Volcanic Stratigraphy, Alteration, and Sea-Floor Setting of the Paleozoic Feitais Massive Sulfide Deposit, Aljustrel, Portugal

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Abstract

The Feitais deposit is one of six polymetallic, volcanic-hosted massive sulfide deposits located adjacent to the town of Aljustrel in the Iberian Pyrite Belt of southern Portugal. The deposit occurs on the upright limb of the Feitais anticline, within the upper part of the regional Volcano-Sedimentary Complex of Devonian to Mississippian age and near the contact with the overlying Culm Flysch Group. It is stratigraphically underlain by felsic tuffs and flows and overlain by a unit of feldspar-bearing felsic tuff that passes upward into chert, then argillite, and finally graywacke turbidites. The massive sulfide lens is about 1,000 m in length, 500 m wide, and up to 100 m thick. Although mainly fine-grained pyrite, it commonly has a Cu-rich base that passes upward through a low-grade pyritic zone to a Zn-Pb–enriched upper portion. Sulfide minerals include sphalerite, galena, chalcopyrite, tetrahedrite, and minor arsenopyrite. Copper stockwork veins in rhyolite underlie the thicker sections of the deposit and appear to be spatially associated with growth faults that controlled basin geometry. These faults also influenced the distribution of tuffaceous and cherty (exhalative) units that overlie the sulfides.

In terms of mined plus reserve ores, the Feitais deposit was estimated in 1998 to contain 54.5 Mt grading 3.72 percent Zn, 0.42 percent Cu, 1.2 percent Pb, and 44 g/t Ag (Leistel et al., 1998). Recent drilling has identified a new Zn resource in the upper part of the massive sulfide lens consisting of a measured and indicated resource of 15.22 Mt grading 6.00 percent Zn, 0.21 percent Cu, 1.85 percent Pb, and 67.4 g/t Ag; and a deeper Cu resource straddling the lower part of the massive sulfide lens and the underlying stockwork mineralization and consisting of an indicated resource of 4.57 Mt grading 0.85 percent Zn, 2.12 percent Cu, 0.24 percent Pb, and 13.5 g/t Ag. The deposit is open downplunge to the northwest for 200 m. It is truncated by the northeast-striking, steeply dipping Represa fault. The deposit is offset right laterally about 500 m along this fault, north of which it is called the Estação deposit.

Application of lithogeochemical methods to 170 new and 80 published analyses of the Feitais host rocks led to the chemical identification of five main felsic rock types that have distinctive immobile element signatures. These signatures are maintained even where the rocks are strongly altered. The deposit is underlain mainly by a thick (>150 m) unit of rhyolite A, the most fractionated of the felsic rocks. Rhyolite X occurs in two deep footwall holes. Rhyolite B occurs mainly downdip of the massive sulfide lens but also is present as meter-scale intervals near the base of the sulfide lens. The deposit is overlain stratigraphically by 5 to 30 m of tuffaceous rhyolite C, which is followed by 2 to 20 m of Fe-bearing chert. A centimeter-scale crystal tuff bed with a distinctive felsic composition overlies the cherts and forms a marker horizon that can be traced at least 700 m along the strike of the deposit. The massive sulfide lens becomes thicker downdip to the northeast, then terminates against an uplifted block of footwall rhyolite A capped by rhyolite B. Field relationships and isopach data suggest that an asymmetrical sea-floor graben bounded by a synvolcanic fault was filled by massive sulfides, followed by rhyolite C, then chert, with the chert also extending laterally beyond the graben margin.

Footwall and hanging-wall felsic volcanic rocks are altered to chlorite-sercite-pyrite-quartz-carbonate assemblages and contain stockwork chalcopyrite-pyrite-quartz-carbonate veins. Hydrothermal alteration is strongest in the upper 50 m of rhyolite A below the orebody but extends at least 200 m into the footwall along the main synvolcanic fault zone. Rhyolite C above the orebody is also strongly altered. These areas have experienced significant additions of Fe and Mg, with variable gains or losses of Si. Barium is enriched for up to a few tens of meters above and laterally from the orebody.

Dominating the central part of the Aljustrel area is a quartz-feldspar (QF) porphyry that shows primary enrichment in Fe, Ti, and V relative to the rhyolites. At Feitais, this lithology was only encountered deep in the footwall, structurally below rhyolite X. No andesitic or mafic extrusive rocks have been identified. The QF porphyry is chemically unrelated to the four rhyolite types. The rare earth element (REE) patterns of the rhyolites show moderate enrichment in the light REE, with near-flat middle to heavy REE. The rhyolites are of tholeiitic to transitional affinity, with moderately high Zr (180–380 ppm) but low Nb (7–15 ppm) contents. These collective features are consistent with a rift-related, continental-margin setting, behind an arc, for the rhyolite volcanism.

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Introduction

The Aljustrel massive sulfide deposits are hosted by a sequence of Upper Paleozoic volcanic rocks within the Iberian Pyrite Belt of southern Portugal (Fig. 1). Within an area of 5 × 2 km centered on the town of Aljustrel are six main deposits: Gavião, São João, Moinho, Algares, Estação, and Feitais (Fig. 2; Gavião is not shown). In total, these deposits contain at least 230 million metric tons (Mt) of pyrite-rich massive sulfides, one of the largest such accumulations in the world. The deposits occur as stratiform, northwest-striking lenses hosted within the upper part of the Volcano-Sedimentary Complex (VSC), which is overlain by the flyschlike shales and sandstones of the Culm Group. The VSC regionally overlies Upper Devonian sedimentary basement rocks (the Phyllite-Quartzite Group, not seen at Aljustrel). At Aljustrel, the VSC consists of felsic volcanic and subvolcanic rocks that are overlain by cherts, then shales and siltstones of the Paraiso Formation (Barriga and Fyfe, 1988, 1998). Recent dating of the VSC in Portugal and Spain indicates that felsic volcanism spanned the range of 349.8 ± 0.9 to 356.2 ± 0.7 Ma, including an age of 352.9 ± 1.9 Ma for the QF porphyry at Aljustrel (Barrie et al., 2002).

Several large-scale anticlines and synclines (and thrusts) occur within the VSC at Aljustrel. The northern end of the Complex is truncated by the east-northeast–striking Messa- jana fault (Fig. 2). North of this fault, the VSC has been downdropped and is only exposed in erosional windows through a Tertiary sedimentary cover. The Feitais deposit occurs on the upright limb of the Feitais anticline, near the contact with the overlying Culm flysch. The axial plane of the anticline strikes northwest and dips moderately to steeply east. The deposit is truncated by the northeast-striking, steeply dipping Represa fault. It is offset right laterally about 500 m along this fault, north of which it is called the Estação deposit (Fig. 2).

The Feitais orebody stratigraphically overlies at least 150 m of largely tuffaceous rhyolites and is generally overlain by 5 to 30 m of rhyolite tuff, followed by 2 to 20 m of cherty rocks, some 50 m of siltstones and dark argillites (the Paraiso Formation), and a >300-m-thick flysch sequence of Lower Carboniferous age (regionally the Baixo-Alentejo flysch or Culm Formation; Barriga and Fyfe, 1998). A quartz-feldspar megacrystic unit, referred to here as the QF porphyry, is present over much of the central part of the Aljustrel area (Fig. 2). The QF porphyry lies west of the Feitais volcanic sequence.

Fig. 1. Main tectonic and stratigraphic terranes of southern Portugal and Spain (modified from Tournos, 2006). Massive sulfide deposits hosted in the VSC: AL = Aljustrel, ATE = Aguas Tenidas Este, AZ = Aznalcollar, CO = Concepcion, LF = Los Frailes, LC = Las Cruces, LO = Lousal, LP = Lomero-Poyatos, LZ = La Zarza, MI = Migollas, NC = Neves Corvo, RT = Rio Tinto, RO = Romanera, SD = Sao Domingos, SO = Sotiel, SM = San Miguel, SP = San Platon, TH = Tharsis. The Aljustrel group of six deposits (AL) is located near the northwestern end of the pyrite belt.
and east of the sulfide and chert horizons that extend from São João in the northwest to Algares in the southeast.

Relative to the Paraíso shales and siltstones, the Culm Formation contains a greater proportion of thicker and coarser grained graywacke turbidites. In the field, it is generally not possible to define the Paraíso-Culm boundary exactly due to the interbedding of shales, siltstones, and graywackes, and to disruptions by thrust faulting. This deformation takes the form of meter-scale zones of intense quartz veining and crumpling or brecciation of shales and thin siltstones. In some places, thrust faulting appears to have interleaved panels of the Paraíso and Culm Formations.

This paper focuses mainly on the host rocks of the Feitais massive sulfide deposit. It is based on some 170 new lithochemical samples and 80 previous analyses by Barriga (1983). About 200 of the samples are from drill core and the remainder from outcrops. The objectives of the study are to (1) describe the main features of the Feitais massive sulfide deposit and its host rocks; (2) use lithochemical methods to identify and correlate the volcanic units hosting the orebodies; (3) calculate mass changes resulting from hydrothermal alteration in the vicinity of the deposit; and (4) ascertain the paleotectonic setting of the deposit.

The Feitais Deposit

The Feitais massive sulfide lens is about 1,000 m in length, 500 m wide, and up to 100 m thick (Fig. 3). Although it consists mainly of fine-grained pyrite, the deposit shows broad metal zoning, with a Cu-rich base, a central low-grade pyritic zone, and a Zn-Pb–enriched upper portion (Dawson et al., 2000, 2001). After pyrite, the main phases are sphalerite, galena, chalcopyrite, tetrahedrite, and minor arsenopyrite. In terms of mined plus reserve ores, the Feitais deposit was estimated in 1998 to contain 54.5 Mt grading 3.72 percent Zn, 1.2 percent Pb, 0.42 percent Cu, and 44 g/t Ag (Leistel et al., 1998). Drilling completed for a feasibility study commissioned in 2000 by EuroZinc Mining Corp. (now Lundin Mining) identified a new Zn resource in the upper part of the massive sulfide lens and a deeper Cu resource straddling the lower part of the massive sulfide lens and the underlying stockwork mineralization. Grades and tonnage details are given in Table 1.

The deposit stratigraphically overlies >150 m of felsic tuffs, flows, and small subvolcanic intrusions and is overlain by 5 to 30 m of feldspar-phryic felsic tuffs, then cherts. Host felsic volcanic rocks are commonly altered to chlorite-sericite-pyrite ± carbonate ± quartz assemblages. Copper-bearing stockwork veins underlie the thicker part of the deposit and also outline a probable synvolcanic fault along its eastern margin. Primary and pseudosecondary fluid inclusions in quartz and carbonate in stockwork veins yield homogenization temperatures (T_h) of 270° to 305°C and salinities of 2.2 to 8.1 wt percent NaCl equiv (Inverno et al., 2008). The δ^{18}O values of quartz from the massive sulfides suggests that it formed at
about 175° to 190°C, significantly lower than the temperatures estimated for quartz in stockwork veins (Inverno et al., 2008). Typical altered felsic volcanic rocks from the footwall and hanging wall are shown in Figure 4. The QF porphyry, which is generally only weakly altered, is shown in Figure 5.

Lithogeochemistry

All new samples were analyzed by X-ray fluorescence at the Geochemical Laboratory of McGill University, Montreal, using glass disks for the major elements, as well as Ba, Cu, Zn, Co, V, Cr, and Ni, and pressed pellets for Zr, Y, Nb, Rb, Sr, Sn, Th, U, and Pb. Rare earth elements were analyzed by ICP-MS at Activation Laboratories, Ancaster, Ontario. The analyses reported by Barriga (1983) were carried out by XRF, using both glass disks and pellets, at the University of Western Ontario, London, Ontario.

Table 1. Grades and Tonnages of Resources at the Feitais Massive Sulfide Deposit, Aljustrel, Portugal

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<tr>
<th>Resource</th>
<th>Mt*</th>
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<th>Cu (%)</th>
<th>Pb (%)</th>
<th>Ag (g/t)</th>
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<td>0.21</td>
<td>1.85</td>
<td>67.4</td>
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<td>6.14</td>
<td>0.16</td>
<td>1.66</td>
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</table>

| Copper resource   | 1.5% | 0.88    | 2.12   | 0.24   | 13.5     |
| Measured + indicated | 4.87 | 0.88    | 2.12   | 0.24   | 13.5     |
| Inferred          | 1.87 | 0.70    | 2.13   | 0.18   | 10.4     |

* Million metric tons

Representative analyses of altered host rocks are given in Table 2, which includes, for each rock type, one sample with large net mass gain and one with large net mass loss. Rare earth element (REE) analyses of representative samples are given in Table 3, along with selected trace elements. Typical least altered samples of each rock type are given in Table 4. These samples were selected on the basis of their relatively low loss-on-ignition (LOI) values, minimal Na₂O depletions, and minor contents of alteration minerals. Altered rocks having the same immobile element ratios as the least altered samples were given the same names. The least altered samples were also used as the basis for the mass-change calculations. Selected mass-change results are given in Table 5.

Magnetic affinity can be assessed using certain incompatible trace element ratios, such as Zn/Y, La/Yb, Nb/Zr, and Th/Yb. These ratios are generally not modified by typical VMS-type alteration involving chlorite, sericite, albite, carbonate, quartz, and sulfides. As a general guideline, rocks with Zr/Y ratios of <4 have a tholeiitic affinity, whereas ratios of 4 to 7 are transitional, and ratios >7 are calc-alkaline or alkaline. The slopes of chondrite-normalized REE patterns, as approximated by the (La/Yb)₁₈₀ ratio, also provide information on magmatic affinity. (La/Yb)₁₈₀ ratios are generally 0.5 to 2 for tholeiitic rocks, 2 to 5 for transitional rocks, and 5 to 10 or more for calc-alkaline and alkaline rocks. Magmatic affinity should be assessed using both of these ratios. In extremely chloritized and sericitized rocks, however, Y and the light REE can become mobile. Such samples can be identified by comparing Y/Zr and La/Zr ratios with, respectively, Nb/Zr and Yb/Zr ratios.
FIG. 4. a. Hydrothermally altered and sulfide-veined footwall felsic volcanic rocks, drill hole FS98-01. All rock samples are of rhyolite A composition (see Lithogeochemistry section). The veins are mainly chalcopyrite + quartz + pyrite. Width of core = 5 cm. b. Hanging-wall rocks, drill hole FS98-01; core pieces from bottom to top are feldspar-phyric rhyolite C, semimassive sulfides and dark magnetite-rich bands; gray chert (LS) and pink chert (RS) with a central magnetite-rich band; red jasper passing down into gray to pink banded chert, then a magnetite-rich band; a bed of quartz-feldspar crystal tuff (QFXT) that is compositionally distinct from all other felsic types. Width of core = 5 cm. c. Massive sulfide lens conformably overlying an interval of sparsely feldspar-phyric rhyolite B tuff; contact is in third slot down, just left of lens cap. Moinho deposit, drill hole B41. Width of core = 5 cm. d-f: Photomicrographs. d. Altered footwall rhyolite A, showing quartzose spherulites in a Mg chlorite-rich matrix (crossed polars), drill hole F20, 92.2 m. e. Altered feldspar-phyric hanging-wall rhyolite C tuff, showing remnant albic phenocryst in upper center and sheaths of sericite-rich alteration (crossed polars), drill hole FS98-01, 347.7 m. f. Altered footwall rhyolite B tuff, shows remnant feldspar phenocrysts and siderite-bearing foliation laminations (crossed polars), drill hole FS98-23, 180.7 m.
In order to identify rock types in altered volcanic terranes, plots of immobile elements involving Al₂O₃, TiO₂, and Zr are commonly used, as discussed by MacLean and Kranidiotis (1987), MacLean (1990), and Barrett and MacLean (1991, 1994a, b). Samples of altered rocks from an originally homogeneous volcanic unit will plot along linear arrays (alteration lines) that connect the samples with the origin. These linear arrays are caused by net mass loss or mass gain of mobile elements during alteration. Different precursor compositions yield alteration lines of differing slope.

Samples from the felsic volcanic sequence and overlying shales plot along a series of linear trends in standard immobile-element plots (Fig. 6). The main rock types defined by these trends are rhyolites A, B, C, and X, QF porphyry, and...
shales. The limited scatter along each trend indicates that the precursor rocks were nearly homogeneous prior to the effects of alteration. Although a given rhyolite type can overlap another type in terms of one immobile element ratio, the other ratios do not overlap. Rock identifications in this study are based on 3 or 4 ratios. Rhyolites A and C overlap in an Al\(_2\)O\(_3\) versus TiO\(_2\) plot (Fig. 6a) but can be readily separated in plots of TiO\(_2\)-Zr (Fig. 6b) and Al\(_2\)O\(_3\)-Zr (not shown). Rhyolite B is distinguished from rhyolites A and C using plots of Al\(_2\)O\(_3\)-TiO\(_2\) (Fig. 6a) and Nb-Zr (not shown). The QF porphyry can be readily identified using the TiO\(_2\)-Zr plot alone (Fig. 6b). On the other hand, rhyolite X is best revealed using an Al\(_2\)O\(_3\)-Zr plot (not shown).

The QF porphyry crops out over much of the central part of the Aljustrel area and in general separates the eastern deposits (Estação, Feitais) from those in the west (Gavião, São João, Moinho, Algares). It contains quartz and feldspar crystals up to 5 and 20 mm across, respectively. The feldspars range from orthoclase to albite (Barriga, 1983). The QF porphyry contains about 70 percent SiO\(_2\) but is notably higher in Ti, Fe, P, Cr, and V than typical rhyolites, and can be described as a crystal-rich ferrohyolite. Despite a wide range in the size and proportion of crystals, the QF porphyry shows little variation in its immobile element ratios and is distinct from all other rhyolite types (Fig. 6).

Shales and siltstones of the Paraiso Formation and Culm graywackes lie along a distinctive trend line (“Seds,” Fig. 6). The spread of points along this line is partly due to hydrothermal alteration of samples from the lowest 5 to 10 m of the Paraiso Formation. For stratigraphically higher samples, the spread of points along the line is mainly due to differing amounts of clastic quartz in the sedimentary rocks.

**Ratio-ratio plots**

In plots of one immobile element ratio against another, involving elements such as Al, Ti, and Zr, the effects of alteration are removed. In Figure 7a, for example, the relative position of a given rhyolite type along the Y-axis simply reflects siltstones. The limited scatter along each trend indicates that the precursor rocks were nearly homogeneous prior to the effects of alteration. Although a given rhyolite type can overlap another type in terms of one immobile element ratio, the other ratios do not overlap. Rock identifications in this study are based on 3 or 4 ratios. Rhyolites A and C overlap in an Al\(_2\)O\(_3\) versus TiO\(_2\) plot (Fig. 6a) but can be readily separated in plots of TiO\(_2\)-Zr (Fig. 6b) and Al\(_2\)O\(_3\)-Zr (not shown). Rhyolite B is distinguished from rhyolites A and C using plots of Al\(_2\)O\(_3\)-TiO\(_2\) (Fig. 6a) and Nb-Zr (not shown). The QF porphyry can be readily identified using the TiO\(_2\)-Zr plot alone (Fig. 6b). On the other hand, rhyolite X is best revealed using an Al\(_2\)O\(_3\)-Zr plot (not shown).

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the slope of its alteration line in Figure 6b. The small spread of points within each rhyolite field is probably due to minor magmatic fractionation effects, or, in the case of volcaniclastic rocks, to minor intermixing of other felsic clast types.

Rhyolites A and C generally have lower Zr/Y and Zr/Nb ratios than rhyolites B and X (Fig. 8). This suggests that these two rhyolite “pairs” were derived from different magma types. Zr/Y ratios for the QF porphyry overlap with those of rhyolites B and X, but its Zr/Nb ratios are similar to those of rhyolites A and C. This suggests that it represents a third and different magma type. In Figure 8 the vertical variation within each field is somewhat greater than for the respective
groups in Figure 7. It is uncertain if this variation is a primary effect or caused by minor mobility in Y and Nb during alteration. A few strongly chloritized rhyolites have unusually high Zr/Y ratios of more than 10 but normal Al-Ti-Zr ratios. These few samples, in which Y was likely mobile during alteration, have been omitted from Figure 8a.

Rare earth element plots

REE patterns for the various rock types at Feitais are shown in Figures 9 to 11, normalized to the chondrite values of Evensen et al. (1978). Rhyolites A, B, C, and X have similar patterns, with moderate enrichment in the light REE but nearly flat middle to heavy REE. In Figure 9a, the REE pattern of a sample of rhyolite A with net mass gain is compared with relatively unaltered rhyolite A. Net mass gain of mobile elements such as Si and Fe, serves to dilute the relatively immobile REE. In Figure 9b, the REE pattern of a sample of rhyolite B with net mass loss is compared with relatively unaltered rhyolite B. In this case, the REE have been residually increased by net mass loss resulting from chloritization and sericitization. In both figures, the altered samples show a slight change in slope relative to the least altered samples, suggesting that minor redistribution of the REE also occurred.

Fig. 9. Representative chondrite-normalized REE plots for rhyolites at the Feitais deposit. a. Rhyolite A. In the altered sample, net mass gain of silica and sulfides has diluted the initial contents of REE in the rock but left the pattern almost unchanged. b. Rhyolite B. In the altered sample, net mass loss of silica and alkalies has residually concentrated the REE but left the pattern almost unchanged.
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**Notes:** QF porphyry = quartz-feldspar porphyry, QFXT = quartz-feldspar crystal tuff; analytical methods: Zn to Lu: inductively coupled mass spectrometry; Cr to Au: instrumental neutron activation analysis

1 Shale = pale green shale from the Paraiso Formation (overlying the chert formation)
REE patterns of relatively unaltered samples of rhyolite C, rhyolite X, and QF porphyry are shown in Figure 10. The QF porphyry has notably steeper REE patterns than those of the other rhyolite types, with (La/Yb)n of 10 to 11. This supports the earlier inference that the QF porphyry represents an unrelated magma type.

The REE patterns for rhyolites A, B, C, and X are closely similar to those of felsic volcanic rocks elsewhere in the Iberian Pyrite Belt (Thiéblemont et al., 1998; Rosa et al., 2006). Such patterns, with (La/Yb)n ratios of 4 to 6 and moderately high ΣREE contents, are fairly common for rhyolites in rift-related settings where the underlying crust is continental, although somewhat steeper or flatter patterns are also known (Hildreth, 1979).

The REE patterns of two Paraiso siltstones are shown in Figure 11a. The patterns resemble those of the QF porphyry, but this is coincidental, as all other immobile element ratios are different. The two siltstones are fine-grained turbidites located a few meters above the top of the chert formation, and their REE patterns probably reflect the average composition of their source area. Almost all sedimentary rocks above the chert formation sampled to date have immobile element ratios notably different from those of the Aljustrel rhyolites, suggesting that the sediments were derived from a different, extra-basinal source.

The REE patterns of two cherty rocks are shown in Figure 11b. Fe-Mn-Ca–rich chert from drill hole FS-20 has small negative Ce and Eu anomalies. Si-rich cherts containing iron oxides in drill hole FS-15, some 200 m updip, have similar REE patterns (Barriga, 1983). Precipitates from sea-floor vent fluids having temperatures above 250°C can display positive Eu anomalies, although this depends partly on the mineralogy of the precipitating phase (Morgan and Wandless, 1980; Barrett et al., 1990). By contrast, precipitates formed at temperatures of less than 100°C inherit their REE mainly from normal seawater and display the negative Ce anomaly of seawater. The cherts at Feitais lack a positive Eu anomaly but commonly contain Fe oxide and Mn-bearing phases, suggesting that they formed from relatively low temperature, oxygenated bottom waters (cf. Sverjensky, 1984; Barrett et al., 1988). The cherts in most places lie above a 5- to 30-m-thick interval of rhyolite C tuff that caps the sulfide orebody; presumably by the time the cherts were formed, the hydrothermal system had waned sufficiently for bottom waters to become oxygenated.
Chemostratigraphic Relationships

In this section, downhole plots of several drill holes through and near the Feitais deposit are presented. In each plot, logging units are shown in the left column and immobile element ratios plus the inferred precursor rock types in the right column. Boundaries between chemostratigraphic units are placed either at physical contacts seen in drill core, or if no contacts were evident due to alteration, at the midpoint between consecutive samples.

Section 550 NW

Drill holes FS98-02 and FS-22, respectively, intersected the thickest part of the orebody and the downdip margin of the orebody. In drill hole FS98-02, the orebody rests directly on altered rhyolite A and is overlain by the generally observed sequence of rhyolite C followed by chert; in drill hole FS-22, by contrast, rhyolite A is overlain by two thin intervals of massive sulfides, followed by rhyolite B and then chert (Fig. 12). The absence of rhyolite C tuff in drill hole FS-22 may be due to higher paleo-sea-floor relief in this area, where extrusion of rhyolite B occurred instead. As discussed in a later section, the thickness of rhyolite C tuff is greater above the main portion of the orebody than above its margins, suggesting a partly tuff infilling a depression on the sea floor. Although the massive sulfides in drill hole FS-22 are thin, they are underlain by a stockwork and alteration zone that extends at least 150 m (true thickness) into the rhyolite A footwall. This stockwork is interpreted to be a major fluid upflow zone located along a sea-floor fault that now bounds the downdip margin of the main sulfide deposit.

The chemically defined volcanic units in section 550 NW, based on all sampled holes, are shown in Figure 13. Rhyolite A forms most of the footwall to the Feitais massive sulfide lens, whereas rhyolite C forms a relatively thin unit that caps much of the orebody and extends laterally away from it. Rhyolite B occurs mainly along the downdip margin of the sulfide lens; it also locally forms thin intervals at the base of, and within, the massive sulfides. A synvolcanic fault scarp is inferred to have been present between holes FS-12 and FS-20. Rhyolite X and the QF porphyry do not occur in section 550 NW but lie downhole of footwall rhyolite A in two deep holes in a different section.

A feature of note in section 550 NW and in a few nearby holes is the occurrence of thin intercalations of rhyolite B at, or near, the base of the massive sulfides (Fig. 13). These are...
interpreted to be volcaniclastic beds derived from a paleotopographic high of rhyolite B that was located near the downdip (northeastern) margin of a graben in which the massive sulfides accumulated. It is likely that a synvolcanic fault uplifted rhyolite A together with a capping of rhyolite B on the downdip side of the fault; only minor amounts of sulfides accumulated in the uplifted block.

Section 400 NW

In drill hole FS-20 in section 400 NW, at least 190 m of footwall rhyolite A is directly overlain by about 35 m of rhyolite B, followed by 70 m of rhyolite C, then 10 m of chert (Fig. 14). There are no massive sulfides at the top of rhyolite A (or above). However, major intervals of stockwork veins occur in the footwall rhyolite at depths of 560 to 575 and 650 to 753 m (where the hole ended). Even though rhyolite B has a limited spatial distribution at Feitais, hole FS-20 provides evidence that the temporal sequence of eruption was rhyolite A (preore), then rhyolite B (synore), then rhyolite C (postore),

Closer to the surface, in drill hole FS-15 (not shown), the massive sulfide lens is overlain by the usual sequence of rhyolite C, then chert. However, the chert is followed by about 30 m of interbedded shales and minor felsic tuffs. These upper tuffs include rhyolite A and C compositions and also a centimeter-thick bed of QF crystal tuff that has a distinctive chemical composition relative to all other rhyolite types. The QF crystal tuff forms a thin but important marker bed that has been traced more than 700 m laterally along the strike of the deposit.

Section 320 NW

Hole Fi-2 in section 320 NW was drilled deep into the footwall from the level of the orebody. Although altered rhyolite A underlies the massive sulfides, much of the drilled footwall consists of rhyolite X, which comprises sandy to lapilli tuffs containing variable amounts of small feldspar crystals and dark-green wispy patches (altered fiamme?, Fig. 15). Felsic clasts up to a few centimeters across are scattered here and through some of the tuffs. In the downhole direction, rhyolite X is in direct contact with rhyolite C, which typically contains 2- to 5-mm-sized feldspar crystals. Between the rhyolite C interval and the QF porphyry are 4.3 m of chloritic rock (not sampled) containing cherty wisps, disseminated sulfides, and 0.2 m of massive sulfide. The QF porphyry has been intersected only in one other hole at Feitais (deep hole Fi-1 in section 450 NW).
Regional geologic relationships (Barriga, 1983) suggest that the two deep holes may have intersected rocks belonging to the overturned limb of the Feitais anticline, in which case rhyolite C in hole Fi-2 would be overturned. Core loss in the thin sedimentary interval between rhyolite C and the QF porphyry suggests that a fault zone runs through this interval.

Section 240 NW

In hole FS99-39 in section 240 NW, massive sulfides are absent above rhyolite A, although they occur in nearby holes. Instead, rhyolite A is overlain by a few meters of tuff containing minor sulfide bands, then rhyolite C (Fig. 16). About 60 m lower in the footwall, a few meters of semimassive sulfides occur. Much of the intervening rhyolite A is massive, with some zones of autobreccia. The absence of thick massive sulfides in this hole may be due to the development of a local paleotopographic high of massive rhyolite A. This high was eventually buried by deposition of rhyolite C and chert, both of which can be traced with only minor undulations in thickness across section 240 NW.

### Table 4.

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Note: LOI = loss on ignition

Hydrothermal Alteration

**Mass-change calculation methods**

The six main rock types at Aljustrel—rhyolites A, B, C, X, QF porphyry, and fine-grained sedimentary rocks—display little variation in their immobile element ratios, and therefore mass changes were determined by applying the single-precursor method (MacLean and Kranidiotis, 1987; Barrett and MacLean, 1991) to each of the six groups. The procedure yields gains or losses of individual elements on an absolute basis. The results can be used to establish the dimensions of a hydrothermal system and define alteration gradients (vectors) that help to guide exploration. Examples of mass-change results applied to the alteration systems of volcanogenic massive sulfide (VMS) deposits are given in Barrett and MacLean (1994b) and Barrett et al. (2001).

The precursor compositions used for the calculations were based on the averages of the least altered samples in each group (listed in Table 4). The Al₂O₃/TiO₂ pair has been used as the immobile element anchor for all calculations. In this procedure, the ratio of the Al₂O₃ content of the precursor to
that of the altered sample yields a mass-change factor, which is then used to calculate a reconstituted value for each element of each altered sample. The mass changes are determined from the difference between the reconstituted and precursor compositions on an element-by-element basis (Table 5). Mass changes are given in terms of absolute wt percent or parts per million, rather than relative percent change, as the former give a better idea of the real mass of material moving into, or out of, the rocks. All iron in the original analyses was converted to FeO to standardize the mass-change calculations.

General features of alteration

At Feitais, the upper 50 to 150 m of rhyolite footwall and lower 20 m of rhyolite hanging wall show variable degrees of chloritization, silicification, sericitization, carbonatization, and sulfidization. Chloritization is the dominant alteration in the sulfide-veined stockwork zones. The chert unit, although dominated by silica, in places contains significant amounts of hematite and magnetite, or barite, or Fe sulfides, or Mn-bearing phases.

Rhyolites that have experienced large mass additions of Fe, but not Mg, represent sites of upwelling of relatively undiluted hydrothermal fluids, i.e., fluids that have not mixed appreciably with normal Mg-rich seawater. Rhyolites that show only mass gains of Mg were likely located in hydrothermal recharge (downwelling) zones lateral to the main vent areas (Barrett and MacLean, 1994a). Rhyolites with additions of both Fe and Mg probably were situated in a zone of subsurface mixing between rising, hot, somewhat acidic mineralizing fluids, and cooler, near-neutral, seawater-like fluids. Mass additions referred to in this paper as large are on the order of 10 to 30 wt percent for Fe and 6 to 15 wt percent for Mg. Mass changes in Na and Ca in most of the sampled rhyolites are large, that is, –3 to –4 and –1 to –2 wt percent, respectively, which represents near-complete removal of these elements.

The largest net mass gains are shown by samples of rhyolites A and C, where the original Al2O3 contents have been reduced to about 60 to 80 percent of the precursor value (see Fig. 6a). Such mass gains are commonly the result of primary porosity (breccias, pumice, etc.) infilling or open sea-floor
### Table 5. Calculated Mass Changes for Rocks from Selected Feitais Drill Holes

| Hole | FS07 | FS07 | FS07 | FS07 | FS10 | FS10 | FS10 | FS10 | FS10 | FS10 | FS10 | FS20 | FS20 | FS20 | FS20 | FS20 | FS20 | FS20 | FS20 | FS20 |
|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|
| Depth (m) | 7.4  | 35.2 | 57.1 | 64.9 | 271.5 | 298.1 | 327.8 | 358.7 | 396.3 | 417.8 | 433.2 | 477.0 | 493.8 | 525.8 | 549.8 | 560.8 | 585.5 | 610.3 |
| Chemical type | Rhodite | Rhodite | Shale \(^1\) | Rhodite | Rhodite | Rhodite | Shale \(^1\) | Rhodite | Rhodite | Rhodite | Rhodite | Rhodite | Rhodite | Rhodite | Rhodite | Rhodite | Rhodite | Rhodite | Rhodite | Rhodite |
| SiO\(_2\) (wt %) | 314.4 | 312.7 | 127.2 | 130.4 | -16.6 | -25.1 | 19.1 | 26.8 | -17.1 | -34.3 | 13.5 | 29.9 | 27.1 | 0.3 | -22.9 | 3.6 | -5.6 | -11.0 |
| TiO\(_2\) (wt %) | 0.02 | 0.00 | 0.00 | -0.01 | -0.03 | -0.01 | 0.03 | 0.00 | -0.02 | -0.01 | -0.01 | 0.00 | 0.02 | 0.00 | 0.00 | 0.00 | 0.01 |
| FeO (wt %) | 3.4  | 3.9  | 16.5  | 2.1  | 2.4  | 2.3  | 0.0  | 1.1  | 0.1  | 4.9  | 0.1  | -0.2 | 0.3  | -0.5 | -0.5 | 0.2  | 0.3  | 4.7  |
| MnO (wt %) | 0.1  | 0.2  | 0.5  | 0.2  | 0.0  | 0.2  | 0.1  | 0.0  | 0.2  | 0.1  | 0.0  | 0.0  | 0.0  | 0.0  | 0.0  | 0.0  | 0.0  | 0.0  |
| CaO (wt %) | 29.4 | 31.2 | 3.7  | -0.3 | -0.3 | -0.3 | -0.3 | -0.3 | -0.3 | -0.3 | -0.3 | -0.3 | -0.3 | -0.3 | -0.3 | -0.3 | -0.3 | -0.3 |
| Na\(_2\)O (wt %) | 6.3  | 3.4  | 0.5  | -0.1 | -0.1 | -0.1 | -0.1 | -0.1 | -0.1 | -0.1 | -0.1 | -0.1 | -0.1 | -0.1 | -0.1 | -0.1 | -0.1 | -0.1 |
| K\(_2\)O (wt %) | 1.6  | 1.6  | 0.5  | -0.5 | -0.5 | -0.5 | -0.5 | -0.5 | -0.5 | -0.5 | -0.5 | -0.5 | -0.5 | -0.5 | -0.5 | -0.5 | -0.5 | -0.5 |
| P\(_2\)O\(_5\) (wt %) | 0.3  | 0.3  | 0.3  | 0.3  | 0.3  | 0.3  | 0.3  | 0.3  | 0.3  | 0.3  | 0.3  | 0.3  | 0.3  | 0.3  | 0.3  | 0.3  | 0.3  | 0.3  |

Notes: QF porphyry = quartz-feldspar porphyry, QFXT = quartz-feldspar crystal tuff; mass changes of altered rocks were calculated in relationship to the precursor compositions of each chemical group, as given by the least altered average compositions in Table 3; the single-precursor calculation method was used for each group; mass change correction factors for each sample were based on Al\(_2\)O\(_3\) (except for the two QFXT samples, where TiO\(_2\) was used)

\(^1\) Shale = pale green shale from the Paraiso Formation (overlying the chert formation)
VOLCANIC STRATIGRAPHY, ALTERATION, AND SETTING OF THE FEITAIAS MASSIVE SULFIDE DEPOSIT, PORTUGAL

Fig. 12. Downhole geologic logs and chemostratigraphic units for drill holes FS98-02 and FS-22, section 550 NW, Feitais deposit. Hole FS-22 is located about 250 m northeast of hole FS-98-02. The paleosea floor in the area of hole FS-22 is interpreted to have had higher relief, leading to the accumulation of only thin massive sulfides, with no deposition of rhyolite C and only thin chert. Common stockwork veins and chlorite alteration in rhyolite A over some 200 m suggests that hole FS-22 drilled down the main feeder zone. EOH = end of hole.

Fig. 13. Geology and chemostratigraphic units in section 550 NW, Feitais deposit (based on results from this study and geologic data from EuroZinc Mining Corporation (now Lundin Mining). The abrupt downdip termination of the thick massive sulfide lens is interpreted to be the result of a synvolcanic growth fault. Rhyolite B (rather than rhyolite C) accumulated on the downdip side of this fault. The hanging-wall chert and shale formations, however, are present on both sides.
fractures by quartz, carbonates, and sulfides. Mass can also be added if these components precipitate directly on the sea floor and become intermixed with volcanic material.

Mass-change results for section 550 NW

In hole FS-21, no Fe has been added to the upper 60 m of footwall rhyolite A, although there are modest Mg gains (Fig. 17). However, the next 100 m of rhyolite A below this display large gains of Fe and Mg. Some of the Fe is in chlorite and some in sulfide veins. Most of this zone contains 200 to 1,300 ppm Zn and locally a few hundred ppm Cu. The large Mg additions suggest that the hole is located on the margin of the main hydrothermal system which formed the Feitais deposit. The stockwork zone continues to the end of the hole at 843 m, but the lowest 40 m were not sampled. Above the rhyolite A sequence are two samples of rhyolite B (607, 621 m), which show little alteration. These are overlain by 90 m of felsic volcanic rocks (not sampled), then chert.

This hole appears to have intersected a local basement high with rhyolite C resting directly on rhyolite A (no intervening massive sulfides)

Fig. 14. Downhole geologic log and chemostratigraphic units for drill hole FS-20, section 400 NW, Feitais deposit. Despite variations in facies and degree of alteration, the three main rhyolite types that flank the Feitais orebody can be identified. Although the chert formation is present, massive sulfides are absent in this hole. They would normally be located at the top of rhyolite A. EOH = end of hole.

Fig. 15. Downhole geologic log and chemostratigraphic units for drill hole Fi-2, section 320 NW, Feitais deposit. This is one of the few holes that penetrated below the thick part of the orebody. The normal rhyolite A footwall is followed downhole by rhyolite type X, which had not been encountered before at Feitais. The presence of rhyolite C downhole of rhyolite X was also unexpected, as rhyolite C normally overlies the massive sulfides at Feitais. The QF porphyry intersected at the end of the hole is presumably the same body that crops out in the central Aljustrel area (Fig. 2). EOH = end of hole.

Fig. 16. Downhole geologic log and chemostratigraphic units for drill hole FS99-39, section 240 NW, Feitais deposit. In this hole, no massive sulfides are present between rhyolites A and C, which bracket the main ore horizon at Feitais. This hole appears to have intersected a local basement high within the marginal part of the main sulfides lens. EOH = end of hole.

fractures by quartz, carbonates, and sulfides. Mass can also be added if these components precipitate directly on the sea floor and become intermixed with volcanic material.

Mass-change results for section 550 NW

In hole FS-21, no Fe has been added to the upper 60 m of footwall rhyolite A, although there are modest Mg gains (Fig. 17). However, the next 100 m of rhyolite A below this display large gains of Fe and Mg. Some of the Fe is in chlorite and some in sulfide veins. Most of this zone contains 200 to 1,300 ppm Zn and locally a few hundred ppm Cu. The large Mg additions suggest that the hole is located on the margin of the main hydrothermal system which formed the Feitais deposit. The stockwork zone continues to the end of the hole at 843 m, but the lowest 40 m were not sampled. Above the rhyolite A sequence are two samples of rhyolite B (607, 621 m), which show little alteration. These are overlain by 90 m of felsic volcanic rocks (not sampled), then chert.
Mass changes for FeO in section 550 NW are summarized in Figure 18, which also shows an outline of the zone of major mass additions to the footwall rhyolites (10–30 wt % FeO; locally up to 60–70 wt %). These rhyolites, as noted earlier, contain Fe-bearing chlorite, vein sulfides, and probably some replacement sulfides. The highest mass gains require either that significant new void space was generated in the form of stockwork fissures which were then filled with sulfides, or rhyolitic debris was intermixed, on the sea floor, with a high proportion of sulfides. The contact between the base of the massive sulfide lens and the top of the rhyolite footwall is commonly transitional over several meters via a series of sulfide-rich zones and rhyolite-rich enclaves.

The boundaries of the zones of large Fe gains in Figure 18 are unconstrained in some directions, as certain holes were not sampled (i.e., LC-3 and FS-13). However, the Fe-rich zones represent at least some of the main pathways along which the mineralizing fluids moved. The deepest rhyolites sampled in holes FS-9802 and FS-22 still show Fe gains of >10 wt percent, and thus it is possible that Fe enrichment continues deeper into the footwall in this area. The largest gains in Cu (not shown) are below the central part of the main sulfide lens and follow the Fe-rich zone; this also suggests that the hottest fluids traveled through this zone.

Na2O and CaO (not shown) have been extensively depleted in the footwall due to chloritization and sericitization, with combined values of <1 percent, and commonly <0.5 percent. As a result, these elements are generally not effective at showing alteration variations, at least not within the sampled footwall. The top two samples of rhyolite A in hole FS-21 are exceptions; they contain 2.6 and 3.5 percent Na2O. The hanging-wall rhyolites are not as depleted in Na2O and CaO; combined values of 2 to 3 wt percent occur in rhyolite C, immediately above the orebody, and also in rhyolite B, downdip from the orebody (in holes FS-22 and FS-21).

Mass gains for BaO in section 550 NW are shown in Figure 19. The largest additions of BaO (0.5–2.0 wt %) occur immediately below and above the updip portion of the massive sulfide lens. These zones are almost mutually exclusive of the areas of Cu enrichment. Rhyolite C, which caps the massive sulfide lens, shows notable BaO gains of up to 1.6 wt percent. One sample in hole F-19, which overlies several meters of massive sulfide, contains 15.4 percent BaO. The argillites and siltstones of the Paraiso Formation also show modest gains in BaO, although sampling is limited to two holes. The BaO gains can be detected up to a few tens of meters above the cherts.

Thickness Variations in Massive Sulfides and Rhyolite C

In order to examine paleotopographic effects, isopach maps have been drawn for the massive sulfide, rhyolite C, and chert units. The thickness data are taken from the drilling logs,
Fig. 18. Calculated mass changes for FeO (in wt %) in section 550 NW, Feitais deposit. Numbers in brackets are the analyzed (raw) values of FeO in cherty rocks, for which mass changes were not calculated. Also shown are the main chemostratigraphic volcanic units (rhyolites A, B, and C).

Fig. 19. Calculated mass changes for BaO (in wt %) in section 550 NW, Feitais deposit. Numbers in brackets are the analyzed (raw) values of FeO in cherty rocks, for which mass changes were not calculated. Also shown are the main chemostratigraphic volcanic units (rhyolites A, B, and C).
without correction for drilling angles. However, almost all holes are at a high angle to stratigraphy. In a few cases, the rhyolite C interval includes other rhyolite types or the chert interval includes thin sulfide or rhyolite tuff layers. Nonetheless, the thickness assigned to the rhyolite C interval is a measure of the total accumulated material between the top of the massive sulfides and the base of the chert, both of which are well-defined surfaces. In the following figures, thicknesses are shown in an inclined longitudinal section; the plane of the page represents the approximate paleohorizontal. The black dots mark the locations of drill hole pierce points on this plane. The thickness data have been contoured by hand, using four arbitrary thickness bins.

Thickness variations in the massive sulfides and rhyolite C are shown in Figure 20a and b, respectively. It is clear that there is an overall increase in thickness of the massive sulfides in the downdip direction, particularly in the area north of the Cross fault. The isopaths are crudely lenticular, which suggests that the main structures controlling the thickness of the massive sulfides plunge at about 40° (on the inclined plane). The main massive sulfide bodies likely formed accumulations in fault-bounded grabens, rather than positive topographic features such as mounds, given that both the sulfides and the rhyolites that were present laterally to the sulfides on the sea floor are blanketed by rhyolite C tuff and chert. Variations in the thickness of the massive sulfides appear to have resulted mainly from a topographically irregular sea-floor infilling (all rhyolite).

The downdip (northeast) increase in thickness of the massive sulfides, followed by their rather abrupt terminations in this direction, suggests that they accumulated in an asymmetrical trapdoor graben, with a gentle flexure at the updip margin, and a growth fault at the downdip margin. Figure 20a suggests that sulfides also filled two, much smaller, grabens lying updip of the main graben and perhaps separated from it by narrow highs. The massive sulfide isopaths show apparent mismatches on either side of the Cross fault, which could result from strike-slip offset of a few tens of meters long this fault. However, they could also reflect original discontinuities on the sea floor. On modern spreading centers, normal and transverse faults combined with local volcanic eruptions can produce a lozenge-like pattern of local basins and highs.

Isopachs of rhyolite C also show a marked downdip increase in thickness (Fig. 20b), broadly similar to the pattern shown by the massive sulfides. Thicknesses of chert of 10 to 20 m or greater (not shown) generally occur above the thickest occurrences of both massive sulfides and rhyolite C. Thick cherts also occur in a few small areas along the shallow, upplunge margin of the deposit.

**Discussion**

**Possible eruption sequence**

At Feitais, rhyolite B is volumetrically minor, occurring only near the southern margin of the sulfide-filled graben, where it overlies rhyolite A and is overlain by rhyolite C, which is the youngest volcanic rock. Based on drilling to date, rhyolite A is the most voluminous volcanic type. Rhyolite X lies below rhyolite A in two deep drill holes and is the structurally, if not stratigraphically, lowest unit. Rhyolite X has the highest Zr content and Zr/TiO₂ ratio of any of the Feitais rhyolites (Table 1) and, therefore, may be the most fractionated unit. In terms of decreasing Zr/TiO₂ ratios, rhyolite X is followed by rhyolites A, B, and C. Rhyolite C has only half the Zr content of rhyolite X. If these rhyolites originated from one main felsic magma chamber, which was chemically stratified due to fractionation effects, then it is conceivable that the eruption order, from the top of the chamber down, was X → A → B → C. Zr/Y and Zr/Nb ratios, however, suggest that the concept of one fractionating magma type is too simplistic, as rhyolites B and X appear to represent one chemically related pair and rhyolites A and C another pair. This might be explained by the existence of two, smaller, coeval chambers containing magma derived from different source rocks; one chamber may have erupted rhyolite X then rhyolite B, while the other erupted rhyolite A then rhyolite C.

Rhyolite C contains the largest feldspar phenocrysts (3–6 mm) and rhyolite A the smallest (1–2 mm), whereas rhyolite B feldspars have intermediate sizes. Rhyolite X is aphyric or contains small quartz and feldspar crystals. Thus, the first rhyolites at Feitais (X, A) were aphyric or contained small crystals, whereas the last (C) contained rather large crystals. Rhyolite C may have been derived from a lower part of the magma chamber than rhyolite A.

The QF porphyry differs from the rhyolites in having higher precursor contents of Fe, Ti, P, and V that are more typical of dacites. It is unlikely that the QF porphyry represents a less fractionated portion of the magma chamber that produced the other rhyolite types, as it has different Zr/Y, Y/Nb, and La/Yb ratios, and it also contains common quartz phenocrysts, whereas rhyolite types A, B, and C contain feldspar but no quartz crystals. The QF porphyry magma was likely derived from a different source area relative to the rhyolites, and the magma was probably in a more reduced state, as inferred from its higher contents of Fe and Ti, which suggest that titanomagnetite was not removed during earlier stages of fractionation (as in some of the Fe-Ti-enriched felsic rocks in the Matagami area of Quebec: Barrett and MacLean, 1999). The QF porphyry magma must have undergone a significant amount of crystallization at depth to produce the large phenocrysts prior to eruption.

**Alteration effects**

Footwall rhyolite A is strongly altered for at least 30 m below the orebody. Most drill holes, with the exception of Fi-1 and Fi-2, did not penetrate far enough to reach the bottom of the zone of sulfide veins and chlorite alteration. In these two holes, rhyolite X, which underlies rhyolite A, is only weakly altered. Holes FS-20, FS-21, and F-22, which penetrated some 150 m into the footwall rhyolite, but at locations downdip of the main orebody, intersected zones of strong alteration and sulfide veining that continue to the ends of the holes. These zones, which show large additions of Fe and Mg, are interpreted to be conduits of focused upflow of mineralizing fluids. Copper is also commonly enriched in these zones, and locally Zn. The conduits were formed by synvolcanic faulting along the southeastern side of the graben. Based on the sulfide isopach data, the synvolcanic scarp was probably a site of long-lived hydrothermal fluid flow. Above the orebody, rhyolite C is moderately altered (mainly chloritization and
Fig. 20. Inclined longitudinal section, showing hand-contoured isopachs for the massive sulfide unit (a) and stratigraphically overlying rhyolite C tuff unit (b). The numbers at the top and bottom (e.g., 400, 480, etc.) refer to the drilling grid and are in meters. The cross-hatched areas between the −100 and −200 levels are underground workings.
sericitization, with minor additions of pyrite or barite). Near the up-plunge margin of the orebody, Ba also has been added to rocks immediately below and lateral to the orebody. Fe and Mn are enriched in the cherts above various parts of the orebody and in shales and siltstones up to several meters above the cherts.

**Position of massive sulfides and cherts**

The massive sulfides at Feitais probably accumulated largely by precipitation from euxinic bottom-water layers, as suggested by the fine-grained, massive, vaguely layered texture of the sulfides, the dominance of pyrite + sphalerite but near absence of barite, and the lack of obvious chimney structures or redeposited sulfide debris. Much of the orebody is overlain conformably by 5 to 30 m of rhyolite C tuff, and most of the chert formation lies above rhyolite C. Rhyolite B is locally present along the base and downlap margin of the orebody.

Locally, the massive sulfides pass upward into chert containing mainly Fe oxides (± Mn phases ± barite), suggesting that euxinic bottom-water layers were replaced by more oxidized waters as the input of high-temperature reduced fluids waned. Rhyolite C locally contains layers of sulfides or chert and in places contains enrichments in Ba or Mn of Fe oxides. Rhyolite C, like the massive sulfides, probably filled depressions on the paleocean floor, which produced an upper surface that was flatter than the lower surface. The area over which cherts were subsequently precipitated extends an unknown distance beyond the orebody. The formation of a thick and laterally continuous chert unit may have required the stabilization of a silica-saturated bottom-water layer, as silica-rich deposits do not precipitate from normal, modern ocean-bottom waters, which are silica undersaturated.

It has been suggested (Barriga and Fyfe, 1988) that the cherts at Aljustrel formed a cap rock to the hydrothermal system and that leakage of fluids through the cap rock probably produced black smokers on the sea floor. However, this seems unlikely given that the massive sulfides are almost always overlain by 5 to 30 m of rhyolite C tuff, not chert. Also, a siliceous precipitate on the sea floor probably would have been in the form of an ooze or gel, not chert, and therefore would not have been effective as a cap rock. The rhyolite C tuff, which would have been unconsolidated, would not itself have been effective as a cap rock (it contains sulfide impregnations but no veins).

**Tectonic setting**

The rhyolites at Feitais have chemical features consistent with a rifted continental margin (although not exclusive to that setting). These include tholeiitic to transitional Zr/Y ratios of 3 to 5, Zr ≈ 180 to 380 ppm, and (La/Yb)_n = 2 to 5. The relatively low contents of Nb (7–15 ppm) are more consistent with a subduction-influenced continental margin than an interior continental rift setting. In the Nb-Y discrimination diagram (not shown) of Pearce et al. (1984), the rhyolites plot near the intersection point of the three main fields and therefore cannot be reliably classified. Unfortunately, there are no mafic volcanic rocks in the Aljustrel sequence, as these commonly provide good constraints on paleotectonic settings. Elsewhere in the Iberian Pyrite Belt, the mafic rocks range from arc-type tholeiites to alkaline basalts (Thiéblemont et al., 1998). Massive sulfide deposits in the Iberian Pyrite Belt generally lie within shale members of the so-called Volcano-Sedimentary sequence, although the deposits overlie felsic volcanic rocks at Rio Tinto and Zarza (Leistel et al., 1998). At Neves Corvo, massive sulfide deposits overlie both felsic units and shale units (Oliveira et al., 2004).

Other VMS deposits which are both underlain and overlain by rhyolitic rocks include the Archean Scuddles deposit in Australia (Ashley et al., 1988), and the Triassic Kutcho Creek deposit in British Columbia (Bridge et al., 1986). The Scuddles deposit overlies a series of rhyolitic ash-flow tuffs and is overlain by thin intervals of andesite, ash flow, and exhalite, then a major interval of quartz-phyric ash-flow tuffs (Ashley et al., 1988). The hanging-wall felsic rocks at Scuddles have higher TiO_2 contents than those of the footwall (as at Feitais). The tectonic setting of the deposit is interpreted to be a calc-alkaline continental margin arc (Ashley et al., 1988). At Kutcho Creek, the hanging-wall rhyolites are quartz-feldspar-phyric and also have higher TiO_2 and Zr contents than the footwall rhyolites, which are crystal-poor lapilli tuffs (Barrett et al., 1996). At the Paleozoic Parys Mountain deposit in Wales, massive sulfides occur at the contact between footwall shales and a hanging-wall felsic volcanic sequence that includes four chemically distinct rhyolite types (Barrett et al., 2001). The Parys Mountain rhyolites, which have higher Nb contents but otherwise are chemically similar to those at Aljustrel, are interpreted by these authors to have formed on a rifted continental margin.

**Conclusions**

Application of immobile element methods to the Feitais host volcanic sequence has led to the recognition of several major felsic units which have a consistent position with respect to the mineralization. The inferred sequence of volcanic events is shown schematically in Figure 21. This diagram pertains to the relationships in the area of sections 440 to 600 NW (see Fig. 3b).

Rhyolite A forms the majority of the immediate footwall to the Feitais orebody, excluding a few thin occurrences of rhyolite B near the base of the orebody, mainly along its southeastern margin. Based on two deep drill holes, rhyolite A was preceded by rhyolite X. Basement rocks such as the regional Quartz-Phyllite Group have not been intersected at Aljustrel. Prior to and during sulfide accumulation, the rhyolitic basement underwent faulting, notably along the southeastern margin, allowing mineralizing fluids to discharge into an asymmetrical graben. Sulfide-veined and chloritized rhyolites are present in this area and also under the main part of the orebody. Large amounts of Fe and Mg have been added to the rhyolites in these zones, whereas Si mass changes range from major additions to major depletions. Na and Ca are strongly depleted throughout most of the footwall. The orebody consists mainly of 20 to 100 m of massive Zn-bearing pyritic sulfides, with a basal interval of 5 to 10 m of Cu-bearing sulfides that includes the uppermost part of the stockwork veins. A 5- to 30-m-thick unit of rhyolite C tuff caps most of the orebody. Thickness variations in the massive sulfides, rhyolite C, and the cherts reflect gradual infilling of one main asymmetrical graben. Field and chemical relations indicate that the rhyolites were erupted in the order X → A → B → C,
that is, from more to less fractionated magma. Rhyolite C is overlain stratigraphically by 2 to 20 m of cherts, then 10 to 30 m of shales and siltstone turbidites of the Paraiso Formation, followed by >200 m of graywacke sandstones and shales of the Culm Flysch. The Paraiso Formation sedimentary rocks do not contain a chemically discernible rhyolitic component but have immobile element ratios similar to those of the terrigenous Culm Flysch and thus were probably derived from an extra-basinal source.

Near the up-plunge margin of the massive sulfide lens, interlayering occurs between thin layers of rhyolite C, various types of chert, and sulfides. Cherts are variably enriched in Mn or Ba, or pyrite, or hematite and magnetite. The chert is interpreted to be a relatively low-temperature precipitate that accumulated under mainly oxidizing conditions, after both the massive sulfides and rhyolite C had been deposited, and not a cap rock that played a role in massive sulfide formation. Following deposition of the cherts, the sea floor was relatively flat and the first Paraiso shales began to accumulate. A thin bed of quartz-feldspar crystal tuff with a distinctive composition occurs just above the chert formation in three holes and forms a marker horizon that can be traced laterally for at least 700 m.

Two deep footwall holes at Feitais ended in quartz-feldspar porphyry, a lithology that makes up much of the central part of the Aljustrel area. Field and petrographic features suggest that the porphyry was emplaced partly below and partly on the seafloor, and to the west of the Feitais deposit. The magnetic affinity of the porphyry suggests that it was derived from a different source area relative to Aljustrel rhyolites. The geochemistry of the rhyolites is consistent with formation in a rifted continental margin setting behind an arc.

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