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Digital geologic map, petrography and U-Pb geochronology of the Río Santiago Shear Zone, southernmost Sierra Madre Occidental, western Mexico ☆

Mapa geológico digital, petrografía y geocronología U-Pb de la Zona de Cizalla del Rio Santiago, sur de la Sierra Madre Occidental, oeste de México

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Abstract

The boundary between the Sierra Madre Occidental (SMO) and the Trans-Mexican Volcanic Belt (TMVB) is well exposed along the Santiago River, on the border of the states of Nayarit and Jalisco. This region includes a polydeformed belt produced by the relative motion between the Jalisco Block and the SMO, here defined as the "Rio Santiago Shear Zone" (RSSZ). In this work, we present detailed geological cartography, petrographic descriptions, and new zircon U-Pb ages that allow us to establish the stratigraphy of the region surrounding the RSSZ, providing temporal constraints to its tectonic evolution. In the mapped area, the base of the SMO stratigraphic column consists of a succession of massive andesitic lava flows intruded by felsic dikes and a felsic subvolcanic body of 27.5 and 27.2 Ma, and it is covered by a series of ignimbrites of 26.8 and 25.3 Ma. A red beds succession separates a second package of ignimbrites of ~20-19 Ma, in turn capped by rhyolitic lava domes of 19.7 and 18.6 Ma and a rhyodacitic lava flows of 15.6 Ma, this Miocene succession is also intruded by a felsic body of 18.3 Ma west of the La Yesca dam. The SMO succession is covered by rocks belonging to the bimodal volcanism of the TMVB, emplaced between the end of the Miocene and the Pleistocene. The RSSZ developed through several deformation phases that occurred since the end of the Oligocene. The Oligocene succession of the SMO is affected by NE-SW and WNW-ESE trending lateral faults, NW-SE open folds and WNW-ESE and E-W trending reverse oblique faults. Some of the reverse oblique faults were later reactivated as normal faults. WNW-ESE trending normal faults associated with the Tepic-Zacoalco Rift affected the area south of the Santiago River during the Pliocene and Pleistocene. Normal faulting produced an accumulated vertical offset up to 700 m between the northern and southern regions of the Santiago River.

Keywords: Rio Santiago Shear Zone, Sierra Madre Occidental, Jalisco Block, geological cartography, Cenozoic stratigraphy

Resumen

El límite entre la Sierra Madre Occidental (SMO) y la Faja Volcánica Trans-Mexicana (FVTM) está bien expuesto a lo largo del Rio Santiago, en la frontera de los estados de Nayarit y Jalisco. Esta región incluye una franja polideformada producida por el movimiento relativo entre el Bloque Jalisco y la SMO, que aquí definimos como "Zona de Cizalla del Rio Santiago" (ZCRS). En este trabajo presentamos una cartografía geológica detallada, descripciones petrográficas y nuevas edades U-Pb en zircones que nos permitieron establecer la estratigrafía de la región circunstante a la ZCRS y constriñen temporalmente su evolución tectónica. En el área mapeada, la base de columna estratigráfica de la SMO consiste en una sucesión de flujos de lava andesítica masivos intrusionados por diques félsicos y un cuerpo subvolcánico félsico de 27.5 y 27.2 Ma. La sucesión andesítica está cubierta por una serie de ignimbritas de 26.8 y 25.3 Ma. Una sucesión de capas rojas separa un segundo paquete de ignimbritas de ~20-19 Ma, a su vez coronadas por domos de lava riolítica de 19.7 y 18.6 Ma y flujos de lava riodacítica de 15.6 Ma. Esta sucesión del Mioceno también está intrusionada por un cuerpo félsico de 18.3 Ma al oeste de la presa La Yesca. Las sucesiones de la SMO están cubiertas por las rocas del vulcanismo bimodal de la FVTM, emplazadas entre el final del Mioceno y el Pleistoceno. La ZCRS se desarrolló debido a varias fases de deformación ocurridas desde finales del Oligoceno. La sucesión del Oligoceno de la SMO está afectada por fallas laterales de dirección NE-SO y ONO-ESE, pliegues abiertos NO-SE y fallas inversas oblicuas con dirección ONO-ESE y E-O. Algunas de las fallas oblicuas inversas se reactivaron como fallas normales desde el Mioceno medio. Fallas normales de dirección ONO-ESE asociadas con el Rift Tepic-Zacoalco afectaron el área al sur del río Santiago durante el Plioceno y el Pleistoceno. El fallamiento normal produjo un salto vertical acumulado de hasta 700 metros entre las regiones norte y sur del Río Santiago.

Palabras clave: Zona de Cizalla del Río Santiago, Sierra Madre Occidental, Bloque Jalisco, cartografía geológica, estratigrafía cenozoica

1. Introduction

Purpose of the work

The southernmost part of the Sierra Madre Occidental (SMO) silicic large igneous province is exposed along the Santiago River northwest of Guadalajara, Jalisco, where it is covered by the Late Cenozoic Trans-Mexican Volcanic Belt (TMVB) (Figure 1). In this area the Santiago River runs along a highly deformed corridor, which resulted from the motion of the Late Cretaceous-Paleocene Jalisco Block (JB), whose northern boundary is inferred just south of the Santiago River (Ferrari and Rosas-Elguera, 2000). This polydeformed corridor, here defined as the "Rio Santiago Shear Zone" (RSSZ), decouples the Jalisco Block from the SMO. The RSSZ was active since the late Oligocene in response to the opening of the Gulf of California rift (Ferrari et al., 2018). Previous works provided local information about the geology, deformation, and geochronology of this region (Damon et al., 1979; Nieto-Obregón et al., 1985; Ferrari, 1995; Frey et al., 2007, Paez, 2010). However, the spatial distribution and geometry of the tectonic structures, as well as the timing of the different volcanic and tectonic episodes have remained not well known.

To unravel the complex tectonic evolution of this tectonic boundary we defined the regional stratigraphy of the RSSZ between eastern Nayarit and western Jalisco states. We present a geological-structural map, petrographic descriptions, and zircon U-Pb geochronology, accompanied by a detailed stratigraphic column and structural cross-sections. The geologic map is presented in both static and interactive format, which include all available isotopic ages and a complete petrographic description with photomicrographs of the studied samples. This material provides the framework for a study on the tectonic evolution of the RSSZ that will be presented in a separate paper elsewhere.

2. Regional geologic setting

The mapped area covers the boundary between two different crustal blocks: the Oligocene-Miocene Sierra Madre Occidental silicic large igneous province and the Late Cretaceous-Paleocene Jalisco Block (Figure 1). The boundary is mostly covered by the Late Miocene-Pleistocene volcanism of the TMVB

The Jalisco Block is a continental crustal unit mainly composed of the Late Cretaceous Puerto Vallarta batholith with crystallization ages ranging from 100 to 75 Ma (Schaaf et al., 1995; Valencia et al., 2013), but with a main peak of crystallization and cooling ages at around 80–82 Ma (Schaaf et al., 2020).

Pre-batholithic rocks consist of metasedimentary rocks with ages from Triassic (?) to Early Cretaceous, which crop out at the margins of the Puerto Vallarta batholith (Bissing et al., 2008; Valencia et al., 2013; Schaaf et al., 2020). Scarce limestones and argillaceous rocks are also locally reported as roof pendants within granitic plutons with late Oligocene-early Miocene ages (Gastil et al., 1979). The youngest lithostratigraphic unit is represented by a Late Cretaceous-Paleocene ash flow tuff succession (Carmichael silicic ash flow tuff succession; Valencia et al., 2013). This unit crops out at the southwest corner of the mapped area.

The stratigraphy of the southern SMO consists of late Eocene to early Miocene ignimbrite successions, traditionally included in the Upper Volcanic Supergroup of Mcdowell and Keizer (1977), which were emplaced in two main regional flare-ups (McDowell and Clabaugh, 1979; Ferrari et al., 2007). The first ignimbrite flare-up occurred mainly from 36 to 28 Ma (Ferrari et al., 2007; McDowell and McIntosh, 2012; Ferrari et al., 2018) and is extended from part of southwestern USA southward to Chihuahua, Durango up to Jalisco and Nayarit in Mexico. The late Eocene ignimbrites are commonly separated from the underlying Lower Volcanic Complex by continental clastic successions (McDowell and Clabaugh, 1979; Montoya-Lopera et al., 2019).

The second flare-up occurred between 24 and 18 Ma and is restricted to the southwestern part of the SMO (Ferrari et al., 2002, 2007; Bryan and Ferrari, 2013). Although silicic ignimbrites are the dominant rocks, rhyolitic lava domes and mafic lava flows and dikes are also observed in several places (Ferrari et al., 2002, 2013; Murray et al., 2013; Ramos-Rosique, 2013). Based on structural relationships and geochemical data, this bimodal volcanism is associated with the early extension that eventually led to the formation of the Gulf of California (Ferrari et al., 2018).

In the southern part of the SMO the late Eocene and Oligocene ignimbrite successions are mostly exposed in the Aguascalientes, Zacatecas, and northern Jalisco states (Lang et al., 1988; Nieto-Obregón et al., 1981; Nieto-Samaniego et al., 1999; Ferrari et al., 2002) whereas in Nayarit and westernmost Jalisco they are covered by the early Miocene ignimbrite succession (Ferrari et al., 2013; 2018).

The TMVB rocks cover the SMO just south of the Santiago River. Its base consists of a thick succession of mafic lava flows of 11 to 8.5 Ma (Damon et al., 1979; Nieto-Obregón et al., 1985; Moore et al., 1994; Rossotti et al., 2002). This unit, informally named San Cristobal basalts, is well exposed with up to 800 m of thickness along the Santiago River north and northwest of Guadalajara (Moore et al., 1994) and in a geothermal exploratory well drilled south of the Ceboruco volcano just west of the mapped area (Ferrari et al., 2003). This mafic volcanism was followed by widespread silicic lava domes and pyroclastic flows emplaced between 7.2 and 5 Ma

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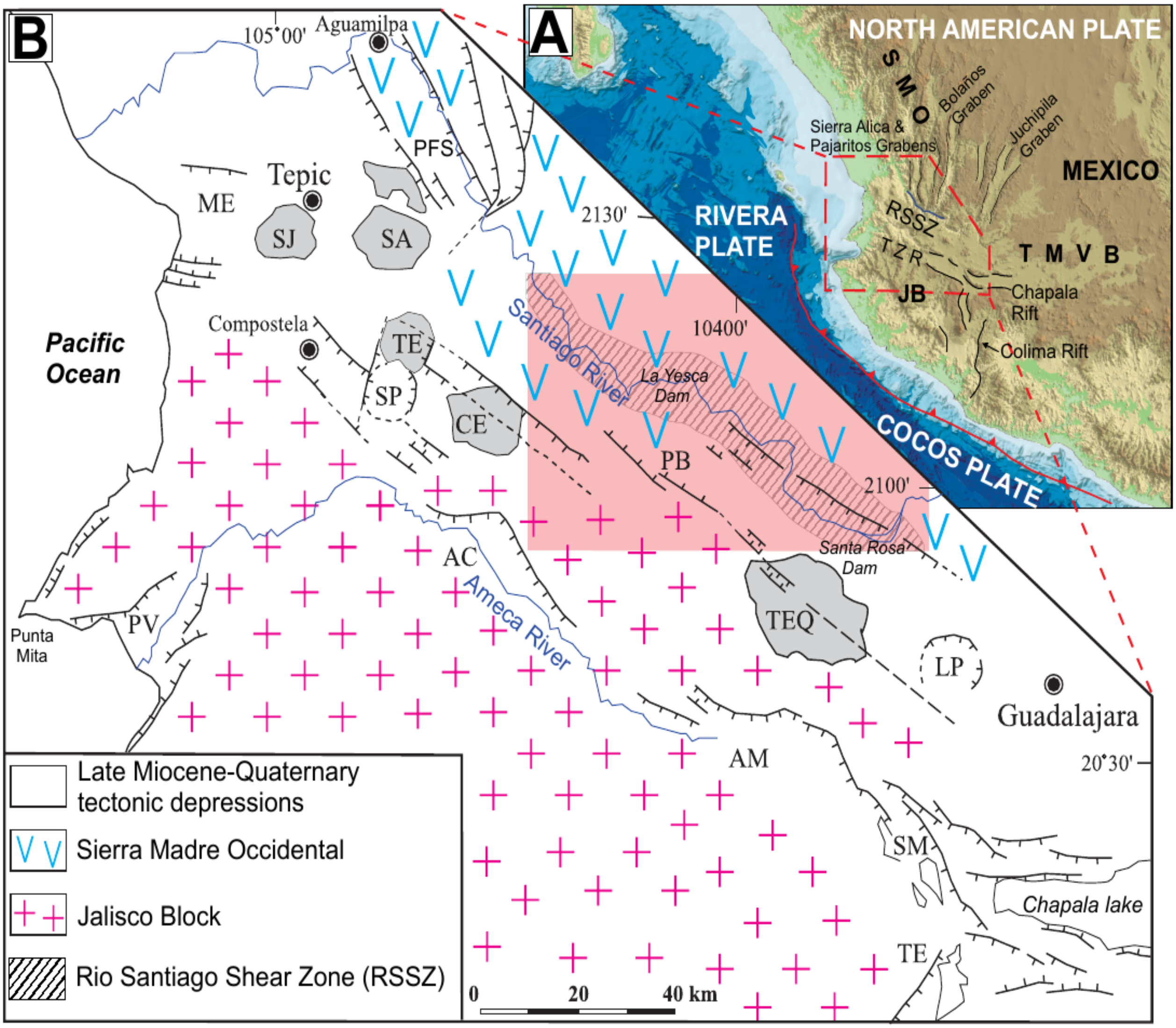

Figure 1: Geological framework of the southernmost SMO. A) Main regional structures and geological provinces. B) Study area (red polygon) and major structures and lithological suites, modified from Ferrari and Rosas-Elguera (2000). Geologic provinces: JB–Jalisco Block, SMO–Sierra Madre Occidental, TMVB Trans-Mexican Volcanic Belt. Structures: TZR–Tepic-Zacoalco Rift, SP–San Pedro Caldera, LP–La Primavera Caldera, AC–Amatlán de Cañas graben, AM–Ameca Fault, ME–Mecatan Graben, PB–Plan de Barrancas Fault, TE–Techaluta Fault, SM–San Marcos Fault, PFS–Pochotitlán Fault System. Volcanoes: TEQ–Tequila, CE–Ceboruco, TE–Tepeltitic, SJ–San Juan, SA–Sangangüey. / Figura 1: Contexto geológico de la porción más meridional de la SMO. A) Principales provincias geológicas y estructuras regionales. B) Área de estudio (polígono rojo) y principales estructuras y conjuntos litológicos, modificado de Ferrari y Rosas-Elguera (2000). Provincias geológicas: JB–Bloque Jalisco, SMO–Sierra Madre Occidental, TMVB–Faja Volcánica Trans-mexicana. Estructuras: TZR–Rift Tepic-Zacoalco, SP–Caldera San Pedro, LP–Caldera La Primavera, AC–Graben Amatlán de Cañas, AM–Falla Ameca, ME–Graben Mecatan, PB–Falla Plan de Barrancas, TE–Falla Techaluta, SM–Falla San Marcos, PFS–Sistema de Fallas Pochotitlán. Volcanes: TEQ–Tequila, CE–Ceboruco, SJ–San Juan, SA–Sangangüey.

(Rossotti et al., 2002; Frey et al., 2007), and an ignimbrite succession emplaced between 5 and 3 Ma (Frey et al., 2007), which in turn is capped by late Pliocene-Quaternary basalts, some of them with a clear intraplate affinity (Petrone et al., 2003). All this bimodal volcanism is associated with the extensional tectonics that formed the Tepic-Zacoalco Rift.

3. Tectonic setting

The southern SMO is characterized by three structural domains: 1) an eastern domain characterized by NNE to N-S trending grabens (Juchipila, Tlaltenango, Bolaños) that affect the late Oligocene to Early Miocene successions; 2) a western domain with N-S to NNW-SSE trending half-grabens (Sierra Alica, Sierra Pajaritos, Jesús María), which tilt the Early Miocene ignimbrites to the E and ENE; and 3) a southern domain with en echelon NW-SE open folds and smaller reverse and transcurrent faults (Ferrari et al., 2007). The RSSZ studied in this work is part of the southern domain, which is partly overprinted by younger WNW-ESE normal faults associated with the Tepic-Zacoalco Rift (Ferrari and Rosas-Elguera, 2000). It consists of graben and half-graben structures developed in the northern part of the JB since the late Miocene (Quintero-Legorreta et al., 1992; Ferrari, 1995; Rosas-Elguera et al., 1997; Ferrari and Rosas-Elguera, 2000). The rift can be divided into two branches (Figure 1): 1) a southern one formed by the Puerto Vallarta graben, Amatlán de Cañas half-graben, and the Ameca, San Marcos, and Zacoalco faults; and 2) a northern branch that includes the San Pedro–Ceboruco graben and the Plan de Barrancas-Cinco Minas graben, which overprint the SMO–JB boundary (Ferrari and Rosas-Elguera, 2000; Ferrari et al., 2003).

4. Methods

4.1. Geological mapping

We elaborated a geological and structural map of the southern boundary of the SMO in an area of 8250 km2 located between Ixtlán del Río, easternmost part of Nayarit state, and the Santa Rosa Dam, western part of Jalisco state, along the Santiago River. To record field observations and structural data we use topographic maps at 1:50,000 scale from INEGI (Instituto Nacional de Estadística y Geografía). Fieldwork included recognition of lithological contacts and description of the rock's characteristics, in addition to measurement and description of structures. Field observations were done along the available roads and the Santiago River. Structural data from previous works (Ferrari, 1995, Ferrari et al., 2000, 2002; Nebocat, 2002; Paez, 2010) were included in the map. The map design and integration were first done with Google Earth satellite images and then exported and refined with the ArcMap software. The stratigraphic column was reconstructed based on field observations, a petrographic study and zircon U-Pb geochronology. This work is accompanied by a static and interactive map. The interactive map contains petrographic descriptions and photomicrographs of representative samples for each lithostratigraphic units, as well as our new U-Pb ages (See Supplementary material) and published K-Ar and U-Pb ages.

4.2. U-Pb geochronology

Ten samples were dated by U-Pb zircon geochronology. The samples comprise rhyolitic ignimbrites, granitic intrusive rocks, and felsic lavas. Crushing, sieving, and mineral separation from rock samples were performed following standard methods. Zircons were mounted in epoxy resin and polished. Laser ablation target points were selected after cathodoluminescence sample recognition to identify crystal cores and edges. We considered the ages obtained from the crystal edges as representative of crystallization ages. Zircon samples were analyzed by LA-ICPMS technique in the Laboratorio de Estudios Isotópicos (LEI) at Centro de Geociencias, Universidad Nacional Autónoma de México, following the methodology described in Solari et al. (2018). Concordia and weighted mean diagrams were plotted using Isoplot v. 4.1 (Ludwig, 2008).

5. Stratigraphy of the study area

5.1. Sierra Madre Occidental

5.1.1. Late Oligocene

San Pedro Analco Andesites

The older lithostratigraphic unit in the study area consists of andesitic lava flows, cropping out along the Santiago River between Cinco Minas and San Pedro Analco (Figure 2A). These are dark to reddish lavas which exhibit mainly aphanitic to porphyritic textures and massive structure (samples RS06, RS22, SPA03, SPA17A, SPA18A, SPA19A). This unit underlies a succession of ignimbrites (Rio Santiago Ignimbrites), and it is intruded by a swarm of felsic and mafic dikes and by felsic subvolcanic bodies described below (Figure 2B). The andesitic lavas are affected by WNW-ESE trending normal faults, which are associated with veins filled with calcite, quartz, sulfides, and oxides minerals. Epithermal veins hosted in the andesitic lavas in the Cinco Minas area were dated at 24 Ma (Ar-Ar in adularia; Camprubí et al., 2016).

Chattian subvolcanic granites and felsic dikes

An NW-SE trending body of dominantly granitic composition and subordinated intermediate composition intrusions is exposed in the Santiago River between San Pedro Analco and Cinco Minas, cutting the San Pedro Analco Andesites. Granitic rocks exhibit porphyritic to phaneritic textures, while intermediate intrusions exhibit porphyritic to aphanitic textures. Some zones of the granite rocks contain andesitic xenoliths.

Petrography reveals that the granites have micrographic to porphyritic textures, with quartz and feldspar phenocrysts and secondary hornblende and biotite. Biotite is commonly replaced by elongated chlorite and radial epidote. Quartz and feldspar in the granites show evidence of intracrystalline deformation (dynamic recrystallization, subgrains, undulate extinction) (samples RS10, RS12, SPA23, SPA27, SPA28, SPA29 and SPA31). A swarm of mafic dikes is hosted in this unit, and cross-cutting relationships suggest two generations of mafic intrusions. These are likely related to the mafic volcanism of the TMVB.

We dated two representative samples of the felsic dikes collected to the north of La Yesca Dam (SPA22 and SPA05). We obtained U-Pb ages of 27.52 ± 0.31 Ma and 27.21 ± 0.33 Ma (Figure 3, Table 1). Nieto Obregon et al. (1985) obtained similar K-Ar ages of 26.6 ± 0.6 Ma (hornblende) for the subvolcanic granitic body exposed in the Santiago River south of San Pedro Analco and an age of 26.7 ± 0.6 Ma (on groundmass) for a microdioritic dike near to Cinco Minas.

Rio Santiago Ignimbrites

This unit consists of rhyolitic ignimbrites and subordinate intermediate lavas. The volcanic succession crops out mostly to the north of the Santiago River, it is in tectonic contact or overlayed by a red beds succession (Las Juntas Red Beds) and intruded by a subvolcanic body west of La Yesca dam. This unit is intensively fractured and affected by normal, lateral, and reverse faults, and it is intensely intruded by felsic and mafic dikes. Pyroclastic rocks show a wide variety of textures and volcanic lithoclasts (see samples RS01, RS02, RS03, RS11, RS19, SPA02, SPA07, SPA11, SPA12, SPA13, SPA14, SPA15, SPA16, SPA18c, SPA24a, SPA26b, and SPA36; in the interactive map). Texture varieties correspond to lithic and vitreous tuffs and eutaxitic and rheomorphic ignimbrites (Figure 2C). They contain quartz and feldspar crystals and lithics with vitreous, felsitic, microlithic, and lathwork textures. Interbedded lavas are hypocrystalline rocks with mainly feldspar phenocrysts and less than 5% of quartz; these lava flows were classified as latites and trachytes. We obtained two

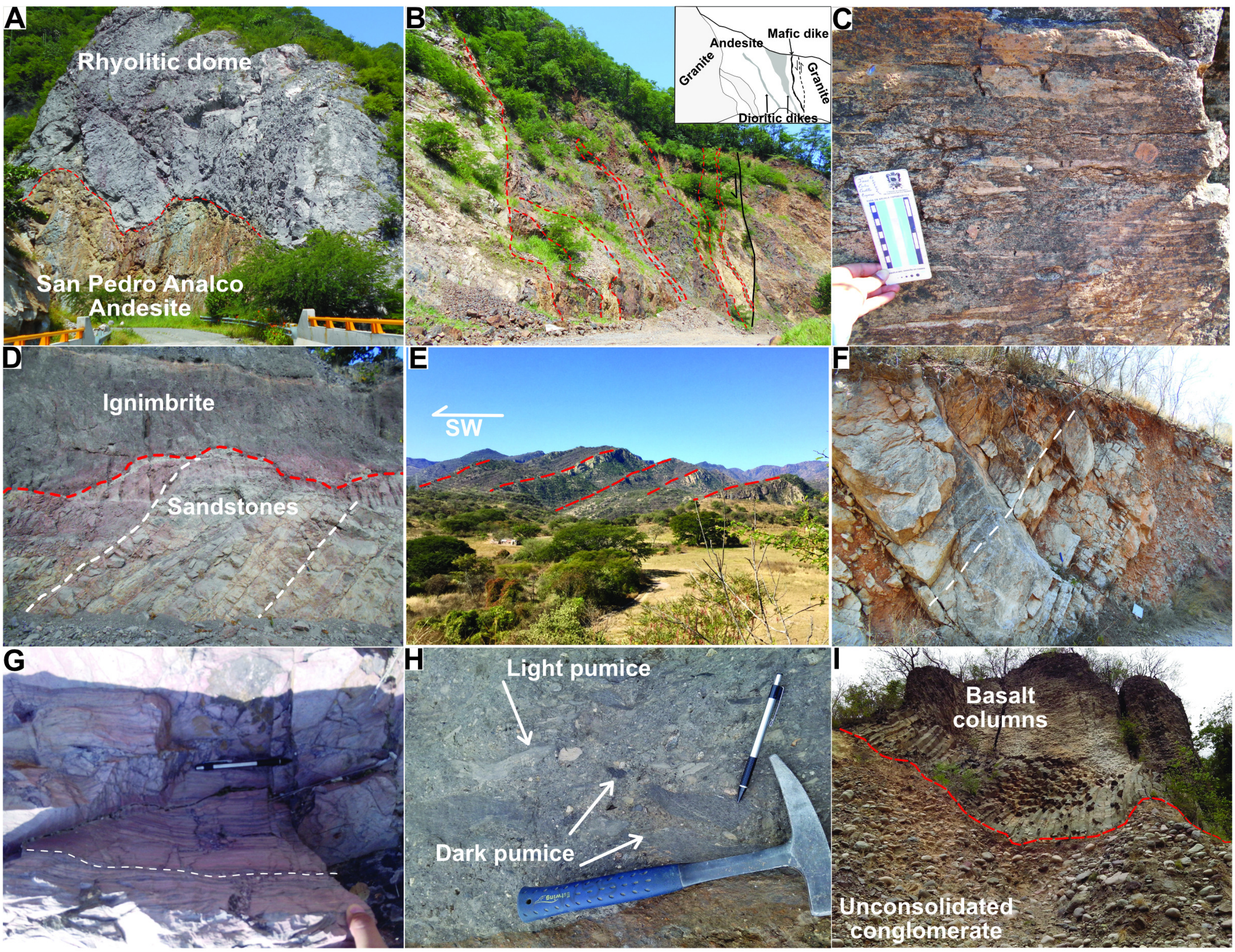

Figure 2: Outcrops photographs. A) San Pedro Analco Andesite underlaying an Early Miocene rhyolitic lava-dome. B) Late Oligocene granite intruded by mafic and intermediate composition dikes. C) Eutaxitic ignimbrites from the Rio Santiago ignimbrites. D) Unconformity between Las Juntas Red Beds and the Monte del Favor Ignimbrites. E) Tilted Early Miocene ignimbrites south of La Yesca dam. F) La Playa Granite with banded structure. G) Reomorphic rhyolite from the Late Plio-Quaternary succession. H) Late Pliocene-Quaternary Ignimbrite with two composition pumice from Hostotipaquillo. I) Plio-Quaternary columnar basalt overlying an unconsolidated conglomerate near La Yesca dam. / Figure 2: Fotografías de afloramientos. A) Andesita San Pedro Analco subyaciendo un domo de lava riolítica del Mioceno temprano. B) Granito del Oligoceno tardío intrusionado por diques de composición máfica e intermedia. C) Ignimbritas eutaxíticas de la sucesión Ignimbritas Río Santiago. D) Discordancia entre las capas rojas Las Juntas y las ignimbritas Monte del Favor. E) Ignimbritas del Mioceno temprano basculadas, localizadas al sur de la presa La Yesca. F) Granito La Playa con estructura bandeada. G) Riolita reomórfica de la sucesión del Plioceno tardío-Cuaternario. H) Ignimbrita del Plioceno tardío-Cuaternario con pómez de dos composiciones, en Hostotipaquillo. I) Basalto columnar sobreyaciendo un conglomerado no consolidado cerca de la presa La Yesca.

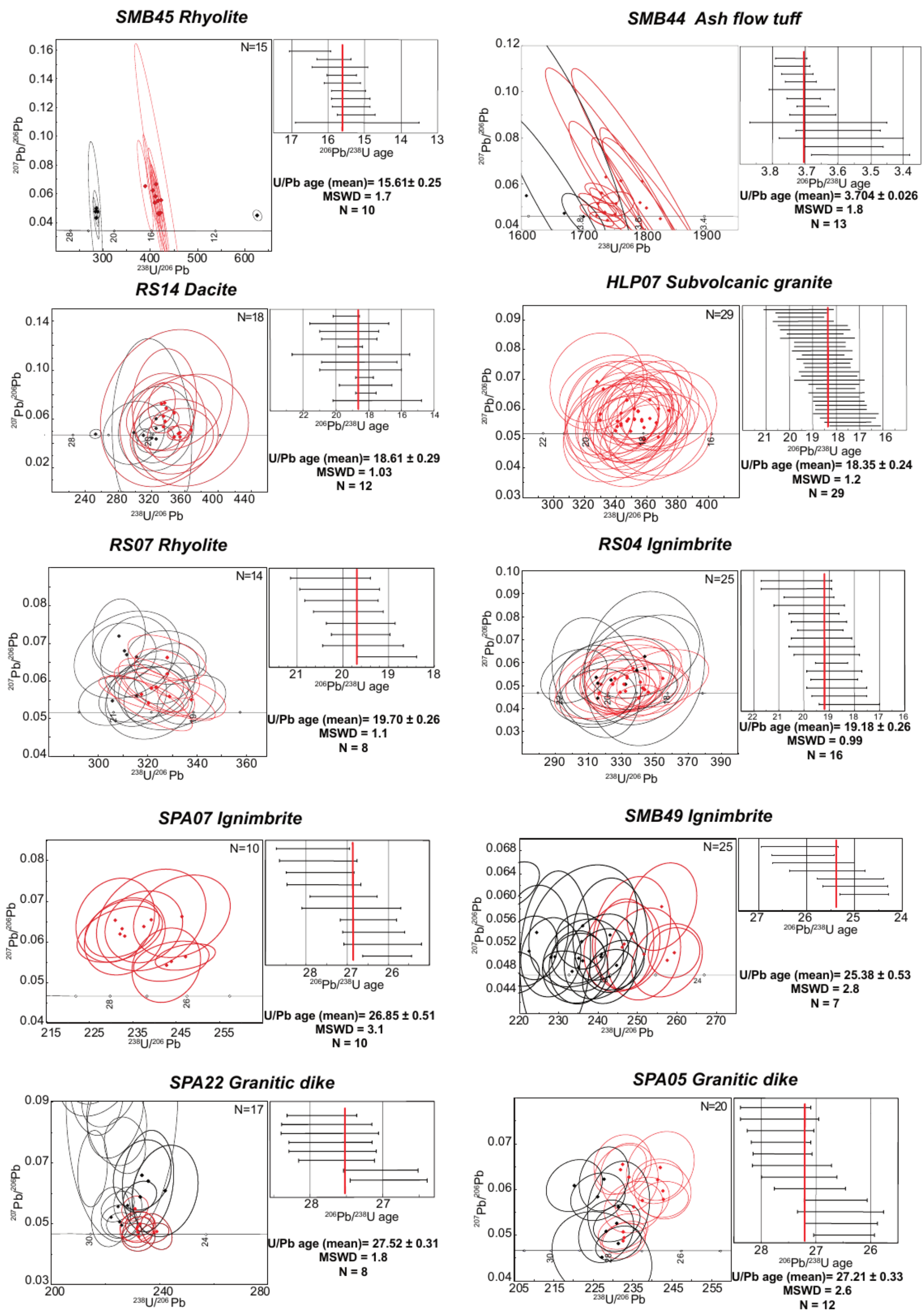

Figure 3: Tera-Wasserburg and mean weighted age diagrams from the analyzed samples by zircon U-Pb method. Red circles and diamonds represent the data used for the calculated mean weighted age. Errors are 2σ / Figura 3: Diagramas de Tera-Wasserburg y de edades por promedio ponderado de las muestras analizadas por el método U-Pb en zircón. Los círculos y diamantes rojos representan los datos usados para el cálculo de la edad por promedio ponderado. Los errores son 2σ.

Table 1: Zircon U-Pb ages results. Reported ages are weighted mean age. Errors are 2σ / Tabla 1: Resultados de las edades Zircon U-Pb. Las edades informadas son la edad media ponderada. Los errores son 2σ

Sample	Location	Long (W)	Lat (N)	Rock type	$^{206}Pb/^{238}U$ mean age	Error (2σ)	Observations
SMB44	El Salvador, Jal	103.74	20.97	Ash, flow, tuff	3.70	0.03	Moderately welded ash flow tuff. MSWD = 1.8, n = 13. Crystals in the range of 3.53 – 4.0 Ma. Possibly antecrystic inheritance. Two zircons (17.08 Ma, 27.35 Ma)
SMB45	North of Amatitán, Jal	103.71	20.91	Rhyolite	15.61	0.25	Porphyritic rhyolite. MSWD = 1.7, n = 17. Crystals in the range of 10.3 – 22.6 Ma
HLP07	RSSZ	104.19	21.19	Granite	18.35	0.24	Phaneritic granitic intrusion. MSWD = 1.2, n = 29. Crystals in the range of 17.2 – 19.5 Ma. Possibly antecrystic inheritance. One zircon (59.4 Ma)
RS14	RSSZ	104.07	21.26	Dacite	18.61	0.29	Porphyritic dacite. MSWD = 1.03, n = 12. Crystals in the range of 17.5 – 25.5 Ma
RS04	RSSZ	104.25	21.18	Ignimbrite	19.18	0.26	Lithic ignimbrite. MSWD = 0.99, n = 16. Crystals in the range of 18.2 – 21.4 Ma
RS07	Monte Del Favor, Jal	104.16	21.12	Rhyolite	19.70	0.26	Spherulitic rhyolite with fluidal structure. MSWD = 1.1, n = 8. Crystals in the range of 19 – 22 Ma
SMB49	East of Hos-totipaquillo, Jal	103.91	21.04	Ignimbrite	25.38	0.53	Rich crystal ignimbrite with volcanic lithics. MSWD = 2.8, n = 7. Crystals in the range of 24.8 – 30 Ma. Possibly antecrystic inheritance. One zircon (60.6 Ma)
SPA07	RSSZ	104.09	21.24	Ignimbrite	26.85	0.51	Eutaxitic lithic ignimbrite. MSWD = 3.1, n = 10. Many discordant zircons. Crystals in the range of 26 – 27.8 Ma
SPA05	RSSZ	104.10	21.20	Granitic dike	27.21	0.33	Porphyritic granite. MSWD = 2.6, n = 12. Crystals in the range of 26.5 – 29 Ma
SPA22	RSSZ	103.97	21.12	Granitic dike	27.52	0.31	Biotite-bearing granitic dike. MSWD = 1.8, n = 8. Crystals in the range of 22.5 – 20 Ma. One 42.7 Ma xenocryst

zircon U-Pb ages of 26.85 ± 0.51 Ma and 25.38 ± 0.53 Ma for two ignimbrites representative of this succession (SPA07 and SMB49, Figure 3, Table 1).

Las Juntas Red Beds

This is a siliciclastic succession consisting of conglomerates and sandstones with interbedded ignimbrites at the bottom and in its upper part. West of the La Yesca dam, sandstones with interbedded limestones are also observed. This succession overlies the Rio Santiago Ignimbrites and unconformably underlies the Monte del Favor ignimbrites (Figure 2D).

Both conglomerates and sandstones are compositionally and texturally immature. Sandstones are mainly classified as a feldspathic and feldspar-lithic sandstones of Garzanti (2019), which contain lithics with felsitic, vitreous, microlithic and lathwork textures (see samples HLP04, HLP05, RS05, SPA33a, and HLP01 in the interactive map). Clasts of conglomerates are rhyolitic porphyritic and pyroclastic rocks and porphyritic mafic to intermediate rocks. The interbedded pyroclastic flow deposits are 15 to 30 cm in thickness, they exhibit mainly eutaxitic texture, and are rich in pumice clasts and vitreous lithics. The red beds tilt ~30° to the SSW due to WNW-ESE trending normal faults. This unit is also affected by older transcurrent faults. However, to the north of the Santiago River, these red beds tilt to the NE. Based on its stratigraphic position, this unit can be assigned to the latest Oligocene to early Miocene.

5.1.2. Early Miocene

Monte del Favor Ignimbrites

This unit consists of ignimbrites cropping out to the south and to the north of the Santiago River. Pyroclastic rocks show a wide variety of textures and components (samples RS04, HLP17, SPA21c, SPA33b, HLP03, HLP06, HLP08, HLP14, and HLP15 in the interactive map), with crystaloclasts of quartz and feldspar and, sometimes, subordinate biotite or amphibole crystaloclasts. Lithics exhibit felsitic, microlithic and vitreous textures. This unit is affected by three main fault sets. South of the Santiago River ignimbrites are affected by E-W trending normal faults that produced a southward tilting (Figure 2E). Near Cinco Minas, the predominant faults direction is WNW-ESE, whereas the north region of the Santiago River is affected by N-S trending normal faults (see map plate). We obtained a zircon U-Pb age of 19.18 ± 0.26 Ma for an ignimbrite sample (RS04) (Figure 3, Table 1), indistinguishable within error from the U-Pb age of 20.0 ± 0.8 Ma obtained by Bryan et al. (2008) for ignimbrites of the same succession.

El Vigía Domes

Several rhyolitic to dacitic lava domes cap the Monte del Favor ignimbrite succession. A first group is associated with the WNW-ESE faults south of the Santiago River, whereas a second one is located north of the Santiago River with a main N-S trend. Petrographically, the domes can be classified as porphyritic rhyolites and dacites, with subordinate lavas of intermediate composition (see samples RS07, RS14, RS15, and HLP09 in the interactive map). South of La Yesca dam, they are affected by normal faults with an E-W direction. It is remarkable that the domes north of Santiago River lie ~700 m higher than those to the south due to the activity of the Rio Santiago fault (see map plate). We dated three samples (RS07, RS14 and SMB45) by zircon U-Pb geochronology, which yielded a mean weighted age of 19.70 ± 0.29 Ma, 18.61 ± 0.29 Ma, and 15.61 ± 0.25 Ma (Figure 3, Table 1).

La Playa Granite

Over the E-W trending segment of the Santiago River, a banded phaneritic biotite-bearing granite (sample HPL07 in the interactive map) cuts the Rio Santiago Ignimbrites (Figure 2F). The pseudostratification has an ESE direction and is dipping ~60° to the southwest. For this unit, we obtained a U-Pb crystallization age (sample HLP07), with a mean weighted age of 18.35 ± 0.24 Ma (Figure 3, Table 1). Nieto Obregón et al. (1985) also report a K-Ar age of 19.5 ± 0.5 Ma for a quartz-feldspathic dike near San Pedro Analco. Altogether, these ages point to a second pulse of intrusions roughly coeval with the younger silicic volcanism of the SMO.

5.2. Trans-Mexican Volcanic Belt

Late Miocene – Pleistocene

The TMVB volcanic rocks display a bimodal composition and mainly crop out in the southern part of the study area covering the SMO volcanic succession. These rocks are grouped into five informal units (see map plate) and mainly consist of mafic and rhyolitic lava flows, rhyolite lava domes and pyroclastic deposits: 1) Late Miocene basaltic lava flows capped by small shield volcanoes mostly exposed in the southeastern part of the area; 2) Late Miocene-Early Pliocene rhyolitic domes and associated pyroclastic flows covering the previous basaltic lava flows for which we obtained a zircon U-Pb age of 3.70 ± 0.03 Ma (SMB44) (Figure 3, Table 1); 3) Late Pliocene-Pleistocene alkaline basaltic lava flows associated with the main normal faults of the Tepic-Zacoalco Rift (see samples SPA35 and RS20 in the interactive map); 4) Plio-Pleistocene rhyolitic lava domes, lava flows and pyroclastic deposits and 5) the unit at the top which is represented by poorly consolidated siliciclastic deposits.

6. Summary of deformation

Our new geological mapping and geochronological data allow a better understanding of the polyphase deformation de-

Geological map of the Rio Santiago Shear Zone, southern Sierra Madre Occidental, Mexico

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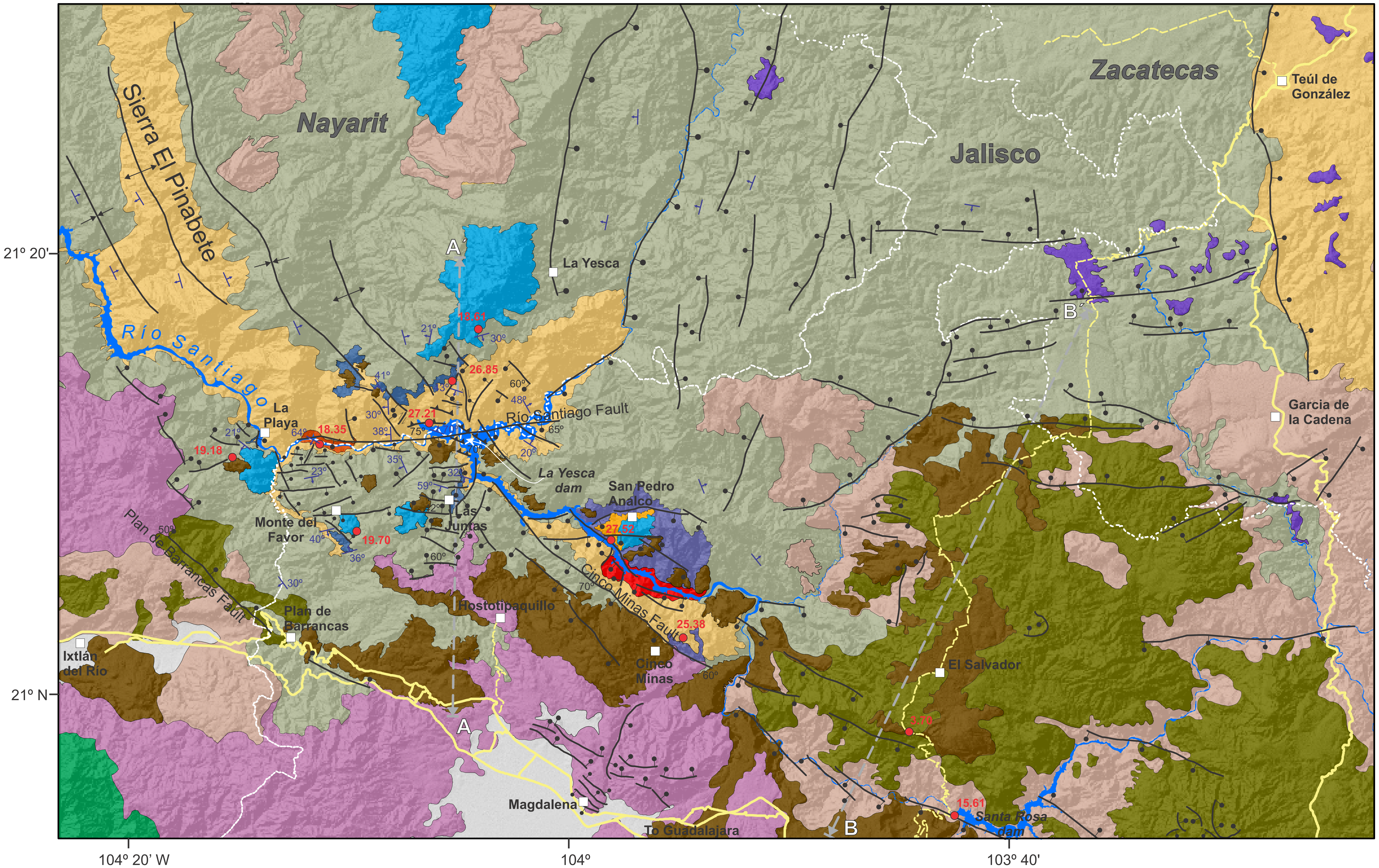
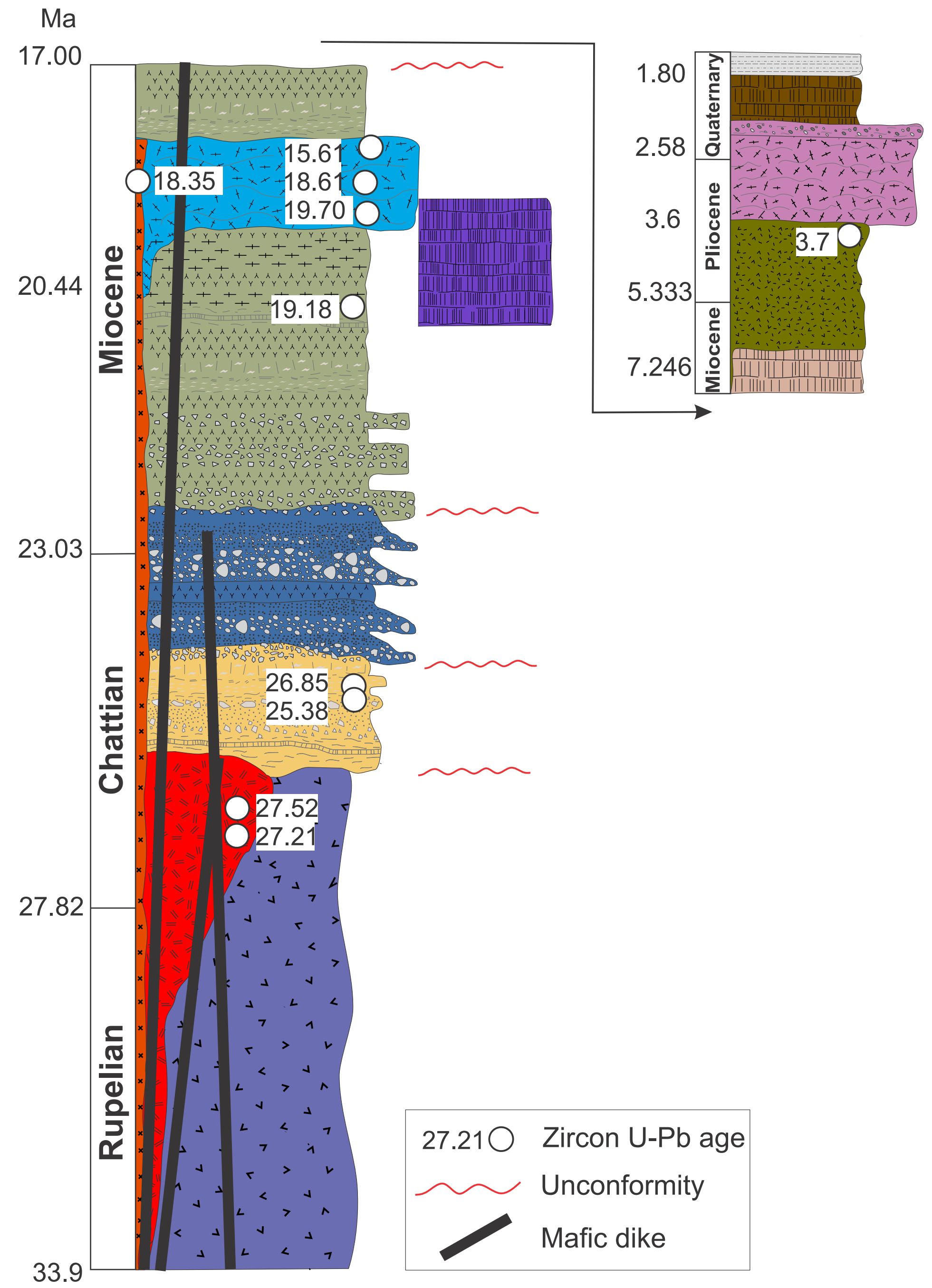




Trans-Mexican Volcanic Belt

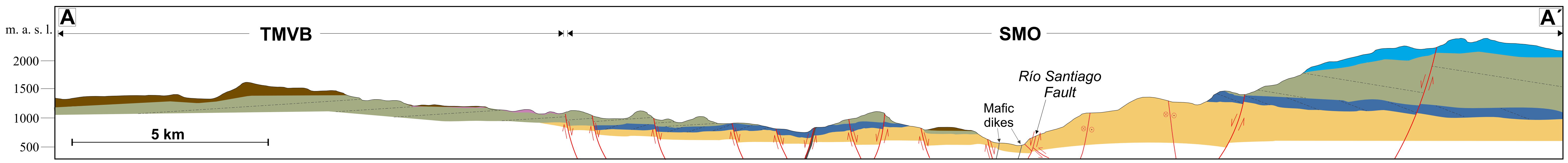
- Sandstones and conglomerates (Quaternary)
- Alkaline basaltic lava flows (Late Pliocene-Pleistocene)
- Rhyolitic domes and pyroclastic deposits (Late Pliocene-Pleistocene)
- Rhyolitic domes (Late miocene-Early Pliocene)
- Basaltic lava flows (Late miocene)

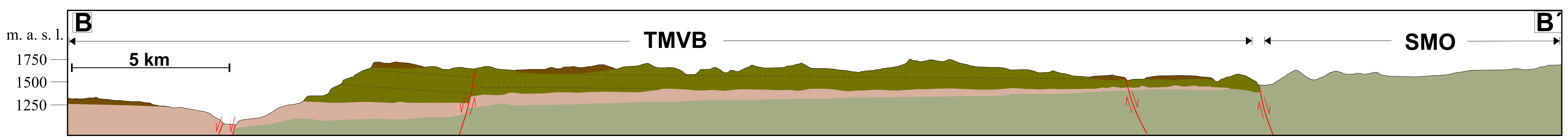
Sierra Madre Occidental

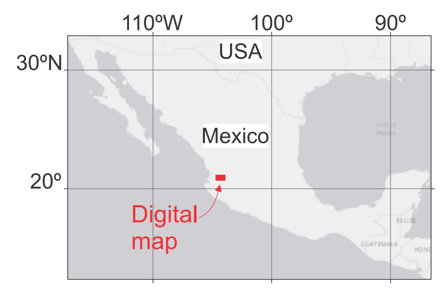
- La Playa Granite (~ 18.35 Ma)
- Basaltic lava flows (Early Miocene)
- El Vigía domes (~18.6 Ma)
- Monte del Favor ignimbrites (~19 Ma)
- Las Juntas Red Beds (Early Miocene)
- Río Santiago ignimbrites (~27- 25 Ma)
- Subvolcanic Granite (Chattian)
- San Pedro Analco Andesites (Eocene-Oligocene)

Jalisco Block

- Vulcanosedimentary and intrusive suite (Late Cretaceous)







N
Coordinate system
GCS_WGS_1984
kilometers
0 5 10

- Normal fault
- Reverse fault
- Left-lateral fault
- Right-lateral fault
- Right-lateral fault (cross section)
- Anticline
- Syncline
- Bedding attitude
- U-Pb ages
- Town
- Cross section
- Main road
- Secondary road
- Main river
- State boundary

veloped since the Oligocene along the RSSZ. A detailed analysis of this deformation will be presented in a forthcoming paper; here we present a brief summary of the tectonic evolution.

The Chattian Rio Santiago ignimbrites are affected by oblique reverse and lateral faults and en-echelon array folds in the Sierra El Pinabete region (see map plate). Reverse faults and its associated lateral faults are restricted to the Chattian ignimbrites while the open folds also affect the Monte del Favor ignimbrites (ages up to ~22.5 Ma). Locally, the RSSZ has favored the intrusion of subvolcanic bodies through NW-SE faults which are associated to epithermal deposits (~24 Ma; Camprubí et al., 2016) between San Pedro Analco and Cinco Minas, which are contemporary with the development of the reverse faults observed in La Yesca Dam and with the beginning of the folding north of the Santiago River. The early Miocene successions (Las Juntas Red Beds and Monte del Favor ignimbrites) are affected by E-W and NW-SE normal faults and show similar tilting, though more pronounced, to that displayed by the Pliocene rocks of the TMVB further south, which are affected by the youngest WNW-ESE normal faults of the northern branch of the Tepic-Zacoalco Rift.

7. Conclusions

Our new mapping, structural and geochronological data allow us to conclude the following:

- The older unit in the study area is represented by a package of andesitic lava flows which are undated but it is older than intrusive subvolcanic bodies dated 27.5 Ma.

- Together with felsic dikes and the Rio Santiago Ignimbrites these intrusive rocks represent a second magmatic event of Chattian age. The subvolcanic granite has been partly exhumed by the Cinco Minas and San Pedro Analco normal faults, which also expose a 24 Ma epithermal mineralization.

- Polyphasic deformation observed in the RSSZ can be summarized as follow: 1) a Chattian transpressional deformation locally recorded at La Yesca Dam and in the older activity of the Cinco Minas fault, associated to the emplacement of the Subvolcanic Granite, 2) early to late Miocene N-S extension that affect Las Juntas Red Beds and the Monte del Favor successions, which is represented by E-W normal faults between La Yesca Dam and Hostotipaquillo and 3) late Miocene-Pliocene extension associated to the development of the northern segment of the Tepic-Zacoalco Rift; this extensional phase affect both the SMO and the TMVB rocks and reactivated the structures of the previous deformation phases.

- The contact between the Rio Santiago ignimbrites and the Monte del Favor ignimbrites, as well as the base of the El Vigia lava domes lies at different topographic levels to the north and to the south of the Rio Santiago. This difference can be attributed to the occurrence of the wide deformation zone of the Rio Santiago Fault in between, which accumulates a vertical offset of up to 700 m.

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Interactive map:	10.22201/igg.25940694e.2022.1.96.204
Suppl. Material:	10.22201/igg.25940694e.2022.1.96.206