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SEQUENCE STRATIGRAPHY AND PALEOGEOGRAPHIC SETTING OF THE ANTIMONIO FORMATION (LATE PERMIAN–EARLY JURASSIC), SONORA, MEXICO

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ABSTRACT

The Antimonio Formation is a Late Permian, Triassic and Early Jurassic sedimentary succession composed of 14 fining-upwards unconformity-bounded sequences. It contains the Permian-Triassic and Triassic-Jurassic systemic boundaries, which are represented as well-marked disconformities. The most complete section of this unit crops out in the northern part of the Sierra del Álamo, in northwestern Sonora, Mexico, where it unconformably overlies the Permian Monos Formation. Other correlative, partial sections of this formation crop out in several other ranges in northwestern Sonora. Some of these here reported include Barra Los Tanques, Pozo de Serna, Sierra de Santa Rosa, Cerro La Flojera, and the eastern part of Sierra Santa Teresa. All these sections are in proved or suspected tectonic contact with older rocks, for which they are considered to be part of an allochthonous block. Other possible correlative strata with the Antimonio Formation are sections of Permian, Triassic, and Early Jurassic age in the southwestern United States. Also, probable correlative sections of Late Permian, Early Triassic, Late Triassic and Early Jurassic age are in the Baja California Peninsula. The original depositional setting of the Antimonio Formation has been considered to be in a fore-arc basin that was located further to the northwest, probably close to the southwestern margin of the North American craton and adjacent to the proposed correlative section of southeastern California and Nevada. If this hypothesis is correct, the Antimonio section of Sonora was located and deposited between a Late Permian to Early Jurassic arc to the north and Early Mesozoic subduction complexes to the south, and it was later transported to its present position (most probably during Jurassic time) along with the Caborca block by the Mojave-Sonora megashear.

Key words: Permian-Triassic, Triassic-Jurassic, systemic boundary, Mesozoic, Sonora.

RESUMEN

La Formación Antimonio es una sucesión sedimentaria de edad pérmica tardía, triásica y jurásica temprana, que está compuesta por 14 secuencias limitadas por discordancias. Esta unidad contiene los límites sistemáticos Pérmico-Triásico y Triásico-Jurásico representados por discordancias. Su sección más completa aflora en la parte septentrional de la sierra del Álamo en el noroeste de Sonora, México, donde yace discordantemente sobre la Formación Monos (Pérmico Tardío). Afloran secciones incompletas pero correlacionables con la Formación Antimonio en varias localidades del noroeste de Sonora, como en Barra Los Tanques, Pozo de Serna, Sierra de Santa Rosa, Cerro La Flojera y en la parte oriental de la Sierra Santa Teresa. Todas estas secciones están en contacto tectónico probado o inferido con rocas más antiguas, por lo cual son consideradas como parte de un mismo bloque alóctono. Se propone también que la sección de la Formación Antimonio sea correlacionable con estratos de edad pérmica, triásica y jurásica temprana que afloran en el sureste de California y Nevada en los E.U.A., así como con secciones del Pérmico Superior, Triásico Inferior y Superior y Jurásico Inferior que afloran en áreas localizadas en Baja California. Se propone que la sección del Antimonio haya sido depositada originalmente en una cuenca de frente de arco (*fore-arc basin*), la cual estuvo localizada hacia el noroeste de su posición actual, formando parte del margen sudoccidental del cratón de América del Norte y adyacente a las secciones equivalentes de California y Nevada. Si esta hipótesis es correcta, la sección del Antimonio estuvo localizada y fue depositada entre un arco volcánico de edad pérmica tardía a jurásica temprana, que se desarrolló hacia el norte sobre esa parte del cratón y un complejo de subducción del Mesozoico temprano, localizado hacia el sur en Baja California, y posteriormente fue transportada (durante el tiempo Jurásico) con el bloque Caborca hasta su posición actual por la megacizalla Mojave-Sonora.

Palabras clave: Pérmico-Triásico, Triásico-Jurásico, límite de sistemas, Mesozoico, Sonora.

INTRODUCTION

The Antimonio Formation was first described from the Sierra del Álamo in northwestern Sonora (Figure 1) as a 3.4-km-thick, mostly marine section of Upper Triassic to Lower Jurassic strata (González-León, 1980). Further work in this formation and its correlative strata in Sonora was developed since 1992 by the author and by others, which has led to more recent contributions that better constrain its paleontology and age (Stanley *et al.*, 1994; Lucas and González-León, 1994; Estep *et al.*, 1997a), the nature of the Triassic-Jurassic boundary within it (Lucas, 1993; González-León *et al.*, 1996; González-León, 1997a), its stratigraphy and sequence stratigraphy (González-

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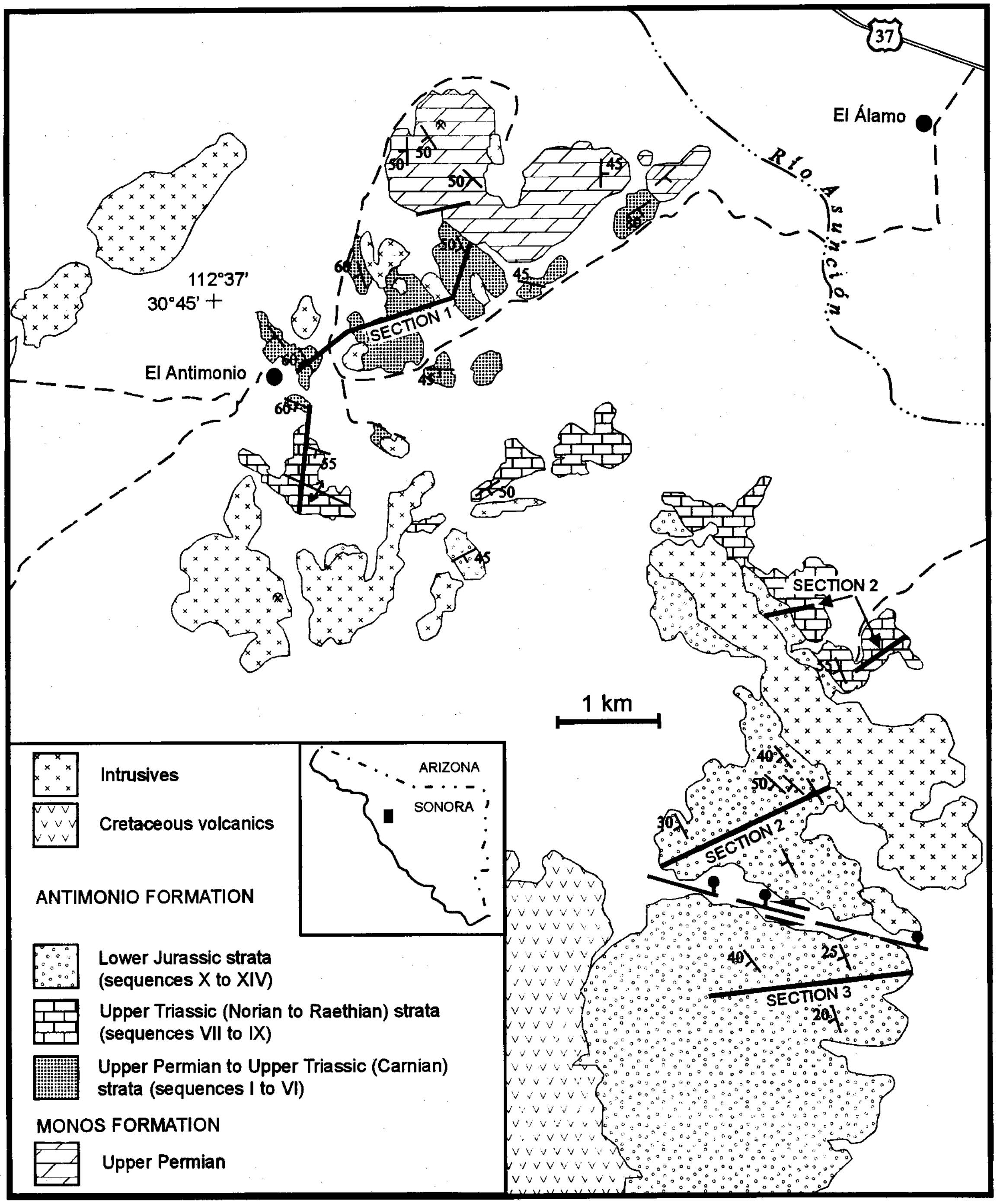

Figure 1. Geologic map of the northern part of the Sierra del Álamo, northwestern Sonora, showing outcrops of the Monos and Antimonio Formation.

León, 1997b; Lucas, Silberling and Marzolf, 1997), and its correlation, paleogeography and tectonic setting (Stanley and González-León, 1995).

Previous stratigraphic and paleontological descriptions of this unit along with its Permian basement were made by Burckhardt (1930), Dunbar (1953), Cooper (1953a, b), Cooper and Arellano (1946), King (1939), Buitrón and González-León (1982), and Callaway and Massare (1989).

The present work follows a preliminary summary recently published (González-León, 1997b) and presents a synthesis of the most recent advances in the knowledge of the Antimonio Formation and correlative strata in northwestern Sonora, and discusses its stratigraphy, paleontology, correlation, and the probable paleogeographic setting of this section of Upper Permian-Triassic and Lower Jurassic age.

STRATIGRAPHY AND SEQUENCE STRATIGRAPHY

The best outcrops of the Antimonio Formation are exposed in the northern foothills of the Sierra del Álamo, in northwestern Sonora, where it unconformably overlies the Permian Monos Formation (Cooper, 1953a) (Figure 1). A recent and detailed measurement of its lithostratigraphic column, along with further fossil collecting and paleontologic identifications that better constrain its age, have led to a redefinition of this unit as an almost completely marine sedimentary succession that ranges from latest Permian to Early Jurassic in age. The Upper Permian and Triassic section which forms the lower member of the Antimonio Formation (González-León, 1980) crops out in an extensive belt of poorly exposed and intruded outcrops, that extends for about 6 km from the Antimonio mine, and the ghost town of same name in the western part of the area, to the southeastern part of the area (Figure 1). The Lower Jurassic section (upper member of the formation; González-León, 1980) composing this unit is best exposed in the higher ranges located to the south within the Sierra del Álamo.

The 3.4-km-thick lithostratigraphic section of the Antimonio Formation was measured along sections 1 and 2, and it is divided for purposes of description into 21 (from base upwards) informal numbered units that form 14 unconformity-bounded sequences (González-León, 1997b) (Figure 2). These measured sections are proposed as the Antimonio Formation stratotype. The complete Antimonio section can reach, however, a thickness of up to 4.1 km, when the unfossiliferous section measured along Section 3 is considered as part of it (Figure 1).

Lithologies of the Permian and Triassic part of the Antimonio Formation are mostly fine-grained sedimentary strata of interpreted shallow- to deep-marine environments. The Lower Jurassic strata of the Sierra del Álamo, and correlative units in other ranges in Sonora, are mostly fine-grained terrigenous rocks with a few minor intervals of limestone; they are however very fossiliferous, containing ammonoids and bivalves.

Descriptions that follow of the Antimonio Formation are made to distinguish unconformity-bounded packages of strata that form distinctive fining-upwards sequences within it. As discussed below, almost all these sequences start with a fluvial conglomerate at the base, and grade upwards to shallow marine fine-grained sandstone, siltstone and limestone, and in some cases, they grade in the upper parts to finer-grained lithologies representing deeper marine environments. Sequences 1 through 6 are better exposed along section 1 (Figure 1), whereas sequences 7 through 14 are exposed along section 2, as described below.

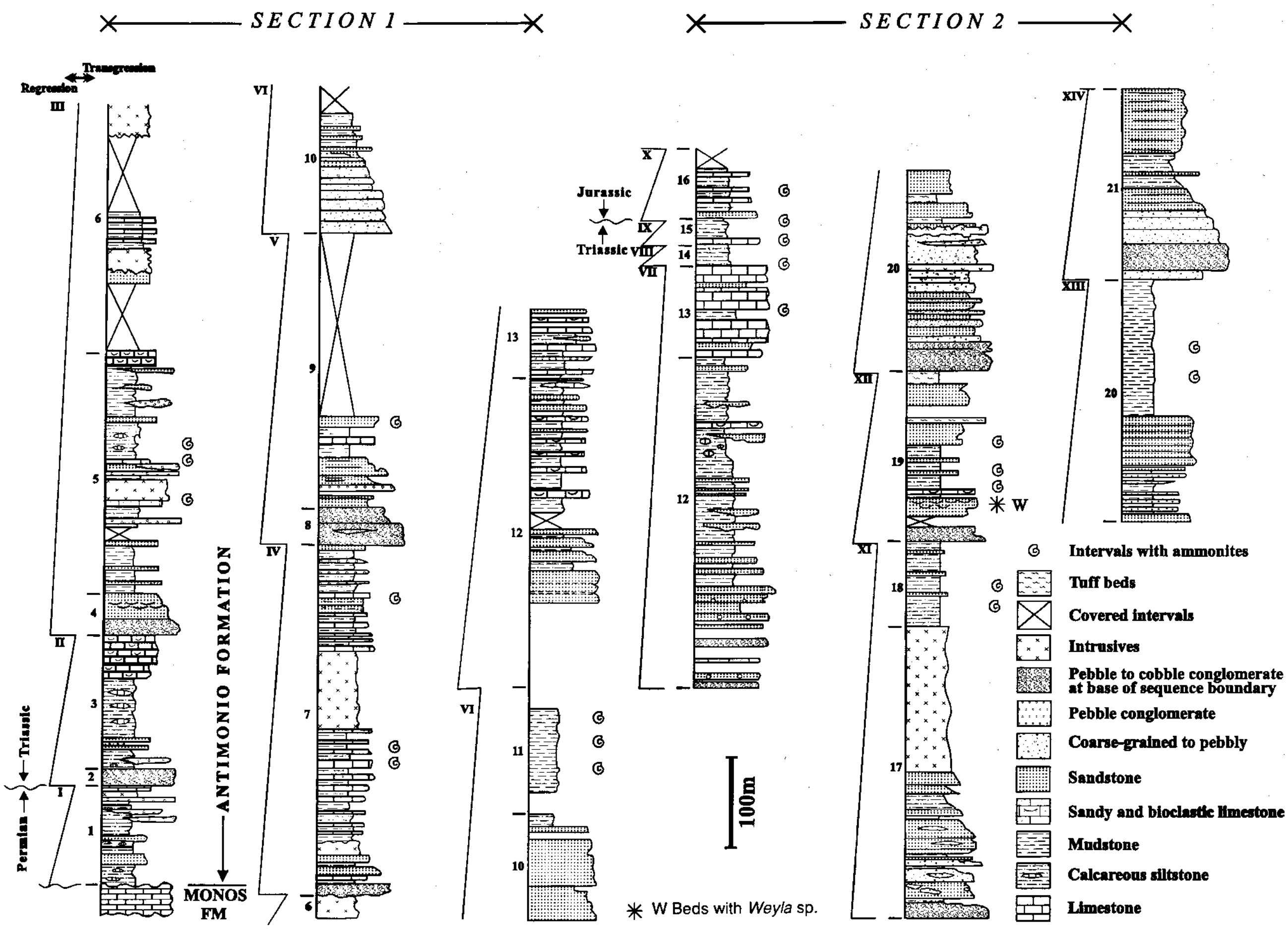

Figure 2. Stratigraphic column of the Antimonio Formation showing fossil localities and interpreted unconformity-bounded sequences.

SEQUENCE I

It rests disconformably on a karstic surface developed on the upper limestone beds of the Permian Monos Formation (Figure 2). As reported by Stanley and González-León (1995), these karstic structures are filled by red siltstone, which is a typical lithology of the lower part of this sequence. Sequence I consists of very thin-bedded calcareous red siltstone with calcareous nodules, rare thin-bedded limestone, medium- to thick-bedded, fine-grained sandstone, and occasional thin, lenticular beds of pebble conglomerate. Clasts in the conglomerate beds are of chert, limestone, quartzite and igneous (quartz porphyry and granitic compositions) rocks. Calcareous siltstone in the lower part of the formation yielded poorly preserved brachiopods *(Orbiculoidea* sp., *Spiriferellina sonorensis* Cooper and *Composita* sp.) and bryozoans (Lucas, Kues *et al.,* 1997). The brachiopods *Orbiculoidea* and *Composita* were reported from the underlying Monos Formation and *S. sonorensis* was first described from that unit by Cooper (1953b). Cooper (1953b) assigned a Late Permian, Guadalupian age for that formation and based on these fossils, a similar age is herein considered for sequence I. Sequence I is 100-m thick.

SEQUENCE II

This sequence is composed at its base by a massive, clast-supported conglomerate of unit 2, and by unit 3 (Figure 2). The 15-m-thick basal conglomerate sharply overlies unit 1 and its clasts consist of poorly sorted, subangular, fine- to coarse-pebbles of limestone, chert, and minor rhyolite and granite, and it is interpreted as fluvial in origin. The sequence grades upwards to unit 3 composed of reddish siltstone with calcareous nodules containing rare shell fragments, occasional thin interbeds of fine-grained sandstone, and its uppermost 40 m consist of thin- to medium-bedded, muddy to sandy limestone with occasional shell remains of shallow marine origin. Sequence II is 115-m thick.

Sequence II occurs between sequence I of Late Permian age and sequence III of Spathian age. However, it only yielded poorly preserved unidentifiable fossils and it is probably either part of the Late Permian sequence or Smithian in age. Tentatively, the Permian-Triassic boundary is considered to be at the base of sequence II (Lucas, Kues *et al.*, 1997).

SEQUENCE III

This sequence is composed of units 4 to 6. Its base (unit 4) is a 15-m-thick poorly sorted, clast-supported fluvial conglomerate that sharply overlies unit 3. It grades from small boulder conglomerate in its lower part to fine-pebble conglomerate and coarse-grained sandstone in its upper part. Clasts in this conglomerate are subrounded to subangular, mostly composed of limestone, granitic rocks, chert, quartzite and sandstone (Figure 3). Paleozoic limestone clasts are distinguished by abundant brachiopods, bryozoans, and the large fusulinid *Parafusulina antimonioensis* (C. Stevens, written communication, 1996) whose type species was described by Dunbar (1953) from the underlying Monos Formation. This conglomerate is followed upwards by an interval (unit 5) 235-m thick of coarse- to fine-grained, trough cross-stratified sandstone and interbedded reddish siltstone that form fining-upward cycles. Sandy and muddy limestone intervals become abundant toward the upper part of this interval, some of which yielded poorly preserved conodonts and ammonoids of Spathian age (*Tirolites* sp.) (Lucas, Estep *et al.,* 1997). The upper part of the sequence (unit 6) is a very covered and intruded interval with local exposures of medium-bedded impure limestone with interbedded siltstone/mudstone, and fine-grained sandstone. The total thickness of this sequence is 500 m.

Figure 3. Clast supported conglomerate of unit 4 (Figure 2) that contains large clasts of limestone with the Permian fusulinid *Parafusulina sonoraensis* (Dunbar).

SEQUENCE IV

This sequence starts at its base with a poorly exposed clast-supported, chert-pebble conglomerate interpreted as fluvial in origin, and is followed upwards by thin- to medium-bedded fine-grained sandstone, siltstone, and limestone of shallow marine origin. Poorly preserved ammonoids occur in the middle and upper parts of this unit. Also, in the upper part there is an interval with thin-bedded, aulacoceratid-oriented packstone and trace fossils representing the *Nereites* ichnofacies (Figure 4) which could indicate deep marine intervals for this part of the sequence. Ammonoids from this interval have been identified as cf. *Paracrochordiceras* (Welter) and *Paranevadites* cf. *P. furlongi* (Smith) (Estep *et al.*, 1997b) that indicate this sequence is of Middle Triassic (Anisian) age.

SEQUENCE V

At its base, this sequence has a 28-m-thick interval (unit 8) of poorly sorted, clast-supported, coarse pebble to cobble

Figure 4. Trace fossils, probably *Nereites* from upper part of unit 7 (Figure 2).

conglomerate that fines upward. Clasts in this conglomerate are subangular and subrounded, composed of encrinitic, micritic and fossiliferous limestone (50%), quartzite (40%), chert (8%), volcanics (1%), and sandstone (1%). This basal conglomerate is followed upwards by unit 9 that consists of coarse- to fine-grained sandstone, interbedded siltstone, calcareous mudstone, and limestone beds with unidentifiable aulacoceratids and ammonoids, ichthyosaur bones, and echinoid spines. A couple of ichthyosaur vertebrae identified by J. Callaway (written communication, 1996) belongs to the Family Shastasauridae and can probably indicate a Carnian age for this sequence. Otherwise and after further study of the ammonoids in this sequence, it could probably represent the Ladinian stage. This sequence is 323-m thick but it is covered in its uppermost 170 m, where an upper boundary is inferred to be present.

SEQUENCE VI

The base of this sequence may be covered close to the base of unit 10, which consists of a coarse-grained to fine-pebble conglomeratic sandstone with *Skolithus*; it is interpreted as shallow marine in origin. This sandstone grades upwards to fine- and medium-grained sandstone with interbedded siltstone, and coarse-grained, massive sandstone. These lithologies are overlain with an apparent gradational contact by unit 11 which is composed of light gray to reddish, massive to finely laminated mudstone, interbedded encrinitic limestone, aulacoceratid packstone, packstone-grainstone with diverse shell fragments, ammonoid packstone, and minor very fine-grained sandstone beds. Fauna from this package has been previously reported (Keller, 1928; Burckhardt, 1930; King, 1939; Callaway and Massare, 1989; Lucas and González-León, 1995; Stanley *et al.*, 1994; Stanley and González-León, 1995). The age of sequence VI is constrained in its upper part as late Carnian in age based on its fauna of ammonoids (Estep *et al.*, 1997a). The uppermost part of sequence 6 is not exposed as it is overlain by a covered interval 120 m thick. The boundary with the overlying sequence 7 should fall within this interval. The estimated thickness for this sequence is 440 m.

SEQUENCE VII

It is composed of units 12 and 13 and it is well exposed in the upper part of section 1 and lower part of section 2 (Figure 1). Although the contact with sequence 6 is covered at both localities, its lowermost outcrops consist of fluvial, poorly exposed, fine- to coarse-pebble conglomerate with clasts of limestone, quartzite, minor chert, volcanics and granitic rocks that grade upwards to fluvial, coarse-grained and pebble sandstone with poorly exposed intervals of siltstone. Large fossil logs occur within some sandstone beds. Upwards, it is composed of siltstone with interbedded medium- to coarse-grained sandstone that grades upwards to calcareous siltstone, fine-grained sandstone, and coquinoid and bioclastic limestone of interpreted shallow marine origin. The age of unit 12 is considered as early Norian according to ages of underlying and overlying units, and by Late Triassic bivalves identified from this unit (Damborenea and González-León, 1997).

Unit 12 is gradationally overlain by unit 13 that consists of lenticular intervals of biostromal limestone in beds up to 10 m thick, impure limestone, interbedded argillite and mudstone, calcareous, fine-grained sandstone, and dolomitic and mottled limestone. Unit 13 contains an abundant shallow-water marine fauna of corals, sponges, spongiomorphs, bivalves, gastropods, and brachiopods (Stanley *et al.*, 1994; McRoberts, 1997; Damborenea and Gonzalez-León, 1997; Goodwin and Stanley, 1997; Stanley and González-León, 1997). Rare ammonoids in this unit constrain the age of this sequence to late Norian (Columbianus and Cordilleranus Zones) (González-León *et al.*, 1996). The maximum measured thickness of this sequence along section 2 is 390 m.

Strata of unit 12 along the upper part of section 1 (Figures 1 and 2) were considered by Lucas, Silberling, and Marzolf (1997) to be in fault contact with the Carnian and Norian rocks of units 11 and 13, respectively, because these authors misidentified some coarse-ribbed Triassic bivalves in this unit as Early Jurassic *Weyla* sp. (Lucas, Silberling and Marzolf, 1997). However, as discussed by González-León (1997a, b), no significant tectonic juxtaposition of strata can be drawn at these localities and this controversy has been resolved through paleontologic studies of the bivalves, which clearly are of Late Triassic (Norian) age (Damborenea and González-León, 1997).

SEQUENCE VIII

It is composed of thin-bedded to massive calcareous siltstone with calcareous nodules with ammonoids, crinoids

(*Pentacrinus* sp.), bivalves, and rare plant fragments. Ammonoids in upper part of this package represent the late Norian Amoenum Zone. It sharply overlies unit 13 and has a thickness of 17 m.

SEQUENCE IX

This sequence is composed of unit 15. It has at its base a lenticular interval 2-8 m thick of a distinctive reddish colored bioclastic to sandy limestone and siltstone lithology with an abundant and diverse fauna including ammonoids, bivalves, crinoids, ichthyosaur bones, nautiloids, and reworked colonial corals (Stanley and González-León, 1998). This interval grades upwards to calcareous siltstone, fine-grained sandstone, and thinly laminated to massive mudstone with ammonoids. The bioclastic interval at the base of the sequence is interpreted to represent either lowstand tempestites related to a fall and subsequent rapid rise of sea level (Sageman, 1996), or a concentration lag (González-León *et al*., 1996). The upper part is considered to be deep marine. Ammonoids in this sequence indicate that it is of Rhaetian age (Crickmayi zone). Thickness of unit 15 or sequence IX ranges from 27 to 43 m; its base sharply overlies unit 14, whereas its top is an erosional surface below unit 16 which marks the Triassic-Jurassic boundary (González-León, 1997a).

SEQUENCE X

It is composed of unit 16. It has in its lowermost part a laterally continuous, base-erosive, coarse-grained to pebble sandstone that fines upward into a calcareous sandstone with ammonoids. Upwards the sequence is composed of mudstone/siltstone and interbedded fossiliferous limestone of shallow marine origin. Ammonoids in this sequence indicate it is late Hettangian to early Sinemurian (González-León *et al.*, 1996). It is 60-m thick but covered in its upper part.

SEQUENCE XI

It is constituted by units 17 and 18. Its base is a 20-m-thick, clast supported, fine- to coarse-pebble conglomerate that grades upward to interbedded coarse-grained sandstone and siltstone of fluvial origin. Clasts in this conglomerate are rounded to subrounded and consist of quartzite (70%), volcanic and intrusive rocks (20%), and chert, sandstone and quartz (Figure 5). Volcanic clasts of rhyolitic and ignimbritic composition, and intrusive clasts of granitic composition occur in about the same proportions. The middle part of this sequence is occupied by a dioritic intrusive. Its upper part (unit 18) consists of massive to finely laminated calcareous mudstone with calcareous nodules and thin interbeds of siltstone. Intervals with ammonoids and thin-shelled bivalves provide a Hettangian-Sinemurian age for this sequence (Taylor *et al.*, 1996). Its estimated thickness is 280 m.

Figure 5. Clast-supported conglomerate of base of unit 17 showing rounded clasts of quartzite, ignimbrites and intrusives, chert, sandstone and quartz. Pen for scale is 14 cm long.

SEQUENCE XII

It consists of unit 19. Its base is marked by an interval composed of a 5-m-thick bed of massive, lenticular, pebble-conglomerate that is gradationally overlain by coarse-grained, thick-bedded to massive sandstone with large-scale trough cross-bedding, by laterally continuous trough and planar cross-stratified, coarse to pebbly sandstone, and by a thick bed of bivalve coquina. The coquina grades upwards to mudstone/siltstone, thin limestone beds with ammonoids (preliminary identifications of this material include *Asteroceras* sp.; D.G. Taylor, written communication, 1995), fine-grained sandstone, and thin beds of volcanic tuff. A single bed of limestone in this sequence yielded scarce bivalves belonging to the Early Jurassic bivalve *Weyla*. A probable Sinemurian age is assigned to this sequence which totals 115 m in thickness.

SEQUENCE XIII

It contains at its base amalgamated thick beds of pebble conglomerate, pebbly sandstone, and coarse-grained sandstone with a few intervals of interbedded mudstone/siltstone and tuff beds. These lithologies represent fluvial to marginal marine environments that grade upwards to fine-grained sandstone and laminated to thin-bedded mudstone and siltstone. In the middle and upper parts of the unit, several turbiditic mudstone/siltstone intervals preserve abundant soft-sediment deformation and current sole marks (Figure 6). Trace fossils (*Nereites* ich-

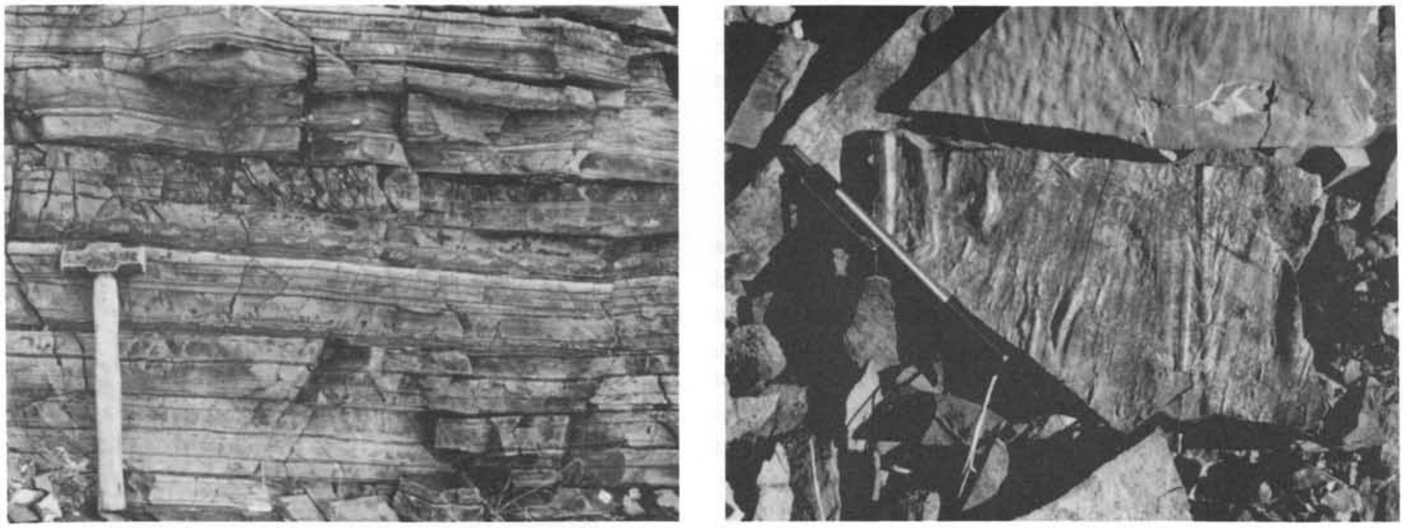

Figure 6. Finely laminated muddy limestone with small-scale soft-sediment deformation (*A*) of upper part of unit 20. Small ammonites and current structures (*B*) are abundant in this interval.

nofacies) and ammonoids of Sinemurian and probably Pliensbachian age are abundant in some beds. Sequence XIII is 465-m thick.

SEQUENCE XIV

It is composed of unit 21 that, at its base, contains a thick interval of amalgamated beds up to 5 m thick of fluvial, clast supported, coarse-pebble conglomerate that fines upwards to sandstone and interbedded siltstone. Its uppermost 50 m consist of medium- to coarse-grained sandstone of probable shallow marine origin. Conglomerate clasts are of quartzite, chert, limestone, volcanics and minor quartz (Figure 7). It is 150-m thick.

An estimated 600-m-thick section of this formation is well exposed along section 3. Section 3 is separated from section 2 by a normal and probable left-lateral strike-slip fault. Its base is composed of massive conglomerates that resemble those at the base of unit 21, and thus is considered as the uppermost part of the Antimonio Formation in Sierra del Álamo. This section is composed exclusively of fine-grained, thin- to thick-bedded sandstone with minor intervals of siltstone/mudstone, and although no fossils were found, it is interpreted as basinal deposits of probable Toarcian to early Middle Jurassic age.

Figure 7. Clast-supported conglomerate of unit 21 showing abundant angular clasts of limestone.

DEPOSITIONAL SETTING

The most probable depositional setting of the Antimonio Formation is a fore-arc basin as proposed by Stanley and González-León (1995). This is indicated by its location between a subduction complex as old as Late Triassic (Sedlock and Isozaki, 1990) and a volcanic-arc sequence of Middle to Late Jurassic (Kimbrough, 1985), both of which are located to the south in west-central Baja California; and a Late Triassic to Middle Jurassic continental volcanic arc located to the north and northeast (Saleeby and Busby-Spera, 1992). Additional data provided by regional correlations of this formation, as discussed in the next section, give further support to this interpretation.

CORRELATION

Scattered outcrops of established Upper Triassic and Lower Jurassic strata in northwestern Sonora lithologically correlate with parts of the Antimonio Formation and belong to the same terrane (Figures 8 and 9). Part of the carbonate-dominated Norian-age unit 13 of the Antimonio Formation is present in small hills near Barra Los Tanques (Figure 10), southwest of the Sierra del Álamo. A more complete section comprising unit 13 and probably part of the Lower Jurassic section

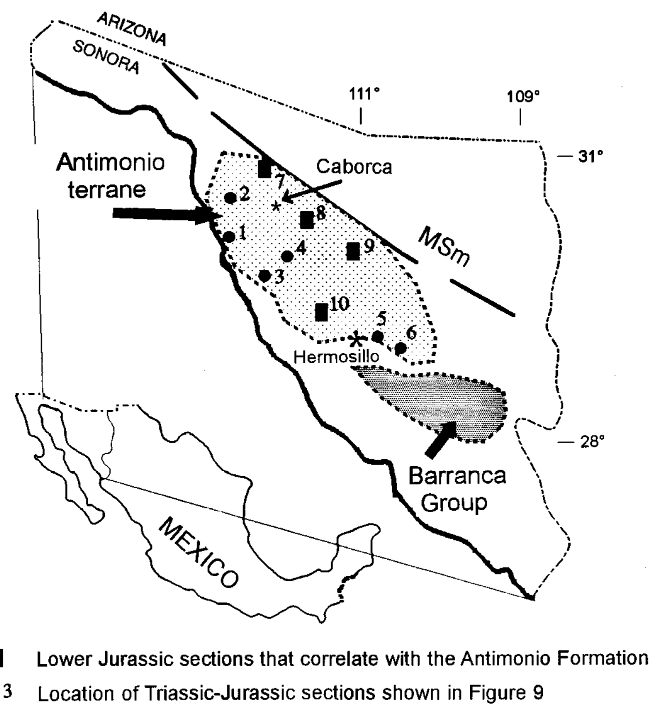

Figure 8. Generalized map of Sonora showing location of different outcrops that are correlative with strata of the Antimonio Formation and that are grouped within the Antimonio terrane. Also shown is area where Upper Triassic strata of the Barranca Group are reported. Localities are: 1, Barra los Tanques; 2, Sierra del Álamo; 3, Pozo de Serna; 4, Sierra de Santa Rosa; 5, Cerro la Flojera; 6, Sierra Santa Teresa; 7, Cerro Basura; 8, Cerro Chinos; 9, Sierra Caracahui; 10, Sierrita de López.

crops out in Sierra Santa Teresa (Figure 9) (Stewart *et al.*, 1997). A section with Carnian ammonoids and bivalves probably equivalent to unit 10 is also present in low hills of Cerros La Flojera (Figure 9), near Hermosillo (Lucas and González-León, 1994). Similarly, parts of the Jurassic section crop out in the Pozo de Serna area where they range in age from Sinemurian and early Pliensbachian to Middle Jurassic (Calmus *et al.*, 1997; Linares *et al.*, 1997), and in the Sierra de Santa Rosa (the Sierra de Santa Rosa Formation of Hardy [1981]) where they are Sinemurian to Toarcian in age (Figure 9). Other poorly exposed and mainly terrigenous localities with Lower Jurassic outcrops are in Sierra Caracahui, and in Sierrita de López.

Other sedimentary sections of Late Triassic age in Sonora are those of the Barranca Group (Figure 8) (Alencáster, 1961) which is composed of the Arrayanes, Santa Clara, and Coyotes Formations. Of these, only the Santa Clara Formation has fossils which indicate a Carnian age at least for this unit. The Barranca Group apparently overlies both platform and basinal deposits of Paleozoic age in its outcrops in central Sonora, and it is considered as a rift basin deposit that developed after amalgamation of the basinal strata against the platform belt of Paleozoic age (Stewart and Roldán-Quintana, 1991). According to Poole (1993), the presumed time of accretion was between Late Permian and Early Triassic.

The Antimonio Formation, along with the Monos Formation and the correlative Antimonio sections here discussed, has been considered as part of the Antimonio terrane (Figure 8) by González-León (1989) and considered different from the Barranca Group because of the many dissimilarities in stratigraphy, age, fossil content, basement type, and sandstone provenance (as discussed in Stanley and González-León, 1995). Other authors like Stewart and collaborators (1997) however, leave the possibility open that the Antimonio Formation could represent lateral marine facies of the Barranca Group (as first proposed by Alencáster [1961]). In this regard, it is important to consider that the new age of the Antimonio Formation (Late Permian to Early Jurassic) makes it even more distinct from the Barranca group, as it does not record the eugeoclinal-miogeoclinal accretion (Sonoran orogeny) of central Sonora to which the Barranca Group is post-tectonic.

On a more regional scale, the best sections to be correlative with the Antimonio Formation are located in southeastern California and southeastern Nevada (Figure 11). This comparison is now favored by the author over the previous one proposed by Stanley and González-León (1995) with the Luning assemblage of west-central Nevada, on the basis of more complete data herein presented for the Antimonio Formation which remarkably modify its previous age, stratigraphy and sequence stratigraphy. It is recognized, however, that favorable comparisons can be made between both regions regarding the fossiliferous content and sequence stratigraphy of the Norian, Rhaetian and upper Hettangian intervals (Stanley and González-León, 1995; González-León *et al.*, 1996).

In the area of California and Nevada, Lower Triassic strata of the Moenkopi, Silver Lake, Fairview Valley, and Union Wash Formations unconformably rest on a Permian (Wolfcampian to Guadalupian) basement composed of the Kaibab and Toroweap Formations, and the Owens Valley Group (Walker, 1987, 1988; Stone *et al.*, 1991; Saleeby and Busby-Spera, 1992). Lower Triassic (Smithian) strata of the Del Indio unit (Delattre, 1984; Buch, 1984), that unconformably rests on Lower and Upper Permian turbiditic strata of the El Mármol, Zamora, and Cerro Volcán units, are also present in the El Volcán area in the eastern part of northern Baja California (Figure 11*C*). Such Permian-Triassic stratigraphic relationships resemble the Monos/Antimonio contact.

Formations from the same region of southwestern U.S.A. that can be correlated with the middle and upper parts of the Antimonio Formation are shown in Figure 11*D;* they range in age from Middle Triassic to Toarcian (Saleeby and Busby-Spera, 1992). The Late Triassic-Lower Jurassic San Hipólito Formation of the Vizcaíno Peninsula in Baja California is also time correlative with the middle part of the Antimonio Formation.

PALEOTECTONIC SETTING OF THE ANTIMONIO TERRANE

Outcrops of the Antimonio terrane rest in an allochthonous position on the Precambrian through Lower Permian sedi-

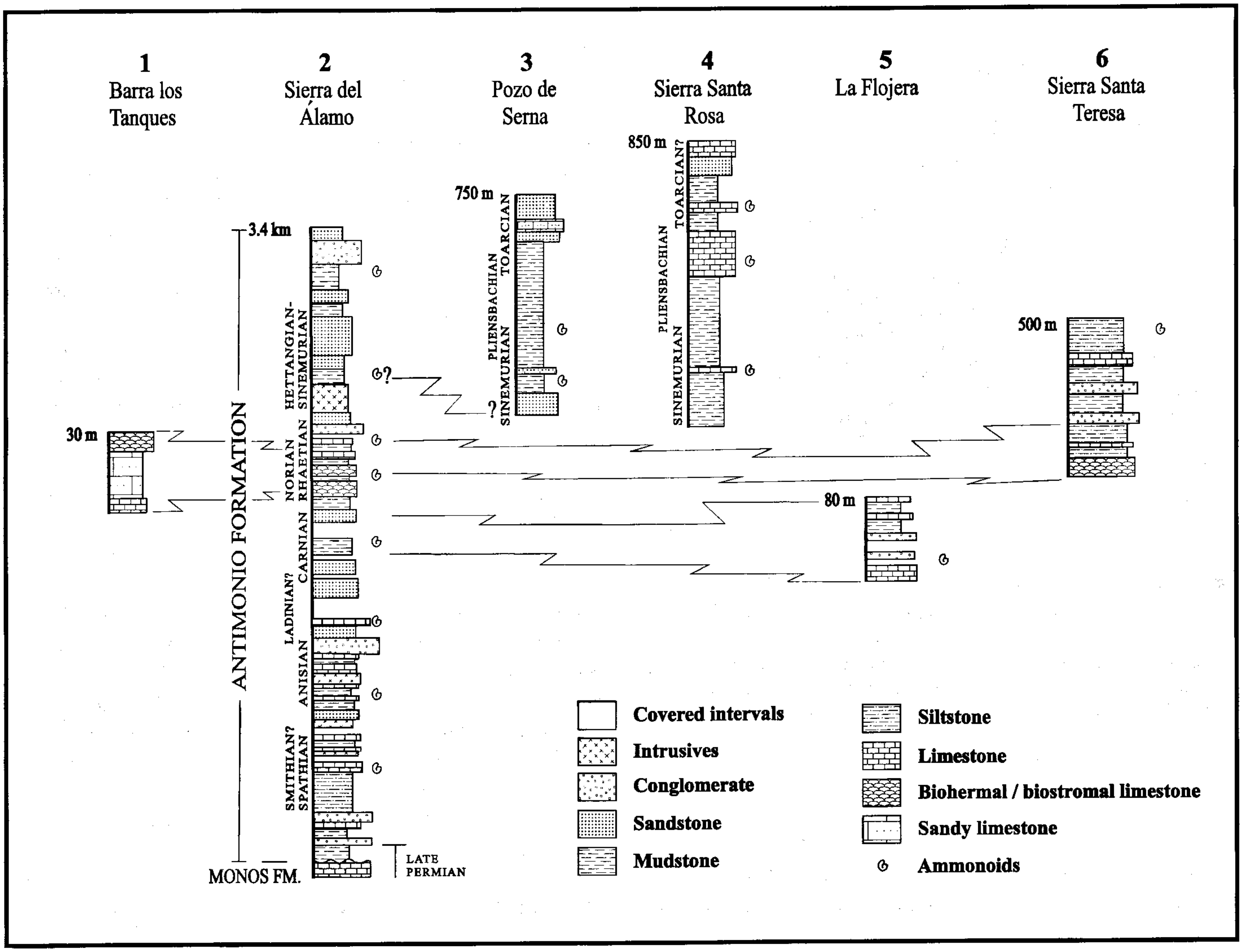

Figure 9. Stratigraphic columns that correlate measured sections of the Antimonio Formation in northwestern Sonora. Ages for the Pozo de Serna section are according to ammonoids described in Calmus and collaborators (1997), Linares and collaborators (1997) and D.G. Taylor (personal communication, 1996). Sierra de Santa Rosa section, measured by the author, includes part of the lower member and middle and upper members of the Sierra de Santa Rosa Formation of Hardy (1981), and the ages are according to D.G. Taylor (personal communication, 1996). Section at Sierra La Flojera is according to Lucas and González-León (1994). Estimated thickness of sections at Barra Los Tanques and Sierra Santa Teresa according to the author (see Stewart and collaborators [1997] for more detail).

mentary section of the Caborca terrane, and together, they constitute a stratigraphic thickness of about 8 km. However, no correlative rocks of the Precambrian to Jurassic sedimentary section are present on cratonic rocks north of the trace of the proposed Mojave-Sonora megashear—MSm—(Anderson and Silver, 1979) (Figure 8). Most of the outcrops north of the MSm are formed by Jurassic igneous rocks, but these rocks are not present south of the MSm. These facts indicate that the Caborca terrane is not in its original position, but that it was displaced from some other geographic location. The most probable original position of the Caborca terrane is in southeastern California, as proposed by Anderson and Silver (1979). After reconstruction, as in Figure 11*B*, correlation is apparent between the Triassic and Jurassic sections of southeastern California and Nevada, and the Antimonio Formation. Likewise, a continuation is also encountered between the truncated Antler/Sonoma and the Sonoran orogen belt (this last formed during the Sonoran orogeny [Poole, 1993; Poole *et al.*, 1991]).

The proposed tectonic reconstruction (Figure 11) shows, from northeast to southwest, a transition from Triassic cratonal (Moenkopi-Chinle) strata to shallow marine strata with interbedded volcanics (Union Wash-Kings sequence) that grade to deeper marine rocks of the Antimonio and to basinal deposits of the San Hipólito Formation in Vizcaíno, Baja California (Figure 11*C* and *D*). Similarly, cratonal rocks (Figure 11*D*, locality 8) of Early Jurassic (Hettangian-Toarcian) age grade to volcanics (9), intra-arc (10), fore-arc (11 and 6), and basinal rocks (12). Igneous strata in sections 9 and 10 (Figure 11*D*) indicate they were located within, and record inception and development of the NW-SE-trending Late Permian to Triassic-Jurassic intracratonic volcanic arc of southwestern U.S.A.

Figure 10. Outcrop of a section of Norian limestones in locality of Barra Los Tanques (Figure 8) with sponges and corals that belong to unit 13 of the Antimonio Formation. The Norian section is 30-m thick and it is thrust over Paleozoic strata.

The Caborca terrane moved southeastward along the MSm, to its present position, during Middle to Late Jurassic time. However, in order to avoid disruption of the Late Permian to Triassic magmatic arc (Miller and collaborators [1995]; also note alignment in fig. 4 of Triassic plutons in southern California taken from Burchfiel and collaborators [1992]) and correlative sections of the Antimonio Formation in southwestern U.S.A., the most favorable position of the MSm should be traced as shown in Figure 11*B*. Although most of this fault has been obliterated by the Sierra Nevada batholith, it could probably coincide with the San Andreas fault system in southern California, and with the Foothills Suture in central California.

DISCUSSION

The Antimonio Formation of northwestern Sonora is herein redefined as an almost completely marine sedimentary succession about 4-km thick that ranges in age from Late Permian to Early Jurassic. It contains 14 unconformity-bounded sequences that probably represent eustatic sea-level changes, as each is roughly coincident with third order cycles of Haq and collaborators (1988). Most of these sequences start at its base with a fluvial conglomerate that grades upward to finer-grained lithologies representing shallow to deep-marine environments. Based mainly on ammonoid identification, the Spathian, Anisian, Carnian, Norian and Rhaetian stages of the Triassic System are recognized. Sequence II could be of Smithian age and sequence V could be of Ladinian age. The Jurassic System is also represented by the upper Hettangian, Sinemurian, and Pliensbachian Stages.

The Antimonio Formation also contains the Permian-Triassic and Triassic-Jurassic systemic boundaries, which are represented by unconformities. The Permian-Triassic systemic boundary is believed to fall at the base of sequence II, whereas the Triassic-Jurassic system boundary falls at the base of sequence X.

Other correlative stratigraphic sections of the Antimonio Formation are partial sections of Triassic and Lower Jurassic strata that are widely distributed in northwestern Sonora, established as fragments of the Antimonio terrane. Strata in these areas have marked differences with Upper Triassic strata of the fluvial to marginal-marine Barranca Group of central Sonora, which is linked with the craton. The time of thrusting of the Antimonio terrane over the Caborca terrane has been proposed to be older than, or contemporaneous with, movement on the MSm, as Lower Jurassic rocks at Cerro Basura just north of Caborca (Figure 8) are strongly deformed along the trace of the MSm (González-León, 1989).

The Antimonio section is also herein proposed to be correlative with Upper Permian, Lower, Middle and Upper Triassic, and Lower Jurassic strata that crop out in southeastern California and the southern tip of Nevada. The position of the Antimonio terrane is considered originally to have been located just south of these sections and later translated to its present position during Jurassic time along the Mojave Sonora megashear. The Permian to Middle Triassic strata of California record sedimentation from a cratonal to a shallow shelf (Moenkopi Formation), grading into deeper marine environments (including the lower Antimonio Formation) to the south, and turbiditic strata in Baja California (El Volcán locality). The Middle and Upper Triassic sections of that region in the United States record in the same way sedimentation grading from continental (Chinle Formation) to shallow marine (*i.e.*, Union Wash Formation) and volcanics (like in the Inyo Mountains; Figure 11*D*), and to shallow shelf sedimentation, like in the Kings Sequence (Figure 11*D*) and Antimonio Formation. Basinal deposits, on the other hand, are recorded in the Triassic part of the San Hipólito Formation in Baja California, most likely at the site of a subduction zone (Finch and Abbott, 1977).

Strata of Early Jurassic time in California record an increase in igneous activity in the volcano-plutonic arc that began activity probably in Late Permian time (Walker, 1988). South of the volcanic arc, rocks of this time interval are represented by mostly marine deposits in the southern Sierra that grade southward to deeper marine deposits in the Antimonio and San Hipólito Formations. The Lower Jurassic sandstone and conglomerate strata of the Antimonio terrane, however, clearly record the proximity of this volcanic activity by an increase in its volcanic detritus and interbedded tuffs, compared with Triassic rocks (Stanley and González-León, 1995).

According to these ideas, it is suggested that the Antimonio Formation records mostly deposition in a forearc basin that was bordered to the north by a volcano-plutonic arc and to the south by subduction complexes. The location of the MSm in southeastern California, which later transported the

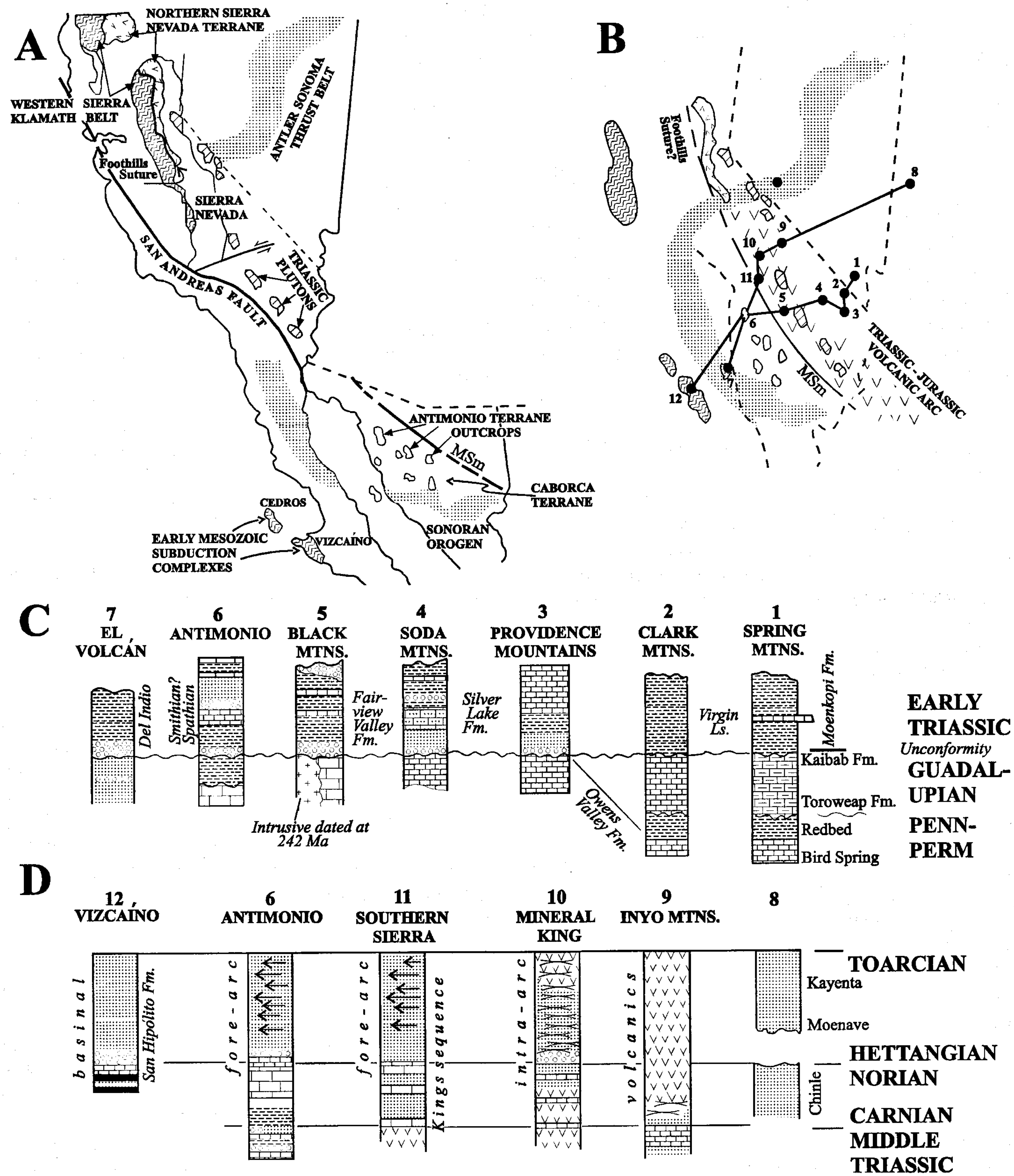

Figure 11. *A*, Generalized tectonic map of southwestern U.S.A. (from Saleeby and Busby-Spera, 1992) and northwestern Mexico. *B*, Interpreted pre-Late Jurassic paleogeography of the SW margin of the North American craton showing the proposed location of the Mojave-Sonora megashear (MSm) and location of correlated Permian, Triassic and Lower Jurassic outcrops (location numbers same as in *C* and *D*). *C*, Correlation of Upper Permian and Lower Triassic strata of southeastern Nevada, southeastern California (information taken from Burchfiel and collaborators [1992], and Walker, [1987]), Sonora, and Baja California along restored position of the Caborca terrane prior to movement along the MSm. *D*, Correlation of Middle to Upper Triassic and Lower Jurassic rocks on restored position of the Caborca terrane (sections 8 to 11 redrawn from Saleeby and Busby-Spera [1992]; section 12 from Finch and Abbott [1977] and from Whalen and Pessagno [1984]). Lithologic symbols same as in Figure 2.

Antimonio terrane about 800 km to the southeast, should be placed just south of the sections in California, which are probably in their original location. The trace of this major structure probably coincides in part with the San Andreas fault and continues northward along the Foothills suture in California (Figure 11).

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