

The Minas Viejas Formation (Oxfordian) in the Area of Galeana, Northeastern Mexico: Significance of Syndepositional Volcanism and Related Barite Genesis in the Sierra Madre Oriental

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ABSTRACT

The Minas Viejas Formation consists of carbonates and sulfates that are the first evidence of marine incursion into northeastern Mexico during the Late Jurassic (Oxfordian). In the area southwest of Galeana, Nuevo Leon, this evaporite sequence is intensively deformed, but a consistent stratigraphic succession and separation of two members is recognizable. In addition to the Las Minas Member that was defined by Götte (1988), we introduce the La Primavera Member. Our data suggest that only one largely evaporitic succession exists in the region and that the terms Minas Viejas and Olvido are synonyms for the same stratigraphic unit. Lateral and vertical changes of facies in the Minas Viejas Formation are the result of syndepositional normal faulting and relate to the onset of sea-floor spreading in the Gulf of Mexico. Alkaline volcanic rocks occur in the La Primavera Member of the Minas Viejas Formation. This Oxfordian volcanism is hitherto undescribed in the area and links the tectonostratigraphic evolution of northeastern Mexico to early sea-floor spreading in the Gulf of Mexico. In addition, barite deposits in the Galeana area likely are related to this Late Jurassic volcanism. Barite mineralization is restricted mainly to stratigraphic levels older than the alkaline volcanism in the Minas Viejas Formation and is not the result of magmatism of Tertiary age. Apparently, carbonatite magmatism that provided the source for barium by hydrothermal activity was associated with Late Jurassic volcanism.

INTRODUCTION

The Upper Jurassic evaporates and carbonates of the Minas Viejas Formation are of special interest because they mark the onset of marine incursion into northeastern Mexico and the northern part of the modern Sierra Madre Oriental (Figure 1). It is generally believed that this area was affected during late the Callovian to Oxfordian by continental extension related to sea-floor spreading in the Gulf of Mexico (e.g., Michalzik, 1988; Götte, 1990; Salvador, 1991a; Goldhammer, 1999). Remarkably, no volcanism has been known to exist in northeastern Mexico that would have accompanied this rifting. Our paper documents the existence of volcanic rocks that are syndepositional with the Minas Viejas Formation. Their alkaline geochemistry and the apparent

association with carbonatites agree well with a rift-related origin. Volcanic products such as redeposited feldspar crystals and ash layers are characteristic components of the Las Minas Member of the Minas Viejas Formation and are used here to recognize and correlate this member in the strongly deformed formation. Our data allow separation of two members in the Minas Viejas Formation. We agree with Götte (1990) and Götte and Michalzik (1992) that only one evaporitic unit, the Minas Viejas Formation, is present in northeastern Mexico. This unit conformably overlies shallow-water carbonates of the Oxfordian Novillo Formation (in the Ciudad Victoria region) or terrestrial siliciclastic sediments of the La Joya Formation (in the Galeana region), or it overlies metamorphic basement (on the road to Aramberri). It underlies a carbonate succession, the Zuloaga

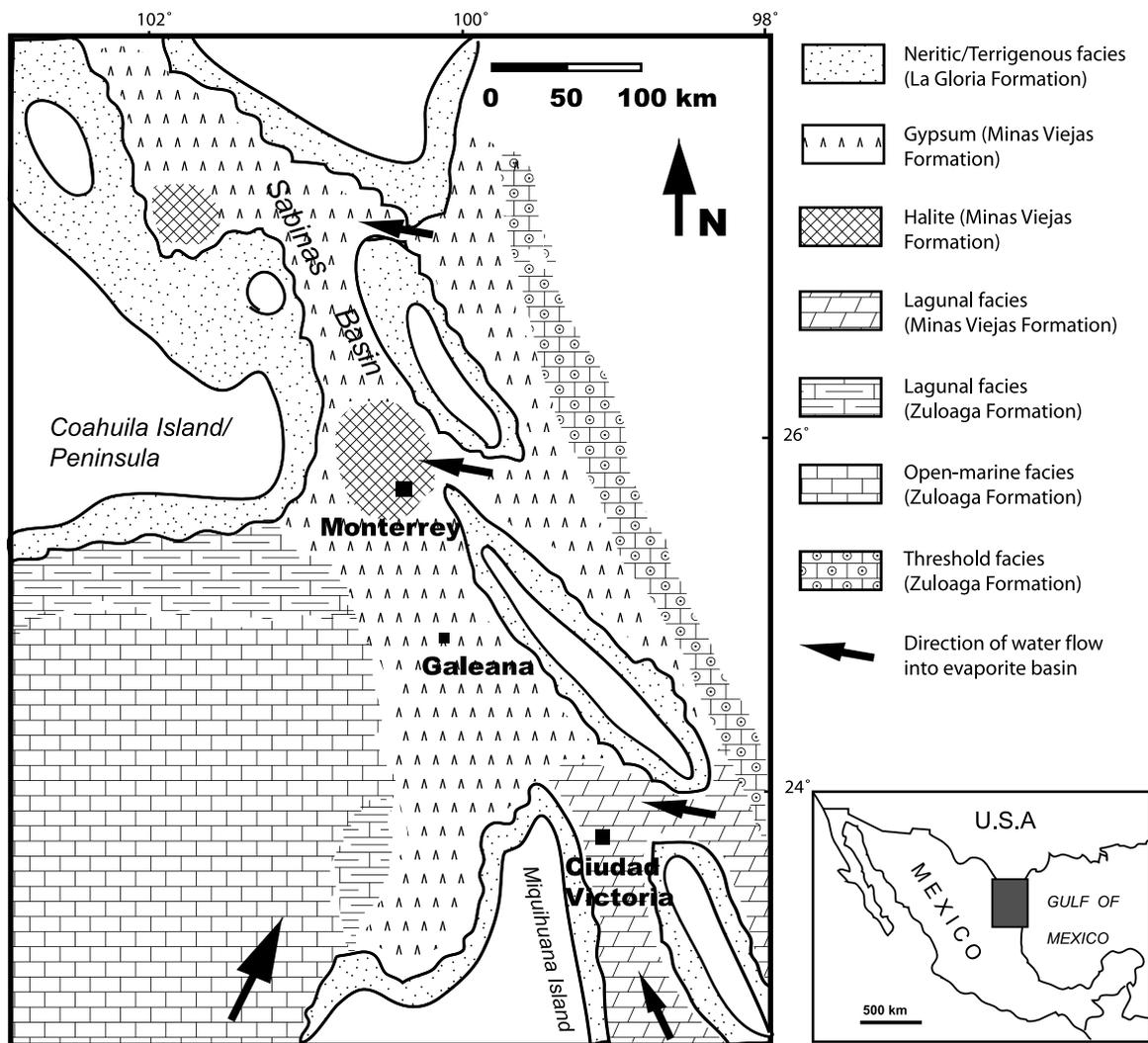


Figure 1. Paleogeographic configuration of northeastern Mexico in the late Oxfordian/early Kimmeridgian without palinspastic reconstruction (modified after Götte, 1990).

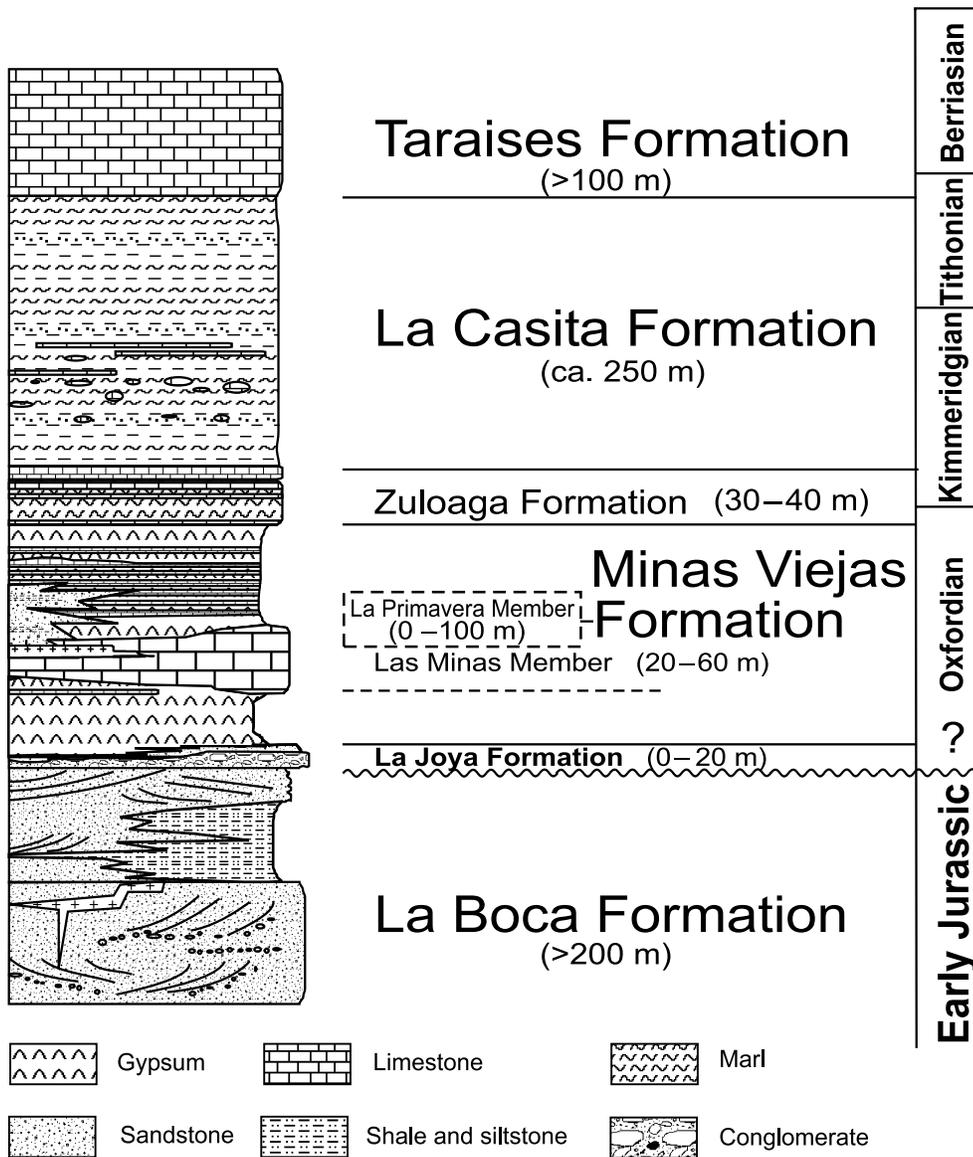


Figure 2. Stratigraphy of the San Marcos–La Primavera area.

Formation (Mixon et al., 1959; Huizachal Formation of Imlay et al., 1948; Carillo Bravo, 1961; Belcher, 1979; Michalzik, 1988, 1991; Salvador, 1991b; see Rueda-Gaxiola et al., 1993a; Rueda-Gaxiola, 1999; and Barboza-Gudino et al., 1999, for definition). Near Galeana this red bed unit is more than 200-m thick, but the base is not exposed (Figure 2). The La Boca Formation *sensu* Barboza-Gudino et al. (1999) is of probable Early to Middle Jurassic age (Rueda-Gaxiola et al., 1993b). Strata of the La Boca Formation are extensively faulted in the San Marcos area by southwest-northeast- and northwest-southeast-oriented normal faults (Figure 3). These faults extend into the overlying La Joya Formation and contain hydrothermal barite mineralization. Our stratigraphic work shows that

Formation. We describe the facies of the Minas Viejas Formation and their distribution in order to demonstrate the link between sedimentation and tectonism. There are indications (e.g., local uplift and associated red beds) that volcanism was of significant volume and of considerable impact on the environment. Late Jurassic magmatism also appears to be the likely source of barite, which forms deposits of economic interest in the area. These barite deposits previously have been considered to be of Tertiary age (Kesler et al., 1988).

REGIONAL STRATIGRAPHY

La Boca Formation

The oldest rocks exposed in the Galeana area are terrestrial shale, siltstone, and sandstone of the La Boca

this faulting was still active during deposition of the Minas Viejas Formation. Slickenside lineations suggest that left-lateral strike-slip and oblique-slip motions occurred subsequent to normal fault movements. The age of transcurrent offset is not known. Normal faulting that postdates laramide folding is mainly in the northwest-southeast direction in the map area (Figure 3) and may have reactivated Late Jurassic faults.

La Joya Formation

The La Joya Formation overlies the La Boca Formation in the San Marcos area with an angular unconformity of approximately 5° (Figure 2). A coarse polymictic conglomerate at the base of the La Joya Formation is several meters thick and grades up-section into sandstones and shales. The conglomerate

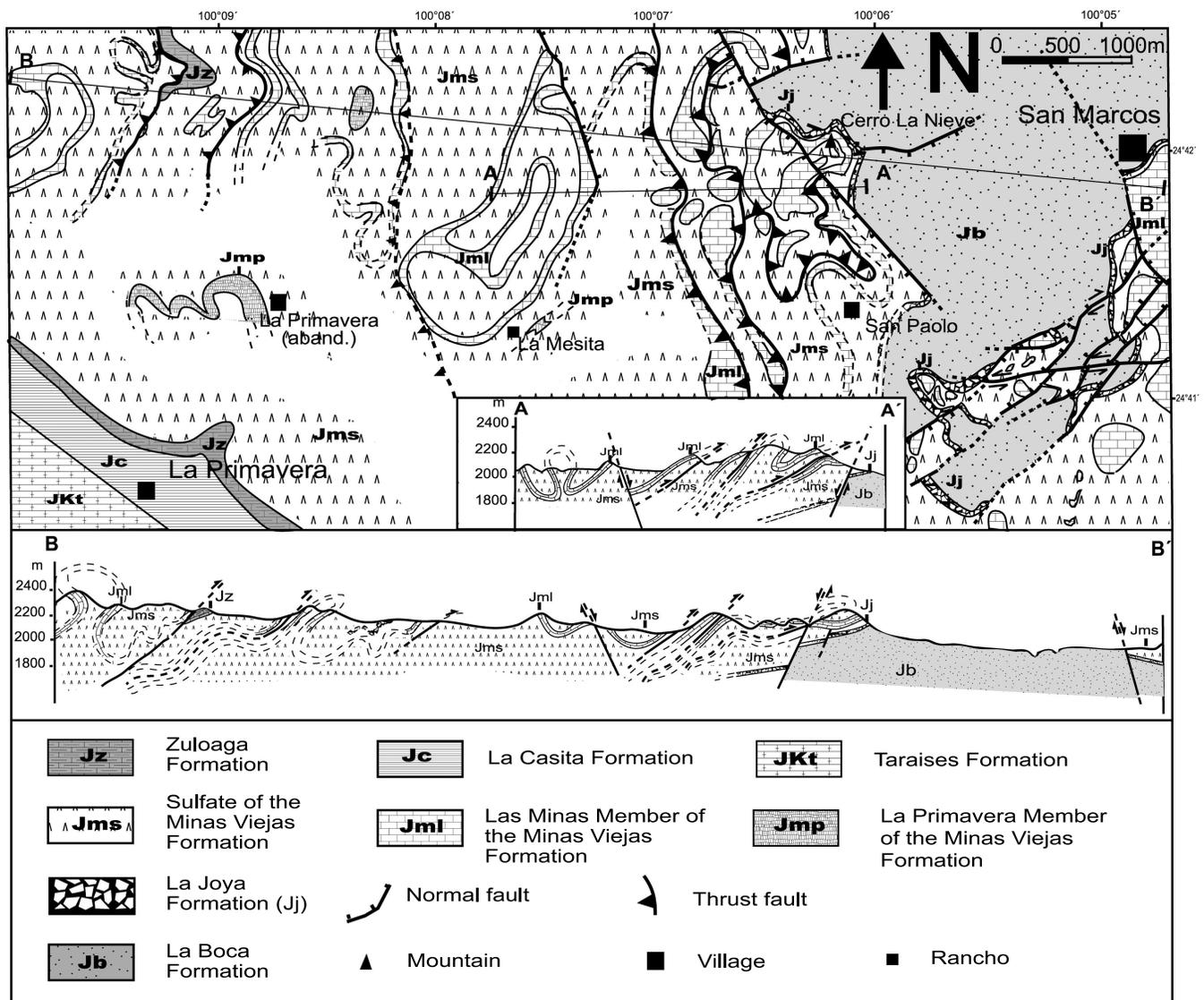


Figure 3. Geological map and cross sections of the San Marcos–La Primavera area southwest of Galeana.

is locally absent and the base of the La Joya Formation must be identified by the unconformity. At the top of the La Joya Formation, a succession of alternating red and green sandstone and gypsum several meters thick characterizes the transition to the Minas Viejas Formation. The thickness of the La Joya Formation varies from about 5 m to approximately 20 m. No fossils have been found, but the age can be deduced from the overlying units as pre-late Oxfordian.

Minas Viejas Formation

The term Minas Viejas Formation was formally introduced by Humphrey (1956) for a succession of gypsum, limestone, dolomite, and intercalated siltstone that is exposed below the massive Zuloaga limestone at Potrero Grande, located in the Sierra de

Minas Viejas near Monterrey (Figure 4). A similar succession of evaporitic, carbonate, and siliciclastic sediments west of Ciudad Victoria was called the Olvido Formation by Heim (1940). In that area, limestone of the Novillo Formation underlies the evaporitic unit. Imlay (1943) correlated the Novillo Formation with the Zuloaga Formation, which also consists of shallow-water limestone. Götte (1990) discussed the validity of the three units. He concluded that, although the Novillo and Zuloaga Formations resemble each other lithologically and in fossil content, they occupy different stratigraphic positions; the Zuloaga Formation always overlies the Minas Viejas Formation, whereas the Novillo Formation underlies it. In consequence, Minas Viejas and Olvido are different names for the same unit (see also Götte and

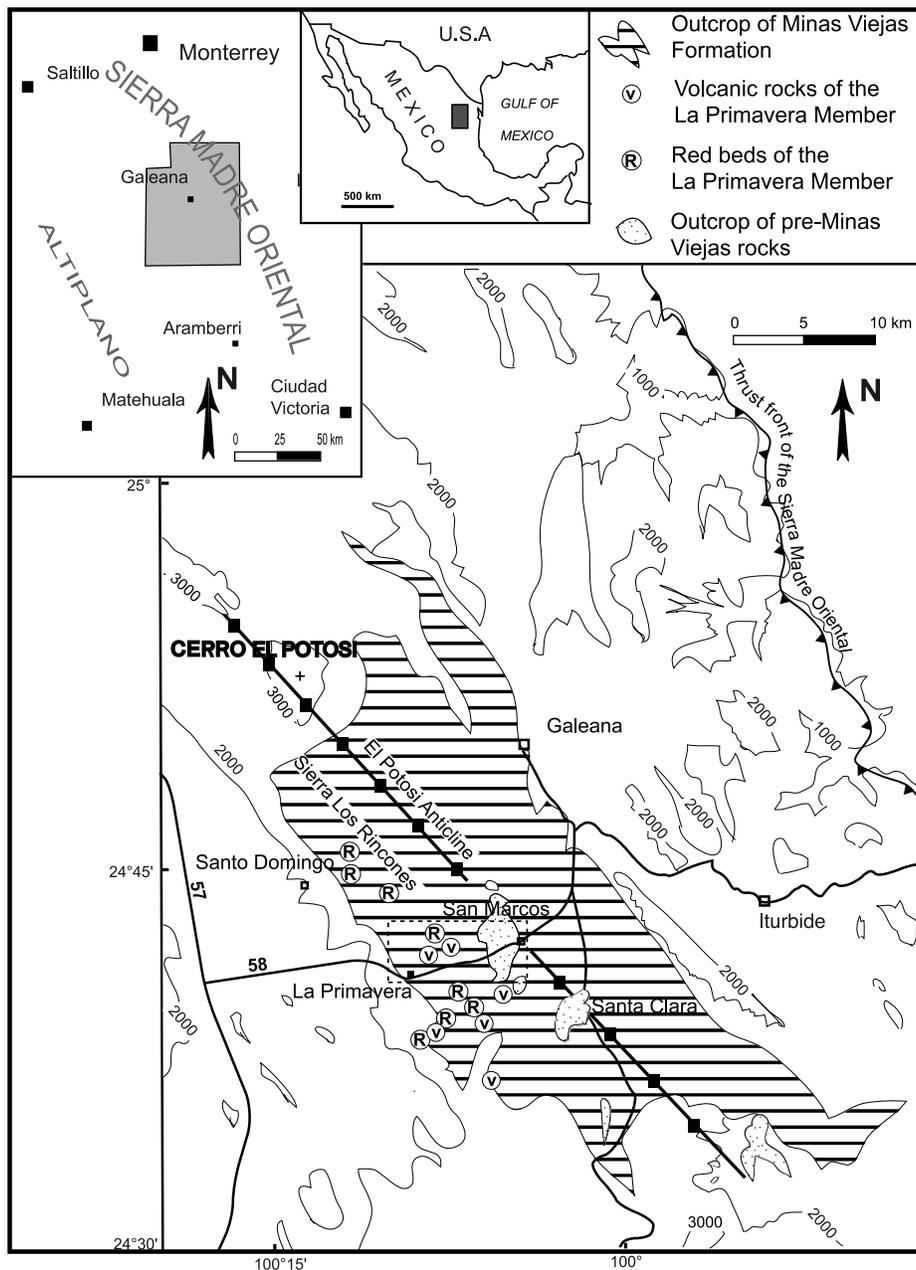


Figure 4. Map of the Galeana area (modified after Götte, 1990).

Minas Viejas Formation. No datable fossils are known to occur in the Zuloaga, Novillo, or Minas Viejas Formations, but Oxfordian to early Kimmeridgian ages are deduced, as fossil assemblages at the base of the La Casita Formation are of late early Kimmeridgian age (e.g., Götte, 1990; Villaseñor et al., 2000).

Uppermost Jurassic Units

In the late Oxfordian to early Kimmeridgian, relative rise of sea level established more open-marine conditions and terminated deposition of evaporites in the region of the Sierra Madre Oriental. This termination is marked by carbonates of the Zuloaga Formation, which are widespread in northeastern Mexico and everywhere overlie the Minas Viejas Formation (Götte and Michalzik, 1992). In the La Primavera area, the Zuloaga Formation is between 30- and 40-m thick and consists of thin-bedded limestone, marl and shale, and isolated limestone or dolomite layers as much as 2-m thick (Figures 2 and 3). In addition, a 2–3-m-

thick layer of gypsum is present at about 20 m above the base of the unit. This gypsum layer may correspond to the 144 Ma supersequence boundary recognized by Goldhammer et al. (1991) and Goldhammer (1999) in the Altiplano of northeastern Mexico. In the Primavera area, the Zuloaga Formation contains abundant terrigenous detritus, indicating local uplift. The La Casita Formation is in gradational contact with the underlying Zuloaga Formation and indicates deepening from shallow-marine environments toward outer-shelf conditions. The La Casita Formation reaches a thickness of approximately 250 m in the area and consists of gray and brown shale, marl,

Michalzik, 1992). Götte (1990) suggested that the name Olvido be abandoned and that the name Minas Viejas Formation should be used for the Jurassic evaporates and intercalated carbonates that conformably overlie the La Joya or Novillo Formations and underlie the Zuloaga Formation. He further distinguished several lithological members in the Minas Viejas Formation, of which we retain two (Figure 2): the Las Minas Member, a limestone unit that is intercalated in sulfate of the Minas Viejas Formation, and the La Primavera Member, which consists of terrigenous sediments and volcanic rocks that are interlayered locally with the Las Minas Member and sulfate of the

uncommon thin limestone layers, and black limestone concretions. The transition to the Taraises Formation is principally by gradual increase in carbonate. Microfossils (calpionellids, radiolarians) in these sediments indicate further deepening and an early Berriasian age (Adatte et al., 1994).

STRUCTURAL GEOLOGY, LITHOSTRATIGRAPHY, AND MICROFACIES OF THE MINAS VIEJAS FORMATION

Structural Geology

The San Marcos–La Primavera area forms part of the northwest-southeast-striking El Potosí anticline (Figure 4). The Minas Viejas Formation has been stacked into several thrust sheets, which are overprinted by disharmonic second-order folding (Figure 3). Folds usually are asymmetric and axes commonly change direction, even within individual folds. Main strike directions are north-northwest–south-southeast, south-southwest–north-northeast, and west-southwest–east-northeast, with the latter trend being the youngest. Main transport of Minas Viejas thrust sheets occurred early during Laramide orogenesis and was directed eastward. At a later stage, evaporites intruded into faults and fractures, but we recognized no large-scale independent movements of single carbonate blocks or major rotations of blocks. In consequence, reconstruction of the original stratigraphic succession and distribution of facies of the Minas Viejas Formation is still possible. Units below and above the Minas Viejas Formation are much less deformed. Normal faulting that postdates Laramide folding is oriented mainly northwest-southeast.

Sulfates

Gypsum forms the base of the Minas Viejas Formation and essentially consists of structureless to laminated gypsum, although chicken-wire nodules of gypsum also occur. No significant amounts of detrital or organic matter are present below the Las Minas Member. We suggest that the evaporites were formed in a shallow oxygenated basin, in accordance with the “shallow-water–shallow-basin model” of Kendall (1984, 1992; see also Michalzik, 1988, and Götte, 1990). According to this model, nodular gypsum is the result of diagenetic alteration of anhydrite rather than a relict of nodular anhydrite formed on a sabkha (see Warren and Kendall, 1985). Transformation from gypsum to anhydrite occurred during the Early Cretaceous under conditions of increased temperature and

pressure resulting from burial below at least 1000 m of younger sediments (Götte, 1990). This transformation of gypsum and deformation during Laramide orogenesis likely overprinted original sedimentary structures. Near the surface, anhydrite is dissolved, and gypsum is formed anew. Interbedded red and green sandstone occurs in the transition zone between the La Joya and Minas Viejas Formations.

At Cerro La Nieve, sandstone of the La Joya Formation directly underlies limestone of the Las Minas Member of the Minas Viejas Formation, and no gypsum is intercalated (Figure 3). This limestone is rich in siliciclastic detritus, which is absent elsewhere. Southeast of San Paolo and south of San Marcos, gypsum is reduced in thickness to 5 to 10 m, and it is interbedded with red and green sandstone. West of Cerro La Nieve and east of San Marcos, gypsum is present again below the Las Minas Member and rapidly increases in thickness to more than 50 m, thus indicating significant paleorelief in the area of San Marcos. Underlying the Minas Viejas Formation, the basal conglomerate of the La Joya Formation does not vary much in thickness, which suggests that the paleorelief formed after deposition of the conglomerate, apparently by the initiation of syndepositional normal faulting.

Sulfates also are present in the area above the Las Minas Member. Thickness of the gypsum reaches at least 80 m, with a total of seven intercalated limestone units, each between 2- and 5-m thick. Horizontally bedded to laminated shale, marl, and siliciclastic layers also are intercalated with the gypsum. The limestone is recrystallized or dolomitized. Ripple marks were observed on the upper surfaces of limestone beds, whereas stromatolites, desiccation cracks, or other evidence for sabkha conditions has not been recognized. We suggest, rather, that deposition of the gypsum of the Minas Viejas Formation in the area of La Primavera–San Marcos took place under shallow subtidal conditions. In a sabkha environment, precipitation of gypsum likely would have destroyed horizontal lamination in the shales (Kendall, 1992).

Las Minas Member

The Las Minas Member consists of limestone and was named by Götte (1988) after Cerro Las Minas, which is 2 km southwest of Galeana. The Las Minas Member also forms the tops of the mountain ridges of the Sierra Los Rincones (Figure 4). South of San Marcos and at Cerro La Nieve, the member reaches a

thickness of more than 60 m, but to the west, it decreases to 20 to 30 m (Figures 3 and 5). In general, thickness of individual limestone layers also decreases to the west.

Near Cerro La Nieve, the limestone microfacies are dominated by peloidal packstone and grainstone with strongly deformed peloids, mostly between 0.1 and 0.3 mm in diameter but reaching as much as 1 mm (Figure 6a). They are probably fecal pellets of crustaceans. Burrows (*Thalassinoides*) are abundant, whereas body fossils are rare and confined mostly to the bivalve *Nannogyra* and nerineid gastropods. Limestone of the Las Minas Member south of San Marcos contains abundant *Favreina* pellets (0.5–2 mm) and grapestones that are absent elsewhere (Figure 6b). To the west of Cerro La Nieve, these strata grade into wackestone and mudstone with only minor content of peloids, larger intraclasts, and bryozoans. At several locations, large numbers of *Nannogyra* shells are present. These shells appear to be autochthonous, which suggests water depths of less than 20 m.

Approximately 3 km northeast of La Primavera, between the rancho La Mesita and the abandoned village of La Primavera, black mudstone occurs in the upper third of the Las Minas Member. This mudstone presents small oscillation ripples, desiccation cracks, birds eyes, and algal lamination and suggests intra- to supratidal environments. Dolomite and limestone beds at this location contain burrows that resemble *Psilonichnus*.

Red colors in some of the limestones in the area between La Primavera and San Marcos and deep bioturbation indicate well-oxygenated bottom conditions and slow cementation. The latter is also indicated by strong deformation of peloids, with the exception of peloids protected below bivalve shells. The low fossil content but dominance of *Nannogyra* and *Nerinea* s.l. probably reflects high salinity.

Detrital crystals of albite are striking components in the upper third of the Las Minas Member, forming nearly 50% of some beds. Crystals are less than 0.1-mm long, with short tabular habit and Carlsbad and albite twins. The feldspar crystals are enriched in bedding surfaces and have slightly rounded edges, thus indicating transport and redeposition (Figure 6c). West of San Marcos, redeposited feldspars are widespread in the upper third of the Las Minas Member; south of San Marcos, redeposited feldspars have not been observed.

Authigenic albite occurs in all sections of the Las Minas Member and is distinguished by larger size (as

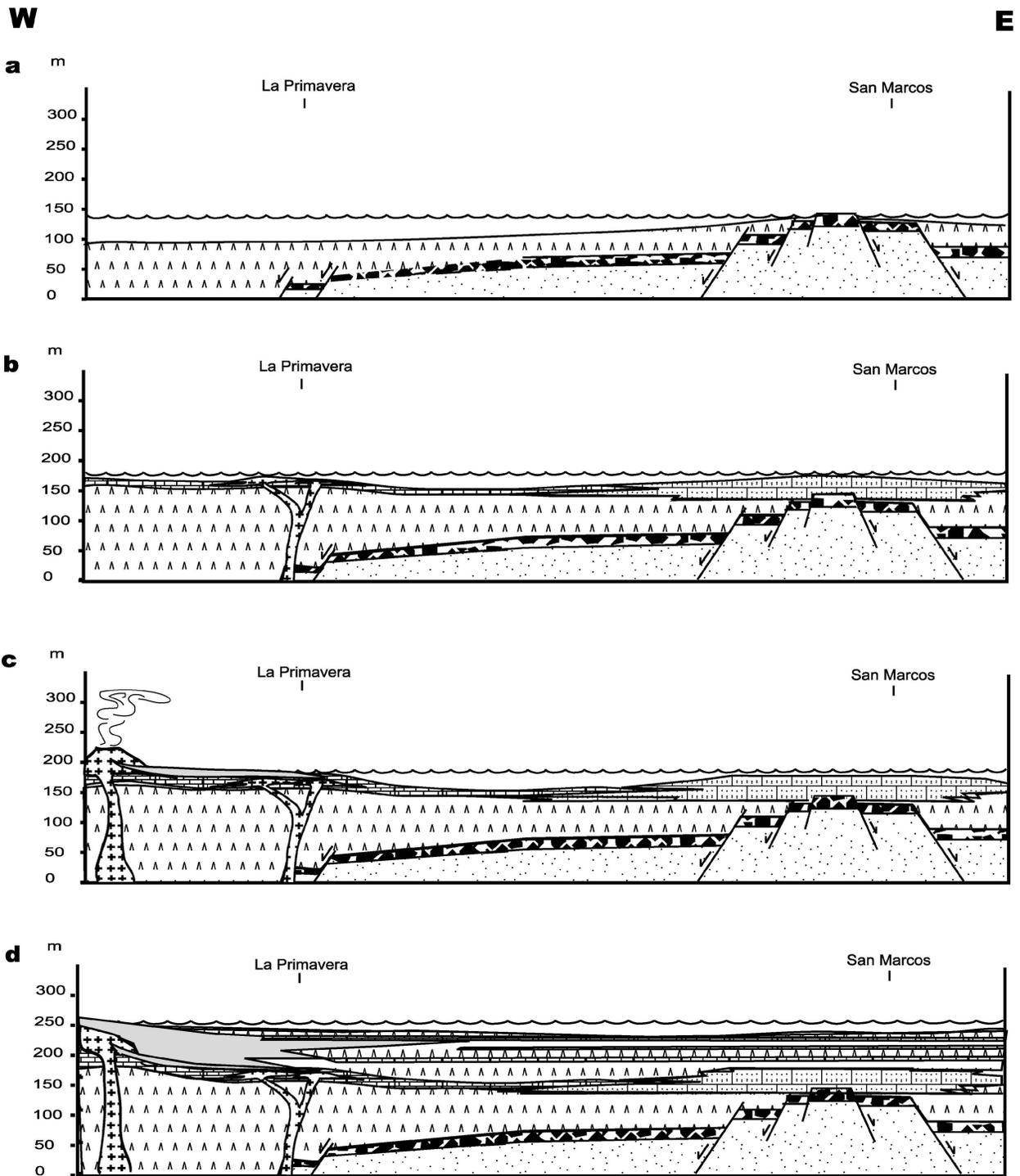
much as 3 mm) and growth as “Roc Tournée” twins (Figure 6d). Specimens do not appear to be re-worked, and some are observed to intersect peloids, thus demonstrating an authigenic origin. Authigenic feldspars locally reach abundances of about 5%. Similarly high concentrations are known to characterize limestone associated with evaporites (Füchtbauer, 1988).

La Primavera Member

The La Primavera Member of the Minas Viejas Formation is found at several isolated outcrops in the area of La Primavera and Santo Domingo (Figure 4). A succession of volcanic rocks and intercalated red siltstone and sandstone crops out at rancho La Mesita (Figure 7). The unit is approximately 20-m thick. Outcrop conditions are not good, and the lateral extension of the complex is not precisely known, although the volcanites are intercalated in limestone of the Minas Viejas Formation. The base of the unit is formed by porphyritic volcanic rocks. They are composed of large hypidiomorphic phenocrysts that are as much as 3 mm in diameter and are replaced by dolomite in a micro- to cryptocrystalline matrix composed of albite (Figure 6e). The volcanites also contain rare vesicles that are filled with albite. Above that lie 5 m of intercalated volcanic and sedimentary rocks. The sedimentary rocks are gray to red siltstone and sandstone that consists of quartz and feldspar with idiomorphic hematite crystals as much as 2 mm in diameter (Figure 6f). The volcanic rocks are gray and aphanitic, some with phenocrysts of quartz or weathered feldspar. The uppermost 1 m consists of coarse (as much as 3 mm) crystalline calcite that appears to be pseudomorphous after dolomite (Figure 6g). Inclusions of albite and idiomorphic crystals of hematite reach as much as 1 cm in diameter.

These rocks underlie fine-grained laminated limestone of the Las Minas Member that contains mollusk fragments and two thin, red shale layers. This upper contact of the volcanogenetic sequence is characterized by vertical fissures in the laminated limestone filled with crystalline calcite. Apparently, this calcite intruded the limestone from below prior to lithification. This is indicated by the upward bending of depositional lime mud laminae along the fissure zones (Figure 7).

Green and red shale and siltstone are present at and west of the abandoned village of La Primavera (Figure 3). In these outcrops, the sediment sequence is strongly folded but laterally traceable. It conformably overlies 5 m of volcanic rocks at the top of the



Minas Viejas Formation

- | | | | | | |
|--|----------------------------------|--|--|--|---|
| | La Primavera Member (magmatites) | | La Primavera Member (red beds) | | Sulfates and intercalated limestone |
| | Sulfates | | Las Minas Member (packstone to grainstone) | | Las Minas Member (mudstone to wackestone) |

Pre-Minas Viejas Units

- | | | | |
|--|-------------------|--|-------------------|
| | La Boca Formation | | La Joya Formation |
|--|-------------------|--|-------------------|

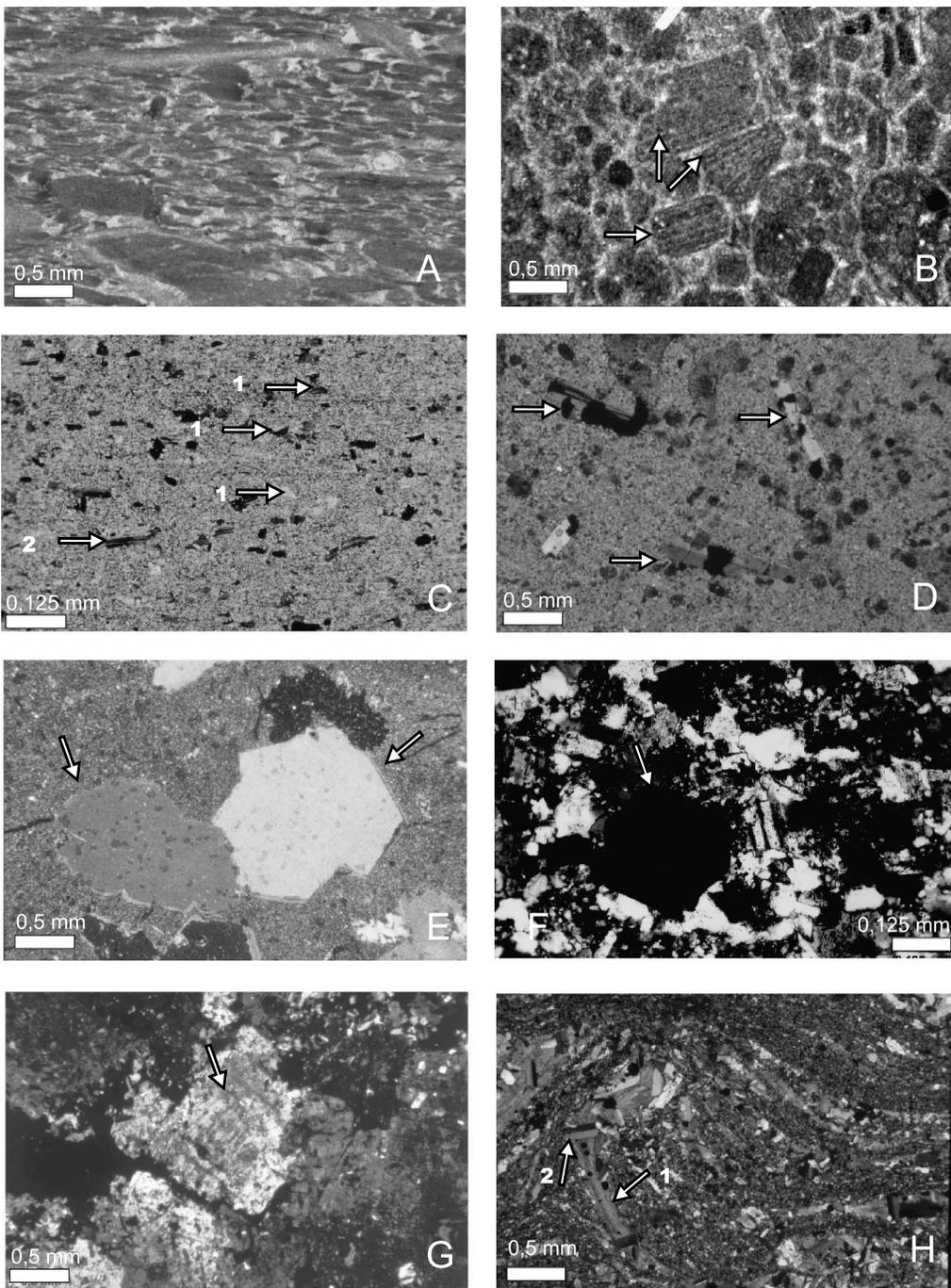


Figure 6. A: Peloidal grainstone of the Las Minas Member of the Minas Viejas Formation. Note that peloids are tightly elongated. B: Peloidal grainstone of the Las Minas Member east of San Marcos with *Favreina* pellets (arrows). C: Redeposited feldspars (1) in the Las Minas Member (upper part) and authigenetic feldspars (2). D: Authigenetic feldspars in the Las Minas Member forming Roc Tournée twins (arrows). E: Porphyritic texture in fenitized volcanogenic rocks at La Mesita (La Primavera Member), with dolomite pseudomorphs of phenocrysts (arrows) in albite matrix. F: Hematite crystal (arrow) in volcanic-lithic sandstone (La Primavera Member) at La Mesita. G: Calcite pseudomorphs of dolomite (arrow) in intrusive crystalline calcite at top of the La Primavera Member at La Mesita. H: Limestone of the Las Minas Member below the base of the La Primavera Member. Note soft sediment deformation of carbonate mud (1) and abundant albite crystals (2).

Las Minas Member and conformably underlies gypsum of the Minas Viejas Formation. The volcanic rocks are red, porphyritic, strongly weathered, and contain large carbonate crystals. Thickness of the

red beds reaches nearly 100 m. Green and red shale also is present 2 km northeast of the abandoned village of La Primavera. The contact to gypsum at the base and top of the unit is not well exposed.

Figure 5. Depositional facies of the Minas Viejas Formation and syndepositional volcanism, schematic model without palinspastic reconstruction. Minas Viejas Formation (a) at the beginning of marine ingresson (note syndepositional normal faulting); (b) during deposition of the lower part of the Las Minas Member (note onset of volcanic activity); (c) deposition of the upper part of the Las Minas Member (note maximum volcanism and onset of red bed sedimentation of the La Primavera Member); and (d) deposition of gypsum of the upper part of the Minas Viejas Formation, coeval erosion of volcanic structures, and deposition of the La Primavera Member.

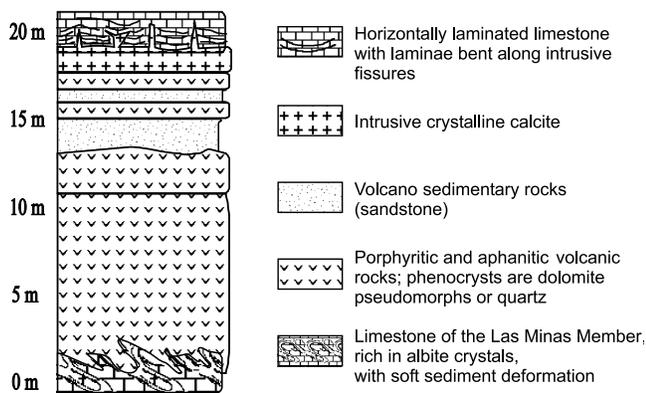


Figure 7. Sequence of the La Primavera Member at La Mesita; upper and lower contacts with limestone of the Las Minas Member. See Figure 3 for location.

At La Mesita and west of La Primavera (abandoned village) the volcanic rocks overlie limestone that shows evidence for soft-sediment deformation and high amounts of idiomorphic feldspar of varying sizes, in addition to hematite. These rocks are between 1-m (La Mesita) and 4-m thick (west of La Primavera, abandoned village). Their texture suggests reworking and mixing of sedimentary lime mud with volcanogenic minerals during volcanic activity (Figure 6h).

At Santo Domingo (Figure 4), shales and sandstones of the La Primavera Member reach a thickness of 95 m. The sandstone is of fluvial or eolian origin. Main components of the sandstone are quartz, albite, mica, and lithic fragments. The sandstone is rich in tourmaline and zircon (Götte, 1990).

Volcanic activity clearly occurred during deposition of the Minas Viejas Formation. At La Mesita, volcanic rocks are part of the Las Minas Member, which in this area is reduced to a few meters. The porphyritic texture indicates an effluent volcanic origin. Soft-sediment deformation at the base of the volcanic rocks and intrusion of calcite in the overlying sediments prior to lithification suggest that magmatism was contemporary to the deposition of the Minas Viejas Formation. We suggest that volcanic activity was more widespread in the La Primavera area and that redeposited feldspars and red clay-rich layers in the Las Minas Member also are related to this volcanism.

DISCUSSION

During the Late Triassic to Early Jurassic, the breakup of Pangea and drifting of the North American Plate away from the African and South Amer-

ican Plates led to stretching of crust, normal faulting, and the development of graben structures in northeastern Mexico (Buffler and Sawyer, 1985; Winker and Buffler, 1988). Volcanism also accompanied the rifting process at many locations in northeastern Mexico, where it predated, accompanied, and postdated the La Boca Formation (Meiburg et al., 1987; Winker and Buffler, 1988; Michalzik, 1988; Götte, 1990; Byerly, 1991; Salvador, 1991b; Sedlock et al., 1993; Eguiluz, 2001).

During the late Callovian to Oxfordian, a second phase of rifting, related to initial spreading and formation of oceanic crust in the Gulf of Mexico, affected northeastern Mexico (e.g., Schmidt-Effing, 1980; Buffler and Sawyer, 1985; Winker and Buffler, 1988; Michalzik, 1988). The angular unconformity at the base of the La Joya Formation generally is thought to be a consequence of uplift related to this process (e.g., Michalzik, 1988; Salvador, 1991b; Sedlock et al., 1993). Sediments of the La Joya Formation and the Minas Viejas Formation overlying the angular unconformity indicate a gradual transition from terrestrial to marine deposition during the Oxfordian. Subsidence in northeastern Mexico likely correlates to stretched crust and origin of extensive graben systems. Subsidence related to cooling of the dense oceanic crust in the Gulf of Mexico should have occurred at a later stage and may explain the change from shallow-marine to basinal facies during deposition of the La Casita and Taraises Formations.

It is remarkable, however, that no Late Jurassic (Oxfordian) rift-related volcanism has been described so far in northeastern Mexico that would correspond to the rifting in the Gulf of Mexico. This volcanism should occur in the relatively thin and stretched continental crust adjacent to the spreading center. Here we present such evidence. Volcanic or subvolcanic rocks are present at various locations within 10 km of La Primavera and La Mesita. Mineral paragenesis (e.g., south of San Marcos) comprises quartz, feldspar, mica, and hematite. Volcanism appears to have been contemporary with deposition of the Las Minas Member: This is indicated by the stratigraphic succession (e.g., sections in the La Primavera area) and by redeposited feldspars in the Las Minas Member. The work of Garrison and McMillan (1999) is supportive of this interpretation. They reported allochthonous blocks of metavolcanic and metaigneous origin in the El Papalote salt diapir of the La Popa Basin, northwest of Monterrey. These blocks are as much as 200 m in diameter and are commonly surrounded by reaction aureoles. High field-strength element

(HFSE) and rare-earth element (REE) compositions exhibit patterns typical of continental rift magmatism. The absence of foliation and high Nb and Ta content suggest that the rocks are not part of the pre-Mesozoic basement and, thus, are unrelated to the Permian-Triassic subduction zone in the west of Mexico. A younger age also is indicated by $^{40}\text{Ar}/^{39}\text{Ar}$ determinations, which yielded an age of 146 Ma (Tithonian). Although this age is interpreted to be the age of metamorphism rather than magmatism, Garrison and McMillan (1999) suggested that the closing temperature of biotite (350°C) might not have been reached during metamorphism. In this case, an Oxfordian age of magmatism is permissible, similar to the volcanogenic rocks described here. Eguiluz (2001) has found dolerite dikes that intrude red beds and evaporites in the Galeana area and, thus, also may be related to Oxfordian volcanism.

Apparently, volcanism in the Galeana area was accompanied by local uplift and the formation of barriers or even islands that rose above sea level (Figure 5). For instance, limestone of the Las Minas Member northeast of La Primavera contains algal lamination and bird's-eye structures indicative of supratidal depositional environments. Sandstones of the La Primavera Member are eolian or fluvial (Götte, 1990). We suggest that volcanogenic rocks successively were uplifted, exposed, and eroded subsequent to volcanic activity. The origin of the red beds of the La Primavera Member appears to be linked directly to volcanism and to be a consequence of erosion and redeposition of volcanic material in areas adjacent to the volcanic centers. Sandstone of the La Primavera Member is rich in tourmaline and zircon (Götte, 1990), which also indicates a magmatic origin. Its deposition is equivalent in time to the deposition of the uppermost Las Minas Member and the overlying gypsum. Fine-grained siliciclastic debris of probable volcanic origin is present even in the Zuloaga Formation, which suggests that redeposition persisted into the late Oxfordian. We, therefore, propose that volcanism in the La Primavera area is of Oxfordian age and synchronous with the deposition of the Minas Viejas Formation.

Volcanism and normal faulting are considered to be a consequence of sea-floor spreading in the Gulf of Mexico. The development of this spreading center caused uplift and stretched crust in northeastern Mexico, resulting in extensional tectonics in the Sierra Madre Oriental (Salvador, 1991b; Sedlock et al., 1993). This tectonic activity apparently did not influence the thickness of the La Joya conglomerate,

but it is recorded by thickness changes in the Minas Viejas Formation. West of San Marcos, the absence of gypsum below the Las Minas Member and reduction in thickness of the Las Minas Member indicate the presence of a shallow or emergent area forming a barrier during deposition of the Minas Viejas Formation. This structurally high area also is indicated by the absence of *Favreina* pellets west of San Marcos and redeposited feldspar south of San Marcos. The barrier thus separated two basinal areas: an area around La Primavera that was influenced by volcanic activity, and a basinal area to the southeast of San Marcos. Northwest-southeast- and southwest-northeast-oriented faults indicate an egg-box shape of the relief that formed the barrier. Its apparent prevalent northwest-southeast orientation (Figure 3) is interpreted to be a result of reactivation of northwest-southeast-oriented faults after Laramide folding. The barrier was an area of high carbonate production, as compared to a more restricted basinal area around La Primavera, where evaporites were deposited at the same time. The return to more restricted conditions and deposition of evaporites above the Las Minas Member likely was related to a relative fall in sea level.

Chemistry of the volcanic rocks is very unusual. The mineral paragenesis at La Primavera (abandoned) and La Mesita is restricted to albite, dolomite, or calcite, quartz, and hematite. Pseudomorphic replacement of the original phenocrysts by dolomite documents alteration of the original mineralogy of the volcanic rocks. The presence of albite in all magmatic rocks at La Mesita may be a result of sodium metasomatism (sodium fenitization). It is possible that the original texture of the rock is preserved during the process of fenitization (e.g., Verwoerd, 1966). Redeposited albite in the upper part of the Las Minas Member likely was also formed by sodium-rich fluids. In this case, fenitization, which is often associated with carbonatites (Pirajno, 1992), must have occurred shortly after volcanism. Carbonatite magmatism is indicated by intrusive calcite at the top of the La Primavera Member at La Mesita. Carbonatite volcanism commonly is related to continental rifting in response to lithosphere doming and major fault zones (Woolley, 1989). This supports a connection between the late Oxfordian volcanism in the La Primavera–Galeana area and sea-floor spreading in the Gulf of Mexico.

During later stages of carbonatite magmatism, hematite and barite are abundant (Kapustin, 1986). Barite mineralization in the Galeana area, therefore,

may be a result of Oxfordian carbonate magmatism. Kesler et al. (1988) estimated a quantity of approximately 5 million tons for the Galeana Barite District and suggested that mineralization occurred during the early Oligocene when magmatic activity in the Altiplano mobilized barium from the La Boca Formation, and barium-rich fluids reacted with gypsum of the Minas Viejas Formation (Kesler et al., 1988). This chemical reaction explains why barite is present along faults of the La Boca and La Joya Formations, which underlie the Minas Viejas evaporites, and is rarely found in rocks younger than the Las Minas Member. Rare deposits of barite in rocks younger than the Minas Viejas Formation may be due to later remobilization. We suggest that barite mineralization is unrelated to Tertiary magmatism for the following reasons: (1) no intrusions, dikes, or hydrothermal activity of indisputable Tertiary age are known to exist in the Galeana area or elsewhere in the northeastern Sierra Madre Oriental, and Tertiary intrusions are restricted to the Altiplano farther to the west; and (2) the La Boca Formation has been considered to be the source of barium, although today this unit is not enriched. Alternatively, we suggest that barite mineralization is a product of upper Oxfordian carbonatite magmatism. Extensional tectonism and normal faulting at that time favored the formation of barite veins. If our interpretation is correct, the huge amount of barite in the area suggests that magmatism was of much higher volume than presently indicated by the few outcrops near La Primavera.

CONCLUSIONS

Evaporites and shallow marine limestones of the Minas Viejas Formation are of Oxfordian age and mark the onset of the late Mesozoic marine transgression into northeastern Mexico. Patterns of sedimentation were influenced by uplift, extension of continental crust, and syndepositional normal faulting in the area of the present Sierra Madre Oriental. The crustal extension that gave rise to normal faulting was a consequence of sea-floor spreading in the Gulf of Mexico: Uplift and extensional tectonics in the study area caused deposition of the La Joya Formation. Continuing extension resulted in the formation of basins where the marine Minas Viejas Formation was deposited. Extensional tectonics gave rise to continental rift volcanism and mobilization of fluids in the La Primavera area southwest of Gal-

eana. These volcanic rocks are intercalated between siliciclastic sediments in the La Primavera Member of the Minas Viejas Formation. Barite mineralization in the Galeana area may have resulted from associated Late Jurassic carbonatite magmatism, which provided the source of barium by hydrothermal activity.

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