Southern Louisiana salt dome xenoliths: First glimpse of Jurassic (ca. 160 Ma) Gulf of Mexico crust

Robert J. Stern[1]*, Elizabeth Y. Anthony[2], Minghua Ren[2], Brian E. Lock[3], Ian Norton[4], Jun-Ichi Kimura[5], Takashi Miyazaki[5], Takeshi Hanyu[5], Qing Chang[5], and Yuka Hirahara[5]
[1]Geosciences Department, University of Texas at Dallas, Richardson, Texas 75083-0688, USA
[2]Department of Geological Sciences, University of Texas at El Paso, El Paso, Texas 79968, USA
[3]Department of Geology, Box 44530, University of Louisiana, Lafayette, Louisiana 70504, USA
[4]Institute for Geophysics, Jackson School of Geosciences, University of Texas at Austin, Austin, Texas 78758, USA
[5]Institute for Research on Earth Evolution (IFREE), Japan Agency for Marine-Earth Science and Technology (JAMSTEC), Yokosuka 237-0061, Japan

ABSTRACT

No direct information about the age and composition of rift-related igneous activity associated with the Late Jurassic opening of the Gulf of Mexico exists because the igneous rocks are deeply buried beneath sediments. Three salt diapirs from southern Louisiana exhume samples of alkalic igneous rocks; these salt domes rise from the base of the sedimentary pile and overlie an isolated magnetic high, which may mark the position of an ancient volcano. Three samples from two domes were studied; they are altered but preserve relict igneous minerals including strongly zoned clinopyroxene (diopside to Ti-augite) and Cr-rich spinel rimmed with titanite. $^{40}Ar/^{39}Ar$ ages of 158.6 ± 0.2 Ma and 160.1 ± 0.7 Ma for Ti-rich biotite and kaersutite from two different salt domes are interpreted to represent the time the igneous rock solidified. Trace element compositions are strongly enriched in incompatible trace elements, indicating that the igneous rocks are low-degree melts of metasomatized upper mantle. Isotopic compositions of Nd and Hf indicate derivation from depleted mantle. This information supports the idea that crust beneath southern Louisiana formed as a magma-starved rifted margin on the northern flank of the Gulf of Mexico ca. 160 Ma. These results also confirm that some magnetic highs mark accumulations of mafic igneous rocks buried beneath thick sediments around the Gulf of Mexico margins.

INTRODUCTION

The Gulf of Mexico opened as the westernmost arm of Tethys, related to breakup of Pangea and synchronous with opening of the Central Atlantic (Pindell, 1985). In spite of this general understanding about when and how it opened, the Gulf of Mexico is a rare example where the origin of a sizable oceanic basin at low latitudes is unclear, due largely to thick blanketing sediments (to 16 km; Muehlberger, 1992) and the lack of correlatable, spreading-related magnetic anomalies. Indirect evidence indicates opening between ca. 165 and 139 Ma (Late Jurassic) and that the transitional crust ranges from a narrow, magma-rich volcanic rifted margin beneath the Texas coast to a broader, magma-poor rifted passive margin beneath Louisiana (Mickus et al., 2009; Stern and Dickinson, 2010). We have no direct way to sample and study this Jurassic seafloor, but salt diapirs, sourced from Louann Salt that was deposited on top of the Late Jurassic crust, occasionally bring up samples of igneous rocks (Lock and Duex, 1996; Ren et al., 2009). The Five Islands of southern Louisiana are part of seven uniformly spaced salt diapirs that define a linear northwest trend (Fig. 1). The Five Islands trend overlies transitional crust thought to have formed during Gulf of Mexico opening (Dobson and Buffler, 1997; Harry and Londono, 2004). The diapirs containing mafic igneous rocks (Jefferson, Avery, and Weeks) rise over a magnetic high (Fig. 1), as might be expected from a significant volume of buried mafic igneous rocks. Salt mine exposures reveal highly deformed bedding defined by interlayered halite and anhydrite with inclusions of Oligocene sandstone, shale, and igneous rocks, as well as pockets of water, oil, and gas (Lock and Duex, 1996). Structure in the salt domes is essentially vertical, with multiphase isoclinal folding. The original stratigraphic position of the igneous samples is not known, but must have been immediately beneath, interbedded with, and/or intruded into or above the salt (Fig. 2). The age of the Louann Salt is bracketed on stratigraphic grounds (Salvador, 1991) as post–Early Jurassic to pre–late Oxfordian, probably mostly Callovian (165–161 Ma; Walker and Geissman, 2009). We report here mineral chemical, whole-rock chemical, Nd and Hf isotopic compositions, and radiometric ages for

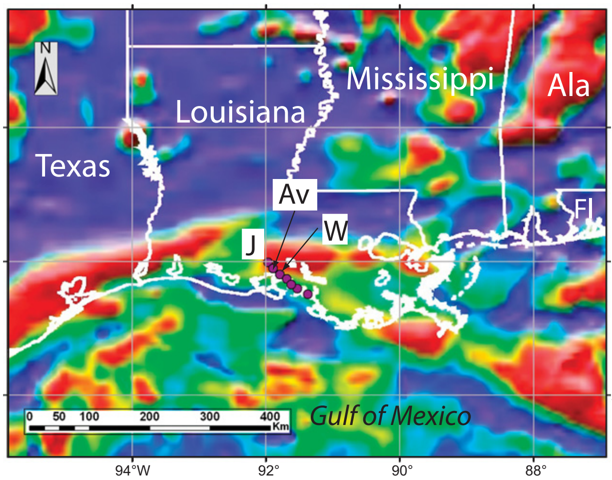

Figure 1. Magnetic anomaly map of Louisiana (United States) and environs. Red is magnetic high, blue is magnetic low. Seven black dots are salt domes of Five Islands trend. Note that three salt domes containing mafic xenoliths (J—Jefferson, Av—Avery, W—Weeks) are above magnetic high interpreted to mark presence of buried mafic lavas. Magnetic anomalies are from Maus et al. (2007). Fl—Florida, Ala—Alabama.

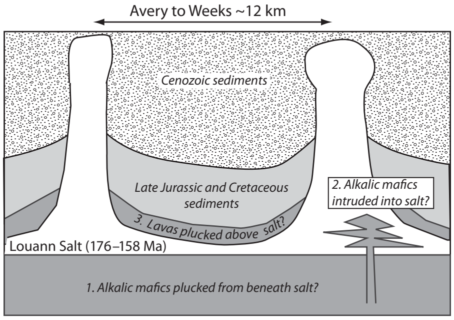

Figure 2. Possible relationship between salt and alkalic mafic rocks. Mafic rocks could be plucked by rising salt from underneath or above, or could have intruded. Note distance between two salt domes containing xenoliths.

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*E-mail: rjstern@utdallas.edu.

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three samples of igneous rocks entrained in two of these salt bodies. A third salt dome, Jefferson Island (Fig. 1), also contains altered mafic xenoliths (Balk, 1953), but samples of this were not available for study. This is the first time that such information has been presented for igneous rocks that formed when the Gulf of Mexico is thought to have opened, in Jurassic time. We use this information to further our understanding of Gulf of Mexico formation.

RESULTS

Methods are summarized in the GSA Data Repository[1] (Ar results and chemical and isotopic analytical procedures). Three samples of porphyritic igneous rocks from two salt domes were studied. Sample 2EO is from the 1000′ (~304 m) level of the Weeks Island dome, and W26 is from the 1300′ (~395 m) level and W25 is from the 1600′ (~486 m) level of the Avery Island dome. The samples are altered, as is obvious from petrographic examination, which reveals that primary igneous minerals such as clinopyroxene are replaced by secondary quartz, vermiculite, calcite, hematite, and K-feldspar (Figs. DR2, DR8, and DR9 in the Data Repository). The K-feldspar assemblage is similar to Deep Sea Drilling Project Site 453 samples described by Natland (1982). Intergrown with calcite is mcgillite, a manganous hydroxychlorosilicate (Stevenson et al., 1984). Because a significant component of this alteration involves carbonate and water-rich vermiculite, a simple way to quantify alteration is with measured loss on ignition (Table DR1 in the Data Repository) for whole-rock samples. By this criterion, and consistent with assessment based on thin-section examination, W26 is the least altered, followed by 2EO. W25 is the most altered.

The rocks contain fresh igneous minerals of diopside, Mg-Al chromite, titanite, kaersutite, and Ti-rich biotite; these are set in a more-altered matrix comprising diopside, titanite, biotite, apatite, and vermiculite (representative mineral compositions and textures are in Table DR2, and Figs. DR1, DR3, DR4, and DR5). Primary mineral assemblages reveal significant disequilibria between cores with compositions characteristic of depleted mantle (diopside, Cr-rich spinel) and rims that are strongly enriched in Ti (titanaugite, titanite), indicating that early refractory minerals reacted with an alkaline mafic melt. Spinels have Cr# (100 Cr/Cr + Al) from 36 to 42 (Table DR2) and are typically rimmed by titanite (Fig. DR3). Diopside also exhibits core-overgrowth textures with two distinct core compositions: one with a high Cr, Si and a second with low Cr, Si (Fig. DR1). Rims for both core types exhibit titanopyroxene ($MgSi_2 = TiAl_2$) and Ca-tschermaks ($MgSi = Al^{vi}Al^{iv}$) substitution and are identical to matrix diopside, indicating that the rim compositions were in equilibrium with the final melt. The diopside cores and chromite are probably xenocrysts and have compositions similar to minerals in mantle rocks, e.g., abyssal peridotites from the Vulcan Fracture Zone (Dick, 1989) or Samoan xenoliths (Wright, 1987; Hauri and Hart, 1994). Kaersutitic amphibole occurs as small grains in W26 and as large phenocrysts in 2EO (Fig. DR4). Similar mineral associations have been reported for alkalic magmas from the Jasper (Gee et al., 1991) and Line Island seamounts (Natland, 1976). Ti-rich (~5%–7% TiO_2) biotite is intergrown with magnetite and quartz. Magnetite has substantial jacobsite (Mn) and ulvospinel (Ti) components, typically $(Mn_{0.5}Fe_{1.1})(Fe_{0.9}Ti_{0.5})O_4$. Relict igneous feldspar was not found. This mineral assemblage, i.e., mantle-like diopside and Cr-spinel with Ti-rich rims and Ti-rich hydrous phases of biotite and amphibole, indicates involvement of moderately depleted mantle, overprinted by water-rich alkaline melts, probably low-degree partial melts. These melts were strongly alkaline, most likely undersaturated basanite or olivine nephelinite (Anthony et al., 1989; Panina and Usoltseva, 2008).

Biotite (W26) and kaersutitic amphibole (2EO) with primary, igneous morphologies were dated at the New Mexico Institute of Mining and Technology using $^{40}Ar/^{39}Ar$ techniques (Fig. 3; for Ar results, see the Data Repository). Both yield well-defined Ar plateau ages: 158.6 ± 0.2 Ma for W26 biotite and 160.1 ± 0.7 Ma for 2EO kaersutite. These minerals are inferred to be original igneous phases, so we interpret these ages as approximating when the magma cooled. These are the first radiometric dates for igneous rocks that can be directly related to opening of the Gulf of Mexico in Jurassic time. These ages are older than previously reported ca. 146 Ma $^{40}Ar/^{39}Ar$ dates from biotite diorite xenoliths found in salt diapirs in the La Popa Basin, northeastern Mexico, interpreted as metamorphic ages by Garrison and McMillan (1999). The ages reported here are, however, consistent with zircon dates obtained from laser ablation–inductively coupled plasma–mass spectrometry from La Popa xenoliths (J. Amato, 2010, personal commun.), consistent with the hypothesis that rifting related to the opening of the Gulf of Mexico also affected the interior of northeastern Mexico (Stern and Dickinson, 2010).

Alteration disturbed primary igneous compositions, especially Si, alkali metals, alkaline earths, Pb and H_2O, but not high field strength elements (HFSE, e.g., Ti, Zr, Hf, Nb, Y; Fig. 4A). This interpretation is confirmed by elevated abundances of immobile incompatible trace elements (Fig. 4A), the most incompatible of which are one to two orders of magnitude enriched relative to normal mid-oceanic ridge basalt (N-MORB). This implies that the alkalic mafic magma was derived from extremely low degree of partial melts (~2%–3%) in contrast to MORB melts produced by ~10% melting (Fig. 4A). The mantle source was more enriched than expected for MORB-type asthenosphere considering extremely high highly incompatible elements. Positive anomalies for Zr and Hf suggest that melting of amphibole in the source was involved.

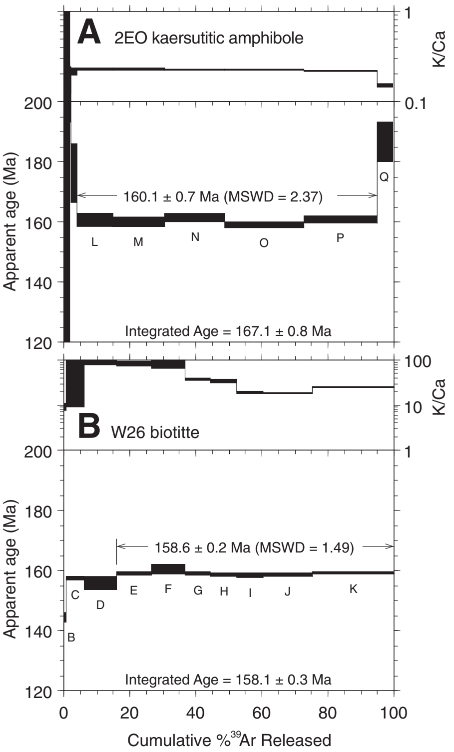

Figure 3. $^{40}Ar/^{39}Ar$ age and K/Ca spectra. A: Weeks Island kaersutitic amphibole (sample 2EO). B: Avery Island biotite (sample W26). MSWD—mean square of weighted deviates.

Nd and Hf are much less mobile than Sr and Pb during alteration, so their isotopic compositions are most likely to reflect those of the unaltered magmas and mantle source. This inference is supported by the fact that Nd and Hf isotopic compositions are indistinguishable for the three samples (Table 1), in spite of the fact that these show different extents of alteration. These results indicate derivation of the magma from mantle with a long-term depletion history (high Lu/Hf and Sm/Nd). The mantle source was not as depleted as MORB-type mantle, but similar to the depleted mantle source of Hawaiian basalts (εHf ~+9, εNd ~+7 at 160 Ma; Table 1; Fig. 4B).

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[1] GSA Data Repository item 2011108, Figures DR1–DR9, Ar results, chemical and isotopic analytical procedures, Table DR1 (whole-rock chemical data), and Table DR2 (representative mineral compositions), is available online at www.geosociety.org/pubs/ft2011.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, USA.

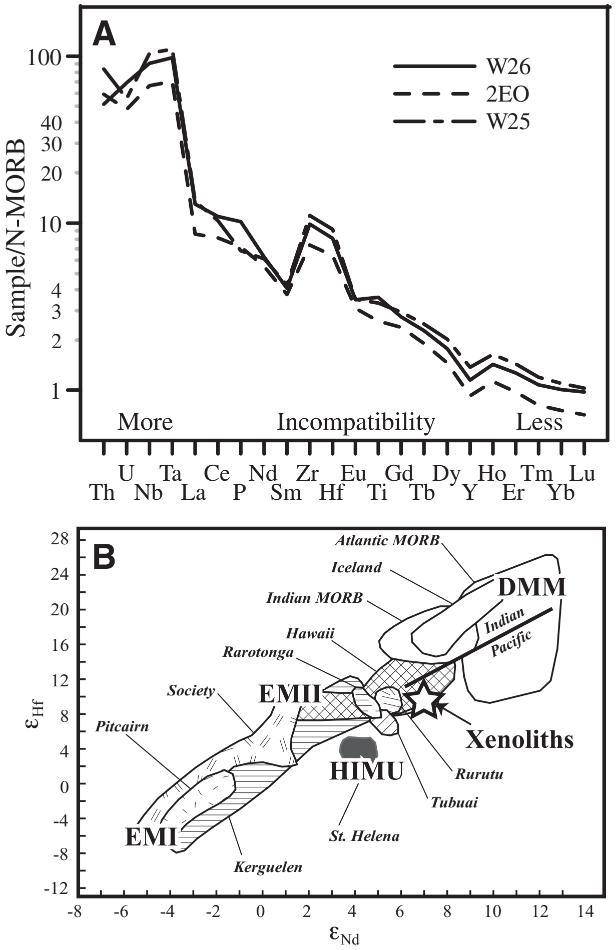

Figure 4. Plots of geochemical and Nd-Hf isotopic data. A: Relatively immobile trace element abundances normalized to normal mid-oceanic ridge basalt (N-MORB; Sun and McDonough, 1989). Elevated abundances of high field strength elements and rare earth elements are consistent with original lamprophyric magma. B: Hf-Nd isotope diagram comparing initial isotopic compositions of Nd and Hf in 160 Ma alkalic mafics with those of present mantle sources (EMI, EMII [enriched mantle types], DMM [depleted mantle MORB], HIMU [high ^{238}U/^{204}Pb ratio]). Also shown is Indian-Pacific mantle domain boundary in southwestern Pacific. X-Y axes are in ε units to allow us to correlate present-day mantle source and salt dome samples. References for mantle sources and Indian-Pacific boundary are from Salters and White (1998) and Pearce et al. (2007).

TABLE 1. Nd AND Hf ISOTOPIC RESULTS

Sample	^{143}Nd/^{144}Nd ±2σ	^{147}Sm/^{144}Nd	ε_{Nd}(160)*	^{176}Hf/^{177}Hf ±2σ	^{176}Lu/^{177}Hf	ε_{Hf}(160)†
W26	0.512941 ± 7	0.1409	7.05	0.282944 ± 6	0.00377	9.20
W25	0.512944 ± 8	0.1511	6.90	0.282960 ± 5	0.00354	9.81
W25(r)	0.512943 ± 6	0.1522	6.86	0.282948 ± 6	0.00361	9.39
2EO	0.512940 ± 5	0.1489	6.87	0.282950 ± 7	0.00352	9.45
JB-2	0.513079 ± 6			0.283241 ± 7		
JNdi-1	0.512091 ± 5§					
JMC-475				0.282141 ± 11**		

Note: (r) indicates duplicate dissolution and analysis.
*Relative to CHUR (chondritic uniform reservoir) ^{143}Nd/^{144}Nd = 0.512638.
†Relative to CHUR ^{176}Hf/^{177}Hf = 0.282772 (Blichert-Toft and Albaréde, 1997).
§Mean of 3 analyses.
**Mean of 7 analyses used for normalization to ^{176}Hf/^{177}Hf = 0.282160.

The isotopic and trace element data considered together indicate that the mantle source was recently enriched as a result of metasomatism; this enrichment may have been associated with Gulf of Mexico rifting. Alkalic mafic composition is typical of rift-initiation magmas from strongly metasomatized source regions (Maria and Luhr, 2008; Elkins-Tanton et al., 2007), a conclusion consistent with petrographic evidence that the salt dome xenoliths formed from volatile-rich melts.

DISCUSSION

Three points are discussed in this section: (1) the significance of ca. 160 Ma low-degree melts of metasomatized mantle beneath rifted crust of the Louisiana margin; (2) the implications of salt dome mafic xenoliths for understanding regional magnetic fabric; and (3) the significance of xenolith ages for understanding the age of the Louann Salt and when Gulf of Mexico rifting occurred.

Relict igneous minerals in the xenoliths are strongly zoned, with cores showing characteristics of depleted mantle (Cr-rich spinel and diopsidic clinopyroxene) and rims showing strong alkaline affinities (titanite and Ti-augite; see Figs. DR1 and DR3). Ti-rich amphibole and biotite are related to the late alkaline overprint, and demonstrate the hydrous nature of the infiltrating alkaline melt. These petrographic features can be explained if depleted mantle was infiltrated by a volatile-rich alkaline metasomatic melt, perhaps accompanying early stages of extension and mantle upwelling as the Gulf of Mexico began to open. Because the metasomatic agent transported Ti, it must have carried HFSEs as well as large ion lithophile elements. Thus, the isotopic compositions of Nd and Hf are almost certainly dominated by the metasomatizing melt. These isotopic compositions indicate derivation from a mantle source with a time-integrated history of light rare earth element and Hf/Lu depletion, with no evidence for participation of old continental lithosphere. Instead, these samples have an oceanic isotopic character, as expected for the igneous rocks of an embryonic oceanic basin.

The correspondence of salt diapirs containing alkalic mafic xenoliths and a magnetic high in coastal Louisiana supports the hypothesis that magnetic fabrics along the northern Gulf of Mexico reflect rift-related crustal structure, with magnetic highs marking accumulations of mafic igneous rocks and magnetic lows corresponding to intervals of stretched continental crust (e.g., Mickus et al., 2009). This study is, to our knowledge, the first time that magnetic highs in the northwestern Gulf of Mexico have been directly correlated with mafic igneous rocks in the crust. This is consistent with geophysical cross sections depicting the Louisiana margin as lacking extensive magmatism (Harry and Londono, 2004). Extrapolating from our observations, we predict that if and when mafic Jurassic xenoliths are recovered from salt domes along the Texas margin, they will be higher degree tholeiitic basalts, inasmuch as these overlie a much more continuous and broad magnetic high (Mickus et al., 2009).

Deposition of the Louann Salt marked a critical time between rifting and seafloor spreading in the nascent Gulf of Mexico. Salt was deposited on transitional crust on either side of the Gulf of Mexico as the gulf began to open. Seawater was able to flow into the basin, but this narrow connection was repeatedly closed, allowing seawater in the basin to evaporate. Untold cycles of seawater flooding and evaporation occurred before the basin widened sufficiently that communication with the world ocean was permanently established. Salt deposition thus ended about the time that seafloor spreading began to form true oceanic crust, or shortly thereafter. The age of salt deposition thus constrains when Gulf of Mexico rifting occurred, but has been difficult to determine. Salvador (1987) correlated the Louann Salt with the Callovian Huehuetepec Formation evaporite sequence in Mexico and other stratigraphic relationships to bracket deposition as post–Early Jurassic to pre–late Oxfordian (176 Ma to 158 Ma). Allowing for the imprecision of the stratigraphic data, the ca. 160 Ma igneous activity represented by the xenoliths is essentially contemporaneous with the end of salt deposition. The radiometric ages reported here thus constitute an important constraint, that rift-related mafic igneous activity occurred ca. 160 Ma, about the same time that the Louann Salt deposition ended.

These results firmly support the interpretation that the Gulf of Mexico opened in Late Jurassic time and encourage geoscientists to search for more evidence of early igneous activity associated with its opening in the many salt diapirs around the flanks of the Gulf of Mexico.

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