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Ferrari, Luca, Lopez-Martinez, Margarita, Orozco-Esquivel, Teresa, Bryan, Scott E., Duque-Trujillo, Jose, Lonsdale, Peter, & Solari, Luigi (2013) Late Oligocene to Middle Miocene rifting and synextensional magmatism in the southwestern Sierra Madre Occidental, Mexico: the beginning of the Gulf of California rift. Geosphere, 9(5), pp. 1161-1200.

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https://doi.org/10.1130/GES00925.1
Late Oligocene to Middle Miocene rifting and syn-extensional magmatism in the southwestern Sierra Madre Occidental, Mexico: the beginning of the Gulf of California rift

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Keywords: Gulf of California rift, Sierra Madre Occidental silicic province, geochronology, extensional tectonics, syn-extensional magmatism
ABSTRACT

Although Basin and Range-style extension affected large areas of western Mexico since the Late Eocene, most workers consider that extension in the Gulf of California region, began as subduction waned and ended at ~14-12.5 Ma. A general consensus also exists in considering the mid-Miocene Comondú group as subduction-related whereas post ~12.5 Ma volcanism has been identified as extension-related. Here we present a new regional geologic study of the south-east Gulf margin (Sinaloa and Nayarit states, Mexico), backed by 43 new Ar-Ar and U-Pb mineral ages and geochemical data that document an earlier and widespread phase of extension across the southern Gulf Extensional Province between late Oligocene and early Miocene, which subsequently focused in the region of the future Gulf in the Middle Miocene. Late Oligocene to early Miocene rocks across northern Nayarit and Southern Sinaloa were affected by major ~N-S to NNW striking normal faults prior to ~21 Ma. Then, between ~21 and 11 Ma, a system of NNW-SSE high-angle extensional faults continued extending the southwestern side of the Sierra Madre Occidental. Rhyolitic domes, shallow intrusive bodies, and lesser basalts were emplaced along this extensional belt at 20-17 Ma. Rhyolites, in particular the domes and lavas, often show strong antecrystic inheritance but only a few Mesozoic or older xenocrysts, suggesting a genesis in the mid-upper crust triggered by an extension-induced basaltic influx. In northern Sinaloa, large grabens were occupied by huge volcanic dome complexes at ~21-17 Ma and filled by continental sediments with interlayered basalts dated at 15-14 Ma - a stratigraphy and timing very similar to that found in central Sonora. Early to middle Miocene volcanism was thus emplaced in rift basins, and was likely associated with decompression melting of upper mantle (inducing crustal partial melting) rather than by fluxing of fluids from the young subducting plate. Along the Nayarit and Sinaloa coast and at Farallon de San Ignacio island off-shore Los Mochis, flat-lying basaltic lava flows dated at ~11.5 to 10 Ma are exposed just above the present sea level. Here, crustal thickness is almost half that in the unextended core of the Sierra Madre Occidental, implying significant lithosphere stretching before ~11 Ma. This mafic pulse, with subdued Nb-Ta negative spikes, may be related to the detachment of the lower part of the subducted slab, allowing an upwards asthenospheric flow into parts of the mantle previously fluxed by subduction fluids. Appearance of very uniform OIB-like lavas occurred by the late Pliocene and Pleistocene, only 20 m.y. after the
onset of rifting and ~9 m.y. after the end of subduction, implying the pre-existing subduction-modified mantle had now become isolated from melt source regions. Our study shows that rifting across the southern GEP began much earlier than Late Miocene and provided a fundamental control on the style and composition of volcanism from at least 30 Ma. We envision a sustained period of lithospheric stretching and magmatism during which the pace and breadth of extension changed at ~20-18 Ma to be narrower, and again after ~12.5 Ma, when the kinematics of rifting became more oblique.
INTRODUCTION

In the past 30 Ma the western North American plate margin has switched from convergence to highly oblique divergence through a complex interaction with the Pacific plate that produced two pairs of parallel structures: the San Andreas fault system and the Eastern California Shear Zone-Walker Lane (ECSZ-WL) in the US, and the San Benito-Tosco-Abreojos fault system and the Gulf of California rift in Mexico (Figure 1). In both regions strike-slip deformation has moved inland so that at present, the ECSZ-WL accommodate ca. 25% and the Gulf of California ca. 90% of the Pacific – North American relative plate motion (Wesnousky, 2005; Plattner et al., 2009). Stretching of the continental lithosphere preceded direct interaction of the Pacific and North America plates and produced the Basin and Range composite extensional province (Dickinson, 2002). In Mexico, the Basin and Range episode of extension is recognized across a wide region north of the Trans-Mexican Volcanic Belt (e.g., Henry, 1989; Henry and Aranda-Gomez, 1991, 2000; Calmus et al., 2010) (Figure 1) although the western limit of this extension has been poorly defined. More focused extension in the Gulf area, bounded to the west by the Main Gulf Escarpment of Baja California and to the east by the “unextended core” of the SMO, has been referred to as the “Gulf Extensional Province” (GEP) (Gastil et al., 1975) (Figure 1) or the proto-Gulf (Karig and Jensky, 1972). Early studies (e.g, Stewart, 1978; Henry, 1989) argued that proto-Gulf rifting substantially preceded the formation of a Pacific-North America plate boundary at this latitude (i.e. ~14-12.5 Ma) i.e. they occurred when subduction was still occurring. However, after the influential work of Stock and Hodges (1989) most authors (Henry and Aranda-Gómez, 1992, 2000; Umhoefer et al., 2001, 2011; Fletcher et al., 2007; Lizarralde et al., 2007; Seiler et al., 2011; Sutherland et al., 2012; Miller and Lizarralde, 2013) have assumed that extension in the Gulf region began only at the end of middle Miocene, when subduction ended and the onset of transfer of Baja California to the Pacific plate began. In fact, the Lower to Middle Miocene rock units forming the Comondú Group in southern Baja California were interpreted as distal to proximal facies of a continental arc located to the east (i.e. in the present Gulf) that constituted a topographic high (e.g. Hausback, 1984; Dorsey and Burns, 1994; Umhoefer et al., 2001; see also Figure 13B in Fletcher et al., 2007). In the past two decades workers have debated the onset of oblique rifting in the Gulf (e.g. Stock and Hodges, 1989; Gans,
1997; Oskin and Stock, 2003; Fletcher et al., 2007; Miller and Lizarralde, 2013), but a general consensus has existed that considers the Gulf opening as a fundamentally post-subduction event, controlled by the highly oblique, NW-ward motion of Baja California that was able to rift the continental lithosphere in just ~6-10 Myr (Umhoefer, 2011).

Separating extension of the GEP from that of the Basin and Range is particularly challenging in the northern part of the SMO (Figure 1) (see discussion in Calmus et al., 2010). In fact in Sonora and Chihuahua extension has affected the entire volcanically active region, and appears spatially contiguous and temporally continuous, leading to different opinion about the boundary between the two extensional provinces (Figure 1). In western Chihuahua extension is poorly dated but affects ignimbrites as young as ~29 Ma (McDowell and Mauger, 1994) and is considered to have started at ~30 Ma on the basis of geochemical considerations (Cameron et al., 1989; McDowell and Mauger, 1994). Near the Chihuahua-Sonora border extension has been recently established by detailed geologic mapping and geochronology at ~27-25 Ma (Murray et al., in press). In central Sonora, clastic sedimentation in extensional basins as well as development of metamorphic core complexes began almost concurrently along a ~200 km wide zone at the end of Oligocene and continued throughout the middle Miocene (McDowell et al., 1997; Gans, 1997; Gonzalez-León et al., 2000; Vega-Granillo and Calmus, 2003; Nourse et al., 2004; Wong and Gans, 2003; Wong et al., 2010). Low-angle detachment faulting in the core complexes waned by 15 Ma (Wong et al., 2010), but high angle normal faulting continued until ~8.5 Ma in coastal Sonora (McDowell et al., 1997; Mora-Alvarez and McDowell, 2000; Roldán-Quintana et al., 2004). In their pioneer work Gastil et al. (1975) placed the eastern limit the GEP in the coastal region of Sonora. Stock and Hodges (1989), in turn, extended it to the western SMO (Figure 1), thus including the belt of early to middle Miocene core complexes. More recently Calmus et al. (2010) placed the boundary at the Longitude of Hermosillo (Figure 1) considering that extension to the west is younger than 12 Ma. In this way they reiterate the notion that rifting in the Gulf is a post-subduction process.

Pre-late Miocene extension has been also reported in a few locations in the northern Gulf, although it has been generally neglected because it has been overprinted by late Miocene-Pleistocene deformation. In Baja California, Late Oligocene to middle Miocene extension is reported at Bahía de Guadalupe (~24-14 Ma; Axen, 2003), whereas extension at least
partially concurrent with the Basin and Range of central-western Sonora is documented near the Main Gulf Escarpment of northern Baja California at Sierra el Mayor (~15-10 Ma; Axen et al., 2000) and southern Sierra de Juárez (16-11 Ma; Lee et al., 1996) (Figure 1). Micropaleontological studies of deep wells drilled in the Wagner, Consag, and Tiburón basins (Figure 1) also suggest the presence of shallow marine sedimentation in some areas of the northern Gulf in middle Miocene (Helenes et al., 2009). These data contrast with the geology of Isla Tiburón (Oskin et al., 2003; Bennett et al., 2012)(Figure 1) which clearly indicates that marine incursion at this site is latest Miocene. Despite contrasting interpretations about the timing of marine sedimentation (see also the discussion section), an early onset of extension in the northern Gulf region cannot be ruled out and the possibility exists that the Basin and Range and the GEP can be at least partly overlapping in space.

Cenozoic magmatism preceding and accompanying the development of the Gulf has also been divided into two different episodes, supposedly controlled by the tectonic setting at the plate boundary. Oligocene and early Miocene silicic to bimodal volcanism comprising the Sierra Madre Occidental (SMO) silicic large igneous province in mainland Mexico as well as the middle Miocene intermediate Comondú Group in Baja California have for many years simply been interpreted as the expression of supra-subduction arc magmatism (e.g., Sawlan and Smith, 1984; Sawlan, 1991; Hausback, 1984; Umhoefer et al., 2001), whereas the appearance of more heterogeneous magma types (adakites, Nb-enriched basalts, magnesian andesites etc.) after 12 Ma has been associated with the development of the oblique-divergent plate boundary (see reviews in, Pallares et al., 2008; Calmus et al., 2010). Implicit in this view is the idea that a given tectonic setting should be promptly and clearly reflected in magma composition. However, the use of geochemistry to track the transition from subduction to rifting has been proved inconclusive in Sonora (Till et al., 2009) and is challenged also in Baja California, where calc-alkaline volcanism has been emplaced well after subduction ended, and until the Pleistocene (Martin-Barajas et al., 1995; Biggioggero et al., 1995; Schmitt et al., 2006; Calmus et al., 2010).

On the other hand, it has been shown that the dominantly silicic SMO volcanics have a strong crustal contribution (Ruiz et a., 1988; 1990; Albrecht and Goldstein, 2000; Bryan et al., 2008; this work) such that the calc-alkaline and other subduction-related signatures like
Nb-Ta depletions essentially reflect the composition of the crust involved in partial melting and do not directly provide any constraints on the tectonic setting of magmatism. Rapid large scale crustal melting during the Oligocene and early Miocene (Ferrari et al., 2007) is atypical of modern subduction zones and indicate that the SMO cannot be classified as a normal volcanic arc. In a similar line of reasoning, the origin of the compositionally distinctive, but volumetrically minor intermediate volcanism of the Comondú Group in southern Baja California is more consistent with mixing and hybridization in upper crustal reservoirs promoted by an ongoing extensional tectonics, and the architectural characteristics of the group are more akin to emplacement in continental extensional basins than to a constructive volcanic arc (Bryan et al., 2013).

Due to poorer access and, partly, security reasons, the southeastern side of the Gulf has been comparatively less studied than the western side in Baja California. This region, comprising the state of Sinaloa, the northern part of Nayarit, and the western part of Durango, Zacatecas and Jalisco (Figure 2), includes both the unextended core of the SMO and the GEP (Figure 1). A better definition of the onset of rifting in the southeastern side of the Gulf can help to define the timing of extension in the whole GEP. In pioneering work, Henry and Fredrikson (1987) and Henry (1989) suggested that extension in Sinaloa adjacent to the Gulf of California might be as old as Late Oligocene based on the age of a few dated NNW trending dikes in the region, and a maximum age of 17 Ma was reported for extensional faulting. Subsequent works have assumed that the GEP in this area developed since the end of Middle Miocene (Henry and Aranda Gómez, 2000; Ferrari et al., 2002; Aranda Gómez et al., 2003; Sutherland et al., 2012) although geologic studies and radiometric ages to support this interpretation were restricted to a number of locations.

In this paper we present results of a regional geologic study supported by 43 new $^{40}\text{Ar}-^{39}\text{Ar}$ and U-Pb ages (Figures 3, 4 and 5) and geochemical data that test the possibility of an early extension in the southern GEP. We document a Latest Oligocene to middle Miocene phase of extension concurrent with the early Miocene episode of the SMO silicic volcanism and show that significant crustal thinning was accomplished before the end of subduction at 14-12.5 Ma. We conclude that distinguishing Neogene magmatism and extension in western Mexico into two-stages with a separate subduction and rifting history is incorrect, as crustal extension and decompression-driven mantle melting and crustal melting have
been the controlling factors since at least the end of Oligocene. In this perspective, Basin and Range extension and particularly the bimodal volcanism of the SMO represent the initial stage of a long rifting process that led to the formation of the Gulf of California.

METHODS

Geologic mapping

Few geological studies exist for the southeastern border of the Gulf of California and, where available, are mostly at a reconnaissance level (Henry and Fredrikson, 1987; Henry, 1989; Ferrari et al., 2002). A first regional geologic synthesis was presented in Ferrari et al. (2007) based on the available literature data and the integration of 1:250,000 scale maps published by Servicio Geológico Mexicano (Mexican Geological Survey, SGM) completed in 2002. In the past decade, the SGM has systematically mapped many quadrangles at 1:50,000 scale (freely available at: http://mapserver.sgm.gob.mx/cartas_impresas/productos/cartas/cartas50/geologia50/numcarta50.html), thus improving the regional geologic database. Although these maps generally have a good field control they often lack absolute age information. For the purpose of this study we have compiled a new regional geologic map through the reinterpretation of the 1:50,000 scale maps of SGM incorporating our new geochronologic data and fieldwork carried out between 2006 and 2010. The map design and integration was accomplished through the use of Google Earth Pro and Quantum GIS (http://www.qgis.org/).

Geochronology and geochemistry

Previous geochronologic data were limited and unevenly distributed across the studied region. McDowell and Keizer (1977) dated by K-Ar the ignimbrite successions along the Durango-Mazatlán highway and some of these samples were later re-dated by $^{40}\text{Ar} - ^{39}\text{Ar}$ (McDowell and McIntosh, 2012), but without any significant change to the assigned ages. Henry and Fredrikson (1987) and Henry et al. (2003) reported U-Pb, Thermal Ionization Mass Spectrometer (TIMS) and K-Ar ages for plutonic and volcanic rocks in southern Sinaloa. Ferrari et al. (2002) provided $^{40}\text{Ar} - ^{39}\text{Ar}$ ages of the main ignimbrite sequences in northern Nayarit. Additional, sparse, K-Ar and $^{40}\text{Ar} - ^{39}\text{Ar}$ ages mostly without geologic
context are found in Damon et al. (1979), Solé et al. (2007), and Iriondo et al. (2003, 2004). However, large areas of the SMO in Sinaloa still lack geochronologic data.

As discussed elsewhere in the literature, the main problem with the K-Ar dating method is its inability to detect thermal resetting or excess Ar (Faure and Mensing 2005). As a further complication, laser ablation–inductively coupled plasma–mass spectrometry (LA-ICP-MS) zircon dating of SMO ignimbrites (Bryan et al., 2008) revealed significant age discrepancies, beyond analytical error, between U-Pb zircon and K-Ar or \(^{40}\text{Ar}^{39}\text{Ar}\) biotite and feldspar ages. In several cases, the discrepancy reflected the incorporation of xenocrystic and antecrystic zircons that skewed the population age toward ages older than the eruption. Inheritance signatures particularly plague zircons from early Miocene rhyolites (see also Ramos Rosique, 2012; Murray et al., in press), which are suspected to be extensive in the study area. A fundamental conclusion of these recent studies in neighboring areas in the SMO is the importance of stratigraphic control on dated samples and the requirement to “double date” by both \(^{40}\text{Ar}^{39}\text{Ar}\) and LA-ICP-MS techniques to obtain stratigraphically relevant ages (Bryan et al., 2008), an approach that we have followed in this study for critical samples. We are aware that the term antecrysts is not univocally used in the literature. In this paper we maintain the use we adopt in a previous paper on the SMO silicic volcanism (Bryan et al., 2008), where zircons with ages up to 3-4 Myr older than the eruption age are considered antecrysts associated with one of more episodes of remelting within a magma chamber during the same magmatic pulse.

For the present study we collected a large suite of samples from representative rock units exposed along the southeastern margin of the Gulf of California, with the aim of better constraining extensional faulting and volcanism in space and time. Three samples were also obtained from the rifted continental blocks submerged in the Gulf of California during the NSF-funded DANA and ROCA cruises in 2004 and 2008. Forty-three new mineral ages were obtained by U-Pb LA-ICP-MS and \(^{40}\text{Ar}^{39}\text{Ar}\) methods. U-Pb ages were determined at Centro de Geociencias, Universidad Nacional Autónoma de México (UNAM), campus Juriquilla. Ages are summarized in Table 1. Procedures are described in Appendix 1 together with complete analytical results. The \(^{40}\text{Ar}^{39}\text{Ar}\) dating was performed at the Geochronology Laboratory of the Departamento de Geología, Centro de Investigación Científica y de Educación Superior de Ensenada (CICESE). The \(^{40}\text{Ar}^{39}\text{Ar}\) ages are
summarized in Table 1. All the relevant $^{40}$Ar-$^{39}$Ar information and a discussion of each experiment are given in Appendix DR2.

A selection of samples dated in this work and in Ferrari et al. (2002) plus others for which we have a good stratigraphic control was analyzed for major and trace elements. Major elements were analyzed with a Siemens SRS-3000 X-ray fluorescence instrument at Instituto de Geología, UNAM, according to the procedures outlined in Lozano-Santa Cruz et al. (1995). Trace element analyses were obtained by inductively coupled plasma mass spectrometry (ICP-MS) using a Thermo Series XII instrument at Centro de Geociencias, UNAM, Querétaro, Mexico. Major and trace element analysis of samples DANA 46a, ROCA 3J 4a and ROCA 24J 33 were obtained at the GeoAnalytical Laboratory of Washington State University. Results are presented in Table 2. Further details of procedures and measurements are given in Appendix 3.

REGIONAL GEOLOGIC SETTING

The study region encompasses the western part of the southern and central SMO as defined in Ferrari et al. (2007). The region is here divided into three domains: northern Nayarit (Figure 6 and 7), southern Sinaloa and northern Sinaloa (Figure 8, 9, 10, and 11) based on the dominant dip and tectonic transport direction during Gulf of California rifting (Figure 2) (e.g., Axen, 1995) as well as the type of underlying basement. The pre-volcanic basement in northern Sinaloa consists of metavolcanic and metasedimentary assemblages of Paleozoic to Late Jurassic age (El Fuerte Group; Mullan, 1978; Vega-Granillo et al., 2008, 2012; Keppie et al., 2006) covered by shale, marl and limestone of Berriasian to Turonian age (SGM, 1999a; 2000). In southern Sinaloa deformed granitoids intruding phyllitic sandstone, quartzite, and quartz-biotite-muscovite schist yielded Jurassic to Early Cretaceous ages (Henry et al., 2003) and are covered by limestone of Albian-Cenomanian age (Bonneau, 1970). In northern Nayarit the pre-volcanic basement consists of undated slate and phyllites only exposed in small outcrops 14 km NW of Acapona (SGM, 1999b) (too small to be shown in Figure 6). Continental magmatism making up the lower part of the SMO - the Lower Volcanic Complex (LVC) of McDowell and Keizer (1977) - ranges
in age from Cenomanian to Early Eocene (Ferrari et al., 2007, and references therein) and has been interpreted to record an inland migration of arc magmatism that made up the Peninsular Ranges batholith of Baja California in Aptian-Albian times (Gastil, 1975; Ortega-Rivera, 2003). The LVC is capped by a 1 to 1.5 km thick bimodal volcanic succession named Upper Volcanic Supergroup (UVS) in Durango and Sinaloa (McDowell and Keizer, 1977). Silicic volcanic rocks in this package constitute approximately 85% of the erupted material and occurred in two pulses or ‘flare-ups’ at ~34-28 Ma and ~24-18 Ma (Ferrari et al., 2002, 2007; Bryan et al., 2008; 2013), which for simplicity we refer to as the “Oligocene” and “early Miocene” pulses in the following discussion. The Oligocene pulse is recognized across the entire SMO and its volume is approximately three times larger than the early Miocene pulse, being mainly observed in the central and southern SMO (Ferrari et al., 2007). Mafic volcanism was less abundant but is found ubiquitously interspersed in the main ignimbrite successions since the late Oligocene. Post-ignimbritic volcanic rocks consists of basaltic lavas of Late Miocene (11-10 Ma), Late Pliocene and Pleistocene age, which is mostly located in the coastal area.

The regional volcanic stratigraphy revised by us and constrained by new age data presented herein provides the key basis for establishing the age of extension in the southwestern SMO adjacent to the Gulf of California. The geologic constraints of this early phase of extension in the three rift domains defined above are described in the following section from south to north.

EXTENSIONAL FAULTING AND SYN-EXTENSIONAL MAGMATISM IN THE NORTHERN NAYARIT DOMAIN

Geologic and tectonic setting

The northern Nayarit domain is bounded to the south by a left lateral transpressional zone located just to the north of the Trans-Mexican Volcanic Belt (Ferrari, 1995; Ferrari et al., 2002) and to the north by the Río Mezquital lineament, a fault zone accommodating opposite tilting of strata (Figure 2). The northern Nayarit domain is a footwall segment in the Axen (1995) terminology, with rocks dominantly dipping E to ENE due to N-S to
NNW striking largely W-dipping normal faults (Figure 6 and 7). The presence of the Lower Volcanic Complex is substantiated by a small granite body 20 km north of Huajicori (Figure 6) that yielded a Late Maastrichtian U-Pb zircon age (Duque-Trujillo et al., in preparation), by the occurrence of Late Paleocene detrital zircons in modern sands from the Acaponeta and San Pedro rivers (Fletcher et al., 2007, their samples SM1 and SM 2) as well as by Late Cretaceous to Paleocene zircon xenocrysts found in early Miocene rhyolitic domes dated in this study (samples MdCh 10, RUIZ 7 and RUIZ 34b; Table 1, Table DR1).

Most of the northern Nayarit segment is covered by silicic ignimbrites, domes and basalts of the UVS. Rocks of the Oligocene pulse were reported only in the northeastern part of the area, where Ferrari et al. (2002) dated several ignimbrites and a dome in the 31.2 - 27.9 Ma age range (Figure 6); however they may underlie most of the area based on the ages of an ignimbrite and of inherited zircons found in this work in the western part of the study area (see below). The rest of the area is covered by rocks associated with the early Miocene ignimbrite flare-up, ranging between ~24 and 17 Ma. These rocks can be grouped into three packages: the Las Canoas ignimbrite succession (24-23 Ma), the Nayar ignimbrite succession and associated rhyolites and basalts (~22-20 Ma), and rhyolitic domes and intrusions emplaced in a belt along the western margin of the SMO (~22-18 Ma, Figure 6 and 7).

Extensional faulting affected almost the whole region apart from a northerly elongated elliptical area, ~25 x 35 km wide, centered in the Mesa del Nayar, where ignimbrites are flat-lying. At least two generations of high-angle normal faults can be recognized: 1) N-S-striking faults affecting the whole region and bounding grabens and half-grabens (Atengo, Jesus Maria, Huajicori, Puente de Camotlán, Huajimic and Sierra de Alica half graben; La Ventana and San Agustín graben); and 2) NNW-striking faults developed along the western margin of the SMO crosscutting the N-S faults (Pochotitán and San Pedro-Acaponeta fault systems, Figure 6). Constraints on the age of faulting are available in a number of areas and indicate prolonged extension beginning at the Oligocene-Miocene boundary.

**Atengo half graben**

Faulting in the Atengo half graben has resulted in tilts up to 25° for ignimbrites as young as 28 Ma (Ferrari et al., 2002). On the western side of the half graben, ~N-S rhyolitic dikes,
5-10 m in thickness, cut across the ignimbrite sequence and fed a large rhyolitic dome dated at 27.9 Ma (Ferrari et al., 2002) (Figure 6, 7a, and 12a). The rhyolitic dikes are emplaced along the flexure separating tilted blocks on the east from flat-lying ignimbrites in the west, so they can be considered to mark the inception of the extension. Several microporphyritic basaltic lava flows surround and partly cover the rhyolites. These flows are only moderately tilted (~10°) and show an intraplate affinity (see geochemistry section), suggesting that they were emplaced after extension began. A small amount of plagioclase suitable for dating was separated from one of these basaltic lavas (TS 16). The 40Ar-39Ar experiments yielded a consistent plateau age of 24.38 ± 0.75 Ma (Figure 5a, Appendix DR2), confirming the inception of extension in the Atengo half graben in the Late Oligocene. These basalts underlie the Las Canoas ignimbrite succession, dated at 23.5 Ma by K-Ar (Damon et al., 1979) and 23.3 Ma by 40Ar-39Ar (Ferrari et al., 2002). Similar aged basaltic lavas also occur in the lower part of the ~24 Ma El Salto-Espinazo del Diablo ignimbrite sequence, exposed along the Mazatlán-Durango highway 130 km to the northwest (McDowell and Keizer, 1977; age from McDowell and McIntosh, 2012) (Figure 8), and below the 23.5 Ma Alacrán, ignimbrite exposed in the Bolaños graben 90 km to the southeast (Ramos Rosique, 2012). In the Bolaños graben, N-S faulting started ca. 1 m.y. before the emplacement of the Alacrán ignimbrite at ~23.5 Ma and continued until at least 15 Ma (Ramos-Rosique, 2012). Other correlative basaltic lavas associated with normal faulting are found in the Rodeo half-graben and in the Nazas area (Luhr et al., 2001).

**Jesús María half graben**

To the west of the Atengo half graben, the Jesús María half graben drops the Las Canoas succession approximately 1,700 m to the west, where it is found tilted up to 30° (Figure 7b). The Jesús María fault system also downthrows the Nayar ignimbrite succession about 1,300 m. As defined by Ferrari et al. (2002) the Nayar succession consists of several ignimbrite sheets that thicken toward the Mesa del Nayar area, where at least eleven cooling units form a 1 km thick sequence with 40Ar-39Ar ages ranging between 19.9 ± 0.4 and 21.2 ± 0.3 Ma. Basaltic-andesitic lavas dated at 21.3 ± 0.3 Ma found along the Jesús María fault system (Ferrari et al., 2002)(Figure 7b) suggest that extension associated with half graben formation was ongoing at this time. The top of the flat-lying Nayar succession
reaches a maximum of ~1950 m elevation just west of Mesa del Nayar. The Nayar succession is not exposed in the Jesús María footwall block, where the top of the 23.5 Ma Las Canoas ignimbrite succession lies at ~2450 m elevation. These relations indicate that extension along the ~N-S faults of the Jesús María half graben must have initiated before the emplacement of the Nayar succession at ~21 Ma, so that the footwall was already a topographic barrier to the east, preventing further eastward outflow of the Nayar ignimbrites. Extension must have continued for a few more Myrs to tilt and downthrow the Nayar succession east of Mesa del Nayar (Figure 7b). Further constraints on the age of faulting in the area just west of Mesa del Nayar come from a rhyolitic dome located 25 km to the southwest, which covers a N-S fault without being cut by the fault (Figure 12b). A sample from this dome yielded 26 U-Pb ages in the range 23-17 Ma (sample RUIZ 34b; Figure 3, Table 1). A weighted mean including all the analyses would yield an age of 19.02 ± 0.3 Ma, with an MSWD of of 3.7, indicating an age spreading beyond the obtained analytical error. A further weighted mean, obtained with the 5, concordant and overlapping youngest analyses, yields an age of 18.35±0.3 Ma (MSWD= 0.34, n=5), which is interpreted as the best estimation of the zircon crystallization in this rhyolite dome. Given the large age range we also dated a biotite concentrate from the same sample by Ar-Ar laser step heating. The resulting isochron yielded an age of 17.57 ± 0.19 Ma (Table 1, Figure 4a), which we consider as the best estimation of the emplacement age of the dome. We also dated a large rhyolite dome capping the Nayar succession west of Mesa del Nayar, which is unfaulted and whose top is mostly flat (i.e. does not appear tilted) (sample RUIZ 16; Table 1). Plagioclase separated from the rhyolite was step heated and yielded an isochron of 17.91 ± 0.20 Ma (Figure 4a), indistinguishable within error from the biotite age of the RUIZ 34b dome. These geologic relations suggest that by ~17.6 Ma extension associated with the N-S faults had essentially terminated.

Huajicori-Picachos fault system

The Huajicori area is located in northwestern Nayarit (Figure 6). Here a system of N-S striking and west-dipping normal faults creates a ~1,800 m escarpment that bounds the SMO ignimbrite plateau toward the coastal plain (Huajicori-Picachos fault system, Figure 7c). The lowermost ignimbrite exposed by the fault system is a pink colored, crystal-rich
welded ignimbrite with biotite, quartz, feldspar and plagioclase. We dated by the $^{40}$Ar-$^{39}$Ar method a biotite concentrate from this ignimbrite (sample HUA 1) obtaining a plateau age of $26.48 \pm 0.15$ Ma (Figure 5a, Table 1) from the weighted mean of the last four fractions of the second experiment. We have also dated some zircons from an aphyric dacitic lava in the same succession about 20 km to the north of HUA 1 (sample MdCh 03). We performed a total of 27 zircon analyses, which once filtered, yielded 18 concordant to variably discordant ages. In particular, three analyses yielded concordant and overlapping results, with a $^{206}$Pb/$^{238}$U weighted average age of $22.7 \pm 0.8$ Ma (MSWD= 0.31, n= 3) (Figure 3), which is in accordance with the stratigraphic position of the sample. Covering the Oligocene ignimbrite and dacite is a succession of approximately 1,000 m of ignimbrites of which we dated one of the highest near the Los Picachos site. This is a moderately welded and poorly indurated ignimbrite with biotite and feldspar phenocrysts (HUA 2) that forms a distinctive erosional morphology with sharp peaks. Duplicate experiments by laser step heating on a biotite concentrate gave a well-defined plateau age of $22.99 \pm 0.14$ Ma and an isochron age of $23.19 \pm 0.27$ Ma, of which we consider the former the best estimate age for the emplacement of this sample because of its smaller error (Table 1). The ignimbrite succession is capped by a large dacitic dome from which we were able to separate 31 zircons that gave concordant to slightly discordant U-Pb ages in the range ~28-23 Ma and four xenocrysts with ages of 72-63 Ma (Sample MdCh 10, Table 1, Figure 3). The $^{206}$Pb/$^{238}$U weighted mean of 16 crystals yields an age of $23.8 \pm 0.2$ Ma. The stratigraphic position of this dome above the HUA 2 ignimbrite dated at 22.99 Ma suggest that antecrystic inheritance may bias this age. For this reason we also dated a plagioclase concentrate from the same sample by the $^{40}$Ar-$^{39}$Ar method. The sample yielded an isochron age of $22.51 \pm 0.90$ Ma and a plateau age of $22.15 \pm 0.93$ Ma (Fig 4a and 5a, Table 1), which are consistent with the stratigraphic relations and confirms the presence of a subtle antecrystic inheritance in this dacitic lava (e.g. Bryan et al., 2008).

Several other silicic domes are emplaced in the hanging-wall of the Huajicori-Picachos fault system. The Cuchara and Caramota domes are particularly interesting because they were emplaced above one of the N-S faults without being obviously cut. For the Cuchara dome, 28 zircons with acceptable discordance (i.e. <10% of deviation from Concordia) gave a $^{206}$Pb/$^{238}$U weighted mean U-Pb age of $25.9 \pm 0.2$ Ma (MSWD= 1.7, n=27) (sample
MdCH 05; Table 1). The somewhat high MSWD is indicative of age dispersion, confirmed by the ^{40}\text{Ar}-^{39}\text{Ar} dating. A groundmass concentrate from the same sample was laser step-heated and a well-defined plateau (14 fractions out of 19 steps) gave an age of 17.41 ± 0.07 Ma (Figure 5a, Table 1). Given the high quality of this age it must be concluded that all zircons in this dome are inherited from previous igneous episodes (i.e. antecrysts), represented by other dated rocks exposed in the proximity (e.g. ignimbrite HUA1 and dacite lava MdCh 03, Table 1). In the case of the Caramota dome (sample MdCH 6, Table 1), two ^{40}\text{Ar}-^{39}\text{Ar} experiments yielded a reproducible age spectra, with a wide plateau age of 20.54 ± 0.79 Ma and an isochron age of 20.25 ± 0.64 Ma, which we consider to be the best age. We also dated a microporphyritic olivine basaltic lava vented from one of the ~N-S faults 15 km east of Huajicori (sample MdCH 09, Table 1). A plagioclase concentrate from this lava was laser step-heated yielding a plateau age of 18.34 ± 0.39 Ma defined by five consecutive fractions with 72.06% of the ^{39}\text{Ar} released, which is identical to the isochron age of 18.32 ± 0.40 Ma, obtained with the combined data of the two experiments. Finally, we have dated a poorly indurated and poorly welded ignimbrite exposed in the Acaponeeta river near Huajicori. This ignimbrite is tilted up to 25° to the east but is not exposed in the footwall of the Huajicori-Picachos fault system, where the topmost ignimbrite was dated at 21.1 ± 0.7 Ma (sample ESC 3; Ferrari et al., 2002). A plagioclase concentrate from the Huajicori ignimbrite (sample HUA 5, Table 1) was laser step-heated and yielded an isochron age of 18.98 ± 0.30 Ma, which is considered our best age estimate.

In summary, the new ages obtained in the Huajicori area, as well as the geologic relations described above, indicate that a significant part of displacement along the ~N-S faults of the Huajicori-Picachos system occurred before the emplacement of the ~18.98 Ma Huajicori ignimbrite and was waning by ~17.4 Ma when the Cuchara dome was emplaced on one side of the fault escarpment. Basalts dated at ~18.3 Ma vented from the N-S faults were likely providing the thermal input to cooling magma bodies that generated the rhyolitic domes. Similar age relations are deduced 45 km NW of Huajicori near the coast, where basaltic-andesitic lavas vented from a ~N-S fault cover in angular unconformity by ignimbrites tilted to the east (Figure 6). A plagioclase concentrate from these basaltic andesite lavas (sample ESC 7, Table 1), was dated by the ^{40}\text{Ar}-^{39}\text{Ar} method by step heating in a temperature controlled Ta-furnace, yielding a plateau age of 22.39 ± 2.56 Ma. This
suggests that extensional faulting in the area began before the early Miocene and was likely waning by the time the mafic lavas were emplaced (youngest age within error = 19.83 Ma).

**Pochotitán and San Pedro-Acaponeta fault systems**

Two major systems of NNW-striking normal faults post-date the N-S fault systems forming a major breakaway zone bounding the Gulf of California (Figures 6, 7a, 7b and 7d). They consist of a series of normal faults that tilt ignimbrites of the Nayar succession up to 35° to the ENE (Ferrari et al., 2002). Geologic maps of the Mexican Geologic Survey interpret some of the rocks cropping out at the base of the tilted succession as Paleocene to Oligocene. However our new ages indicate that in most cases they are Miocene in age. We dated a tilted ignimbrite near the southern end of the Pochotitán fault system (sample ORO 2, Table 1), and the lowermost ignimbrite in the hanging wall of the southern part of the San Pedro fault system (Sample RUIZ 7, Table 1). Sample ORO 2 is from a moderately welded, indurated ignimbrite with feldspar, quartz, biotite and lithics, tilted 15° to the ENE. A biotite concentrate from the ignimbrite was laser step-heated and we conclude the resulting isochron age of 20.74 ± 0.44 Ma is the best eruption age estimate (Figure 4a; Table 1). Sample RUIZ 7 is a pink colored, well-indurated and moderately welded ignimbrite with quartz and sanidine, steeping 20° to the ENE. Zircons separated from the ignimbrite yielded 17 acceptable ages in the range 23-24 Ma, with an inherited crystal of ca. 56 Ma. The $^{206}\text{Pb}/^{238}\text{U}$ weighted mean yields an age of 23.6±0.2 Ma (MSWD= 1.3, n= 15) (Figure 3). We have also dated zircons from a porphyritic intrusion cross-cut by NNW faults 30 km south of Acaponeta, in the coastal plain (sample MicBar 01, Table 1). The rock is silicic with quartz, feldspar and biotite in a glassy matrix, which locally shows flow banding and probably represents the inner part of a dome. Twenty-seven zircons yielded ages in the range of 20-22 Ma, with a $^{206}\text{Pb}/^{238}\text{U}$ weighted mean of 20.8 ± 0.1 Ma (MSWD= 1.9, n= 25). Other shallow intrusive bodies exposed by the Pochotitán and San Pedro-Acaponeta fault systems yielded ages between ~20 and 17 Ma (Ferrari et al., 2002; Duque Trujillo et al., in preparation). As a whole, the above relations indicate that ~ENE extension, associated with the Pochotitán and San Pedro-Acaponeta fault systems, began after ~21 Ma and that the faults served as an ascent path for discrete batches of silicic magmas between 20 and 17 Ma, which either reached the surface as domes or crystallized
at shallow depth. The upper limit of this extensional episode is constrained by undeformed basaltic lavas emplaced along the coast. A 28-km-wide and 35-km-long basaltic plateau is exposed northwest of Tepic and west of the Pochotitán fault system (Ferrari et al., 2000a and 2000b; Figure 6, Figure 7a). It consists of an up to 300 m thick succession of basaltic lavas with an almost constant dip of 4-5° toward the NW, in striking contrast with the 20° to 35° dipping ignimbrites exposed to the north and to the east. The uppermost lavas were dated between 8.9 to 9.9 Ma (Gastil et al., 1979; Righter et al. 1995) and paleomagnetic studies indicate they were not affected by significant tectonic deformation after their emplacement (Goguitchaichvili et al., 2002). An even clearer angular unconformity can be observed at Cerro Peñitas, located 5 km west of Estación Ruiz (Figure 6 and 7b). Here flat-lying basaltic andesite lavas emplaced in the coastal plain surround a block of ignimbrites tilted 25° to the WSW (Figure 7b). Laser step-heating experiments on whole rock from this basaltic andesite (sample HUA 6) yielded a plateau age of 10.45 ± 0.15 Ma (Table 1, Figure 5b). In addition many ~11-10 Ma and NNW-striking mafic dikes are emplaced along, and parallel, to the Pochotitán and San Pedro-Acaponeta extensional fault systems (Ferrari et al., 2002; Frey et al., 2007). Most of the dikes are vertical and although some of them dip up to 70° they are not sheared, indicating that their inclination is due to the intrusion into pre-existing normal fault planes that were already inactive. We thus conclude that extension associated to the NNW-striking Pochotitán and San Pedro-Acaponeta extensional faults systems must have terminated before ~10.5 Ma.

EXTENSIONAL FAULTING AND SYN-EXTENSIONAL MAGMATISM IN THE SOUTHERN SINALOA DOMAIN

Geologic and tectonic setting

North of the Río Mezquital lineament the general architecture of the rift is dominated by WSW-tilted ignimbrites and NNW-striking normal faults (Figure 8, 11a and 11b), which define a hanging wall segment in the Axen (1995) terminology. This style of faulting continues to the north up to the Piaxtla river valley, where ignimbrites are again tilted to the ENE (Figure 2 and 8). A smaller domain of ENE tilted ignimbrites is observed farther
inland in the Tayoltita and Mala Noche mining areas (Enríquez and Rivera, 2001; Aranda-Gómez et al., 2003; this work). The Mezqital lineament also marks the southern limit of a basement high, because to the north, the Lower Volcanic Complex and its host rocks are well-exposed or lie at shallower depth than in the northern Nayarit segment (Figure 8). In Sinaloa, Cretaceous to Paleogene intrusive rocks likely constitute a large composite batholith whose oldest parts were deformed during the Laramide orogeny. Henry et al. (2003) dated a syn-tectonic intrusion at ~105 Ma (TIMS U-Pb on zircon). A more recent study using both U-Pb dating of zircons and $^{40}$Ar-$^{39}$Ar dating of muscovite constrains the deformation in the Mazatlán area between ~98 and 93 Ma (Ramos Cuéllar et al., 2012). Post-tectonic intrusions consist of granodiorite to dioritic bodies that thickened the batholith toward the east in Campanian to Eocene times (Figure 8 and 11). These are covered by ignimbrites and domes of the Oligocene pulse dated west of Durango between 31.7 and 28.5 Ma and by the 24-23.9 Ma Espinazo-El Salto volcanic sequence (Figure 8) (McDowell and Keizer, 1977; McDowell and McIntosh, 2012). Upper Miocene mafic dikes and Upper Pliocene lavas are observed along the coast. Scattered Upper Miocene intraplate basalts are also exposed in the eastern part of the SMO in the Río Chico-Canatlán graben (Figure 8) (Henry and Aranda-Gómez, 2000).

Extensional structures affect the western half of the SMO, in Sinaloa state, as well as a narrow belt on its eastern side, just west of Durango. Like in the northern Nayarit segment two episodes of extension can be recognized: 1) an ~E-W to WSW extension responsible for NNW striking faults observed in the Piaxtla, Presidio and Baluarte river valleys and, possibly, the coastal area; and 2) subsequent WSW extension restricted to the coastal area (Pánuco, Concordia and Villa Unión half grabens) and a belt east of the SMO (Río Chico-Canatlán graben) (Figure 7). Timing of faulting can be inferred from geologic relations in a number of areas described below.

**Early extension-transtension in westernmost Durango: Tayoltita-Pueblo Nuevo fault system**

To the NW of Mazatlán, the Piaxtla river and the Presidio river cut ~2 km deep incisions orthogonal to the Gulf coast into the SMO igneous succession. The top of the succession is made by the Espinazo-El Salto volcanic sequence, making a plateau at an average 2,700 m
of elevation. Originally recognized and dated at ~23.5 Ma by McDowell and Keizer (1977) the sequence has been recently re-dated at 23.8-24 Ma by 40Ar-39Ar (McDowell and McIntosh, 2012). It consists of a thick package of ignimbrites and tuffs (unit A), covered by massive rhyolites (unit B), basaltic lavas (unit C), and by three ignimbrite packages (unit D, E and F or “plateau series”) briefly described in Aranda-Gómez et al. (2003). The sequence can reach 1,000 m in thickness in the La Ciudad area (Figure 8 and 11a) and along the Baluarte river (Figure 12c) but toward the east, in the El Salto area, only the uppermost three units can be recognized, with an approximate thickness of 350 m. East of La Ciudad, the Espinazo-El Salto sequence is essentially flat-lying and only affected by minor faulting. However, our reconnaissance fieldwork shows that it clearly filled a topographic trough that resulted from a previous episode of normal faulting. Along the Presidio river valley, between Mala Noche and Cerro Cuadrado (MN and CC, respectively in Figure 8), a thick succession of ignimbrites and andesites are tilted up to 35° to the ENE, making a spectacular angular unconformity with the ~24 Ma Espinazo-El Salto succession, which lie almost horizontal (Figure 12e, 12f and 12g). We have dated a sample of an ignimbrite at about 350 m below the top of the tilted sequence near Ejido San Pablo (ES 11, Table 1). The 22 dated zircons range between 31.4 and 33.4 Ma. The \(^{206}\text{Pb}/^{238}\text{U}\) weighted mean yields an age of 32.5±0.2 Ma (MSWD= 0.89, n= 21) (Figure 5). This ignimbrite could be correlative with the Registro tuff and other ignimbrites dated by McDowell and Keizer (1977) and McDowell and McIntosh (2012) west of Durango City, which underlie the El Salto sequence. Andesitic lavas underlying the ignimbrites were also dated (Sample ES 10, Table 1). A plagioclase concentrate from these lavas yielded an isochron of 33.82 ± 0.28 Ma, confirming the early Oligocene age of this succession. 

Tilting of this Oligocene ignimbrite and andesite succession occurs to the west of a NNW striking and west-dipping breakaway fault zone northwest of El Salto that is part of a regional structure, here named Tayoltita-Pueblo Nuevo fault system (see below). A prominent NNW alignment of rhyolitic domes lies along this fault zone (Figure 8). Among them is the massive Las Adjuntas dome (LA in Figure 8), intersected by highway 40 west of El Salto (Figure 8 and 11a), previously dated at 28.5 Ma by K-Ar (McDowell and Keizer, 1977; age corrected for modern decay constants). Fifteen zircons separated from this dome yielded a \(^{206}\text{Pb}/^{238}\text{U}\) weighted mean age of 29.5±0.3 Ma (MSWD= 1.3, n=14)
(sample SIN 18, Table 1) with single ages comprised between 30 and 28 Ma, which in comparison to the K/Ar age, may indicate the occurrence of antecrysts. The emplacement of large volume, viscous rhyolitic domes coupled with the occurrence of inherited zircons is indicative of an extensional regime allowing the re-melting of upper crustal, potentially still partially molten, plutons as well as an easy ascent of these viscous rhyolitic magmas. On this basis, we consider the Las Adjuntas dome to mark the initial extensional activity along the Tayoltita-Pueblo Nuevo fault system.

Toward the north, this pre-Miocene faulting episode is also reported in the Piaxtla river valley, the next valley to the north (Figure 8). Here, in the Tayoltita mining district, Eocene to mid Oligocene rocks are tilted up to 70° to the ENE whereas tilts of Lower Miocene ignimbrites do not exceed 30° (Enríquez and Rivera, 2001). Microstructural studies established that the first episode formed a negative flower structure defined by N-S to NNW striking faults with right lateral extensional kinematics, distributed in a 4 km wide belt east of Tayoltita (Horner and Enríquez, 1999). This right-lateral transtensional corridor is the northern prolongation of the breakaway fault zone observed in the Presidio river valley (Tayoltita-Pueblo Nuevo fault system). At Tayoltita, the transtensional faults displace the mineralized veins dated between ~38 and ~32 Ma (Horner and Enríquez, 1999). This constrains this first extensional episode as Late Oligocene as inferred in the Presidio valley. The second episode of extension must have occurred after the emplacement of the capping ignimbrite sequence, dated between ~24.5 and 20.3 Ma (Enríquez and Rivera, 2001).

**Coastal belt of extensional faults**

Between Espinazo del Diablo (EDD in Figure 8) and the coast the ~24 Ma volcanic sequence is also faulted and tilted due to a subsequent extensional episode. In a 60-km-wide belt parallel to the coast, volcanic successions are tilted to the WSW by NW striking and NE dipping normal faults. Pre ~24 Ma rocks are tilted up to 40° whereas the Espinazo-El Salto ignimbrites dip more gently, not exceeding 20° (Figure 12f). About 12 km southwest of Espinazo del Diablo two rhyolite domes aligned on the prolongation of a NW striking fault are crossed by highway 40 (Figure 8). The northernmost dome covers part of the Lower Miocene succession and has a sub-horizontal base. The lava is a coherent
porphyritic rhyolite with plagioclase, lesser alkali feldspar and hornblende that was considered part of the Espinazo-El Salto succession by McDowell and Keizer (1977)(their unit B, undated). However, zircons separated from the rhyolites gave 16 acceptable ages in the range 12.7-14.7 Ma. The $^{206}$Pb/$^{238}$U weighted mean yields an age of 13.7±0.3 Ma (sample SIN 21, MSWD= 1.4, n= 16, Table 1). Since the dome does not appear faulted this age can be taken as a minimum age for the activity of the NW striking faults in this area.

Near the coast the NW striking faults form several asymmetric grabens. The largest of these extensional basins are the Villa Unión and the Concordia half grabens (Figure 8). In the eastern part of the Villa Unión half graben, gravel fills are tilted up to 24° and lie in unconformity over a 22.6 Ma old dacitic lava that is tilted up to 40° (Henry and Fredikson, 1989; Aranda-Gómez et al., 2003). The graben fill is intruded by ~11 Ma, N-S to NNW trending mafic dikes dipping 65° to the E, suggesting that extension began sometime in the Middle Miocene and continued for a short time after 11 Ma (Aranda-Gómez et al., 2003).

We tried to constrain the age of the Concordia half graben by dating two rhyolitic domes in the eastern part of this structure (Figure 8). Sample SIN 05 (Table 1) comes from a block and ash flow deposit associated with a dome that appears to be cut in half by a normal fault parallel to, and antithetic with, the Concordia fault. Zircons separated from glassy rhyolite lava blocks from this deposit yielded 34 acceptable ages in the range 35-30 Ma. The large age range is indicative of antecrystic inheritance; so we consider the $^{206}$Pb/$^{238}$U weighted mean age of 31.5±0.4 Ma as the maximum age for the emplacement of this dome. Sample SIN 07 (Table 1) was collected from a rhyolite dome apparently vented along a NE striking and SE dipping normal fault that put in contact the metamorphic basement with ignimbrites tilted to the SW and is in turn cut by a fault parallel to the Concordia fault. This dome yielded an age identical to SIN 05, with a $^{206}$Pb/$^{238}$U weighted mean age of 31.5 ± 0.4 Ma (MSWD= 1.5, n=20). Although these ages do not help to narrow the age range of the Concordia half graben they nevertheless indicate the presence of Oligocene magmatism in this area, which would thus extend along a ~150 km wide belt from Durango to coastal Sinaloa. On the other hand, the alignment of these rhyolitic domes in proximity to the Concordia Fault suggests early activity of this structure, which can be thus contemporaneous to the Tayoltita-Pueblo Nuevo fault zone. In this case, the two fault zones would define a 75 km wide graben, a hypothesis supported by the occurrence of polymictic
conglomerates with reworked tuffs at the base of the Espinazo-El Salto sequence at several places within this inferred tectonic depression.

EXTENSIONAL FAULTING AND SYN-EXTENSIONAL MAGMATISM IN THE NORTHERN SINALOA DOMAIN

Geologic and tectonic setting

The Piaxtla and Elota rivers mark a tectonic boundary that apparently displaces the pre-volcanic basement and the LVC batholith in a more inland position (Figure 8). While in southern Sinaloa these rocks crop out along the coast, to the north of these rivers, they are separated from the Gulf of California by a 35 to 60 km wide coastal plain. In this region, extensional structures form a 65 to 85-km-wide belt of NW striking normal faults with block tilting both to the SW and the NE. They bound a series of grabens and half grabens cut into the Late Eocene and Oligocene silicic volcanic succession of the UVS, batholiths of the LVC and their roof pendants, as well as the pre-volcanic basement (Figure 8, 9, 10 and 11c and d). These tectonic basins are filled by continental sediments and by concurrent bimodal volcanism, a geologic setting similar to that of Sonora to the north, where intracontinental extensional basins were developed since the early Miocene (Gans, 1997; McDowell et al., 1997). The timing of extension in northern Sinaloa, however, has remained unknown. Our reconnaissance study allows documenting the age of extension in two areas.

Conitaca graben and Sierra El Infierno dome complex

Sierra El Infierno is a huge silicic complex made of domes, lavas, ignimbrites, and shallow subvolcanic intrusions, which rise from the alluvial deposits of the coastal plain. No previous study exists on this silicic complex. It covers a ~600 km² area and some peaks reach 1,400 m above sea level (Figure 8 and 12h). This voluminous amount of silicic magma was fed, at least in part, by large N-S trending silicic dikes, which are clearly seen in aerial imagery and were observed in the field. Lavas are glassy and flow banded rhyolites with variable crystal content (commonly K-feldspar, quartz, and plagioclase,
sometimes biotite and hornblende) and occasional fragments of pre-existing intermediate lavas. The Sierra El Infierno is emplaced in the north-western part of the Conitaca graben, a tectonic depression bounded toward the east by a series of NNW-striking and west-dipping normal faults (CG in Figure 8). The graben is filled by indurated sandstone and polymictic conglomerate interleaved with and capped by basaltic lavas that abut against the silicic rocks of the Sierra El Infierno. Sandstone and conglomerate are crudely stratified and dip 10° to 25° whereas capping basalts are only gently tilted. The time of faulting is clearly established by the ages of the Sierra El Infierno silicic complex and the basaltic lavas intercalated and capping the continental sedimentary succession.

We have dated two domes in the southern and western part of Sierra El Infierno. Sample SIN 39 is a porphyritic to glomeroporphyritic coherent rhyolite with plagioclase, biotite and alkali feldspar exposed at the northwestern tip of the Sierra. Twenty-five dated zircons range between 24 to 21 Ma with a $^{206}\text{Pb} / ^{238}\text{U}$ weighted mean age of 21.5±0.1 Ma (MSWD= 1.17, n= 22)(Table 1, Figure 3). Sample SIN 09 comes from a crystal-rich rhyolite with plagioclase and biotite from which we dated 26 zircons in the range 20 to 16 Ma with a dominant population yielding a $^{206}\text{Pb} / ^{238}\text{U}$ weighted mean age of 18.6±0.3 Ma  (MSWD= 1.00, n= 25) Ma. If these ages are representative for the whole Sierra el Infierno, the silicic volcanism in this area would be overlapping with that of northern Nayarit, although with a much larger volume.

A previous age of 15.8 Ma was reported in Iriondo et al. (2004) for a basaltic lava in the Conitaca graben, although the geologic context of this sample was not provided. We have dated a sample located at 17 km to the southeast near the dam of the El Salto reservoir (Figure 8) that belongs to the upper part of the basaltic lavas inside the graben. The lava is a fine-grained microporphyritic basalt with plagioclase, clinopyroxene and olivine (sample SIN 25, Table 1, Figure 4b). The laser step-heating experiment performed on whole rock yielded an isochron age of 14.01 ± 0.23 Ma, which we consider the best estimation for this rock. Sample SIN 15 is also a plagioclase, clinopyroxene, and olivine-phyric basaltic lava that covers rhyolitic lavas in the western part of Sierra El Infierno. Laser step heating experiments of the groundmass gave an isochron age of 13.62 ± 0.17 Ma for this sample, which within the error almost overlaps the age of SIN 25 (Table 1, Figure 4b).
Basaltic lavas also crop out along the coast just southwest of Sierra el Infierno. These lavas are petrographically similar to those exposed farther inland in the Conitaca graben fill but are generally flat-lying. We have dated a groundmass concentrate of a basaltic andesite lava from a quarry near the western tip of Sierra el Infierno (sample PER 8, Table 1, Figure 5b). One laser step-heating experiment was performed on a groundmass concentrate from the sample and our preferred age of 10.94 ± 0.23 Ma is taken from the weighted mean of three consecutive fractions with 84.57% of the 39Ar released (see Appendix DR2 for details). The geologic relations coupled with our new ages constrain extension in the Conitaca-Sierra El Infierno area to the Early to Middle Miocene.

Several other remnants of flat-lying fissure-fed basaltic lavas are distributed along the coast between Sierra El Infierno and Culiacán (Figure 8 and 9). The similarity in the mineralogy and composition of the lavas suggest that these outcrops could have been part of a single, 60-km-long belt of mafic lavas. We have dated a sample from the lower part of a 380 m thick succession south of Culiacán (Figure 8; La Pedrera microwave peak). A groundmass concentrate from a basaltic-andesite lava (sample PER 7, Table 1, Figure 5b) was laser step-heated and the two experiments yielded reproducible results with a plateau age of 10.54 ± 0.20 Ma.

**Badiraguato graben**

This is a composite tectonic trough bounded by NW-striking normal faults cut into Late Cretaceous to Paleocene intrusions of the LVC and their roof pendants (Figure 9). To the south, the graben is covered by Middle Pleistocene basaltic lavas of the Pericos Volcanic Field (see next section). The Badiraguato graben is filled by sandstone and polymictic conglomerate with intercalations of basaltic lavas and some rhyolitic domes and lavas. The conglomerate is tilted 15° to 38° both to the SW and the NE (Figure 9 and 11d). We have dated a basaltic andesite lava collected from an eroded succession of lavas between the Badiraguato and Mocorito grabens (sample PER 12, Table 1, Figure 4a). Although the lava is not in direct contact with the conglomerate it is considered equivalent to the basaltic lavas within the graben on a petrographic basis. A groundmass concentrate was step-heated with the temperature controlled Ta-furnace and we take the isochron age of 17.42 ± 0.77 Ma as the best estimate for this sample. Other basaltic lavas are exposed along the coast,
about 30 km to the SW. Similarly to those more to the south, these coastal lavas are flat lying. We have dated a basaltic andesite (sample PER 14, Table 1, Figure 4b and 12j) by step-heating using the temperature controlled Ta-furnace. The age spectrum is somewhat perturbed, but an isochron age of $10.33 \pm 0.88$ Ma can be confidently calculated. In summary the ages of the graben fill and the post extension lavas again indicate that extension in this part of Sinaloa is Early to Middle Miocene in age.

**LATE MIOCENE VOLCANISM OF NORTHERN SINALOA AND OFFSHORE AREAS**

We have recognized additional late Miocene (~12-10.5 Ma) mafic lavas and dikes in the northernmost part of Sinaloa at Sierra de Navachiste, and at the small Farallón de San Ignacio island southwest of Los Mochis (Figure 10), and within the Gulf of California at Santa Catalina island (Figure 2) and in the submerged rifted blocks. Sierra de Navachiste is an erosional remnant of a volcanic field made of basaltic, andesitic, and dacitic lavas and some intermediate domes presently covering an area of 170 km$^2$ along the coast. The lavas are essentially flat-lying and their base stands at sea level. We dated a groundmass concentrate from a dacitic lava interbedded with more mafic lavas (sample LM 2, Table 1, Figure 4b). The preferred age is taken from the isochron age of $10.97 \pm 0.75$ Ma calculated excluding the fractions of suspected excess Ar (see Appendix DR2). Similar ages were obtained by the K-Ar method by Pallares (2007) and Gastil et al. (1979) for andesitic lavas in the northwestern part of the field near Topolobampo (Figure 10).

Farallón de San Ignacio is a tiny island, 0.3 km$^2$ in size, 25 km offshore Sierra de Navachiste and just north of the NW fault scarp bounding the Farallon Basin (Figure 2 and 10). On the island, a massive rhyolitic lava flow is covered by two basaltic lavas 5 to 8 m in thickness. The top of basaltic lavas is horizontal and they cover the original irregular morphology of the rhyolite without any visible paleosoil. The rocks are too altered to be dated by $^{40}$Ar-$^{39}$Ar but we managed to separate eleven zircons from the lower rhyolitic lava. Single zircon ages of sample ROCA F6 range from 9 to 10 Ma with a $^{206}$Pb/$^{238}$U weighted mean age of $9.45\pm0.3$ Ma (MSWD= 1.9, n=9) . Despite this age not being very precise, it
nevertheless suggests that the overlying flat-lying basalts may be correlative with those of coastal Sinaloa.

Santa Catalina Island is part of a rifted continental block at the Latitude of Sierra de Navachiste in the western part of the Gulf (Figure 2). The bulk of the island consists of late Cretaceous granite of the Peninsular Ranges batholith heavily intruded by Miocene granitoids and aplitic dikes (Piñero-Lajas, 2009). Many NW-striking, SW-dipping mafic dikes exposed in the cliffs of the northwestern part of the island cut all other rocks (Figure 12i). A plagioclase concentrate from one mafic dike was laser step-heated and analyzed in two experiments (sample SC 3, Table 1, Figures 4b and 5b). Although the sample shows evidence of excess argon, we obtained a plateau age of 10.89 ± 0.52 Ma consistent with the less precise isochron age of 10.14 ± 2.59 Ma (see Appendix DR2 for details) that we consider representative of the mafic dike swarm at Santa Catalina Island.

Mafic dikes and silicic rocks of similar ages were also found in the rifted blocks submerged in the Gulf of California. Sample ROCA 3J 5 (Table 1, Figures 4b and 5b) is a lithic tuff that was collected using the ROV Jason at the top of the Tamayo dome (also called Tamayo Bank; Sutherland et al., 2012), a 30 x 40 km wide and ~1000 m high volcanic structure 80 km offshore Mazatlán (Figure 2). Two laser step-heating experiments were performed on a feldspar concentrate defining a plateau age of 11.70 ± 0.07 Ma indistinguishable from the isochron age obtained by combining all the data points from the two experiments. Silicic volcanism of Late Miocene age is widespread in Sonora (Mora and McDowell, 2000; Vidal-Solano et al., 2005, 2007) but has never been reported to the south. The sample from the Tamayo dome is the first evidence of late Miocene silicic pyroclastic rocks in the southern part of the Gulf. Sample ROCA 24J-33 was also collected using the ROV on a rifted continental block cut by a transform fault bounding to the south the Pescadero basin (Figure 2). It is a porphyritic, fine-grained subvolcanic microdiorite with plagioclase and hornblende (0.25-3.5 mm), scarce biotite and opaque minerals, probably representing a shallow sill. A hornblende concentrate was laser step-heated and we consider the isochron age of 11.29 ± 0.37 Ma as the best estimation for this sample.

Sample DANA 46a was dredged from a prominent NNE striking and 800 m high fault scarp offshore northern Nayarit, about 90 km SE of the Tamayo dome (Figure 2). The sample is a mafic aphyric lava (either a flow or a dike) presumably associated with the fault
scarp. Four experiments with different mass spectrometers and heating methods gave very consistent results yielding a 11.92 ± 0.27 Ma isochron age (Table 1, Figure 4b, Appendix DR2). This age overlaps with those obtained for NW striking mafic dikes in southern Sinaloa and northern Nayarit (Henry and Aranda-Gómez, 2000; Frey et al., 2007). In seismic profiles, Sutherland et al. (2012) recognized an irregular, ropey layer mantling the seismic basement offshore of northern Nayarit that they interpreted as a volcanic layer of the Comondú group (24-12 Ma). Our dated samples ROCA 3J 5 and DANA 46a, collected close to the trace of the seismic profile, provide a direct constraint of the nature and age of the uppermost part of this volcanic layer.

Mafic lavas in the range ~11-9 Ma are reported also in western Sonora (Mora-Alvarez and McDowell; 2004) and in Bahía de Los Angeles, Jaraguay, and Santa Rosalía areas in Baja California (Benoit et al., 2002; Calmus et al., 2003; Conly et al., 2005; Pallares et al., 2007), indicating the occurrence of a regional pulse of mafic magmatism just after the end of subduction in the whole Gulf region.

LATE PLIOCENE AND PLEISTOCENE INTRAPLATE VOLCANISM

Onshore post-Late Miocene volcanism is rare in the southeastern Gulf. The only previously known occurrences were the 3.4 Ma Mesa Cacaxtla shield volcano and the 2.1 Ma mafic lavas at Punta Piaxtla (Aranda-Gómez et al., 2003) both located along the coast ~60 km northwest of Mazatlán (Figure 8). During this study we studied two mafic volcanic fields with young morphologic appearance: Pericos and Choix. These fields were only reported in the geologic maps of the Mexican Geological Surveys but no age and compositional data were available.

The Pericos volcanic field covers an area of ca. 20 × 32 km located ~25 km N of Culiacán (Figure 9). Lava flows, small shield volcanoes, and cinder cones of basaltic composition cover in unconformity Paleocene granodiorite and Oligocene ignimbrites, which are mostly tilted to the WSW. Lavas are porphyritic and contain olivine, plagioclase and clinopyroxene in a microcrystalline matrix. Some lavas contain abundant megacrysts of green clinopyroxene (up to 8 cm), olivine (up to 1 cm), and/or plagioclase (up to 1 cm), or aggregates of olivine and clinopyroxene. We recognized at least sixteen cinder cones and
maars, all with a well-preserved morphology, suggesting a Pleistocene age for this volcanism. We have dated three samples trying to cover the whole age range of the field. The samples (PER1, PER4 and PER 6) have a hawaiitic composition and low K content so that Ar had to be released in a few steps. Nevertheless, they provide consistent Middle Pleistocene ages ranging between 857 ± 51 and 574 ± 113 ka (Figure 5c, Table 1, see Appendix DR2 for details). Rocks from the Late Pliocene Punta Piaxtla sills and Mesa Cacaxtla shield volcano, located 200 km to the SSE along the Sinaloa coast, show remarkably similar composition, mineralogy, and megacryst content (see next section), suggesting that the mantle of this wide region achieved a homogeneous composition that has been maintained during the last 3.4 Ma.

The Choix volcanic field consists of a few cinder cones and lava flows located 120 km NNE of Los Mochis in the northernmost corner of Sinaloa, near the boundary with Sonora and Chihuahua (Figure 9). Lavas are emplaced on top of Paleocene granodiorite and undated, but likely Oligocene, ignimbrites. Sample CHO 4 comes from an alkali-basalt lava coming from a very well preserved cinder cone near the Huites reservoir dam (Figure 9). The lava is vesciculated with phenocrysts of plagioclase, olivine, pyroxene and megacrystals of pyroxene (up to 3 cm) and olivine (up to 0.5 cm). Due to the very low K content and the presumed young age only four fractions were collected. The bulk of the $^{39}$Ar was released in the last two fractions and no plateau can be defined. This also yielded an imprecise isochron age of 29 ± 181 ka. The best estimate for this sample is 138 ± 107 ka, taken from the third fraction containing the bulk of the $^{39}$Ar released (see Appendix DR2 for further details). Although imprecise, this age confirms the very young age of the Choix volcanic field.

**GEOCHEMISTRY**

Major and trace element analyses were obtained for volcanic rocks of latest Oligocene to early Miocene, late Miocene and Pleistocene age (Table 2) distributed along the southeastern margin of the Gulf of California.

*Latest Oligocene to early Miocene*
Late Oligocene to early Miocene samples display a bimodal distribution in the total alkali vs. silica diagram (Figure 13a; LeBas et al., 1986). Samples with low silica content (SiO$_2$ = 48.7 – 55.2 wt. %) are lavas and dikes that classify as hypersthene (hy)-normative basalts and quartz (q)-normative basaltic andesite, whereas silicic samples (SiO$_2$ = 68.2 – 83.0 wt. %) from domes, lava flows, tuffs and ignimbrite classify as peraluminous (molar Al$_2$O$_3$/CaO + Na$_2$O + K$_2$O, A/CKN >1), corundum (c)-normative dacite and rhyolite, with a predominance of rhyolitic compositions. Most samples plot in the field of subalkaline rocks of Irvine and Baragar (1971), with the exception of one basaltic lava from the Atengo half graben (TS 16), which has the lowest SiO$_2$ content and plots in the field of alkaline rocks (Figure 13a). None of the mafic samples can be regarded as primitive mantle melts, as they have relatively low MgO and Cr contents (Figure 13b, d) and low Mg# (100×molar MgO/MgO+FeO$_{tot}$) of 42.1 to 52.5 (Table 2). The TiO$_2$ content is variable (Figure 13c), and is highest for the alkaline sample (TS 16; 2.39 wt. %).

Mafic rocks have variable trace element patterns in multi-element diagrams normalized to primitive mantle values (Sun and McDonough, 1989) (Figure 14e). Negative anomalies in Nb and Ta are absent in the TiO$_2$-rich, alkaline sample (basalt TS 16), and are variably developed in the subalkaline basalts and basaltic andesite. Positive Pb and Sr anomalies are present in all samples, but are more pronounced in the basaltic andesite. The lack of a Nb-Ta anomaly in sample TS 16 indicates an origin in an intraplate setting; nevertheless, the enrichment in Pb and Sr, which is not a common feature of intraplate magmas, could be rather related to the assimilation of crustal material (feldspar contamination) by the mafic magma. Trace element patterns of the subalkaline samples have the typical features of subduction-related rocks; however, in this sample group, crustal assimilation processes can have also contributed to generate signatures similar to those found in arc volcanic rocks. Alternatively, the subduction signature can be inherited from mantle domains previously modified by subduction components, which partially melted under the extensional regime that generated the intraplate magmas.

Silicic rocks are enriched in the most incompatible elements (Rb-U) and display well-developed negative Nb-Ta and positive Pb anomalies (Figure 14f). Despite the high silica content of these rocks, negative Ba anomalies, which result from the fractionation of K-feldspar, are absent. Eu and Sr negative anomalies are small in dacitic rocks, implying
negligible plagioclase fractionation. The trace element behavior indicates that crystal fractionation had a restricted role in the early evolution of the silicic magmas, which is supported by the fact that inherited zircons remained in the melt. This feature is often associated with crustally-derived magmas (e.g., Miller et al., 2003; Bryan et al., 2008). An origin in the crust is also consistent with the bimodal composition of the magmas emplaced in this period.

**Late Miocene**

Volcanic rocks emplaced in the late Miocene have mainly a bimodal compositional distribution (Figure 13a). Mafic to intermediate samples (SiO$_2$ = 51.4 – 57.2 wt. %) are classified as subalkaline q-normative basaltic andesite, low-silica andesite and potassic trachybasalt. Unlike rocks emplaced in the previous event, basalts are absent and more differentiated compositions with lower MgO and Cr contents (Figure 13b, d) and Mg$^+$ (36.7-53.5) occur. Analyses of scarce rocks with SiO$_2$>62 wt% indicate metaluminous (A/CKN<1) high-silica andesite, dacite and rhyolite compositions.

Low-silica rocks from the coastal area and Farallón de San Ignacio display relatively similar, subparallel trace element patterns in a mantle normalized multi-element diagram (Figure 14b), with weakly developed Nb-Ta anomalies, positive anomalies of Ba, Pb and Sr, and relatively flat rare earth element (REE) patterns (chondrite normalized La/Yb$_n$ = 3.7-5.3). Quite similar compositions are reported for the nearest known outcrops to the north of the study area, in the central Sonora coast (Till et al., 2009), and for the Santa Rosalía area in Baja California (Conly et al., 2005) (Figs. 1 and 14b). Regional compositional variations are suggested by one potassic trachybasalt from the submarine Nayarit scarp in the southeastern Gulf (Figure 2), which has the lowest SiO$_2$ content (51.4 wt. %) and is more enriched in most trace elements, resulting in a more pronounced Nb-Ta anomaly. Also, a basaltic andesite collected northeast of Pueblo Nuevo (Figure 8) within the Sierra Madre Occidental (SMO), has a Nb-Ta anomaly similar to that of the coastal lavas, but is more enriched in the most incompatible elements (Rb to Sr), and has a stronger depletion in the heavy REE with respect to the light REE (La/Yb$_n$ = 11.5). A more marked difference is observed in late Miocene mafic lavas from the Río Chico-Canatlán graben, located in the eastern part of the SMO (Figure 8)(Henry and Aranda-Gómez, 2000), which
have the high Nb contents of intraplate rocks. Differences in composition from east to west indicate changes in the mantle source composition from the Gulf of California to the eastern SMO, probably related to decreasing contributions of subduction components to the mantle and to increasing magma segregation depth.

Late Miocene silicic rocks from coastal and offshore areas display well-developed negative Nb-Ta and positive Pb anomalies, but differ in the abundance of trace elements (Figure 14c, d). Rhyolite R-F6 from Farallón de San Ignacio (Figure 10) and high-silica andesite R 24J 33 from the South Pescadero transform (Figure 2) show a pattern similar to those of the latest Oligocene to early Miocene, with less enrichment in all elements, no Ba anomaly, and less pronounced Sr and Eu anomalies, despite its high SiO₂ content. A dacitic tuff (R3J-4a) from the submarine Tamayo dome (Figure 2) has a higher abundance of most elements and displays pronounced negative anomalies in Ba, Sr and Eu that indicate extensive feldspar fractionation. Similar differences are observed in middle to late Miocene silicic rocks (SiO₂>70 wt. %) from the central Sonora coast (Till et al., 2009), and from the Santa Rosalía area in Baja California (Conly et al., 2005) (Figure 2 and 14d). A markedly different trace element pattern characterizes a dacite sample from Sierra Navachiste (Figures 10 and 14c), which has a much lower Nb-Ta abundance, positive Ba and Sr anomalies, no Eu anomaly, and stronger depletion toward the heavy REE (La/Yb_n = 13.3). The composition of this sample is similar to those of samples from Sierra Libre, in the central Sonora coast (Till et al., 2009), and also coincide relatively well with that of clinopyroxene-bearing andesite from Santa Rosalía (Conly et al., 2005), and Mg-andesite reported for the Borja and Jaraguay volcanic fields (Pallares et al, 2008), in the central Baja California peninsula. The variable composition of the late Miocene silicic rocks points to variable magma generation processes acting during this event. These processes may have involved crustal melting/assimilation or differentiation of mafic rocks through crystal fractionation, but further studies are needed to better constrain the origin of the observed differences.

**Pleistocene**

Lava samples from the Pleistocene Choix and Pericos volcanic fields (Figures 9 and 10) plot in the field of alkaline rocks (Figure 13a). One sample classifies as hy-normative
basalt, and the rest are nepheline (ne)-normative hawaiite and alkali basalt. The samples have the highest MgO, TiO₂ and Cr contents of all studied samples (Figure 13b, c, d), and Mg# of 48.2-57.9, but these values are lower than those expected for primary magmas derived from the mantle, implying that differentiation occurred during their ascent.

The samples have quite uniform trace element patterns (Figure 14a), which resemble those of OIBs, with the highest normalized abundances in Nb and Ta and strong enrichment of the light REE with respect to the heavy REE (La/Ybₙ = 9.4 – 13.5). The trace element pattern of a late Pliocene hawaiite from Mesa Cacaxtla (Figures 8, 14a), reported by Aranda-Gómez et al. (1997), is also remarkably similar to that of Choix and Pericos, considering the different emplacement times (Cacaxtla at 3.2 Ma, Aranda-Gómez et al., 1997; Pericos at 0.585-0.884 Ma, and Choix at 0.138 Ma, this work) and the distance between them.

The alkaline character and the trace element composition suggest that the Pleistocene magmas originated in a deeper, enriched OIB-like mantle source in the stability field of garnet, and differentiated at crustal levels.

**DISCUSSION**

**Timing of extension in the southern Gulf Extensional Province**

Figure 15 summarizes the ages of extension documented in this work and the literature. A precise determination of the direction of extension awaits a structural study of the kinematics of the various fault systems, which is in progress and will be published later. Although a strike-slip component of motion has been observed along some of the faults, the large vertical displacement and the consistent tilting of blocks indicate a dominant normal motion and an almost fault-orthogonal direction of extension. At a regional scale, we recognize a fairly consistent pattern along the ~700 km of length of the southeastern GEP with episodes of extension since ~29 Ma.

A Late Oligocene (29-24 Ma) phase of extension is documented in the central part of the study region (southern Sinaloa domain) in the area bounded by the Tayoltita-Pueblo Nuevo fault system to the east and the Concordia fault to the west (Figure 8). This early extension
would be only slightly younger than that reported in the Rodeo and Nazas area (Luhr et al., 2001) and in the northern part of the Rio Chico-Canatlán graben (Loza-Aguirre et al., 2012) to the east of the SMO unextended core (Figure 15). We expect a similar Late Oligocene extensional phase to have affected also areas to the north (northern Sinaloa domain, Figure 9), particularly in the more inland part of the GEP, which was not directly studied in this work. In fact, extension of this age was documented further to the north in the Guazapares area of southernmost Chihuahua (Murray et al., in press). Because of the extensive cover of early Miocene ignimbrites, the existence of a late Oligocene phase of extension is difficult to prove in the northern Nayarit domain. However, late Oligocene normal faulting are documented at least in the central Bolaños graben (Figure 2), where some of the faults (e.g., the prominent Ballena and Cabreras faults) are also NW trending and served as mineralization pathways during the early Miocene (Ramos-Rosique, 2012). The direction of extension during this first phase is not well-constrained but, considering the right-lateral component of motion reported in the northern part of the Tayoltita-Pueblo Nuevo fault system (Horner and Enríquez, 1999), it may be slightly oblique with respect to the main faults, i.e. WNW-ESE directed (Figure 15).

Extension continued during the early and middle Miocene (~24-12 Ma) in Sinaloa and northern Nayarit. In Nayarit this phase can be further divided into two main episodes with different directions of extension. Normal faulting with ~N-S trend affect a 180 km wide area between Bolaños and Huajicori (Figure 15) between ~24 and 18 Ma (see section 4) and is postdated by NNW trending fault systems (Pochotitán and San Pedro-Acaponeta) active between ~18 and 11 Ma along the coast (Figure 6). In Sinaloa, early to middle Miocene extensional faults strike essentially NNW, forming grabens and half grabens filled by 21 to 17 Ma dome complexes and volcaniclastic sediments interlayered with ~17 to 13 Ma basalts. This last phase of extension is postdated by flat-lying basaltic flows fed by NNW trending dikes dated between 11.3 and 10.3 Ma. These geologic and geochronologic relations make the Sinaloa area the southern prolongation of the latest Oligocene-mid Miocene extensional belt of Sonora, where high-angle faulting and volcaniclastic sedimentation of the Baucarit Formation occurred since 24 Ma and was essentially over by ~12 Ma (McDowell et al., 1997).
The western limit of this early extension is poorly constrained due to the superposed subsequent faulting and sedimentation in the Gulf of California. However, the shallow nature and rapid cooling of \( \sim 21-15 \) Ma old plutons exposed along the coast and in the rifted blocks inside the southern Gulf suggest that they were emplaced into an extending crust (Duque-Trujillo et al., 2012; in preparation). An early onset of rifting in the southern Gulf is suggested from the interpretation of seismic images recently provided by Miller and Lizarralde (2013) in the Guaymas basin. In the presented seismic profiles, these authors recognized a 2-km-thick evaporite deposit on top of seaward dipping reflectors (SDR). These SDRs may correlate with the \( \sim 12-10 \) Ma basaltic lavas we described at Farallón de San Ignacio and along the coast of Sinaloa, with up to 380 m of exposed thickness south of Culiacán. Similar basalts, dated at \( \sim 11-9.1 \) Ma, were also found in the Sante Rosalia area (Figure 2) below the Boleo evaporites that Miller and Lizarralde (2013) correlated with those seen on seismic sections. This tectonic setting implies that by the initial deposition of evaporites (\( \sim 7-8 \) Ma; Miller and Lizarralde, 2013) the basaltic lavas were below sea level and had been tilted. East of the evaporite basin, in the SMO, the pre-volcanic basement and Late Cretaceous to Early Tertiary batholithic rocks are exposed at up to 1,500 m of elevation and capped by \( \sim 1,000 \) m of mid-Tertiary ignimbrites. Even if the SMO ignimbrites may be much thinner or not even present within the Gulf, the middle and upper member of the Comondú group, with a thickness of up to 1,000 m (Umhoefer et al., 2001) should certainly underlain the late Miocene basalts. Therefore, the batholithic rocks must have been tectonically lowered a minimum of 2.5 km by \( \sim 10 \) Ma, something unlikely to have occurred in just 2-3 Myrs if extension began at the termination of subduction as has been widely assumed.

Sparse, but often unrealized indications of an Early to Middle Miocene extension are also reported for southern Baja California. Mark et al. (2012) found apatite U-Th(He) exhumation ages of 25-17 Ma in the Loreto area that fit well into the early extension of the southern GEP evident from our study. The formation of the Los Cabos basin in southernmost Baja California (Figure 15) may have also begun in middle Miocene times. The basin is bounded to the west by the San José de Los Cabos fault and several other normal faults are inferred by a gravity study beneath the basin fill (Busch et al., 2011). The Cretaceous Los Cabos batholith reaches 1,800 m of elevation in the footwall, while it is
inferred to be up to 2 km below sea level in the hangingwall, totaling 3.8 km of vertical displacement (Busch et al., 2011). Thermochronology of Upper Cretaceous granites from the footwall of the Los Cabos fault indicates a middle Miocene onset of rapid cooling and apatite FT ages show that by ~10 Ma these batholithic rocks were at ~2 km of depth (Fletcher et al., 2000). The onset of faulting is constrained by the oldest sediments in the associated basin which consist of red terrestrial sandstone and conglomerate (Calera Formation; Martínez-Gutiérrez and Sethi, 1997) overlying tilted silicic volcanic rocks correlative with the ~21-19 Ma old ignimbrites of the La Paz area. The sediments are conformably covered by the marine Trinidad Formation, assigned to the late Miocene on a paleontological basis (Martínez-Gutiérrez and Sethi, 1997). Batholithic rocks of the eastern part of the Los Cabos block show a geochronologic, geochemical and isotope similarity with those of the Jalisco block in mainland Mexico (Schaaf et al., 2000) and those exposed in the Maria Madre Island in between (Pompa-Mera et al., 2013), suggesting that the two blocks were contiguous in a NNW alignment prior to rifting (Figure 15). Based on these constraints, we speculate that the normal faults in the Los Cabos blocks may be partially coeval with the last extensional faulting in the northern Nayarit domain (~18-12 Ma).

In summary, despite the onset of rifting the cannot be precisely dated yet, several geological data suggest that at least by the middle Miocene the area now occupied by southern Gulf was already an extending basin.

**Pre-Late Miocene extension in the northern Gulf Extensional Province**

The early extension we have documented in this work cannot be limited to the southern GEP. Early to middle Miocene extension well documented in eastern and central Sonora (McDowell et al., 1997; Gans, 1997; Gonzalez-León et al., 2000; Vega-Granillo and Calmus, 2003; Nourse et al., 2004; Wong and Gans, 2003; Wong et al., 2010) constitutes the obvious prolongation to the north of the extensional belt of Nayarit and Sinaloa described on this work. However, the western boundary of this extensional belt is uncertain. Micropaleontological studies of several deep wells drilled in the Wagner, Consag, and Tiburón basins (Figure 1) reported the occurrence of over 1 km of marine sediments with shallow water (<200 m) foraminifera, dinoflagellates, and nanofossils older than 11.2 Ma (Helenes et al., 2009). Recent reinterpretation of these data by the same authors (Helenes
and Carreño, written communication) indicates that part of the recovered well material is reworked, a fact already reported for other sites in the northern Gulf (e.g. Imperial Formation, McDougall et al., 1999; Laguna Salada, Martín-Barajas, 2001; Isla Tiburón, Gastil et al., 1999). Given that the Peninsular Range Batholith of Baja California was uplifted in the early Eocene (Axen et al., 2000) the widespread occurrence of reworked mid-Miocene marine microfossils suggests the proximity of shallow marine environments within the northern Gulf of California by the middle Miocene. This interpretation is apparently at odds with the geology of Isla Tiburón (Fig. 1) (Oskin et al., 2003; Bennett et al., 2012), where marine incursion has been well dated at the latest Miocene. However we note that Isla Tiburón lies at the southeastern margin of a basin which, in its central part, has over 7 km of sediments overlying the late Cretaceous basement (Martín-Barajas et al., 2013). The well T-1 drilled by PEMEX near the deepest part of the Tiburón basin encountered ~4.8 km of marine deposits (Helenes et al., 2009), which in their lower part are considered not reworked and with an upper limit of 11.9 Ma based on the microfossils Ciclycargolithus floridanus (known range: 37-11.9 Ma), Cribroperdinium tenuitabulatum (69.9-11.63 Ma), Paleocystodinium golzowense (56-9.2 Ma) and Dapsilidinium pseudocolligerum (56-7.12 Ma) (Helenes, written communication). The recent seismic profiles of Martín-Barajas et al. (2013) show that the lowermost sedimentary package pinches out to the south and is not deposited on the basement high in the southeastern margin of the basin (Tiburon shelf) of which Isla Tiburón is part. Therefore the latest Miocene age of marine incursion at Isla Tiburón might not contradict the pre-11.9 Ma marine sediments in the deepest part of Tiburón basin. A definitive answer about the existence and extent of localized marine basins of pre-late Miocene age in the northern Gulf awaits further studies of well stratigraphy and seismic data from the deeper part of the Tiburón and other basins, but the possibility of an early extension in this part of the Gulf cannot be ruled out.

Pre-Late Miocene lithospheric thinning and motion of Baja California

The data reported in this work provide an important constraint about the amount of pre-late Miocene rifting in the southern GEP. Different seismic methods consistently indicate that the crust along the Nayarit and Sinaloa coast is significantly thinner than in the core of
the SMO. Estimations of the Moho depth from receiver functions and seismic refraction along the coast range between ~21 km west of Culiacán to ~18 km in northern Nayarit (Persaud et al., 2007; Lizarralde et al., 2007; Savage and Wang, 2012) (Figure 2). By contrast, the crustal thickness in the unextended core of the SMO is estimated to be 55 km northeast of Culiacán (Bonner and Herrin, 1999), ~40 km northeast of Mazatlán (Couch et al., 1991), and almost 30 km in the unfaul ted part of the Los Cabos block (Páramo et al., 2008). The presence of 11.3 to 10.3 Ma flat-lying mafic lavas at or near sea level along the coast of Nayarit and Sinaloa indicates that no significant tectonic activity occurred in this area after ~11 Ma. This implies that the thickness of the crust was substantially reduced by early extension occurring well before the end of subduction. This crustal thinning would have greatly aided the subsequent rupture, limiting the elastic thickness of the lithosphere to the uppermost crust, typical of a “crème brulée” rheology (Jackson, 2002).

Recognizing the importance of this early phase of extension in the GEP has important implications for the mode of extension and lithosphere rupture that led to the formation of the Gulf. Although the kinematics of opening is debated, previous studies in the past twenty years essentially assumed a ~14 to 12.5 Ma initiation of the rifting process (e.g., Stock and Hodges, 1989; Gans, 1997; Umhoefer et al., 2001; Oskin et al., 2003; Fletcher et al., 2007; Sutherland et al., 2012), implying a very fast rate of crustal thinning and the initiation of sea-floor spreading only ~6–10 m.y. after the onset of extension (Umhoefer, 2011). This is a very short time span for complete rupturing of the lithosphere, which is commonly accomplished over 25-30 m.y. in other examples (see review in Umhoefer, 2011). Our results indicate a more reasonable time span of ~25 m.y. between the initiation of extension and the initial formation of oceanic crust.

An early phase of extension across the GEP also reconciles the apparent discrepancy between the 275-300 km of offset across the northern Gulf since 12.5 Ma estimated by correlative geologic units (Gastil et al., 1973; 1991; Oskin et al., 2001; Miller and Lizarralde, 2013) and the ~450-500 km of offset needed to close the southern Gulf of California based on palinspastic reconstructions using an Airy isostatic model of crustal thickness (Fletcher et al., 2003). In fact, the total offset estimated by Fletcher et al. (2003) can be accounted by the sum of the post 12.5 Ma rifting plus the early extension documented in this work since ~29 Ma. We have tried to estimate the amount of this early
extension by looking at the motion of Baja California during this period (Figure 15). The position of Baja California before extension at 30 Ma is chosen in a way that re-aligns the Late Cretaceous batholiths of Puerto Vallarta (Jalisco Block), Los Cabos, and Sinaloa, as well as by bringing the paleotrench west of Baja in line with the present trench west of Puerto Vallarta (Figure 15). In this reconstruction, the southern tip of Baja California lies 475 km to the SE of its present position, essentially eliminating all the crustal stretching estimated by Fletcher et al. (2003) at the mouth of the Gulf. The position of Baja California at 12 Ma is obtained by removing the 245 km of oceanic crust accreted at the EPR (Lizarralde et al., 2007) plus 115 km of extension on both sides of the oceanic crust: 35 km in the stretched crust SE of the Los Cabos block (Páramo et al., 2008) and 75 km of extension in the 200 km long area of stretched crust between Puerto Vallarta and the continental slope west of Islas Tres Marías (Lizarralde et al., 2007) (Figure 2). In this scenario, the motion of Baja California between ~30 and 12 Ma would amount to 135 km, which, based on the age and geometry of faults, we propose was accomplished by WNW to E-W extension between ~30 and ~18 Ma and by WSW extension between ~18 and 12 Ma. Our reconstruction implies a moderate rate of separation of Baja California of 7.7 mm/yr during the first phase and 8.3 mm/yr in the second. Of note, these values are consistent with the rate of extension of the East African rift (7 mm/yr, Fernandes et al., 2004). The subsequent 355 km of NW-ward motion would have been accomplished with a higher average rate of 29.5 mm/yr. However, if we consider the present fault slip rate of 44.6 mm/yr within the Gulf (Plattner et al., 2009) as an average for the past 5 m.y. of drifting, the rate of motion during the late Miocene phase of NW-ward rifting would amount to 15.7 mm/yr. This progressive increase in the rate of separation (7.7-8.3 mm/yr prior to 12 Ma, 15.7 mm/yr from 12 to 5 Ma, and 44.6 mm/yr afterward) is likely related to the decreasing yield strength of the continental lithosphere as it is mechanically and thermally thinned and, eventually, completely severed by the onset of transtension.

It is worth mentioning that our reconstruction for the original position of Baja California relative to mainland Mexico at ~30 Ma (Fig. 15) approximate those of Fletcher et al. (2007) and Sutherland et al., (2012) at 12.5-14 Ma. These reconstructions implicitly implies no extension prior to 14 Ma and a high rate of separation of 32-35 mm/yr, which are uncommon for continental rifts, where geodetically measured rate of opening is typically
<10 mm/yr (Calais et al., 1998; Fernandes et al., 2004; Bendick et al., 2006). An implication of our reconstruction of ~475 km of NW motion of BC since ~30 Ma is that not much more dextral shear need to be accommodated within the Gulf after 12.5 Ma other than the ~275-300 km estimated from correlation of geologic units (Oskin et al., 2001; Miller and Lizarralde, 2013). However, according to global plate circuit reconstructions, since 12.3 Ma the Pacific plate moved ~600 km to the northwest relative to stable North America at the latitude of southern Baja California (Atwater and Stock, 1998). This implies that about 300 km of additional oblique shear must have been accommodated since that time between the Pacific plate and the stable North America. The most obvious place for this deformation is the belt of faults on the western margin of Baja California (Tosco-Abreojos and San Benito faults), which still accommodate 10% of the Pacific-North America relative motion (Plattner et al., 2009). This possibility would agree on early estimation of right lateral motion of along this fault belt (Stock and Hodges, 1989) but contrast with the more limited motion estimates by Fletcher et al. (2007) through correlation of the Magdalena fan with its most probable source (Figure 1). Another place where late Miocene extension may have been accommodated is the Basin and Range east of the SMO unextended core. In fact, although not quantified, Henry and Aranda (2000) reported an extensional episode in this wide area (Figure 1) between 12 and 6 Ma. A third possibility is that deformation has been underestimated in the GEP and that some additional motion may be distributed in small faults within the Gulf. All these options may jointly contribute to account for the missing ~300 km of displacement between the Pacific and North America plates but more structural, geochronologic, and geophysical data are needed to adequately assess their respective balance.

**Genesis of magmatism**

The significant pre-late Miocene extensional deformation documented in this work for western Mexico has important implications for the genesis of magmatism in the Gulf region. The overall calc-alkaline geochemical character, relatively primitive isotopic signature, and the supra-subduction position of the SMO and the Comondú volcanic rocks have traditionally led to interpretations of these provinces as being the manifestation of arc volcanism, whereas volcanism related to the rifting process would have appeared only after
subduction ceased. This view needs to be revised in light of the results presented here and elsewhere (Bryan et al., 2008; 2013). As we have shown, extension, and crustal thinning, occurred for at least 15 m.y. prior to the end of subduction, spatially associated with volcanism.

Geologically observable extension began in the southern SMO just after the major Oligocene ignimbrite “flare-up”. For example, the ~24 Ma El Salto-Espinazo ignimbrite succession filled a tectonic depression bounded by this early normal faulting. Extension continued during the early Miocene, likely triggering the last major sequence of ignimbrite eruptions at ~21-20 Ma (Nayar ignimbrite succession). At the same time, volcanism became bimodal and was characterized by more effusive activity. A belt of rhyolitic domes was emplaced along NNW trending normal faults that bound extensional basins localized along the site of opening of the Gulf of California. Mafic lava flows and rhyolitic domes filled major grabens along the coast of Sinaloa. Geochemistry of early Miocene silicic volcanism as well as the zircon antecrystic signature of many samples is consistent with significant crustal assimilation/melting induced by the arrival of mafic magmas in the crust. Similarly to Sinaloa, in southern Baja California the middle member of the Comondú group was likely emplaced in actively extending tectonic basins as suggested by the dominance of volcaniclastic sediments with respect to primary volcanic materials (Dorsey and Burns, 1994; Umhoefer et al., 2001; Drake, 2005). The dacitic-andesitic nature of the volumetrically modest Comondú volcanism has alternatively been explained by mixing of basaltic and rhyolitic magmas rather than by fluid fluxing of the mantle wedge above the subducting Guadalupe and Magdalena plates (Bryan et al., 2013). In fact, by ~16 Ma the subducting plate at the trench may have been as young as 3-5 m.y. old (Ferrari et al., 2012, Figure 18) and thus too dry and hot to release any meaningful amount of fluids once it reached the appropriated depth to flux the mantle wedge (i.e. 105 km Syracuse and Abers, 2006; see also Peacock and Wang, 1999). In this scenario, melting of sub-lithospheric mantle was essentially driven by decompression, induced by the significant lithosphere thinning going on at this time. The apparent subduction-related signature of SMO and Comondú volcanics is most likely a feature inherited by the previous >100 Ma history of subduction and acquired by crustal assimilation/melting. Interestingly, our easternmost late Miocene basaltic sample (TS 16, 24 Ma) has an intraplate signature (albeit with some
crustal assimilation), suggesting that by that time, at least beneath the eastern part of the SMO, the mantle was already devoid of any subduction influence. We conclude that since the Late Oligocene, crustal extension and magmatism were intrinsically linked and decompression melting progressively overwhelmed any flux melting of the mantle wedge.

A widespread mafic pulse of volcanism occurred at ~12-10.5 Ma along the Sinaloa and Nayarit coasts, as well as on the conjugated margin of Baja California and in the rifted continental blocks submerged in the Gulf. Although this volcanism post-dates the end of subduction off Baja California it still shows a variable subduction signature and a striking difference with the OIB-like late Pliocene to Pleistocene basalts emplaced in the same areas. The regional distribution of this volcanism over a 700 km long belt from Sinaloa to Nayarit in a narrow time frame points to a common mechanism of mantle melting albeit modulated by different degrees of fractional crystallization and crustal assimilation. We propose that this mafic volcanism is related to the acceleration of the rate of separation between Baja California and mainland Mexico once subduction ended and the peninsula started to be dragged northwest by the Pacific plate. The increasing NW-ward motion of Baja California follows its coupling with the shallow part of the subducted Magdalena plate once the lower part of the slab had detached and started foundering in the mantle (Ferrari, 2004). The precise location of slab detachment in the Gulf area is debated but it is thought to have initiated at 13-12 Ma (Calmus et al., 2003; Pallares et al., 2007; Brothers et al., 2012). The ascent of hot asthenospheric mantle into the slab gap that formed after the slab detachment may have triggered extensive melting of the subduction-modified former mantle wedge, which ultimately led to the ~12-10.5 Ma mafic pulse. However, the scrubbing of a subduction signature from the mantle and the consequent melting of undepleted asthenosphere in the Nayarit-Sinaloa margin was delayed until Late Pliocene, whereas calc-alkaline melts are still being generated in some locations in eastern Baja California.

**Concluding remarks**

The data presented in this work show that the GEP represents the last and most visible phase of rifting in the Gulf of California driven by the oblique divergence of Baja California peninsula from the Mexican mainland. Although different view exists on how
oblique divergence was partitioned between the San Benito-Tosco-Abreojos fault system and the Gulf of California on the two sides of the peninsula (Stock and Hodges, 1989; Gans, 1997; Oskin and Stock, 2003; Fletcher et al., 2007), there is no doubt that this last episode of rifting and its associated volcanism was primarily controlled by plate boundary forces, namely the progressive dragging of Baja California to the NW by the Pacific plate and the upwelling of asthenosphere into the slab gap produced by the detachment of the lower part of the subducted slab.

The causes of the early “Basin and Range” extension, however, are not completely understood. The onset of extension in western Mexico was considered to be Oligocene in the eastern part of the SMO and to have subsequently migrated to the west to reach the Gulf area at the end of Middle Miocene (Cameron et al., 1989; McDowell and Mauger, 1994; Henry and Aranda-Gómez, 2000; Luhr et al., 2001; Umhoefer et al., 2001; Aranda-Gómez et al., 2003). By contrast, our work indicates that a sustained period of lithospheric stretching affected the entire western Mexico, from the eastern part of the SMO to the region of the future Gulf of California, since the Late Oligocene. The first part of this extensional history, producing the Mexican Basin and Range, occurred during the last period of subduction beneath North America, and broadly coincided with the silicic volcanism of the SMO and the intermediate volcanism of the Comondú group. The initial wide zone of rifting between ~30 and 20 Ma subsequently focused in the westernmost part of the SMO and the Gulf region at ~20-18 Ma to form a narrower rift where the Comondú group was being deposited. Subduction of the Magdalena microplate started waning by 15 Ma, and ultimately ceased by ~12-11.5 Ma to be replaced by oblique divergence (Lonsdale, 1991; Tian et al., 2011). Therefore, a significant part of extension in the southern Gulf of California (the proto-Gulf) occurred prior to subduction termination and cannot be directly associated with the interaction between the Pacific and North America plates.

Previous studies (e.g. Ferrari et al., 2002, 2007; Bryan et al., 2008, 2013), confirmed by this work, have shown that the outbursts of silicic volcanism in the SMO (the ignimbrite flare-ups) cannot be explained by an assimilation and fractional crystallization process alone but was dominantly produced by intrusion of large amount of mafic melt in the crust. The accumulation of mafic magma in the crust had to be sufficiently rapid to produce enough silicic melt to feed many large-volume ignimbrite eruptions in a short time span.
(typically 1-2 Myrs). The occurrence in the SMO of two ignimbrite flare-ups suggests that mantle melting and the production of mafic magmas also occurred in two main pulses, ruling out a steady-state flux melting process related to a normal subduction regime.

Silicic magmatism and extension in the US part of the Basin and Range province has been attributed to boundary forces (i.e., trench retreat, rollback and steepening of the subducting Farallon plate; Dickinson and Snyder, 1978; Best and Christiansen, 1991; Ward, 1991; Bohannon and Parsons, 1995; Dickinson, 2002; McQuarrie and Oskin, 2010) or body forces (i.e., active rifting induced by upwelling of hot asthenosphere within a slab window or gravitational collapse of a thickened crust; e.g. Houseman et al., 1991; Gans et al., 1989; Harry et al., 1993; Leeman and Harry, 1993; Axen et al., 1993; Wilson et al., 2005; Wong et al., 2010). As shown by Sonder and Jones (1999) a single mechanism is unable to explain all the extensional deformation of the western United States and a combination of both groups of forces is required. The cause of the Basin and Range extension and the ignimbrite flare-ups in the Sierra Madre Occidental is probably related to a similar combination of processes but assessing the role and weight of each factor needs a more complete dataset on fault activity, magmatic evolution, and crustal structure.

We conclude that, in the past 30 Myrs, western Mexico has been dominated by lithospheric extension that was produced by different geodynamic mechanisms. The real change at ~12.5 Ma was the direct interaction between the Pacific and North America plate that resulted in rifting focusing on the westernmost part of a wide and already thinned belt of lithosphere and in changing the kinematics of deformation, imposing a high degree of obliquity. In this context, the GEP can be only distinguished from the previous episodes of extension by its right lateral component of deformation and thus should be more properly called the Gulf Transtensional Province.

Acknowledgments:
Research supported by grant CONACyT 82378 and 121513 (to L.F.) and CONACyT P46600-F (to MLM). We thank M. Cerca for information and discussions on the tectonics of Baja California Sur, C. Ortega for assistance in U-Pb dating, O. Pérez Arvizu for ICP-MS trace element analysis, M.A. García Gracía for help in the Ar-Ar mass spectrometry, L.
Luna for helping with maps preparation, A.S. Rosas Montoya, V.M. Pérez Arroyo, G. Rendón and L. Gradilla for Ar-Ar sample preparation, A. Ramos Rosique, J. Pelaez, G. Antillón Mata, V. Reyes, C. Cornejo-Jiménez, Y. González Romo, J. González Romo, V. Reyes Orozco, M. García Sierra, J.C. Castro Clímaco, for field assistance and zircon separation. Samples DANA and ROCA were collected in the Gulf of California during cruises funded by grants NSF…. to P. Lonsdale. Axel Schmitt and Joann Stock provided detailed and very constructive reviews that improved the original submission.

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Figure captions

Figure 1. Regional tectonic map of the Gulf of California and adjoining areas showing distribution of different type of lithosphere, the Basin and Range and Gulf Extensional Province (dashed orange lines) and the extent of the Sierra Madre Occidental silicic large igneous province (dashed red line). The extent of the unextended core of the Sierra Madre Occidental has been revised according to this study. Patterns of oceanic plate boundaries and crustal isochrons from Lonsdale (1991) and Tian et al. (2011). GEP = Gulf Extensional Province (note different eastern boundary in Sonora according to the definition of Stock and Hodges (1989) and of Calmus et al. (2010)); MGE = Main Gulf Escarpment; BG = Bahía Guadalupe; BA = Bahía de Los Angeles; IT = Isla Tiburón; TB = Tiburón Basin; ITM = Islas Tres Marias; MF = Magdalena Fan; EPR = East Pacific Rise. Inset show the main fault systems presently defining the Pacific-North America plate boundary (SAF = San Andreas fault system; WL-ECSZ = Walker Lane–Eastern California shear zone; SBTA = San Benito–Tosco Abreojos fault system; GoC = Gulf of California fault system) and the Sierra Nevada (SN) and Baja California (BC) microplates.

Figure 2. Tectonic map of southern Gulf of California and adjoining regions showing the main Neogene faults and crustal thicknesses (from Persaud et al., 2006 and Lizarralde et al., 2007). Offshore samples not included in Figures 6, 8, 9 and 10 are also included (R3 = Roca 3J 5; R24 = ROCA 24J 33; D46 = DANA 46a). RML = Río Mezquital Lineament; TL = Tayoltita Lineament; Bo = Bolaños graben; RCC = Río Chico-Canatlán graben; NC = Nayar Caldera field; TC = Temoaya Caldera; MC = Mesa Cacaxtla shield volcano; PVF = Pericos volcanic field; CVF = Choix Volcanic Field; JB = Jalisco Block; TAF = Tosco-
Abreojos fault system; SMF = Santa Margarita Fault; FSI = Farallón de San Ignacio island; SC = Santa Catalina Island; SR = Santa Rosalia; EGE = Eastern Guaymas Evaporites.

Figure 3a and b. Histogram and concordia diagrams of U-Pb ages for zircons of silicic rocks. Given errors in calculated ages are 2σ. Full details of the U-Pb experiments are given in Appendix DR1.

Figure 4. $^{36}$Ar/$^{40}$Ar versus $^{39}$Ar/$^{40}$Ar correlation diagrams for the samples analyzed. The isochron age calculated is given for each sample. a) Sierra Madre Occidental pre- and syn-rift volcanism; b) Coastal and offshore lavas; c) Pericos and Los Choix volcanic field. Full details of the $^{40}$Ar-$^{39}$Ar experiments and discussion of results are given in Appendix DR2.

Figure 5. $^{40}$Ar-$^{39}$Ar age spectra for the samples analyzed. a) Sierra Madre Occidental pre- and syn-rift volcanism; b) Coastal and offshore lavas; c) Pericos and Choix volcanic field. Full details of the $^{40}$Ar-$^{39}$Ar experiments and discussion of results are given in Appendix DR2. The plateau age given in the figure was calculated with the weighted mean of the fractions identified with the horizontal arrow. First experiment in pale blue and second experiment in yellow. For illustrative purpose the 13 one-step laser fusion experiments from sample DANA 46a are plotted as a pseudo-age spectrum in pink.

Figure 6. Regional geologic map of northern Nayarit showing the main extensional structures, and new and published ages (rounded at the closest decimal). JM = Jesús María, Pic = Picachos, Ca = Caramota dome, Cu = Cuchara dome.

Figure 7. A, B, and C: Gulf-orthogonal geologic sections showing rifting style and syn-extensional volcanism for northern Nayarit (locations in Figure 6). Note variable vertical exaggeration. D: aerial picture of the Pochotitán fault system looking north (geologic section A). Note 21 to 20 Ma ignimbrites tilted up to 35° to the ENE. E: aerial picture of the western side of the N-S trending San Agustín graben looking north (geologic section C).
Figure 8. Regional geologic map of southern and central Sinaloa showing the main extensional structures, and new and published ages. SIG = San Ignacio Graben; CG = Conitaca graben; EDD = Espinazo del Diablo; LA = Las Adjuntas dome; MN = Mala Noche; CC = Cerro Cuadrado.

Figure 9. Regional geologic map of Culiacán and Pericos areas (northern Sinaloa) showing selected geologic units, the main extensional structures, and new and published ages.

Figure 10. Regional geologic map of Los Mochis-El Fuerte areas (northern Sinaloa) showing selected geologic units, the main extensional structures, and new and published ages.

Figure 11. Gulf-orthogonal geologic sections showing rifting style and syn-extensional volcanism for Sinaloa (location in Figure 8 and 9). Note variable vertical exaggeration.

Figure 12. Pictures illustrating geologic and tectonic relations described in the text. A: Rhyolitic dikes feeding a large dome dated at 27.9 (Ar-Ar, Ferrari et al., 2002) in the western part of the Atengo half graben. Dikes are 10 to 15 m thick (see person in inset for scale). B: N-S striking normal fault covered by a rhyolitic dome dated at 17.5 Ma (sample RUIZ 34b, Table 1). C) View of the Baluarte bridge (world’s second highest bridge) looking south. Note the 400 m deep canyon cut into the massive, flat-lying, basal unit of the Espinazo-El Salto ignimbrite sequence. D: North looking view of west dipping ignimbrites at Mazatlán lighthouse (Cerro El Crestón). E: NNW looking view of angular unconformity between flat-lying Espinazo-El Salto ignimbrite sequence (Cerro Cuadrado) and pre-Miocene ignimbrites south of the Presidio river canyon. F: Angular unconformity between slightly-tilted El Salto-Espinazo ignimbrite sequence and strongly tilted pre-Miocene ignimbrites. View looking north-west from the southern side of Baluarte river canyon. G: Angular unconformity as in E, but north of the Presidio river canyon looking NNW from Ejido San Pablo. H: North looking view of the southeastern dome complex of Sierra El Infierno. The base of the Sierra lies at 50 m and the highest peak reaches 1400 m. I: NNW striking mafic dikes cutting Late Cretaceous granites and aplite dikes at Santa Catalina.
Island, Baja California Sur. The dike is dated at 10.9 Ma (sample SC 3, Table 1). J: Flat-lying mafic flows along the Sinaloa coast south of Guamuchil dated at 10.3 Ma (sample PER 14, Table 1). K: Sub-vertical, NNW striking mafic dike cutting a tilted ignimbrite succession near Pericos (Figure 9). Dike likely fed flat-lying basaltic flows like those dated at 10.3 Ma nearby (photo J). L: Late Pliocene hawaiite sill at Punta Piixtla. The sill contains xenoliths of spinel lherzolite, granulites, pyroxenites and megacrysts.

Figure 13. Composition of volcanic rocks of latest Oligocene to early Miocene, late Miocene, and Pleistocene age, from the southeastern margin of the Gulf of California. a) Total silica vs. alkalis classification diagram (LeBas et al., 1986), showing the line dividing alkaline from subalkaline compositions (Irvine and Baragar, 1971); A: andesite, B: basalt; BA: basaltic andesite; D: dacite; H: hawaiite; KTB: potassic trachybasalt; R: rhyolite. Also showed is the variation of SiO₂ vs. MgO (b) and TiO₂ (c), and of MgO vs. Cr (d).

Figure 14. Multielement diagrams of volcanic rocks from the southeastern margin of the Gulf of California, normalized to primitive mantle (PRIMA) values of Sun and McDonough (1989). Pleistocene (0.884–0.138 Ma) mafic lavas (a); late Miocene (11.9–9.7 Ma) mafic lavas (b) and silicic rocks (c, d); latest Oligocene to early Miocene (24.38–17.4 Ma) mafic rocks (e) and silicic rocks (f). Letters next to sample numbers indicate rock composition, A: andesite, AB: Alkali basalt; B: basalt; BA: basaltic andesite; D: dacite; H: hawaiite; KTB: potassic trachybasalt; R: rhyolite. In diagrams a) through d), data compiled from the literature for rocks of similar age in mainland Mexico and Baja California peninsula are shown for comparison. SMO: Sierra Madre Occidental.

Figure 15. Regional tectonic map summarizing the main structures and age of extension of the conjugate margins of the southern Gulf of California. PV = Puerto Vallarta; Hua = Huajicori; JM = Jesús María. Geographic coordinates refer to present position of Mexico mainland. Position of Baja California at 12 Ma is obtained by moving the southern tip of Baja California (Cabo San Lucas) 350 km to the SE parallel to the Tamayo transform, removing all the oceanic crust accreted at the EPR to the south. The position at 30 Ma is obtained by aligning the paleo trench off Baja California with the present trench off the
Jalisco block and joining the late Cretaceous batholith of the Los Cabos block in Baja California with the Sinaloa and Jalisco block batholith. See text for discussion.

**Appendix 1 – U-Pb LA-ICP-MS dating methodology**

U-Pb ages on separate zircons were obtained by laser ablation–inductively coupled plasma–mass spectrometry (LA-ICP-MS) at the Laboratorio de Estudios Isotópicos, Centro de Geociencias, Universidad Nacional Autónoma de México, according to the procedures reported in Solari et al. (2010). The analytical data are reported in Table DR1. The Plešovice reference zircon (ca. 337 Ma; Sláma et al., 2008) was used in combination with NIST 610 standard glass to correct for instrumental drift and down-hole fractionation and to recalculate elemental concentrations, using Iolite software (Paton et al., 2010) in combination with the VisuaAge data reduction scheme of Petrus and Kamber (2011). Precision on the measured $^{207}\text{Pb}/^{206}\text{Pb}$, $^{206}\text{Pb}/^{238}\text{U}$, and $^{208}\text{Pb}/^{232}\text{Th}$ ratios typically was ~0.95%, 0.7%, and 1.1% 1σ relative standard deviation, respectively. Replicate analyses of the Plešovice zircon indicate an external reproducibility of 0.95%, 0.7%, and 1.6% on the measured $^{207}\text{Pb}/^{206}\text{Pb}$, $^{206}\text{Pb}/^{238}\text{U}$, and $^{208}\text{Pb}/^{232}\text{Th}$ ratios, respectively. These errors are quadratically included in the quoted uncertainties for individual analyses of the analyzed zircons. Because its signal is swamped by the $^{204}\text{Hg}$ contained in the carrier gases, $^{204}\text{Pb}$ was not analyzed during this study. When needed, the common Pb correction was thus performed employing the algebraic method of Andersen (2002). It is important to bear in mind that with this method, the analysis of Tertiary zircons is a complex task, due to the tiny signal of $^{207}\text{Pb}$, which yields somewhat imprecise (i.e., discordant) analyses, difficult to correct with the Andersen (2002) algorithm. A concordance filter is thus not applied, because this would eliminate most of the obtained ages. The concordia, weighted mean ages, as well as age-error calculations, were performed using Isoplot v. 3.70 (Ludwig 2008). The $^{206}\text{Pb}/^{238}\text{U}$ ages are preferred for grains younger than 1000 Ma because of the uncertainty involved in determining the $^{207}\text{Pb}$ isotope in young crystals.

**Appendix 2 - $^{40}\text{Ar}-^{39}\text{Ar}$ Methodology**

The 29 new ages presented here were obtained over a period of six years. All the samples were step-heated. The temperature controlled Ta-furnace was used to extract the argon of
four samples; for these, the argon isotopes were analyzed with the MS-10 mass spectrometer. The rest of the samples were step-heated using an argon-ion laser beam and the extracted argon was analyzed with the VG5400 mass spectrometer. The technical details and interpretation of the 40Ar-39Ar experiments for each sample will be given as they are presented. With the exception of samples ESC 7; MdCH 10; LM 2; PER 12 and PER 14, which were prepared at the mineral separation laboratory of the CGEO-UNAM, the samples were prepared at CICESE’s Dept. of Geology. The basic sample preparation consisted of crushing and sieving, then rinsing with distilled water followed by 98% acetone. The rock fragments were dried overnight at ~60° C. The rock fragments or mineral crystals selected for analysis were generally ~ 500µ in size; only five samples were smaller than this: feldspar ROCA 3J 5 was ~ 300µ; and samples ESC 7, LM 2, PER 12 and PER 14 were ~ 200µ. The fraction selected to prepare the samples was chosen from the fraction where the fragment size was closest to the size of the minerals to be separated or where it could be observed that the groundmass fragments were free of phenocrysts. Mineral separation procedure consisted of magnetic Frantz separation, heavy liquids if necessary and final examination of the samples under the microscope to insure >99% purity of the concentrate. For some samples, no mineral concentrate could be separated, these samples were examined under the microscope and the phenocrysts were eliminated by hand; these were labelled groundmass. If no phenocrysts were observed, the sample was labelled whole rock.

The majority of rock fragments and minerals were irradiated in position 5C and sample ES 10 was irradiated in position 8C. The irradiations were performed in the U-enriched research reactor of McMaster University in Hamilton, Ont. Canada. Since the project was conducted over several years, the samples were irradiated in different groups. Samples DANA 46a and ES 10 received 40 MWH; the rest of the samples received 30 MWH. With the exception of sample DANA 46a that was irradiated without a Cd-liner; rock fragments were covered with a Cd-liner to block thermal neutrons. The irradiation monitors used were: TCR-2 (split G93) sanidine (28.34 ± 0.28 Ma, Renne et al 1998); FCT-2 sanidine (28.201 ± 0.046 Ma; Kuiper et al., 2008); HD-B1 biotite (24.18 ± 0.09 Ma; Schwarz and Trieloff, 2007); CATAV 7-4 biotite (89.13 ± 0.35 Ma; internal standard calibrated with
hornblende hb 3gr at the University of Toronto, with hornblende MMhb 1 at the University of Nice and at CICESE with sanidine TCR-2, sanidine FCT-2, biotite HD-B1 and 128.1 Ma biotite LP-6, Roddick 1983). The irradiation monitors were distributed among the samples. The irradiation monitors were fused in one step to calculate J. The J value used for the samples came from the monitor that was closest to the sample during irradiation.

All the argon experiments were preceded by a blank measurement, where all the argon masses were measured. Upon blank subtraction, the argon isotopes were corrected for mass discrimination, calcium, potassium and chlorine neutron-induced interference reactions. The parameters used to correct for neutron-induced interference reactions were:

\[(39\text{Ar}/37\text{Ar})\text{Ca} = 6.51 \times 10^{-4}; (36\text{Ar}/37\text{Ar})\text{Ca} = 2.54 \times 10^{-4}; (40\text{Ar}/39\text{Ar})\text{K} = 2.87 \times 10^{-2}\]

for DANA 46a. For the rest of the samples, which had Cd-liner the parameters:

\[(39\text{Ar}/37\text{Ar})\text{Ca} = 6.50 \times 10^{-4}; (36\text{Ar}/37\text{Ar})\text{Ca} = 2.55 \times 10^{-4}; (40\text{Ar}/39\text{Ar})\text{K} = 0,\]

were used. Mass 36 was also corrected for chlorine-derived 36Ar \((35\text{Cl} (n, \gamma) 36\text{Cl} \rightarrow 36\text{Ar} + \beta \text{ with } t_{1/2} = 3.1 \times 10^5 \text{ a}).\) Isotopes 37Ar and 39Ar were corrected for radioactive decay. The constants recommended by Steiger and Jäger (1977) were used in all the calculations while all the straight line, calculations were performed with the equations presented in York et al., (2004). All errors are reported at 1σ level. The errors in the integrated, plateau, isochron and weighted mean age include the uncertainty in the J parameter. Additionally for the plateau, isochron and weighted mean ages, the goodness of fit was included in the age uncertainty whenever the MSWD exceeded 1. The integrated ages were calculated adding the fractions of the step-heating experiments. Plateau ages were calculated with the weighted mean of three or more consecutive fractions, which were in agreement within 1 σ errors excluding the uncertainty in J. All the data were plotted on an 36Ar/40Ar versus 39Ar/40Ar correlation diagram to determine the composition of the \(40\text{Ar}/36\text{Ar}\) of the samples. Tables with the relevant 40Ar-39Ar data of all the experiments are given here. A brief discussion of the 40Ar-39Ar results follows. Tables with the relevant \(^{40}\text{Ar}-^{39}\text{Ar}\) data of all the experiments and the figures with age spectrum, \(^{37}\text{Ar}_{\text{Ca}}/^{39}\text{Ar}_{\text{K}}\) diagram and the \(^{36}\text{Ar}/^{40}\text{Ar}\) versus \(^{39}\text{Ar}/^{40}\text{Ar}\) correlation diagram for each sample are given in the Appendix DR2.
Appendix 3 - Sample preparation for trace element analysis

Mafic to intermediate samples were analyzed using the procedure described in Mori et al. (2007). For silicic samples (SiO2 > 60%), two additional digestion steps were carried out, in order to achieve complete dissolution of refractory minerals (e.g., zircon). The same amount of sample (50 mg) was weighted in 15 mL Teflon vials, and after an initial overnight attack with 1 mL HF and 0.5 mL 8 N HNO3 on a hot plate at 90 °C, followed by evaporation to almost dryness, samples were transferred to 1.5 mL teflon vials with 1 mL HF and 0.5 mL 8 N HNO3. Closed vials were then placed inside the teflon liner of metal-jacketed Parr pressure bombs, to which 3 mL of a 2:1 HF-8 N HNO3 mixture were added in order to equalize the pressure inside and outside the vials and prevent solution loss. The bomb was sealed and heated in an oven at 190 °C for five days. Thereafter, the bomb was allowed to cool to room temperature and the vials were removed, opened and placed on a hot plate to evaporate the acids to almost dryness. After addition of 1.5 mL HCl, the vials were placed again in Parr bombs and 3 mL of 6N HCl were added to the Tefon liner. The bombs were heated at 190 °C in an oven for 24 hrs. This step is required in order to decompose the fluoride that might have formed in the previous steps. After cooling, vials were removed from the bombs and the samples were transferred to the original 15 mL vials, which have a larger surface area that allows faster evaporation. The final steps consisted in evaporating the samples to dryness, fluxing the samples twice with 16N HNO3, evaporating the sample to dryness after each step. Then, 2 mL deionized water and 2 mL 8N HNO3 were added to the samples and the closed vials were left overnight on a hot plate at 90 °C. For analysis, the samples were diluted by weight to 100 g (1:2000 dilution) with an internal standard solution containing Ge (10 ppb), In (5 ppb), Tm (5 ppb) and Bi (5 ppb). Calibration was performed with the international rock standards AGV-2, BHVO-2, BCR-2, JB-2, and JR-1.

Samples DANA 46a, ROCA 3J 4a and ROCA 24J 33 were analyzed by X-ray fluorescence spectrometry and by inductively coupled plasma–mass spectrometry at the GeoAnalytical Laboratory of Washington State University with the methods described in Castillo et al., (2010).