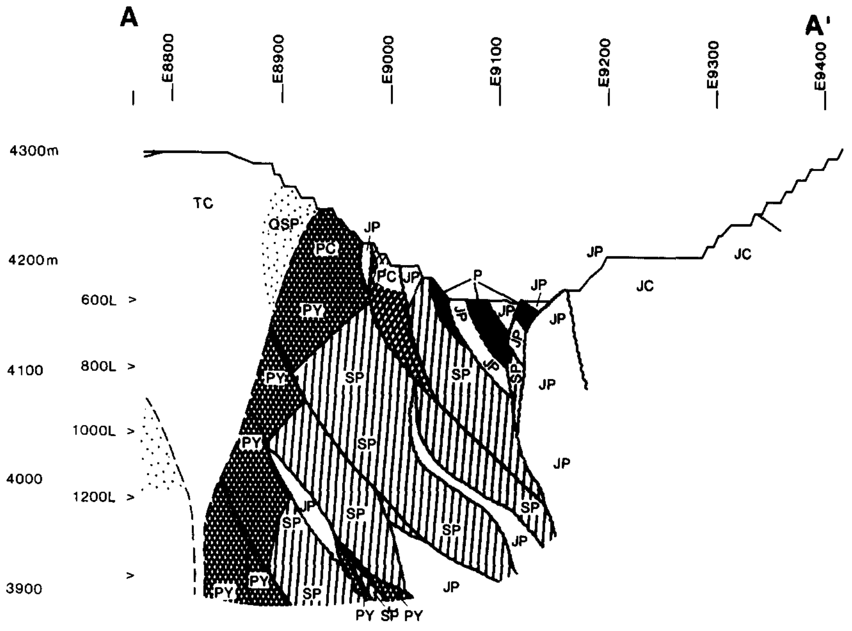

Fig. 4. Cross section of the Cerro de Pasco deposit along A–A^1 of Fig. 3

dulatory extinction and as euhedra without undulatory extinction (Lacy 1949, p. 109). More conspicuously, blocks and slabs of aphanitic dark cherty rock give the ore the appearance of a breccia (Fig. 5 A) or of a replacement deposit (Fig. 5d). Pyrite veinlets commonly cut the cherty rock (Figs. 5b and d). In the following discussion, where this rock contains more than 3% fragments of dark cherty rock, it is termed "pyrite-chert".

A small proportion of the pyritic body has 0 to 3% fragments of cherty rock greater than 5 mm. Pyrite without any cherty rock has the texture of mild steel and commonly has vugs less than 1 cm long. Some pyrite without chert is conspicuously banded and without vugs (Fig. 5h), and some has a network of veinlets of chalcedony and alunite with microscopic matildite on microfractures (H. Alvarez 1987, personal communication). The latter contains as much as 600 g/t Ag; it was not mapped in the present study.

Massive ore is sphalerite, galena, and pyrite with minor amounts of pyrrhotite, other sulfides and gangue (Ascencios 1966; Einaudi 1977). Sphalerite is commonly dark grey; grains average about 1 mm in diameter. Associated pyrite is usually the same size. The most conspicuous occurrence of galena is as grains up to 5 mm in veinlets 0.5 to 1 cm wide cutting sphalerite-rich rocks.

In Fig. 3 the ore is subdivided into bodies in which sphalerite is more abundant than pyrite and galena, and those in which pyrite is more abundant than either of the other two. Detailed mapping probably could recognize several types of ore based on the relative amounts of ore and gangue minerals and several types of pyrite based on the percentage of cherty fragments. Hereafter, for simplicity, all sphalerite-bearing ore is referred to as massive sphalerite.

The pyrite-enargite veins cut the western half of the massive pyrite assemblage and extend westward into the Vent and the Excelsior Formation (see Figures in CdP 1950; Ward 1961; Petersen 1965). The east-west fracture systems shown in Fig. 3 host these veins. The veins are up to 500 m long and 2 m wide (Graton and Bowditch 1936; Petersen 1965).

In the open pit, the volcaniclastic rocks of the Vent consist of upward-fining cycles. The bottom part of a cycle is unsorted, unstratified, unwelded, and contains clasts up to 0.6 m supported in a sand-sized matrix. Most clasts are dark chert and dark phyllite, presumably derived from the Excelsior Formation. The other most conspicuous clasts are white (hydrothermally altered) quartz monzonites. A cycle grades upward into crudely bedded units containing smaller clasts supported in a sandy matrix. Most clasts in the bedded units are less than 1 cm; the maximum commonly is 3 cm. Bedding varies in thickness from 1 to 25 cm.

Along the western margin of the massive pyrite, unbedded volcaniclastic rocks of the Vent are altered to quartz-sericite-pyrite (Figs. 3 and 4; Rodgers 1983). Pyrite exceeds 2%. The normally grey rock is altered to white and is conspicuously rusty weathering on the walls of the pit.

Age of the Cerro de Pasco deposit

This section shows that the massive sulfide portions of the deposit are older than, and thus unrelated to, the Vent. Evidence includes dikes of quartz monzonite within the deposit, fragments of massive pyrite in the Vent, and the fact that the Longitudinal fault cuts the deposit but not the Vent.

Dikes

As shown in Fig. 6, dikes of quartz monzonite associated with the Vent intrude the northern end of the deposit. This relationship is well documented (Bowditch 1935, Figs. 4 and 5; Lacy 1949, Fig. 2; CdP 1950, Fig. 43; Ward 1961, Fig. 4; Petersen 1965, Fig. 7; Ascencios 1966,

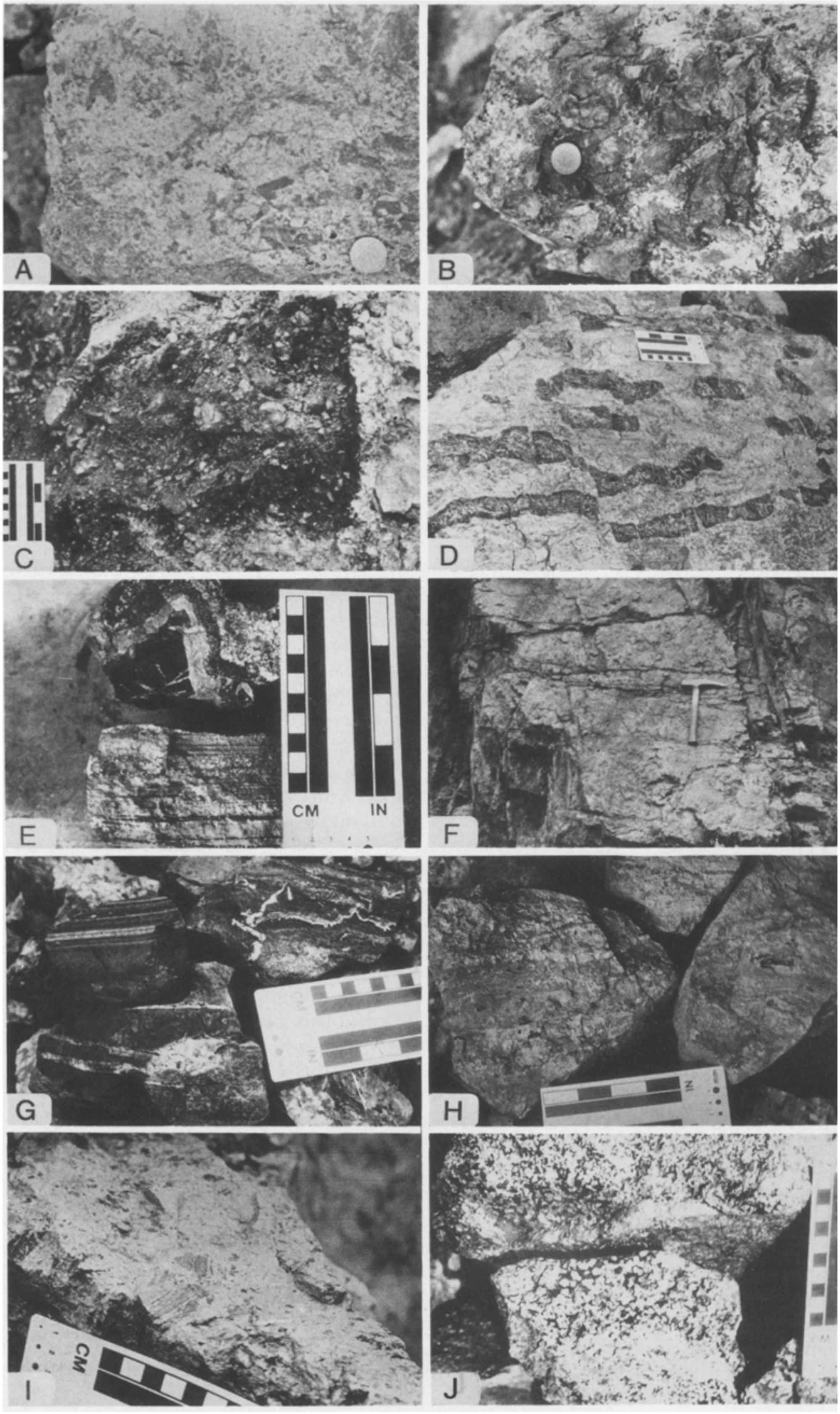

Fig. 5A–J. Mesoscopic features in pyrite *light* and cherty rock *dark*. Samples are from dumps unless otherwise indicated. Coin in Figures 5a and b is 3 cm in diameter; hammer in 5f is 33 cm long; scale in the other figures is in centimeters and inches. **A** Irregular blocks of cherty rocks in pyrite, from 4220 level, west side; **B** veinlets and irregular clots of pyrite cutting cherty rock, from 4220 level, west side; **C** the right-hand 9 cm is brecciated limestone; the left part of the figure consists of similarly brecciated pyrite with pyrite fragments *light* in a matrix of fine-grained (sandy) pyrite *dark*, from 4160 level at N-9780 and E-9140; **D** folded and faulted black layers of cherty rock in a matrix of less deformed pyrite and cherty rock; note that the large dark layers of cherty rock are cut by pyrite veinlets and that faults coincident with offsets of the black cherty layers are not visible in the matrix; **E** two specimens showing laminated (*below*) and folded (*above*) bands of pyrite and cherty rock; **F** meter-scale, steeply east dipping, cherty rock (*light gray*) and pyrite; hammer is on pyrite, the dark horizontal lines are fractures, from 4260 level at N-9250 and E-8970; **G** specimens of banded and laminated pyrite in graywacke (dark); **H** banding in massive pyrite lacking mesoscopic cherty rock; **I** fragment of laminated pyrite and chert (above second to fourth cm-scale division) within massive pyrite with >3% cherty rock, from 4270 level at N-9310 and E-8930; **J** porphyroblasts of pyrite in graywacke

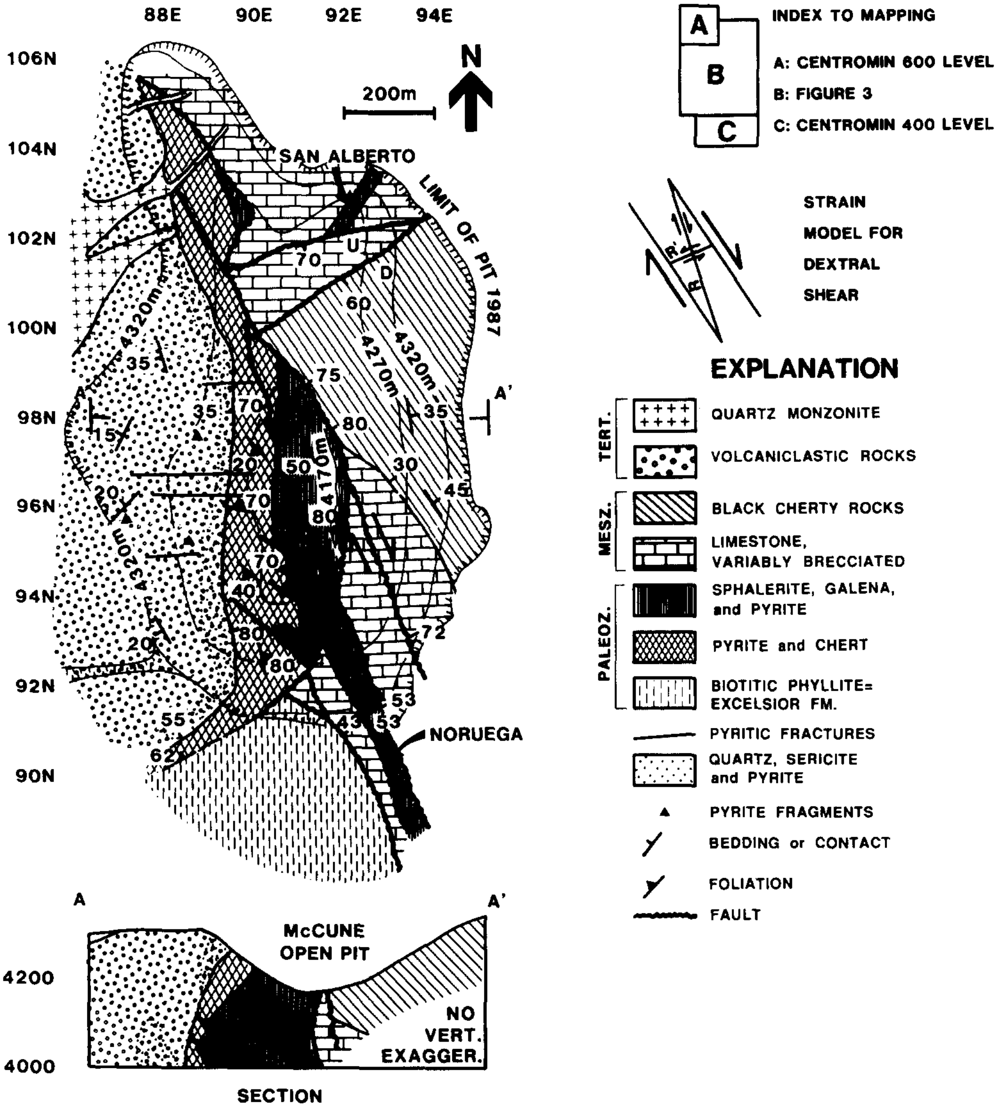

Fig. 6. Tectonic map of the Cerro de Pasco deposit

Fig. 3; Einaudi 1977, Fig. 2). One such dike with minor supergene (?) alteration, yielded a K-Ar date of 15.2 ± 0.2 Ma from a large, relict phenocryst of sanidine (Silberman and Noble 1977). Silverman and Noble (1977), Einaudi (1977), and Rodgers (1983) believed that this was also the approximate age of the Cerro de Pasco deposit.

Inclusions of massive pyrite

Rare fragments of massive pyrite do occur in the volcaniclastic rocks of the Vent (three solid triangles on Fig. 3; Rodgers 1983, p. 22). Thus, the obvious conclusion is that the volcaniclastic rocks, like the dikes, cut the massive sulfide portion of the deposit. No fragments of massive sphalerite or galena have been discovered in the volcaniclastic rocks; this may be due to their extreme rarity or dark color, but most likely is due (at the level of observation in the pit) to the fact that massive pyrite occurs between massive sphalerite and the Vent (Fig. 3).

Longitudinal fault

Recent authors (CdP 1950; Petersen 1965; Einaudi 1977) have not emphasized that the massive pyrite and massive sphalerite are cut by the Longitudinal fault. Yet, Bowditch (1935, p. 89) and Lacy (1949, p. 131) explicitly stated that the Longitudinal fault does cut the pyrite body. Bowditch (1935, p. 39 and 98) and Ward (1961, Fig. 8) noted that "pyrite breccia" (Fig. 5c), and "soft pyrite" composed of friable, sandy-textured pyrite are restricted to eastern bodies of pyrite (that is, along the trace of the Longitudinal fault) and to the Noruega zone (see Fig. 6). Bowditch (1935, p. 98) stated that these pyrites, a zone of "border sediments" (which he suggested are Excelsior Formation but which probably are the black cherty rocks of Fig. 3), and a soft, blue grey rock that borders the Pucará are "undoubtedly related to movement and alteration along the Longitudinal fault"; nonetheless, he believed that these were due to minor late reactivation of the fault. In addition to "pyrite breccia" and "soft pyrite", brecciated sphalerite-galena also occurs along the fault,

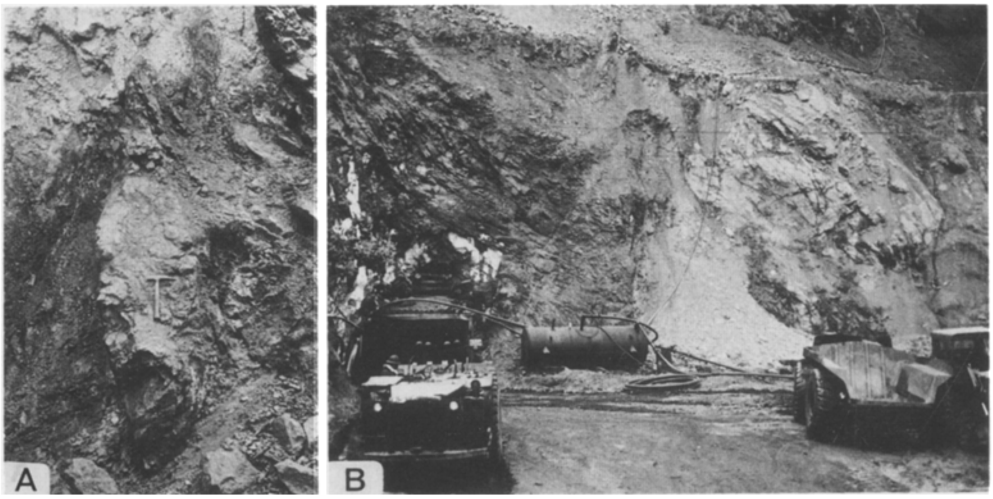

Fig. 7 A, B. Tectonic contacts of sulfide bodies. **A** vertical lens of pyrite with >3% cherty rock surrounded by brecciated limestone; the pyritic lens extends four hammer-lengths above and below the hammer, from 4200 level, N-9940 and E-8960; **B** faulted contact of pyrite with cherty rock with brecciated limestone (*white on right*) along the longitudinal fault; the upward tapering triangular body behind the fuel tank is sphalerite and pyrite with minor galena (looking north at the decline on 4200 level at N-10050 and E-8950)

Figs. 3 and 4 show that virtually every contact involving sulfide bodies (except for the contact of pyrite-chert with the Vent) is sheared or brecciated. Figs. 5c, 7a, and b show these relationships on increasingly larger scales. Figs. 3, 4, and 6 show that the Longitudinal fault is a zone 200 m wide, that cuts massive pyrite and sphalerite. Because the floor of the pit is covered with ramps and other roadways, many of the benches are obscured by talus, and much of the southern part of the pit consists of backfill from previous underground mining, the continuity of many of the individual faults cannot be demonstrated. Nonetheless, because the Vent is not cut by any subparallel faults, the Longitudinal fault is inferred to be older than the Vent.

Northwesterly trending faults in the southwestern corner of the pit bound zones of pyrite without chert but do not offset the contact of the massive pyrite with the Vent (Fig. 3). Furthermore, along the contact of the massive pyrite and the Vent, northwesterly trending fractures up to a few meters apart in pyrite-chert do not continue into the Vent. The northeasterly trending fault zone that cuts the San Alberto orebody in the northeastern corner of the pit does not displace either the pyrite-chert or the pyrite-Vent contact, and must, therefore, be truncated by the Longitudinal fault (Fig. 3).

The southeastern extension of the deposit, the Noruega zone (Fig. 6), is bounded by strands of the Longitudinal fault. Bowditch (1935, p. 95 and 119) and Lacy (1949, Fig. 2) described the Noruega as a tabular body below a fault. Drilling in 1985 demonstrated that the Noruega also is underlain by a zone of brecciated limestone (H. Alvarez 1987, personal communication). A comparison of Figs. 3 and 6 shows that the northwestern end of the Noruega projects into the pit (as backfill) and that its northeastern contact is a fault.

According to Jenks (1951) the Longitudinal fault is a regional thrust fault, but Figs. 3 and 6 illustrate that it probably has a component of dextral strike-slip. The best evidence is the dextral displacement of the Noruega body from the rest of the massive sulfide. In addition, shears mapped in the pit (Fig. 3) can be interpreted as Riedel shears in a system of dextral movement (see inset on Fig. 6). Thus, on the scale of the deposit, the fault is similar to strike slip duplexes described by Woodcock and Fischer (1986). Duplexes caused tectonic thickening of the deposit, making open-pit mining feasible.

The cross section (Fig. 4) was drawn assuming that almost all contacts, especially limestone-sulfide contacts, are tectonic and that thrusting was westward. Subsurface information is from the best available (scale 1:2400) maps in Centromin's files; these maps do not subdivide massive pyrite or massive sphalerite into mappable units and do not have structural symbols to indicate the nature of contacts. The lack of structural correlation between footwall and hangingwall segments (which is to say that the cross section is unbalanced) is attributed to strike-slip movement across the plane of the cross section and to the lack of detailed subsurface structural mapping. Fig. 6 was generated by reducing Fig. 3 into domains of predominantly pyrite, ore, limestone, and cherty rock and by drawing as few major faults as possible through the data of Fig. 3. The tectonic lens of pyrite with chert in Fig. 7a is inferred to be a small-scale analogue of the lenses shown in Figs. 3, 4, and 6.

Regional stratigraphy

Regional stratigraphic relations also suggest that the Longitudinal fault is older than the Vent. In various places in central Peru, folded lower Tertiary clastic rocks are unconformably overlain by only gently dipping terrestrial felsic volcanic rocks. These volcanic rocks can be as old as 22.5 Ma but are generally younger than 15 Ma (Jenks 1951; Silberman and Noble 1977; McKee and Noble 1982, and references cited therein; McKee et al. 1986); some plutons are as old as 30 Ma (Soler and Bonhomme 1988). These relationships imply that felsic volcanic/intrusive centers (such as the Vent) post-date the folding and associated thrusting.

Alteration

The replacement origin of both massive pyrite and massive sphalerite at Cerro de Pasco was proposed because on a map scale the contact between the sulfides and the limestone appears to be irregular, and ... "if a geometrically probable position of the contact between the rocks of the Vent and limestone be drawn on the geologic map of each level, nearly all of the known lead-zinc bodies ... lie on the east (limestone) side of such a line" (CdP 1950, p. 164). Furthermore, bands of cherty rock within massive pyrite (such as those shown in Figs. 5d–f) and mappable inclusions of shale and chert up to 80 m long and 4 m thick (Einaudi 1977, Fig. 5a) were regarded as unreplaced residuals (Lacy 1949; Ward 1961; Petersen 1965; Einaudi 1977).

Yet, alteration (other than brecciation) of the Pucará Formation adjacent to the deposit is so "spotty and inconspicuous" (Rodgers 1983, p. 54) that the limestone is virtually unaltered. Alteration of the limestone "is usually a gougy zone, varying in width from a few inches to many feet, that defies accurate description ... There is no evidence of contact metamorphism with the usual development of silicates" (Bowditch 1935, p. 94). In contrast, skarn does occur in the 1 km-long block of the Pucará on the norhtwest side of the Vent (Rodgers, 1983); this is the block of Pucará shown in the northwestern part of the Vent in Fig. 2.

Fig. 6 shows that the south end of the deposit is in contact with Excelsior Formation, not the Pucará limestone. Thus, the presence and replacement of Pucará limestone were not necessary to generate the massive pyrite.

The previously cited irregular nature of the contacts of massive sulfides with the host rocks (which was regarded as evidence for replacement) deserves comment. In the past, the contacts were neither recognized nor mapped as faults. Thus, when contacts were drawn, the resultant patterns (in a complex imbricate fault zone) were irregular.

Fig. 3 confirms that an alteration zone of quartz-sericite-pyrite occurs in the Vent adjacent to the pyrite body. Several authors have noted that this zone seems to prove the post-Vent age of the pyrite body. An alternative interpretation is that the rocks of the Vent were sufficiently hot (and water-bearing) that when emplaced, they reacted hydrothermally with the massive sulfide (in much the same way that post-ore dikes in other sulfide deposits undergo contact sulfidization and alteration).

Discussion

Those who favor the previous Tertiary magmatic hydrothermal (replacement) interpretations might argue that the sulfide bodies formed during the Miocene intrusive/volcanic episode and that related (but later) igneous activity injected the dikes that cut the ore and formed the fragmental rocks that incorporated fragments of pyrite. Others might suggest that the dikes are pre-ore but somehow unreceptive to replacement. The Longitudinal fault might be envisioned as a pre-ore fault that was reactivated after early hydrothermal activity associated with the Vent generated the massive sulfide (Bowditch 1935). Alternatively, both the Vent and the massive sulfides might be considered to be older than the Longitudinal Fault, and the reason that the Vent is unfractured is that it was more competent than the massive pyrite and was more distant from the fault. It might be argued that Zn-Pb-Ag vein and manto deposits in carbonate rocks (such as those at Bingham, Utah described by Rubright and Hart 1968) typically have spotty and inconspicuous alteration; and relict stratification similar to the features of Figs. 5d–h. The massive pyrite at the southwest end of the deposit that is bounded on the southeast by the Excelsior Formation (Fig. 6) might be interpreted to indicate that the Pucará was folded or faulted into the Excelsior Formation and then completely replaced.

The major problems with these alternative hypotheses is their complexity (especially if more than one is involved), and that the evidence for them either has been eroded or exists below or beyond the volume of rock that can be inspected. The simplest explanation is that, no matter what its origin, the body of massive sulfide is older than the Vent.

Bowditch (1935, p. 36), CdP (1950, p. 162), and Petersen (1965, p. 438) stated or implied that ore-forming solutions might have entered the Longitudinal fault and replaced brecciated or fractured rocks along it. However, Fig. 3 confirms that the texturally massive sulfides, the so-called replacement ores, are offset and brecciated by the Longitudinal Fault, not deposited along it. This confirmation also disposes of similar ideas that the "hydrothermal solutions associated with the volcanic activity formed a massive replacement and fissure-vein sulfide deposit ..." (Einaudi 1977, p. 896) or pluton-related Cordilleran vein or lode deposit (Einaudi 1982, p. 177 and Table 7.12).

Historically the polymetallic sulfide deposits of central Peru have been considered to be Tertiary magmatic (or volcanic) hydrothermal. Many districts certainly are magmatic hydrothermal: Casaplaca (Petersen 1965; Wu and Petersen 1977), Morococha (Petersen 1965; Eyzaguirre et al. 1975), Julcani (Petersen et al. 1977), Huanzala (Imai et al. 1985), Huancavelica (McKee et al. 1986), Milpo-Alacocha (Soler and Bonhomme, 1988), and Quiruvilca (Bartos 1987). However, Cerro de Pasco (except for the pyrite-enargite veins) must be excluded from this group. Cheney et al. (1991) develop the suggestion (Cheney 1985) that Cerro de Pasco has characteristics (including the textures shown in Figs. 5d–j) typical of a deformed sediment-hosted massive sulfide deposit.

Conclusions

Mapping of the McCune pit has confirmed and expanded oft-ignored observations that the texturally massive sulfides at Cerro de Pasco are cut by the Longitudinal fault. In contrast, the Vent is younger than both the fault and the massive sulfides. Thus, the massive sulfides cannot be genetically related to the Vent, unless the histories of the Longitudinal Fault, the Vent, and sulfide deposition were more complex and overlapping than can be determined at the present levels of observation in the open pit and underground mines.

Although mapping of the McCune pit has confirmed that the Longitudinal Fault cuts massive pyrite and massive sphalerite, the exact nature of the Longitudinal Fault within the mine will remain uncertain until the underground portion of the mine is remapped. Surface mapping in the McCune pit suggests that the fault, which regionally is a thrust, has a component of dextral slip. Duplexes in the Longitudinal fault zone thickened the deposit so that it can be mined by open pit. Much additional work will be needed to fully describe the deposit and to determine whether significant, as yet undiscovered, orebodies are offset by the Longitudinal fault.

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