The transition between shortening and extensional regimes in central Mexico recorded in the tourmaline veins of the Comanja Granite

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A B S T R A C T

In central Mexico, there is a major angular unconformity separating two lithologic groups. Below the unconformity, the rocks display shortening deformation structures produced by the Laramide orogeny, overprinting those shortening structures there are normal faults related to the Cenozoic Basin and Range tectonics. Above the unconformity, the rocks are affected only by the Basin and Range tectonics, displaying mainly normal faults and in minor amount, lateral-oblique faults. We analyzed the Comanja Granite in the Sierra de Guanajuato, it is a large pluton that contains tourmaline veins. The Granite lacks of the shortening structures that pervasively affected the Mesozoic host-rocks; for this reason, we infer that the granite was formed after the main shortening event. We determined that the emplacement of the Comanja Granite took place between 51.0 ± 0.3 Ma and 49.5 ± 0.8 Ma, and that the tourmaline veins of the granite were formed at ~51.0 Ma. At the microscopic scale, the tourmaline veins contain three kinds of tourmaline, called T1, T2, and T3, according to the order of their formation. The T1 tourmalines are brown colored and appear affected by brittle-ductile (D1) and brittle (D2) deformations. The cataclasites formed during D2 overprinted the brittle-ductile structures of D1, indicating the transition from deeper to shallower levels. In contrast, T2 and T3 tourmalines were not involved in those deformations. At the outcrop scale, we identified two slickensides in the tourmaline veins. The older, related to D1, is strike-slip with a small thrust component and the younger, related to D2, is normal with oblique components. The T1 tourmalines (which are deformed) were formed before the lateral-thrust faulting, whereas the T2 and T3 tourmalines, which are not deformed, were deposited after the faulting occurred in the veins. Our interpretation is that T1 tourmalines were deposited in the later phases of the Comanja Granite emplacement, with the minimum principal compressional stress (σ3) being vertical, whereas the T2 and T3 were formed during the exhumation process of the Comanja Granite, with the minimum principal stress (σ3) being horizontal. We infer that the lateral-thrust faulting represents the transition between the Laramide shortening and the Basin and Range extension in the Sierra de Guanajuato. There are Paleogene intrusive bodies in the southern Mesa Central that were exhumed before the Oligocene. This observation strongly suggests that the uplift of the Sierra de Guanajuato could represent a wide event in the southern Mesa Central of Mexico.

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1. Introduction

In central Mexico there are two groups of rocks with a major angular unconformity between them (Nieto-Samaniego et al., 2005, 2007). Below the unconformity, pre-Cenozoic rocks are deformed by shortening. They exhibit structures varying from schist foliation to folds and thrust. Those deformation structures are related to at least two shortening events (Martini et al., 2016); the last one is attributed to the Laramide orogeny (Nieto-Samaniego et al., 2007; Tristán-González et al., 2009; Cuellar-
Cardenas et al., 2012). Above the unconformity, Cenozoic rocks are affected by brittle normal faults with some oblique and lateral faults, which have been related to the Basin and Range tectonics (Henry and Aranda-Gómez, 1992; Nieto-Samaniego et al., 2007; Tristán-González et al., 2009). The knowledge about the transition between the shortening and extension is very poor; only two studies are focused on this point: Tristán-González et al. (2009) presented a study about the tectonomagmatic evolution of the central and eastern Mesa Central (MC), focusing on the magmatic evolution more than on the structural or tectonic analysis. Botero-Santa et al. (2015) studied the structural evolution of the northern Sierra de Guanajuato. They inferred a transtensional phase arguing that the intrusion of the Comanja Granite is the evidence, because it required a large volume for the emplacement. The stratigraphic record of the Mesa Central indicates that emplacement and exhumation of some plutonic bodies, like the Comanja Granite, roughly occurred during the transition between Laramide shortening and the Basin and Range extension (Nieto-Samaniego et al., 2007).

In this contribution, we document the age and type of deformation occurred in the Sierra de Guanajuato during the transition between shortening and extension. Our study includes a detailed map of the faults and tourmaline veins in the southeastern zone of the Comanja Granite, and also an analysis of mineralogy and structures observed in the infill veins.

2. Analytical techniques

2.1. Mineral separation

Two dike samples (C2, TC32) and one sample of the main granite body (GC-08) were analyzed. The samples were crushed, powdered and sieved (200–50 mesh). Heavy mineral fractions with zircons were obtained by panning. Final mineral separates were hand-picked under a binocular microscope. Zircons were mounted in epoxy resin together with the standard proposed by National Institute of Standards and Technology (NIST), and polished. Laser ablation target points were selected after cathodoluminescence sample recognition in order to identify zircon cores and re-growth zones. 20 to 30 target points were selected in the most external zones of zircons for dating the latest crystallization phases. Some points were located in zircon cores to obtain additional data of inherited zircons.

2.2. U-Pb age dating

The zircon samples were analyzed at the laser ablation system facility at Laboratorio de Estudios Isotópicos (LEI), of the Centro de Geociencias, Universidad Nacional Autónoma de México. The laboratory consists of a Resonetics excimer laser ablation workstation (Solari et al., 2010), coupled with a Thermo XII-Serie quadrupole ICPMS. The laser ablation workstation operates a Coherent LPX 200, 193 nm excimer laser and an optical system equipped with a long working-distance lens with 50–200 μm focus depth. The ablation cell is He-pressure capable of fast signal uptake and washout. The drill size employed during this work was of 30 μm, and the drill depth during the analysis is about 20–25 μm, for a total mass ablated during each analysis of ~70–80 ng. Seventeen isotopes are scanned during each analysis including those necessary for U-Pb dating (lead, uranium and thorium), as well as detailed monitoring of major and trace elements such as Si, P, Ti, Zr and REEs. For each analysis, 25 s of signal background are monitored, followed by 30 s of signal with laser firing with a frequency of 5 Hz and an energy density of ~8 J/cm2 on the target. The remnants 25 s are employed for washout and stage repositioning. A normal experiment involves the analysis of natural zircon standards, as well as standard glasses. NIST standard glass analyses are used to recalculate the zircons U and Th concentrations. Repeated standard measurements are in turn used for mass-bias correction, as well as for calculation of down-hole and drift fractionations.

2.3. Microprobe analysis

Samples described in this paper were collected from various generations of tourmaline veins in the Comanja Granite. All elemental analyses of tourmaline were obtained from polished thin sections using a Cameca SX-100 electron microprobe at the Oregon State University (Oregon, USA). Analyses were conducted using a 15 kV accelerating voltage, 10 nA beam current and 5 μm beam diameter with counting times between 10 and 30 s. Raw data were corrected using a stoichiometric PAP correction model (Pouchou and Poirier, 1985) to a suite of natural and synthetic standards by microprobe software, which also provides estimates of lower limit of detection for each element.

3. Geologic context

The Sierra de Guanajuato (SG) is located at the southwestern limit of the Mesa Central physiographic province, central Mexico (Fig. 1). The first map of the SG was published by Martínez-Reyes (1992). He proposed two groups of lithostratigraphic units: the older group is Mesozoic and consists of Jurassic-Lower Cretaceous marine volcano-sedimentary strata, a plutonic suite including tonalite and diorite, zones of basaltic and doleritic dike swarms, and an outcrop of ultramafic rocks; all of these rocks were deformed by, at least, two shortening events (e. g., Ecchegoyán-Sánchez et al., 1975; Martínez-Reyes, 1992; Lapierre et al., 1992; Ortiz Hernández et al., 2003; Mortensen et al., 2008; Martini et al., 2011). Resting unconformably on the volcano-sedimentary rocks appears La Perlita fossiliferous limestone of Albian age, which was deformed by only one shortening event (Quintero-Legorreta, 1992; Martini et al., 2013). The younger group consists of continental Cenozoic formations which overlie the Mesozoic rocks by angular unconformity, and are affected by normal faults, indicating an extensional tectonic regime (Botero-Santa et al., 2015; Nieto-Samaniego et al., 2016). The base of the Cenozoic cover is a conglomerate with few intercalated lava flows and pyroclastic deposits. This conglomerate has been separated into two formations: (a) The Guanajuato Conglomerate that crops out in the Guanajuato City (Fig. 1) (Edwards, 1955; Ecchegoyán-Sánchez et al., 1970); its older age was obtained from a lava flow at 49 ± 1 Ma (K-Ar in plagioclase), which is intercalated towards the lower part of the conglomerate (Aranda-Gómez and McDowell, 1998). The conglomerate rests under a volcanic unit dated at 33.5 ± 0.48 Ma (Ar-Ar in K-feldspar, Nieto-Samaniego et al., 2016). (b) The second formation is the Duarte Conglomerate (Martínez-Reyes, 1992; Botero-Santa et al., 2015) that crops out along the SW front of the Sierra de Guanajuato. The Duarte conglomerate contains, in the lower part, rhyolitic lava flows of 53.4 ± 0.33 Ma (U-Pb in zircon, LA-ICPMS; Olmos-Moya, 2016) and underlies the Bernalejo andesite of 31.36 ± 0.24 Ma (U-Pb in zircon, LA-ICPMS, Botero-Santa et al., 2015). The Duarte conglomerate and Bernalejo andesite are covered by a pile of rhyolitic pyroclastic flows, andesite lavas and some rhyolite flows, which are Oligocene to Miocene in age (Olmos-Moya, 2016).

In the Sierra de Guanajuato is the Comanja Granite. It is a large pluton which intrudes the Mesozoic rocks and rests below the Cenozoic volcanic cover. The granite is formed of massive bodies and dikes, and the composition varies from biotite granite to granodiorite. The mineralogy consists of quartz (Qtz) + K-Feldspar (K-Feld) + plagioclase (Pl) + biotite (Br) and accessory minerals as
zircon, apatite and opaque minerals. The cooling age of the Comanja Granite was previously determined at 53.11 ± 0.27 Ma (Ar-Ar in biotite, Botero-Santa et al., 2015); similar dates (49.5 ± 1.5 to 51 ± 1.3 Ma) were obtained using K-Ar method in biotite by Stein et al. (1994).

4. The Comanja Granite

4.1. Field and petrographic description

The name Comanja Granite was introduced by Echegoyen-Sánchez et al. (1970). These authors described the unit as a batholithic granite body exposed from Comanja to the Mineral de la Luz (Fig. 1). The first complete map of the granite exposures was published by Martínez-Reyes (1992) and the main descriptions come from studies in the Comanja area (Yta and Chiodi, 1987; Quintero-Legorreta, 1992; Botero-Santa et al., 2015). The Comanja Granite forms a ~45 km long and 2–7 km wide quasi-continuous outcrop of granitic rocks (Fig. 1). In the Comanja area, Yta and Chiodi (1987) reported compositional variations from alkaline granite to quartz rich granite, and the presence of alkali-feldspar syenite xenoliths. Quintero-Legorreta (1992) reported a calc-alkaline composition based on mineralogy Qz > K-feldspar > Pl (albite-oligoclase) with biotite as ferromagnesian mineral. Petrographic description of Botero-Santa et al. (2015) in the same area is Qz + K-feldspar + oligoclase > biotite.

In the Comanja Granite it is very noticeably the presence of tourmaline veins with cataclastic or brittle-ductile structures. Also, there are faults or shear zones adjacent to those veins. The tourmaline veins do not appear in the Oligocene to Miocene units, they

Fig. 1. Regional geologic map showing the location of the study area. SMOc Sierra Madre Occidental, MC Mesa Central, SMOr Sierra Madre Oriental, FVTM Transmexican Volcanic Belt, A Aguascalientes, C Comanja, L Mineral de La Luz, D Duarte, G Guanajuato, SMA San Miguel de Allende, FB El Bajío Fault, Gvr Villa de Reyes Graben.
only are emplaced into the granite and in the contact metamorphic halo with the Mesozoic rocks. Because the tourmaline veins were emplaced just after the intrusion, their internal structures must register the earlier phases of deformation of the Comanja Granite.

We studied the Comanja Granite in the zone located around La Estancia (Fig. 2). There, the exposed area of the granite is roughly elliptic, 12 km long and 3.5 km wide, with the major axis oriented NW-SE. The exposed area of granite is ca. 30 km² and the maximum elevation difference is ca. 350 m. The granite intrudes marine mesozoic rocks (the Sierra de Guanajuato volcanosedimentary Complex) developing locally a metamorphic halo. The granite rests unconformably below andesitic lavas of Miocene age (Fig. 2).

In the center, the Comanja granite is mainly formed of wide intrusive bodies, more or less being homogeneous, which contain some dikes. In contrast, near the borders are abundant dikes. The wide intrusive bodies are homogeneous, commonly presents textural variations and without significant changes in the mineralogical composition. They are leucocratic phaneritic rocks, formed of quartz + oligoclase + orthoclase > biotite. Under the microscope the texture is holocrystalline, phaneritic, hypidiomorphic, with quartz (50%) > oligoclase (30%) > orthoclase (20%), the ferromagnesic mineral is biotite. Acicular tourmaline and zircon were identified as accessories.

4.2. Dikes

We grouped all the dikes of the Comanja Granite in four groups, according to the mineralogical composition, texture and the cross-cutting relationships.

The first group is formed of pegmatite dikes of coarse phaneritic texture, they contain miarolitic circular cavities with centimetric crystals (Fig. 3A). We observed many patches of pegmatite and schlieren structures, both are sub-parallel to the magmatic foliation. The mineralogy of the pegmatite dikes is orthoclase + quartz + biotite >> tourmaline.

The second group is formed of NW-SE leucocratic aplite dikes, with fine-grained phaneritic texture with quartz + K-feldspar + biotite (Fig. 3B). These dikes were observed cutting both the magmatic foliation and the pegmatitic dikes.

The third group is formed of K-rich feldspar dikes. They commonly have nuclei of tourmaline and K-feldspar alteration halos (Fig. 3C, D, 3E). The dikes are formed of K-feldspar (55%) >> quartz (30%) >> oligoclase (10%)>5% formed of hornblende, tourmaline, biotite and allanite; as accessory minerals we identified silex, ilmenite, apatite and zircon. Frequently, these dikes are associated with zones of cataclastite formed of tourmaline + quartz. In some cases, thin dikes could be confused with alteration zones around the quartz-tourmaline veins, but in detail, we could see the thin zone of quartz + K-feldspar that forms the dike. We observed dikes emplaced in the granite with cataclastic deformation in the core and ductile deformation in the contact with the granite. The dikes of the third group cut the dikes of the second group. We dated the sample C2 at 51.0 ± 0.6 Ma (U-Pb, LA-ICPMS in zircon) (Fig. 4A, Table 1 in supplementary data).

The fourth group is formed of green color granodiorite dikes of porphyric texture; the matrix is aphanitic to cryptocrystalline with chloritic alteration (Fig. 3D). Phenocrysts are quartz + plagioclase >> K-Feldespar + hornblende. We identified epidote, silex, zircon and apatite as accessory minerals. The dikes have disequilibrium textures showing embayed quartz crystal and the hornblende is replaced by chlorite and muscovite. The granodiorite dikes cut the tourmaline veins. We dated the sample TC-32 at 49.5 ± 0.8 Ma (U-Pb, LA-ICPMS in zircon) (Fig. 4B, Table 1 in supplementary data).

The first dike group was emplaced to the end of the main granitic intrusion under semi-plastic conditions, some with diffuse borders. The second group of dikes was emplaced in fractures with well-defined borders. The third group of dikes represents a minor
magma pulse associated with the main tourmaline event, emplaced under fragile-ductile conditions. The dikes of the fourth group are hypabyssal bodies emplaced at shallow depth, under brittle conditions and without associated tourmaline event.

4.3. The age of the Comanja Granite

Different isotopic ages have been obtained: Múgica-Mondragón and Jacobo-Albarrán (1983) reported two K-Ar ages in biotite, 55 ± 4 Ma and 58 ± 5 Ma; Zimmerman et al. (1990) two K-Ar ages in biotite of 53 ± 3 Ma and 51 ± 1 Ma; Stein et al. (1994) reported three K-Ar ages in biotite 52.9 ± 2.7 Ma, 51 ± 1.3 Ma and 49.5 ± 1.5 Ma; Botero-Santa et al. (2015) reported one Ar-Ar plateau age in biotite of 53.11 ± 0.27 Ma, one Ar-Ar isochron age in orthoclase of 53.63 ± 0.75 Ma, and one U-Pb age of 51.7 ± 0.2/-0.8 Ma using LA-ICPMS in zircon. In our study we dated the sample GC-08 obtaining 51.0 ± 0.3 Ma using U-Pb LA-ICPMS in zircon (Fig. 4C, Table 1 in supplementary data).

Using the mean values of the U-Pb ages obtained in our study and considering the dikes as part of the granite, we calculated that the Comanja Granite emplacement last 1.5 m.y. If we include the analytical errors, the maximum emplacement time is 2.6 m.y. These ages span into a reasonable time lapse for the emplacement of a large pluton as the Comanja Granite (Chesley et al., 1993; Schaltegger et al., 2009).

5. Faults and tourmaline veins in the study area

5.1. The major fault systems

The major fault systems in the study area are the El Bajío fault system and the Villa de Reyes Graben (Fig. 1). Both are formed of Cenozoic normal faults and have multiple reactivation phases (Nieto-Samaniego et al., 2007).

The El Bajío fault system is located west of the study area (Fig. 1). The accumulated dip-displacement of the Oligocene units has been estimated of 1200 m near León, Guanajuato, and the vertical displacement of middle Miocene units in El Cubilete range is ca. 500 m (Nieto-Samaniego et al., 2007). The system is formed of three sub-systems of faults: (a) A northwest trending arrangement of
linked fault segments forming a large fault zone that extends from León to the Presa Duarte. This fault zone constitutes the main contact between the Mesozoic and Cenozoic rocks (Fig. 2); field data collected along this fault correspond to minor associated faults and show a mean strike of N58°W and dip of 58°SW. (b) The second sub-system is formed of many overlapped or soft-linked NW individual faults that generally dip to the SW. Some of those structures appear buried by lithologic units recording different phases of activity (Fig. 2). (c) The third subsystem does not crop-out, it is buried by the alluvial deposits that fill the El Bajío basin. The existence of this subsystem has been inferred because the volcanic units in the foot-block are truncated and they appear below the fill-basin deposits, evidencing normal displacement of hundreds of meters (Ramos-Leal et al., 2007) (Fig. 2).

The Villa de Reyes Graben is a major NE structure that cuts the Sierra de Guanajuato near the study area (Fig. 1). In the central part of this graben the main displacement took place before the Miocene (Tristán-González, 1986). In the intersection zone between the two major systems, the El Bajío faults show well-defined scarp whereas the morphologic expression of the Villa de Reyes Graben disappears, indicating that the El Bajío fault displays the latest displacements.

5.2. The tourmaline veins

In the study area the Comanja Granite contains tourmaline veins (or faulted tourmaline veins) which appears in four main localities: One is near La Estancia, the veins trend WNW with dips to the NE and SW; the second locality is to the west of Mesa El Gallo, where the veins trend NW-SE to WSW-ENE and dip to the NE (Fig. 2). The two other zones are more discreet. One is located east of the Cerro Verde, in that place the faults and veins strike NW-SE with dips to the SW; the other is located in the northern part of the studied area, the faults and veins strike NW-SE and dip to the NE (Fig. 2). We describe in more detail the outcrops located in La Estancia and to the west of the Mesa El Gallo.

The observed structures are hydrothermal breccias, veins with fault planes, and anastomosing shear zones. The veins are formed of black tourmaline with fragments of granite and quartz. There are hydrothermal breccias that form subvertical poorly defined planes (Fig. 5A) and a few subhorizontal veins of tourmaline (Fig. 5B). The most common structures are sheared veins associated with faults, which contain well-defined striated planes (Fig. 5C). Most of those structures dip with moderate to high angles (Fig. 5D). The sheared veins exhibit slickensides, breccias, cataclasite, very thin bands of pseudotachylite and ribbons of quartz (Fig. 5E).

Tourmaline veins were formed close to the end of the Comanja Granite emplacement and are absent in other lithologic units, with exception of the Mesozoic rocks in the contact with the granite. The tourmaline deposit took place between 51 and 50 Ma because the tourmaline veins are younger than the Comanja Granite (51.0 ± 0.3 Ma), and dikes of the fourth group (49.5 ± 0.8 Ma) cut the veins.

Fig. 4. U–Pb isotopic ages from the Comanja Granite and dikes. The left column shows concordant U–Pb isotopic analyses of zircons. Central column represent the distribution of the analyzed zircons ordered by age; rectangles indicate the zircons used for mean age calculation, the discarded ages appear in grey. In the right column the mean weighted ages obtained from the younger zircons, with discordance <20%, which form a coherent group and have mean weighted age in agreement with the stratigraphic position. Analytical results are given in Table 1 (in supplementary data).
Thin sections of tourmaline veins show the presence of three tourmaline generations, recognized by the crystal habit, color, texture, crystal overgrowth and the chemical composition determined by electron microprobe (EMP) analysis. The older tourmalines (T1) are dark brown, anhedral to subhedral and constitute the microcrystalline groundmass (Fig. 6A and B). Within the shear zones there are cataclasites and angular to subangular granite and quartz fragments (Fig. 6A). They are considered as the older tourmalines because younger tourmaline crystals grow from this brown groundmass, or appear as euhedral crystals above it. Tourmalines of the second generation (T2) are brown at low magnifications and show bluish tonalities at high magnification. Crystals are euhedral to subhedral with acicular habit, filling fractures and commonly growing from T1 crystals; also appear within quartz crystals or granite fragments (Figs. 6B and 5C). Most of the observed T2 crystals are euhedral and do not show evidence of cataclasis. The tourmaline crystals of the third generation (T3) commonly are larger than crystals of T1 and T2; most of them are prismatic, euhedral and blue or brown colored (Fig. 6D). The T3 crystals appear on the quartz, on crystals of previous tourmalines, or on granite fragments. As the T2 tourmalines, T3 do not show evidence of cataclasism.

Based on the petrographic study, we selected T1, T2 and T3 crystals (28 T1, 16 T2 and 25 T3) for microprobe analysis on thin polish sections (Table 2 in supplementary data). Data were processed using WinTcac program (Yavuz et al., 2013) with normalization to 6 silicon atoms, based on the formula XY3Z6 (T6O18) (BO3)3W proposed by Henry et al. (2011), where:

\[ X = Na^{+}, K^{+}, Ca^{2+} \text{ or vacancy; } Y = Fe^{2+}, Mg^{2+}, Mn^{2+}, Zn^{2+}, Ni^{2+}, Cu^{2+}, Al^{3+}, Fe^{3+}, Cr^{3+}, V^{3+}, Ti^{4+}, Li^{+}; Z = Al^{3+}, Fe^{3+} \]
Cr³⁺, V³⁺, Mg²⁺, Fe²⁺; T = Si⁴⁺, Al³⁺, B³⁺; B = B³⁺; V = OH⁻¹, O²⁻; see the results in Table 3 (in supplementary data). In Fig. 7A the samples fall in the alkali and X-site vacancy groups. Most of the T1 are alkali tourmalines, whereas T2 and T3 samples are more scattered in alkali and X-site vacancy groups (Fig. 7A). The alkali tourmalines are Fe rich and correspond to schorl variety with few exceptions of dravite composition (Fig. 7B), whereas the tourmalines of the X-site vacancy group are foitite (Fig. 7C).

In Fig. 7B there are samples of the same generation dispersed from Fe rich to Mg rich, and there are tourmalines from different generations with similar composition. We suggest that the compositional superposition among T1, T2 and T3 occurs because younger tourmalines grew from older tourmalines, resulting in the observed compositional changes during crystal growth. Fig. 7D illustrates the phenomenon: A single (T2) crystal sampled in the base and final parts exhibits different compositions. The lowermost parts have alkali-schorl composition, similar to the T1 tourmalines because crystal grew from a T1 tourmaline. In the tip, the crystals change to X-vacancy-dravite, which reflects a change of composition of T2 fluid with respect to T1 fluid composition.

In summary, samples show that hydrothermal system responsible for the tourmaline veins evolved from alkali Fe-rich phase (T1) to X-vacancy Mg-rich phase (T2). The compositional variations of T3 in Fig. 3A suggest the third event of tourmalines also grew partially from T1 and T2 tourmaline crystals. This behavior could be interpreted like the evolution from proximal-intermediate to distal location of the hydrothermal system (Pirajno and Smithies, 1992).

6. Deformation events

The progressive shallow levels of deformation were evidenced by the mineralization events and structures observed in the tourmaline veins. The older tourmaline (T1) was deformed by the D1 deformation phase under brittle-ductile conditions together with parts of the granitic host rock. Some crystals of quartz appears stretched forming ribbons and strips of recrystallization (Fig. 8A). At microscopic scale we observed clasts of T1 tourmaline forming sigma-delta structures, some of them in cataclastic regime and others with recrystallization tails (Fig. 8B).

During the deformation phase D2, most of the veins were sheared in cataclastic regime, with low or null crystal-plastic strain. Within the veins, the cataclastic zones cut the ductile deformed areas. We identify protocataclasite mainly formed of angular clasts; cataclasite formed of very fine material with angular clasts (Fig. 6A); and small zones of ultracataclasite formed of dark material with few or without crystals (Fig. 8A). Pseudotachylite is present forming very thin bands of black material, which is isotropic under polarized light (Fig. 8A).

The D3 deformation phase produced the observed brittle faults that cut the tourmaline veins. This faulting event took place after of the deformation that occurred within the tourmaline veins. The T2 tourmaline is observed without cataclastic deformation, it forms acicular crystals growing from T1 tourmaline (Fig. 6B and C). The last tourmalinization event T3 was less intense than T1 and T2, and represents the final hydrothermal activity related with the Comanja Granite. T3 tourmaline is scarce and was not observed participating in the cataclastic deformation. The crystals are euhedral and appear isolated onto T2 and T1 tourmaline crystals (Fig. 7). These relationships permit to reconstruct the following sequence of events: After the emplacement of the main granite body, a pneumatolytic-hydrothermal episode formed the F-rich tourmaline T1. The presence of undeformed subhorizontal veins indicates that the hydrothermal fluids did not reach the surface. The D1 deformation phase took place under brittle-ductile conditions. The ductile deformation that affects only the quartz indicates a moderate temperature and low strain rate. The T1 tourmaline veins were intensely sheared, in contrast to the granite that presents scarce faults or shear zones. We interpreted that veins acted
Fig. 7. Composition of the tourmalines. A: most of T1 belong to alkali group whereas most of T2 belong to X-site vacancy group indicating an evolution of the hydrothermal events. B: Li-Fe-Mg tourmaline classification diagram (modified from Hawthorne and Henry, 1999) of the x-vacancy group analysis, where most of the tourmalines are schorl. C: Li-Fe-Mg tourmaline classification diagram (modified from Hawthorne and Henry, 1999) of the alkali group analysis, most of the tourmalines are foitite; B and C diagrams show the Fe-rich character of all tourmalines. D: example of the change in composition along the T2 crystals; from the base (star) to the tip of the crystal (triangle) the composition changes from alkali to x-vacancy and from Fe-rich to Mg-rich. Plots were elaborated with WinTcac program (Yavuz et al., 2013).
as planes of weakness accommodating most of deformation. The dikes of the fourth group cut the tourmaline veins, indicating the D1 deformation phase and T1 occurred after the emplacement of the main granite body (51.19 ± 0.33 Ma), and before the emplacement of the fourth group of dikes (49.5 ± 0.8 Ma). The D1 deformation phase in the study area was also inferred from the lateral-thrust slickensides observed in the tourmaline veins of La Estancia and Mangas de la Estancia zones. The inversion of these fault-slip data indicates a lateral-thrust fault regime with N35°/C14°W principal shortening (Fig. 9A). We consider this faulting corresponds to the D1 deformation phase (brittle-ductile) because it is the old deformation registered in the tourmaline veins. The D1 deformation phase is coeval with the last intrusions of the Comanja Granite indicating their emplacement was under shortening-transpressional regime. These events coincide with the end of the Laramide orogeny deformation in central Mexico, considering the ages proposed by Cuéllar-Cárdenas et al. (2012).

The cataclastic shearing of D2 deformation phase, occurred in a brittle regime, was superposed to the brittle-ductile deformation phase D1. The cataclastic event did not affect the tourmaline T2, or the tourmaline event was active after the main cataclasis. It is noticeably that many pseudotachylite bands were formed contemporaneously with cataclasites evidencing a very high strain rate. We observed an intense normal faulting superimposed to the lateral-thrust event. Normal faulting affects the same tourmaline veins affected by the lateral-thrust faulting and without exemption, the normal-oblique slickensides overprint the lateral ones. Inverting the fault-slip data of La Estancia and Mangas de la Estancia, we
obtained a normal-oblique fault regime with the principal horizontal extension oriented N23°E (Fig. 9). We associate the D2 deformation phase with the normal faulting, because occurred on the same veins affected by the lateral-thrust faulting and before the last tourmaline T3 that is not affected by the cataclasis. Within the veins, the younger tourmaline T3 is not deformed although normal faulting continued long after. An extensional phase D3 has been well documented in all the Mesa Central of Mexico from Eocene to, at least, the Miocene (Tristán-González et al., 2009; Nieto-Samaniego et al., 2007).

The sequence of tourmaline → semi-ductile faulting → tourmaline → brittle faulting suggests that hydrothermal events were contemporaneous with the granite exhumation process. The progressive unloading depressurized the granite and could produce successive hydrothermal episodes. The hydrothermal fluids moving throughout fractures and faults at high pressure could promote displacements by reducing the effective normal stress. Our observations are in agreement with the occurrence of feedback among exhumation, tourmalinization and faulting events (Fig. 10).

7. Discussion

Cuéllar-Cárdenas et al. (2012) documented that deformation of the Laramide Orogeny has been still active after 62 Ma in San Luis Potosí, which is located 100 km to the north of the study area. In the mapped area, the older undeformed rocks are rhyolitic lavas of 53.4 ± 0.33 Ma intercalated in the Duarte Conglomerate (Olmos-Moya, 2016). Then, the shortening deformation of the Laramide orogeny finished between 62 and 53 Ma (Thanetian-Selandian) in the Sierra de Guanajuato, giving a post-tectonic character to the Comanja Granite.

Some authors proposed Eocene strike-slip faulting in the MC before the Oligocene extensional phase (Tristán-González et al., 2009; Botero-Santa et al., 2015), but nowhere the Eocene lateral faults have been documented. The strike-slip phase was inferred from the displacements observed in outcrops of Mesozoic strata (Tristán-González et al., 2009), by using paleomagnetic directions in Eocene and Oligocene rocks (Andreani et al., 2014), or arguing that a transitional strike-slip regime is needed to change from a shortening regime to extension (Botero-Santa et al., 2015). In this contribution we document lateral-thrust faults in the Comanja Granite that were active during the Ypresian (51 Ma). These faults represent a transient phase between the shortening (σ3 vertical) and extensional (σ1 vertical) tectonic regimes. The large volume occupied for the Comanja Granite, the presence of not-sheared horizontal tourmaline veins and the results of fault-slip inversion (Fig. 9) are stronger arguments for the granite emplacement with σ3 vertical. The magma may have ascended with σ3 horizontal, but for installing the large granite body in the crust, σ3 has to change to
vertical. In the literature, the favored mechanisms for emplacement of large plutons are laccolith inflation and sill-stacking (e.g., Vigneresse et al., 1999; Menand, 2011). For both mechanisms the local c3 must be vertical (Menand, 2011). The general (regional) tectonic stress regime could be different, but it tends to be changed to vertical c3 due to the intrusion process itself (Vigneresse et al., 1999). It is clear that large plutons can be intruded in different tectonic regimes; however, a regional c3 vertical is more favorable for magma accumulation.

Within the Sierra de Guanajuato the extension continued during the Oligocene and Miocene. Fig. 9C shows that poles of tourmaline veins fall along a great circle that have a pole oriented 290.5°/08° (trend/plunge). This axis is the line around which the tourmaline veins rotated. Because the tourmaline veins are of Eocene age, we interpreted this axis as the rotation tilting axis around which the whole range tilted to the NE throughout the Oligocene-Neogene.

The evolution of the state of stress in the Sierra de Guanajuato during the emplacement-exhumation of the Comanja Granite is illustrated in the Fig. 10. For the Laramide shortening regime with the stress state of Fig. 10A, the vertical stress (σv = lithostatic pressure) is σ3. The maximum principal compression σ1 is horizontal and oriented ~ NE-SW, as has been inferred from the strike of thrust faults that cut the tourmaline deformed rocks (Martini et al., 2016; Botero-Santa et al., 2015). The stress difference (σ1−σ3) must be the adequate to touch the envelope line of the Mohr circle. According to Byerlee (1978), the envelope line was drawn using a slope of 0.85, considering a depth lesser than 10 km. The end of the Laramide orogeny implies diminishing of the σ1 stress, and σ2 decreasing due to the Poisson ratio (ν) of the granite. The Fig. 10B shows the situation of strike-slip faulting with a minor thrust component observed in the tourmaline veins. The NE-SW stress (σ1) decreases and it is transformed into σ2; in this way, we have the σ1 oriented ~ NW-SE, as was obtained from fault-slip inversion (Fig. 9A). As σ1 and σ2 decreased, the radius of the Mohr circle diminishes and does not touch the envelope line. The field observations show that lateral-thrust faults was coeval with intense hydrothermal activity responsible of tourmaline veins formation. The presence of hydrothermal fluids in the faults is equivalent to introduce a pore pressure in the system, and the Mohr circle is moved to the left. Introducing the pore pressure it is possible the slip on the fault planes (Fig. 10B). The Fig. 10C corresponds to the extensional regime. The magnitudes of σ1 and σ2 decrease until they are lesser than σν. The Mohr circle is small but it can touch the envelope line with or without pore pressure.

The Comanja Granite is not an isolated case of exhumed intrusive of Eocene age: in the Sierra de Catorce, S. L. P., there are granitic bodies of ca. 45 Ma (Mascunano et al., 2013); in Penón Blanco, S. L. P., there is a granite dated in 50.94 ± 0.47 Ma, with tourmaline veins very similar to Comanja Granite (Aranda-Gómez et al., 2007). The outcrops of intrusive bodies similar to the Comanja Granite suggest that the uplift and/or exhumation of the Sierra de Guanajuato could occur in a wide area of the southern Mesa Central of Mexico, although not necessarily at the same time. We must consider that the end of the Laramide shortening has not the same age in the whole MC.

8. Conclusions

The emplacement of the Comanja Granite lasted 1.5–2.4 m.y. It initiated with the intrusion of the main body at 51.0 ± 0.3 Ma and culminated with the intrusion of the granodiorite dikes at 49.5 ± 0.8 Ma. A large amount of tourmaline veins were formed at ca. 51.0 Ma coeval with lateral faults with a minor thrust component. We recognized three phases of tourmaline, T1, T2 and T3 in chronological order, which vary in composition from Fe-rich alkali-line schorl to Mg-rich X-site vacancy tourmaline. We inferred three phases of deformation: D1 took place under brittle-ductile conditions and produced lateral faulting with small thrust components. D2 was normal faulting with oblique components that overprinted the structures of D1 and formed cataclasites and pseudotachylites. Both phases of deformation are recorded within the tourmaline veins and affected only the T1 tourmalines. D3 consists of brittle faults that cut the tourmaline veins. Our interpretation is that T1 tourmalines were formed in the last phases of the emplacement of the Comanja Granite, whereas the T2 and T3 were formed after the cataclasis (D2) and during the exhumation process of the Comanja Granite.

Prior to the intrusion of the granite, the tectonic regime in the Mesa Central was horizontal shortening associated with the Laramide orogeny. The lateral-thrust faulting (D1) occurred after the Laramide shortening and before the Basin and Range extension. We propose that D2 represents the transition between the Laramide and Basin and Range tectonic regimes.

The exhumation of the Comanja Granite initiated at ca. 51 Ma (Ypresian). This event could be a wide process in the southern Mesa Central because there are other Paleogene plutons which were exhumed before the Comanja Granite.

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Appendix A. Supplementary data

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.jsames.2016.12.004.

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