SPECIAL ISSUE DEDICATED TO THE INTERNATIONAL WORKSHOP ON THE GEOLOGY OF NORTHWESTERN SONORA

FOREWORD

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Northwestern Sonora contains late Paleozoic to early Mesozoic rocks and structural elements crucial for understanding the paleogeography and tectonic history of the region. Most geologic maps and field investigations typically terminate at the international political borders. Yet the solutions to many relevant geologic problems need close integration of findings from both the United States and adjacent Mexico. Geologic investigation benefits from strong international scientific collaboration.

This special issue of the Revista Mexicana de Ciencias Geológicas bridges the international gap separating Mexican and U.S. researchers and offers the cross pollination of ideas and approaches necessary to resolve many geologic problems of northwestern Sonora. The papers serve to introduce a variety of themes presented at the International Workshop on the Geology of Northwestern Sonora held in Hermosillo, Sonora, Mexico, 6–10 January 1997.

The purpose of this workshop was to target a number of topics of special geologic significance. Presentations focused primarily on late Paleozoic and early Mesozoic stratigraphic sequences, paleontology, and plutonic/tectonic events along the ancient North American margin. This workshop brought together U.S. and Mexican researchers and was organized by George D. Stanley, Jr. and Carlos González-León. It was funded jointly by the National Science Foundation and Consejo Nacional de Ciencia y Tecnología (CONACYT-Mexico).

Fifteen U.S. and seven Mexican geologists presented papers at the workshop. Their conclusions were instrumental in setting an agenda for future research in the region. Abstracts from the workshop (González-León and Stanley, 1997) presented abbreviated but significant new findings. The importance of these findings underscored a need for fuller development, and this need led us to organize and edit this special volume.

Late Paleozoic and early Mesozoic time found the region of western Sonora situated somewhere near the western margin of the ancient one-world landmass of Pangea. Complex tectonic events and sedimentary processes dramatically shaped the land to culminate in the present-day geology of western Sonora. Fragmented portions of the craton, ancient island arcs, displaced terranes bearing Tethyan faunas along with key structural elements comprise northwestern Sonora (Figure 1). Some features include: the Caborca terrane—a fragmented portion of the western Pangean craton; the Cortés terrane—an eugeoclinal succession of Paleozoic strata that was thrust against the Caborca terrane; the Antimonio terrane—an outboard terrane with thick and extensive Permian to Lower Jurassic stratigraphic record thrust over the Caborca terrane and subsequently preserved as isolated outcrops; the Mojave-Sonora megashear—a major tectonic feature with left-lateral shear, postulated to have rearranged the margin of the craton. To the south of the exposures of the Antimonio terrane lies the Barranca Group, a thick succession of Triassic and possibly younger strata. The actual physical correlations and relationships of these rocks to those of the Antimonio terrane are unclear.

The complex geologic history in northwestern Sonora involved interactions between subducting oceanic plates of the western Pacific, volcanic island-arc terranes and the North American craton (see Busby-Spera *et al.*, 1998). The late Paleozoic to early Mesozoic breakup of Pangea and the opening of the embryonic Atlantic are expressed in tensional tectonics of the region. Such processes must have operated in conjunction with compressional tectonics involving subduction and the interaction of the Pacific plates along the western side of Pangea. These processes may have controlled and influenced the accretion of Paleozoic and Mesozoic terranes and the displacement and movement of marginal crustal fragments. Such events may have highly altered the original paleogeography.

The sedimentologic and biotic responses to these dramatic tectonic events are expressed within the thick sedimentary successions of Sonora such as the Antimonio terrane and the Barranca Group (Figure 1). Paleontological, stratigraphic, and sedimentological studies of these units offer data to increase our understanding of the tectonic events and the paleogeography. The Permian Monos Formation (Guadalupian age), which underlies the Antimonio Formation, is a unit unique to the Antimonio terrane. It yields diverse clastic rock types including deeper-water rocks of turbiditic origin and some carbonate beds containing Guadalupian fossils (Cooper *et al.*, 1953). The carbonate beds contain tropical-subtropical bryozoans, brachiopods and giant fusulinids. Such fusulinids are known from other terranes of the Cordillera (Ross and Ross, 1983) and perhaps also from the craton. Although the base of the Monos is not exposed, it is presumed to be a thrust fault.

In addition to the Monos, some Upper Permian strata are recognized in the basal portions of the overlying Antimonio Formation. The Antimonio Formation attains an estimated

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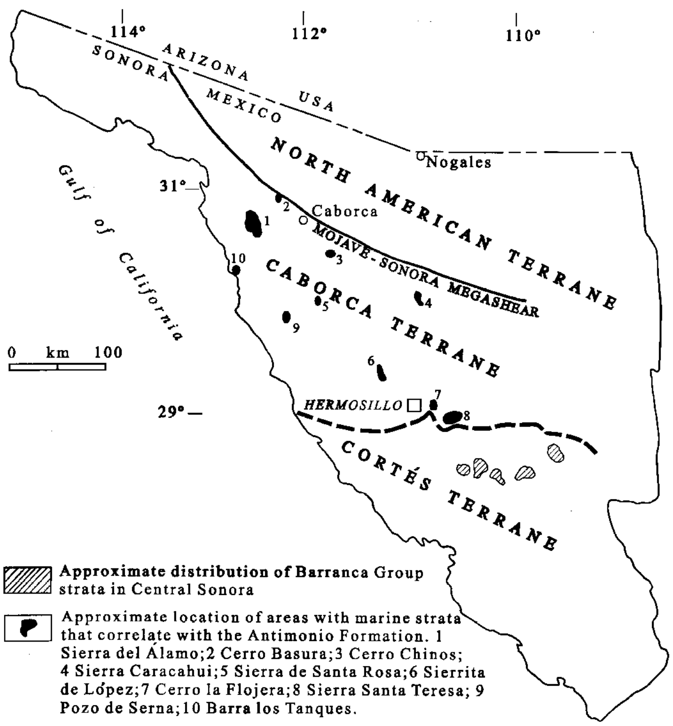

Figure 1. Approximate location of areas in Sonora, studied or referred to by authors in this issue.

thickness between 3.4 and 4.1 km. It also offers a fairly fossiliferous succession of overlying Triassic to Lower Jurassic rocks, making it a centerpiece for future studies of the geology, sedimentology, biostratigraphy, and tectonics. The Antimonio Formation, along with the Monos, is included in the Antimonio terrane (González-León, 1989). During late Paleozoic and early Mesozoic time, this low-latitude terrane was located at tropical to subtropical latitudes somewhere off the coast of the North American craton. Unfortunately, the precise paleogeographic position of the Antimonio Formation remains unclear.

The Antimonio Formation, well exposed and studied in the stratotype at Sierra del Álamo, has presumed correlatives in a number of widely scattered sites (Figure 1). Many of these remain inadequately studied, and stratigraphic correlations need to be worked out. For example, Lower Jurassic strata of the Sierra de Santa Rosa Formation, located farther to the south, bear fossils and rock types similar to and most likely correlative with the upper member of the Antimonio Formation.

In research stimulated by a CONACYT Project (3934-T94), paleontological investigations of lower Mesozoic and Paleozoic rocks of the Antimonio have progressed considerably during the past seven years. The age of the Antimonio Formation is now much better constrained thanks to new paleontological findings. Permian rocks are suggested to occur within the Antimonio Formation, previously regarded as only Mesozoic in age, and boundaries between Permian-Triassic and Triassic-Jurassic rocks have been recognized and discussed.

Paleontological research has progressed considerably. Study of the Antimonio Formation fossils has revealed many of Tethyan extraction, but it includes also some unique and endemic species and some taxa known from terranes in Nevada, California, Oregon and western Canada and from South America in Peru and Chile (Table 1). Eleven new species have been described from the Antimonio Formation and a large collection of bivalves and ammonoids presently remains under study. Rather than being a truly exotic fragment rafted from the far-reaches of the ancient Pacific, the Antimonio terrane is thought to have formed in the northern hemisphere, relatively close to the North American craton. The diverse paleogeographic admixtures among the faunas make for very complex patterns. These could be taken to infer a paleogeographic position for the Antimonio terrane between the craton of North America and some of the inboard Cordilleran terranes. Some of the Upper Triassic marine fossils show strong correlations with the western Great Basin of Nevada, specifically the Luning allochthon, with lesser faunal links with some of the inboard Cordilleran terranes.

The Antimonio rocks are interpreted as having been deposited in a fore-arc basin (Stanley and González-León, 1995) but, surprisingly, there is an absence of much evidence of volcanism such as volcanic tuffs and pyroclastic and effusive rocks. Fossils, stratigraphy, and other attributes of the Antimonio Formation contrast sharply with rocks of the 3.0 km-thick Barranca Group, located further south (Figure 1). The Barranca, dated as Late Triassic, is dominated by terrestrial deposits with only a few small incursions of sedimentary, deltaic intervals of marine origin. The Barranca Group contains thick but poorly dated strata attaining at least 3.2 km in thickness. While marine faunas are exceedingly rare, there is a fairly rich fossil flora (Weber, 1997). Evidence indicates that the Barranca is Late Triassic in age but owing to the great thickness of the sequence, it could encompass some Jurassic strata as well. Thus the Barranca appears coeval with part of the Antimonio. Various interpretations of origin exist for the Barranca Group and possible correlations have been suggested with the Antimonio (Alencáster, 1961; Lucas, 1997; Stewart *et al.,* 1997). The Barranca could be a kind of overlap assemblage deposited on the Cortés and Caborca terranes (Stewart and Roldán-Quintana, 1991) and related to the Antimonio terrane, or alternatively, it could be unrelated in a depositional sense to the Antimonio (see Stewart *et al.*, 1997; González-León, 1997, for different opinions).

In its regional distribution, the Barranca exhibits a series of east to west-trending outcrop patterns suggestive of deposition in rift basins that developed during the initial stages of the opening of the Atlantic (Stewart and Roldán-Quintana, 1991). In northwestern Sonora, the Caborca, Antimonio and other rocks are separated from the more stable craton by the Mojave-Sonora megashear—a tectonic lineation interpreted by Silver and Anderson (1974) to have undergone major left-lateral movement. The trace of the megashear was postulated to continue northward into southern California. Approximately 800 to 1,000 km of southward movement have been postulated to have occurred in post-Early Jurassic time, juxtaposing radically dif-

Table 1. Geographic distribution of invertebrate marine fossils from northwestern Sonora. E: Endemic, Sonora; EKT: Eastern Klamath terrane, northern California; ST: Stikinia terrane; NAT: other North American terranes; CNA: Cratonal North America; WT: Wallowa terrane; WRT: Wrangellia. Based on new descriptions presented in this issue as well as from Stanley and collaborators (1994).

Late Triassic Antimonio Formation

TAXON	OCCURRENCES Nevada	Western Tethys	Other
Microcoprolites			
Palaxius shastaensis			EKT
Sponges			
Nevadathalamia cylindrica	X		ST
Fanthalamia polystoma	X		ST
Cinnabaria expansa	X	?X	ST
Corals			
Distichomeandra austriaca	X	X	Peru
Retiophyllia norica	X	X	
Alpinophyllia flexuosa	X	X	
Chondrocoenia waltheri	X	X	
Astraeomorpha sonorensis	X		E
Cuifastraea granulata	X	X	WT
Acanthostylis sp.		X	
Acanthostylis acanthophora		X	WT, WRT
Meandrostylis antimoniensis			E
Hydrozoans and Disjectoporids			
Heterastridium conglobatum	X	X	Widespread
Pamiropora sonoraca			E
Stromaporidium lamellatum			E
Brachiopods			
Spondylospira lewesensis	X		CNA/NAT, Peru
Pseudorhaetina antimoniensis			E
Bivalves			
Alatoform bivalve n. gen. et sp.			E
Paleocarditia peruviana			Peru/Chile
Myophorigonia jaworskii			Peru/Chile
Septocardia sp.	X	X	Widespread
?Lopha cordillerana	X		E
Xiaoschuiculana tozeri			E
Pinna sp.			Widespread
Mysidioptera mexicana			E
Palaeolopha cf. *P. haidingeriana*	?	X	New Zealand/Myanmar
Costatoria? sp.			Widespread
Myophoriopis sonorensis			E
Propeamussium cf. *P. schafhaeutli*	X		
Chlamys sp.			?E
Gervillaria sp.			?Widespread
Cardinioides sp.			Japan, Widespread
Schafhaeutlia sp.			?E
Gastropods			
Gabrocingulum sp.		X	Widespread
Worthenia sp.		X	Widespread
Guidonia cf. *G. intermedia*			Peru
Guidonia cf. *G. parvula*			Peru
Tyrosoecus sp.		X	Widespread
Eucycloscala subbisertus	X	X	
Promathilda sp.		X	Utah, Peru
Omphaloptychia sp.		X	Widespread
Ammonoids			
Catenohalorites sp.	X	X	Widespread
Sagenites cf. *S. schaubachi*	X	X	Widespread
Choristoceras cf. *C. crickmayi*		?	NAT
Arcestes sp.	X	X	Widespread
Sunrisites sunrisensis	X		
Arcestes gigantogaleatus	X		
Arcestes cf. *A. nevadanus*	X		
Coleoids			
Dictyoconites cf. *D. reticulatum*	X		
Calliconites cf. *C. drakei*			EKT
Calliconites milleri			E

Early Jurassic (Sierra de Santa Rosa Formation and Antimonio Formation)

	South America	Tethys	Canadian Cordillera	Other
Bivalves				
Neocrassina? sp.	X	X		
Weyla (W.) alata	X	X		Americas
Lucinidae indet.	X	X		Widespread
Plagiostoma cf. *P. punctatum*	X	X		Widespread
Entolium (E.) disciforme	X	X	X	Widespread
Pholadomya cf. *P. fidicula*	X	X		Widespread
Falcimytilus sp.	X	X	X	Widespread
Pinna (P.) sp.	X	X	X	Widespread
Modiolus cf. *baylei*	X		X	Widespread
Myoconcha neuquena	X			
Pholadomya cf. *P. ambigua*	X	X	X	
Pachymya? sp.	?	X		
Ceratomya sp.	X	X		Widespread
Gresslya cf. *G. striata*	X	X	X	Widespread
Platymyoidea sp.	X	X		Widespread

ferent types of rocks in northwestern Sonora. The existence of the megashear has neither been fully supported nor entirely refuted, but the concept has spawned considerable discussion. The megashear emerges as a common thread in many of the papers presented in this volume and it serves to explain correlations of some magmatic and tectonic events in Mexico and adjacent southwestern United States and to match plutonic bodies in far-flung regions of Mexico (Jones *et al.*, 1995). Resolution of the problem using paleomagnetic approaches has proved frustrating. Remagnetization of the Antimonio rocks continues to thwart full resolution of the timing and magnitude of movements along the megashear (Molina-Garza and Geissman, 1996).

A promising approach to resolving questions of paleogeography and the megashear lies in sedimentology and provenance studies and application of zircon techniques. Zircon provenance studies have already been applied to some samples of the Barranca Group (Gehrels *et al.*, 1995). Sedimentological studies of early Mesozoic units in Sonora are however still in their infancy but they offer much potential in resolving problems of paleogeography.

The 12 papers included in this volume are summarized below. The first paper by Stewart and collaborators describes a late Paleozoic stratigraphic succession from Sierra Santa Teresa in central Sonora. It consists of a complete Mississippian to Lower Permian shallow-water carbonate that is depositionally overlain by Lower or Middle Permian siliciclastic strata of deep-water origin. Permian relationships in which shallow-water carbonate rocks intergrade with deeper-water strata are reported here for the first time. They have significant implications for late Paleozoic and early Mesozoic tectonics. Stewart and collaborators also report an Upper Triassic to probable Lower Jurassic succession from Sierra Santa Teresa. According to these authors, the rocks contain Upper Triassic carbonates with corals and sponges similar to those found in the Norian interval in the Antimonio Formation stratotype. Santa Teresa rocks also have lithologies resembling strata in the Barranca Group, making them appear as a transitional facies between both units. Stewart and collaborators propose a different interpretation that rocks of the Antimonio terrane could be autochthonous upon the Caborca terrane and thus represent an overlap assemblage covering the deformed rocks of the Late Permian to Middle Triassic Sonoran orogeny (Poole *et al.*, 1991).

Next, González-León provides an overview of the sequence stratigraphy of the thick Antimonio Formation. Ongoing field research into ammonoids and other biostratigraphically useful fossils demonstrates that the Antimonio ranges from Late Permian, through most of the Triassic, and encompasses also much of the Lower Jurassic. The Antimonio rocks are shown to represent a thicker, more complete stratigraphic succession than previously realized. Careful documentation of the Antimonio section affords opportunities for comparisons and paleogeographic correlations with more distant sites in the United States. Six key sections are illustrated across northwestern Sonora. The rock units of the Antimonio are ordered into sequence-stratigraphic units. The predominantly fine-grained, fossiliferous succession represents both shallow- and deeper-water rocks deposited within a fore-arc basin. The almost complete Upper Permian-Triassic and Lower Jurassic stratigraphic record of the Antimonio Formation does not indicate a tectonic event like that of the Sonoran orogeny which makes it even less similar to the Barranca Group. González-León offers new and thought-provoking correlations with coeval stratigraphic sequences in the Sierra Nevada region of California and adjacent areas of Nevada.

The geology of the western Great Basin of Nevada seems to be similar to that of Sonora. Fossils and rock types have been compared. For example, González-León and collaborators (1996) showed striking similarities of ammonoid faunas and sequence-stratigraphic units in the Sonoran Antimonio Formation and the Luning sequence of west-central Nevada. Stanley and González-León (1995) hypothesized that these regions once were connected in Triassic times, as part of a continuous faunal province that subsequently was disrupted and moved south by left-lateral fault movements. However, Gómez-Luna and Martínez-Cortés (1997) point out evidence disputing these correlations. In a review of the Triassic ammonoid faunas found in the Antimonio Formation and the Luning-Gabbs succession, the authors summarize Spathian, Anisian, Carnian, Norian, and Rhaetian ammonoid occurrences. Further, they note structural and stratigraphic dissimilarities between the two areas, and they point out as well some differences in depositional and stratigraphic settings.

Both a Triassic-Jurassic boundary (González-León *et al.*, 1996) and a Permian-Triassic boundary (Lucas *et al.,* 1997) have been reported from the Antimonio Formation. In the new sequences of González-León presented in this volume, the Permian-Triassic boundary most probably is located above sequence I. It could be represented by a distinctive basal conglomerate found in sequence II. Sequence I contains a brachiopod assemblage that was previously reported from the underlying Monos Formation by Cooper (1953), while sequence II is barren in fossils. Sequence III of the Antimonio Formation, on the other hand, has yielded Spathian ammonoids and conodonts in its middle part. Lucas and collaborators illustrate some of these fossils and suggest that the basal sequences of the Antimonio Formation record the same Triassic eustatic events found in the southwestern United States. To further support the amazingly complete Triassic record of the Antimonio Formation, Estep and collaborators report a Middle Triassic ammonoid fauna from the lower member of this unit. Although the ammonoids are not very well preserved and limited in variety, this brief report illustrates their biostratigraphic utility.

Goodwin and Stanley give an overview of reef-like, Upper Triassic sponge and coral biostromes in the Antimonio Formation at Sierra del Álamo. Their paper complements a previous description of the invertebrate faunas from the biostromes (Stanley *et al.,* 1994). In this volume, the authors recognize a variety of lithofacies in which the invertebrates occur. The carbonate-siliciclastic Norian rocks include highly biogenic beds dominated by bivalves, sponges, corals, and other fossil organisms. These beds are similar to occurrences found in the Luning sequence of west-central Nevada. Characterized as biostromes rather than reefs, the Antimonio examples thicken and thin and contain taxa well known from Upper Triassic reefs of the Tethys and some North American Cordilleran terranes. A close correspondence seems to exist between the rock types and faunal associations in the sequence, and the authors relate the faunal occurrences to paleoecology and depositional environments.

In a paper that follows, Stanley and González-León describe new Upper Triassic scleractinian corals from Sierra del Álamo. These come from both Norian and Rhaetian intervals of the Antimonio Formation. The paper expands the number of corals to 11 taxa. The new corals show complex paleogeographic patterns and links with the Pamir Mountains, Russia, central Europe, the Wallowa terrane of Oregon and possibly the Luning assemblage of west-central Nevada. The corals affirm some degree of isolation of the Antimonio terrane and reinforce the previously noted connections with the Tethys, especially the western part of this distant province.

In the next paper, McRoberts considers the Norian and Rhaetian bivalve faunas of the lower member of the Antimonio Formation. Only three Upper Triassic bivalves previously were known from the Sierra del Álamo site (Stanley *et al.,* 1994). Recognition of 10 additional taxa, two of them new species, confirms a much higher bivalve diversity than previously realized and demonstrates strong affinities of the Antimonio fauna with those from South America, Nevada, and some other North American terranes. McRoberts also reassigns the previously identified *Myophorigonia salasi* (Tamura *in* Stanley *et al.,* 1994) to *M. jaworskii* from the Antimonio Formation. *M. salasi* was first described from the Barranca Group by Alencáster (1961) and its supposed presence in the Antimonio Formation supported the only paleontologic link between the two units. The paper stresses the importance of further bivalve studies in order to obtain a more accurate picture of bivalve diversity and paleobiogeography.

Bivalves continue as subjects of the next paper by Damborenea and González-León (1997). Some Triassic and Lower Jurassic bivalves are described from the upper member of the Antimonio Formation at Sierra del Álamo, and Lower Jurassic taxa from the Sierra de Santa Rosa Formation are treated. Lower Jurassic bivalves are shown to be more diverse than previously realized. They reveal a distinct Tethyan influence but also there arise strong affinities with an Eastern Pacific province. This paper also resolves a long-standing controversy about the age of the lower member of the Antimonio. Bivalves previously misidentified as Early Jurassic *Weyla* were used to support a structural displacement of Lower Jurassic strata into the Triassic succession. They are here recognized as Late Triassic (Norian) in age with the identification of a new species of Upper Triassic *Mysidioptera*. This species is described along with other Upper Triassic bivalves. The recognition of Upper Triassic *Mysidioptera* demonstrates the value of careful systematic study in resolving biostratigraphic and tectonic controversies within the Antimonio Formation.

The three papers that follow deal with important regional topics. The first one by Sandy gives a review of the brachiopod distribution in the Mesozoic of Mexico and discusses paleogeographic affinities. Another paper by Weber discusses some key flora of the Santa Clara Formation, Barranca Group. Weber assigns this unit to a Carnian and probably Norian age and correlates the Santa Clara flora with the Late Triassic flora of the Huizachal Group in Tamaulipas. Weber illustrates and describes a new species from the Matzitzi Formation in central Mexico and notes some historical problems in stratigraphy and age assignment of the flora from San Mateo, Hidalgo, in Mexico. Based mostly on original field mapping and geochemical studies, the next paper by Centeno-García and Silva-Romo analyzes Mesozoic tectonic events that occurred in central Mexico. This area is located at the present boundary between the Guerrero and Sierra Madre terranes, and the authors present the probable tectonic events that best explain the present-day geography of Mexico.

Many refreshingly new paleontological, stratigraphic and tectonic insights are contained in this volume. We hope that the disparate papers in this special issue of the *Revista Mexicana de Ciencias Geológicas* will help fit together some of the vital pieces of the great and complex geologic puzzle of Sonora and its relationship to adjacent areas of Mexico and southwestern United States. Many pieces of this puzzle are still missing, and we trust that this volume will serve to fuel further geologic investigations in the region.

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