U-Pb geochronology and Hf isotopes of the Grenvillian Río Hondo gneisses, Puebla: Redefining the western edge of Oaxaquia

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ABSTRACT

In situ Río Hondo (Puebla, southern Mexico) gneiss samples, as well as clastic samples recovered from the nearby outcropping latest Paleozoic Matzitzi Formation, a fluvial unit mainly sourced by Grenvillian rocks, were historically interpreted as representative of the northernmost exposures of the Oaxacan Complex, the largest outcrop of ortho and metasedimentary units, made up of mostly 1.0–1.3 Ga protoliths, affected by local migmatization (ca. 1.1 Ga) and granulite facies metamorphism at ca. 0.98 Ga, constituting the most prominent outcrop of the Oaxaquia microcontinent.

U-Pb geochronology and Lu–Hf isotopic determinations in zircon by LA-(MC)-ICP-MS were performed on both in situ and clast samples. In situ basement samples record a ca. 1.2 crystallization event, together with a younger one at ca. 1.02 Ga. Both lacking inherited >1.3 Ga components. The clasts have an unimodal zircon U-Pb age distribution, recording a crystallization event at ca. 1.2–1.27 Ga. Scarce inherited zircon cores between ca. 1.4–1.6 Ga were found, with only a few samples with a broader age distribution, suggesting a detrital protolith with zircon cores as old as ca. 1.8 and 2.4 Ga. No zircon overgrowths or geochemical-petrographic evidences are indicative of granulite metamorphism. Furthermore, all the studied metaigneous samples show discordant zircon ages produced by Pb loss events barely constrained between the latest Paleozoic to the Mesozoic.

Hf isotopes reveal that zircon crystals from clasts have a range of εHf (1.25 Ga) ≈ +1 to +5 and yield Hf model ages from 1.7 to 1.9 Ga. On the other hand, the Th zircon Hf isotopes of one analyzed basement sample reveal a higher range of εHf (1.25 Ga) ≈ +7 to +9, and Hf model ages from 1.5 to 1.6 Ga.

Both ca. 1.2 Ga and 1.02 Ga events are consistent with magmatic ages previously documented elsewhere in Oaxaquia, interpreted as indicating portions of the NW Amazonia-Oaxaquia arc system with cratonic influence or to slices of Baltica thrust over Oaxaquia during the Grenville orogeny. However, the absence of granulite facies indicators, such as zircon metamorphic ages and/or granulite paragenesis (typically, in other Oaxaquia samples, orthopyroxene and garnet) are interpreted as prime evidence that the studied samples didn’t undergo such high grade of metamorphism. Río Hondo gneisses, as this sequence is informally named, must belong to a source that had the influence of an older continental crust and can be tentatively associated either with rocks recently described in the Sierra de Juárez, or those belonging to the central basement of the Maya block, currently exposed farther to the SE in Chiapas.

Keywords: Grenville orogen; Oaxacan Complex; Mexico; U-Pb geochronology; Hf isotopes.
INTRODUCTION

The ca. 0.95–1.3 Ga Grenville orogen is one of the most studied and complete tectonic systems that emerged during the Proterozoic. It is the result of the amalgamation of the supercontinent Rodinia, originated by the convergence of Laurentia, Baltic, and Amazonia (Li et al., 2008; Cawood et al., 2013). Mexico is considered the site of a significant portion of such basement, which constitutes the ca. 0.95–1.3 Ga, N-S framework of the microcontinent Oaxaquia (e.g., Ortega-Gutiérrez et al., 1995; Ortega-Gutiérrez et al., 2018). While such units crop out discontinuously along the Mexican territory, the Oaxacan Complex (OC) exposed in southern Mexico constitutes the most extensive and continuous outcrop of approximately 7000 km² (Figure 1). Several papers in the last two decades documented the tectonic history of the OC basement rocks, primarily using geochronology and isotopic techniques (e.g., Keppie et al., 2001 and 2003; Solari et al., 2003, 2004, 2014 and 2021; Weber et al., 2010; Weber and Schulze, 2014; Adame-Martínez et al., 2020), mainly focusing on several localities in the Oaxaca State.

In this paper, we present new geochronology and isotopic data of a previously unstudied locality situated north of those mentioned above, in the Coatepec and Río Hondo creeks of the southern Puebla state, which constitutes the northernmost known direct outcrop of gneissic rocks south of the Quaternary Trans Mexican Volcanic Belt (Figure 1, inset). This locality is tectonically crucial because it lies exactly E of the Caltepec fault zone, a dextral transform shear system, interpreted by Elias-Herrera and Ortega-Gutiérrez (2002) and Elias-Herrera et al. (2005) as the tectonic, accretionary boundary between the Mixteco (Acatlán Complex) and Zapoteco (Oaxacan Complex) terranes during the mid-Permian. In situ samples are complemented with gneiss boulders found in the unconformable conglomerate of the late Permian-Early Triassic Matzitzi Formation (Bedoya et al.,

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2021; Martini et al., 2022) to contribute to the study of the Proterozoic basement of southern Mexico and to refine the tectonic models in which Oaxaquia interplayed with other crustal blocks, leading to the final assembly of Rodinia.

**GEOLOGIC SETTING**

The studied area is located in the Coatepec Creek, in the southern Puebla state, where the latest Permian-mid Triassic fluvial Matzitzi Formation unconformably overlies a small outcrop of high-grade gneiss interpreted as belonging to the OC (Figure 2, see also Elías-Herrera et al., 2005).

The OC, the most prominent outcrop of Grenvillian granulite-facies rocks in Mexico, crops out almost continuously in southern Mexico, from the central valleys of the Tehuacán-Oaxaca region, almost to the Middle America Trench nearby Pochutla (Figure 1a). Solari et al. (2003) defined the Zapotecan orogeny as the ca. 990 Ma granulite-facies metamorphism widespread not only in the OC but also throughout Oaxaquia (ca. 730–850 °C and 7.5 ± 1 kbar; Mora and Valley, 1985; Solari et al., 2004). Before that event, several magmatic pulses were recognized: intraplate, tholeiitic anorthosite-mangerite-charnockite-granite (AMCG) magmas, dated at ca. 1020–1005 Ma in the northern OC (Keppie et al., 2003; Keppie and Dostal, 2007), but also recognized in the Novillo Gneiss (ca. 1030 Ma, Cameron et al., 2004), in the Huiznopala Gneiss (anorthositic gabbro dated at 1007 ± 3 Ma, Lawlor et al., 1999), and in the Guichicovi complex (Weber and Kohler, 1999). ca. 1280–1150 Ma alkaline, intraplate gabbro, syenite and charnockite were also recognized in the OC and Huiznopala Gneiss (Lawlor et al., 1999; Keppie et al., 2001, 2003), as well as in the Guichicovi Complex (ca. 1230 Ma, Weber and Kohler, 1999; Weber et al., 2010) and the Novillo Gneiss (ca. 1170 Ma, Cameron et al., 2004). Older magmatic pulses were also reported locally, in some of the same outcrops, with peaks at around 1.4 Ga (Weber and Schulze, 2014). Scarc granulite orthogneisses were also described as characterized by an arc-like geochemical signature, at least in the southern OC (Keppie et al., 2001) and in Huiznopala (Lawlor et al., 1999), thus reflecting the similar association of arc and backarc (intraplate) protoliths described by Weber and Hecht (2003) in the Guichicovi Complex.

A wealth of Hf isotopes has been published during the last decade on granulite-facies Oaxaquia rocks, pioneered by Weber et al. (2010) and Weber and Schulze (2014), who defined a primitive field named “typical Oaxaquia,” characterized by εHf values ranging from +5 to +7, which would correspond to a marginal or oceanic arc setting, distinguishing it from a second more evolved group (primarily based on samples from the Huiznopala Gneiss), named “continental Oaxaquia” and probably allochthonous. The less evolved crustal precursor was already connected to the active continental margin of NW Amazonia during the ca. 1.2 Ga arc magmatism. During this time, partial melting of the different crustal precursors would have occurred and the different Hf isotopic signatures (“typical Oaxaquia”, “continental Oaxaquia” or the continuum between these fields) would be attributed to varying amounts of less evolved material and recycled crustal components (Weber et al., 2010; Weber and Schulze, 2014; Ibanez-Mejia et al., 2015, Solari et al., 2021). A more extensive database by Solari et al. (2021) on samples belonging to the northern OC somewhat elaborates on this concept, showing that most OC samples have εHf values constituting a continuum from more primitive values to more evolved ones, in which the continental Oaxaquia field constitutes an end member, whose protoliths had an estimated TDM age of ca. 1.5–1.7 Ga.

Figure 2. Geologic map of the studied area. Modified from Elías-Herrera et al. (2011), Juárez-Zúñiga et al. (2021), and Martini et al. (2022).
The Matzitzi Formation (Weber, 1997; Centeno-García et al., 2009; Juárez-Zúñiga et al., 2020; Bedoya et al., 2021; Martini et al., 2022) is a fluvial unit representing an anastomosing channel that was active during the latest Permian. According to the model proposed by Martini et al. (2022), the Matzitzi Formation was deposited during the early rifting of equatorial Pangea during the latest Permian. While it is mainly composed of coarse to medium-grained sandstone, the portion deposited just above the outcropping gneisses constitutes a very coarsely-grained conglomerate, with well-rounded boulders as large as 50 cm in diameter. The boulders consist of gneisses (the focus of this work), although volcanic (andesitic, dioritic, and rhyolitic) and granitic clasts of variable dimensions and, principally, of Permian age are also present (e.g., Juárez-Zúñiga et al., 2020). Some of the granitic boulders are in the age range of the nearby Cozahuico granite, ca. 270 Ma, associated with the Permian shearing along the dextral, transpressional Caltepec shear zone (e.g., Elias-Herrera and Ortega-Gutiérrez, 2002; Elias-Herrera et al., 2005).

In this work, we studied some in situ gneiss samples, which we called Rio Hondo gneisses, and some of the gneissic boulders found in the Matzitzi conglomerate. With this strategy, we would characterize the high-grade gneisses, for which there are no available data, being the known, studied localities of the OC about 90 km farther to SSE (e.g., Solari et al., 2003), as well as the gneiss boulders, to determine whether they all resemble the in situ samples or if some of those found have distinct characteristics, in terms of mineralogy, age, and isotopy.

METHODS

After crushing, heavy minerals were concentrated from the selected samples by conventional separation techniques (e.g., Solari et al., 2007). Handpicking and mounting of zircon grains were performed under a binocular microscope, followed by epoxy pouring, curing, and polishing. Cathodoluminescence (CL) imaging was carried out using a luminoscope connected to a stereographic microscope to resolve internal structures, choose the spots to be analyzed, and eventually help the interpretation of the geochronological results. While the whole of the CL images is available in Jaramillo-Jaramillo (2020), one example of those images (one boulder and one in situ sample) is available as Figure 1 of the Supplementary Material.

U-Pb zircon geochronology was performed at the Laboratorio de Estudios Isotópicos (LEI), Centro de Geociencias, Universidad Nacional Autónoma de México, employing the methodology reported by Solari et al. (2018) by laser ablation inductively-coupled plasma mass spectrometry (LA-ICP-MS). All U-Pb analyses were obtained by coupling a Thermo ICap Qc quadrupole mass spectrometer with a Resonetics Resolution M050, 193 nm ArF excimer laser-ablation system. A 23 µm spot was employed for all U-Pb determinations, with a measured fluence of 6 J/cm2. The international standard zircon 91500 was used as the reference standard (Wiedenbeck et al., 1995), whereas the Plešovice zircon (ca. 337 Ma; Sláma et al., 2008) as the control (secondary) standard. NIST 610 synthetic glass was also used as an external standard to recalculate the elemental concentrations, employing 28Si as an internal standard in zircon. The three standards were interspersed along the whole analytical sequence, repeating their measurement twice for each of the ten unknown zircon analyses. The raw data were reduced offline using Iolite v. 4.1 (Paton et al., 2011) and the VizualAge data reduction scheme of Petrus and Kamber (2012). The same software performed the quadratic error propagation of the standard zircon grains (91500) on the unknowns. During these analyses, the control standard yielded a mean 206Pb/238U age of 338.2 ± 1.6 Ma, in agreement with its accepted age. Concordia and mean age diagrams were generated using IsoplotR (Vermeesch, 2018). The obtained data were filtered for discordance, removing those analyses that yielded >30% normal and >5% inverse discordance. All the analyzed isotopic and elemental concentration data are available in the Supplementary Material Table S1.

Hf isotopes were measured in situ by LA-MC-ICP-MS on some of the zircon grains previously dated by U-Pb. Hf analyses were conducted using a spot of 44 µm in diameter, right on top of the 23 µm spot used for the U-Pb analyses, employing the same zircon mount washed in ultrapure water before the run session. The methodology is the same as that of Ortega-Obregón et al. (2014). The Neptune Plus Jet interface was used to improve sensitivity in laser mode, achieving a tuning (parameters in Table 1) optimized to maximize the Hf signal, minimize oxide formation, and avoid the formation of rare-earth element (REE) oxides (cf. Payne et al., 2013), as well as control the mass bias. Once correctly tuned, the high sensitivity of the Neptune Plus allowed an average total Hf signal of more than 10 V (Table S2 of the Supplementary Material), a value that is similar to and, in many cases, exceeds other works with a similar setup (e.g., Gerdes and Zeh, 2009; Fisher et al., 2011). We avoided analyzing Hf in those zircon grains that were too small for the 44 µm spot size or those that yielded discordant U-Pb ages. Tuning was thus performed in NIST 610 standard glass, employing the same analytical conditions used during analyses (Table 1). 9–10 mL/min of N2 was added to the He carrier gas before the plasma, to increase plasma temperature and decrease oxide formation. Compared to U-Pb laser ablation analyses, downhole fractionation is not an issue for Hf analyses, but the correction for interferences of Yb and Lu is of seminal importance (e.g., Woodhead et al., 2004; Hawseshworth and Kemp, 2006; Gerdes and Zeh, 2009). To correctly apply power laws and correct for those interferences, the Yb mass bias was calculated using the measured 172Yb and 175Yb masses and the Chu et al. (2002) Yb isotope abundances, together with the 172Yb/173Yb “true” ratio of 1.35274. The 176Lu was also measured, but due to the absence of a second interference-free Lu isotope, the Yb mass bias was applied instead, assuming similar fractionation behavior between Yb and Lu. The 176Lu/177Lu ratio of 0.02656 was also used (Blichert-Toft and Albarede et al., 1997). This type of correction allows accurate and precise results to be obtained, as demonstrated by repeated analyses of several natural standard zircon grains, commonly analyzed for Hf isotopes (Table S2 Supplementary Material), and by the repeated analyses of the synthetic zircon grains of Fisher et al. (2011) doped with different amounts of REEs. These synthetic zircon grains, which contain a REE range higher than terrestrial zircon crystals, were also used to include the external reproducibility and propagate it onto the internal two standard error (2SE; i.e., twice the standard error of the mean, defined as in Paton et al., 2011; Fisher et al., 2014) measured in unknown zircon grains (e.g., Fisher et al., 2014). The raw data obtained with our analytical setup were processed off-line with a data reduction scheme written in Iolite, which corrects the detected interferences, normalizes against the reference zircon (synthetic zircon grains of Fisher et al., 2011), and propagates the external reproducibility. The 176Hf/177Hf normalizing value of 0.7325 (Patchett and Tatsumoto, 1981) was used. The 176Hf/177Hf decay constant of 1.876 × 10^{-11} (Scherer et al., 2001) and the chondritic Hf values of Bouvier et al. (2008) were used to calculate εHf and depleted mantle (DM) model ages (TDM). The εHf and TDM, calculated employing the chondritic and depleted mantle values, respectively, were generally considered as reflecting minimum ages for the zircon’s host magma source. A second model age (TDM2) was then calculated using a value for the average continental crust of 176Lu/177Hf = 0.015 (Griffin et al., 2002) to ideally project the initial εHf of zircon grains to the depleted mantle model curve and infer possible zircon sources.
Table 1. LA-ICPMS and LA-MC-ICPMS parameters employed during the analytical sessions.

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<th>Acquisition parameters for Hf analyses</th>
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<td>Ablation time</td>
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Tuning $^{238}$U in NIST 610 (raster at 32 mm), max sensitivity, checking the following parameters:
- U/Th: 1–1.1
- UO/U: <0.2 %
- ThO/Th: <1 %
- Average tuning achieved: >600 mV $^{238}$U

Tuning $^{177}$Hf in NIST 610 (raster at 32 mm), max sensitivity, checking the following parameters:
- U/Th: 1–1.1
- UO/U: < 0.2 %
- ThO/Th: < 1 %
- Average tuning achieved: 90–100 mV $^{177}$Hf

Cup configurations

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<tr>
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Iolite v. 4
Data reduction

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Chu et al., 2002
U-Pb RESULTS

We dated four in situ samples, two collected south of Coatepec and the other two along the Río Hondo Creek, about 7 km south of Coatepec (sample locations in Figure 2). Further, 12 samples were boulders extracted from the conglomerate at the unconformity between the outcropping gneisses and the Matzitzi Fm. The petrographic characteristics of the studied samples are reported, together with the U-Pb results for each sample.

In situ samples

Sample M50 is a quartz-feldspar gneiss made up of quartz, feldspar (perthitic and microcline), plagioclase, biotite, and scarce green amphibole, frequently altered to chlorite (Figure 3a). We dated 35 zircon crystals from this sample, which yielded a concordant age distribution of ca. 1200–1250 Ma (Figure 4a). Several grains are discordant, probably due to Pb loss. A discordia line traced through the analyzed samples gives an upper intercept of 1237.8±8.2 Ma, interpreted as the protolith crystallization age of this sample. The lower intercept of 265.6±10.6 Ma is a possible indicator of the Pb loss time.

Sample M40 is a fine-grained granular igneous rock made up of quartz, perthite, plagioclase, and scarce opaques (Figure 3b). Secondary alteration (e.g., sericite in plagioclase, calcite) accounts for post-crystallization and fluid-induced weathering processes. Thirty-five zircon grains were separated and dated. They are ovoidal to prismatic in shape, often with bi-pyramidal terminations. Most of the concordant ages cluster between ca. 1000 to ca. 1030 Ma (Figure 4b).

About a third of the dated zircon show discordant ages, aligning along a discordia line that goes from an upper intercept of 1024.7±8.4 Ma, interpreted as the age of crystallization, to a poorly constrained lower
intercept of 107.8±16.6 Ma, possibly indicating an episode of Pb loss during the Mesozoic.

Sample RH22-1 is a quartz-feldspathic gneiss collected about 5 km south of Caltepec, along Rio Hondo Creek. We dated 100 spots on zircon grains separated from these samples. Most of the analyzed zircon, both core and rims, are concordant. At the same time, some are variably discordant due to Pb loss (Figure 4c). They define a discordia, with an upper intercept of 1022.4±10 Ma, interpreted as the protolith crystallization age and a poorly constrained lower intercept of ca. 95 Ma, indicative of a Mesozoic thermal disturbance.

Sample ME23-1 is a deformed granitoid made up of quartz, sericitized plagioclase, microcline, and it hosts poikilitic garnet, with some reaching sizes up to 4 mm (Figure 3c). This sample was collected along the Rio Hondo Creek, about 1 km W of sample RH-22-1. Sixty spots were analyzed to sample the core and rims of the predominantly prismatic grains. Out of the dated grains, 58 passed the discordia filters. The resulting analyses (Figure 4d) are mostly concordant, with a group, represented mainly by core analyses, spanning between 855 to 1315 Ma (two other grains are even older, aged 1458 and 1970 Ma). A second group, mainly represented by high luminescent rims, has ages ranging between 250 and 300 Ma (Figure 4d, inset). While the Proterozoic cores probably inherited zircon grains from the protolith, the high luminescent Permian rims indicate the granite crystallization.

Figure 4. U-Pb geochronological data of in situ dated samples. All error ellipses and reported ages are at two sigma.
Boulder samples

After conducting petrographic analysis, we selected and dated 12 samples belonging to boulders collected in the conglomerate cropping out E of Coatepec at the structural bottom of the Matzitzi Formation. The selected samples are quartz-feldspathic gneisses; some have a barely foliated structure, while others have a more polygonal grain arrangement (examples in Figure 3d to 3f). In the thin section (we studied about 50 of them to choose those to be dated), only two of them had Fe-Mg bearing minerals (in one case, poikilitic garnet and, in another, 2 pyroxene grains) aside from quartz, plagioclase, feldspar (microcline and perthite), oxide minerals and accessory such as apatite, zircon, epidote, few allanite. Red biotite is sometimes observed, together with uncolored to pale-green amphibole of the second generation (after the breakdown of primary mafic minerals, impossible to distinguish).

Despite the petrographic variations, ten of the dated boulders have the same age behavior (Figure 5a to 5j), with most of the dated zircon grains concordant and some that define a variable discordia. The upper intercepts defined by concordant grains range from 1192.2±7.8 Ma to 1268.8±7.2 Ma, interpreted as indicative of the protolith’s crystallization ages. The lower intercepts are generally poorly constrained but indicate different thermal episodes leading to Pb loss, mostly during the Mesozoic (middle Cretaceous to Late Triassic). The other two dated boulders, namely, samples M4Ca and M3Cg, are not petrographically different and are still classified as quartz-feldspar gneisses. However, they differ in the age behavior since most of the dated zircons in each are concordant but straddling the Concordia curve in a wide age range (ca. 920 to 1295 Ma for sample M4Ca and ca. 1010 to ca. 1800 Ma for sample M3Cg, respectively, Figure 5k and 5l). This behavior is typical of sedimentary protoliths, to which these boulders are tentatively ascribed.

Hf isotope results

Nine of the dated samples, eight belonging to boulders and one in situ sample, were chosen to perform Hf isotope determinations by LA-MC-ICPMS for approximately 100 analyses performed (Table S2).

εHf(t) values for each analyzed zircon were calculated concerning the depleted mantle (DM) reference values. From the DM curve, the first five εHf units were considered juvenile, the following five moderately juvenile, and the remainders evolved, indicating isotopically more evolved sources (Bahlburg et al., 2011).

For all the studied zircon grains belonging to the chosen samples, the εHf(t) values, recalculated to the zircon crystallization age, fall in a restricted range limited to positive values, from +0.78 to +8.5 (Figure 6a). Only the in situ sample (M50) presents zircon analyses falling in the juvenile field. In contrast, all the boulder samples are moderately juvenile, with only eight analyses straddling the evolved field.

Assuming a Hf isotopic evolution similar to the average continental crust, with a ratio of \(^{176}\text{Lu}^{177}\text{Hf} = 0.015\) (e.g., Griffin et al., 2002, dotted lines in Figure 6), the obtained data indicate \(T_{\text{DM}}\) ages between 1.5–1.6 Ga for the in situ sample M50 (U-Pb crystallization age of 1237 Ma, see above and Figure 4a), whereas the moderately juvenile studied boulders suggest a derivation from an older crustal component of a ca. 1.7–1.9 Ga.

**ZIRCON GEOCHEMISTRY**

Zircon geochemistry obtained by LA-ICPMS evidence how the totality of studied grains is suggestive of igneous crystallization, with chondrite-normalized REE plots with increasing HREE content, negative Pr and Eu anomalies as well as marked Ce and Sm ones (Figure 7). In general, the decreasing, discordant zircon ages are accompanied by a decreasing of Yb/Gd ratio. In contrast, an increase of \(\sum\text{LREE} / \text{MREE}\) normally accompanies the decrease in ages (arrows in insets in Figure 7). This behavior is often associated to hydrothermalism or microinclusions in the analyzed zircon grains (e.g., Zhong et al., 2018). The igneous interpretation is also supported by the Th/U ratio (see Table S1), always \(>0.01\), a value often taken as discriminant between zircon igneous and metamorphic crystallization (see discussion in Harley et al., 2007). Sc/Yb vs. Nb/Yb and U/Yb vs. Nb/Yb tectonic discrimination diagrams (Grimes et al., 2015) show how all the zircon samples fall in the continental arc domain (Figure 8a and 8b).

**DISCUSSION**

**Age and isotopic interpretation**

The combination of data presented here allows us to unravel the existence of two age groups in this basement block: the oldest of roughly 1200–1270 Ma (sample M50, in situ, and most of the boulder’s upper intercepts), followed by a younger event at ca. 1022–1024 Ma (two in situ samples). A common feature of all those studied samples, presumably of igneous origin, is that they all show strong evidence of post-crystallization (Phanerozoic) Pb loss. On the other hand, M4Ca and M3Cg boulders, as well as the fourth studied in situ sample (meta granitoid ME23-1), present a distinct age distribution pattern, characterized by primarily concordant zircon grains, which straddle the concordia curve but are not affected by any post-crystallization Pb loss event. The Pb loss in igneous samples is sometimes poorly constrained. However, it roughly indicates events constrained from the Permian to the Mesozoic, which in principle coincide with late Paleozoic magmatism and deformation described in the area (Elias-Herrera and Ortega-Gutiérrez, 2002; Elias-Herrera et al., 2005; Juárez-Zúñiga et al., 2020), and tectonic reorganization during and at the end of the Gulf of Mexico opening (Bedoya et al., 2021; Martini et al., 2022).

While there is no doubt about the Proterozoic crystallization ages of the studied samples, there is an extensive range for their metamorphic ages. The absence of granite facies metamorphism, as previously described in the neighboring rocks of the Oaxacan Complex (e.g., Solari et al., 2003 and 2014), is clear. However, it is also evident that these gneisses’ metamorphism predates the Permian partial melting and mylonitization of the Cozahuico granite and deposition of the Matzitzi Fm. (e.g., Elias-Herrera et al., 2005 and Martini et al., 2022). By comparison, two Precambrian localities of similar gneisses were recently described, with U-Pb metamorphic ages of ca. 940 Ma: the Catarina Unit in the Chiapas Massif Complex (Valencia-Morales et al., 2022) and the Pochotepec suite in the nearby Sierra de Juárez Complex (Espejo Bautista et al., 2023). It is possible that the Río Hondo gneisses shared the same metamorphic history, although at a lower metamorphic grade since the zircon grains do not show a clear metamorphic overgrowth. Alternatively, the Río Hondo gneisses could constitute a different region that didn’t undergo Precambrian metamorphism and was thus only affected by a Phanerozoic event.

The obtained Hf isotope data allow comparison with similar data published for the Grenvillian rocks of Mexico (e.g., Weber et al., 2010; Weber and Schulze, 2014; Solari et al., 2021) and NW South America (e.g., Garzón, La Macarena and Guapotón Massifs in Colombia, Weber et al., 2010 and Ibañez-Mejía et al., 2015). In particular, the Río Hondo M50 sample is as primitive as granulite samples OC1019 and OC1015 (south of Ejutla and west of S. María Peñoles, respectively, see Solari et al., 2021), which have crystallization ages of ca. 1350–1400 Ma. The remainder of boulders have εHf(t) values slightly more primitive than the typical Oaxaquia field of Weber et al. (2010), resembling the
Figure 5. U-Pb geochronological data of boulder dated samples. All error ellipses and reported ages are at two sigma.
Figure 5 (cont.). U-Pb geochronological data of boulder dated samples. All error ellipses and reported ages are at two sigma.
values previously obtained in meta gabbro and metasyenite samples OC0008 and OC1007 by Solari et al. (2021). These comparisons can be applied to illustrate the similarities between the TDM obtained in the Río Hondo gneiss samples, both in situ and boulders, and those calculated for the OC, between 1.5–1.65 Ga for the typical Oaxaquia, without discarding a more evolved and older crustal component for those samples yielding slightly negative εHf(t) values (cf. Weber et al., 2010; Solari et al., 2021). Similar conclusions can be extrapolated by plotting the εHf(t) values vs. the 176Lu/177Hf corrected values measured in zircon of the Río Hondo samples, together with those reported by Solari et al. (2021) for the OC samples (light brown samples in Figure 9). There is an almost complete overlap between Río Hondo and OC Hf data, reinforcing the idea that this crustal segment had a common derivation, as a mixing of a juvenile component of ca. 1.5–1.65 Ga, and mechanical incorporation of an even older crustal component of ca. 1.9 Ga, at least in some of the more evolved samples.

**Tectonic implications**

The calculated ages situate the main magmatic event that formed the Río Hondo sequence in two pulses that occurred in the Mesoproterozoic (ca. 1200–1270 and ca. 1025 Ma), while the sample’s Hf isotopic signature suggests consanguinity with Oaxaquia rocks. The striking difference is related to the absence, in the Río Hondo samples, of granulite facies metamorphism that is always observable in the not-so-far Oaxacan Complex and, more in general, in the whole Oaxaquia outcrops. These findings imply that the Río Hondo gneisses probably belong to an external, marginal unit of the main Oaxaquia orogen, that did not suffer the Zapotecan metamorphism (Figure 10a to 10e). Instead, a lower metamorphic grade, as that shown elsewhere by the ca. 940 Ma units which didn't undergo granulate metamorphism and were interpreted as outer units concerning the orogen core (Catalina Unit in Chiapas, Valencia-Morales et al., 2022; Pochotpec suite in the Sierra de Juárez Complex, Espejo-Bautista et al., 2023) would help to reconcile the absence of evident zircon recrystallization (cordelia diagrams of Figures 4 and 5), with the clear metamorphic overprint that the Río Hondo metaigneous rocks suffered.

The discovery of the Río Hondo gneisses as an external Oaxaquia unit also has implications related to the Acatlán Complex formation and its tectonic juxtaposition against the Oaxacan Complex. These two concepts, described in recent years and several papers (e.g., Elías-Herrera and Ortega-Gutiérrez, 2002; Elías-Herrera et al., 2005; Keppie et al., 2016 and 2018) will require further studies to be fully sustained. Our data point in indicating that the Río Hondo gneisses are, in fact, in tectonic contact with the Acatlán Complex along the Caltepec fault zone (and that they represent the protolith that undergoes partial melting to generate the Cozahuico granite and migmatites, e.g., our sample MEH23-1). Furthermore, having similar TDM as the Oaxacan Complex, but a lower grade of metamorphism and more hydrated mineralogy than the Oaxacan Complex granulite they are, at least in principle, more fertile to generate granitic melts, such as the Ordovician granitoids widespread in the Acatlán Complex and studied by Keppie et al. (2018). These two hypotheses are compelling and will require further studies to be proven or discarded.
Figure 7. Chondrite-normalized REE analyses for the studied samples. Insets in each plot correspond to the variation of Yb/Gd and ∑LREE with age, respectively. (continues)
Figure 7 (cont.). Chondrite-normalized REE analyses for the studied samples. Insets in each plot correspond to the variation of Yb/Gd and ∑LREE with age, respectively.
Figure 8. Sc/Yb vs. Nb/Yb and U/Yb vs. Nb/Yb discrimination diagrams for the zircon crystals analyzed in this work. In situ samples are represented by squared symbols, whereas clast samples with round ones. The continental arc, OIB and MORB fields, as well as the grey area representative of the mantle-zircon array, are from Grimes et al., 2015.

CONCLUSIONS

The Río Hondo sequence consists of Mesoproterozoic (ca. 1200–1270 and ca. 1025 Ma) metaigneous rocks, metamorphosed under medium-grade conditions. Isotopically they resemble rocks elsewhere found in Oaxaquia (e.g., the nearby Oaxacan Complex), with $T_{DM}$ ages of ca. 1.5–1.65 Ga, and some minor reworked crustal components of ca. 1.9 Ga. The absence of granulite-facies metamorphism, indicative of the Zapotecan event widespread in Oaxaquia, points toward an element that escaped those extreme metamorphic conditions. Although further studies are required to demonstrate its tectonic significance fully, we hypothesize that the Río Hondo sequence is directly related to the Paleozoic magmatic genesis of the Acatlán Complex.

Figure 9. $\varepsilon$Hf vs. initial $^{176}$Lu/$^{177}$Hf corrected ratios of the studied samples, compared with similar values of the Oaxacan Complex zircon grains obtained from Solari et al. (2020), light brown circles.
SUPPLEMENTARY MATERIAL

The Figure 1S and Tables S1 and S2 can be downloaded from the website of this journal www.rmcg.unam.mx at the abstract's preview page of this paper.

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