Revision 1

Magnetite spherules in pyroclastic iron ore at El Laco, Chile

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ABSTRACT

The El Laco iron deposits in northern Chile consist of magnetite (or martite) and minor hematite, pyroxene and apatite. The orebodies are situated on a volcanic complex and resemble lavas and pyroclastic deposits, but a magmatic origin is rejected by some geologists who regard the ores as products of hydrothermal replacement of volcanic rocks. This study describes spherules of magnetite in the ore at Laco Sur, and outline a previously unrecognized crystallization process for the formation of spherical magnetite crystal aggregates during volcanic eruption.

Mining at Laco Sur, the second largest deposit at El Laco, shows that most of the ore is friable and resembles pyroclastic material; hard ore with vesicle-like cavities occurs subordinately. The friable ore is a porous aggregate of 0.01-0.2 mm magnetite octahedra with only a local stratification defined by millimeter-thin strata of apatite. Films of iron phosphate are common on magnetite crystals, and vertical pipes called gas escape tubes are abundant in the ore. A SEM study reveals that magnetite spherules in the range 0.05-0.2 mm occur in most samples of friable ore from the central-lower part of the deposit. The proportion of spherules in a sample varies from high to nil, but overall the spherule content is low in the ore. The spherules are aggregates of octahedral crystals, or single octahedra, that have been rounded by stepwise, subparallel growth of magnetite with a systematic slight shift in orientation of successive steps. The shape of the spherules demonstrates that they formed unattached to any surface. Growth from hot magmatic gas saturated in iron in a volcanic plume and deposition as ash fall can account for the features of the spherule-bearing friable ore.

Keywords: Crystal growth, Fe, eruption, magmatic gas, plume, volcanic ash

INTRODUCTION

The El Laco deposits are the best preserved examples of apatite iron ore of Kiruna type in the world. They occur on the flanks of a Plio-Pleistocene volcanic complex of andesitic to dacitic composition in the High Andes of northern Chile. There are seven deposits of high-grade iron ore within an area of 30 km^2, with total resources exceeding 500 million tons (Fig. 1). The orebodies are composed of magnetite (or martite), and minor amounts of apatite, pyroxene and hematite.

The first published report of the El Laco deposits (Park 1961) described the orebodies as magnetite lavas due to their morphological similarity to flows of vesicular basalt. Exploration trenching and mining subsequently revealed that much of the ore below the surface is friable and resembles pyroclastic material (Henríquez and Martin 1978; Nyström and Henríquez 1994; Naslund et al. 2002; Henríquez et al. 2003; Nyström et al. 2008). According to these authors the El Laco deposits formed from volatile-rich iron-oxide magmas that intruded the andesitic to dacitic volcanic structure at shallow depth and locally erupted to the surface.

This magmatic interpretation has been questioned but the similarity in appearance of the ore to silicate lavas and pyroclastic material is not in dispute. Some authors believe that the El Laco deposits formed from iron-rich hydrothermal fluids that completely replaced silicate rocks whose volcanic structures and textures were inherited (Rhodes and Oreskes 1999; Rhodes et al. 1999; Sillitoe and Burrows 2002). Here we report new information that is inconsistent with a replacement origin.

A SEM study of friable ore of pyroclastic appearance from one of the major orebodies, Laco Sur, reveals that ca. 0.1 mm diameter spherules of magnetite occur in most of the investigated samples. Such spherules have to the best of our knowledge not been reported before from iron deposits in the literature. The purpose of this paper is to describe these spherules, and to show that they formed by rapid crystal growth in a volcanic plume during eruption of iron-oxide melt.

THE FRIABLE ORE

Laco Sur is the second largest deposit at El Laco (Fig. 1) and the only deposit that has been exploited. Mining has taken place intermittently, leaving a c. 150 m long open pit (Fig. 2). The pit wall is c. 25 m high in the central part of the section, where it consists of four benches, and lower at the sides. The appearance and physical character of the exposed ore varies considerably. Portions of the ore are hard and contain 1-15 mm large, often elongated open spaces similar to vesicles. This ore type is resistent to erosion and corresponds to the “magnetite lava” reported by Park (1961). However, the major part of the exposed ore in the open pit is friable. The spherules described in the present study occur only in the friable ore type.

The friable ore is a porous aggregate of fine-grained magnetite octahedra. The crystals are mainly between 0.01 and 0.1 mm in diameter, although some are 0.2 mm wide. The magnetite is unaltered in the open pit except near the upper surface and along steep faults where the oxidation to hematite is considerable to strong; martitized ore is not included in this study. Apatite (fluorapatite, Naslund et al. 2002) is another constituent of the ore, present in small to trace amounts. It occurs in two ways: as microscopic euhedral prisms which commonly are unbroken

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and adhere to magnetite crystals, and as needles projecting from magnetite crystals in porous ore and vesicle-like cavities. Some cavities are white due to an abundance of apatite needles.

Most of the friable ore lacks discernible structure or shows only a local, faint stratification (Fig. 3A). However, in some places a conspicuous stratification defined by millimeter-thin strata rich in apatite prisms can be followed for a few meters (Figs. 3B-C); cross-bedding is also observed (Fig. 3D). Stratified ore of different character is found in a roadcut 100-200 m southwest of the open pit (Fig. 1). The ore beds here are more extensive. They are size-sorted, lack visible apatite, and consist of euhedral to anhedral hematite crystals and crystal aggregates of coarser grain size than the friable magnetite ore in the open pit.

From a distance, planar structures that extend for several meters to tens of meters and resemble bedding planes, can be distinguished in the pit wall (Fig. 2). They are subhorizontal or dip up to 30° away from the massive ore outcropping above the open pit (Fig. 1). The planar structures in the lowest bench are partly outlined by white inclusions of altered volcanic rock. Such inclusions are more common, and larger, outside the central section of the open pit. The rock inclusions show knife-sharp contacts towards the ore (Naslund et al. 2002). Inclusions of massive ore are also found, but their quantity is difficult to estimate due to often small textural contrasts with surrounding friable ore.

The friable ore has a black to dark gray color. However, a dark green tone caused by a thin film of iron phosphate (lipscombite, $Fe^{2+}Fe^{3+}{}_2(PO_4)_2(OH)_2$) on the magnetite crystals is common in the central part of the open pit. Locally, the color of the film varies from iridescent blue to purple due to the presence of other, undetermined iron phosphates. A few, up to 1 cm large, flattened lumps of orange diadochite, $Fe^{3+}{}_2(PO_4)(SO_4)(OH)\cdot 6H_2O$, are observed in the ore (Fig. 3C). Diadochite is widespread in the stratified ore in the road cut southwest of the open pit (Naslund et al. 2002).

The consolidation of the friable ore in the open pit is extremely variable. In places, the ore is an almost unconsolidated aggregate that easily crumbles into its constituents. In other places it grades into hard, dense ore. One controlling factor for this change is the proximity to open vertical pipes referred to as gas escape tubes (Figs. 3C and 4A-B). Such pipes are a characteristic feature of the friable ore in the open pit. They are meters to tens of meters long, and centimeters to tens of centimeters in diameter, with circular to oval cross sections (Naslund et al. 2002). Some of these open channels are more fissure-like than tubular and cross the entire 25 m high section.

The interior surfaces of the gas escape tubes are partly coated by large magnetite octahedra with curved surfaces (Fig. 4B). Strongly altered prisms of pyroxene, and empty molds after this mineral revealed by occasional relicts, also line some tubes. In addition, pyroxene is intergrown with magnetite and minor apatite in a few veins cross-cutting the ore body. With the exception of these occurrences, pyroxene appears to be absent in the friable ore exposed in the open pit. However, drill cores from Laco Sur and other deposits in the district show that up to 3 cm long prisms of pyroxene occur as radiating prisms in rims around inclusions of altered rock, and as a matrix mineral at depth in the ore (Naranjo et al. 2010).

MAGNETITE SPHERULES

Small spherical to spheroidal particles of magnetite, here referred to as spherules, were found during an inspection of friable ore from Laco Sur under a stereomicroscope. A systematic study was then made of all ore samples from the open pit at Laco Sur collected by one of us (JON), using a Hitachi S-4300 scanning electron microscope (accelerating voltage = 6 kV, beam current = 10 μA) at the Swedish Museum of Natural History in Stockholm. It resulted in the discovery of spherules in 13 out of 17 investigated samples of friable ore of different texture and apatite content. Occurrence of spherules appears to be unrelated to the presence or absence of stratification or apatite content; apatite is abundant, sparse or absent in these samples. No spherules were found in the 'vesicular' ore type corresponding to the "magnetite lava" of Park (1961). All investigated samples of friable ore show a limited range in grain size, and lack inclusions of coarser material.

The magnetite spherules have diameters between 0.05 and 0.2 mm, the majority being 0.1-0.15 mm in diameter. Their form varies from almost spherical to ellipsoidal bodies, often with concavities (Figs. 5A-B). Some spherules with two concavities look like short cylinders or drums (Fig. 5C). The spherules occur mixed with aggregates and single crystals of octahedral magnetite of the same size range as the spherules (Figs. 5D-F). The main visible difference between octahedral aggregates and spherules is the rounded form of the latter. Particle aggregates approximately 0.1 mm in diameter consisting of up to ten small spherules joined together have been observed but are uncommon. The proportion of spherules varies: no sample consists solely of spherules; a few samples are dominated by spherules, but most contain a low proportion of spherules, and some lack spherules entirely. Overall, the content of spherules is low in the 17 investigated samples.

The spherules are aggregates of octahedral crystals (Figs. 6A-B), or single octahedra, that have been rounded by stepwise, subparallel growth of magnetite. A systematic slight shift in orientation of the individual steps constituting the overgrowth has generated curved crystal faces. They mimic the curved faces of large magnetite octahedra coating gas escape tubes (Fig. 4B). The outer surface of a spherule with subparallel overgrowth may be rather smooth (Fig. 5A), or have a morphology that is jagged in detail (Figs. 6C-D). Concavities are parts of spherules with less or no overgrowth. They reveal that the crystals in the aggregate below the overgrowth as a rule are coarser than the partial rim of overgrown crystals (Figs. 6B-C). With the exception of this rim, the spherules lack internal layering.

In three of the samples the crystal faces of magnetite octahedra are decorated with tiny projecting magnetite lamellae of bladelike form. The up to 0.1 μm thick lamellae occur single (Fig. 6E) or grouped closely together in bands along octahedral planes (Figs. 6F and 7A). These projecting bands give a rough texture to the crystal surfaces. In addition, bladelike magnetite lamellae of different orientation form small rosettes on the octahedra (Fig. 6E), and on apatite prisms (Fig. 7B). However, most of the bladelike magnetite lamellae on apatite are predominantly oriented along its *c*-axis. Moreover, 10-25 μm clusters of 0.1-0.5 μm thick euhedral plates of hematite occur as local overgrowths on decorated magnetite octahedra (Fig. 6F).

None of the other investigated samples have projecting lamellae of magnetite and clusters of hematite plates on octahedral faces. The magnetite in these samples may have a thin coating of precipitated silica, sparsely sprinkled with tiny droplike bodies of the same composition (Figs. 6C-D), or a patchy crust composed mainly of silica. Samples cemented by silica are relatively hard and come from the vicinity of gas escape tubes. Some magnetite crystals in samples at gas escape tubes have a corroded appearance.

One spherule looks different from all the others observed in this study. It is an aggregate of magnetite platelets (Fig. 7C). High magnification reveals the same projecting bladelike lamellae of magnetite and clusters of hematite described above. The morphology of the platelets appears to be the result of parallel twinning (cf. Fregola et al. 2005). These platelets differ in appearance from the platy magnetite made up of octahedra in parallel intergrowth reported by Nyström and Henríquez (1994, fig. 7D). Such thin plates were also found in this study, especially in samples without spherules. They look like single octahedra preferentially grown in one direction (Fig. 5B).

The composition of the magnetite was not determined in this study, leaving the question of chemical differences between magnetite in spherules and octahedral aggregates unexplored. A previous study (Nyström and Henríquez 1994) shows that magnetite at El Laco is rather uniform in composition.

DISCUSSION

Spherules of different origins

Magnetic spherules of similar dimension as those discovered at El Laco have been recovered from many environments, for example deep-sea sediment, polar ice, and areas with heavy industry. These spherical to subspherical particles are magnetite-bearing and can be of extraterrestrial, anthropogenic and, less commonly, volcanic origin.

Cosmic spherules (Genge et al. 2008) form by melting of micrometeorites. There are two types rich in iron: spherules composed predominantly of magnetite and wüstite, and spherules consisting of magnetite dendrites in silicate glass. Ablation of meteorites and impact events can also produce iron-rich spherules. The magnetite typically occurs as dendrites or dendritic arrays in these spherules (Zbik and Gostin 1995; Marini et al. 2004; Stankowski et al. 2006; Genge et al. 2008), in contrast to the octahedral aggregates at El Laco.

Anthropogenic spherules, formed by melting, are now found everywhere as contamination. They are present in fly ash, a waste material generated from the combustion of coal, and in emissions from metallurgical, metal-processing and other industries. Fly ash is characterized by a prevalence of spherical particles consisting of glass matrices with spinel minerals and silicates. The spinel phase is mostly magnetite, occurring as feathery or fanlike dendrites and octahedra (Sokol et el. 2002; Sulovsky 2002).

Spherules can also form from low-viscosity magmas erupting in fire fountains (Lefèvre et al. 1986; Meeker and Hinkley 1993). These spherules consist largely of glass and their magnetite content is low. No silicate glass has been observed in the spherules from the open pit at Laco Sur, and basalts or other rocks from low-viscosity magmas are unreported from the volcanic complex hosting the ores. Iyer et al. (1999) suggested that magnetite-rich spherules found in pelagic clay from the Indian Ocean are volcanogenic-hydrothermal in origin. However, their argument against a cosmic origin rests solely on geochemical grounds.

A model for the formation of spherules at El Laco

The magnetite spherules discovered at El Laco formed in a volcanic environment. The shape of the spherules demonstrates that they grew unattached to any surface, and their crystalline nature rules out formation of their spherical shape by abrasion. They crystallized in a medium that permitted unimpeded growth in all directions, which means a melt or fluid. It is very unlikely that the spherules crystallized in an iron-rich melt below the surface because their delicate features would not have survived an eruption undamaged, nor would the discrete apatite prisms coexisting with spherules in friable ore. Neither the apatite prisms nor the spherules have a surface coating as might be expected if they had been ejected from a melt and had retained a thin layer of melt on their surface (a silica coating, when present, is a late feature). Spherules have not been observed in orebodies morphologically similar to lava flows at El Laco. Thus, formation in a fluid or gas phase is indicated.

The hydrothermal models for the origin of the El Laco ore put forward by Rhodes and Oreskes (1999), Rhodes et al. (1999), and Sillitoe and Burrows (2002) are unable to explain the formation of unconsolidated ore containing spherules. The lack of attachment surfaces, the growth morphology, and the internal crystal texture of the spherules preclude formation by replacement or post-depositional recrystallization. Rhodes and Oreskes (1999) and Rhodes et al. (1999) proposed a multistep model in which andesite is replaced by scapolite, followed by pyroxene, which is in turn replaced by magnetite, without destruction of the original volcanic structures and textures. However, a study of drill cores from ore at depth in the area north of Laco Sur (Pasos Blancos; Fig. 1) by Naranjo et al. (2010) shows that the reverse took place: pyroxene formed after the main body of magnetite, and scapolite formed after (or together with) pyroxene.

We suggest that growth from hot, iron-saturated, magmatic gas in a volcanic eruption column accounts for the features of the spherule-bearing friable ore. The postulated existence of iron-oxide magma at a geologically realistic temperature requires large amounts of dissolved volatiles (Gibbon and Tuttle 1967; Weidner 1982), which are released during an eruption. Nyström et al. (2008) inferred a melt temperature of the order of 1000°C based on oxygen isotope data for magnetite from El Laco. Pyroxene, a late stage mineral in some of the ore, records temperatures in excess of 800^{o}C in some samples, based on fluid inclusion homogenization (Broman et al. 1999; Rhodes et al. 1999) and pyroxene Ca-Fe-Mg exchange geothermometry (Lindsley 1983; Naslund et al. 2002). Large volumes of released volatiles are consistent with the widespread occurrence of apatite and iron phosphates in the porous, friable ore of the open pit. The apatite prisms in stratified ore probably formed from elemental phosphorus in the eruption column. The dark green film of lipscombite on magnetite is pervasive in large portions of the friable ore. The abundance of gas escape tubes in this ore type bear witness of vigorous degassing of the iron-oxide magma.

Crystallization of magnetite is believed to have started immediately on eruption in the expanding and cooling column. Experiments have established that magnetite crystallizes rapidly on quenching in Fe-rich melts and that no iron-oxide glass forms even at cooling rates > 100^oC/sec (Philpotts 1967; Naslund 1983), in contrast to volcanism involving silicate magmas, where glass is produced by quenching under analogous conditions.

The friable ore in the open pit has a grain size corresponding to fine ash. The limited size range of the magnetite crystals, crystal aggregates and spherules in the samples, and the local stratification, suggest gravitational sorting. Variations in eruption intensity could account for the millimeter-thin strata defined by apatite. Rapid crystallization of magnetite from innumerable nuclei in the eruption column might also explain the limited size range of the magnetite.

The magnetite crystals and crystal aggregates composing the friable ore could to a large extent be quenched, small droplets of iron-oxide melt. However, the spherules, or at least the overgrowth of subparallel magnetite that enhances their rounded form (Figs. 5A and 6C), and the finest ash particles probably crystallized from the magmatic gas driving the eruption.

Experimental data support the idea that hot magmatic gas could carry considerable amounts of iron as halogen complexes. Experimental studies indicate that dilute chloride solutions at 500°C can contain in excess of 1000 ppm Fe (Helz 1971), 1M HCl at 600°C may contain in excess of 40,000 ppm Fe (Whitney et al. 1985), and that concentrated chloride solutions at 500°C can contain in excess of 100,000 ppm Fe (Chou and Eugster 1977). The predominance of fluorine over chlorine in halogen-bearing minerals at El Laco (Naranjo et al. 2010) strongly suggests that fluorine complexes played the principal role. Given the corrosive nature of HF solutions, there are little data on Fe solubilities in F-rich solutions at high temperature. At ~100°C, however, Fe concentrations in excess of 90,000 ppm can be obtained by dissolving $FeSiF_6{\cdot}6H_2O$ in water (Perry 2011). Any fluid or gas exsolved from an iron-oxide magma before or during an eruption would necessarily be saturated in iron. The changes in pressure and temperature associated with an eruption, however, are likely to cause dissolved iron to sublimate directly from a fluid/gas phase into solid magnetite. Precipitation of magnetite and hematite by sublimation from hot volcanic gas is a common feature in the upper parts of siliceous ignimbrites (McBirney and Williams 1979).

Large volumes of porous white rock of low density that consist almost exclusively of siliceous material outcrop between Laco Sur and Laco Norte (Fig. 1). It is an intensely leached volcanic rock. Leaching on such scale is consistent with an environment permeated by hydrofluoric acid. The molds after pyroxene at gas escape tubes also reflect the action of hydrofluoric acid.

The hot magmatic gas driving the eruption was probably ejected at high speed (cf. Sparks et al. 1997). Gas flow within the column and during the eruption could have varied from laminar to turbulent. Flow variations and collisions of particles within a turbulent eruption column might result in different spherule morphologies: rounded in some samples (Figs. 5A-B), angular in others (Fig. 5F), and even cylindrical (Fig. 5C).

The spherules at El Laco contain no silicate glass, and the octahedra composing them (Figs. 6A-C) lack the ordered arrangement visible on the surface of spherules of cosmic origin consisting largely of magnetite (cf. fig. 3d in Stankowski et al. 2006, and fig. 2:1 in Marini et al. 2004). The two quoted figures show skeletal crystals formed by continued crystallization of dendrites. The spherules at El Laco are aggregates of octahedra, not skeletal crystals. The spherules of cosmic origin formed from 'super-heated' glass, which would, as such, be devoid of any crystal nuclei and would be likely to result in dendritic growth. The El Laco melt was never super-heated, and as a result, likely retained sufficient crystal nuclei to form octahedral crystals upon cooling, even when quenched.

The formation of magnetite rather than hematite indicates a low oxygen fugacity during crystallization. Water was either absent or present in very low concentration in the eruption column, or the volcanic gas was buffered at an oxygen fugacity within the stability field of magnetite. The presence of S-SO_2, CO-CO_2, or H-HF in the gas stream could have acted as such a buffer. The dry environment and small size of magnetite crystals in the eruption column might mean that electrostatic forces influenced the growth of crystal aggregates (cf. Sparks et al. 1997). The stratified, size-sorted ore in the roadcut southwest of the open pit that consists of hematite (Fig. 7D) was deposited during a different style of eruption or from another vent than the ore in the open pit.

It is likely that magnetite crystals and apatite prisms formed in the eruption column settled out as fine ash and gave rise to the thick pyroclastic deposit of friable ore now exposed in the open pit. A few of the investigated samples were collected in parts of the ore pile penetrated by hot magmatic gas which resulted in dendritic overgrowths of magnetite: the magnetite lamellae decorating crystal surfaces (Figs. 6E to 7B). These dendrites apparently grew after the deposition of the ore, as shown by the fact that *all* crystals are decorated with dendrites in the only samples where they occur; *none* of the magnetite crystals in other samples are decorated with dendrites.

With increasing oxygen fugacity and/or lower temperature hematite became the stable phase and crystallized as clusters of small plates (Fig. 6F). The magnetite dendrites and hematite clusters enhanced the rounded form of the spherules. The apatite needles projecting from magnetite crystals in friable ore and occurring in cavities, and the apatite crystals in gas escape tubes and in late veins appear to have crystallized from a residual gas/fluid phase.

The deposited magnetite ash was sufficiently unconsolidated to be blown out locally by streaming gas. Subsequently, a few of the gas escape tubes were partially filled with bedded fine-grained magnetite. The fact that the 25 m high central section of the open pit contains many gas escape tubes, some crossing the entire section, strongly suggests that most of the ore in the open pit is pyroclastic. Magnetite from the vicinity of gas escape tubes is somewhat corroded. Deposition of silica at a late stage cemented the ore near open channelways.

The "magnetite flow" reported by Park (1961) is situated above the open pit (Fig. 1). The lava-like ore is very hard and might have protected the friable ore from erosion. Part of the "flow" looks like a dike with vertical gas escape tubes along a planar surface (fig. 7 in Park 1961). Henríquez and Martin (1978) interpreted this ore dike as a feeder for the flow. Other evidence for eruption of gas-rich iron-oxide melt at El Laco are spindle-shaped magnetite bombs (Henriquez and Nyström 1998) and scoriaceous ore (Naslund et al. 2002).

It is possible that the eruption forming the ore exposed in the open pit at El Laco took place in a glaciated environment (Ammann et al. 2001; Naranjo et al. 2010). However, even eruptions that start under thick extensive ice sheets can evolve into sub-aerial eruptions with much ash. Such an eruption would border on magmato-phreatic and would have a variety of features not seen in the open pit. For example, a subglacial eruption is likely to have hematite in place of magnetite, as a result of alteration during cooling in a wet environment, and would be likely to have a clay-sized matrix.

Most of the samples of friable ore contain spherules, and this ore type makes up the predominant part of the exposed ore in the open pit. A genetic model for El Laco must be able to explain the formation of the spherule-bearing, friable ore simultaneously with the formation of the deposit. Pyroclastic deposits composed of magnetite or hematite ash is not an ore type unique to El Laco. A recently described example is the Oligocene La Perla deposit in Mexico which even contains well-preserved fossil pollen in the pyroclastic ore (Corona-Esquivel et al. 2010), confirming surface deposition as unconsolidated ash at near ambient temperatures.

IMPLICATIONS

A previously unrecognized crystallization process for the formation of spherical magnetite crystal aggregates has been described. The magnetite spherules discovered in friable iron ore at Laco Sur formed by rapid crystal growth in hot, iron-saturated magmatic gas exsolved from an iron-oxide melt. The occurrence of spherules in unconsolidated, locally stratified and even cross-bedded deposits of 0.01-0.2 mm large magnetite crystals and crystal aggregates indicates that the ore was deposited as ash. The magmatic origin of the spherule-bearing ore is supported by its close association with magnetite ore characterized by cavitites that resemble vesicles in lava. Other, unexploited orebodies at El Laco look like lava flows, dikes and subvolcanic bodies, and their magmatic nature would not be questioned were it not for their composition. The implication is that less well-preserved deposits of similar ore in other parts of the world also were derived from iron-oxide melts. Thus, the magnetite spherules at El Laco can elucidate the controversial origin of the magnetite-apatite ores of Kiruna type.

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Figure captions

FIGURE 1. The El Laco deposits in northern Chile before mining. This study is based on samples from Laco Sur. An inset shows the location of the open pit (OP) and two outcrops of “magnetite lava” (L) reported by Park (1961); roads are indicated by thick black lines.

FIGURE 2. Part of the northwestern wall of the open pit at Laco Sur (bench height = 6 m). Subhorizontal to shallow-dipping planar structures resembling bedding planes are indicated with white arrows. Steep structures are gas escape tubes and postdepositional fractures.

FIGURE 3. Stratification in friable magnetite ore at Laco Sur. A = poorly consolidated ore without visible apatite; the ore strata are cut by a few steep silica-cemented fractures. B = bedded ore with thin strata of apatite (cf. figs. 4A-B in Nyström and Henríquez, 1994). C = bedded ore cut by a gas escape tube (left side); the bedding is best seen at the right side, above two flattened lumps of orange diadochite and a white apatite layer; the structure of the ore below the diadochite is obscured by rain-induced flow of ash-sized magnetite; the ore in the central part has an iridescent blue to purple color due to a film of iron phosphates (undetermined). D = ore with cross-bedding (the yellowish brown material in the upper right corner is silica colored by goethite).

FIGURE 4. Gas escape tubes. A = length-section through a gas escape tube in a block of friable ore without bedding; a cross-section through the tube is seen at the bottom of the block (in shadow). B = large magnetite crystals with curved octahedral faces coating a gas escape tube.

FIGURE 5. SEM images of magnetite spherules in friable iron ore from Laco Sur. A and B = spherules with concavities (sample LS-57); note the apatite prism at the left side and the thin magnetite plate in the upper right part of B. C = spherules looking like short cylinders (sample LS-15). D = ore relatively rich in spherules (sample LS-57); the spherule in the upper central part is shown in A. E = spherules and octahedral aggegates of magnetite from unconsolidated ore (sample LS-36). F = spherules in ore with apatite strata (apatite-free portion of sample LS-41).

FIGURE 6. Magnetite spherules. A = anatomy of a spherule in poorly consolidated ore (sample LS-58), showing an aggregate of octahedra with partial, subparallel overgrowth of magnetite. B = spherule with concavities (sample LS-57). C and D = spherules with concavities and curved outline generated by stepwise, subparallel overgrowth of magnetite; the tiny drop-like bodies on the magnetite consist of late silica (sample LS-15). E = magnetite crystals decorated with projecting magnetite lamellae of bladelike form along octahedral planes (sample LS-57); the bladelike magnetite also occurs as small rosettes. F = magnetite decorated with bands of magnetite lamellae, and an overgrown roselike cluster of euhedral hematite plates in the central part (sample LS-58).

FIGURE 7. A = magnetite decorated with magnetite lamellae (sample LS-57). B = apatite prisms decorated with bladelike magnetite lamellae, oriented along the *c*-axis, and forming small rosettes (sample LS-57). C = spherule composed of tabular magnetite crystals (inset shows magnified part; sample LS-58). D = euhedral, partly corroded hematite crystals from

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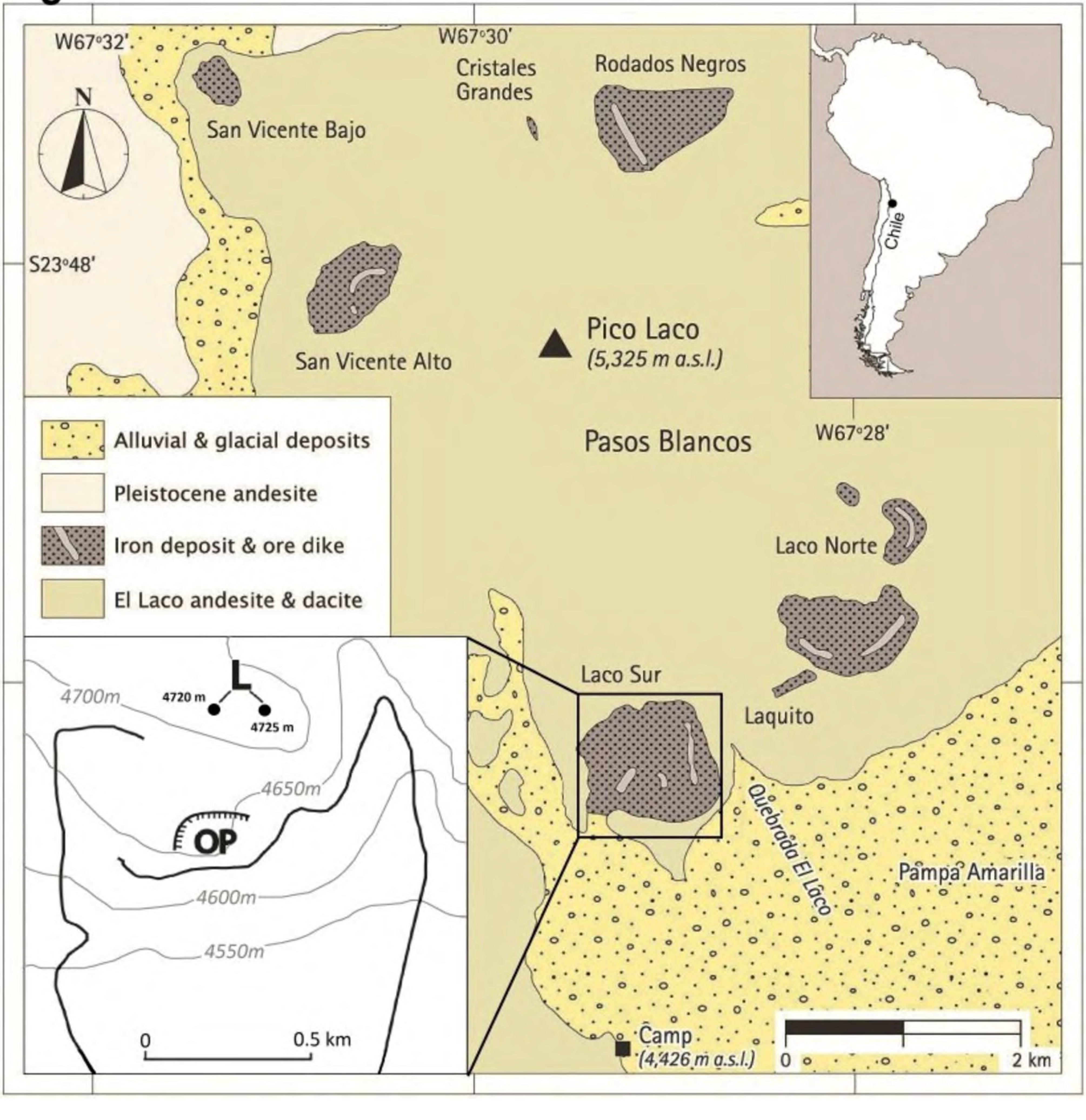
unconsolidated, stratified ore in a roadcut 100-200 m southwest of the open pit (Fig. 1; sample LS-25D).

Fig. 1



W67°32'
W67°30'
Cristales Grandes
Rodados Negros
N
San Vicente Bajo
Chile
S23°48'
San Vicente Alto
Pico Laco
(5,325 m a.s.l.)
Pasos Blancos
W67°28'
Alluvial & glacial deposits
Pleistocene andesite
Iron deposit & ore dike
El Laco andesite & dacite
Laco Norte
Laco Sur
Laquito
4700m
L
4720 m
4725 m
4650m
OP
4600m
4550m
0
0.5 km
Quebrada El Laco
Pampa Amarilla
Camp
(4,426 m a.s.l.)
0
2 km

Fig. 2

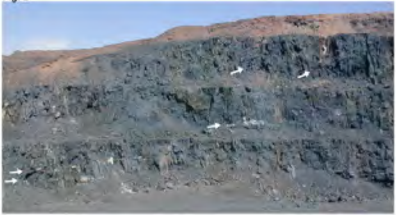


Fig. 3A

Fig. 3B

Fig. 3C

Fig. 3D

Fig. 4A

Fig. 4B

Fig. 5

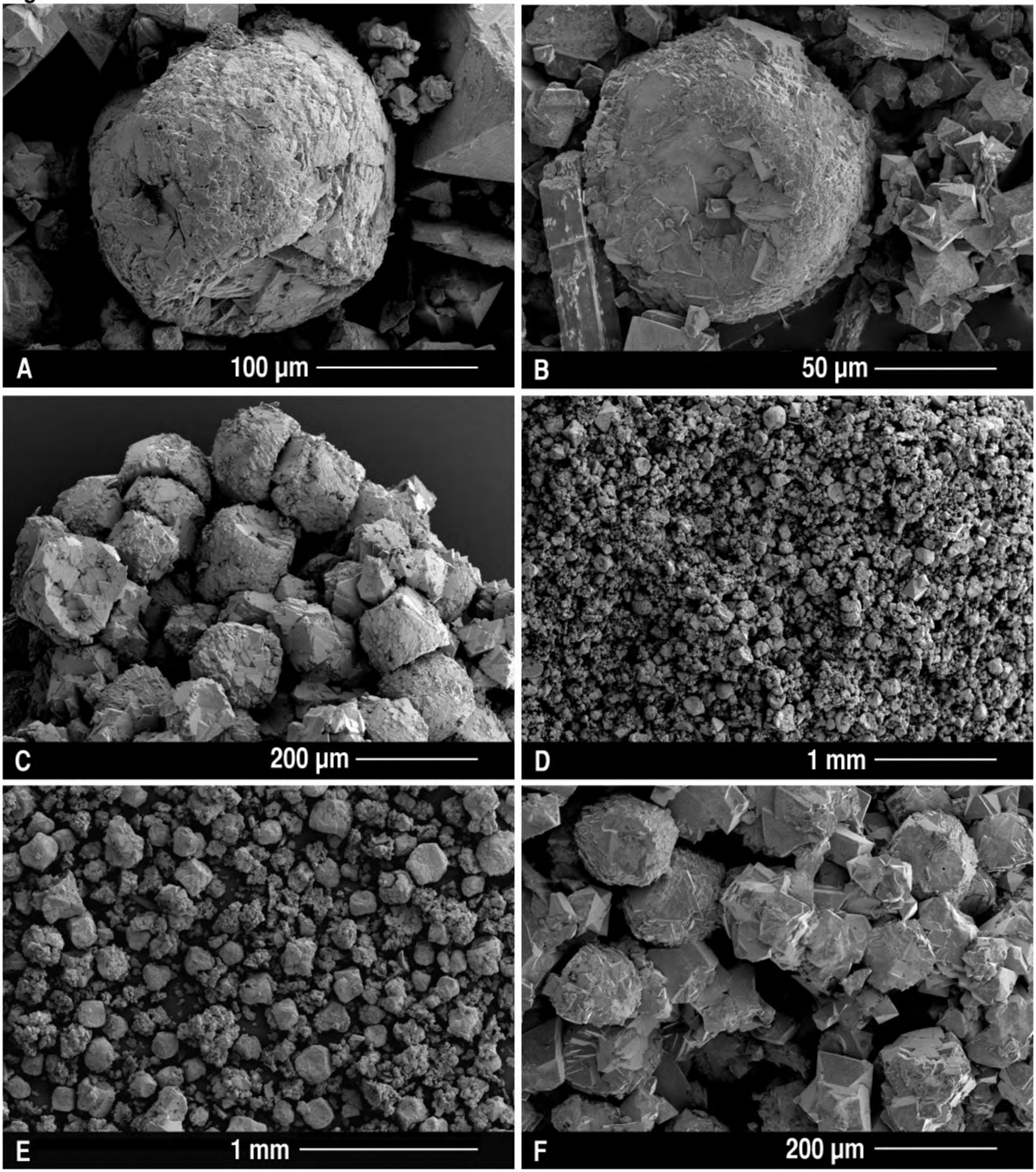


Fig. 6

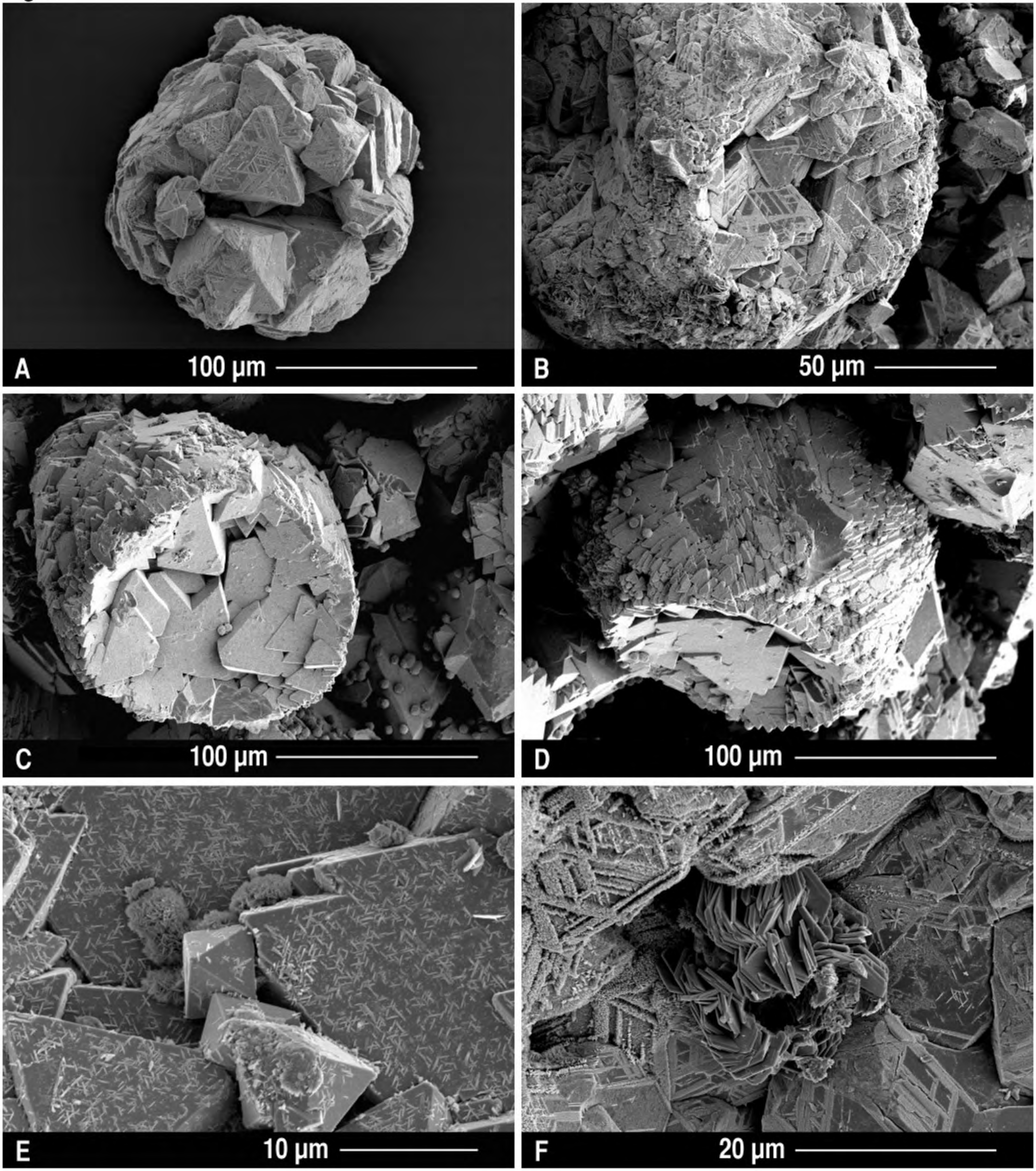


Fig. 7