



Fault-related carbonate breccia dykes in the La Chilca area, Eastern Precordillera, San Juan, Argentina



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ABSTRACT

Carbonate fault breccia dykes in the Cerro La Chilca area, Eastern Precordillera, west-central Argentina, provide clues on the probable mechanism of both fault movement and dyke injection.

Breccia dykes intrude Upper Carboniferous sedimentary rocks and Triassic La Flecha Trachyte Formation. The timing of breccia dyke emplacement is constrained by cross cutting relationships with the uppermost Triassic unit and conformable contacts with the Early Miocene sedimentary rocks. This study supports a tectonic-hydrothermal origin for these breccia dykes; fragmentation and subsequent hydraulic injection of fluidized breccia are the more important processes in the breccia dyke development.

Brecciation can be triggered by seismic activity which acts as a catalyst. The escape of fluidized material can be attributed to hydrostatic pressure and the direction of movement of the material establishes the direction of least pressure.

Previous studies have shown that cross-strike structures have had an important role in the evolution of this Andean segment since at least Triassic times. These structures represent pre-existing crustal fabrics that could have controlled the emplacement of the dykes. The dykes, which are composed mostly of carbonate fault breccia, were injected upward along WNW fractures.

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1. Introduction

Cross-strike structures are steeply dipping structural discontinuities represented by wide areas of brittle–ductile deformation (Wheeler, 1980; Cook and Thomas, 2009), sometimes representing reactivation of pre-existing structures inherited from earlier tectonic phases.

The Nazca plate is being subducted at a rate of 6.3 cm/year beneath the South American plate to depths of up to 100 km (Barazangi and Isacks, 1976; Pilger, 1981; Kendrick et al., 2003) between 27° and 33° south latitude with a convergence azimuth of around 78° (Vigny et al., 2009) (Fig. 1a). The flat geometry of the subducted slab is attributed to the oblique subduction of the Juan Fernández ridge beneath the South American plate (Pilger, 1981;

Anderson et al., 2007; Rosenbaum and Mo, 2011). From the Upper Miocene, tectonics have resulted in the development of the Principal and Frontal Andean Cordilleras, Precordillera and the Sierras Pampeanas in the eastward foreland region of this part of South America (Ramos, 1988) (Fig. 1a).

Although there are only a few references about cross-strike structures in the Pampean flat-slab segment, they are mentioned in the studies by Baldi and Vaca (1985), Ré et al. (2001), Ré and Japas (2004), Japas et al. (2008), Oriolo et al. (2013) and Perucca and Ruiz (2014). These authors recognized two systems of conjugate brittle–ductile megashear zones in the Precordillera: NNW and NNE transpressional structures, and WNW and ENE transtensional ones. WNW structures represent the main structural control in the emplacement of Triassic magmatism in the area (Castro de Machuca et al., 2013).

Next to the transition zone between Eastern and Central Precordillera (Fig. 1b), WNW trending tectonically controlled breccia dykes contrast sharply with nearby stratified sedimentary and volcanic rocks and are distinctive features of the Cerro La Chilca area. They were not described by early workers in the region; thus,

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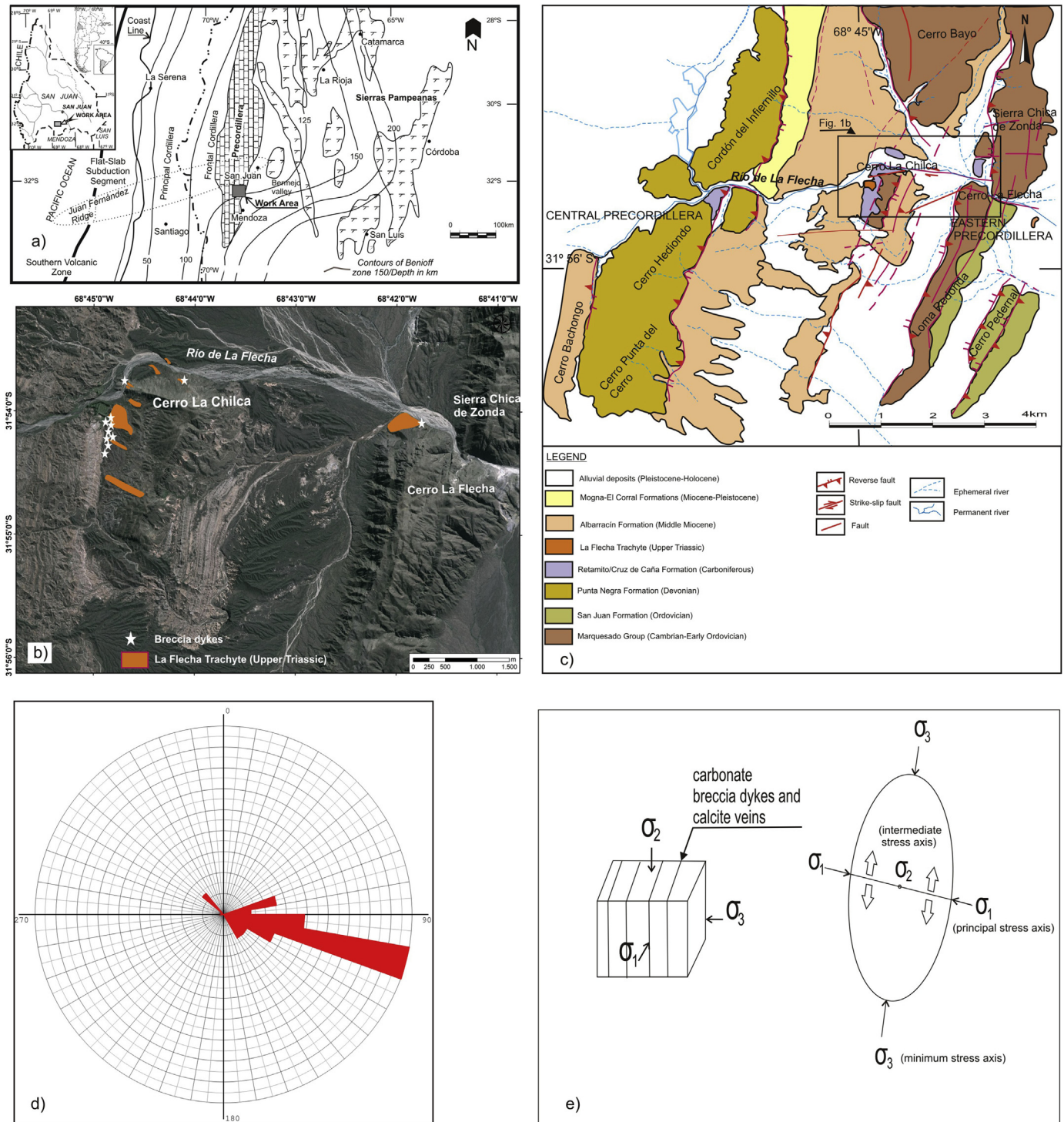


Fig. 1. a) General location map of San Juan province showing the Pampean flat-slab segment between 28° and 32° S latitude, the contours show depth to the oceanic slab (modified from Ramos et al., 2002); b) satellite image of the study area highlighting outcrops of uppermost Triassic trachytes and breccia dykes; c) geologic map of the study area; d) rose diagram of breccia dykes showing the WNW mean mode and the two subordinated NNW and ENE modes (N = 18); e) schematic cartoon of vertical carbonate breccia dykes and calcite veins emplacement. Orientation of stress field based on dynamic stress analysis of field data and projected strain ellipsoid.

these bodies have not been previously studied. This is the first study that systematically describes breccia dykes in the Argentine Pre-cordillera Province.

Relationships between the breccia dykes and the surrounding host rocks set constraints upon the timing of their emplacement and may hold strong clues as to their formation and significance to

the tectonic history of the area. Breccia clasts are composed of fragments of the adjacent limestone, sedimentary siliciclastic and volcanic rock formations.

This paper describes the geologic setting, structural and petrographic characteristics, and evolution of these breccia dykes which we believe to have experienced widespread fluidization.

2. Geologic setting

2.1. Stratigraphy

The study area is located in the south-central region of the province of San Juan, west-central Argentina, about 50 km south-west of the city of San Juan (Fig. 1a). It belongs to the Eastern Precordillera tectonic system characterized by a thick Cambrian to Lower Ordovician carbonate platform succession that includes the Cerro Bayo, Loma Redonda, Cerro Pedernal and Cerro La Chilca (Fig. 1c). The total thickness of the calcareous succession outcropping in the area reaches, as a minimum, 1500 m (Harrington, 1971). It consists, according to Peralta et al. (2000), from the base upwards, the La Laja Formation (Lower to Middle Cambrian) which includes mudstones, oncolitic and oolitic fossiliferous wackestones, intraclastic and oncolitic packstones, marls and calcareous siltstones; the Zonda Formation (Middle Cambrian) mainly dolomites; the La Flecha Formation (Middle–Upper Cambrian) characterized by abundant stromatolites and trombolites; the La Silla Formation (Upper Cambrian?–lowermost Ordovician) composed of limemudstones and wackestones; and the San Juan Formation (Arenigian to Early Llanvirnian) composed of fossiliferous limestones. The first two formations are grouped in the Marquesado Group (Bordonaro, 1980). In all exposures noted the boundaries between them are conformable. At the top of the succession, the San Juan Formation shows an erosional denudation surface. These carbonate formations are also widely distributed in the Central Precordillera.

The Punta Negra Formation (Middle to Upper Devonian) has been identified to the west of the studied area as being a thickening and coarsening-upward succession of sandstones interbedded with mudstones.

Carboniferous outcrops showing development of continental, glacial-marine and marine facies also occur on the western flank of the Cerro Pedernal. These sedimentary rocks belong to the Retamito Formation (basal conglomerate mainly composed of well-rounded metamorphic and granitic clasts from the Proterozoic–Lower Palaeozoic crystalline basement), and to the Cruz de Caña Formation (siliciclastic sandstones and siltstones) according to Achem (1994 and references therein). The total thickness of the Carboniferous rocks varies between 150 m and 240 m (Achem, 1994).

Sills and lava flows of alkaline volcanic rock (La Flecha Trachyte) up to 40 m thick intrude through and/or erupt over the Cambrian–Lower Ordovician and Carboniferous sedimentary successions. The trachyte has been dated as uppermost Triassic by Castro de Machuca et al. (2013).

The Neogene continental alluvial Albarraicín, Mogna and Corral Formations are typical synorogenic deposits that lie in angular unconformity over the older formations.

2.2. Structure

The study area lies on the boundary between the Precordillera and the Western Sierras Pampeanas geologic provinces, within the active deformation belt of the south-central Andes (Fig. 1a–c). The active front of the Argentine Andes between 31° and 33° is formed by a thrust system affecting different crustal levels and showing opposed vergences. The Central Precordillera thrust system has east-vergence whereas the Eastern Precordillera and Sierras Pampeanas systems have west-vergence (Vergés et al., 2007). The Central Precordillera is formed by mountain ranges running from latitudes 29°–32° S. It has been described by several authors (Jordan et al., 1983; Allmendinger et al., 1990; Von Gosen, 1992; Jordan et al., 1993; Cristallini and Ramos, 2000) as a typical thin skinned fold-and-thrust belt due to Neogene crustal shortening on

west dipping, imbricated structures. The ranges forming the Eastern Precordillera trend N–S and are formed by structures that are mostly large asymmetric anticlines whose axes are sub-parallel to the mountain chains. Their axial planes are steeply inclined to the east, and most of their western flanks are vertical, overturned or have been eliminated by high angle reverse faults sub-parallel to the structural axes.

Throughout the Upper Permian to Lower Triassic, the south-western segment of South America between 31° and 36° S, was characterized by transtensional conditions (Kleiman and Japas, 2009) culminating during the Triassic with a generalized extension. In the study area, the La Flecha Trachyte and older rocks were locally affected by normal and oblique-slip normal faults with WNW to NW trends, structures that were not inverted by the Cenozoic tectonics. This situation is analogous to that described by Cortés et al. (2006) to the south of the study area, providing evidence on the existence of blocks that exhibit less disturbance by the Andean deformation than other areas of the Precordillera. Moreover, Japas et al. (2005) determined that the deposition of Triassic volcanic rocks in the southern part of the province of Mendoza was controlled by NW tensional, WNW (dextral) and NNW (sinistral) transtensional faults, which also continued deforming the Triassic record.

Based on stratigraphic displacement of the Upper Palaeozoic deposits, a dextral offset of about 300 m produced by the Río de La Flecha fault was measured by Baraldo and Cardinali (2014). This fault controlled the emplacement of the vertical breccia dykes and calcite veins that intrude the Palaeozoic units. Both calcite veins and dykes are truncated by unconformities at the base of the Neogene deposits, constraining a minimum Mesozoic – Paleogene age interval for the occurrence of extensional tectonics.

Perucca and Ruiz (2014) described evidence of oblique faulting such as W–E–trending calcite veins with horizontal striae and dextral offsets in the northern section of Cerro La Flecha, and faults with trends from 100° to 130° affecting Neogene rocks in the Cerro La Chilca area. Moreover, in this area, WNW-trending fault breccias were found in the trachyte in contact with the Ordovician limestones, indicating post-Triassic tectonic activity (Fig. 1d). Further evidences of cross-strike faulting were identified to the north of the study area on the eastern piedmont of Sierra Chica de Zonda (Perucca and Ruiz, 2014). On the other hand, Fazzito et al. (2009) mentioned that between 31° 30' and 33° 30' south latitude the Precordillera has evolved under the influence of structural anisotropies as oblique mega-shear zones with NW-trending and paleogeographic features of Palaeozoic and Triassic age (Cortés et al., 2005, 2006).

3. Breccia dykes features

3.1. Outcrop description

The breccia dykes occur as discrete tabular bodies crosscutting and/or interbedded with unbrecciated sedimentary and igneous rocks of Carboniferous to Upper Triassic age (Retamito Formation, Cruz de Caña Formation and La Flecha Trachyte, respectively). The dykes are more frequently seen in the sedimentary rocks than in the trachyte because they are resistant to erosion and the greater colour contrast between dykes and fine-grained deep purple- and buff-weathering sandstones and siltstones. Contacts are straight and sharp (Fig. 2a–b). Most bodies are steeply dipping (near vertical to vertical) and range in thickness from a few centimetres to 60 cm; and from 1 m to 4 m in length. Length is usually many times width. Commonly, they have a fairly uniform thickness over short distances but some bifurcate and abruptly pinch out or reconnect along strike (Fig. 2c–d). The breccia dykes trend almost entirely to



Fig. 2. Photographs of breccia dykes in thin-bedded Upper Carboniferous siltstones: a–b) being more resistant to erosion, the carbonate cemented dyke stands out in bold relief from the softer and steeply dipping host rock; c) irregular shape of a polymictic cement-supported breccia dyke in thin-bedded siltstone. The dyke pinches and swells as it follows and cuts across bedding, reaching up to 30 cm in thickness; d) close-up of the breccia dyke showing rounded predominately granitoid clasts from the Retamito Formation conglomerate in calcite cement. The pen is 14.5 cm long.

the WNW along fractures (Fig. 1d) and do not show abrupt changes in trend through the host rocks. Such strong parallelism suggests that they were intruded following tensional structures under specific stress conditions with σ_2 much greater than σ_3 (Jolly et al., 1998), indicative of significant tectonic control at the time of dyke intrusion. In homogeneous rocks, vertical dykes are possible if σ_1 or σ_2 are vertical; whilst sheets suggest that σ_3 is vertical (Suppe, 1985; Sibson, 1998) (Fig. 1e). Compressional reactivation of inherited steeply-dipping faults would also be linked to flat-lying tensional structures (Sibson, 1998, 2004).

Breccia dykes in general have a chaotic appearance and show a restricted range of clast sizes and clast composition that include adjacent rock types. Most of the dykes consist almost entirely of limestone clasts (> 80%) in carbonate cement (Fig. 3a–h), some of them contain scattered fragments of metamorphic, sedimentary and/or felsic volcanic rocks originating from the surrounding host rocks (Fig. 2c–d). Clasts are distributed randomly throughout the breccia dykes but, in a few places, an NW alignment of elongate clasts parallel to the wall rock in the direction of flow can be observed on sub-horizontal (planview) surfaces. The flow pattern is identifiable only by the presence of clasts.

3.2. Petrography

Thirty two thin-section samples of breccia dykes were studied. Based on petrographic and textural criteria and according to the classification for breccias in cave-collapse systems (Loucks, 1999), the analysed breccia dykes have been subdivided into two main groups with transitions between them.

The first group is the most common and consists mostly of monomictic carbonate breccias, both clast-supported (dominant) and cement-supported (Fig. 3a–h, Fig. 4a–j). The second group includes unsorted polymictic carbonate breccias either clast- or cement-supported (Fig. 5a–f, Fig. 6a–j).

In both groups clastic matrix is not obvious and, when present, it consists of finer-grained rock clasts derived from comminution of larger clasts. Commonly the clastic matrix is absent and the clasts are cemented by chemically precipitated calcite. The chemically precipitated calcite is critical in highlighting the role hydrothermal fluids played in the overall brecciation event, and their role in the transportation of the clasts through fluid flow and cementation through chemical precipitation.

The monomictic breccias are grey to milky-white in colour and consist of limestone, dolomite and calcite fragments (≥ 95 percent of total clasts). Small quantities of basement quartzites, quartz veins, quartz-mica schists, phyllites, granitoid rocks, sandstones and siltstones may also occur (Fig. 4b, g–h). The clasts are cemented by micritic or microsparitic calcium carbonate to form a resistant rock that breaks with conchoidal fracture. Within this group, the clast-supported breccia type has a matrix-cement/clast ratio of about 20:80 (Fig. 4a–b). The clasts are randomly oriented and vary from a few millimetres up to 3.5 cm in size, but typically are between 1 and 1.5 cm. Clasts are mostly low-sphericity and, at any scale of observation, are angular to sub-angular in shape; however, sub-rounded clasts mainly from crystalline basement rocks, are sometimes present. In the matrix/cement-supported breccia type (Fig. 4c–j) the ratio matrix-cement/clast is about 70:30. The clast size and composition are similar to those of the

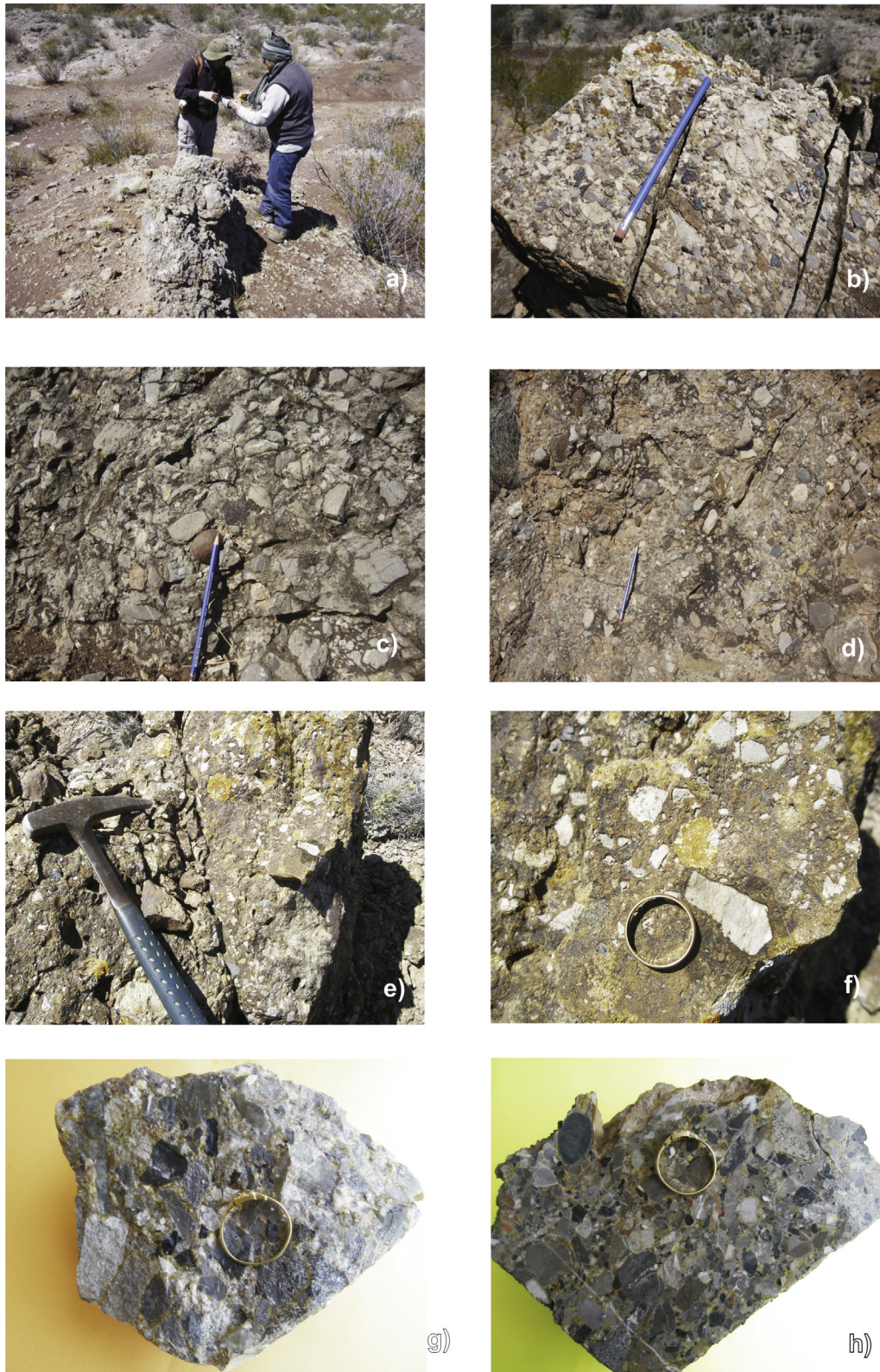


Fig. 3. Photographs of monomictic carbonate breccia dykes: a) clast-supported breccia dyke within Carboniferous sedimentary rocks; b) clasts showing a shape-preferred orientation; c) angular to subangular grey limestone clasts are by far more common, but a rounded clast of granitoid rock is also noted; d) cement-supported breccia dyke within sedimentary siliciclastic rock; e) dyke crosscutting the La Flecha Trachyte; f) close-up of (e) showing angular clasts of whitish limestone cemented by calcite; g) hand sample of monomictic clast-rich carbonate breccia with dark to whitish-grey fragments consisting of various kinds of limestone cemented by calcite; h) subangular to sub-rounded clasts are > 90% limestone rock type. The pencil is 16 cm long and the ring is 1.8 cm in diameter.

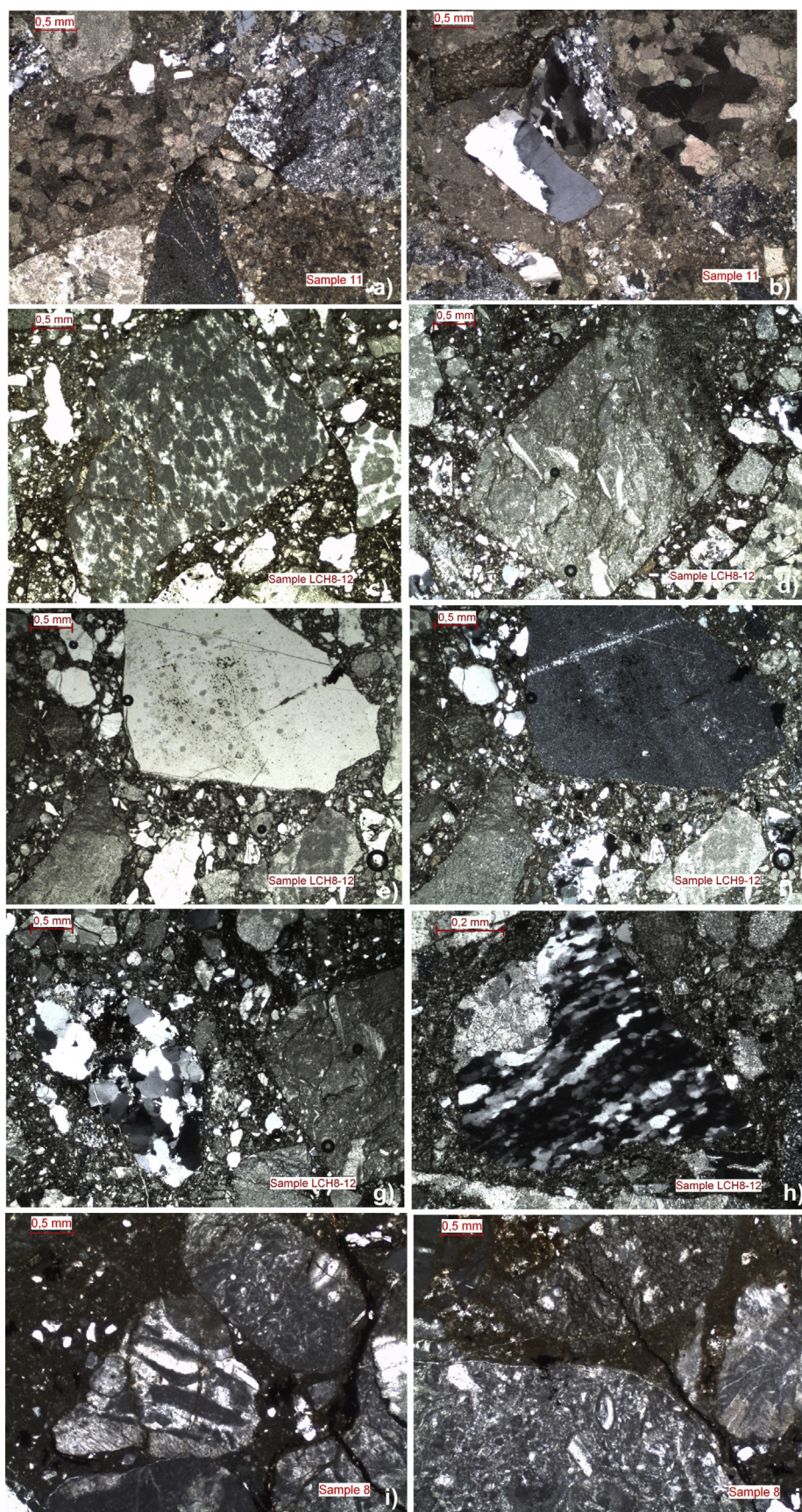


Fig. 4. Photomicrographs of monomictic clast-supported carbonate breccias: a) chaotically oriented limestone fragments; b) a fragment of quartz vein is also noted; c–f) photomicrographs of monomict matrix/cement-supported carbonate breccia. Angular to subangular limestone clasts in a matrix consisting of fine grained rock material cemented by calcite. In c) the largest clast is broken and filled by cement along the microfractures; g) clast of quartz vein; h) clast of metamorphic quartzite; i–j) fossiliferous limestone clasts, some of which are rounded, cut by Fe-oxides veinlets. Photomicrographs c–d–e) taken under plane polarized light, the remainder with crossed polarized light.

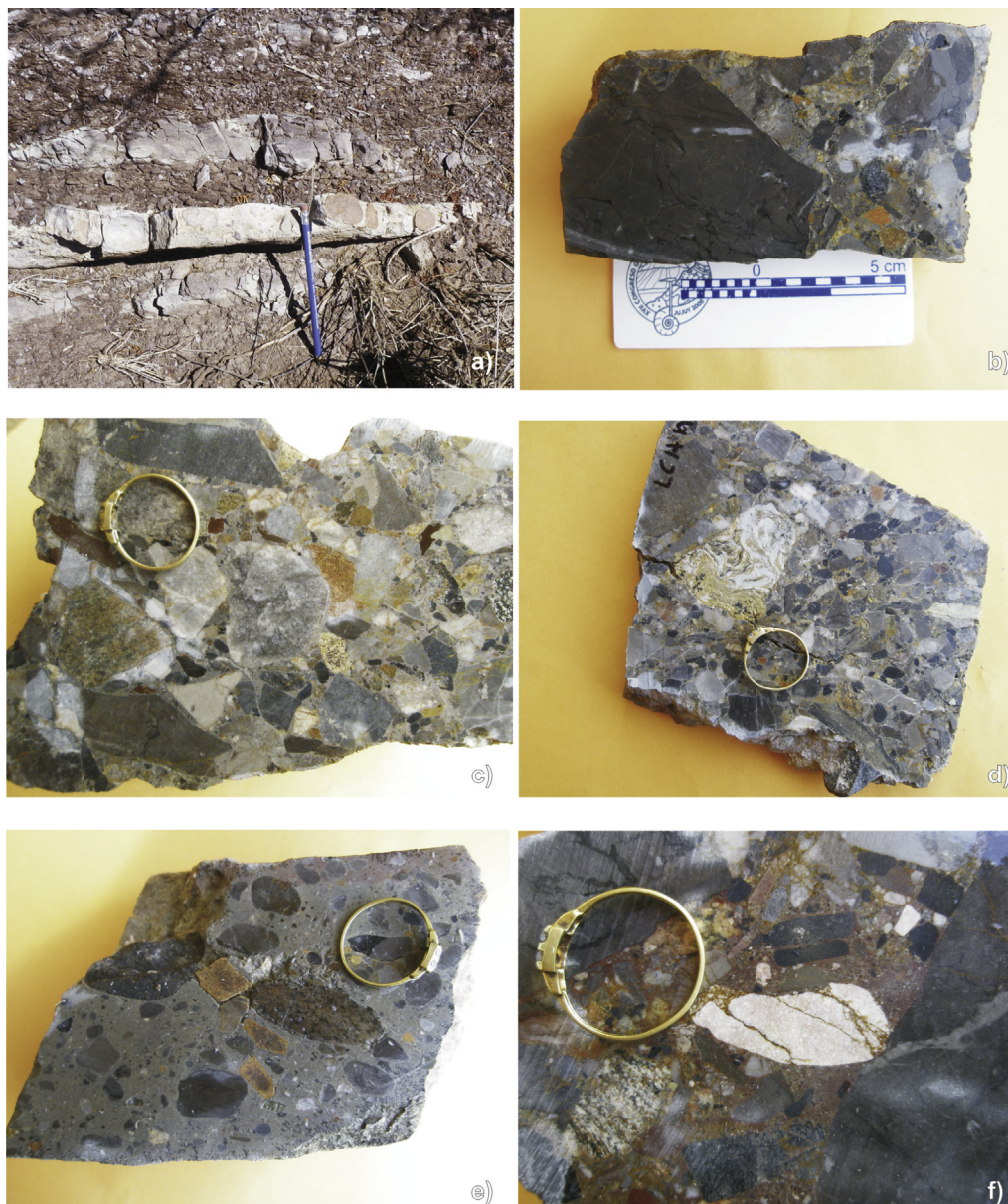


Fig. 5. Polymictic carbonate breccias: a) breccia dyke interbedded within Carboniferous siltstone, rounded pink clasts are granitic rocks; b) hand sample of polymictic carbonate breccia, the largest clast is grey micritic limestone up to 10 cm in length, the smaller orange clasts are of trachyte; c–d) polymictic clast-supported breccia with clasts of different composition in contact with each other. The clasts are typically irregular in shape and vary from angular to subrounded to slightly rounded; e) polymictic cement-supported breccia type. Elongated sub-rounded clasts of different composition (limestones, granite, trachyte) are separated by abundant calcite cement and are rarely seen in contact with each other; f) internally brecciated clast with microfractures filled by carbonate cement stained by Fe-oxides. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

clast-supported type, although some clasts are typically sub-rounded to rounded, mainly ellipsoidal in shape (Fig. 3g–h, Fig. 4i–j), and are rarely oriented.

In contrast to the abundance of monomictic carbonate breccias, unsorted polymictic breccias are uncommon. They are texturally and compositionally more heterogeneous and contain low-sphericity angular to sub-rounded clasts of variable sizes, between a few millimetres to 10 cm (Fig. 5a–f). Most of the clasts are of carbonate rocks with variable amounts (up to 20 percent) of fragments of granitic, metamorphic and sedimentary siliciclastic rocks (Fig. 6a–d). In addition, some contain scattered angular fragments of volcanic rock (trachyte) (Fig. 6e–g). The interfragment spaces are filled by chemically precipitated calcite, and hence

cemented. Sometimes, clasts are slightly oriented (Figs. 5e and 6h). According to Loucks (1999) they can be classified as cement-rich either clast- or cement-supported chaotic breccia.

Clast lithology within both groups is derived from local host rocks, predominantly from the Palaeozoic sedimentary rocks (Lower Palaeozoic limestones and Upper Palaeozoic conglomerate, sandstones and siltstones). They appear relatively fresh and have not been overgrown by any late alteration or replacement products. The limestone clasts observed in these breccia dykes are typical of the limestone facies that occur in the Cambrian to Lower Ordovician carbonate succession; these include wackestones, grainstones, mudstones and neomorphic crystalline limestones, amongst others. Dolomite clasts are scarce. Meanwhile, the rounded granitic

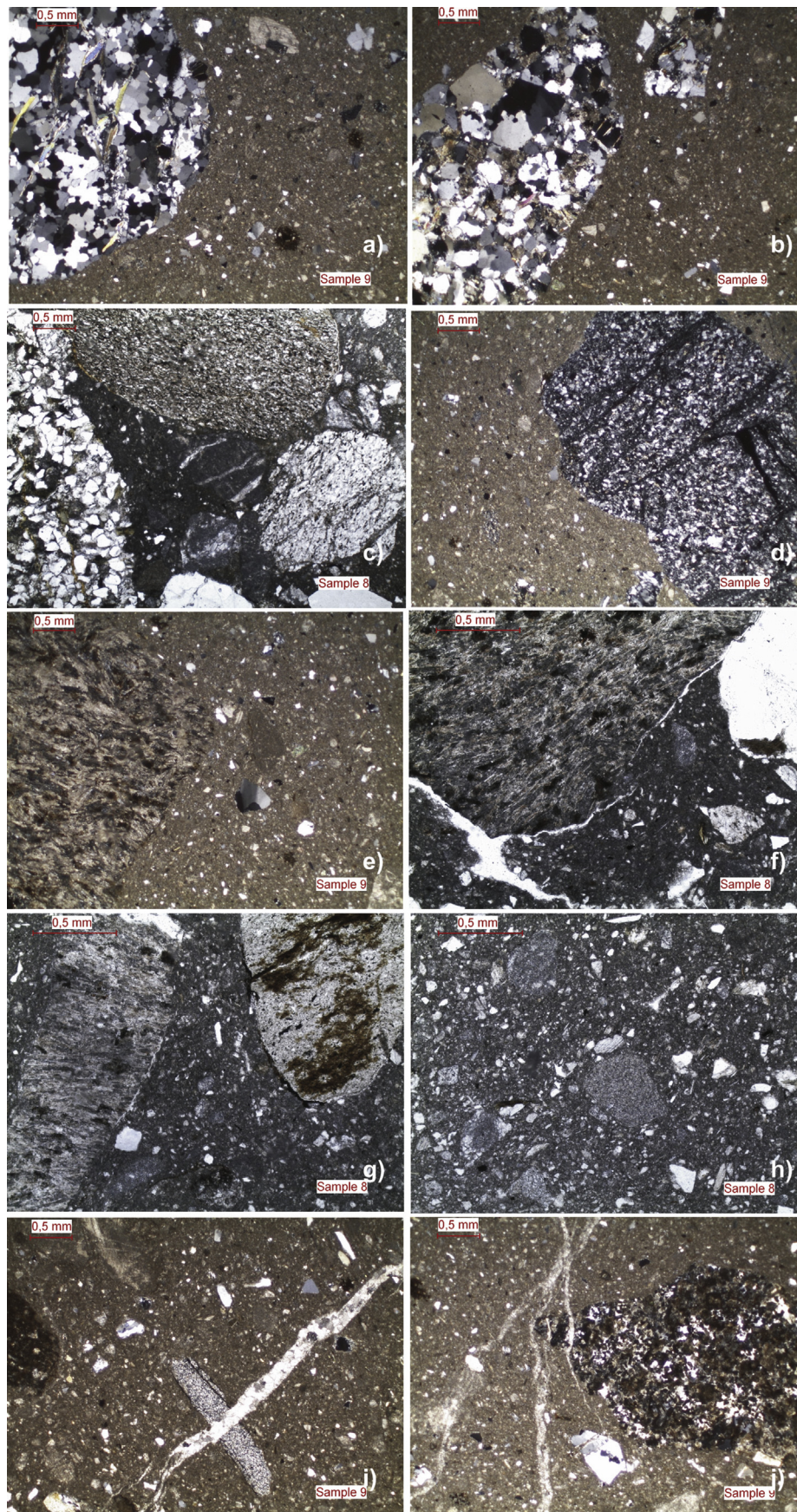


Fig. 6. a–b) Photomicrographs of polymictic cement-supported carbonate breccia dykes. Clasts of quartzite and quartz-mica schist are isolated within an ultra-fine grained carbonate cement; c) polymictic clast-supported carbonate breccia with sub-angular to rounded clasts of sandstones and siltstones; d) Carboniferous sandstone fragment in cement-supported carbonate breccia; e–g) trachyte clasts show pronounced trachytic fabric due to orientation of alkali feldspar laths; h) cement-supported breccia showing incipient flow structure defined by alignment of clasts in the presence of abundant carbonate cement; i–j) thin discontinuous calcite veins cut the cement/matrix and offset clasts. All photomicrographs were taken under crossed polarized light.

and metamorphic clasts from the crystalline basement are believed to have been torn from the Carboniferous basal conglomerate of the Retamito Formation (Achem, 1994). Siliciclastic sedimentary rocks (sandstones and siltstones) are from the Carboniferous Cruz de Caña Formation and the trachyte clasts are from the Upper Triassic La Flecha Trachyte. Initial movement along the cross-strike structures was responsible for brittle fracturing of these lithologies and subsequent incorporation of the carbonate breccia during the process of dyke intrusion.

Some clasts within the dykes are in various states of disruption. They are composed of many closely spaced, isolated, joint-bound fragments separated by and dispersed in the cement. These clasts represent an intermediate stage of fragmentation and reflect the outline of comminuted larger clasts. Injections of carbonate cement into the internal joints and fractures in the clasts indicate that at some stage, the cement was highly fluidized and injected in the hydrofractures due to fluid overpressure (Figs. 4c, 5f and 6i–j). Thin (< 1 mm) and discontinuous veinlets of calcite and Fe-oxides are noted cutting the matrix/cement and offset the clasts (Fig. 4 i–j).

4. Age of emplacement

The carbonate breccia dykes crosscut the Upper Carboniferous sedimentary rocks and also the La Flecha Trachyte. The later has been dated at 208 ± 5 Ma by means of the K/Ar method on whole rock (Castro de Machuca et al., 2013), setting a lower limit on the age of the dykes to the uppermost Triassic. The breccia dykes do not intrude the Neogene sedimentary rocks outcropping in the study area (Fig. 1b–c); thus setting the upper age limit for the emplacement of the breccia dykes to the deposition of the continental alluvial deposits of the Albarracín Formation assigned to the Middle Miocene.

5. Brecciation mechanism and mode of emplacement: discussion

Breccia dykes may be produced from a number of different processes (Pollock and Williams, 2000), these include: (a) a gas-flow from an igneous source; (b) Neptunian dykes or sedimentary filling of existing fractures; and (c) injection dykes or movement of liquefied and fluidized sediments. Fluids exert a fundamental control on the mechanical and chemical behaviour of all types of fault and shear zones (Smith, 2008 and references therein).

The carbonate breccia dykes at the Cerro La Chilca area exhibit features of both fluidization and injection (Smith, 2008) which include: (1) brittle clast fragmentation; (2) no grain-scale evidence for typical frictional deformation mechanisms; (3) the shape and variety of clasts; (4) an association with carbonate cement indicating that fluids were CO₂-rich; and (5) an incipient clast-preferred orientation suggesting that fluids were moving vertically and spreading laterally along the faults. Additional evidence for the origin of the dykes comes from the occurrence of carbonate material in fractures of the competent clasts due to forceful injection of highly pressurized cement. This indicates that at some stage the cement was highly fluid and the fluid pressure in the cement was higher than that in the enclosed clasts. In addition, these breccias contain low values of fragmented counterparts, providing complementary grain scale evidence that they experienced fluidization (Smith, 2008).

The observed features coincide with what Lash (1987) interpreted as a liquefied fluid flow or injection model which involved the upward movement of over-pressurized CO₂-rich fluid along with a poorly sorted mixture of more competent clasts of strata encountered during movement of the fluid. Fluids and fluidized clasts only need to follow local and regional pressure gradients

and to flow from an over-pressurized area to an overlying adjacent area of lower pressure to generate the conditions necessary for the liquefaction, fluidization, and injection (Cousineau, 1998).

The breccia dykes were not formed by a simple *in situ* fragmentation where the clasts did not travel far because the adjoining rocks are not brecciated. The variety and irregular shape of clasts derived from the host rocks require significant flow and mixing, probably over distances of hundreds of metres. The abundance of diverse types of limestones from the carbonate succession of the Eastern Precordillera provides evidence for the origin and transport of the clasts and indicates movement over significant distances. Although numerous faults and related frictional breccias with mosaic texture have been observed in the Lower Palaeozoic carbonate rocks, none have been found that contain breccia dykes. Injection of a fluidized material provides an appropriate mechanism by which the dominant limestone elements may be supplied to the system and transported; thus, a tectonically-driven forceful hydraulic injection of CO₂-rich fluidized breccia into WNW transtensional fractures is proposed. Moreover, transport in a fluidized medium seems a feasible explanation for the occasionally observed orientation of the hard-rock clasts.

The source of CO₂ rich-fluid may have included late hydrothermal fluid flow associated with the intrusion of the La Flecha Trachyte or, most likely, deeply-circulating meteoric fluid. It is assumed here that the thick succession of carbonate rocks acted as an important source of non-volcanic CO₂-bearing fluids. In addition to the carbonate cement, there are abundant calcite hydrofracture veins controlled by the main La Flecha strike-slip fault (Fig. 1c), confirming that the fluids which were circulating adjacent to the faults were also CO₂-rich. Pressurized CO₂-rich fluids can be released during tectonic activity and ascend towards shallower crustal levels that are under lower hydrostatic pressure. On their journey, the high-pressure fluids crack the country rocks and incorporate the clasts. Rounding of rock fragments is less common as the formational event of the breccias is assumed to be brief. However, the rounded to sub-rounded nature observed in some of the clasts could be interpreted as demonstrating particle transport in the presence of a fluid (Clark and James, 2003).

In a general sense, the breccia dykes at the Cerro La Chilca area can be attributed to a combination of both tectonic fragmentation and hydrothermal sealing processes. Tectonic fragmentation played a fundamental role in the formation and/or localization of the breccia dykes. The WNW faults represented the main channels for the flow.

To explain the process of breccia dykes generation it is assumed that the Lower Palaeozoic and Carboniferous sedimentary rock succession together with the deposition of the Triassic volcanic rocks, created an overburden capable of generating sufficient hydrostatic pressure in the underlying rocks. The trachyte, just above the limestone and siliciclastic layers formed a seal pressurizing the groundwater in the sedimentary rocks. Once the water pressure became too high, possibly enhanced by an external force such as a seismic shock and/or as a consequence of a phase of generalized faulting, it exceeded a threshold value and the rock layers became brecciated and fluidized. The unstable water-saturated carbonate breccia was transported upwards along the WNW faults to form the dyke-like bodies which intruded the entire lithologic sequence. The majority of these fluids contained fine-grained (muddy to sandy) sediment, however, a much rarer escape of centimetre-sized or even decimetre-sized clasts has been reported (Van Loon et al., 2013). A similar explanation was proposed for calcibreccia dykes in the Heart Mountain, Wyoming, by Voight (1973b in Pierce, 1979), who suggested that dykes were injected as part of a fault emplacement mechanism. This author (1974 in Pierce, 1979) also

cited the clastic dyke of fault-zone material along the Muddy Mountain thrust in Nevada, as evidence for the former existence of high fluid pressure along that fault. On the other hand, [Pierce \(1979\)](#) suggests that the extensive brecciation of rock above the fault surface, which is observed to occur immediately above a line of seismic discontinuity, may well have been caused by a catastrophic earthquake.

6. Conclusions

In the study area, a succession of Lower Palaeozoic limestones and Carboniferous sedimentary siliciclastic rocks was buried under younger layers of volcanic rocks (La Flecha Trachyte) that acted as a kind of seal. The total overburden allowed the underlying rocks to become over-pressurized. A rupturing of the seal, possibly initiated by an earthquake-related trigger mechanism, resulted in brecciation. Seismic activity may have acted as the catalyst that induced the hydraulic fracturing and sudden decompression of the system leading to fluidization and hydrothermal circulation.

The carbonate breccia dykes appear to have been injected at the same time and show a common mechanism of formation, namely, lithostatic overpressure caused by a thick cover of sedimentary and volcanic rocks. The Lower Palaeozoic limestones of the Eastern Precordillera are the main source of the clasts although there are fragments of younger country rocks.

Based on field work, petrographic and structural analysis, we suggest that the carbonate breccia dykes are the result of two phenomena: a) fracturing and breccia formation by the breaking up of limestones and nearby country rocks, and b) the semifluid mixing of clasts and injection of dykes by groundwater. The fluidized material flowed upward under high pressure, transporting clasts from the breccia and ultimately resulting in the cementation of the fragments by carbonate. Clasts transported over some distance became slightly rounded and others were orientated parallel to the fault planes. When sufficient fluidized material had escaped along faults, the hydrostatic pressure quickly decreased and the fluidized material became 'frozen'. The resulting breccia became preserved as the fault-related carbonate breccia dykes. Thus, the breccia dykes are a product of both tectonic fragmentation and hydrothermal sealing.

Although the factors leading to focused fluid flow and the development of fluid overpressure are still under study, our preliminary observations suggest that the fluidized breccias are representative of an interseismic period along the cross-strike WNW faulting during build-ups in fluid overpressure. The degree of lithostatic pressure needed to initiate intrusion of a dyke into the host rocks would have depended on the degree of consolidation and the character of the overlying rocks, as well as on the fluidity of the carbonate breccia; in some cases perhaps only a few tens or hundreds of meters of overburden may have been sufficient ([Pierce, 1979](#)).

The kinematic-structural analysis suggests that from the Upper Permian, oblique-slip and normal faults evolved contemporaneously under an NNE oriented maximum extension, previous to the Andean horizontal shortening. Cross-strike structures represent the main structural control in the emplacement of La Flecha Trachyte and carbonate breccia dykes. A pre-Paleogene extensional tectonic regime is considered in this work as the major factor in controlling dyke style.

The age of brecciation and dyke emplacement is clearly post-volcanism as shown by the presence of clasts of trachyte. Carbonate breccia dykes crosscut the Triassic rocks but none are found in the adjacent Middle-Upper Miocene rocks; thus, the age of the dykes is constrained to between uppermost Triassic to Early Miocene.

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