AAPG Mem 47

Chapter 17

Magmatic Evolution of the Gulf of California Rift

Michael G. Sawlan
U.S. Geological Survey
Menlo Park, California, U.S.A.

ABSTRACT

Magmatic events in the Baja peninsula-Gulf of California region are closely related to sequential tectonic regimes of: (1) late Tertiary subduction beneath the continental margin until ~16 to 12.5 Ma; and (2) continental to oceanic rifting that began about 13 Ma. Orogenic calcalkaline volcanic rocks formed subparallel belts of rhyolite ignimbrite of Oligocene age (~34 to 27 Ma) east of the Gulf in the Sierra Madre Occidental and andesite of Miocene age (~24 to 11 Ma) along the eastern Baja peninsula. Shutoff of the Miocene andesitic arc broadly corresponds to migration of the Pacific-Farallon (Guadalupe)-North America triple junction along the Baja peninsula. Orogenic andesitic volcanism ended at ~16 Ma in northern Baja, and at ~11 Ma in southern Baja, within ~1 to 2 Ma of cessation of subduction. Waning orogenic magmatism persisted along the southern Baja peninsula during the initial stages of rifting.

Paleogeographic implications of the distribution of circum-Gulf volcanic rocks and their inferred easterly source areas suggest that, from about 13 to 8 Ma, the rift consisted of a narrow seaway along the eastern side of the present Gulf. By about 6 Ma, the Gulf had broadened westward to approximately its present width. The period from 13 to 10 Ma was a time of tectonic transition and magmatic diversity. During this interval, medium-K calcalkaline, high-K calcalkaline, alkalic, and tholeiitic magmas erupted from the central to southern part of the Baja peninsula-Gulf region, and from about 14 to 8 Ma, rhyolite ignimbrite erupted in the northern Gulf region. Since 10 Ma, volcanism on the western Baja peninsula has been dominated by alkalic magmas, the Gulf margins by calcalkaline magmas, and the Gulf by tholeiitic magmas. Postsubduction calcalkaline andesite to rhyolite erupted sporadically and locally along the northern Gulf margins from ~9 Ma through Holocene time.

Alkalic magmas associated with rifting in the Gulf of California are unlike alkalic magmas from intraplate settings. They comprise nepheline- to quartz-normative, basaltic to andesitic rocks characterized by diverse trace element ratios. They are broadly similar to intraplate alkalic rocks in having high K, P, Ba, Sr and the light REE (rare earth elements), but have some trace element characteristics typical of orogenic magmas (low Nb and Ta relative to K, Ba, Sr, and La) that distinguish these alkalic rocks from intraplate or cratonic rift alkalic rocks. Rb abundances (mostly <25 ppm, as low as 5 ppm) are unusually low in these alkalic rocks, both in contrast to the high K (~1.7-4.1 wt% K_2O), Ba (~800-2200 ppm), and Sr (~1000-3700 ppm), and in comparison to Rb abundances in mafic lavas in general; many samples have Rb at levels typically found in low-K tholeiites. The high K/Rb ratios, mostly ~1000 to 5000, are among the highest reported for any lavas. Samples ranging in SiO_2 from 48 to 61% have $Mg' \geq 65$, indicating that a broad range of compositions may represent primary melts. The generally high Mg', and the low Rb, Th, Nb, and Ta in some lavas, suggest that depleted refractory mantle equivalent to a mid-ocean ridge basalt (MORB) source contributed to these melts. The distinctive trace element enrichments are attributed to the stabilization in the source of amphibole and apatite from metasomatic fluids related to prior subduction beneath the peninsula. In discrimination diagrams, these alkalic rocks typically cluster outside previously defined fields for various magma types. The common tectonic setting among these and geochemically similar alkalic suites is the occurrence in a continental margin that is undergoing extension, located along a recently or currently active convergent plate boundary.

Tholeiitic basalts have erupted since the earliest stages of continental rifting through development of oceanic spreading centers. Gulf of California tholeiites exhibit an evolution distinguished particularly by differences in rare-earth-element (REE) abundances. Early-rift magmas are similar in trace element geochemistry to some intraplate tholeiites from ocean islands and continental flood basalts, and have convex-upward REE patterns. The most recent tholeiites from the East Pacific Rise in the mouth of the Gulf are equivalent to N-MORB (normal mid-ocean ridge basalt) from other mid-ocean rifts, and are depleted in the light-REE. The transition in tholeiite geochemistry from intraplate tholeiite to MORB is attributed to progressive fusion of more refractory mantle components. Incipient-rift tholeiites are derived from selective fusion of clinopyroxenite veins, and with continued melting, N-MORB are formed by fusion of peridotite. This tholeiite sequence reflects the evolution of mantle source regions in rifts that sustain an ensialic to oceanic transition.

INTRODUCTION

The Gulf of California-Baja peninsular region presents an excellent opportunity for evaluating associations between magma types and tectonic environments in general, and the evolution of magmas during ensialic through oceanic rifting in detail. The Gulf of California region has undergone rapid changes in tectonic setting, accompanied by marked changes in magma types, over the past 13 m.y. Petrological studies of volcanic rocks in the Gulf of California region are particularly significant because a precise tectonic history of this region is well documented from onland and offshore geological and geophysical studies, independent of inferences based on the magmatic history of the region. Establishing empirical associations between magma types and tectonic environments in the Baja-Gulf region may serve as a basis for interpreting the tectono-magmatic histories of displaced terranes that may have originated by continental fragmentation.

Previous studies of volcanism in the Gulf region have focused exclusively on either the ocean floor magmatism in the Gulf (Saunders et al., 1982a, b; Saunders, 1983) or magmatism on the Baja peninsula (Sawlan, 1981a, b; Hausback, 1984a, b; Sawlan and Smith, 1984a, b; Rogers et al., 1985a; Sawlan, 1986; Saunders et al., 1987), and these have yielded rather provincial perspectives on the evolution of rift magmatism. In the present study, I incorporate data from the submarine and subaerial volcanic records of the Gulf region to integrate these perspectives; this is particularly important with respect to the evolution of Gulf rift tholeiites and their mantle sources during the transition from ensialic to oceanic rifting. A comprehensive account of all volcanic rocks from the Gulf region is not attempted here. In this report, I present a synthesis of representative data for the major magmatic events that characterize the history of the Gulf region.

This paper is presented in three parts. The first section provides an overview of the volcanism and tectonic setting of the Gulf region from Oligocene time to the present. This discussion builds on earlier publications, notably Sawlan and Smith (1984a), in which petrographic and volcanological characteristics and K-Ar data are reported for volcanic rocks from Baja California Sur. In this section, I address some of the recurring questions about Baja-Gulf magmatism, such as: Does the Miocene arc volcanism show a progressive north to south shutoff as the Pacific-Farallon-North America triple junction migrated southward? Are rift magmas similar to those in other continental rifts? Is the rift event reflected in changes in magma chemistry? How does the apparently anomalous postsubduction calcalkaline magmatism, as represented by the Quaternary Tres Virgenes volcano, fit into the tectonic and magmatic scheme?

The following two sections focus on the geochemistry of two main groups of magmas that erupted concurrent with rifting in the Gulf: alkalic volcanic rocks on the Baja peninsula and tholeiitic basalts from circum-Gulf and intra-Gulf locales. Comparisons with volcanic rocks from various rifts and intraplate settings are emphasized to establish a global perspective on the significance of the geochemistry of Gulf rift magmas. The geochemistry of the alkalic and tholeiitic rocks are discussed further in terms of their implications for mantle source regions.

Site locations mentioned in the text are shown in Figure 1. In some instances, the Baja peninsula, which includes the states of Baja California (north of lat. 28°N) and Baja California Sur (south of lat. 28°N), is referred to collectively as Baja. Likewise, the Gulf of California is referred to in brief as the Gulf.

LATE TERTIARY VOLCANIC AND TECTONIC SETTING OF THE GULF OF CALIFORNIA REGION

Oligocene Calcalkaline Volcanism in the Sierra Madre Occidental

The western Mexico continental margin has been the upper plate at a convergent plate boundary throughout most of Tertiary time (Atwater, 1970). Oligocene and Miocene volcanic rocks in western Mexico that are ostensibly related to eastward subduction occur in two northwest-trending belts parallel to the continental margin. The older and easternmost belt is Oligocene in age and occurs east of the Gulf of California in the Sierra Madre Occidental (Figure 2); the younger and westernmost belt occurs along the Baja peninsula and is discussed below.

Oligocene volcanic rocks in the Sierra Madre Occidental are dominantly rhyolite ignimbrite (ash flow tuff) erupted mostly between 34 and 27 Ma (McDowell and Keizer, 1977; McDowell and Clabaugh, 1979). Andesite, dacite, and rhyolite lavas or domes are interlayered with the ignimbrites but comprise less than 10% by volume of the sequence (Cameron et al., 1980). These rocks are characterized by hypersthene phenocrysts and are considered to have calcalkaline affinities based on a lack of iron enrichment with increasing silica (Cameron et al., 1980).

Some Oligocene tuffs found on the Baja peninsula may represent distal facies of the Sierra Madre ignimbrites. Outflow-facies ignimbrite and air-fall tuff (29 to 27 Ma), occur along the southeastern Baja peninsula at Bahia Concepcion (Figure 1) (McFall, 1968; Hausback, 1984a). Farther west in the axial to western parts of Baja California Sur, ash-fall tuffs are interbedded with Oligocene and early Miocene marine strata of the San Gregorio Formation (Hausback, 1984a) and range in age from 27 to 22 Ma (McLean et al., 1984). The oldest (~27 Ma) of these air-fall tuffs are age-equivalent with the youngest ignimbrites in the Sierra Madre and the Concepcion Peninsula, but the younger tuffs in the San Gregorio Formation more likely correlate with ignimbrites ranging in age from 25 to 17 Ma in the La Paz area (Hausback, 1984a, b) and 23 Ma ignimbrites in the Mazatlan area (McDowell and Clabaugh, 1979) (Figure 2).

Early and Middle Miocene Calcalkaline Volcanism in the Baja Peninsula-Gulf of California Region

Andesite Belt along the Eastern Baja Peninsula

Calcalkaline volcanic rocks in the Baja-Gulf region form a northwest-trending belt, ~24 to 11 Ma in age, located along the eastern margin of the Baja peninsula (Figure 2). This belt, or arc, is made up of the dissected remnants of coalesced composite volcanoes dominated by medium-K calcalkaline andesite but including subordinate basalt and dacite. Volcanic facies distributions indicate that the arc axis coincides with the eastern Baja peninsula in the south-central part of the peninsula between ~lat. 28° and 25°N where sequences of lava and tuff breccia are locally thicker than 2 km (Hausback, 1984a; Sawlan and Smith, 1984a). The arc axis is identified by the occurrence of vent-facies rocks including domes, abundant lava flows, dikes, near-vent agglomerate and agglutinate, and channelized pyroclastic tuff breccia. The arc axis can be traced as far north as the Sierra San Francisco near San Ignacio, and south along the Sierra Giganta to south of Loreto, as indicated by the dark shaded band in Figure 2. A broad volcaniclastic apron of tuff breccia and volcanic conglomerate and sandstone lies west of the arc in these areas. Calcalkaline andesite is reported across a broad area in the northern half of the peninsula and coastal Sonora (Gastil et al., 1979), but the volume of these rocks appears to be subordinate to those erupted between ~lat. 28° to 25°N. Volcaniclastic aprons such as those in Baja California Sur have not been reported in the northern Gulf region. No Miocene andesite occurs south of the La Paz area. Hausback (1984b) has suggested that the absence of the arc south of La Paz may be due to truncation and northeast translation of

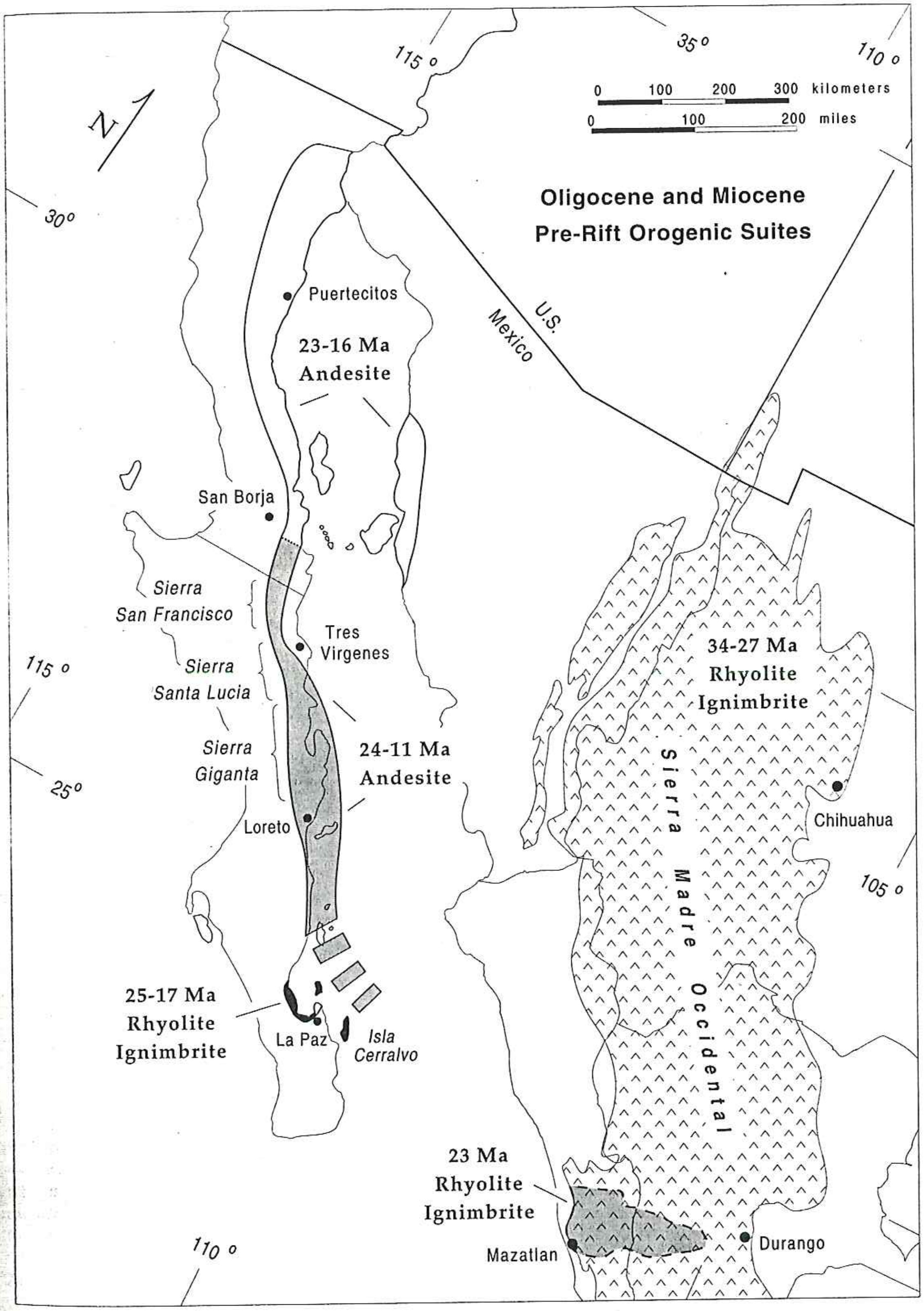

Figure 2—Distribution of the Oligocene and Miocene volcanic belts in northwestern Mexico. Patterned field in the area of the Sierra Madre Occidental represents middle Tertiary volcanic rocks which are dominantly rhyolite ignimbrite (after Swanson et al., 1978, and Cameron et al., 1980). Rocks of similar age occur in Arizona and New Mexico but are mostly omitted from this figure. Distribution of ~23 Ma ignimbrites in the Mazatlan area is schematic, drawn to include locations of samples dated by McDowell and Clabaugh (1979) along a Mazatlan-Durango transect. Distribution of 25 to 17 Ma rhyolite ignimbrite in the La Paz region and adjacent islands represented by solid black areas. Along the southern Baja peninsula, darker-shaded area represents the axis of vent facies, voluminous arc volcanism. Location of the arc axis between Loreto and La Paz corresponds to Hausback's (1984a) core facies. The extension of the arc southeast of La Paz into the Gulf region, represented by the dashed shaded band, is uncertain. This possible extension of the arc is drawn to lie east of Isla Cerralvo, which is underlain largely by pre-Tertiary crystalline rocks and ignimbrites that are most likely age-equivalent to tuff in the La Paz area. Lighter-shaded area along northern Baja and adjacent Sonora represents 23 to 16 Ma andesite that appears to be less voluminous but perhaps broader in the extent of vent areas (after Gastil et al., 1979).

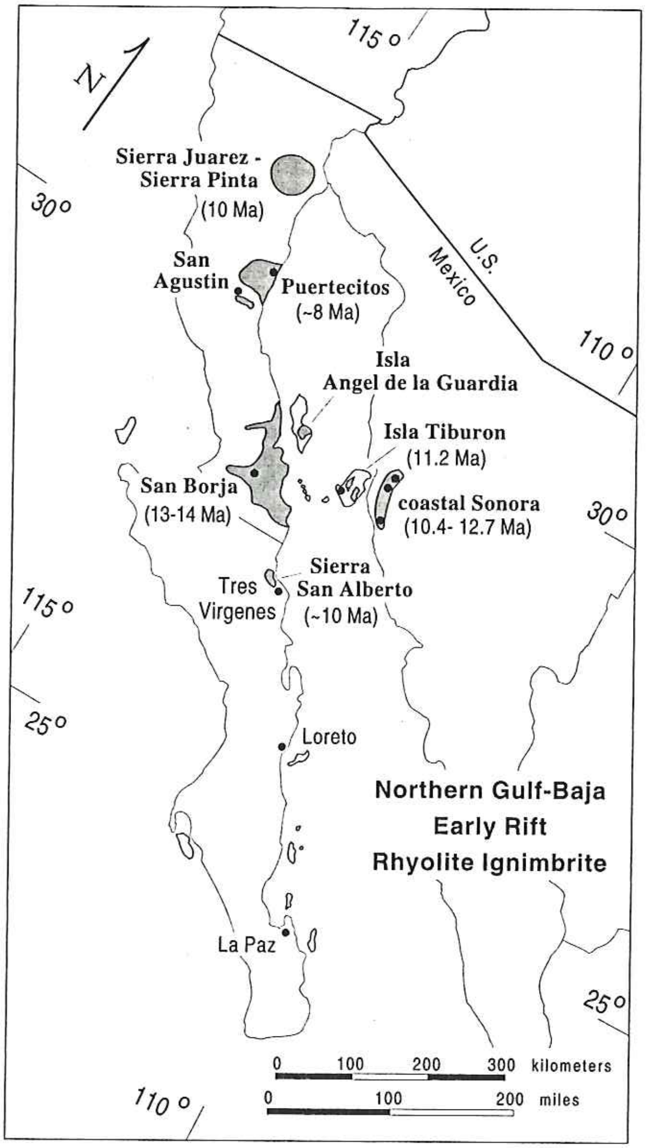

Figure 3—Distribution of 14 to 8 Ma rhyolite ignimbrite (shaded areas) in the Baja peninsula-Gulf of California region. Ages for localities are from Gastil et al. (1979), except for the Sierra San Alberto occurrence, which is from the author (see text for discussion). Distribution of ignimbrites in the northern Baja peninsula is generalized from Gastil et al. (1975). The occurrence in the Sierra San Alberto near the Tres Virgenes area is from the author's mapping and geologic reconnaissance; the northern limit of this ignimbrite is uncertain although the southern extent is well constrained. On the map of Gastil et al. (1975), rhyolite ignimbrites and lava flows are not distinguished, but descriptions in another publication (Gastil et al., 1979) and the author's reconnaissance in several localities were sufficient to identify the rock type. The black dot at southwest Isla Tiburon represents a K-Ar sample locality from an erosional outlier of the main occurrence of ignimbrite. The shaded area shown for coastal Sonora is schematic and includes sample localities (solid dots) for rocks reported as rhyolite by Gastil and Krummenacher (1977).

(Esperanza Basalt) (Sawlan, 1981a) are truncated at their east end by the Gulf escarpment. The linear distribution of these tholeiites between Tres Virgenes and San Ignacio, facies changes in underlying sedimentary rocks, and orientations of flow lobe fronts and pahoehoe indicate that these lavas flowed west down a gently sloping arroyo across the peninsula. Ignimbrites in the northern Gulf (~14 to 8 Ma) represent the westernmost parts of outflow sheets. In their western and southern reaches in Baja, the ignimbrites appear to have been channelized, as suggested by linear map patterns (as in the area near Punta Prieta north of San Borja, Figure 3). No calderas have been identified in Baja, and sources for the ash flows most likely lie submersed in the northern Gulf region. The appearance of the rhyolites at ~14 Ma followed the cessation of synsubduction calcalkaline andesitic volcanism in the northern Gulf region by about 2 m.y. Their derivation from easterly sources implies that, until ~8 Ma, part of the present Gulf region east of the Baja peninsula remained a highland.

The ancient drainages occupied by 10 Ma tholeiites (Esperanza Basalt) cut across the axis of the andesite belt of composite volcanoes which most likely formed a topographic divide from early through middle Miocene time. Development of drainages across the extinct arc suggests that a highland was formed in the east between ~14 and 8 Ma. The lack of eastward-derived volcanics younger than ~8 Ma implies that the sources for the tholeiites and tuffs were isolated from the peninsula either by formation of a structural depression or by widening of an existing depression in the Gulf region after this time. The gentle regional westward dip (typically ≤ 5°) of the orogenic calcalkaline andesites and their clastic aprons on Baja (except for stronger deformation along the Gulf coast) is consistent with a gentle westward tilting caused by incipient-rift inflation in the Gulf region.

In apparent conflict with this inference of a highland fomed in the Gulf region from 14 to 8 Ma is the documentation of 13 Ma marine strata from Isla Tiburon along the eastern Gulf (Smith et al., 1985; Smith, 1991) (Figure 3). This conflict is reconciled if marine sedimentation occurred in a narrow proto-Gulf basin and the sources for the volcanic rocks were located on the adjacent west-sloping flank (Figure 5). This scenario implies that the rift initially formed a narrow basin that, between about 8 and 6 Ma, widened to the west to include vent areas from which the tholeiitic basalts and rhyolite ignimbrites were derived. Minimum ages for widening of the Gulf are constrained by the age of sedimentary basins along the western margins of the Gulf. An early Pliocene age (Wilson, 1955) is reported for the oldest sedimentary rocks of the Boleo Basin at Santa Rosalia, located along the west-central margin of the Gulf (Figure 1). Boehm (1984) reports that the Sierra San Felipe-Sierra Santa Rosa basin, located along the northwestern margin of the Gulf near El Paraiso (Figure 1), had reached middle bathyal depths prior to 6.0 Ma.

Distribution of Magma Types During Rifting

Volcanic rocks representing four markedly different magma types (tholeiitic, alkalic, calcalkaline, and peralkaline) erupted during rifting of the Gulf of California since 13 Ma. These generally exhibit a geographical distribution across the rift. Tholeiites erupted mostly from areas within the Gulf, calcalkaline andesitic to rhyolitic volcanics and minor mildly peralkaline rhyolite occur along the Gulf margins, and Si-undersaturated to Si-saturated alkalic lavas occur on the Baja peninsula.