Fruta del Norte, Ecuador: a completely preserved Late Jurassic epithermal gold-silver deposit

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Abstract. The Fruta del Norte gold-silver discovery in southeastern Ecuador displays key aspects of low- and intermediate-sulphidation style mineralization, including an overlying siliceous sinter horizon. Base metal-poor, quartz-adularia-calcite veins are spatially related to a distinctive feldspar quartz porphyry whereas Mn carbonate- and base metal-rich quartz veins dominate the deposit in andesite to the south and at depth. Both vein styles are succeeded upwards by silicic ore consisting of disseminated marcasite in chalcedonic silicification, veins and breccia. The low-sulphidation veins in the north are partly hosted by the feldspar quartz porphyry (160 Ma) whereas intermediate-sulphidation veins cut Middle Jurassic or older andesite (host to 169 Ma molybdenite). Both underlie the Suárez pull-apart basin, a Late Jurassic clastic-volcanic depocenter linked to the regional Las Peñas fault zone. The exceptional preservation of the epithermal deposit is due to deposition of conglomerate on top of the still-active epithermal paleosurface. Alteration (silicification ± marcasite without gold) continued after the initial burial by conglomerate but ceased before the eruption of Late Jurassic andesitic lava (ca. 157-154 Ma) at the top of the Suárez basin sequence.

1 Introduction

Epithermal precious and base-metal deposits form by hydrothermal processes at shallow crustal levels (<1.5 km), typically at convergent plate margins. Active geothermal sites are recognized as the modern analogs for epithermal precious and base-metal deposits (White 1981; Henley and Ellis 1983). The common association of epithermal deposits with coeval Tertiary or younger volcanic rocks, and the relative paucity of pre-Tertiary examples, may reflect their susceptibility to post-formation erosion. Despite their siliceous character, this is particularly true for epithermal paleosurfaces (Sillitoe 2015), based on the relatively rare preservation of sinter in the geologic record.

The Fruta del Norte Au-Ag vein-stockwork deposit (FDN) is hosted within the Zarza roof pendant of the Zamora batholith in southeast Ecuador about 10 km west of the Peruvian border. The epithermal deposit is noteworthy for its discovery beneath >100 m of mainly unaltered, barren cover; the rich gold endowment (resources of 9.8 million ounces of gold (Au) in ore grading *ca.* 9.59 g/t Au), the combination of low- and intermediate-sulphidation veins; and the exceptional preservation of epithermal textures including an extensive sinter horizon above the deposit (Leary et al. 2016).

We describe the geological circumstances that contributed to the deposit's discovery, and the remarkable preservation of the FDN deposit and epithermal paleosurface. As our observations and data are limited to drill core up to ca. mid-2009, we acknowledge that information produced since then may supersede some of the conclusions presented here.

2 Regional Setting

The Zamora batholith consists of mainly Jurassic, medium- to coarse-grained monzonite, tonalite and granodiorite plutons and associated volcanic rocks in the Cordillera del Cóndor of southern Ecuador (Litherland et al. 1994). The Zamora batholith and volcanic arc rocks were constructed between two marine transgressions on the stable, northwest margin of the Amazon craton (Litherland et al. 1994). Middle Jurassic volcanism (Romeuf et al. 1995) followed limestone deposition and broadly accompanied the change from marine to clastic deposition in the upper part of the Late Triassic-Middle Jurassic Santiago Formation (Baby et al. 2004). Misahuallí volcanism and porphyry magmatism post-dated plutonism and accompanied deposition of the subaerial Middle to Upper Jurassic Chapiza Formation. Early Cretaceous shallow marine quartz sandstone of the Hollín Formation was deposited after erosion of the arc and exposure of its plutonic roots (Litherland et al. 1994). Tectonism during the Andean orogeny exposed the arc relicts beneath the partially eroded Cretaceous and younger cover. Age relationships in roof pendants in the Zamora batholith have been crucial to interpreting the stratigraphic position of Zamora arc volcanic rocks and their metallogeny (Litherland et al. 1994; Chiaradia et al. 2009; Drobe et al. 2013; Leary et al. 2016).

3 Local Setting

The roughly 10 x 50 km, north-trending Zarza roof pendant consists of mainly andesitic volcanic rocks and porphyries that are intruded by phases of the Zamora batholith. The FDN deposit is situated at the northeastern extremity of the pendant between strands of the Las Peñas fault zone, a regional transpressive fault that structurally controls other gold-silver prospects in the pendant to the south. Volcanic host rocks of FDN are assigned to the Piuntza unit of the Santiago Formation (Leary et al. 2016).

The northern 10 km of the Zarza roof pendant, including the FDN deposit, are overlain unconformably by sediments filling the Suárez pull-apart basin, a volcano-sedimentary sequence spatially and temporally related to the Las Peñas fault zone (Leary et al. 2016). This regionally extensive, transpressive fault zone bounds the Suárez basin to the east, and cuts both the pendant and batholith. Down-to-the-west motion on the steep West fault splay thickens the basin to the west and juxtaposes the deposit against unaltered conglomerate. The Suárez basin consists of lower fluviatile conglomerate with interbedded dacitic ignimbrite. The mixed upper siltstone-sandstone-conglomerate beds are in part lateral, facies-equivalent to basin margin conglomerate. Unaltered andesite caps the basin in the west, reaching >500 m in thickness west of the West fault at the southern end of the FDN deposit. Piuntza volcanic and porphyry clasts predominate in conglomerate although clasts derived from the Zamora batholith are also present. The conglomerate base is therefore interpreted as an intra-arc unconformity. Sediments filling the Suárez basin are therefore assigned to the subaerial Chapiza Formation, and the uppermost andesite is correlated with the Misahuallí unit of the upper Chapiza Formation (Leary et al. 2016).

4 The Deposit

The FDN vein-stockwork deposit is up to 300m wide, extends over 300 m vertically and is at least 1.3 km long (Fig. 1). There are two principal types of colloform-crustiform veins. Veins in the northern ca. 500 m of the deposit are composed mainly of quartz, chalcedony, calcite and marcasite, and are manganese and base metal poor. These occur in the hanging wall of a large feldspar quartz porphyry, distinctive from the typical feldspar hornblende porphyry typical of Piuntza andesite. Veins to the south are dominated by quartz and manganoan carbonates, with abundant base metal sulphides. They are hosted by Piuntza andesite and feldspar hornblende porphyry. Colloform, crustiform, botryoidal, cockade, drusy, finely laminated chalcedonic, and saccharoidal bands, plus replacement and recrystallization (microplumose, flamboyant) textures (Sander and Black 1988; Dong et al. 1995) are prevalent in both vein types. The northern and southern veins are typical of low- and intermediate- sulphidation epithermal deposits, respectively (Sillitoe and Hedenquist 2003). Adularia is a common but minor gangue mineral in both vein types. Bladed calcite occurs in both vein types and ranges from preserved calcite with open spaces to blades completely replaced by quartz with quartz infill. These features imply boiling of the mineralizing fluid (Simmons and Browne 2000). In the absence of cross-cutting relationships, especially where the vein types are proximal at the southern end of the feldspar quartz porphyry, the two vein styles are considered broadly contemporaneous.

Each vein type is abruptly transitional upward, and westward toward the West fault, to a third ore type marked by intense chalcedony silicification and disseminated marcasite (± pyrite) veinlets. The upper silicic zone is locally sulphide deficient, the result of a short-lived supergene oxidation event prior to deposition of basal Suárez basin conglomerate (Leary et al. 2016). The upper sulphidic silicic zone is subtly to strongly enriched in As, Sb and Hg relative to the intermediate- and low-sulphidation vein zones. The relationship of veins to the silicic zone and the vertical distribution of trace metals in the hydrothermal system support the Buchanan (1981) model for epithermal precious and base metal vein systems.

The deposit is notable for the widespread occurrence of fine to coarse visible gold, which gives rise to bonanza grades. Visible gold is associated variably with quartz, chalcedony, carbonate (mainly manganoan), and marcasite vein gangue. Semi-porous masses of visible gold are common, including examples of fractal dendrites (cf. Saunders 2012, Fig. 3 with Fig. 11E in Leary et al. 2016). High grades with and without visible gold also accompany vein intervals with masses of crustiform marcasite.

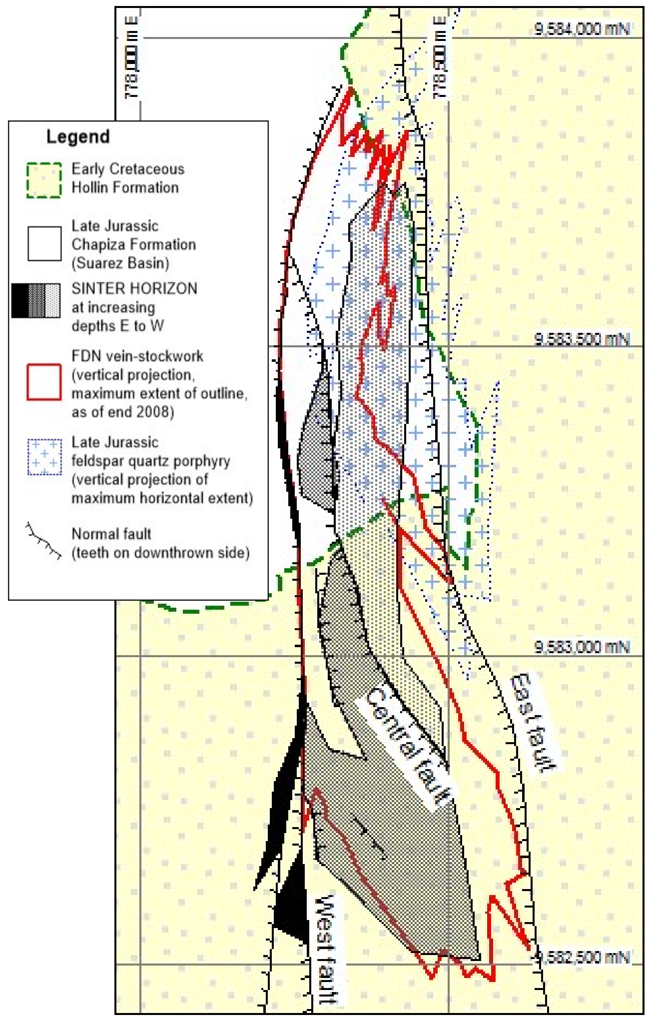

Figure 1. Simplified plan of the geology of Fruta del Norte showing relationship of sinter horizon to the orebody

The upper silicic ore zone is up to 100 m thick above both vein zones, thickening to the west but abruptly disappearing across the West fault. It thins to the east across the Central and lesser, unnamed faults. The protolith is obscured by intense silicification and brecciation, but this Mn-poor zone roughly coincides with an incompletely mapped sequence of texturally diverse, phenocryst-poor tuffaceous rocks overlying porphyritic Piuntza andesite with Mn-rich veins. In places, the silicic ore zone is directly overlain by Suárez basin conglomerate, but commonly there is an intervening sequence (2-25 m thick) of laminated siliceous sinter, weakly sulphidic mud-pool deposits, hydrothermal eruption breccias, and volcanogenic sediments with plant fossils (Leary et al. 2016). This distinctive sinter horizon is traceable for >1 km along the strike of the deposit, in bands at different depths separated by the West and Central faults (Fig. 1). The sinter horizon has many similarities with the Taupo Volcanic Zone sinter, including high temperature vent facies (Lynne 2012). The horizon is texturally gradational with underlying silicic ore and appears to constitute the upper part of the upper tuffaceous unit. Sinter is overlain abruptly by conglomerate wherein clasts of laminated sinter are uncommon (Leary et al. 2016). The FDN orebody lies in unusual proximity to overlying sinter compared with most epithermal vein deposits with preserved sinter (Sillitoe 2015).

4.1 Hydrothermal alteration

Two alteration styles are distinguished in FDN drill core: early porphyry copper-related propylitic and potassic assemblages, and later epithermal quartz/chalcedony-clay-pyrite/marcasite. The widespread pale-green clay mineral in the latter is visually identified as illite.

Andesite and porphyries hosting FDN veins display strong quartz-illite-pyrite alteration. The appearance of calcite in the alteration assemblage typically marks the eastern (and lower) ore boundary. Probable phreatomagmatic breccias cut some porphyry intrusions, mainly below the orebody. These breccias may be overprinted by quartz-illite-pyrite alteration but seldom have economic gold concentrations. The upper silicic zone generally lacks illite. The lowermost ca. 20 m of the conglomerate is silicified, typically with disseminated marcasite, where it overlies sinter or the silicic ore zone. Silicification with marcasite also occurs locally above the West fault, commonly at ignimbrite/conglomerate contacts. Uncommon kaolinite is seen on fractures in silicified conglomerate. Where overlain by silicified conglomerate, the sinter horizon is also silicified. Late-stage drusy barite occurs in silicified sinter and underlying silicic ore, and uncommon cinnabar and metacinnabar impregnations occur in silicified sinter (Leary et al. 2016). The silicified conglomerate and sinter have only subeconomic gold concentrations. Above its base, unaltered conglomerate has the red-brown colour typical of terrestrial sediments, with one critical exception: a steeply inclined silicified zone that connects the underlying deposit to a silicified rib exposed >100 m vertically above the deposit. Drill testing beneath this localized surface expression of epithermal silicification containing anomalous As and Sb values led to the discovery of FDN beneath the Suárez basin (Leary et al. 2016).

The vein minerals and quartz-illite-pyrite alteration indicate near-neutral pH hydrothermal fluids, typical of low- and intermediate-sulphidation deposits (Sillitoe and Hedenquist 2003; Simmons et al. 2005). Changes in vein mineralogy laterally within the deposit differ from coexisting low- and intermediate-sulphidation assemblages at different vertical positions in Mexican vein deposits (Camprubi and Albinson 2007). While the vein types may have required two discrete mineralizing fluids, perhaps due to source intrusions at different depths (Leary et al. 2016), the lateral change in vein mineralogy appears to correspond to the change in predominant host rocks (volcanic andesite in the south vs. feldspar quartz porphyry in the north). Both vein types and silicic ore are suspected to have formed from fluids that ascended via the West and Central faults. The upward ore change from vein dominated to the silicic replacement zone is attributed to cooling of the ascendant fluid on approach to the paleosurface sinter. The progressive burial of an active epithermal paleosurface beneath the Suárez basin fill likely caused telescoping of the deposit, the atypical proximity of ore to sinter and possibly the high grades due to repeated hydrothermal sealing and brecciation. Burial of the epithermal paleosurface may have contributed to the suppression and eventual extinction of the epithermal system, with gold mineralization in the conglomerate being inhibited by rheologic and chemical factors (Leary et al. 2016). Burial during hydrothermal activity clearly prevented erosion of the epithermal paleosurface and underlying mineralization.

5 Geochronology

Porphyry copper-style (center-line pyrite-quartz) veinlets are present below the FDN orebody and propylitic alteration (epidote, chlorite, calcite) is overprinted locally by epithermal veinlets with silica-illite-pyrite alteration. Molybdenite from a quartz veinlet in Piuntza andesite about 700 m south of the orebody was precisely dated by the Re-Os method at 169 ± 1 Ma (Stewart, Stein and Roa, in prep.). The proximity of porphyry copper alteration and mineralization to the conglomerate base (<200 m) indicates substantial erosion of the Piuntza unit before deposition in the Suárez basin. The veinlets and alteration are considered as part of a weakly developed porphyry copper system that is roughly 10-15 m.y. older than Late Jurassic (ca. 158-153 Ma) porphyry copper deposits north of FDN (Gendall et al. 2000; Chiaradia et al. 2009; Drobe et al. 2013).

A maximum age for the FDN deposit is provided by a Late Jurassic U-Pb zircon age of 160 ± 0.2 Ma for the feldspar quartz porphyry that hosts the low-sulphidation veins (Leary et al. 2016; Stewart, Stein and Roa, in prep.). The absence of dikes in the Suarez basin sequence, despite the close proximity of the porphyry to basal conglomerate (<50 m), implies that feldspar quartz porphyry intrusion and solidification predates conglomerate deposition. Hydrothermal activity ceased before eruption of the Late Jurassic andesite in the basin above the deposit (157-153 Ma; $^{40}Ar/^{39}Ar$ amphibole plateau ages; Leary et al. 2016; Stewart, Stein and Roa, in prep.).

Our use of Re-Os to date FDN marcasite is the first known application of this chronometer to this hydrothermal mineral (Stewart, Stein and Roa, in prep.). Late-stage marcasite veinlets cut low-sulphidation vein bands at 159-160 Ma, overlapping with and indistinguishable from the age of the feldspar quartz porphyry. Marcasite in silicified conglomerate is less precisely dated between 160 and 157 Ma. We suggest the deposit formed during the cooling history of the feldspar quartz porphyry, which must temporally precede and overlap with initial Late Jurassic conglomerate deposition.

Vein adularia yields anomalously young Late Cretaceous $^{40}Ar/^{39}Ar$ ages (ca. 79-67 Ma) comparable with ages of 68 ± 11 Ma for plagioclase in the Late Jurassic Suárez basin andesite (with hornblende dated at ca. 154 Ma) and 71.0 ± 2.2 Ma for hornblende in a post-tectonic mafic dike in the Las Peñas fault zone (Stewart, Stein and Roa, in prep.). A strength of the Re-Os chronometer, relative to Ar-based chronometers is the retention of primary ages. The Re-Os chronometer is chemically sensitive whereas Ar-based chronology is thermally sensitive (Stein, 2014).

6 Discussion and conclusions

The deposition of Suárez basin conglomerate on top of the hydrothermal paleosurface was critical to the high degree of preservation of the FDN epithermal Au-Ag orebody. Conglomerate directly overlying the sinter horizon is silicified as is the sinter itself. This observation requires burial of the epithermal paleosurface while the hydrothermal system was still active. Rapid burial, therefore, prevented significant erosion of the hydrothermal system responsible for the FDN epithermal deposit, including the typically friable paleosurface features. Sinter and uncommon epithermal vein clasts in basal conglomerate directly above sinter cannot have been eroded from the underlying deposit and must be derived from other epithermal sites in the conglomerate source region.

The Fruta del Norte epithermal event occurred in the Late Jurassic following a porphyry copper episode at ca. 169 Ma and intrusion of feldspar quartz porphyry at ca. 160 Ma. The absence of dikes or epithermal veins cutting the basal conglomerate suggests that Suárez basin sedimentation began after 160 Ma. Proximity of porphyry copper mineralization to the base of the conglomerate requires substantial pre-conglomerate erosion in order to have brought mineralization formed at +1 km depths closer to the paleosurface. The lack of alteration in the andesite at the top of the Suárez basin sequence shows that hydrothermal activity had ceased before 157-154 Ma.

Late Cretaceous plagioclase in Late Jurassic andesite requires a thermal event sufficient to reset Ar/Ar ages in feldspar. Post-tectonic mafic dikes were emplaced in the Las Peñas fault zone at ca. 71 Ma. Although volumetrically minor, the Late Cretaceous magmatism is inferred to have disrupted Ar systematics in vein adularia at FDN and may represent the earliest stage of magmatism in the Andean orogeny.

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