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Stratigraphy and geochronology of the Comondú Group near Loreto, Baja California sur, Mexico

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Abstract

Upper Oligocene to Middle Miocene volcanic and sedimentary rocks in the Loreto region, Baja California Sur, are widely exposed and make up the Comondú Group as redefined here following McFall. The Comondú Group is part of a volcanic arc and forearc basin that formed along the northwestern margin of Mexico. Regional to detailed scale mapping, stratigraphic analysis, and geochronology in a 10–20-km-wide and 70-km-long belt from the gulf escarpment to the coast near Loreto reveal three main units in the Comondú Group and a composite thickness of ~1.5–2 km. (1) The lower clastic unit (~30–19 Ma) contains 200–300 m of fluvial sandstone and conglomerate with probable local eolian deposits and numerous felsic tuffs and basalt flows that accumulated in a forearc basin. (2) The middle breccia and lava flow unit (~19–15 Ma) is up to 750 m thick and consists of massive andesite breccia that was deposited as proximal debris flows interbedded with minor andesite lava flows. (3) The upper lava flow and breccia unit (~15–12 Ma) consists almost entirely of up to ~600 meters of andesite lava flows a few kilometers west of Loreto that are part of a composite volcano. North and south of Loreto for up to 25 km, the unit is composed of andesite lava flows and massive andesite breccia that formed from thick debris flows near that and other volcanic centers. The three units of the Comondú Group in the Loreto area correlated with the Salto, Pelones, and Ricasón formations of the Bahía Concepción area. The lower clastic unit of this study is time equivalent to the marine San Gregorio, El Cien, and Isidro formations on the western and southern Baja California peninsula. The middle and upper units of the Loreto area are the proximal equivalent to the type section of the Comondú Group near the village of Comondú. During deposition of the lower part of the Comondú Group, the arc lay to the east on mainland Mexico in the Sierra Madre Occidental, and then migrated to the position of the Gulf of California at about 25 Ma. At ~19 Ma the proximal part of the arc migrated abruptly >50 km westward to approximately the position of Carmen Island and at 15 Ma the arc once again stepped west forming eruptive centers along the coast near Loreto until ~12 Ma. Also at 15 Ma, the proximal forearc region changed from aggradational to neutral or erosional such that no rocks of the upper unit are preserved in the gulf escarpment. © 2001 Elsevier Science B.V. All rights reserved.

Keywords: Baja California; Volcanic arc; Stratigraphy; Miocene; Oligocene

1. Introduction

The Baja California peninsula in northwestern Mexico is presently moving northwestward relative

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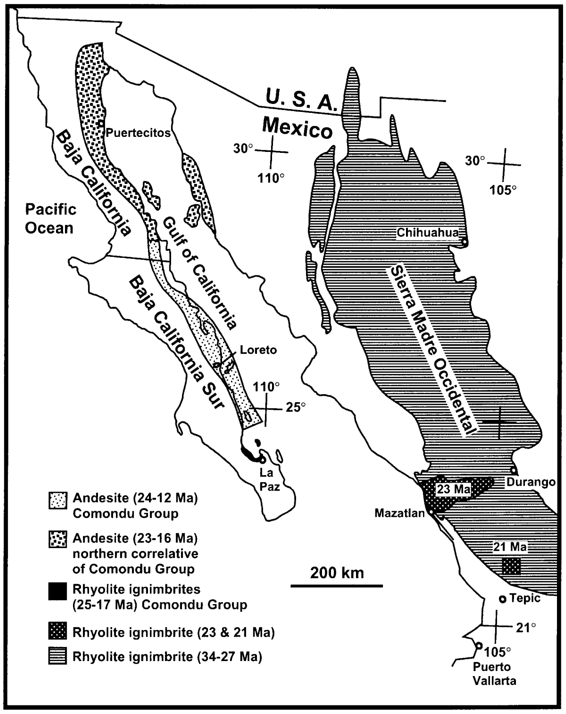

Fig. 1. Map of NW Mexico from Baja California peninsula to Sierra Madre Occidental showing some of the major belts of Cenozoic volcanic rocks (modified from Sawlan, 1991; Ferrari et al., 1999; Nieto-Samaniego et al., 1999). The 23 and 21 Ma ignimbrites shown in black with white dots near Mazatlan and schematically near Tepic are from calderas that are possible candidates for the distal tuffs found near La Paz and Loreto (Ferrari et al., 2000). The older (28–29 Ma) tuffs from the lower part of the Comondú Group near Loreto and Bahia Concepción are probably from the Sierra Madre Occidental. Many small patches of Cenozoic volcanic rocks near the coast east of the Gulf of California are not shown.

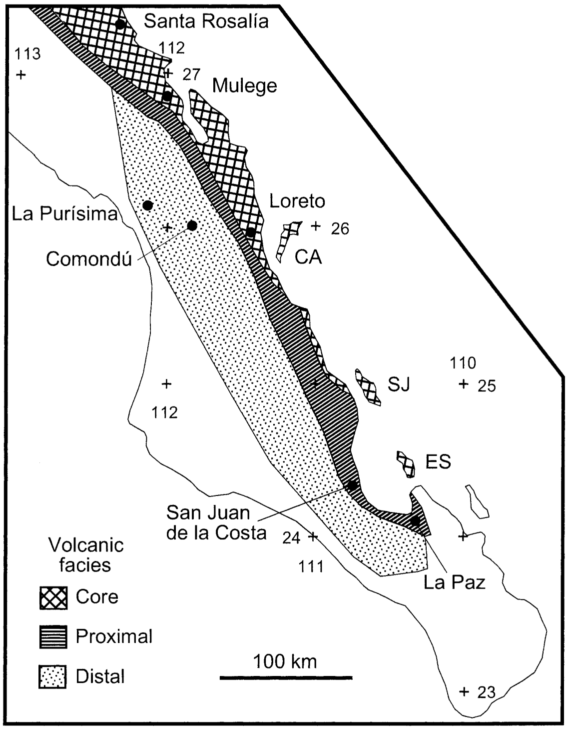

Fig. 2. Map of the generalized volcanic facies belts within the Comondú Group in Baja California Sur (modified from Hausback, 1984).

to mainland Mexico (North American plate) as part of the Pacific plate (Larson et al., 1968). The peninsula has detached from mainland Mexico since the Middle Miocene by first orthogonal, and then oblique, rifting associated with the formation of the Gulf of California (e.g. Moore and Buffington, 1968; Larson et al., 1968; Stock and Hodges, 1989). Prior to the formation of the Gulf of California, when Baja California was attached to mainland Mexico, an extensive terrestrial volcanic arc formed along northwestern Mexico in Late Oligocene to Middle Miocene time (~34–12 Ma; Fig. 1) (Hausback, 1984; Henry, 1989; McDowell et al., 1997; Ferrari et al., 1999). The arc volcanism migrated westward over time. The older, Oligocene, parts of the volcanic arc are mainly located to the east in the Sierra Madre Occidental (Fig. 1) and in coastal regions of Sonora and Sinaloa (McDowell and Keizer, 1977; Henry, 1989; Wark et al., 1990; McDowell and Mauger, 1994; Ferrari et al., 1999). The dominantly Miocene part of the arc is in Sonora, Sinaloa, the southern Sierra Madre Occidental, and along the eastern coast of the Baja California peninsula (Fig. 1) (Hausback, 1984; McLean, 1988; Sawlan, 1991; Ferrari et al., 1999).

Excellent exposures of Oligocene to Miocene arc and forearc rocks are found in Baja California Sur, including the Loreto region (Fig. 2) (Hausback, 1984; Sawlan and Smith, 1984; McLean, 1988; Sawlan, 1991; Zanchi, 1994; Bigioggero et al., 1996). Despite the well preserved nature of this relatively young arc and forearc basin, it has received relatively little detailed study. In the course of studying how the southern Gulf of California formed near Loreto, we have mapped at 1:50,000 and 1:20,000 scales the Miocene arc-related rocks in a ~100-km-long and 10–to 20-km-wide coastal belt, from the coastline to the gulf escarpment, and on Carmen Island.

We report here the overall stratigraphic architecture of the Oligocene–Miocene arc-related rocks and facies trends in the coastal belt. Our work is not a detailed examination of volcanic facies, but it extends significantly the previous work based on less detailed mapping (McLean, 1988; Zanchi, 1994; Bigioggero et al., 1996) and lays a time–stratigraphic foundation for detailed work in the future. Our results confirm the basic arc-related facies of Hausback (1984), but shows that they migrated westward abruptly two to three times. Five new ages using the $^{40}Ar/^{39}Ar$ method, together with fifteen older K–Ar, $^{40}Ar/^{39}Ar$, and fission track ages (Gastil et al., 1979; Sawlan and Smith, 1984; McLean, 1988), provide a quantitative temporal framework for both the lateral and vertical relations of the stratigraphy of the Comondú Group near Loreto. Bigioggero et al. (1996) report petrologic and geochemical data from the Comondú Group in the Loreto area that were not a part of our study.

2. Geologic setting

Few pre-Tertiary rocks are exposed in most of Baja California Sur, except south of La Paz. North of La Paz, pre-Tertiary rocks makeup isolated exposures of Cretaceous granites and metamorphic rocks along the eastern side of the peninsula and on some islands (Gastil et al., 1979) and oceanic, ophiolitic, and island-arc rocks along the west coast on Santa Margarita and Magdalena islands (Sedlock 1993; Bonini and Baldwin, 1998). The Cretaceous rocks are overlain by lower Tertiary marine and local nonmarine rocks or the Oligocene–Miocene arc-related rocks across a regional unconformity (Beal, 1948; Hausback, 1984; McLean, 1988; Zanchi, 1994; Bigioggero et al., 1996). In the Loreto region, McLean (1988) correlated thin quartz sandstone and arkose overlying granite with the latest Cretaceous–Middle Eocene Tepetate Formation, which is best exposed ~150–200 km south of Loreto (Hausback, 1984). No lower Tertiary marine rocks have been found near Loreto, but marine rocks of Eocene and Oligocene age are exposed west of Loreto on the west side of the peninsula near La Purísima and Comondú (Fig. 2) (McLean and Hausback, 1984; McLean et al., 1987).

In general, the Oligocene–Miocene volcanic arc formed on mainland Mexico and in the position of the future Gulf of California, and the forearc basin formed east of, and on, the future Baja California peninsula (Hausback, 1984). This arc was active in the Gulf of California region from ~25–12 Ma, at the same time as the early evolution of the San Andreas transform plate boundary in southern California (Atwater, 1970; Crowell, 1979; Nicholson et al., 1994). The southern triple junction of the transform plate boundary jumped south episodically along northwestern Mexico from 16 to 12 Ma and replaced the trench–forearc system with a transform fault west of the future Baja California peninsula (Stock and Hodges, 1989; Lonsdale, 1991; Stock and Lee, 1996). At the latitude of Loreto in Baja California Sur, arc activity ceased at ~12 Ma (Lonsdale, 1991; Stock and Lee, 1996) and the Tosco–Abreojos transform fault became active west of Baja California Sur (Spencer and Normark, 1991). This scenario for termination of arc volcanism at 12 Ma is confirmed by the new stratigraphy and geochronology from the Loreto region that we report here.

The stratigraphic terminology for the Oligocene–Miocene arc-related rocks in Baja California Sur is controversial, and is summarized below. Hausback (1984) presented a map of three regional facies in the arc-related rocks of Baja California Sur (Fig. 2) that was modified from the concepts of Vessel and Davies (1981). According to this facies scheme, the core facies, representing parts of the volcanic arc, consists of lava flows and massive breccia exposed in a narrow strip along the coast and on the islands in the gulf. The proximal facies (arc–forearc transition) consists of volcanic breccia, conglomerate, and lava flows exposed along and immediately east of the gulf escarpment. The distal facies, or forearc basin, consists of nonmarine sandstone and conglomerate exposed in the central part of the peninsula from the main gulf escarpment toward the west (Fig. 2) and is little deformed. These arc-related facies are the pre-rift foundation upon which the rift structures and basins related to the Gulf of California formed and thus these belts are locally extensively faulted and tilted. A similar lateral trend in Oligocene–Miocene arc-related facies was documented in northern Baja California by Dorsey and Burns (1994).

West of the gulf escarpment in the northern part of Baja California Sur, the forearc rocks are overlain by widespread alkalic basalts that range in age from 13 to 0.5 Ma (Hausback, 1984; Sawlan and Smith, 1984; Sawlan, 1991). Virtually none of these rocks are known east of the gulf escarpment. In the Loreto region, the Oligocene–Miocene arc-related rocks are overlain by local Pliocene basinal strata, Pliocene and Quaternary volcanic complexes, and Quaternary alluvial plains (Fig. 3) (McLean, 1988; Zanchi, 1994; Umhoefer et al., 1994; Bigioggero et al., 1995; Dorsey and Umhoefer, 2000). The region east of the gulf escarpment is extensively cut by normal and strike-slip faults (Fig. 3) (McLean, 1988; Zanchi, 1994, Umhoefer and Stone, 1996; Dorsey and Umhoefer, 2000). The faulted region is bounded on the west by a series of discontinuous down-to-the-east normal faults. East of these faults, the Oligocene–Miocene arc-related rocks and all post-Miocene rocks dip gently to moderately. West of these faults to the gulf escarpment, only the Oligocene–Miocene arc-related rocks and cretaceous granite are exposed and they are tilted $<5°$ along a few small faults (Fig. 3).

3. Stratigraphy

In this section we discuss the history of nomenclature of the Comondú rocks, present the rationale for the revision proposed here, and summarize the stratigraphic relations of the three units within the Comondú Group in the study area. The following section provides a more detailed description of the rock units and an analysis of their depositional setting.

3.1. Nomenclature

The history of naming the rocks that have come to be recognized as the Oligocene–Miocene volcanic arc and forearc basin in Baja California Sur is confusing, and thus we justify our usage here. Heim (1922) first used the term Comondú Formation for sandstones and conglomerates exposed near the village of Comondú, 45 km west of Loreto (Fig. 2). Heim included the thick and widespread breccia and lava flows of the Sierra de la Giganta along the gulf escarpment in the Loreto area (the middle breccia and lava flow unit of this study) in the Comondú Formation. Beal (1948) later used the name Comondú Formation for the entire section of Miocene sedimentary and volcanic rocks in the Sierra de la Giganta. Beal's usage included the alkalic basalts that cap the mesas on top and west of the crest of the Sierra de la Giganta, which are now known to be mainly of late Miocene to Quaternary age and are distinctly different from the older arc-related rocks in terms of petrology and age (Sawlan and Smith, 1984). McFall (1968) studied the Bahía Concepción area near Mulegé (Fig. 2) and included all the Oligocene–Miocene arc-related rocks in a single unit, but changed the name to the Comondú Group with six formations. Gastil et al. (1979) restricted the Comondú Formation to the pre-Pliocene lavas in the Comondú area that overlie the sandstones and conglomerates. In contrast, Demant (1975) stayed closer to Heim's (1922) original designation, but restricted the Comondú Formation to the breccia and related volcaniclastic sedimentary rocks of the Sierra de la Giganta, thus excluding the alkalic basalts that Beal (1948) included in the unit, but are clearly a younger extrusive suite. In a detailed study of the La Paz region and reconnaissance study north to the Loreto region, Hausback (1984) essentially used the same strategy as Demant (1975) and restricted the Comondú Formation to the "Miocene arc-derived silicic and intermediate composition volcanics and volcaniclastics that make up the bulk of the Sierra Giganta and excludes the late Miocene and younger capping basalt flows…" (Hausback, 1984). In the same volume, Sawlan and Smith (1984) suggested that the diverse usage of the name Comondú Formation had led to too much confusion and thus should be abandoned; instead they suggested the name Andesite of Santa Lucia. McLean (1988) and Bigioggero et al. (1996) also used informal names other than 'Comondú' for these rocks. Dorsey and Burns (1994) proposed the same definition as Hausback (1984) for a large area of northern Baja California.

Here and elsewhere (Umhoefer et al., 1994) we have chosen to follow the revised definition of Demant (1975) and Hausback (1984) because (1) it includes the rocks near the village of Comondú originally proposed for the unit by Heim (1922), (2) it includes those volcanic rocks in the Sierra Giganta west of Loreto that Heim (1922) originally included in the unit, (3) it clarifies the mistake made by Beal

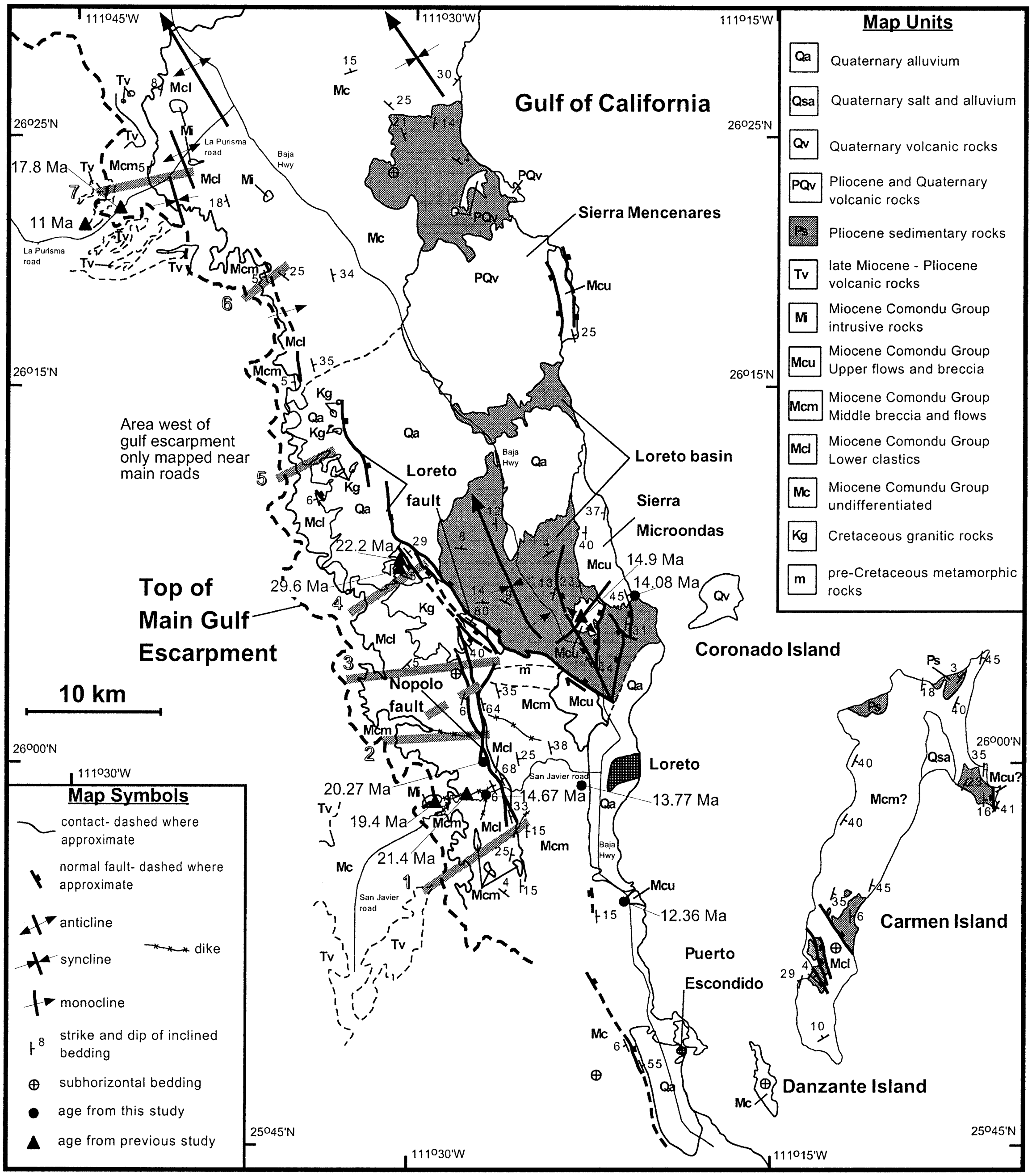

Fig. 3. Simplified geologic map of Loreto region with Comondu differentiated into three main units, geochronology sites (Table 1), and location of composite stratigraphic sections of Fig. 4.

(1948) in adding the younger and distinctly different alkalic basalts to the unit, and (4) this body of rocks is clearly one coherent unit vertically for over a kilometer and laterally for hundreds of kilometers along the peninsula and tens of kilometers across the peninsula without major breaks.

We further propose that by modern stratigraphic definitions of a formation and a group (International Stratigraphic Code, Salvador, 1994), the rocks designated the Comondú Formation by Heim (1922), Demant (1975) and Hausback (1984) are best called a group and not a formation. This change in rank agrees with the suggestion of McFall (1968) for the Bahía Concepción area. We suggest this change in rank of the unit for these reasons. (1) A formation is a unit defined by its lithic characteristics and we believe the Comondú has too much lithologic diversity to be a formation. (2) Groups commonly are bounded by regional unconformities, which is true for the Comondú Group, whereas formations may or may not have unconformities at their boundaries. (3) Groups are commonly defined for regions of complex stratigraphy, which is true for the Comondú Group.

We do not formally name formations within the Comondú Group here because we did not study it in enough detail, but we divide the unit into three informal units that are candidates for formations. These three units in the Loreto area are best correlated with the Salto, Pelones, and Ricasón formations of the Bahía Concepción area (McFall, 1968), and with additional work may well be assigned to those units. Our units here correspond to the strictly lithologic units of McLean (1988) with some modification. Bigioggero et al. (1996) divided the Comondú Group into two stratigraphic units, which appear to be equivalent to the middle and upper units of our study, but it is not clear if there is a strict correspondence. Bigioggero et al. (1996) report important petrologic and geochemical data on the volcanic rocks. The age of the Comondú Group based on numerous dates from volcanic tuffs and flows throughout Baja California Sur is ~30–12 Ma (Table 1) (Gastil et al., 1979; McFall, 1968; McLean, 1988; this study). Considering only the locally derived, more proximal volcanic rocks, the unit has been assigned an age range of 25–12 Ma by many authors (Hausback, 1984; Sawlan and Smith, 1984; Sawlan, 1991).

3.2. Lower clastic unit

We divide the Comondú Group into three units (Figs. 3–5). Along the lower parts and east of the gulf escarpment (Fig. 3), the lower clastic unit is 200–300 m thick and is dominated by coarse clastic rocks and tuffs with complex facies relations (Figs. 4 and 6). The internal stratigraphy of the unit is dominated by fluvial sandstone and conglomerate intercalated in the lower part of the unit with pink, gray, and green-gray tuffs, in the middle with tuffs and mafic lava flows and in the upper part with thick eolian facies and local tuffs. The upper part of the lower clastic unit interfingers laterally with the middle breccia and lava flow unit to the east near the Nopolo fault (Fig. 5) and to the north near the La Purísima road (Fig. 4).

The lower unit sits nonconformably on Cretaceous granite, metamorphic rocks, and pre-Comondú (Eocene?) quartz sandstone and arkose (McLean, 1988) in numerous locations in the footwall of the Loreto fault. It is difficult to determine whether the quartz sandstone and arkose that locally rests on the granite is Eocene in age, as McLean (1988) suggested, or belongs to the basal unit of the Comondú Group. This ambiguity arises because similar quartz sandstone is intercalated with strata of the Comondú Group in the Loreto region. We follow McLean (1988) in most locations and separate these sandstones out from the Comondú Group, but an equally plausible interpretation is that, similar to McFall's (1968) interpretation in the Bahía Concepción area, the basal eolian sandstone is the basal part of the Salto Formation of the Comondú Group. The upper contact of the lower clastic unit with the middle breccia and lava flow unit is conformable and abrupt or gradational over ~5 m in much of the study area. This contact was observed along the gulf escarpment near the San Javier road and a few hundred meters east of the Nopolo fault for many kilometers (Fig. 3). In the northern study area, there is a similar thin transition between the lower and middle units, but we are uncertain if it is the same stratigraphic surface. Two samples of probably the same pink tuff from the middle of this unit along the San Javier road, and a few kilometers north of the road in the Nopolo fault zone, have been dated at 22.2 ± 0.6 Ma (20.4 ± 2.4 by fission track on zircon) (McLean, 1988) and

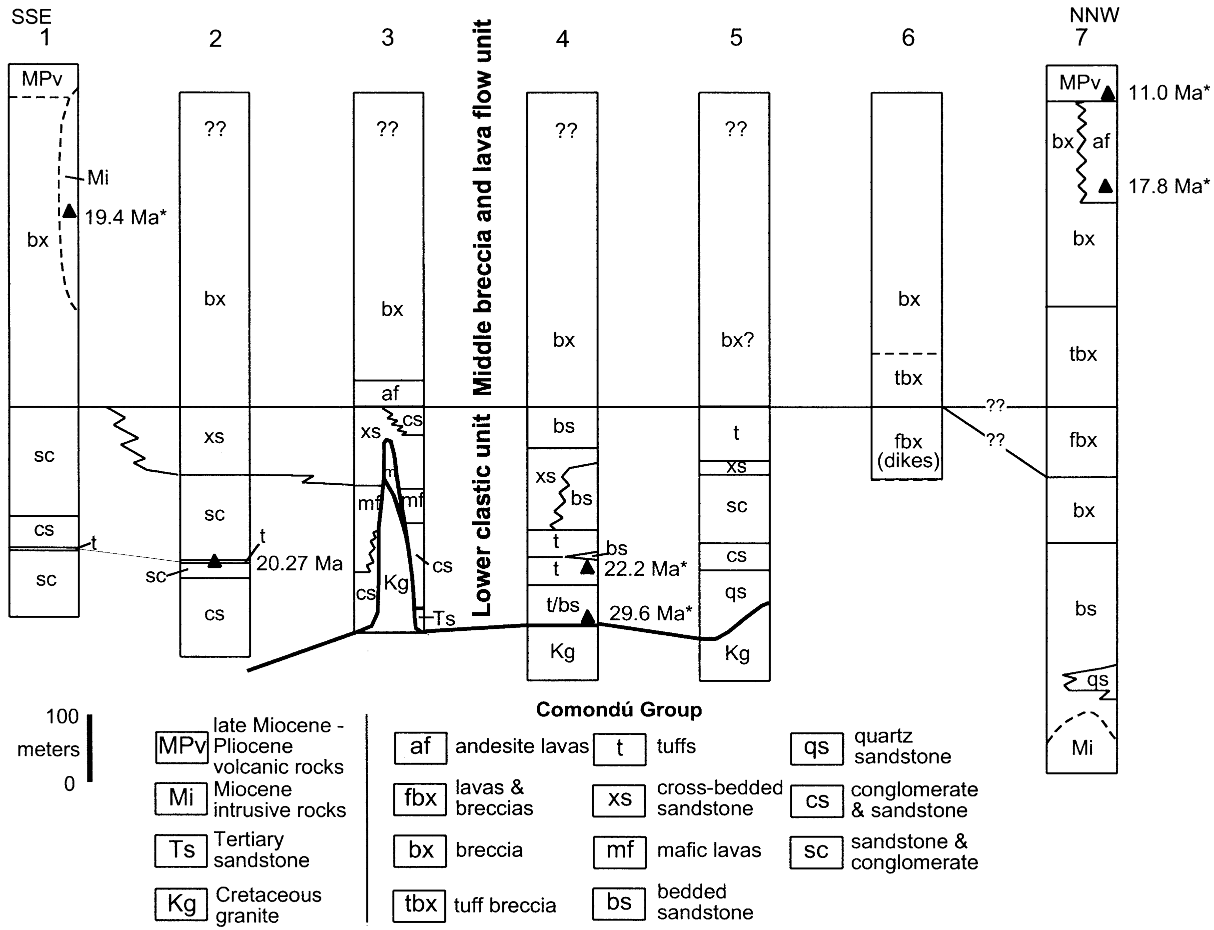

Fig. 4. Composite stratigraphic sections along the eastern front of the gulf escarpment. Location of sections is in Fig. 3. Units in Comondú Group from this study.

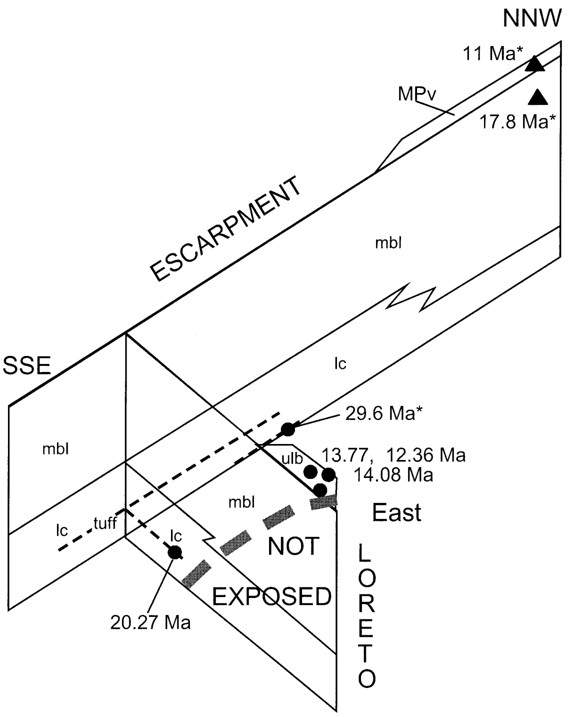

Fig. 5. Fence diagram of the main three units of the Comondú Group in the Loreto area and key geochronology sites to illustrate some of the lateral and vertical relationships amongst the units. The NNW–SSE section is a simplification of the composite sections in Fig. 4. The W–E section is across the Nopolo fault to the city of Loreto (Fig. 3).

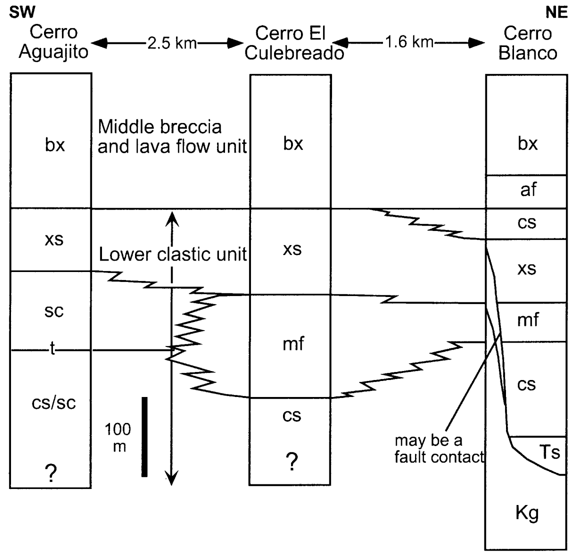

Fig. 6. Three local stratigraphic sections that show the complex facies relations in part of the lower clastic unit of the Comondú Group. The sections are located approximately ,where the dashed gray line is west of Loreto. Unit abbreviations same as in Fig. 4.

20.27 ± 0.08 Ma (this study) respectively. A tuff that lies at the base on the unit in the footwall of the Loreto fault was dated at 29.6 ± 3.5 by fission track on zircon by McLean (1988).

Our 1:50,000 mapping did not allow us to confidently correlate facies of the lower clastic unit along the escarpment from the southern to northern part of the study area. About 250–300 m of bedded sandstone is exposed above a dacite intrusion in the core of an anticline near the La Purísima road (Fig. 3). These sandstones are similar in facies and thickness to the finer grained portion of the lower clastic unit to the south. However, we are not certain if the contact with the overlying breccia correlates to the contact between the lower clastic unit and the middle breccia and lava flow unit that is so prominent in the southern study area. Likewise, a 200–300 m thick section of sandstone and conglomerate on Carmen Island is similar to the lower clastic unit west of Loreto and in a low structural position. These clastic rocks on Carmen Island are probably equivalent to the lower clastic unit of this study.

3.3. Middle breccia and lava flow unit

The middle breccia and lava flow unit is 450 to 750 m thick in and near the gulf escarpment. The unit is composed of massive breccia and minor, but locally thick (a few tens of meters) andesite lava flows. The middle unit makes up the upper part of the gulf escarpment, a belt immediately east of the Nopolo fault, and a poorly defined area east of the northern monocline and northwest of the Sierra Mencenares (Fig. 3). To the east, the middle breccia unit is thicker and the lower part of it may interfinger with the upper part of the lower clastic unit (Fig. 5). Thus the base of the middle breccia and lava flow unit lies directly on the Cretaceous granite and metamorphic rocks a few kilometers east of the northern Nopolo fault (Fig. 3); this probably represents a paleohigh on the underlying pre-Comondú rocks. The upper contact of the middle unit in the gulf escarpment is either eroded away, or is an unconformity with the overlying alkalic basalts of Middle Miocene to Quaternary age (Sawlan and Smith, 1984; Sawlan, 1991). To the east, this unit is overlain by the upper lava flow and breccia unit; the contact is well exposed a few kilometers west of Loreto (Figs. 3 and 5). The middle breccia unit interfingers with sandstone and conglomerate ~5 km west of the gulf escarpment along the La Purísima road (Sawlan and Smith, 1984) and this change occurs about 3–5 km west of the escarpment along the San Javier road (Fig. 3). These sandstones and conglomerates are broadly similar to the fluvial facies of the lower clastic unit of the Loreto area, but are younger.

A flow in the upper part of the middle breccia and lava flow unit yielded an age of 17.8 ± 0.7 Ma by K–Ar on whole rock near the La Purísima road (Fig. 3, Table 1) (Sawlan and Smith, 1984). A shallow level andesite porphyry forms Cerro Las Parras along the gulf escarpment 15 km west of Loreto and has an age of 19.4 ± 0.9 Ma as determined by K–Ar on hornblende (Fig. 3, Table 1) (McLean, 1988). The Cerro Las Parras body intrudes much of the middle breccia and lava flow unit and extends up to 1070 m in elevation. Thus, most of the middle breccia and lava flow unit exposed in the escarpment west of Loreto is older than ~19 Ma if that age is correct (but see below), while most of the same unit exposed along the La Purísima road is older than ~18 Ma (Fig. 5).

3.4. Upper lava flow and breccia unit

The upper lava flow and breccia unit is at least 600 m thick based on the thick section in the Sierra Microondas. The unit is composed of variable amounts of andesite lava flows and massive volcanic breccia, but lavas dominate the unit in most of the Loreto region. The unit is exposed mainly in the Sierra Microondas range 10–20 km north of Loreto and in the belt of hills near the coastal plain west and south of Loreto (Fig. 3). The upper lava flow and breccia unit has yielded ages from 15–12 Ma from locations near the top and base of the Sierra Microondas, a hill 4 km southwest of Loreto, and along the Baja highway 11 km south of Loreto, immediately south of the golf course (Table 1, Fig. 3). In addition, many of the dikes that cut the lower clastic and middle breccia units west of Loreto are probably related to the upper lava flows because (1) the dikes form a radial pattern pointed toward the large exposure of upper lava flows a few km west of Loreto that suggests a volcanic center (Zanchi, 1994) and (2) one dike 11 km west of Loreto within the radial pattern is 14.67 ± 0.09 Ma (Fig. 3, Table 1), within the age range of the upper unit.

4. Facies analysis

Here we describe the lithofacies and distinctive lithologies that comprise the three main units of the Comondú Group in the study area. We use local detailed descriptions combined with three measured stratigraphic sections (Fig. 7) and composite sections compiled from mapping at 1:20,000 and 1:50,000 scale (Figs. 4 and 6).

4.1. Pre-Comondú group sandstones

These sandstones nonconformably overlie Cretaceous granite in numerous isolated locations in the footwall of the Loreto fault that are too small to show on Fig. 3 (see McLean, 1988, for detailed locations). Some sandstone buttresses against paleotopography or paleo-hills formed on the granite erosional surface. In these locations, the sandstone has local bedding attitudes, that are relatively steeper and dip away from the granite, with bedding changing over a couple hundred meters to that more typical of the surrounding area. Note that this sandstone unit may alternatively be the basal unit of the Comondú Group and similar to an eolian sandstone unit in the basal Salto Formation of McFall (1968).

4.1.1. Cross-bedded quartz sandstone

The cross-bedded quartz sandstone is the dominant lithofacies of the pre-Comondú Group rocks. This unit consists of reddish (hematite-cemented) to tan, well sorted, fine- to medium-grained sandstone with abundant cross-bedding. Most cross-bed sets range from about 20–30 cm to ~3 m thick, and include both planar–tabular and trough cross bedding. The well sorted texture, fine- to medium-grain size, and cross bedding up to a few meters in thickness are best interpreted as having an eolian origin.

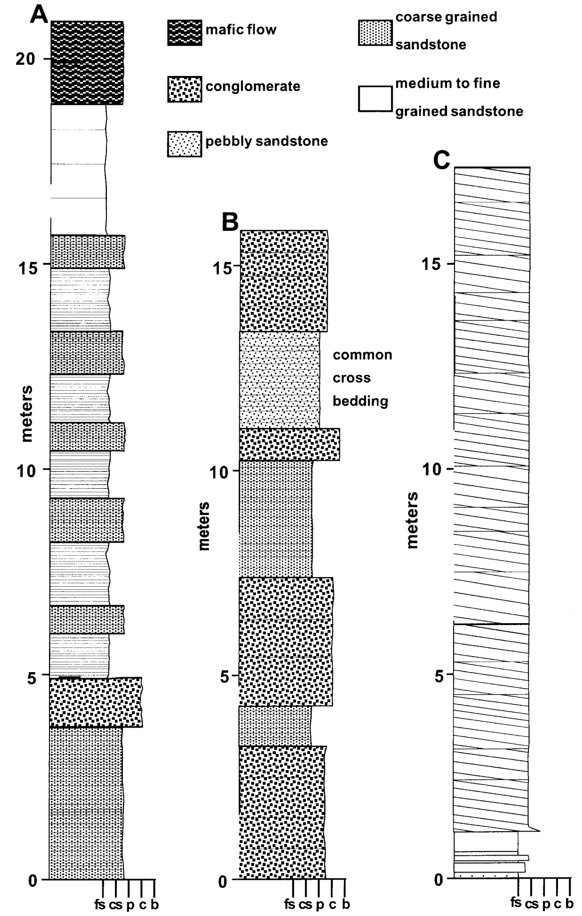

Fig. 7. Three measured stratigraphic sections through part of the: (A) sandstone and conglomerate, (B) conglomerate and sandstone, and (C) cross-bedded sandstone lithofacies. All of the sections were measured in the near-footwall of the northern part of the Nopolo structure on Fig. 3.

4.1.2. Arkosic sandstone and grus

This unit is dominantly a white, pink, and tan, medium- to coarse-grained arkosic sandstone that includes some slightly coarser (coarse sandstone to granule) lithic fragments of granite. It is medium bedded and has some medium-scale cross bedding. The grus consists of very coarse-grained sandstone, granulestone, and fine-pebble conglomerate of granitic detritus with angular fragments of granite and feldspar. The arkose and grus are interpreted to be fluvial deposits that represent local fluvial reworking of weathered granite.

4.2. Lower clastic unit

4.2.1. Conglomerate and sandstone

This unit consists of red-brown to red-gray, moderately to poorly sorted, weakly stratified, clast- and matrix-supported conglomerate containing minor to subequal amounts of interbedded sandstone (Figs. 7 and 8A). Bedding in the conglomerate, is weakly to well defined, medium to thick, and locally lenticular with sharp channelized bases with some normal grading. The conglomerate is often well indurated and resistant. Clasts are composed dominantly of light to dark gray andesite, subordinate (few 10's%) gray and white dacite and rhyolite, and minor sandstone and basalt. The matrix of conglomerate is medium- to coarse-grained sandstone and pebbly sandstone. Sandstone intervals are red-brown, medium grained to pebbly, and poorly to moderately sorted. The sandstone is thin to medium bedded, with common trough cross bedding and reverse grading. Contacts between sandstone beds and conglomerates range from sharp to gradational. Thin (<2 m) beds and lenses of gray, unstratified, matrix-supported andesitic breccia locally occur within the conglomerate and sandstone. The matrix of the breccia contains fragments and subhedral amphibole crystals up to 1 cm in length.

The intimate interbedding (Fig. 7) and grading of the conglomerate and sandstone in this unit indicates simultaneous deposition. In addition, the lenticular, graded conglomerate, and trough cross-bedded sandstone suggest deposition by sediment-rich floods in a shallow braided stream system (e.g. Miall, 1996) flowing westward, in the distal portion of the volcaniclastic apron shed from volcanic centers to the east (e.g. Vessel and Davies, 1981; Smith, 1991). The uncommon breccias are likely remnants of lahars that fed the dominant volcanic clasts to the fluvial system.

4.2.2. Sandstone and conglomerate

This unit consists of brown, red-brown, red-gray, and tan, poorly to moderately sorted, medium-grained to coarse pebbly sandstone with subordinate pebble and cobble conglomerate beds (Figs. 7 and 8B). Sandstone is thin to medium bedded and locally contains low-angle trough cross bedding. Cursory examination of the cross bedding suggests flow to the west. Many of the sandstone beds contain a few outsized clasts (up

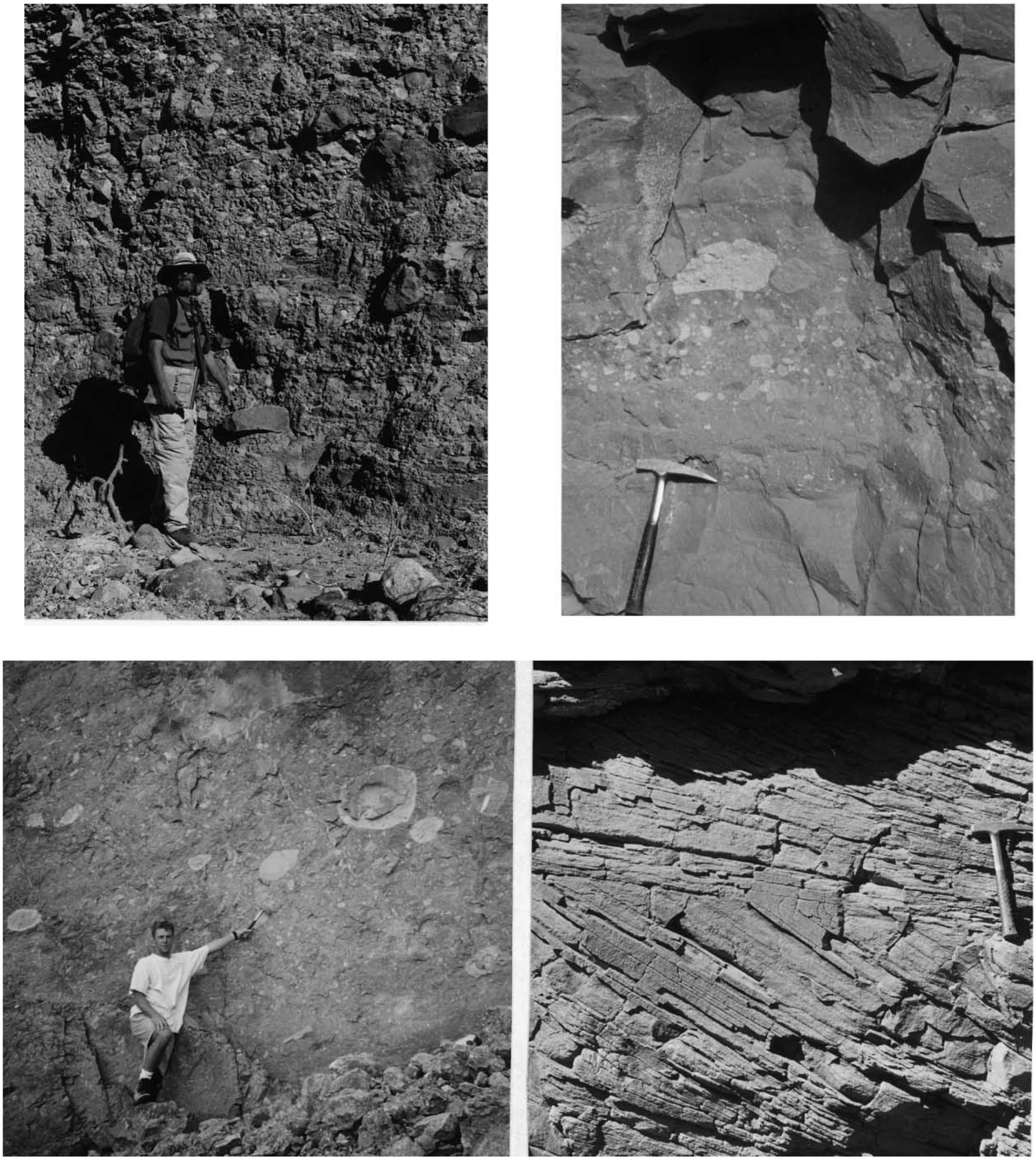

Fig. 8. Photos of some of the main lithofacies of the Comondú Group. (A) upper left conglomerate and sandstone lithofacies, (B) upper right sandstone and conglomerate lithofacies, (C) lower left volcanic breccia lithofacies, and (D) lower right cross-bedded sandstone lithofacies.

to ~40 cm in diameter). Sandstone grains are dominantly volcanic and sedimentary lithics but also contain quartz and feldspar. Red-brown, red-gray, or gray-brown, matrix-supported conglomerate forms conspicuous interbeds between sandstone beds. The conglomerate is medium bedded and commonly forms lenticular channels. Clasts in the conglomerate are andesite and minor sandstone, range from ~2 to ~40 cm in diameter, and are typically subrounded to rounded. The matrix of the conglomerate is coarse-grained lithic sandstone. This unit is similar to the conglomerate and sandstone unit in many of the sedimentary structures, but has a larger portion of sandstone. The unit is interpreted to be a finer grained portion of the same braided stream system as the conglomerate and sandstone unit, in which sandy bars dominate.

4.2.3. Tabular bedded sandstone

This unit consists of gray-red to brown-red, medium-grained sandstone with distinct thin to medium tabular bedding defined by very thin to thin sandy mudstone interbeds. The thin bedding and finer grain size than the conglomerate- or sandstone-dominated units suggests that this unit is the lower energy inter-channel parts, or more distal part, of the same braided stream system inferred above.

4.2.4. Cross-bedded sandstone

The unit is tan, green-gray, and light gray to white, thin to thick bedded, moderately to well sorted, fine- to medium-grained arkosic to quartzose sandstone. Thin pebbly horizons and laminations are locally common. Cross bedding is usually tabular planar and sets commonly range from <0.3 to 2 m thick, but are commonly 0.75 to 1.5 m thick (Fig. 7D); locally cross beds are up to 4 m thick. Measurement of 17 cross beds in one area and cursory examination in other areas, suggests that many of the cross sets dip to the east. The unit interfingers laterally with the sandstone and conglomerate and conglomerate and sandstone lithofacies.

An eolian origin is suggested for this unit based on cross bedding geometry and size and the well sorted nature of framework grains. This facies lacks channels, pebbly sandstone, mudstone lenses, or grading that is common in typical sandy braided stream deposits (e.g. Walker, 1984; Miall, 1996). In addition, the easterly paleocurrent direction for the dunes in the cross-bedded sandstones, contrasts with the overall westward fining and the general westward paleocurrents in the fluvial facies. Because this eolian facies tends to change laterally, commonly into the sandstone and conglomerate or tabular bedded sandstone unit, the cross-bedded sandstone unit may represent small dune fields located adjacent to the braided stream systems. The dunes migrated primarily to the east, toward the arc.

4.2.5. Tuffs and mafic lava flows

There are two minor but distinct volcanic lithologies in the lower clastic unit. Two pink lithic, crystal ash flow tuffs vary from 0.3 to 3 m in the area near the Nopolo fault. These tuffs are moderately to strongly welded. Southwest of the southern Loreto fault, a light green lapilli and ash flow tuff at the base of the section contains granite lithic clasts and is up to a few tens of meters thick. Higher in the lower clastic unit, largely welded pink and gray tuffs are amalgamated up to ~100 thick.

Mafic lava flows are dark gray, aphanitic to porphyritic, and commonly contain conspicuous yellowish zeolite amygdules and dark red altered pyroxene phenocrysts up to 3 mm. Locally large (many cm) plagioclase laths are common phenocrysts in the mafic flows. This unit is highly altered and is distinct from the more common andesite lava flows higher in the Comondú Group.

4.3. Middle breccia and lava flow unit

4.3.1. Volcanic breccia

Volcanic breccia is the most common lithology in the Comondú Group in the Loreto area. The breccias are light gray, purple-gray, and tan, thick bedded to massive, poorly sorted, matrix-supported (~60% matrix, ~40% clasts), and contain clasts that range in size from millimeters to 2 m (Fig. 7C). Rarely clasts are up to 2–4 m in diameter. Clasts include andesite, dacite, andesite porphyry, and minor rhyolite and sandstone. Clasts are generally subangular, although large clasts (>60 cm) are typically subrounded. Matrix of the breccia is a fine- to coarse-grained mixture of ash and sand. The matrix is lithic-rich and contains abundant amphibole crystals and crystal fragments and less common quartz and plagioclase crystal fragments. Bedding in the breccia is thick to massive, typically ~1–5 m, and commonly unstratified. Bedding is typically defined by uncommon thin to lenticular sandstone beds, by slight changes in color, and by crude alignment of large clasts. Thin (a few meters) brown-weathering, andesite lava flows are locally interbedded with the breccia facies. These lava flows typically have plagioclase and pyroxene phenocrysts.

A variation of the breccia facies consists of medium- to thick-bedded tuffaceous breccia in which the bedding is better defined and there is more tuffaceous material in the matrix than the more common massive breccia. This bedded tuff breccia is most common in the northern part of the study area. The breccias of this unit are interpreted to be large debris flows (McLean, 1988) because of the poor sorting, presence of large clasts, massive bedding, and the lack of evidence that they were hot when transported (as in Vessel and Davies, 1981).

4.4. Upper lava flow and breccia unit

This unit varies widely in the proportion of lava flows and breccia, but the lava flows are dominant in most areas. The unit is differentiated from the middle breccia and lava flow unit by this higher portion of lava flows in the upper unit. In our study area, this unit is exposed widely in the Sierra Microondas along the coast 10–25 km north of Loreto and in the low hills a few kilometers west and south of Loreto (Fig. 3). The latter hills are almost all flows while the Sierra Microondas has flows on the top and bottom of the section and a 400–500-m-thick section of breccia in the middle. The breccia is very similar to those of the middle breccia and lava flow unit and therefore are not described separately here.

4.4.1. Andesite lava flows

The andesite lava flows are typically dark gray andesite that is aphanitic to porphyritic and weathers red brown and brown. The lavas contain phenocrysts of subhedral to euhedral, glassy to slightly yellow plagioclase up to ~6 mm in size, and black, glassy euhedral to subhedral amphibole phenocrysts from 0.1 to 3 mm in size. Some lavas have subhedral to euhedral pyroxene, and very few amphibole crystals. The lavas locally preserve a weak to moderately prominant flow foliation.

4.4.2. Dikes

McLean (1988) described two families of dikes that intrude the lower clastic and middle breccia and lava flow units west of Loreto. Similar dikes are locally common along the gulf of escarpment. The dikes west of Loreto have variable orientations and consist mainly of relatively thin (1–2 m) gray andesite dikes with phenocrysts of plagioclase, hornblende, and pyroxene. The more conspicuous family of dikes are a few meters to 40 m thick and up to 7 km long (McLean, 1988). These are lighter colored hornblende andesite dikes. One dike emanates from the 19 Ma (McLean, 1988) hypabyssal stock that forms Cerro Las Parras along the gulf escarpment, but most of the dikes form a roughly radial pattern that has been interpreted to mean they were related to a shallow magmatic body a few kilometers west of Loreto (Zanchi, 1994). Our age of 14.67 ± 0.09 Ma on a dike within this radial family is close to the four ages from the upper lava flows along the coast, and indicates that the dikes are related to volcanoes that produced the upper flow unit.

5. Geochronology

5.1. New ages

We dated five samples from the Comondú Group. $^{40}Ar/^{39}Ar$ dating used the methods and facilities described by Renne et al. (1999). Samples were irradiated for 3 hours in the CLICIT facility of Oregon State University (Corvallis) research reactor. J was determined from standard FCs (28.02 Ma; Renne et al., 1998), irradiated in four positions bracketing the samples, to be 0.0007563 ± 0.000004 (2σ errors here and throughout). All samples were degassed with an Ar-ion laser. The two hornblende samples (3-8-97-2 and 3-9-97-1) were each degassed in five separate incremental heating experiments on 5–10 grains of hornblende. One biotite sample (3-7-97-1) was degassed in six separate incremental heating experiments on single grains. The two plagioclase samples, (3-6-97B and 3-9-97-5) were degassed by total fusion of individual grains.

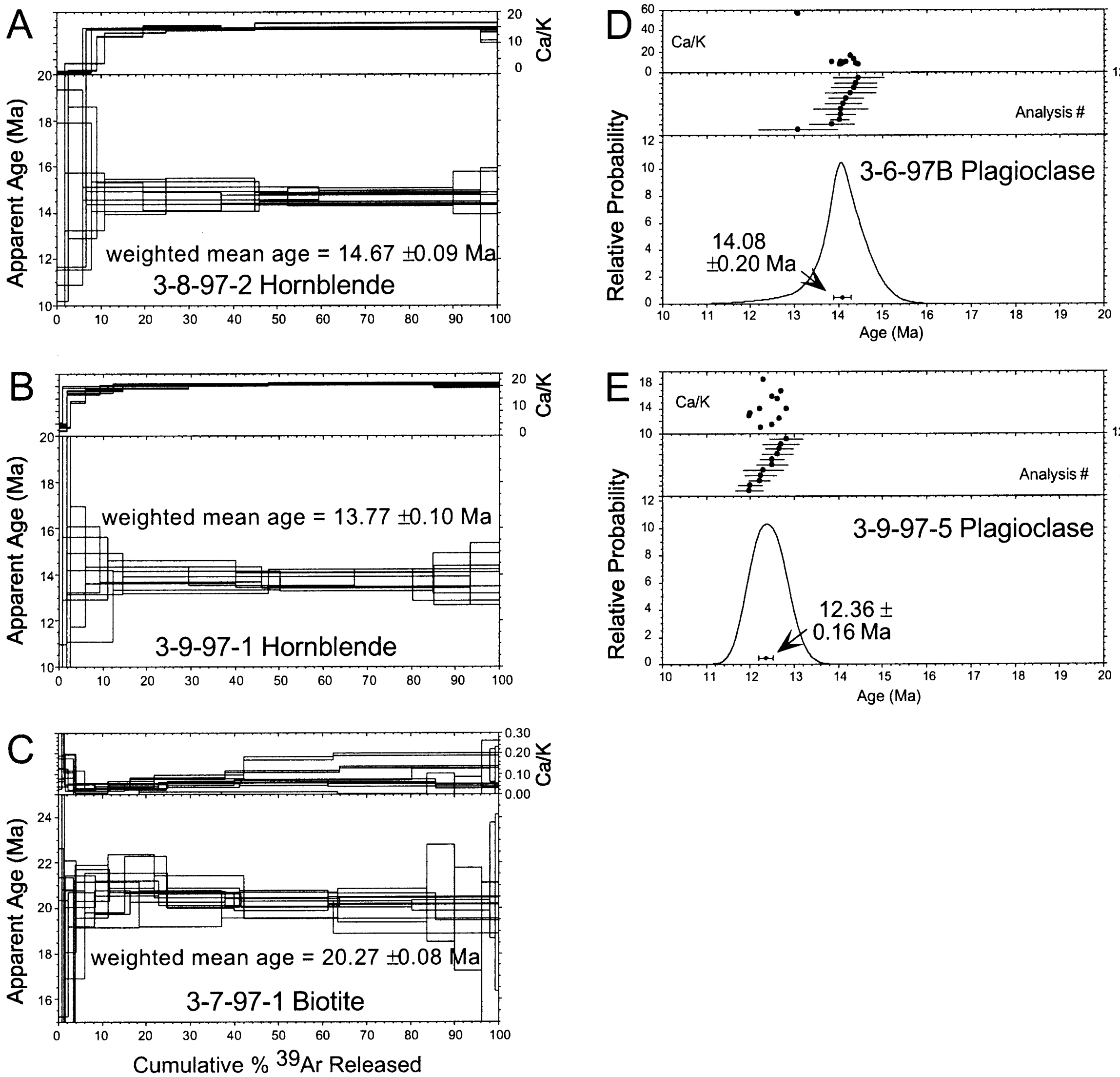

Fig. 9. (A), (B), (C) Apparent age and Ca/K spectra for samples indicated. See text for discussion. (D), (E) Age-probability spectra for single crystal plagioclase analyses of samples indicated. Individual ages are shown with 1 sigma error bars. Sample number and mineral in bold.

Hornblende from 3-8-97-2 is from an andesite dike that trends NNE and crosses an E–W dike emanating from Cerro Pilon de Las Parras (McLean, 1988). The location is 4.3 km east of Cerro Pilon along Arroyo Las Parras. The hornblende yielded well-defined plateaux (each comprising 100% of the ^{39}Ar released) for all five aliquots, with plateau ages tightly clustered between 14.60 ± 0.18 and 14.77 ± 0.20 Ma, with a weighted mean of 14.67 ± 0.09 Ma (Table 1 and Fig. 9A). This is inferred to reflect the age of intrusion of the dike.

Hornblende from 3-9-97-1 is from an andesite lava flow at 100 m elevation on the south side of Cerro El Divisadero (McLean, 1988). This hornblende also yielded well-defined plateaux for all five aliquots, with all but one plateau defined by 100% of the ^{39}Ar released (Fig. 9B). The plateau ages are also well-clustered, ranging from 13.70 ± 0.24 to

13.83 ± 0.26 Ma, with a weighted mean of 13.77 ± 0.10 Ma inferred to represent the age of eruption of the flow.

Biotite from 3-7-97-1 is from a pink felsic tuff that is in a small arroyo ~0.5 km south of Arroyo Las Virgenes (McLean, 1988) in the Nopolo fault zone. The biotite yielded mainly discordant age spectra, with all but one nonetheless defining a plateau (Fig. 9C). The spectra show a consistent rise in apparent age in the first 10–20% of ^{39}Ar released, then decreasing slightly to yield plateaux in all but one case. These patterns are suggestive of recoil loss and redistribution of ^{39}Ar with a minor secondary phase. The five plateau ages and six integrated ages are comparably well clustered, ranging from 20.06 ± 0.36 to 20.37 ± 0.18 Ma versus 19.90 ± 0.40 to 20.33 ± 0.32 Ma, respectively. The weighted mean plateau age (20.27 ± 0.08 Ma) is indistinguishable from the weighted mean of the integrated ages (20.22 ± 0.09 Ma), thus it is unlikely that the possible recoil artifacts impart bias to the plateau ages. We prefer the weighted mean plateau age (20.27 ± 0.08 Ma) as reflecting the eruption age of this tuff.

Plagioclase from sample 3-6-97B is from an andesite lava flow ~1.75 km WNW of Punta El Bajo (McLean, 1988). The plagioclase yielded total fusion ages for 11 individual grains ranging from 13.08 ± 1.02 to 14.46 ± 0.52 Ma (Fig. 9D). The age distribution is symmetric, and reveals no evidence of

Table 1
Ages reported from the Comondú Group and Tv unit, Loreto region

Sample #	Location[a]	Rock type	Material	Age (Ma)	Source
82BSJ116	26°21.26′ 111°44.87′	basaltic andesite	wr	11.0 ± 0.3	2
3-9-97-5	**To be added**	**andesite lava flow**	**pl**	**12.36 ± 0.16**	**4**
3-9-97-1	**To be added**	**andesite lava flow**	**hn**	**13.77 ± 0.10**	**4**
3-6-97B	**To be added**	**andesite lava flow**	**pl**	**14.08 ± 0.20**	**4**
486-12-1	26°05′23″ 111°22′49″	basaltic andesite	pl	14.9 ± 0.5	3
3-8-97-2	**To be added**	**andesite dike**	**hn**	**14.67 ± 0.09**	**4**
920	25°58′00″ 111°24′00″	basalt intbd. clastics	pl	15.4 ± 0.8	1
1034 San JavierRd	25°59′00″ 111°22′00	andesite dike	hn	16.0 ± 2.0	1
1005 San JavierRd	25°58′00″ 111°23′00	andesite dike	hn	17.3 ± 0.4	1
770 Baja Highway	25°44′00″ 112°14′00	andesite	pl	17.3 ± 2.2	1
82BMS559	26°22.06′ 111°42.95′	andesite	wr	17.8 ± 0.7	2
917 Baja Highway	25°42′00″ 112°15′00″	andesite	pl	18.2 ± 0.5	1
582-3-1 San JavierRd	25°58′25″ 111°29′05″	andesite porphyry	hn	19.4 ± 0.9	3
3-7-97-1	**To be added**	**tuff**	**bi**	**20.27 ± 0.08**	**4**
1003 Baja Highway	25°44′00″ 112°14′00″	andesite	wr	20.6 ± 1.4	1
1035 San JavierRd	25°59′00″ 111°23′00″	andesite dike	hn	22.9 ± 2.7	1
385-9-1	25°58′42″ 111°27′53″	tuff	pl	21.4 ± 1.0	3
385-4-3	26°08′00″ 111°30′28″	tuff	pl	22.2 ± 0.6	3

[a] Location is approximate for samples from Gastil et al. (1979) as there was no base map. (Sources of data. (1) Gastil et al. (1979); (2) Sawlan and Smith (1984); (3) McLean (1988); (4) this study.

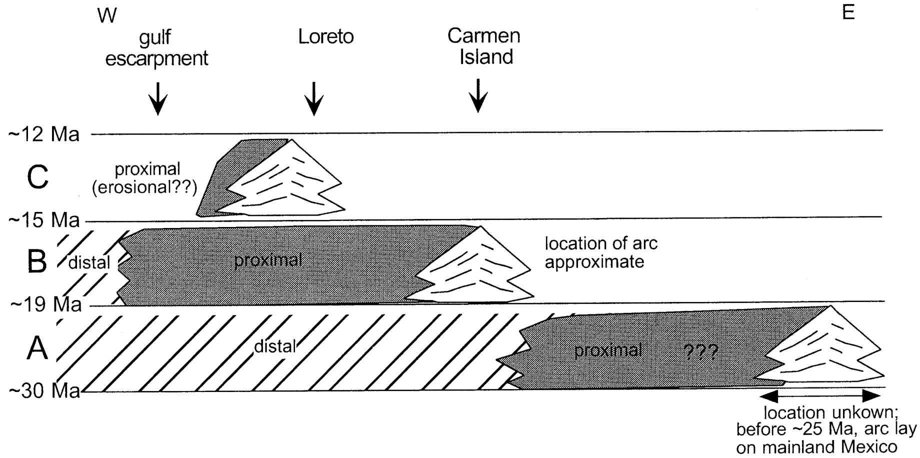

Fig. 10. Schematic reconstructed section of the Comondú Group from west to east near Loreto during the three stages defined here. The volcano represents the core facies and 'distal' and 'proximal' the distal and proximal facies of the volcanic arc following Hausback (1984) after Vessel and Davies (1981).

xenocrystic contamination. The inverse variance weighted mean age is 14.08 ± 0.20 Ma, inferred as the eruption age of the lava flow.

Plagioclase from sample 3-9-97-5, an andesite lava flow at 30 m on the west side of the Baja highway south of the Nopolo golf course (McLean, 1988), yielded total fusion ages for 11 individual grains ranging from 11.98 ± 0.34 to 12.83 ± 0.39 Ma (Fig. 9E). The age distribution is symmetric, revealing no evidence of xenocrystic contamination. The inverse variance weighted mean, inferred to reflect the eruption age of the lava flow, is 12.36 ± 0.16 Ma.

5.2. Summary of age of units (include previous ages)

Our five new $^{40}Ar/^{39}Ar$ ages (Table 1 and Fig. 9), combined with the fifteen previous ages (Table 1) from other workers (Gastil et al., 1979; Hausback, 1984; McLean, 1988), generally give consistent results. The ages from previous workers appear to be systematically too old. The tuff we dated (3-7-97-1) at 20.27 ± 0.08 Ma correlates from extensive mapping at 1:20,000 scale to a similar tuff dated by McLean (1988) at 21.4 ± 1.0 Ma, or 5% older than our sample and slightly outside the 2σ errors for our age. Likewise, the andesite lava flow (3-6-97B) we dated at 14.08 ± 0.20 Ma lies about 400 m below a basaltic andesite lava flow dated by McLean (1988) at 14.9 ± 0.5 Ma, and thus McLean's age was a little older than our sample when it should be a little younger. The best explanation for the consistently older ages (a few to ~10%) from previous workers compared to our data is that older techniques, especially the K–Ar method, were likely to have analyzed relatively large samples (100's or 1000's of grains at a time) and thus are susceptible to xenocryst contamination. In contrast, modern $^{40}Ar/^{39}Ar$ techniques analyze small populations, but do them in replicate so they yield good precision because they can readily identify and reject outlier grains that are likely xenocrysts.

The ages taken together, with the xenocryst problem in older samples considered, suggest that the lower clastic unit of the Comondú Group ranges from ~30– ~ 19 Ma in the Loreto region, and that most of the unit ranges from ~21– ~ 19 Ma. The ~30 Ma age is based solely on the fission track age of 29.6 ± 3.5 Ma on a basal tuff from McLean (1988) with a relatively large analytical error. The lowest sample (tuff, 3-7-97-1) we dated in the unit at 20.27 Ma is at least 150 m above the base of the unit. No tuff or flow was dated from near the base of the unit in this study. The interpretation that the ages obtained previously may be systematically too old suggests that the initiation of the unit at ~30 Ma is not well constrained and there is a need for redating the basal tuff of McLean (1988). The upper age limit of the lower clastic unit is also not well constrained, because there is not a sample from near the contact.

The middle breccia unit ranges from ~19– ~ 15 Ma. The age of the unit is based on the andesite porphyry of Cerro Las Parras along the gulf escarpment west of Loreto that intrudes much of the unit and is dated at 19.4 ± 0.9 Ma (McLean, 1988) and an andesite lava flow that lies high in the unit near Las Purisma road that was dated at 17.8 ± 0.7 Ma (Fig. 4) (Sawlan and Smith, 1984). Given that we dated a tuff that lies about 200 m below the middle breccia unit at 20.27 Ma, we suggest that the 19.4 Ma age on the porphyry of Cerro Las Parras may be too old and that the unit boundary is at ~19 Ma. The upper age limit on the middle breccia unit is constrained to be younger than the 17.8 ± 0.7 Ma age from Sawlan and Smith (1984).

The upper lava flow and breccia unit is suggested to range from ~15–12 Ma. We have dated three andesite lava flows from the unit at 14.08, 13.77, and 12.36 Ma and the stratigraphic position of all three is consistent with their age within the range of 15–12 Ma for the unit. We agree with Zanchi (1994) that the radial dikes west of Loreto may be related to the volcanic center in the upper flow unit 2–7 km west of Loreto. Our one age from a dike in that group of radial dikes is 14.67 Ma.

6. Time — stratigraphic evolution near Loreto

The stratigraphic and geochronologic data presented here provide the basis for a model for how the Comondú arc and forearc evolved near Loreto. Fig. 10 shows a schematic diagram of the evolution discussed here. The Comondú Group on Carmen Island has only been studied in reconnaissance fashion.

6.1. Basal unconformity

The base of the Comondú Group is exposed in many locations, especially west and southwest of the Loreto fault (Fig. 3). The surface is either a disconformity on top of pre-Comondú Group sandstone or a nonconformity on top of Cretaceous granite or metamorphic rocks. The unconformity is generally a low relief surface, but numerous local inselbergs of granite rise up to ~100 m above the surrounding unconformity.

The unconformity likely represents a long period of uplift and erosion during latest Cretaceous to Oligocene time. Deposition occurred locally in the Loreto region during early Tertiary time, but because the pre-Comondú Group sandstone unit is not well dated this is a poorly understood part of the history of the region. Marine rocks of Eocene to early Middle Miocene age are exposed to the west near La Purísima (McLean et al., 1987) and discontinuously to the south along the coast and in a large area north of San Juan de la Costa (Fig. 2) (Hausback, 1984). These marine rocks are probably coeval with the pre-Comondú Group eolian and fluvial sandstones in the Loreto region. It is possible that the older sandstones in the Loreto region were originally much more widespread, but were eroded when the volcanic arc migrated to the west from the Sierra Madre Occidental at the end of the Oligocene (Hausback, 1984).

6.2. Lower clastic unit

The lower clastic unit represents the initial deposition of widespread nonmarine strata in the forearc basin west of the volcanic arc in the Sierra Madre Occidental at approximately 30 Ma (Fig. 10A). In other studies, the beginning of Comondú volcanism was suggested as about 25 Ma (Hausback, 1984). The reinterpretation that the Comondú deposition started at ~30 Ma following McFall (1968) and McLean (1988) is only for the basal ~100 m of strata of the forearc basin, not the proximal volcanic rocks. In fact, if the initiation of Comondú deposition is closer to the ~30 Ma estimate suggested here, then volcanism must have migrated west during deposition of the lower clastic unit, which agrees with the shut off of most of the volcanism in the Sierra Madre Occidental at ~27 Ma. Another implication of the ~30 Ma age for initiation of the Comondú Group near Loreto is that sedimentation rate increased greatly at ~21 Ma or perhaps earlier. The 29.6 ± 3.5 Ma age for the basal tuff and the 20 Ma age of the pink tuff in the middle of the lower clastic unit (Fig. 4), suggest that the forearc basin had a major increase in the rate of sediment accumulation at >21–20 Ma because as much strata is suggested to be ~30–21 Ma as is ~21–19 Ma (Fig. 4).

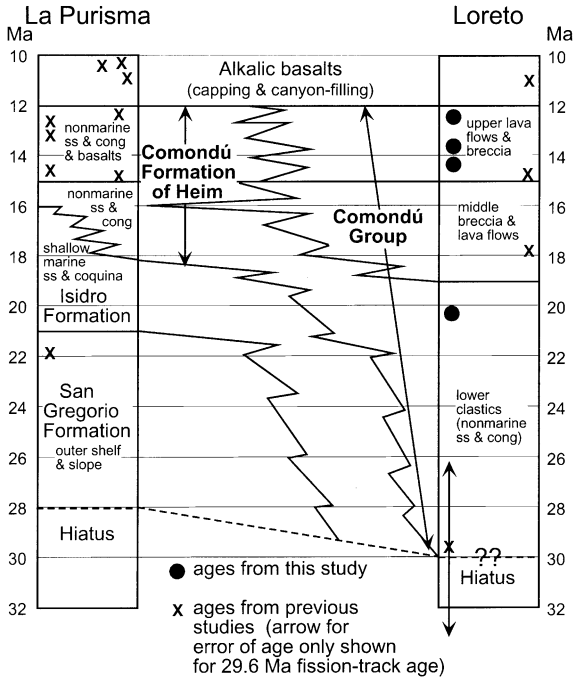

Fig. 11. Comparison between the Oligocene–Miocene stratigraphy of the Loreto and La Purísima areas. Data from the Loreto area from this study and McLean (1988) and those from the La Purísima area mainly from Heim (1922) and McLean et al. (1987). This time–stratigraphic comparison shows how the type Comondú section of the Comondú - La Purísima area (Hausback, 1984) is the forearc equivalent of the proximal and core facies of the middle and upper Comondú Group of the Loreto area. The marine San Gregorio and Isidro formations are equivalent to the nonmarine strata of the lower Comondú Group of this study.

The dominant facies in the lower clastic unit of the Comondú Group are fluvial deposits of a braided stream system that flowed toward the west. We did not quantify the westward flow with paleocurrent data, but the general westward fining of the clastic rocks and the cursory observation of westward directed paleocurrent indicators supports this interpretation. Ash flow and fallout tuffs are locally preserved, probably in paleochannels, and attain tens of meters thickness. The fluvial system had patches of eolian sand dunes developed on top of it that migrated to the east based on the dominant orientation of cross beds, especially late in the deposition of the lower clastic unit. Thin to locally ~100-m-thick sections of mafic lava flows in the upper part of the section are attributed to either long-distant flow of low-viscosity lavas from the east or local fissure eruptions located west of the main arc. These flows further indicate that the volcanic arc had migrated into the Gulf of California from the Sierra Madre Occidental before the upper part of the lower clastic unit was deposited.

The rocks of the lower clastic unit near La Purísima road, and probably correlative rocks on Carmen Island, suggest that it covered most of the Loreto region. In detail, however, correlations of the top of the lower clastic unit from the southern to northern parts of the study area are uncertain. In one interpretation, the contact on top of the lower clastic unit is a regional surface that correlates across the study area and over to Carmen Island. The other interpretation is that the upper part of the lower clastic unit in the southern part of the study area interfingers with volcanic breccia and lava flows to the north and to the east (Fig. 5), which would indicate that the northern area was closer to a volcanic center.

These observations of the lower clastic unit in the Loreto region strongly suggest that the main volcanoes in the arc were tens of kilometers to the east in the Gulf of California while most of the unit was deposited (Fig. 10A). In this interpretation, the entire Loreto region was in the forearc basin in a distal position relative to the arc from ~30– ~ 19 Ma.

6.3. Middle breccia and lava flow unit

At ~19 Ma, there was a rapid progradation of volcanic breccias (proximal debris flows) westward over the lower clastic unit. The lateral facies change from the middle breccias to more distal fluvial sandstone and conglomerate lies 3–5 km west of the gulf escarpment. Because there are probable strata of the lower clastic unit on southern Carmen Island, the lateral transition from the proximal to distal facies probably shifted a minimum of ~50 km to the west at ~19 Ma. The simplest interpretation of this progradation is that it represents a rapid westward migration of the arc volcanoes, or at least local volcanic centers in the Loreto region (Fig. 10B). Based on the minor occurrence of andesite lava flows interbedded with massive breccia of the middle unit and preliminary observations of thick flows and breccia on Carmen Island, we infer that the volcanoes migrated to about the position of Carmen Island during this interval.

6.4. Upper lava flow and breccia unit

Hundreds of meters of andesite lava flows overlie the middle breccia and lava flow unit a few kilometers west and south of Loreto. In the Sierra Microondas north of Loreto (Fig. 3), andesite lava flows of the unit are interbedded with thick to massive flow breccia and volcanic breccia that are probably debris flows similar to the middle breccia unit. Ages from the lava flows in these areas range from 15–12 Ma. The radial pattern of dikes, west of Loreto (Zanchi, 1994) and the dominance of flows that become interbedded with breccia to the north and south, suggests that one volcanic center was near the town of Loreto. There are no equivalent rocks exposed in the gulf escarpment, where breccia and flows of the middle unit are directly overlain by transitional to alkalic basalt flows (Fig. 3) (Sawlan and Smith, 1984) of the Tv unit of McLean (1988).

The nature of the upper unit along the coast and the lack of these rocks in the escarpment suggests that the volcanoes migrated west again to the present coast and that the part of the system now at the position of the gulf escarpment stopped aggrading (Fig. 10C). This cessation of aggradation in the escarpment may have occurred because that area became part of the flanks of the active volcanic edifice, and no longer was part of the forearc basin. Alternatively, the lack of preserved rocks of the upper unit in the gulf escarpment may indicate that the volcanoes of this period of time had significantly less eruptive material.

7. Regional implications for the Comondú arc

There are broad similarities in the Comondú Group north and south of Loreto compared to the study area. In the region from Mulegé to Santa Rosalia and north into northern Baja California, the Comondú Group is generally similar to the Loreto area though no detailed comparisons have been made (e.g. Sawlan and Smith, 1984; Dorsey and Burns, 1994). In the Bahía Concepción area, much of the Comondú Group consists of the core facies of Hausback (1984) based on our reconnaissance and the descriptions of McFall (1968). Importantly, McFall (1968) assigned ~300 m of red, cross-bedded sandstone and light-colored tuff that lie below the thick breccias and flows of the Comondú Group to the Salto Formation (his basal unit of the Comondú Group). He reported an age of 28 Ma for a tuff in the upper part of the Salto Formation. The fission track age of 29.6 ± 3.5 Ma from a basal tuff of the Comondú in the footwall of the Loreto fault (McLean, 1988) further supports the correlation of the lower clastic unit of the Loreto study area to the Salto Formation. The thick section of mainly volcanic breccia (agglomerates of McFall, 1968) of the Pelones Formation near Bahía Concepción is similar to the middle breccia unit of the Loreto area, and both have a sharp contact with the underlying tuff and clastic rocks. The upper part of the Comondú Group at Bahía Concepción is a thick section of lava and breccia (Ricasón Formation of McFall, 1968) that is broadly similar to the upper lava flow and breccia unit of the Loreto area.

Fig. 11 shows the proposed time–stratigraphic relation of the nonmarine Comondú Group of the Loreto area with units to the west near the villages of Comondú and La Purísima (Fig. 2) (Hausback, 1984; McLean et al., 1987). These units cannot be followed continuously from east to west, but biostratigraphic and geochronologic data support these relations. The lower clastic unit of this study is equivalent to the San Gregorio and lower half of the Isidro formations to the west. This regional interfingering of facies represents a change from the proximal, terrestrial deposits of a forearc basin to the east to the distal marine part to the west. The depositional systems and shoreline were prograding to the west because the San Gregorio to Isidro marine units represent a shallowing upward in the La Purísima area, but in an episodic fashion. Based on the long period of fairly similar environment in the bathyal San Gregorio Formation to the west and in the terrestrial lower clastic unit to the east, the change to the shallow marine Isidro Formation at ~21–20 Ma, and the rapid westward movement of the middle breccia unit near Loreto at ~19 Ma, we suggest that the westward progradation may have been gradual in the Late Oligocene to early Miocene and rapid at ~21–20 and 19–18 Ma (Fig. 11). The ~21–20 Ma progradation is further supported because this is when the basin appears to rapidly increase in sediment accumulation.

The middle breccia and lava flow unit of the Loreto area is equivalent in time to the lower part of the terrestrial section of the Comondú Formation of

Heim (1922) (Fig. 11), which in turn interfingers with shallow marine strata of the upper part of the Isidro Formation near La Purísima (McLean et al., 1987). Proximal volcanic breccia is an uncommon, but notable, part of the lower Comondú Formation in the west and supports the rapid westward progradation of the proximal facies of the arc-forearc system at ~19–18 Ma. In depositional setting, the lower part of the Comondú Formation in the Comondú–La Purísima area closely resembles the lower clastic unit of the Loreto area and further supports the overall progradation of the shoreline of the forearc basin westward from ~30 to ~16–15 Ma (Fig. 11).

The upper lava flow and breccia unit of the Loreto area is equivalent to the upper part of the Comondú Formation in the type area, where terrestrial sandstone and conglomerate is interlayered with basalt flows dated from ~15–12 Ma (McLean et al., 1987). These ages overlap the ages of the upper unit of the Loreto area (Table 1). These upper units of the Comondú Group indicate that the major progradation continued to the west up to ~15 Ma, but probably slowed or stopped from 15–12 Ma because volcanic centers are not found much west of Loreto. The upper lava flow and breccia unit is absent on top of the gulf escarpment west of Loreto and the middle breccia unit is directly overlain by 11 Ma alkalic basalt flows directly, while a relatively thin section of the upper unit is present near La Purísima. These relations suggest that the area of the proximal arc may have stopped aggrading, or that the flanks of the arc (where no net subsidence is expected) merely migrated west to the present escarpment.

From Loreto south toward La Paz along the coast, nonmarine Oligocene to Early Miocene strata of the Salto Formation of the Comondú Group correlate to marine bathyal strata of the San Gregorio and El Cien formations (Hausback, 1984; Applegate, 1986; Fischer et al., 1995) found to the south and west respectively. These units record deposition in a forearc basin during a time when volcanism was far to the east in the Sierra Madre Occidental (Fig. 1). Near La Paz, the overall Comondú Group has the same constituents as near Loreto, but it has much more felsic tuff and lesser andesite breccia and lava flows. In the La Paz region, the unit consists of fluvial sandstones and conglomerates interbedded with thin to very thick felsic ash flow tuffs and minor andesite breccia (Hausback, 1984). The percentage of tuff decreases from 75% on Espiritu Santo Island to 20% at San Juan de la Costa and then none 30 km west of there (Fig. 2), which demonstrates that the tuffs originated to the east (Hausback, 1984). Most ages from felsic tuffs range from 24 to 17 Ma and most of the Comondú Group near La Paz correlates with the lower and middle units of the Loreto area. Ferrari et al. (2000) used a regional database from mainland Mexico (Ferrari et al., 1999; Nieto-Samaniego et al., 1999) and suggested that a peak of felsic volcanism at ~23–21 Ma, and specifically a 21 Ma caldera in the state of Nayarit, may have been the source for some of the felsic tuffs of the La Paz and Loreto areas. Andesitic and basaltic lava flows and breccia overlie the felsic tuffs in all areas.

The andesite lava flows at the top of the section near La Paz unconformably overlie the rest of the unit and have two ages of 12 and 16.5 Ma. The age of 12 Ma for the top of the Comondú Group near La Paz is similar to the youngest age from the Loreto area and both areas have all andesite lavas and breccia in the youngest part of the unit.

Using the regional database from Baja California Sur (Fig. 2), we can suggest the following sequence of events. (1) Deposition of the terrestrial Comondú Group began in the Oligocene at ~30 Ma along the east coast of Baja California Sur. This is an estimate because it is based on a fission track age with relatively large error (McLean, 1988) in the Loreto area and an old K–Ar age from the Bahía Concepción area (McFall, 1968). (2) The lower parts of the Comondú Group are dominated on the southern Baja California peninsula by fluvial deposits, and local eolian deposits and felsic tuffs that accumulated in a proximal to medial forearc basin. The tuffs most likely originated from the western coastal region of the southern Sierra Madre Occidental on mainland Mexico near Mazatlan or Tepic (Ferrari et al., 2000), or in the central gulf. The terrestrial clastic deposits interfingered to the west and southwest with marine deposits of the San Gregorio, El Cien, and Isidro formations and similar felsic tuffs are in the San Gregorio Formation at La Purísima (McLean et al., 1987). There probably was a westward progradation of the arc - forearc system at ~21–20 Ma and sediment accumulation increased notably in the Loreto region. (3) The middle of the Comondú Group shows a major westward shift of volcanism and associated proximal debris flows, and a change to dominantly andesitic volcanism, at ~19 Ma in the northern areas, while felsic volcanism continued in the south near La Paz until ~17 Ma. This is part of a major westward shift of volcanism, and change from silicic to mafic + intermediate volcanism, across Mexico (Ferrari et al., 1999). (4) There was another westward shift of the arc at ~15 Ma, with all areas of Baja California Sur experiencing dominantly andesitic volcanism from ~15–12 Ma. Aggradation of the arc-forearc system along the eastern coast of Baja California Sur slowed and locally stopped from ~15–12 Ma. This change in the arc–forearc was caused by either the final shift of the high volcanoes of the arc to the west or a slowing of volcanic productivity as the subducting microplates were transferred to the North American plate (Stock and Lee, 1994).

8. Conclusions

Our study of the excellent exposures of the Comondú Group in the Loreto region gives a framework for the time–stratigraphic evolution of the Oligocene–Miocene arc and forearc basin that lay along the northwestern margin of Mexico. It also provides the template for future detailed study of the arc across an exceptionally well-exposed arc to forearc traverse from Loreto to the west across the peninsula. The lower clastic unit of the Comondú Group in the Loreto area contains ~300 m of sandstones, conglomerates, and tuff that correlate to the Salto Formation of McFall (1968). The lower unit was deposited from ~30–19 Ma in the forearc basin located west of the volcanic arc that lay in the Sierra Madre Occidental and then shifted to the present-day Gulf of California during deposition of the unit, perhaps at ~25 Ma. Stratigraphic relations suggest another westward progradation at ~21 Ma. The lower unit was deposited in a broad fluvial system with local eolian deposits and punctuated by numerous felsic ash flows and fallout and minor mafic lava flows. The terrestrial deposits changed to the west into marine deposits in an overall westward-prograding system.

The arc and proximal forearc migrated abruptly to the west perhaps 50 to a few 100 km to about the position of Carmen Island at ~19–18 Ma. From 19–15 Ma, andesite breccia and minor lava flows were deposited extensively over the Loreto region and felsic tuffs were no longer preserved. These deposits formed from debris flows and lahars that emanated from volcanoes a few tens of kilometers off the coast. These proximal volcanic rocks interfingered to the west into a fluvial system that was similar to the lower unit. At ~15 Ma, the arc again migrated west so that a composite volcano now lay a few kilometers west of Loreto, and andesite lava flows and breccia dominated the areas to the north and south along the coast until 12 Ma, when arc volcanism ceased. The forearc of the system changed at the beginning of this time interval from aggradation to a neutral or erosional surface, such that no upper Comondú Group rocks are found along the gulf escarpment near Loreto and forearc strata are relatively thin to the west near La Purísima. Regions north and south of Loreto in Baja California Sur had broadly similar patterns of episodic westward progradation of the arc–forearc system. One variation is near La Paz where explosive felsic volcanism is better recorded and continued up to ~17 Ma.

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