Original Article

Geological setting of gold-silver mineralization in the La India mining district, Nicaragua

L.T.P. English[1], V.H. Galvan[2], and C.R. Pullinger[3]

Abstract

La India gold mining district covers a 50 km² area of fault-fill gold-silver mineralized quartz-adularia veins on the western margin of a Tertiary volcanic arc in western Nicaragua. Historic mining records and modern mineral exploration data, which to-date has defined a mineral endowment of over 2.3 Moz gold, provide a wealth of geological information. This paper draws on these observations and data to describe and classify the gold-silver mineralisation at La India, identify the geological controls, and interpret the timing of mineralisation within the regional tectonic setting. The district-scale gold-silver mineralisation at La India occurs in two adjacent geological settings with distinct mineralization characteristics and exploration potential: (1) an upland area of strongly faulted felsic to andesitic volcanics where the historic mine workings are located, and (2) an adjacent downthrown graben, the Sebaco Graben, where a thick sequence of andesite is preserved overlying the felsic volcanic sequence. Gold mineralisation is classified as rift margin-type low-sulphidation epithermal gold-silver fault and fracture-fill vein mineralization. In the historic mining area erosion has exposed the top of the high-grade epithermal zone. Minimal erosion in the Sebaco Graben means that the epithermal system is fully preserved at depth, with localised hydrothermal sinter outcrops, sporadic low-grade mineralised veins and a phreatic breccia pipe exposed at surface. Apart from the one phreatic breccia, the gold-silver mineralisation occurs in quartz veins and breccias that filled brittle faults and associated fractures and fissures which developed in an extensional tectonic setting. The structures containing the gold-silver mineralisation were formed as normal and trans-tensional faults with orientations consistent with southwest-directed extension: (1) a predominant northwest to north-northwest set parallel to the subducting plate; (2) secondary but locally extensive east-west, and (3) tertiary shorter and narrower northeast and north-striking veins. A district-scale north-northwest orientated through-going structure linking the major gold-silver deposits in the historic mining area is interpreted as a deep crustal conduit for the gold-silver bearing hydrothermal fluids. Other, as yet unidentified basement feeder structures may have fed mineralised corridors in the east and west of the district. The gold-silver mineralisation is best developed where structures pass through competent felsic volcanics and welded tuffs in the historic mine area, and also in the overlying andesite flows in the Sebaco Graben. Gold-silver mineralisation is less well developed where the structure passes through less competent unwelded tuffs and volcanic agglomerates. Gold-silver mineralisation is interpreted as occurring shortly before or at 8-10 Ma at the end of a long period of slab-rollback induced extension and arc volcanism. Post-mineralisation block faulting split the La India district into the upthrown, and subsequently eroded historic mine area where epithermal mineralisation is largely exposed at surface, and the well-preserved downthrown blocks such as the Sebaco graben where much of the gold-silver mineralisation is still hidden several hundred metres below surface.

Keywords: Gold; silver; low sulphidation epithermal; mineralisation; La India; Nicaragua

Affiliation Info: [1] Condor Gold PLC, 7/8 Innovation Place, Douglas Drive, Godalming, Surrey GU7 1JX, United Kingdom; [2] Fortuna Silver Mines Inc., 650-200 Burrard Street, Vancouver, BC, Canada; [3] LAGEO S.A. de C.V. Final 15 Av. Sur y Boulevard Sur, Colonia Utila, Santa Tecla, La Libertad, El Salvador

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Authors' Contact Info: English, L: lenglish@condorgold.com; Galvan, VH: vgalvan@fortunasilver.com; Pullinger, CR: crpullinger@yahoo.com
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Corresponding Author©: English, L, PhD, Professional Geologist; Email: lenglish@condorgold.com

1 Introduction

Gold and silver have been mined in the La India district in western Nicaragua for well over 100 years (Fig. 1). The first known gold mining in the La India district was by the London-based Corduroy Syndicate who worked a small-scale underground mining operation exploiting the Dos Hermanos vein in the southwestern corner of the mining area in the late 19th or early 20th Century. Industrial-scale underground gold mining was initiated in 1936 on the nearby India vein which Canadian mining company Noranda Inc. acquired in 1938. Noranda expanded underground mining operations and by the time the mine closed in 1956, the La India vein had been worked along a 1200 m strike length to a depth of over 250 m below surface at the deepest part, the neighbouring America-Constancia vein along a 2200 m strike length up to 140 m below the valley floor, and six other smaller underground mine workings had been initiated on satellite veins spread over approximately a 50 km² area (Fig. 2). Available records show annual production peaked at 41,891 oz gold and 39,282 oz silver in 1953 (English 2015)[1]. Since the closure of the La India gold mine and continuing to the present day, artisanal miners have intermittently worked the most accessible upper levels of the mine and extracted ore from small underground workings throughout the district.

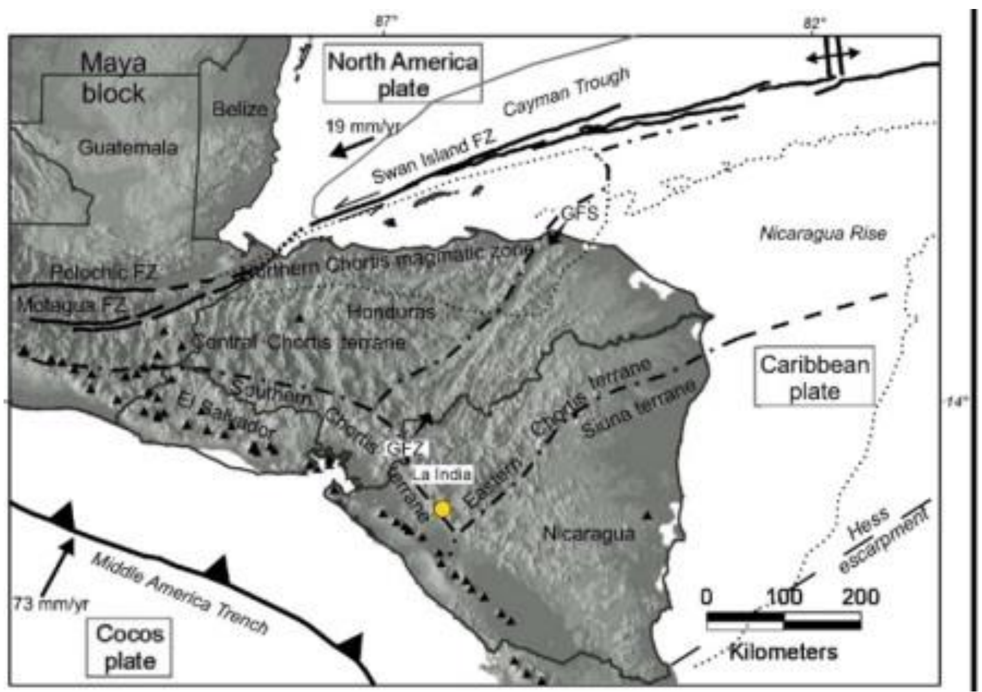

Figure 1. Location of the La India district in western Nicaragua
(After Rogers *et al.* 2007)[2]

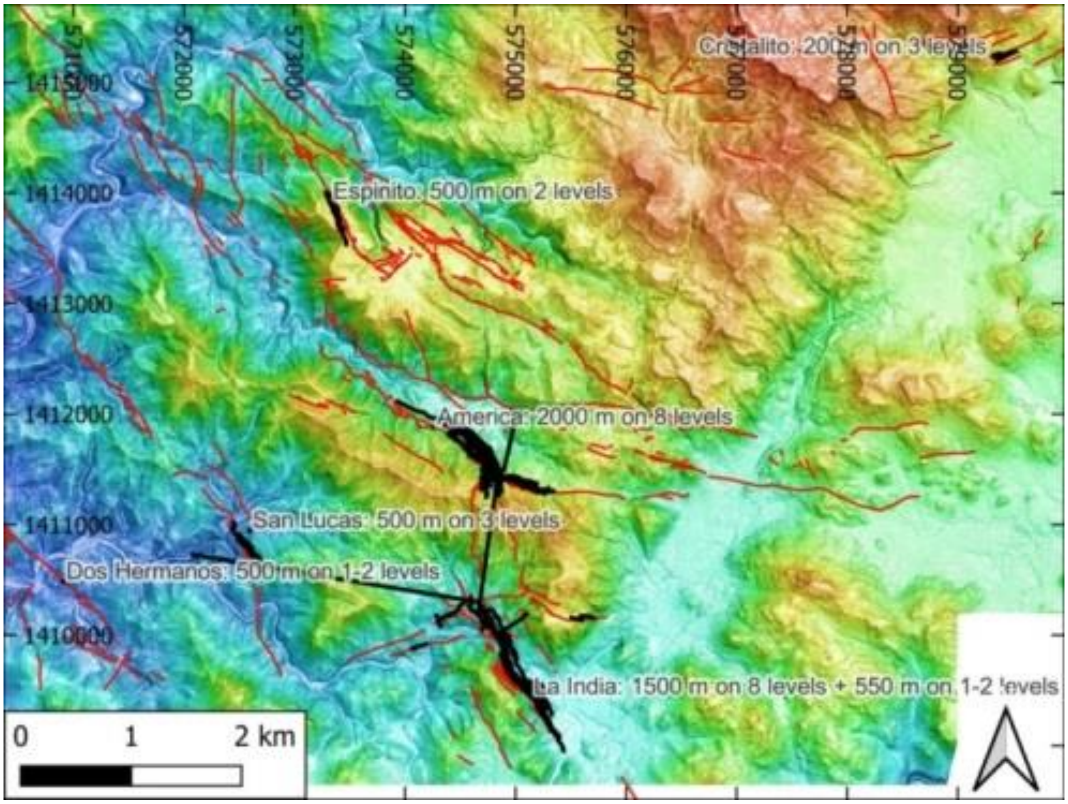

Figure 2. Historic mine workings on the La India gold mining district
(Surface Au-quartz veins in red, underground mine workings in black)

Modern mineral exploration has established that a significant mineral resource remains in the ground adjacent to the old workings and elsewhere in the district: the current concession holders have defined a 2.3 Moz gold endowment in and around the historic mine workings. The modern exploration since the late 1980's has been well documented and provides a database of over 4,500 rock chip samples, a grid of over 12,000 soil samples, 1776 trenches for almost 29,000 m of channel samples, and 625 drill holes for over 96,000 m of rock samples, most of which collected continuous samples of rock core, satellite-derived digital terrain models and a 280km² area airborne radiometric and magnetic geophysical surveys. The geological observations and geochemical analytical results of this exploration provide a wealth of geological information on La India district that forms the basis of this study.

This paper describes the geometry and style of gold-silver mineralisation in the La India district, describes the geological setting, and presents an interpretation of the geological controls, tectonic setting, and proposed timing of gold-silver mineralisation. The work draws on observations and data derived from outcrop and underground rock exposures, trench cuttings and drill core, geophysical surveys, and satellite images collected by numerous exploration geologists and specialist consultants since the late 1980's.

1.1 Gold-silver mineralisation

Gold-silver mineralisation occurs both in the hilly historic La India mining area and in the lower hills and plains of the Sebaco Graben to the southeast (Fig. 3). Block faulting that created the graben was active post-mineralisation so that the gold-silver mineralisation was displaced to a lower elevation within the graben. Differential erosion has resulted in the preservation and exposure of the veins in the hills of the historic La India mining district, and preservation, and local sedimentary covering of a subsurface vein system in the protected lowlands of the downthrown graben block.

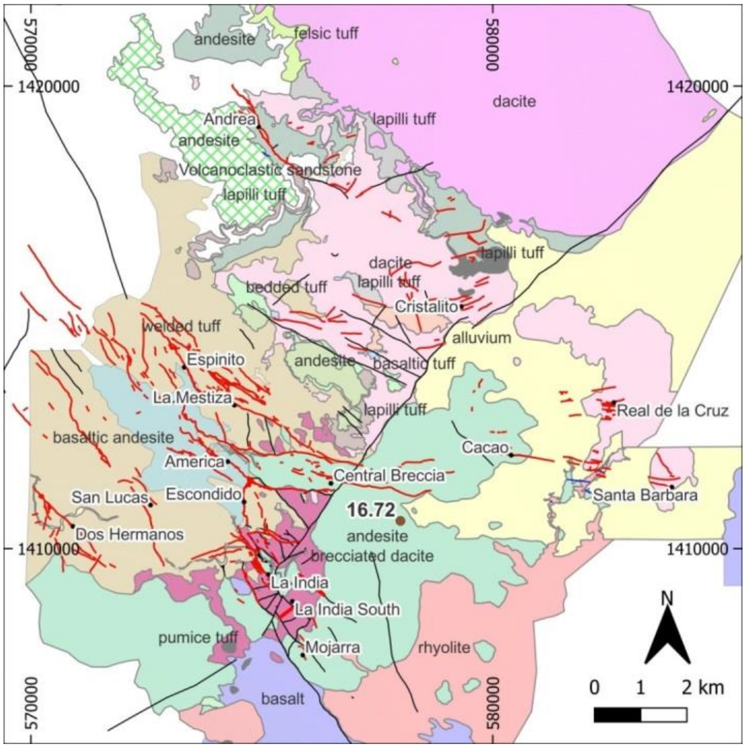

Figure 3. Geological map of La India historic mine area and the Sebaco graben showing the location of an andesite outcrop dated at 16.72 Ma (After Plank *et al.* 2002)[3]

1.2 Gold-silver mineralisation of La India historic mine area

Gold and silver mineralisation in the historic La India mining area occurs in hydrothermal veins filling faults and associated fissures and fracture zones. Analysis of veins from the principle La India and America deposits show that the veins are composed of quartz and adularia veins with gold and silver occurring as 82% fine electrum, 9% native gold, and 9% Uytenbogaardtite (Ag3AuS2), fischesserite (Ag3AuSe2) and gold-silver sulphide (SRK 2022)[4].

Veins exhibit classic low sulphidation textures such as chalcedonic-ginguru banding, crustiform, vughy and drusy textures, and notably large bladed and rhombic calcite replacement textures (Fig. 4). These textures indicate deposition in the hydrothermal boiling zone towards the top of the epithermal system. This would typically occur at depths of 50 m to 700 m below the water table at time of deposition (Hedenquist *et al.* 2000; Fig. 9)[5], but has now been exposed at the surface by erosion. Drilling has traced the mineralisation to depths of over 250 m below the current surface at the principal La India, America, and La Mestiza deposits. The base of mineralisation has not yet been determined.

Several pulses of vein deposition are recognised in active faults as evidenced by fault breccias with quartz clasts cemented by quartz. In some primary faults, including those hosting the La India and America deposits, faults continued to be active after the last pulse of veining. In such cases, veins have been ground to fault breccias of mixed quartz clasts and reddish-brown oxidised fault gouge clay, and even milled to cataclastic sandy clays, all of which can contain significant levels of gold-silver mineralisation (Fig. 5).

Most of the potentially economic gold-silver mineralisation is hosted by massive, indurate felsic volcanics and welded tuffs in La India historic mining area. Wallrock alteration in these rocks is limited to a thin haematite selvedge in these rocks. The haematite is indicative of mixing of the ore fluids with oxygenated ground water and supports the interpretation that veins were precipitated at a relatively shallow level (Corbett 2012)[6]. The restriction of alteration to a narrow selvedge around the vein suggests that these hard, indurate silica-rich lithologies formed an impermeable and relatively unreactive barrier to the hydrothermal fluids, constraining and concentrating the mineral-rich hydrothermal fluids within the faults and fractures (Pratt and Ponce 2016)[7]. The veins become narrower and often dissipated into stockwork zones where the veins extend into surrounding less indurated tuffs and volcaniclastic sediments.

Figure 4. Left: La India vein cockade banded quartz-adularia vein (example grading at 14.1 g/t gold and 192 g/t silver); Right: Platy quartz vein (example grading at 4.3 g/t gold and 6.5 g/t silver)

Figure 5. Left: Gold mineralisation at La Mestiza deposit as quartz veins deposited in active faults include cataclastic sand containing early quartz vein fragments partially overprinted by a later phase of quartz cemented (example grading at 47.7 g/t gold and 40 g/t silver); Right: Fault breccia of mixed quartz clasts and reddish-brown oxidised fault gouge clay (example grading at 41.16 g/t gold and 80 g/t silver)

1.3 Gold-silver mineralisation of the Sebaco Graben

The geology of the downthrown Sebaco Graben block is dominated by a thick sequence of andesite, younger than the underlying felsic volcanics, which has been dated at 16.72 Ma by radiometric dating (Plank *et al.* 2002)[3]. Gold-silver mineralisation and wallrock alteration differ from the historic mining zone. In many places there has been minimal surface erosion and the epithermal and overlying hydrothermal system has been fully preserved. Blocks of hot spring sinter and fluidized volcaniclastic sediment (tuffaceous-breccia) at the Cacao prospect (Pratt 2019)[8], sinter and chalcedonic quartz at the La India South-Mojarra prospect (Fig. 6), and phreatic breccia and associated microbreccia with cross-bedding and grain sorted surficial flow textures at the Central Breccia prospect testify to the preservation of near-surface and surface hydrothermal deposits (Fig. 7). Proximal argillic-pyrite and distal smectite alteration recognised in the wallrock of the mineralised structures are characteristic of shallow level to surficial hydrothermal activity above the epithermal zone (Corbett and Leach 1998; Fig. 9) [9].

Some gold-silver mineralisation does occur near surface, in quartz veins at Cacao, and at less well-explored prospects such as Mojarra, Santa Barbara and Real de La Cruz. However, the main high-grade gold-silver mineralised epithermal zone has been found fully preserved at depths of over 200 m below surface at Cacao and La India South, and is likely to be similarly preserved below surface in the other less well explored prospects (Fig. 8).

Figure 6. Left: Laminated silica sinter deposits at the Cacao; Right: Mojarra prospects

Figure 7. Left: Phraeatic breccia; Right: a silicified microbreccia volcano-sedimentary exhalative flow deposit at the Central Breccia gold-silver deposit

Figure 8. Left: Central Breccia smectite altered clasts with sulphide rims cemented by quartz-calcite (example grading at 32.4 g/t gold and 19 g/t silver); Right: Banded quartz-calcite vein at c.260 m below surface (example grading at 8.20 g/t gold and 52 g/t silver)

Gold mineralisation at the Central Breccia which lies on the graben fault separating the historic mine area from the Sebaco graben differs from the rest of the La India district. The Central Breccia is a 150 m by 300 m phreatic breccia where two stages of hydrothermal breccia development are recognised, an early hydraulic breccia with evidence of clast movement and rotation and a silica-cemented microbreccia matrix, and a later crack and fill brecciation with calcite and minor quartz-cement containing anomalous gold values formed under a more passive dilational regime. High-grade gold mineralisation is associated with a later argillic alteration and pyrite mineralisation overprint (English *et al.* 2012) [10].

Deep drilling at Cacao and La India South has revealed high-grade gold-silver mineralised well-developed and strongly gold-silver mineralised banded quartz-adularia veins with chlorite-carbonate-pyrite (propylitic) alteration more characteristic of the upper epithermal zone at depths of over 100 to 200 m below surface (Figs. 8 and 9).

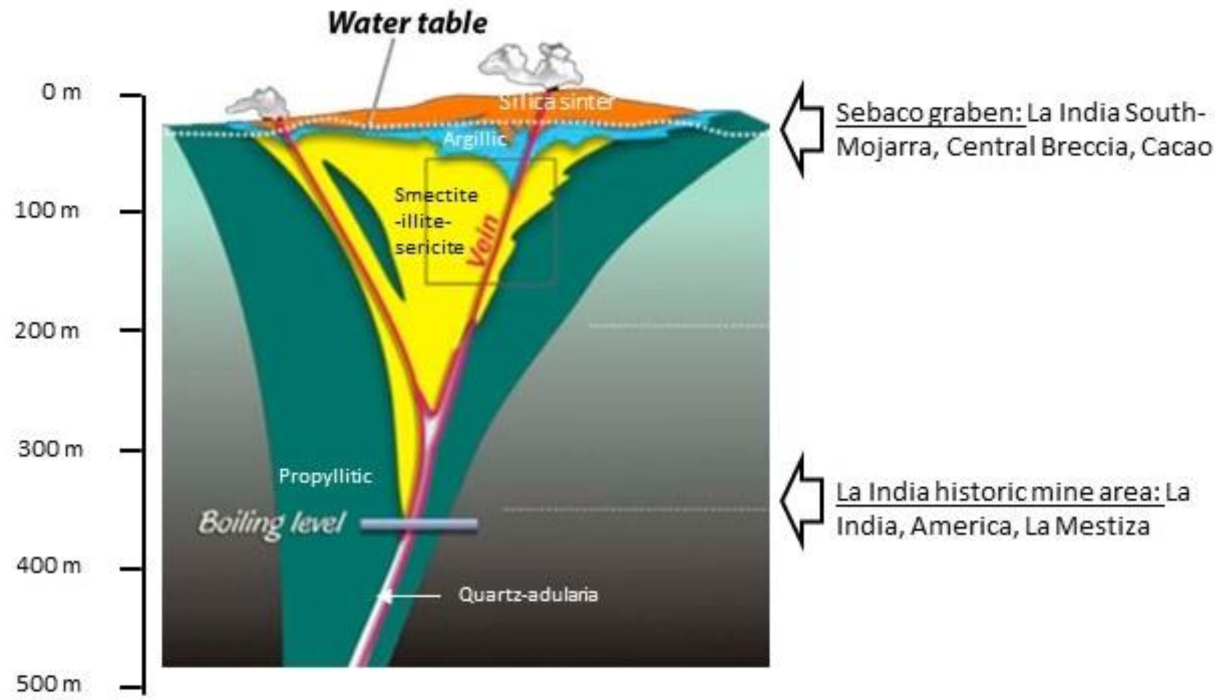

Figure 9. Schematic section through an idealised epithermal gold-silver vein showing interpreted current surface level of the mineralised veins in the un-eroded and fully preserved Sebaco graben and the erosion denuded historic La India mining area (after Corbett and Leach 1998; Hedenquist *et al.* 2000; Corbett 2012)[5,6 & 9]

2 Geological setting

2.1 Regional stratigraphic setting

The La India district is located within a Tertiary-aged volcanic arc at the margin of a major rift. The volcanic arc forms a northwest-southeast trending highland belt across the centre of Nicaragua, tectonically separated by a rift, the 30 km wide Nicaraguan Depression, from a younger, volcanically active arc to the southwest.

The Tertiary volcanic arc that hosts the gold-silver mineralisation at La India district developed as a collection of volcanic complexes including small to medium stratovolcanoes, large strato-shield volcanoes tens of kilometres in diameter, stratovolcanoes with preserved felsic plugs and a couple of minor rhyolite dome complexes (Ehrenborg 1996)[11]. Radiometric dating indicates a general younging in the age of the volcanic rocks southwest towards the rift margin, reflecting migration of the volcanic centre during roll-back of the subducting plate (Ehrenborg 1996, Rogers *et al.* 2002)[11-12]. Two stages of volcanic activity are recognised. The earliest volcanic activity formed Shield volcanos, assigned to the Matagalpa Group. Superimposed on these are younger strato-volcanic deposits designated the Coyol Group which host the gold-silver mineralisation at La India and were formed under a period of more active volcanism coincident with accelerated subduction from approximately 23 to 8 Ma (Rogers *et al.* 2002)[12].

Post-volcanic block faulting has imparted a strong structural fabric on the La India district. The original volcanic complexes can be recognised as faint circular forms in topography and geophysics and the La India district is interpreted as lying on the eastern flank of a denuded and disrupted strato-volcano centred between approximately

10 km and 25 km to the west (Fig. 10). At this location a massive quartz diorite intrusion forms a circular topographic low is interpreted as the central caldera magmatic intrusion. This quartz diorite intrusion is overlain by a thick sequence of pale coarse quartzofeldspathic tuff and subordinate breccia-tuff estimated at several hundred metres thick. The highest peaks in this area are capped by finer welded tuff.

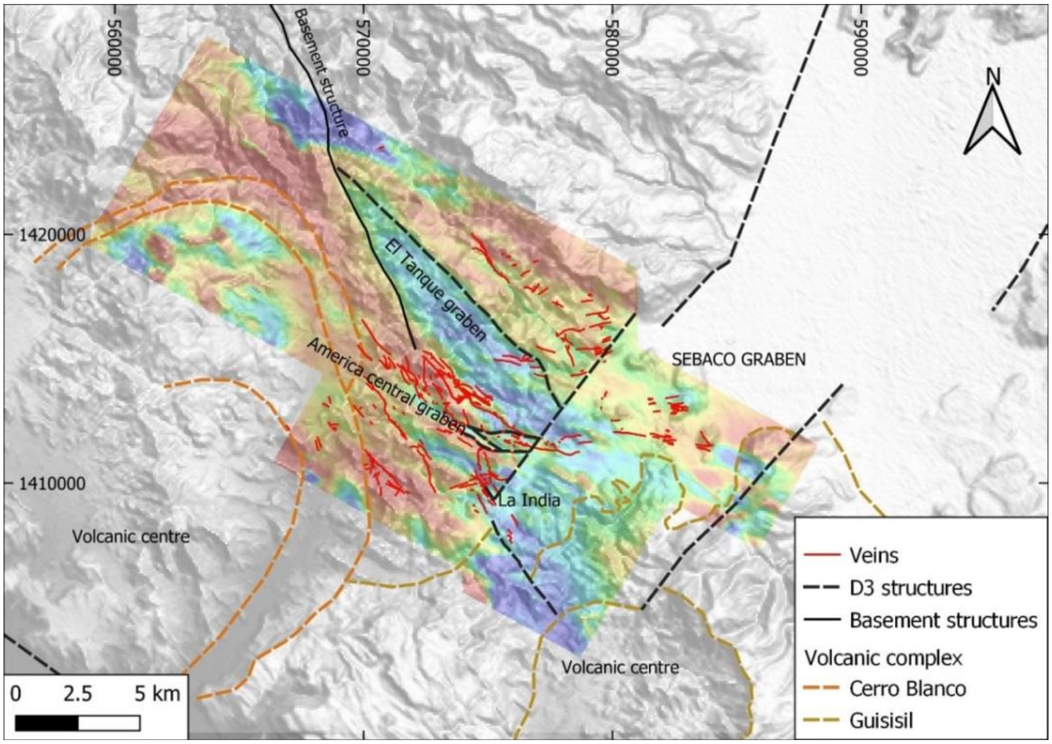

Figure 10. Map showing La India district on the eastern flank of a strato-volcano with the circular caldera and stratigraphic limits interpreted from topography, geophysics and geological mapping. Digital elevation topographic model (grey) overlain by reduced to pole, upward continued for 100 m plus direction filtered overlay with blue interpreted as downthrown graben blocks (Lubbe 2013)[13]

Stratigraphy of La India historic mine area

The geology near the historic La India Gold Mine is dominated by felsic volcanic flows or domes surrounded by thick deposits of volcanic agglomerates; flow front breccias grading distally to pyroclastic agglomerates, tuff-breccias and coarse tuffs. The felsic volcanic flows and associated pyroclastic deposits appears to have interrupted a thick sequence of glassy welded tuff deposit which locally display large pumice fiamme and extends several kilometres beyond the historic La India gold mine, at least as far as the La Mestiza deposit to the north where the welded tuff hosts significant gold-silver vein mineralisation (Fig. 3).

The welded tuff forms a resistant cap rock and it is apparent that the volcanic strata dips to the southwest in the southwestern part of the district, and to the northeast in the northeastern part of the district.

Stratigraphy of the Sebaco Graben

The thick sequence of flat-lying andesite that fills the Sebaco graben to the east of the historic La India mine area overlies felsic volcanics which are interpreted as downthrown exposures of the top of the felsic volcanic sequence as at the historic La India Gold Mine. The source of the andesite flows is uncertain as they only appear to have been preserved in downthrown fault blocks, principaly in the Sebaco graben, but also in the smaller downthrown blocks on the hangingwalls of the La India and America deposits.

The topography in this area exhibits a strong structural fabric such that the large-scale circular volcanic features that are visible elsewhere in the Central Volcanic Province cannot be seen. The structural fabric is oriented northwest parallel to the Nicaraguan Depression and is strongest in the historic La India Gold Mine area adjacent to the Highway Fault, becoming weaker further North. The structural deformation forms an open anticline structure, possibly developed as antithetic tilt blocks, along a northwest-southeast axis parallel to the Nicaraguan Depression. The axis appears to run through the historic America mine area and northwest over the quartz dacite intrusion: Northeast-dipping faults and southwest dipping strata on the southwestern limb and the southwest-dipping faults and the northeast tilted welded tuff and basaltic capped hills on the northeastern limb. Continuation of the fold or rotated blocks across the downthrown Sebaco Graben and into the southeastern concessions has not been established.

2.2 Structural setting

At La India the development of geological structures from the Tertiary onwards reflects stresses caused by the subduction of the Cocos oceanic plate beneath the Nicaraguan landmass on the western edge of the Caribbean Plate. Four fault orientations are recognised: principal subduction trench-parallel northwest-striking faults (120°-300°; i.e. America and La Mestiza veins), and north-northwest-striking linking faults (140°-320°; i.e. La India vein). These primary faults arc-into or cross-cut secondary linking east-west-striking (090°-270°; i.e. Cacao vein), and north-south-striking (180°-360°) faults. The faults and associated fault-fill gold-silver veins developed during three structural deformation phases at the La India district during this time period (Starling 2015; Fig. 7)[14]:

Deformation phase 1 (D1) was a north-northeast to north-south extensional stress regime that was active during, and probably for several million years after deposition of the volcanic rocks, from approximately 23 Ma to 8 Ma. The stress was caused by a phase of rapid subduction following rupturing of the Farallon tectonic plate and formation of the Cocos plate beneath the present-day Pacific Ocean (Rogers *et al.* 2002) [12].

Under this stress regime the principal extensional (normal) faults developed striking northeast, parallel to the subducting trench (Starling 2015; Fig. 11)[14]. In the La India historic mining area these faults impart a strong fabric on the topography and are interpreted as developing an early horst and graben geometry centred America-Central Breccia prospects with faults and veins to the southwest all dipping inwards to the northeast, and faults and veins to the north and east all dipping in the opposite direction towards the south and west. It is possible that a subordinate conjugate set of sinistral trans-tensional north-northwest and dextral east-west trans-tensional linking faults would have developed and that gold-silver mineralisation may have initiated towards the end of this phase.

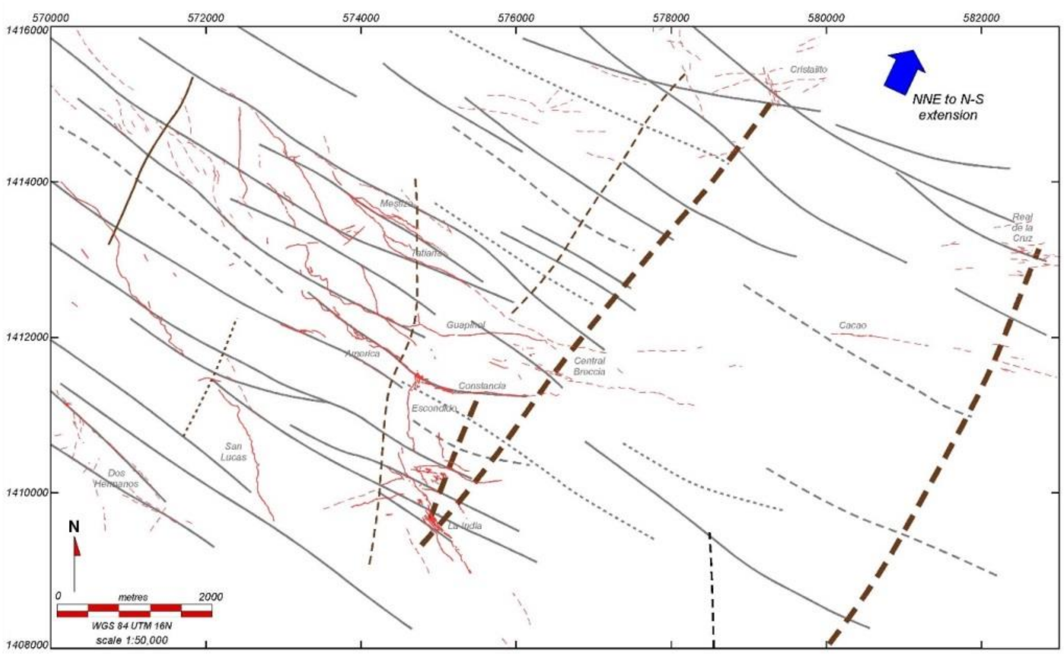

Figure 11. Schematic map showing the primary northeast-striking arc-parallel normal faults formed during the D1 Southwest-directed extension with possible early gold deposition (from Starling 2015)[14]

Deformation phase 2 (D2) occurred when the Cocos ridge collided with the volcanic arc to the southeast of La India (present day Costa Rica) approximately 8-10 Ma ago. This caused the subducting slab of oceanic plate to detach and a pause in volcanic activity. This also caused the Central American forearc slither to start moving northwest relative to the volcanic arc (Karason and van der Hilst 2000, De Mets *et al.* 2000; De Mets 2001) [15-17].
Starling (2015)[14] suggests that the extensional stress regime rotated clockwise to between east-northeast and east-west at this time. Under this regime the north to northwest faults such as the faults hosting the principal La India deposit would have developed as primary normal extensional faults. The D1 arc-parallel normal faults would have been reactivated as trans-tensional with a dextral strike-slip component. The east-west faults would have reactivated and possibly extended as strike-slip faults linking the primary arc-parallel northeast-striking faults (Starling 2015)[14]. This is interpreted as the main gold-silver mineralisation event with the greatest dilation and widest veins deposited in the extensional north-northeast-striking faults such as the La India vein (Starling 2015; Fig. 12)[14].

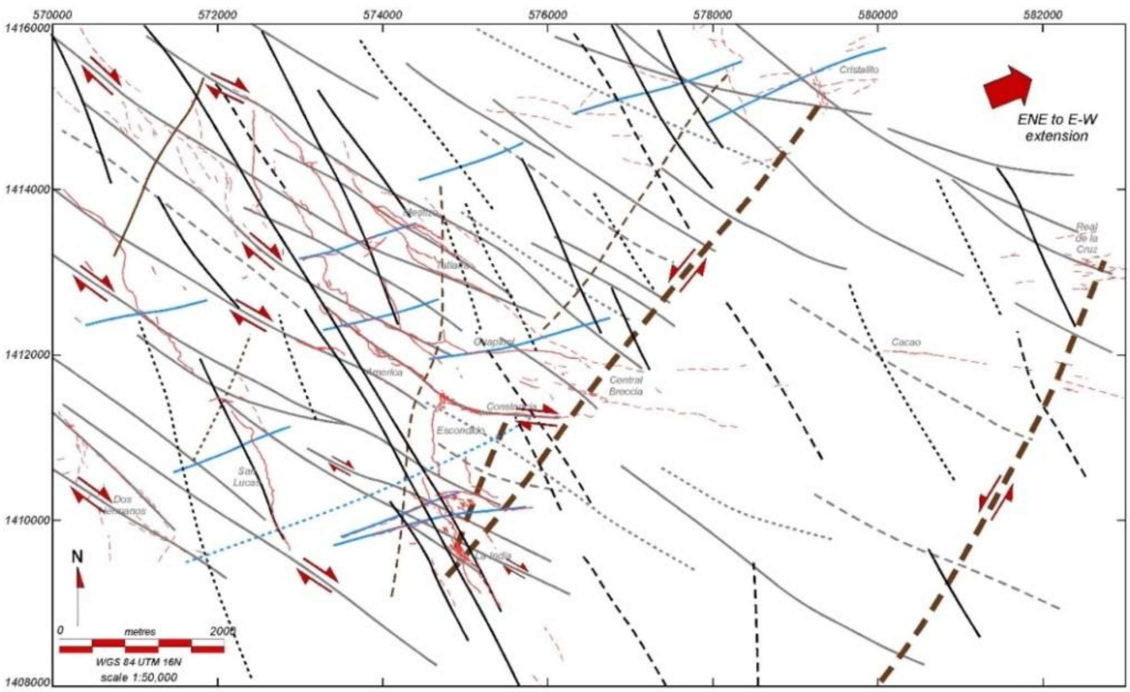

Figure 12. Schematic map showing the faults formed during the D2 West-southwest directed extension associated with the principal gold mineralisation phase (from Starling 2015)[14]

Deformation phase 3 (D3) is the current north-northeast to north-south extensional regime that started approximately 4 Ma ago, after a pause during slab detachment, with establishment of a steeper subduction slab and development of the new, currently active volcanic arc further away from the La India district (Rogers *et al.* 2002)[12]. This phase is characterised by strain partitioning into dextral strike-slip motion of the northwestward sliding fore-arc slither and normal convergence at La India district in the back-arc at the same time as a resumption of slab-rollback (Starling 2015)[14].
Later-stage block faulting (D3), much or all of which occurred post gold mineralisation, would have moved and offset significant segments of gold mineralised veins (Starling 2015)[14]. An important example of this was the downthrow of the 6-10 km wide Sebaco graben that appears to have dropped gold mineralised veins at Cacao several hundred metres below those now exposed at La India, preserving the Cacao vein from erosion (Starling 2015; Fig. 13)[14]. The resumption of the southeast-directed extension also reactivated the existing faults with some D1 arc-parallel northeast-striking faults reactivated as block faults with graben development at the central America prospect, and half graben block tilting at La India prospect and the El Tanque area (Figs. 9 and 12).

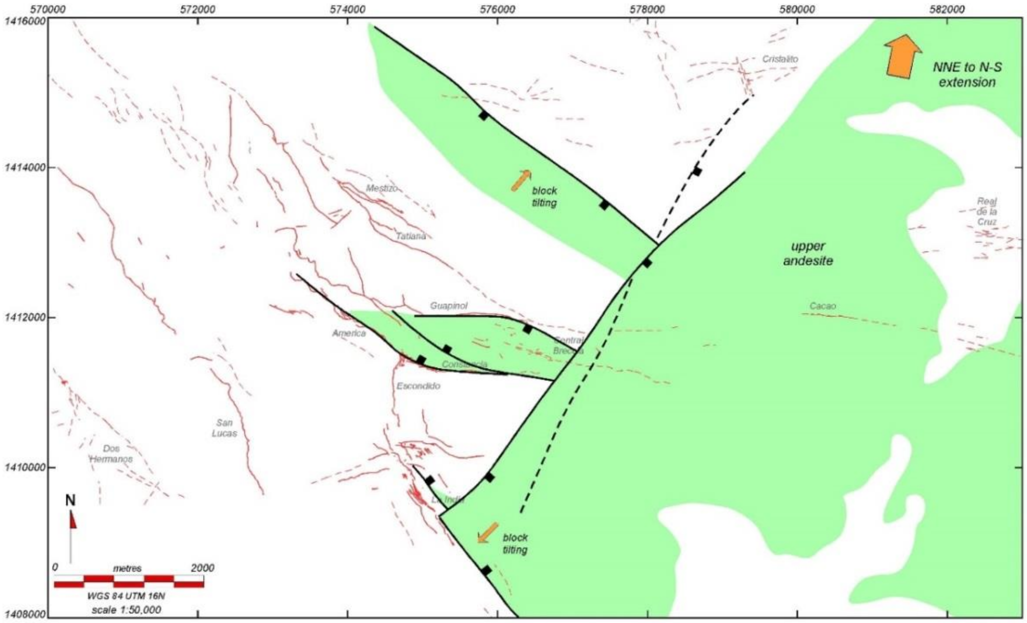

Figure 13. Schematic map showing the faults formed during the D3 block faulting under a more distal southwest-directed extension (From Starling 2015)[14]

3 Localisation of gold-silver mineralisation

Gold-silver mineralisation in the La India district is classified as rift margin-type low-sulphidation epithermal gold-silver vein mineralization (Corbett and Leach 1998)[9]. The gold-silver mineralisation occurs in veins filling open spaces formed by faults and fractures. Economic concentrations of gold-silver mineralisation occur where the largest open spaces formed at epithermal depths on structures that were connected to deep crustal conduits that transported the mineral-rich hydrothermal fluids from their magmatic source.

3.1 Localisation of gold-silver mineralisation at district-scale

The geometry of the upper crustal faults that host the gold mineralisation in the La India district is attributed to the southwest-directed extensional tectonic regime, a setting consistent with the arc-parallel low sulphidation fault-fill and extensional vein systems in an extensional arc setting formed during slab rollback described by Rhys *et al.* 2020[18].

A mineral systems analysis undertaken by Galvan (2014)[19] considered the deep crustal conduits required to transport the gold-silver rich hydrothermal fluids from their magmatic source to the upper crustal epithermal vein deposits at La India district. Galvan identified a regional northwest-southeast trending structural trend, clearly discernible in aeromagnetic, radiometric and topographic data that connect the principal gold-silver mineralised faults in the La India historic mining district (Lubbe 2013; Galvan & Pullinger 2013. Fig. 14)[13 & 20]. These regional structures are interpreted as deep crustal structures that form the feeder conduit for the hydrothermal magmatic fluids. The principal feeder, or backbone structure connects the principal gold deposits of La India, America, and La Mestiza. A possible secondary parallel backbone structure running through the less well explored explored San Lucas and Dos Hermanos structures are also postulated. These deep structures may be transform faults formed perpendicular to the subduction zone, or older reactivated basement structures, perhaps formed along the suture between the basement Chortis and Siuna blocks before the volcanic arc (Venable 1994)[21]. Pratt (2019)[22] suggested that the gold-silver mineralisation is concentrated by dilational jogs on this re-activated basement structure. Pratt (2019)[22] also extended the idea to the north and east, suggesting that the Andrea vein is associated with a similar basement structure and that the two structures are connected by the East-West trending Cacao Structure, implying that the Cacao structure may also be deep-seated.

The northeast-striking Highway Fault that appears to focus the Central Breccia phreatic breccia is interpreted here as having been active throughout D2 and D3 deformation phases. The Highway fault may also be a deep crustal structure that could also have connected hydrothermal fluids across the district. This would be consistent with observations by Wilson and Rowland (2016)[23] who noted that transfer faults and arc-oblique basement faults can also locally influence the position and orientation of epithermal systems.

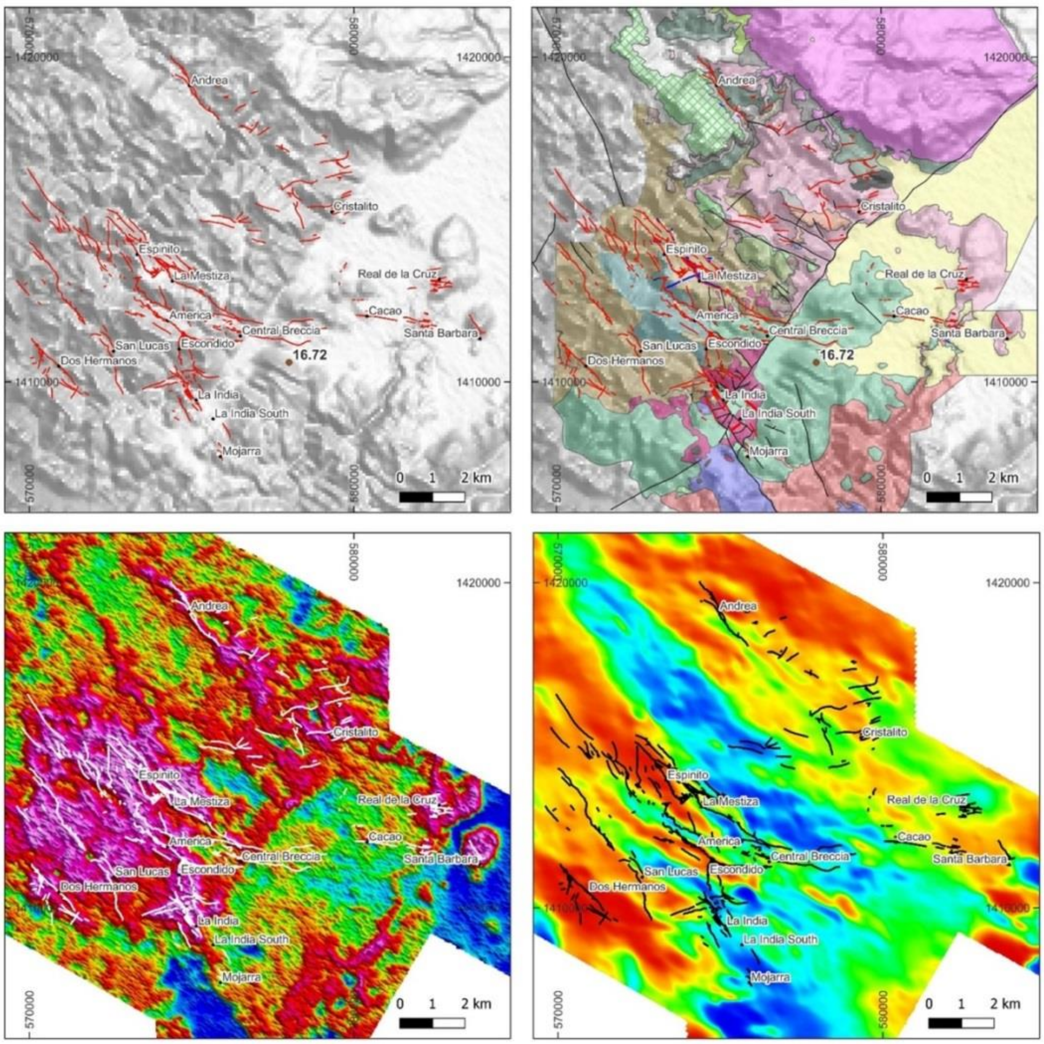

Figure 14. Top: Topography and surface geology of the La India district; Bottom left: Radiometric K showing areas of potassium alteration (red-magenta) and gold-silver veins (white) and interpreted north-northwest through-going structures interpreted as the deep-crustal feeder or 'backbone' conduits for the gold-silver-bearing hydrothermal fluids; Bottom right: reduced to pole magnetics at 100m depth shows the D3 block faulting with downthrown blocks coloured blue

3.2 Localisation of gold-silver mineralisation at deposit-scale

At deposit-scale, gold-silver mineralised ore shoots have developed where there is vein bifurcation, and at the steep upper section of listric faults and fault jogs. The most economic deposit discovered to date, the La India deposit is contained within a fault stack developed where a major normal fault was refracted and bifurcated around and across the edge of a competent rhyodacite and overlying welded tuff forming a steeply-dipping stack of mineralised veins.

The rheology of the host rock influences the form and geometry of the throughgoing faults and therefore the geometry and extent of dilation and vein infill. The host rocks are a layered felsic volcanic stratigraphy in the historic La India mining area, and overlying andesite in the Sebaco Graben. In the La India historic mining area the best developed veins are in the more competent rocks which support brittle fractures: the rhyodacite flows and a fine vitric unit interpreted as a welded tuff. Rhyodacite flow-front autobreccias and more distal polymict volcanic agglomerates and tuffs are poor hosts as they appear to have responded to faulting by absorbing the stresses within the less competent matrix rather than forming open space fractures. The best gold deposits defined to date are hosted by felsic volcanics and welded tuff at La India, and by welded tuff at La Mestiza (Fig. 3). In the Sebaco Graben most of the exploration data is limited to the overlying thick andesite sequence which appears to be a good host rock, concentrating veins into a wide discrete vein and vein sets at the principal Cacao and La India South prospects.

4 Post-mineralisation displacement of gold-silver mineralisation

The development of the Sebaco Graben, orthogonal to the volcanic arc during D3 block faulting phase which initiated after slab detachment at approximately 8 Ma cut the La india district in two. Although there is clear evidence that the Sebaco Graben was downthrown relative to the historic La India mine district post-mineralisation gold mineralisation may have persisted into the D3 block faulting phase after slab detachment at approximately 8 Ma. The Central Breccia's location at a jog on the graben-bounding Highway Fault could be interpreted as late-stage mineralisation that exploiting a D3 structure.

The upthrown block was eroded to expose the low sulphidation epithermal mineralisation at the La India historic mine area which contains a current gold endowment of over 2 Moz. The downthrown Sebaco graben has escaped significant erosion and the epithermal mineralisation is preserved at depth and discoveries of hidden deep-seated exploration are still being made.

5 Timing of gold-silver mineralisation

Brecciated and milled gold-silver veins indicates that mineralisation occurred in active faults, and the structural interpretation places these faults, and consequently the main phase of gold-silver vein emplacement as occurring shortly before or at 8-10 Ma. This was at a period of waning or extinct volcanism which could suggest that gold-silver veins precipitated from heavy metal-rich hydrothermal fluids derived from mature, highly evolved and depleted magma chambers. It also coincided with the onset of mantle upwelling and flood basalt volcanism associated with slab detachment (Rogers *et al.* 2002)[12]. It has been postulated by Sidorov *et al.* (2015)[24] that epithermal mineralisation is driven by such 'microplumes' at the end of arc volcanism in advance of the onset of basaltic volcanism.

The timing of gold-silver mineralisation of the Central Breccia phreatic breccia pipe is less clear. The location on the graben-bounding Highway fault, at an apparent jog in the fault, suggests that the Central Breccia was emplaced along the Highway Fault. This could mean that the Highway fault is a long-lived structure, and was active as far back as the D2 slab detachment phase. An alternative, and less likely explanation is that mineralisation was still occurring at the Central Breccia as recently as the D3 block faulting and graben formation phase from only 4 Ma.

6 Conclusions

Gold-silver mineralization at La India is observed on a district scale on the eastern flank of a 23 to 8 Ma volcanic complex between approximately 10 km and 25 km from the interpreted volcanic centre.

The La India district setting and geometry of mineralisation is an example of an arc-parallel low sulphidation epithermal gold-silver fault-fill and extensional vein systems formed in an extensional arc setting during slab rollback regime as described by Rhys *et al.* 2020[18].

The gold-silver mineralisation is localised along and connected to a few regional through-going structures that are interpreted as forming the deep-seated conduits for the mineral-rich magmatic source fluids. The main deep crustal conduits are north-northwest-striking with a possible east-west striking linking structure providing additional hydrothermal connectivity.

The rheology of the host rock influences the size and grade of gold-silver mineralisation. The epithermal zone at the time of mineralisation occurred a layered felsic volcanic stratigraphy and overlying andesite. The best hosts are competent rocks: rhyodacite flows and a fine vitric unit interpreted as a welded tuff. Rhyodacite flow-front autobreccias and more distal polymict volcanic agglomerates and tuffs are poor hosts as they appear to have

responded to faulting by absorbing the stresses within the less competent matrix rather than forming open space fractures.
Post-mineralisation graben development has split the La India district gold-silver mineralisation between the upthrown historic mining area where erosion has exposed the upper levels of the low-sulphidation epithermal veins, and the downthrown graben where the epithermal mineralisation preserved hidden at depth and is still being discovered.
The gold-silver mineralisation is interpreted as occurring towards the end or immediately after a period of arc-volcanism. Radiometric dating of host rock places the gold-silver mineralisation after 16.72 Ma. It is suggested that gold-silver mineralisation occurred well after this date in the waning stage of arc volcanism during slab rollback and/or at the initiation of a period of slab detachment and mantle upwelling at 8-10 Ma.

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Author contributions L.T.P.E. contributed to the data collection, compilation and interpretation and wrote the paper. V.H.G. and C.R.P. contributed to the data collection and interpretations.

Data availability statement Data sets generated during the current study and internal company reports referenced in this paper are available from the corresponding author on reasonable request, but restrictions apply to any data used in these studies which was collected for exploration, mineral resource evaluation and mine feasibility studies under license, and so are not publicly available. Data referring to mineral resource estimates are available on the Ontario Securities Commission SEDAR+ web-based system and on Condor Gold PLC's website www.condorgold.com.

Declarations The authors declare no competing financial interests.

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