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Tectonic insights from an Upper Jurassic–Lower Cretaceous stretched-clast conglomerate, Caborca–Altar region, Sonora, Mexico

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Abstract

The ranges directly northeast of Caborca and Altar preserve a 2000 + m-thick folded section of the Altar Formation, composed of ductilely deformed Upper Jurassic–Lower Cretaceous polymict conglomerate, sandstone, mudstone, and andesite. Stratigraphic relationships indicate that this section, which accumulated in a 60 km-long northwest-trending basin, is broadly correlative with the Glance Conglomerate. Coarse (boulder–cobble) detritus in the lower part of the section was shed from prominent highlands consisting of the Middle Jurassic magmatic arc and the Neoproterozoic–Paleozoic miogeocline. In the pebbly upper part of the section, abundant sandstone, mudstone, lacustrine(?) carbonate, and felsic tuff interstratified with andesite flows, and breccias record lower-energy depositional conditions interrupted locally by volcanism. By the time of Bisbee Sea incursion into northwestern Mexico, the Jurassic arc source had disappeared and the miogeoclinal source was topographically subdued. The Lower Cretaceous Morita Formation, which conformably overlies the Altar Formation along a gradational contact, records marine transgression that accompanied regional subsidence.

Significant northeast–southwest contraction affected the Altar Formation, Bisbee Group, and Upper Cretaceous strata between 71 and 51 Ma. Characteristics of this Laramide event include asymmetric, northeast-verging folds and thrusts accompanied by penetrative southwest-dipping stretched-clast foliation or cleavage and greenschist-facies metamorphism. Mid-Tertiary normal faults overprint the compressional structures such that deeper levels of the stratigraphy are juxtaposed against shallower levels, and axial planes of major range-scale folds are rotated about horizontal axes relative to one another.

Keywords: Conglomerate; Altar Formation; Faults; Tectonic

1. Introduction

Northern Sonora, Mexico contains extensive exposures of Mesozoic conglomerate (Fig. 1a) whose facies distributions and provenance patterns provide important constraints on tectonic models that have been proposed for the region. Unfortunately, original Mesozoic depositional relationships in northern Sonora are commonly overprinted by metamorphic fabrics and structures associated with mid-Tertiary extensional core complex development and/or Laramide contraction (Salas, 1968; Davis et al., 1981; Nourse, 1990, 1995; Jacques-Ayala et al., 1990; Nourse et al., 1994, 1996). Much debate focuses upon the age of certain deformed conglomeratic sections, specifically, whether they were deposited during Late Jurassic time (Nourse, 1995; Nourse et al., 1996, 2000), Late Cretaceous time (Jacques-Ayala et al., 1990; Jacques-Ayala and De Jong, 1996; Jacques-Ayala, 2000), or both (Rodríguez Castañeda, 1988, 1997). Stratigraphic age assignments for many of these metaconglomerate bodies hinge upon contact relations with adjacent marine or lagoonal strata that have been correlated to the Lower Cretaceous Bisbee Group of southern Arizona (Dickinson et al., 1989; Jacques-Ayala, 1993, 1995). In a broad sense (Fig. 1b), those coarse clastic sections beneath the Bisbee Group correlate with the Glance Conglomerate (Ransome, 1904; Bilodeau et al., 1987), whereas the conglomeratic sections above the Bisbee Group are equivalent to Arizona's Fort Crittenden Formation (Hayes, 1987).

This paper addresses contentious issues regarding the depositional age and tectonic setting of Mesozoic stretched-clast conglomerate, sandstone, mudstone, and andesite (Altar Formation) exposed in several ranges directly northeast of Caborca and Altar (Fig. 2). Utilizing stratigraphic, sedimentologic, and structural field relationships, I argue that the clastic and volcanic section of Sierra El Batamote and southern Cerro El Alamo (Figs. 2 and 3) accumulated during Late Jurassic and Early Cretaceous time and was later affected by Laramide contraction and mid-Tertiary extension. I also propose a stratigraphic-structural

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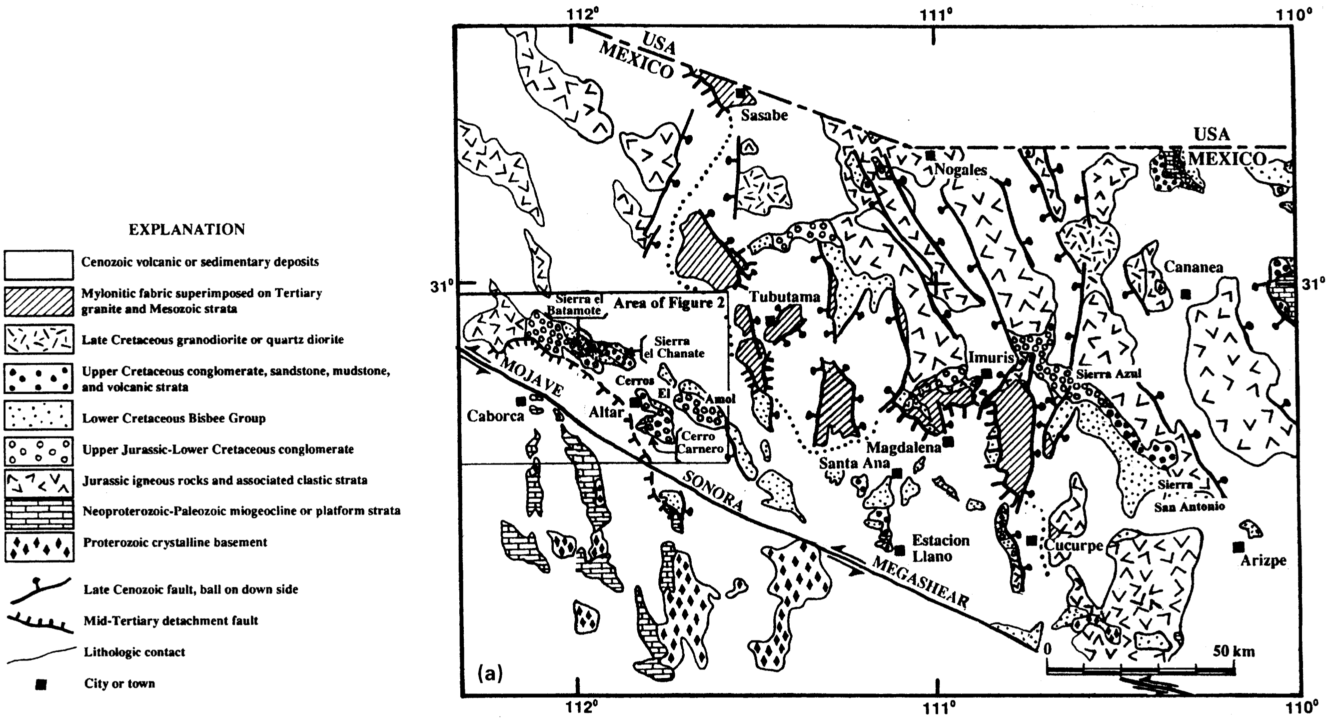


(b)

Stratigraphic Age	Northwest Sonora (Caborca-Altar region)	North Central Sonora (Imuris-Sierra Azul-Sierra San Antonio)	Northeastern Sonora (Cananea Region)	Southern Arizona
Upper Cretaceous	El Chanate Group: El Charro Volcanic Complex Escalante Formation Anita Formation Pozo Duro Formation	El Tuli Formation	Cabullona Group	Fort Crittendon Formation
Lower Cretaceous	Bisbee Group: Cintura Formation Arroyo Sasabe Formation Morita Formation	Bisbee Group: Cintura Formation Mural Limestone Morita Formation	Bisbee Group: Cintura Formation Mural Limestone Morita Formation	Bisbee Group: Cintura Formation Mural Limestone Morita Formation
Upper Jurassic	Altar Formation	Cocospera Conglomerate	Glance Conglomerate	Glance Conglomerate
Middle Jurassic and/or Older	Jurassic arc or Paleozoic miogeocline or Paleoproterozoic basement	Jurassic arc	Jurassic arc or Paleozoic platform or Paleoproterozoic Basement	Jurassic arc or Paleozoic platform or Paleoproterozic Basement

Fig. 1. Pre-Tertiary geology of northern Sonora. (a) Simplified geologic map, modified from Nourse (1995) and González-León and Lawton (1995) and Rodríguez Castañeda (1997), showing the Caborca–Altar study area and the distribution of Mesozoic conglomeratic sections discussed in the text. Trace of the Mojave-Sonora megashear from Anderson and Silver (1979). (b) Generalized correlation of Mesozoic lithostratigraphic units between Sonora and southeastern Arizona. Compiled from Taliaferro (1933) and Bilodeau et al. (1987) and Hayes (1987) and Dickinson et al. (1989) and Jacques-Ayala et al. (1990) and Anderson et al. (1995) and González-León and Lawton (1995) and Nourse (1995) and Rodríguez Castañeda (1997) and McKee and Anderson (1998).

correlation of the Sierra El Batamote section to the type section of Altar Formation in Cerros El Amol (the range directly southeast; see Jacques-Ayala et al., 1990; García y Barragán et al., 1998). This hypothesis, to be tested by future field and geochronological studies, requires an Upper Jurassic rather than Upper Cretaceous stratigraphic age for the Altar Formation. The new interpretation does however acknowledge the importance of Laramide-age contraction and metamorphism in the region as advocated by previous works (Jacques-Ayala et al., 1990; Jacques-Ayala and De Jong, 1996).

2. Regional Mesozoic stratigraphic framework

The interpretations presented in this paper build upon a Mesozoic stratigraphic framework of northern Sonora developed mainly since the late 1970s. Fig. 1b illustrates the general correlation of Mesozoic lithostratigraphic units between northern Sonora and southern Arizona. Mesozoic rocks of Sonora are generally subdivided into equivalents of the Arizona section, for example, mid-Jurassic magmatic arc, Upper Jurassic–Lower Cretaceous Glance Conglomerate, Lower Cretaceous Bisbee Group, and Upper Cretaceous Fort Crittenden Formation. Coarse clastic strata of the Glance Conglomerate and the Fort Crittenden Formation are widely believed to record Late Jurassic and Late Cretaceous tectonic upheavals, respectively. In Sonora, depositional relationships with adjacent Jurassic volcanic rocks and/or Lower Cretaceous marine strata are the key to differentiating these conglomeratic sections. Pertinent studies that facilitate this distinction are summarized below.

Variably metamorphosed rocks associated with the Jurassic magmatic arc occur in numerous ranges between the international border and a line extending southeast from Caborca (Fig. 1a). Stratigraphic relations have been described northwest of Caborca (Corona, 1979), southwest of Nogales (Segerstrom, 1987), south of Cucurpe (Rodríguez Castañeda, 1988), and east of Imuris (Nourse, 1995). Common Jurassic lithologies include rhyolite porphyry flows and tuffs interstratified with quartz arenite, rhyolite-clast conglomerate, porphyritic andesite, and biotite granite porphyry. Graphitic shale and red volcaniclastic sandstone containing Oxfordian ammonites occur in the Tuape–Cucurpe region (Rodríguez Castañeda, 1988). U/Pb zircon ages reported from Jurassic igneous rocks in Sonora range from 149–178 Ma, with most ages falling between 165–175 Ma (Anderson and Silver, 1978; Stewart et al., 1986).

The type Glance Conglomerate of Arizona is a coarse clastic unit stratigraphically sandwiched between the mid-Jurassic magmatic arc and the Lower Cretaceous Bisbee Group (Fig. 1b). Proposed correlative units in Sonora (Fig. 1a) occur southwest of Nogales (Segerstrom, 1987), north of Cananea (Imlay, 1939; González-León and Lawton, 1995), near Imuris (Nourse, 1995), and northeast of Caborca (this study). All of these Upper Jurassic–Lower Cretaceous sections contain locally derived Jurassic and/or older detritus, but lack clasts derived from the Bisbee Group.

Early literature on Lower Cretaceous strata of northern Sonora describes index fossils discovered in ranges north of Caborca (Keller, 1928; Cooper and Arellano, 1946), east of Santa Ana (Salas, 1968), and north and east of Cananea (Imlay, 1939). Work initiated by Cesar Jacques-Ayala in 1979 has refined the Cretaceous stratigraphy and sedimentology of the Caborca–Santa Ana region (Figs. 1 and 2). Jacques-Ayala (1983) mapped a Lower Cretaceous section in Sierra El Chanate and correlated it to Arizona's Bisbee Group (Jacques-Ayala and Potter, 1987). This section consists of light gray or purple sandstone and siltstone, red shale, and subordinate pebble conglomerate divided into lower and upper horizons (Morita and Cintura Formations, respectively) by the Arroyo Sasabe Formation, composed of oyster-bearing limestone, green sandstone, and mudstone. Correlative Lower Cretaceous strata, complexly folded and faulted, occur farther east near Sierra Azul (McKee and Anderson, 1998).

Sierra El Chanate also contains an Upper Cretaceous section (El Chanate Group) composed of conglomerate and sandstone interstratified with andesite flows and breccias (Jacques-Ayala et al., 1990; Fig. 1b). The El Chanate Group unconformably overlies the Cintura Formation and has been correlated (Jacques-Ayala, 1993) with the Fort Crittenden Formation of Arizona (Hayes, 1987) and the Cabullona Group of northeastern Sonora (Taliaferro, 1933; González-León and Lawton, 1995). Additional studies (Jacques-Ayala, 1995) established ties between the Cretaceous section of Sierra El Chanate and sedimentary strata exposed in various ranges between Santa Ana and Altar.

3. Stretched-clast conglomerate of Sierra El Batamote and Cerro El Alamo

The southern part of Sierra El Batamote preserves superb exposures of stretched-clast conglomerate associated with penetratively cleaved sandstone, mudstone, and volcanic rocks (Figs. 3 and 4). This folded section continues to the northwest, where stratigraphically shallower levels are less metamorphosed. Outcrops in the northern Sierra El Batamote and southern Cerro El Alamo may be accessed from the paved highway through Puerto El Alamo. Gradational depositional contacts with overlying Bisbee Group strata exist at several localities in the eastern parts of Sierra El Batamote and Cerro El Alamo.

Details of the stretched-clast conglomerate belt (Altar Formation) were mapped at scales of 1:16,000 and 1:24,000 (Nourse, 1995; Curtis, 1996; Nourse et al., 1996; Figs. 3 and 4). The Altar Formation in Sierra El Batamote and Cerro El Alamo is generally composed of: (1) a lower coarse clastic unit composed mainly of polymict

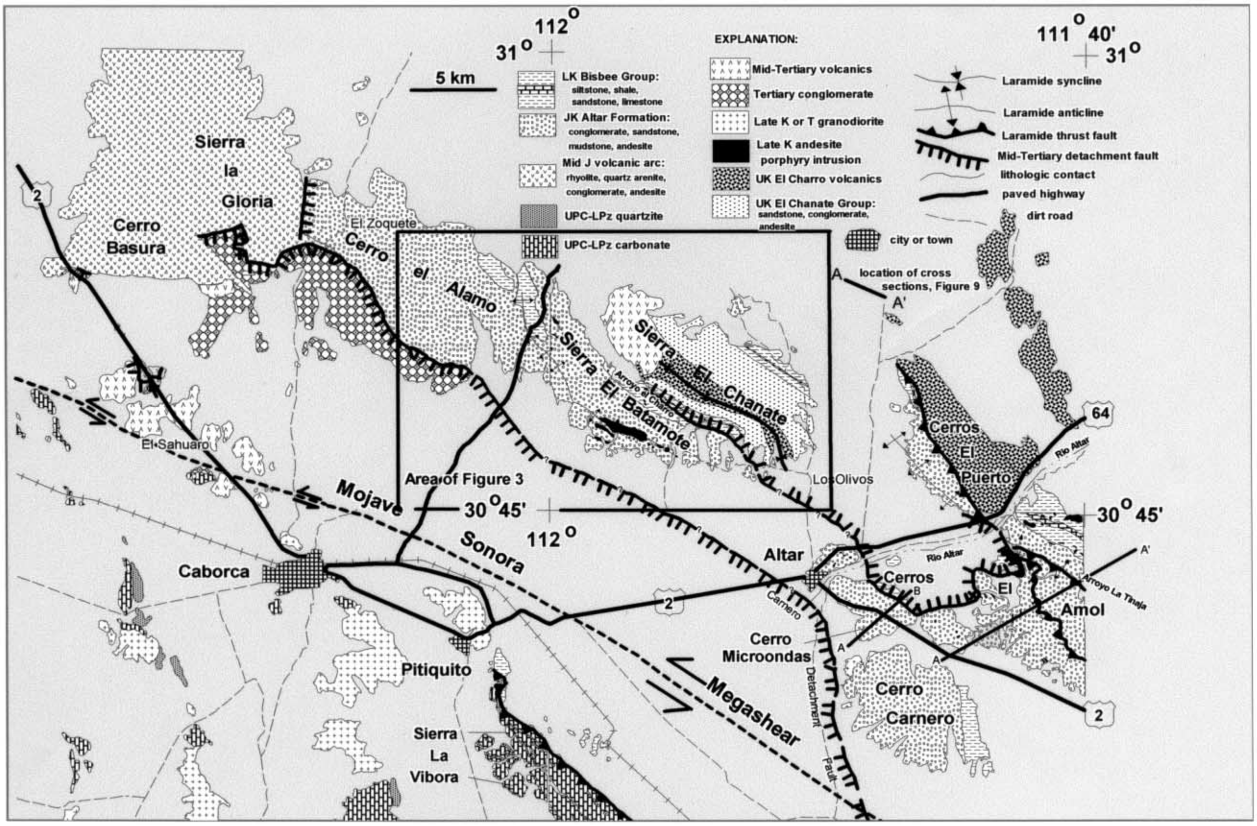


Fig. 2. Geologic map of the Caborca–Altar region. Geology outside the Sierra El Batamote–Cerro El Alamo study area simplified from Corona (1979) and Hayama et al. (1984) and De Jong et al. (1988) and Jacques-Ayala et al. (1990) and García y Barragán (1992) and Jacques-Ayala (1993) and Nourse et al. (1994). Trace of the Mojave-Sonora megashear from Anderson and Silver (1979).

cobble–boulder conglomerate and lithic sandstone, which grades upward into (2) medium-grained sandstone interlayered with phyllitic siltstone and shale. The upper unit is interstratified with andesitic flows and pebble conglomerate lenses. Thin brown lacustrine(?) carbonate layers or calcareous nodules characterize the mudstone horizons within both units. Several traverses through the upper Altar Formation reveal gradational upward transitions into younger strata previously mapped (Jacques-Ayala et al., 1990) as Bisbee Group. This consistent depositional relationship constitutes the main basis for assigning a pre-Lower Cretaceous age to the Altar Formation.

3.1. Stratigraphy and sedimentology

3.1.1. Map relations

The geologic map and cross sections (Figs. 3 and 4) reveal the stratigraphy of Sierra El Batamote and southern Cerro El Alamo. Stratigraphically low parts of the Altar Formation are exposed in the southeastern and central Sierra El Batamote. At this location (sections A-A′ and B-B′ of Fig. 4), a 600–800 m-thick section of foliated polymict conglomerate interbedded with lithic sandstone (map unit JKcg; Fig. 5a–c) forms both limbs of an eroded, locally overturned anticline. In the core of the anticline, resistant quartzose sandstone and quartzite–pebble conglomerate beds are interstratified with strongly cleaved, phyllitic purple-gray siltstone and shale containing prominent brown, recrystallized calcareous nodules. Along strike to the northwest, an older polymict conglomerate underlies these phyllitic beds.

An interval of brown or gray medium-grained lithic sandstone interlayered with cleaved green or purple siltstone and shale and rare brown carbonate (unit JKss) generally overlies the polymict conglomerate-rich section. Calcareous nodules also occur in these beds, which are present on both limbs of the Sierra El Batamote anticline (Fig. 4, sections A-A′, B-B′, and C-C′) and in the vicinity of Puerto El Alamo (section D-D′). A distinctive characteristic of these younger units of the Altar Formation is the occurrence of interstratified and/or laterally interfingering volcanic rocks. Most common are porphyritic andesite flows and breccias (units JKa and JKabr; Fig. 5d), characterized by a groundmass altered to chlorite and epidote. Also present are cream-colored, very fine-grained felsic layers that may have originally been rhyolite tuffs. The deformed thickness of this finer clastic and volcanic portion of the upper Altar Formation varies from 500 m to greater than 1200 m.

Depositional contacts between the upper Altar Formation and Bisbee Group strata (unit Kb) occur in Arroyo El Charro

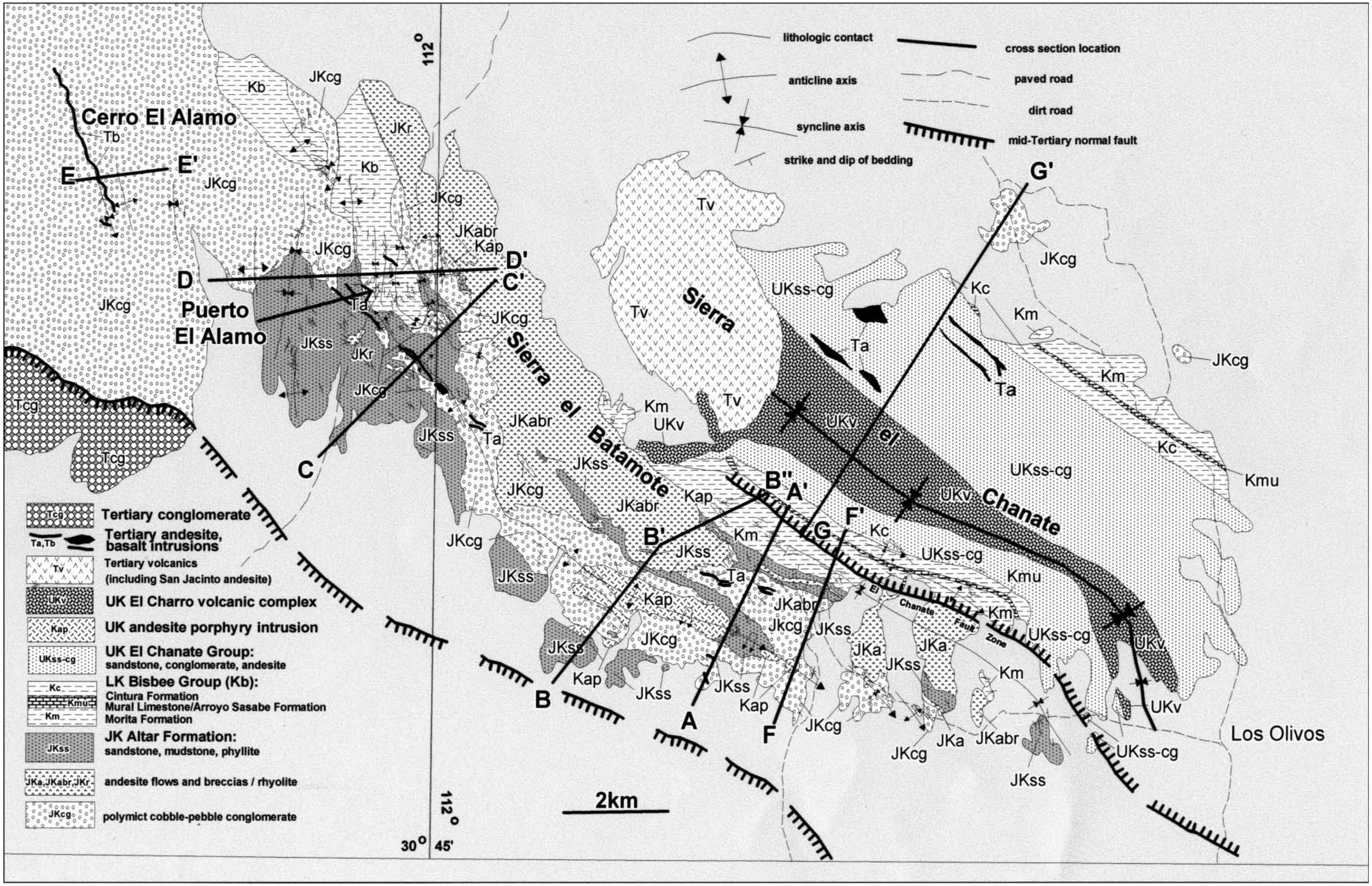
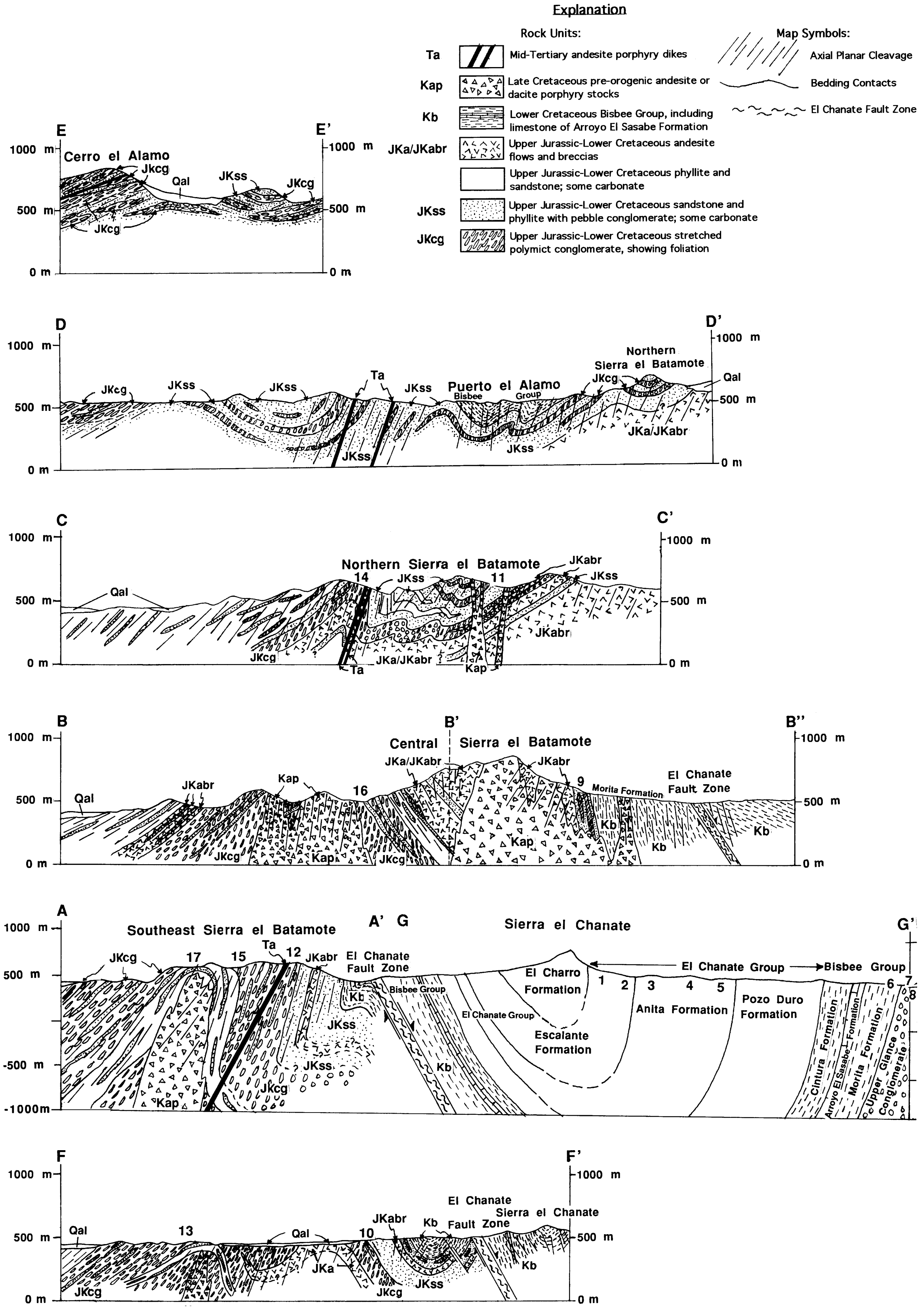


Fig. 3. Geologic map of Sierra El Batamote and the southeastern portion of Cerro El Alamo showing locations of cross sections in Fig. 4. Mapping in Sierra El Chanate compiled from Jacques-Ayala (1993).


Explanation
Rock Units:
Ta
Mid-Tertiary andesite porphyry dikes
Kap
Late Cretaceous pre-orogenic andesite or dacite porphyry stocks
Kb
Lower Cretaceous Bisbee Group, including limestone of Arroyo El Sasabe Formation
JKa/JKabr
Upper Jurassic-Lower Cretaceous andesite flows and breccias
Upper Jurassic-Lower Cretaceous phyllite and sandstone; some carbonate
JKss
Upper Jurassic-Lower Cretaceous sandstone and phyllite with pebble conglomerate; some carbonate
JKcg
Upper Jurassic-Lower Cretaceous stretched polymict conglomerate, showing foliation
Map Symbols:
Axial Planar Cleavage
Bedding Contacts
El Chanate Fault Zone
E
E'
1000 m
500 m
0 m
Cerro el Alamo
Jkcg
Qal
JKss
JKcg
JKcg
D
D'
1000 m
500 m
0 m
JKcg
JKss
JKss
Ta
JKss
Puerto el Alamo
Bisbee Group
Northern Sierra el Batamote
JKcg
Qal
JKss
JKss
JKa/JKabr
C
C'
1000 m
500 m
0 m
Qal
Northern Sierra el Batamote
14
JKss
11
JKabr
JKss
JKcg
JKa/JKabr
Ta
Kap
JKabr
B
B'
B"
1000 m
500 m
0 m
Qal
JKabr
Kap
16
Central
Sierra el Batamote
JKa/JKabr
JKabr
9
Morita Formation
El Chanate Fault Zone
JKcg
Kap
JKcg
Kap
Kb
Kb
Kb
A
A'
G
G'
1000 m
500 m
-500 m
-1000m
Southeast Sierra el Batamote
JKcg
17
15
Ta
12
JKabr
El Chanate Fault Zone
Bisbee Group
Kb
JKss
JKss
JKcg
Kap
Kb
Sierra el Chanate
El Charro Formation
El Chanate Group
Escalante Formation
1
2
3
4
5
El Chanate Group
Bisbee Group
Anita Formation
Pozo Duro Formation
6
7
8
Cintura Formation
Arroyo El Sasabe Formation
Morita Formation
Upper Glance Conglomerate
F
F'
1000 m
500 m
0 m
Qal
13
Qal
10
JKabr
Kb
El Chanate Fault Zone
Sierra el Chanate
JKa
JKss
JKcg
JKcg
Kb

and near roads leading to the El Batamote gold prospects. Along two transects (Fig. 4, sections F-F′ and B′-B″), the section is upright and conformable with generally northeast-dipping bedding pervaded by steeply southwest-dipping or vertical cleavage. A similar sequence is overturned in Section A-A′ where bedding and cleavage both dip southwest. From older to younger, green or dark purple-gray stretched polymict cobble–pebble conglomerate fines upward into pinkish-orange calcareous sandstone and orange-brown lithic sandstone locally interstratified with green siltstone. Stratigraphically up the section is a 50–100 m-thick layer (1200 m-thick in section B′-B″) of green cleaved andesite breccia with interbeds of green sandstone and granule–pebble conglomerate. Conformably overlying this volcanic interval is more brown sandstone or pinkish-red calcareous sandstone with rare layers of recrystallized brown carbonate. The bottom of the Bisbee Group is marked by a concordant transition to grayish-purple sandstone with lenses of purple pebble conglomerate. Farther up the section, dark purple or red siltstone and mudstone characteristics of the Morita Formation are interbedded with light purple sandstone and pebble conglomerate. Several upward-fining sequences suggest that the section faces northeast. Still higher in the section, Bisbee Group strata are folded into an asymmetric range-scale syncline (Figs. 2 and 4, section G-G′). The core of this syncline, exposed in the higher parts of Sierra El Chanate, is composed predominately of conglomerate and sandstone interlayered with andesite flows and breccias (the Upper Cretaceous El Chanate Group and El Charro volcanic complex of Jacques-Ayala et al., 1990).

Similar relationships between the Altar Formation and Bisbee Group are exposed in the northeastern Sierra El Batamote and in the hills southeast of Cerro El Alamo. Metamorphic grade is lower at these localities (Fig. 4, sections C-C′ and D-D′), although the beds are tightly folded along north–northwest or north-trending hinges. The transition from the upper Altar Formation into the Morita Formation is conformable and gradational. Conglomerate beds with similar clast assemblages are present in both units. In this area, the contact is defined by an abrupt color change in siltstone and shale beds from green or olive-gray or dark grayish-purple to bright red or reddish-purple. Also, brown lithic sandstone of the underlying Altar Formation contrasts with the light purple or reddish-pink sandstone of the Morita Formation.

Two varieties of hydrothermally altered andesitic intrusions predate metamorphic fabrics associated with the compressional deformation. In the southern part of Arroyo El Charro and along the lower hill slopes to the west, an older group of 1–5 m-thick dikes forms tabular sheets oriented parallel to foliation in the host JKcg unit (Fig. 5e). These dark green, fine-grained, slightly porphyritic dikes are pervasively altered to chlorite and epidote. Most exhibit aphanitic, relatively resistant chilled margins; however, the dike interiors display a strong cleavage parallel to that in the host conglomerate (Fig. 5f). These dikes may have fed andesite flows in the upper Altar Formation, based on the observation that they nowhere intrude the Bisbee Group strata.

A younger generation of pre-kinematic hypabyssal andesite or dacite porphyry stocks (map unit Kap) intrudes the Altar Formation as well as the overlying Bisbee Group. These massive, medium-grained stocks share cleavage orientation with their host strata, and tend to form prominent ridges in the central Sierra El Batamote (Fig. 4, section B-B′-B″). A distinct green color has resulted from matrix alteration to chlorite and epidote. Uniform, phenocryst-rich textures distinguish these hypabyssal intrusions from the older green andesite breccias and associated fine-grained andesitic dikes. The younger andesite resembles irregular bodies of Late Cretaceous(?) Oquitoa andesite that intrudes the type Altar Formation in Cerros El Amol (Fig. 2).

3.1.2. Conglomerate characteristics and provenance

Clast characteristics (Table 1) of conglomerate beds within the Altar Formation and overlying Cretaceous strata constrain the composition and relative proximity of exposed bedrock sources that supplied coarse sediment to a major basin. In general, clasts from deeper parts of the Altar Formation are larger and less rounded than those observed at shallower stratigraphic levels. The subangular boulders and cobbles observed in clast-supported conglomerate beds at lower levels are suggestive of steep local relief that provided the gravitational potential for intermittent debris avalanches. Well-rounded pebbles and granules in sandy matrices indicate predominantly fluvial depositional mechanisms for conglomerate of the upper Altar Formation and lower Bisbee Group.

Clast-composition data, although not taken systematically, reveal the importance of distinct pre-Cretaceous bedrock sources during Late Jurassic deposition and emergence of new sources during Cretaceous time. Table 1 lists clast lithologies in estimated order of decreasing abundance, with predominant clast types italicized. In general, conglomerate beds in the lower Altar Formation contain abundant rhyolite porphyry, fine-grained felsite, quartzite, quartz arenite, and gray andesite-porphyry clasts. Subordinate but locally conspicuous clasts include black chert, brown or dark-gray carbonate, and green andesite porphyry. Rare basalt clasts also occur. The quartzite, chert, and carbonate clasts are most likely derived from

Fig. 4. True-scale geologic cross sections showing relationship of the Altar Formation to Bisbee Group in Sierra El Batamote and southern Cerro El Alamo. Numbers indicate positions of conglomerate beds described in Table 1. Refer to Fig. 3 for section locations. Section G-G′ is modified from Jacques-Ayala et al. (1990).

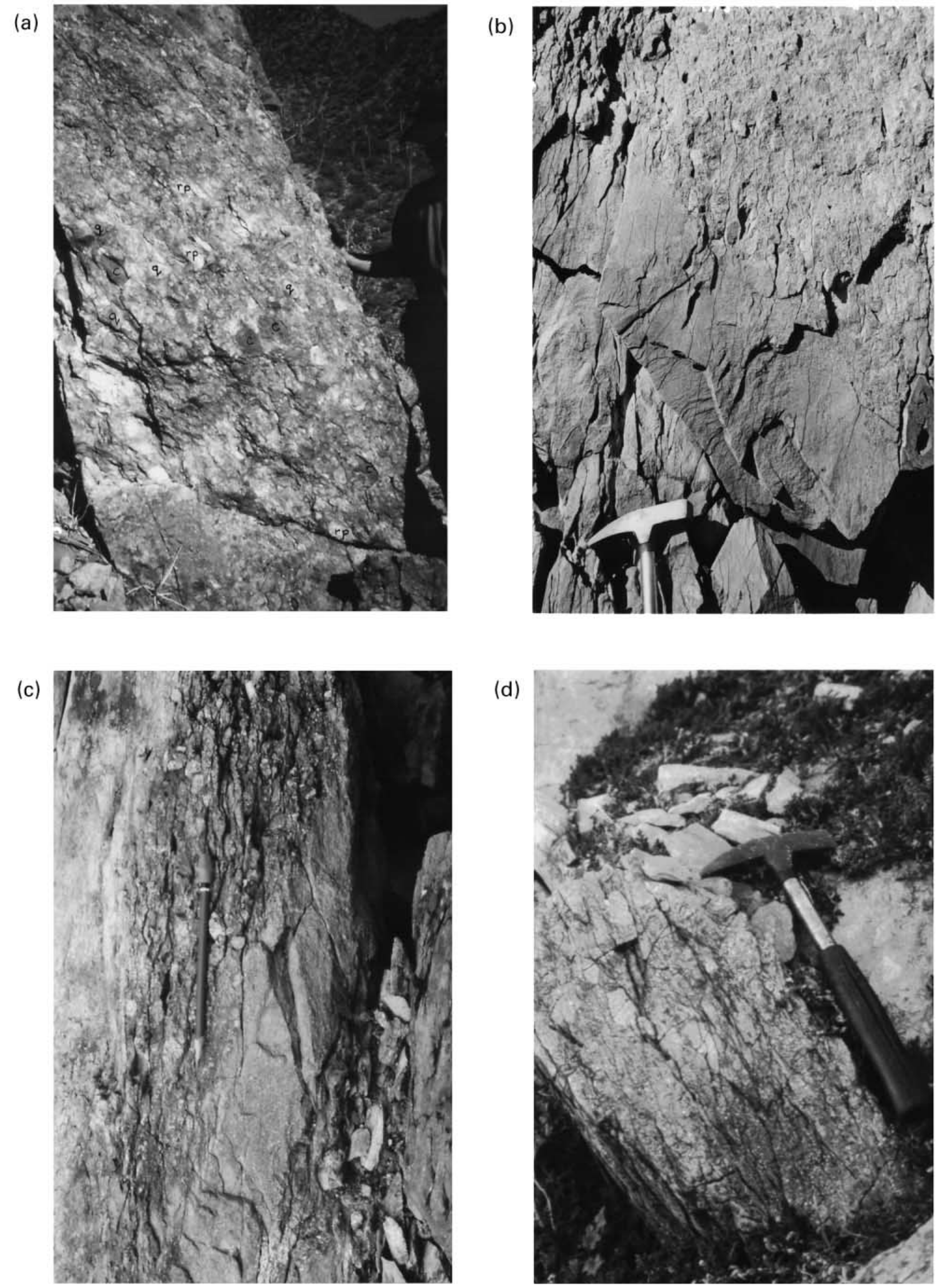


Fig. 5. Photographs of field relationships in Sierra El Batamote. (a) Typical outcrop of stretched Upper Jurassic–Lower Cretaceous polymict conglomerate (map unit JKcg). Note resistant quartzite clasts (q) and fine-grained, more easily weathered carbonate clasts (c). Rhyolite porphyry clasts (rp) are also prominent. View to the southeast. (b) Sandstone bed in contact with stretched conglomerate on the southwest limb of the southern Sierra El Batamote anticline. Note discordant pebble foliation. View to the southeast. (c) Sandstone bed discordant to foliation in stretched polymict conglomerate, on the northeast limb of the El Batamote anticline. View to the southeast. (d) Outcrop of foliated andesite breccia (map unit JKabr) showing distinctive 'diamond' cleavage. View to the southeast. (e) Late Jurassic(?)–Early Cretaceous(?) andesite dike intrudes JKcg unit. Note chilled margins and cleaved interior. (f) Close-up view of chilled margin in Late Jurassic(?)–Early Cretaceous(?) andesite dike (different location from (e)). Note cleavage in dike interior oriented parallel to foliation in the stretched pebble conglomerate host.

Neoproterozoic–Paleozoic sources that characterize the Caborca region south of Highway 2 (Stewart et al., 1984; Figs. 1 and 2). The rhyolite porphyry, felsite, quartz arenite, and andesite clasts probably were shed from the Middle Jurassic arc, exposed directly northwest of the study area in Sierra La Gloria and Cerro Basura (Corona, 1979; Fig. 2). Other possible sources of Jurassic arc detritus occur in ranges located north and northeast of the study area (Anderson and Silver, 1978; Nourse, 1995; Fig. 1a).

Stratigraphically higher levels of the Altar Formation

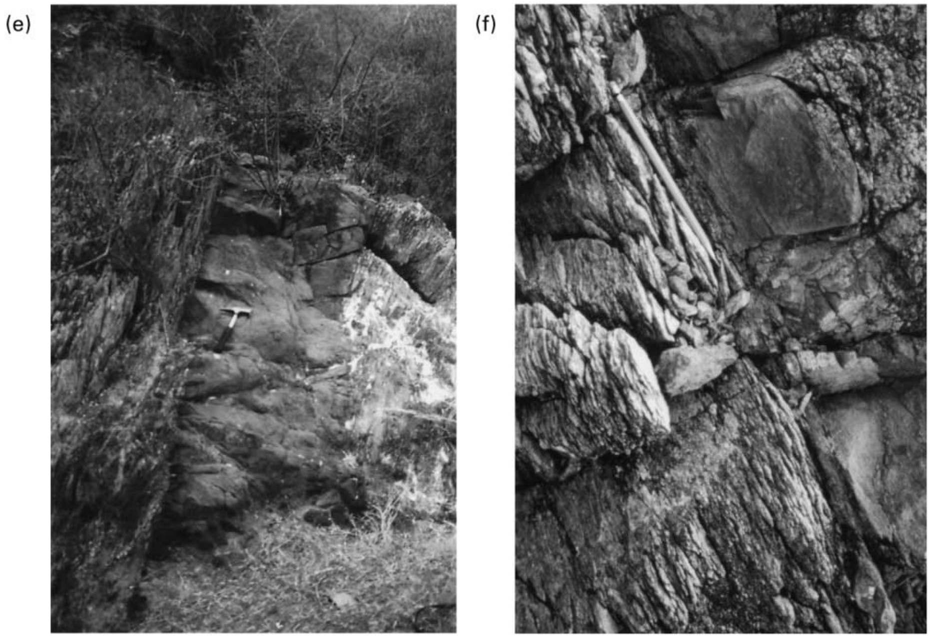


Fig. 5. (*continued*)

include additional clast types (Table 1). Well-rounded rhyolite porphyry, felsite, quartzite, and chert pebbles persist, but subangular gray or green porphyritic andesite fragments (probably derived from the JKa or JKabr units) are more abundant. Within the Morita Formation, pebble–granule conglomerate beds generally lack carbonate clasts but contain abundant red or dark purple mudstone intraformational rip-up clasts in addition to andesite, rhyolite, and quartzite clasts. Conglomerate and breccia in the Upper Cretaceous El Chanate Group (Jacques-Ayala, 1993) contain abundant subangular gray-purple andesite clasts, probably derived from contemporaneous volcanic flows. These beds are also characterized by abundant purple sandstone and red mudstone clasts derived from underlying Bisbee strata. Rare cobbles of light gray oyster-bearing limestone derived from the Aptian–Albian Arroyo Sasabe Formation distinguish conglomerate beds of the El Chanate Group from those in the Altar Formation.

3.2. Structure

Much of the controversy regarding the depositional age of the Altar–Caborca stretched-clast conglomerate belt can be attributed to Laramide and/or mid-Tertiary tectonic overprinting that has disturbed and sometimes obscured primary depositional features. The strata of Cerro El Alamo, Sierra El Batamote, and adjacent Sierra El Chanate are folded and faulted to varying degrees and are commonly pervaded by a cleavage or foliation that accompanied compression and low-grade metamorphism during Late Cretaceous or Early Tertiary time. In addition, the Caborca–Altar region has been affected by mid-Tertiary extension that resulted in dike emplacement, normal faulting, and local detachment faulting. Below, I describe geometric and timing constraints on structures that affect Jurassic and Cretaceous strata of the study area.

3.2.1. Bedding/cleavage relationships

Throughout Sierra El Batamote, a subvertical to steeply southwest-dipping cleavage dominates the mesoscopic structure of all Mesozoic rocks (Fig. 6d,f and h). Cleavage in the northeast slope of Cerro El Alamo generally dips more gently to the southwest (Fig. 6b). The cleavage is especially pervasive in siltstone or shale protoliths. Bedding in these phyllitic strata is generally obliterated or transposed. Conglomerate layers preserve a similarly oriented foliation defined by a prominent plane along which pebbles and cobbles are flattened (Fig. 5a–c). Likewise, the andesite breccia (unit JKabr) exhibits a ‘diamond cleavage’ that anastamoses between flattened breccia clasts (Fig. 5d). Within many sandstone and conglomerate layers, however, bedding is discordant to cleavage or foliation. The best outcrops display contacts between sandstone and conglomerate beds (Fig. 5b and c) or between sandstone and siltstone beds. Systematic variations in bedding (Fig. 6a,c,e and g) relative to cleavage define a series of folds with northwesterly or northerly hinges and southwest-dipping axial surfaces.

The foliated metasedimentary and metavolcanic strata of Sierra El Batamote and Cerro El Alamo preserve syntectonic prograde metamorphic mineral assemblages. Ubiquitous chlorite, epidote, sericite, and very fine biotite in the finer-grained protoliths as well as ductilely flattened conglomerate clasts indicate that deformation occurred under lower greenschist-facies conditions. Newly grown, strongly aligned phyllosilicates define the axial planar

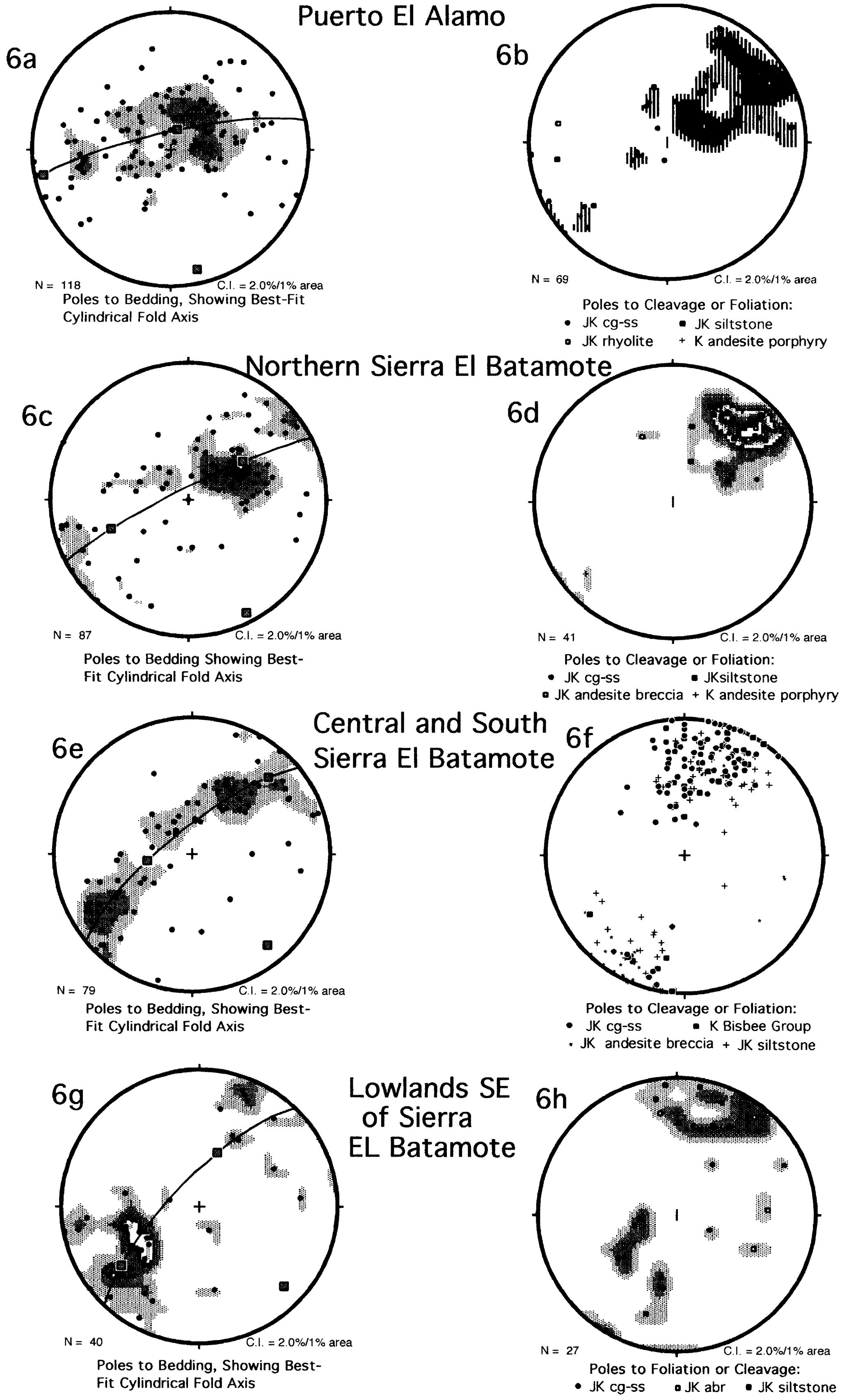


Fig. 6. Lower hemisphere equal area stereonets showing bedding and cleavage in the Altar Formation and Bisbee Group of Sierra El Batamote and Cerro El Alamo. Stereonet plotting and contouring program by Allmendinger (1995).

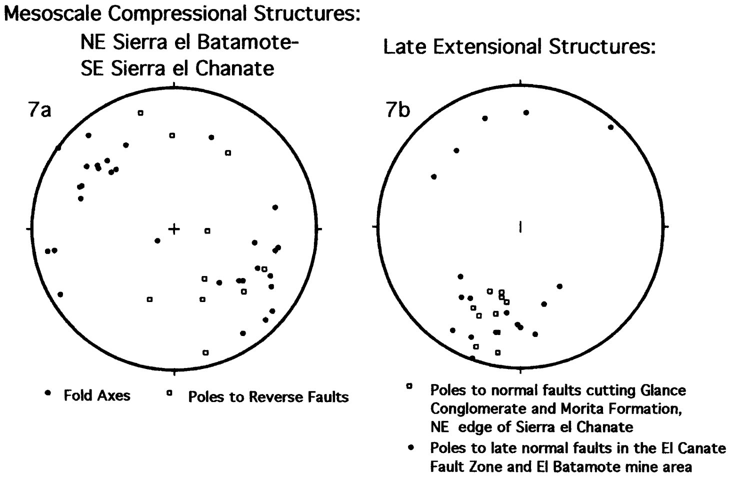


Fig. 7. Lower hemisphere equal area stereonets showing compressional structures and normal faults affecting Jurassic and Cretaceous strata of Sierra El Batamote and Sierra El Chanate. Stereonet plotting and contouring program by Allmendinger (1995).

cleavage that accompanied folding. Abundant quartz veins that crosscut cleavage probably are a manifestation of fluids released during peak metamorphism of the sediments. It is interesting that the strongest deformational fabrics occur in deeper stratigraphic and structural levels of Sierra El Batamote where pre-tectonic andesite or dacite porphyry stocks (unit Kap) are especially common. This observation supports a spatial relationship between intrusion of Kap and subsequent compression and metamorphism.

3.2.2. Map scale folds and associated reverse faults

The map distribution of bedding, cleavage, and individual lithologic units in Sierra El Batamote, Cerro El Alamo, and Sierra El Chanate defines a northwest-striking fold belt (Fig. 3). Structures associated with this contractional belt affect strata as young as the Upper Cretaceous El Charro Formation (Jacques-Ayala et al., 1990). Asymmetries in bedding combined with a consistently southwest-dipping axial-planar cleavage (Figs. 4 and 6) indicate fold vergence to the northeast. These folds are probably linked at depth to northeast-directed reverse faults. The axial surface of the El Chanate syncline dips 65° northeast (Fig. 4, section G-G′), measurably discordant to axial planar cleavage that penetrates Sierra El Batamote. This structural mismatch may be the result of younger horizontal axis rotation of Sierra El Chanate along the El Chanate fault zone and related mid-Tertiary normal faults (see below).

In the Puerto El Alamo area, reversals in bedding define a group of four tight, upright, north or north–northwest-trending fold pairs with subvertical to steeply southwest-dipping axial planes and hinges that plunge shallowly south. These folds project southeastward along strike into the central Sierra El Batamote. Deeper structural levels are exposed in the southeastern Sierra El Batamote, where the structure is dominated by one major overturned anticline associated with steeply southwest-dipping axial planar cleavage (Fig. 4). The locally overturned northeast limb of this anticline, which includes subvertical beds of Morita Formation in the southwest limb of the El Chanate syncline, appears to be tectonically thinned by bedding plane faults. Mesoscopic S and Z folds observed in the anticline–syncline inflection zone (Fig. 7a) are compatible with flexural-slip folding and/or northeast-directed reverse faulting.

The anticline of the southern Sierra El Batamote plunges southeastward into the lowlands surrounding the old El Batamote mining prospect. In this area, several tight folds affect shallower levels of the Altar Formation and lower parts of the Bisbee Group (Figs. 3, 4 and 6g,h). The El Chanate fault zone (described below) separates these folded beds from Lower Cretaceous strata exposed in the southwest slope of Sierra El Chanate.

The fold belt projects into the ranges southeast of the study area, where a faulted anticline characterizes the structure of Cerros El Puerto and Cerros El Amol (Fig. 2). Northeastward fold vergence is indicated by asymmetry of bedding on opposite limbs and locally strong southwest-dipping cleavage. Two thrust faults (postulated below) appear to disrupt the anticline hinge and the southwest limb in Cerros El Amol. Projection of these thrusts northwest of the Rio Altar suggests kinematic linkage to folding in Sierra El Chanate and Sierra El Batamote.

3.2.3. Timing constraints on the compressional structures

The age of compressional deformation in the study areas is loosely constrained between Late Cretaceous and Early Tertiary time. A hornblende andesite flow sampled from the folded El Charro volcanic complex in the core of the El Chanate syncline (Fig. 4, section G-G′) yielded an ^{39}Ar/^{40}Ar age of 71 Ma (Jacques-Ayala, 2000). The undeformed San Jacinto volcanics (Fig. 3, map unit Tv), which overlap the northwestern end of the El Chanate syncline, have yielded a whole-rock K/Ar date of 51 ± 2 Ma (Jacques-Ayala, 2000). In addition, a K/Ar age of

57 ± 3 Ma is reported for a sample of Altar schist collected near Rancho La Bateyera in the southwestern Cerros El Amol (Damon et al., 1962). Assuming that (a) this K/Ar age records the thermal event that accompanied compression and prograde metamorphism in deeper levels of the Altar Formation, and (b) the metamorphic fabrics of southwestern Cerros El Amol formed at the same time as those in Sierra El Batamote, regional shortening occurred during Paleocene time.

Intrusions in Sierra El Batamote, when dated, should provide additional constraints on the age of deposition and timing of contraction. Field relationships indicate that an older group of Late Jurassic(?) andesitic dikes (Fig. 5d and e) fed magma to andesite flows and breccias in the upper part of the Altar Formation. A younger group of andesite or dacite porphyry stocks intruded the Altar Formation and Bisbee Group prior to regional compression. These younger hypabyssal intrusions (labeled Kap on Fig. 3 and correlated with the Late Cretaceous(?) 'Oquitoa andesite' in Cerros El Amol) may be part of a larger igneous body that provided the thermal energy for metamorphism of the Altar Formation.

3.2.4. Bulk strain associated with shortening

The folded Upper Jurassic through Cretaceous section of Cerro El Alamo, Sierra El Batamote, and Sierra El Chanate records horizontal shortening strain of 20–50% in a northeast–southwest or east–west direction. These values are determined from restoration of the cross sections in Fig. 4. Maximum shortening strain occurred in the southeastern Sierra El Batamote and central Sierra El Chanate (Fig. 4, section A-A′–G-G′). At outcrop scale, ductilely deformed conglomerate and andesite breccia clasts on fold limbs exhibit grain shapes indicative of flattening strain. Many outcrops display a weak, down-dip lineation on steep foliation surfaces resulting from modest clast elongation in the southwest direction. This style of ductile fabric contrasts markedly with the subhorizontal mylonitic foliation and strong stretching lineation characteristic of middle Tertiary metamorphic core complexes of north-central Sonora (Nourse et al., 1994).

3.2.5. Miocene(?) extensional structures

Mid-Tertiary magmatism and detachment faulting are known to be important in the ranges southeast of Altar and in the vicinity of Sasabe, Tubutama, and Magdalena (Nourse et al., 1994; Fig. 1). In the study area, Late Cretaceous–Early Tertiary compressional structures are overprinted by dike swarms and normal faults that probably accompanied mid-Tertiary extension. Some of the normal faults may represent segments of regional detachment fault systems whose movements resulted in uplift and rotation of deeper, more metamorphosed levels of the stretched-clast conglomerate belt.

Two groups of Miocene(?) dikes sharply intrude cleaved Altar Formation in Sierra El Batamote and Cerro El Alamo. Several 3–10 m-thick, pink-weathering, medium-grained andesite porphyry dikes (unit Ta) crop out continuously along the axis of Sierra El Batamote (Fig. 4). These steeply southwest-dipping, uncleaved dikes are intruded parallel to foliation in the hinge zone of the range-scale anticline. A second group of 30 cm to 1 m-thick, very fine grained basalt dikes (unit Tb) intrudes parallel to cleavage in the host strata along the southwest flank of Sierra El Batamote. Dikes of similar composition and texture mapped on the northeast face of Cerro El Alamo form shallowly southwest-dipping ledges oriented parallel to foliation in metaconglomerate. Farther northwest in Cerro Basura (Fig. 2), andesite and basalt dikes with northwesterly strikes intrude Jurassic strata. Both groups of dikes may have fed magma to Tertiary volcanic flows and breccias exposed on both sides of Highway 2 northwest of Caborca (Fig. 2).

Sierra El Batamote, Cerro El Alamo, and Cerros El Amol reside in the footwall of the mid-Miocene Carnero detachment system (De Jong et al., 1988; Nourse et al., 1994). This fault appears to be buried in the alluvium between Altar and Cerro El Alamo (Fig. 2). S-C fabrics developed in lower-plate, mylonitized, Miocene granodiorite of Cerro Carnero indicate west–southwest transport of an upper plate composed of Upper Proterozoic and Paleozoic strata (Fig. 2; see also Jacques-Ayala et al., 1990; Nourse et al., 1994). Northwest of Caborca (Fig. 2), a possibly correlative detachment fault separates upper plate Tertiary volcanic and coarse clastic beds from lower plate Jurassic sandstone (Corona, 1979; T. Anderson and J. Nourse, unpublished mapping, 1993–1999). The Tertiary section is consistently tilted to the northeast, suggesting southwest-directed movement on this low-angle fault. The Altar Formation in Sierra El Batamote does not exhibit ductile fabrics that can be related to the Carnero detachment fault. Significant footwall uplift has exposed deep levels of the section, however, and associated rotation of the range along a horizontal axis may have caused the regional southwest dip of an originally subvertical axial planar foliation. These Tertiary rotation effects are more pronounced in Cerro El Alamo, where foliation and subparallel basalt dikes display shallow (10–20°) southwest dips.

The northwest-trending El Chanate fault zone (Jacques-Ayala et al., 1990; see also Figs. 3 and 4) follows the valley between Sierra El Batamote and Sierra El Chanate. Late, brittle faults within this 200 m-wide zone and on the northeast limb of the El Chanate syncline display down-to-the-northeast normal displacement (Fig. 7b). Some of these normal faults cut asymmetric folds and reverse faults (Fig. 7a) that are kinematically associated withLate Cretaceous–Early Tertiary compressional deformation. Movement history of the El Chanate fault zone is complex, and probably included: (1) localized folding, cleavage development, and reverse faulting related to formation of the El Batamote anticline–El Chanate syncline pair, (2) distributed

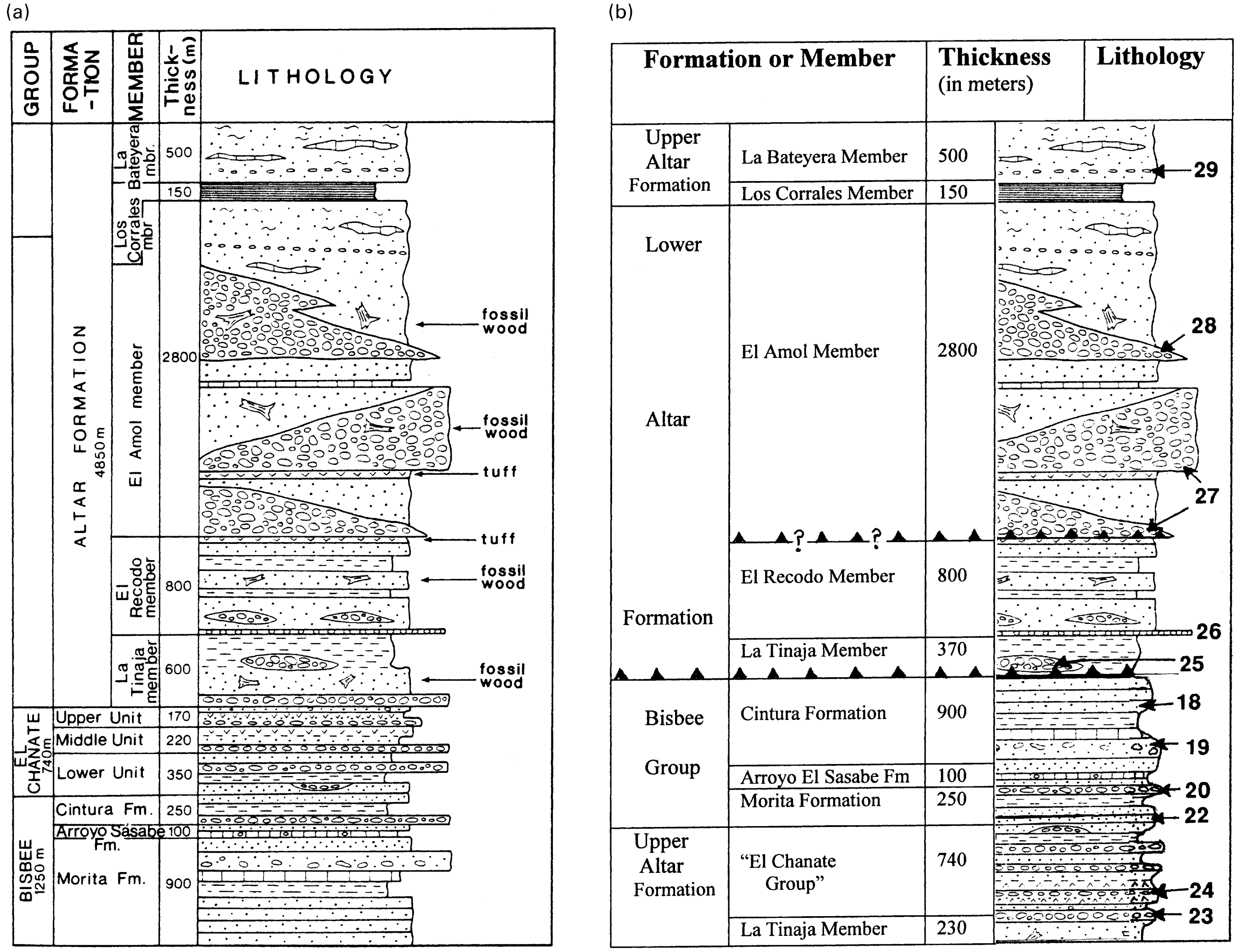


Fig. 8. Stratigraphic columns of the Cerros El Amol area. (a) Type section reproduced from Jacques-Ayala et al. (1990). (b) Proposed new stratigraphic interpretation for Cerros El Amol, showing rearranged rock units at the same scale as (a). Numbers indicate positions of conglomerate beds described in Table 1.

thinning of the anticline–syncline inflection region via bedding-plane faulting and flexural-slip folding within this fold limb, and (3) brittle normal faulting along discrete northeast-dipping planes. Episodes (2) and (3) facilitated uplift of the Altar Formation in Sierra El Batamote and rotation of the Sierra El Chanate syncline to its present orientation with a northeast-dipping axial plane.

Extensional structures of the El Chanate fault zone appear to project across the Rio Altar to the southeast. East of Altar, Bisbee Group strata overlie metasedimentary rocks of the Altar Formation along a moderately northeast-dipping brittle fault (Figs. 2 and 9, section A–B). This younger-on-older structure exhibits the general characteristics of a normal-slip detachment fault, and probably represents a continuation of the El Chanate fault zone. The effect of this fault was to accommodate uplift of the foliated Altar Formation with respect to less-metamorphosed Bisbee Group strata.

4. Proposed correlation to Cerros El Amol

Cerros El Amol, the 30 km-long range to the southeast of Sierra El Batamote, is underlain by an assemblage of metaconglomerate, metasandstone, cleaved andesite, and phyllite that strongly resembles the deformed Sierra El Batamote section. These strata constitute the type Altar Formation (Jacques-Ayala et al., 1990; García y Barragán et al., 1998), originally assigned an Upper Cretaceous stratigraphic age on the basis of a cryptic contact relation with a presumably overturned section composed of the El Chanate and Bisbee Groups (Figs. 8a and 9a). Detailed comparison of lithology and structure in Sierra El Batamote and Cerros El Amol demonstrates continuity of Altar Formation between the two ranges. This correlation, however, requires an older (Upper Jurassic–Lower Cretaceous) depositional age for the Altar Formation in Cerros El Amol.

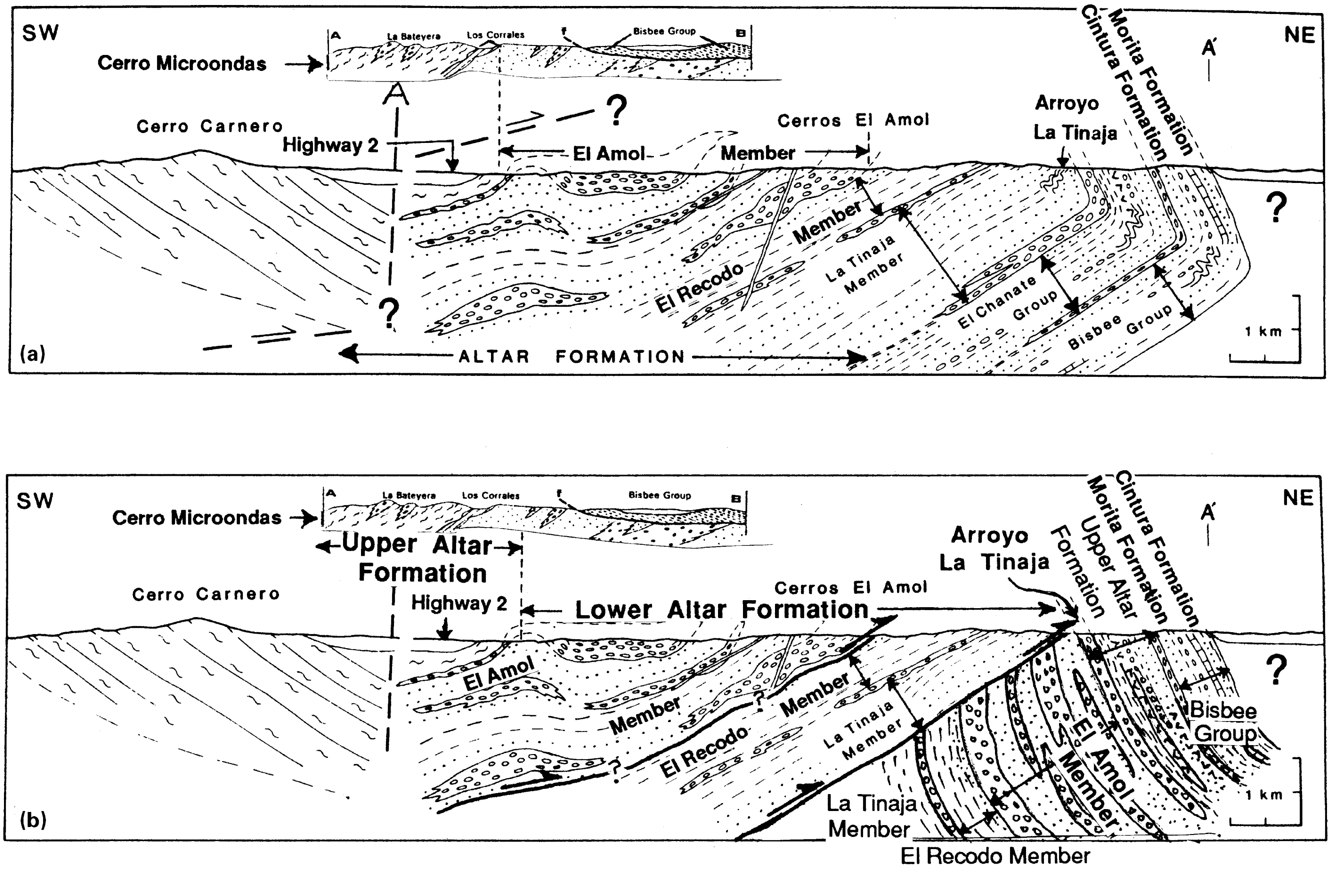


Fig. 9. True-scale geologic cross sections through Cerros El Amol. Refer to Fig. 2 for section locations. (a) Cross section interpretation A-A′ reproduced from Jacques-Ayala et al. (1990), showing the Altar Formation in an Upper Cretaceous stratigraphic position. Section A–B (reproduced from García y Barragán, 1992) illustrates the Los Corrales and La Bateyera members of Cerro Microondas. (b) Alternative cross-section interpretation, showing the Altar Formation in an Upper Jurassic–Lower Cretaceous stratigraphic position. Rock units are at the same scale as (a).

4.1. Proposed changes to the stratigraphy and structure of Cerros El Amol

The stratigraphic columns and cross sections of Figs. 8 and 9 summarize the revisions I propose for the geologic interpretation of Cerros El Amol. Fig. 2 shows these relationships in map view. Figs. 8 and 9 are arranged so that the original stratigraphic and structural interpretation of Cerros El Amol (Jacques-Ayala et al., 1990) may be directly compared with the proposed new model. The Altar Formation in the new model is positioned stratigraphically beneath the Bisbee Group rather than above it. Thus, the Altar Formation is broadly correlative with the Upper Jurassic–Lower Cretaceous Glance Conglomerate (Fig. 1b). This relationship is accomplished by requiring the northeast-dipping Bisbee Group section on the northeast edge of Fig. 2 section A-A′ to be upright rather than overturned. The clastic and volcanic section intervening between the Bisbee Group and the La Tinaja member of the Altar Formation, originally correlated with the Upper Cretaceous El Chanate Group, is viewed as equivalent to the upper Altar Formation. In this perspective, the conformable section exposed northeast of Arroyo La Tinaja represents the upright, northeast-dipping limb of a major anticline.

Bedding reverses abruptly on the southwest side of Arroyo La Tinaja (Fig. 9). From this location to Cerro Microondas, an upright, generally southwest-dipping sequence of metaconglomerate, metasandstone, phyllitic mudstone, and greenschist constitutes the type section of the Altar Formation (La Tinaja, El Recodo, El Amol, Los Corrales, and La Bateyera members; see also Jacques-Ayala et al., 1990; García y Barragán et al., 1998). Intensity of cleavage and metamorphic grade increases progressively southwestward through this section. It is possible that the lower part of the Bisbee Group (Morita Formation) occurs in the shallowest levels of the section southwest of Highway 2, but direct lithologic correlation is precluded by intense metamorphism and strain in this area.

The proposed stratigraphic revisions are based on an anticlinal model for Cerros El Amol. Close examination, however, reveals a mismatch of units across the anticline hinge. Specifically, the southwest-dipping limb reveals a very thick (4620 m) section of Altar Formation, whereas the thinner northeast limb contains only the upper 970 m of Altar Formation overlain by the Bisbee Group. This

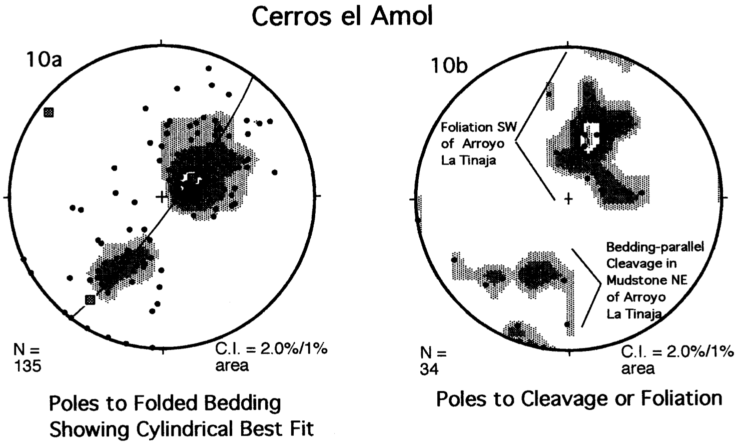


Fig. 10. Lower hemisphere equal area stereonets showing bedding and cleavage in Cerros El Amol. Stereonet plotting and contouring program by Allmendinger (1995). Data plotted with permission from García y Barragán (1992).

discrepancy requires one or more thrust faults (Figs. 2 and 9) to uplift deeper levels of the Altar Formation southwest of Arroyo La Tinaja. These hypothetical faults are compatible with the overall asymmetry of the proposed anticlinal structure, and offer a mechanism for thickening the southwest limb.

4.2. Evidence supporting the new model for Cerros El Amol

Correlation of the Altar Formation of Cerros El Amol to the Upper Jurassic–Lower Cretaceous clastic and volcanic section of Sierra El Batamote is supported by numerous lithologic, structural, and metamorphic similarities between the ranges. Described below are principal observations, comparisons, and arguments relevant to the model.

Lower units of the El Batamote section are predominately clast-supported cobble–boulder conglomerate beds of highly variable thicknesses, interstratified with coarse lithic sandstone. These lithologies correspond most strongly to the El Amol member of the type Altar Formation, composed of conglomerate wedges interfingering with sandstone (Fig. 9). The El Amol member is underlain by finer-grained strongly cleaved sequences of sandstone and mudstones interlayered with rare cobble conglomerate (the La Tinaja and El Recodo members). These deepest levels of the type Altar Formation resemble phyllites and metaconglomerate exposed in the core of south-central Sierra El Batamote anticline.

Existing data permit correlation of the La Tinaja–El Chanate succession north of Arroyo La Tinaja with the metamorphosed Los Corrales–La Bateyera succession near Highway 2. In the model, these two upright sections of upper Altar Formation define opposite limbs of an anticline cored by the La Tinaja, El Recodo, and El Amol members of the lower Altar Formation (Fig. 9b). Comparison of stratigraphically higher units of the Altar Formation between Cerros El Amol and Sierra El Batamote reveals striking similarities: (a) common occurrence of recrystallized carbonate lenses or nodules within purple or green phyllitic mudstone, (b) presence of interstratified volcanic layers (green andesites and felsic tuffs) and tuffaceous sandstone, and (c) overall abundance of siltstone, shale, and sandstone relative to conglomerate.

Conglomerate clasts from the Altar and Bisbee sections of Sierra El Batamote and Cerros El Amol exhibit comparable vertical zonations (Table 1). In general, the deeper levels of the Altar Formation contain abundant subangular to subrounded cobbles and boulders shed from the Neoproterozoic–Paleozoic miogeocline (quartzite, chert, and carbonate) or the Middle Jurassic magmatic arc (rhyolite porphyry, felsite, and andesite). Rounded or subrounded pebbles in upper parts of the Altar Formation include several varieties of andesite derived from intraformational flows and breccias. Pebble and granule conglomerate beds in the Morita Formation are composed mainly of well-rounded quartzite, quartz arenite, or chert clasts and locally derived andesite clasts. Also present are subangular to subrounded red mudstone and reddish-purple sandstone clasts of intraformational origin.

Colors of various rock types also compare well between Sierra El Batamote and Cerros El Amol. Conglomerate beds of the Altar Formation are typically purple-gray or green, while sandstone layers are generally brown and mudstone is olive green, light purple-gray, or occasionally black. The Bisbee section contains purple, gray, or pink sandstone beds interstratified with characteristically red siltstone and shale. This observed upward color transition provides a good field indicator for distinguishing the contact between Altar Formation and Bisbee Group.

Cleavage and bedding patterns within the Cerros El Amol support an asymmetric anticline interpretation of the structure and also permit northwestward linkage to the fold belt of Sierra El Batamote and Sierra El Chanate. Bedding orientations (Fig. 10a) obtained from García y Barragán et al. (1998) define a range-scale anticline with a subhorizontal northwest-striking axis and limbs that dip steeply northeast and moderately to shallowly southwest. The hinge zone is

Table 1
General clast characteristics observed in Jurassic and Cretaceous conglomerate beds from the Caborca–Altar region. Clasts are listed in decreasing order of relative abundance, with predominant clast types italicized. Refer to Figs. 4 and 8b for specific site locations. Clast descriptions in Cerros El Amol from Jacques-Ayala et al. (1990) and García y Barragán et al. (1998)

Numbered location on Fig. 4	Map location	Stratigraphic unit	Clast assemblage (decreasing order of abundance; predominant clast types are in italics)	Mean clast shape/size
Sierra El Batamote/Sierra El Chanate				
1	NE Sierra el Chanate	Upper Escalante Formation	*Andesite*, *purple sandstone*, *red mudstone*, quartz arenite, quartzite, rhyolite porphyry, mural limestone	Angular to subangular cobble
2	NE Sierra el Chanate	Lower Escalante Formation	*Rhyolite porphyry*, *quartz arenite*, *quartzite*, green and purple andesite	Subangular cobble
3	NE Sierra el Chanate	Upper Anita Formation	*Gray-purple andesite*, *purple sandstone*, *red mudstone*, quartzite	Subrounded pebble–cobble
4	NE Sierra el Chanate	Middle Anita Formation	*Andesite*, quartzite, chert, felsite	Subangular pebble–cobble
5	NE Sierra el Chanate	Lower Anita Formation	*Quartzite*, chert, felsite	Rounded cobble
6	NE Sierra el Chanate	Lower Morita Formation	*Red mudstone–siltstone*, *felsite*, quartzite, chert, rhyolite porphyry, green andesite	Rounded pebble
7	NE Sierra el Chanate	Upper Altar Formation	*Rhyolite porphyry*, *felsite*, chert, quartz arenite, quartzite	Subrounded pebble
8	NE Sierra el Chanate	Upper Altar Formation	*Red-purple quartzite*, vein quartz, red chert, dark andesite, felsite	Subrounded pebble
9	South-central Sierra El Batamote	Upper Altar Formation	*Andesite*, quartzite, brown carbonate, rhyolite porphyry	subrounded pebble
10	SSE Sierra el Batamote	Upper Altar Formation	*Rhyolite porphyry*, *quartzite*, green chert, light purple siltstone, gray-purple sandstone, purple-gray andesite porphyry	Subrounded cobble
11	Northern Sierra el Batamote	Upper Altar Formation	Red and purple *andesite*	Subangular pebble
12	SE Sierra el Batamote	Upper–Middle Altar Formation	*Quartzite*, black chert, felsite, rhyolite porphyry limestone	Pebble–cobble
13	SSE Sierra el Batamote	Middle Altar Formation	*Rhyolite porphyry*, *felsite*, *gray porphyritic andesite*, black chert, brown carbonate, quartzite	Subangular pebble–cobble
14	Northern Sierra el Batamote	Middle Altar Formation	Rhyolite porphyry, welded tuff, quartzite, gray siltstone, green andesite	Subangular to subrounded pebble–cobble
15	SE Sierra el Batamote	Middle Altar Formation	*Quartzite*, *rhyolite porphyry*, *felsite*, vein quartz, andesite porphyry, lithic sandstone	Subangular to sub-rounded cobble
16	Central Sierra el Batamote	Lower Altar Formation	*Quartzite*, *andesite*, rhyolite porphyry, brown carbonate	Subangular pebble–cobble

Table 1 (*continued*)

Numbered location on Fig. 8b	Map location	Stratigraphic unit	Clast assemblage (decreasing order of abundance; predominant clast types are in italics)	Mean clast shape/size
17	SE Sierra el Batamote	Lower Altar Formation	*Quartzite*, chert	Subrounded pebble
Cerros El Amol				
18	NE Cerros el Amol	Middle Cintura Formation	*Red sandstone*, *red chert*, felsite, quartzite	Rounded granule–pebble
19	NE Cerros el Amol	Lower Cintura Formation	*Sandstone*, chert, felsite, quartzite	Rounded granule–pebble
20	NE Cerros el Amol	Upper Morita Formation	*Quartz arenite*	Rounded granule–pebble
21	NE Cerros el Amol	Middle Morita	*Quartzite*, andesite	Rounded pebble
22	NE Cerros el Amol	Lower Morita	*Quartzite*	Rounded pebble
23	NE Cerros el Amol	Upper La Tinaja member	*Quartzite*, quartz arenite	Subrounded cobble–pebble
24	NE Cerros el Amol	Middle La Tinaja member	*Green andesite*, chert	Subangular pebble
25	Central Cerros el Amol	Lower La Tinaja member	*Rhyolite porphyry*, *quartzite*, *sandstone*, andesite porphyry, chert, felsite, granodiorite	Angular to subangular boulder–cobble
26	Central Cerros El Amol	Lower El Recodo member	*Rhyolite porphyry*, *andesite*, quartzite, black chert, vein quartz	Subrounded pebble
27	Central Cerros el Amol	Lower El Amol member	Porphyritic andesite, quartzite, chert sandstone, rhyolite	Subangular to subrounded boulder–cobble
28	SW Cerros el Amol	Upper El Amol member	*Limestone*, *quartzite*, andesite, chert, rhyolite porphyry	Subrounded pebble–cobble
29	Cerro Microondas	La Bateyera member	*Quartzite*, a few rhyolite cobbles	Rounded pebble, rare cobbles

disrupted by a reverse fault that follows the trace of Arroyo La Tinaja. A southwest-dipping axial surface is inferred from cleavage (Fig. 10b) that transects shallower bedding of similar strike south of Arroyo La Tinaja. The Cerros El Amol anticline appears to continue northwestward across Rio Altar into Cerros El Puerto (Jacques-Ayala, 1993). Northwest of these hills the anticline hinge projects across an alluvial plain in a position northeast of but parallel to the Sierra El Chanate syncline.

One or more thrust faults (Figs. 2 and 9b) are necessary to explain the great thicknesses of lower Altar Formation exposed on the southwest limb of the Cerro El Amol anticline. The proposed faults correspond to previously mapped cleaved zones that also mark abrupt changes in lithology. One fault, approximately located in Arroyo La Tinaja, corresponds to discontinuously exposed deformation zones as much as 50 m wide in which fine-grained metasedimentary strata are so strongly cleaved that bedding is barely distinguishable. These intensely foliated zones, traceable along strike for more than 12 km, strike N15°–60°W and dip approximately 35°SW. In the cross-section model (Fig. 9b), the La Tinaja thrust breaks the axial plane of an asymmetric anticline, lifting the La Tinaja member of the lower Altar Formation over sedimentary and volcanic strata of the upper Altar Formation (previously correlated with the El Chanate Group). On projection to the northwest is a northeast-side-down fault mapped in Cerros El Puerto (Jacques-Ayala, 1993; see Fig. 2).

A second thrust fault of uncertain importance corresponds to the contact between the El Recodo and El Amol members of the lower Altar Formation, 2–3 km southwest of Arroyo La Tinaja (Figs. 2, 8b and 9b). Semicontinuous zones of intensely cleaved phyllite and sandstone mark the trace of this fault, which has an average orientation of N50°W/30°SW (J.C. Garcia y Barragan, pers. comm., 2000). Possibly, a third thrust fault transects the northeast base of Cerro Microondas, causing the Los Corrales–La Batayera members to be uplifted relative to the El Amol member. This speculation (J.L. Rodríguez Castañeda and J.C. García y Barragán, pers. comm., 2000) stems from difficulty in finding a local correlation for the black graphitic schist and phyllite of the Los Corrales member. The Los Corrales–La Bateyera succession resembles the Upper Jurassic La Colgada Formation and Dos Naciones Formation that crop out in the Tuape area of north-central Sonora (Rodríguez Castañeda, 1988). Inclusion of this third fault in the model would modify the stratigraphy such that the La Bateyera–Los Corrales succession is older than the El Amol member, and perhaps represents the oldest Mesozoic strata exposed in Cerros El Amol.

4.3. Suggested tests of the hypothesis

The tectonic implications of Late Jurassic, as opposed to Late Cretaceous, basin formation in the vicinity of Caborca and Altar are far-reaching with regard to the paleogeography of northern Sonora. Depositional age of the Altar Formation/El Batamote conglomerate is thus an issue that begs careful scrutiny. The model proposed above should be evaluated through a variety of field and laboratory tests that are beyond the scope of this paper. Below, I list some fairly straightforward analyses that might be carried out:

1. Andesitic flows and felsic tuffs interstratified with upper members of the Altar Formation in Cerros El Amol and Sierra El Batamote should be systematically dated, preferably with U/Pb zircon techniques. It is crucial to determine whether these volcanic units correlate with the Upper Jurassic Glance Conglomerate or the Upper Cretaceous El Chanate Group/Fort Crittenden Formation.
2. Granodiorite clasts reported from the La Tinaja member of the Altar Formation should be dated with zircons to establish the age of basement that contributed detritus to the basin. Resolution of a Late Cretaceous age as opposed to possible Proterozoic or mid-Jurassic ages would rule out correlation of this unit with the Glance Conglomerate.
3. The section exposed northeast of Arroyo La Tinaja should be investigated with emphasis on verifying the facing direction. Is this section upright as proposed, or overturned as inferred by previous workers?
4. Detailed geological mapping in Cerros El Amol could confirm or refute the presence of thrust faults in the localities suggested in the model. Are these zones simply a manifestation of strong cleavage or do they mark significant discontinuities in lithology and metamorphic grade? Do mesoscopic folds and other kinematic indicators exist that support reverse movement on southwest-dipping structures?

5. Discussions

5.1. Regional correlation of the altar formation with glance conglomerate

The primary issue of this paper is the depositional age of the Altar Formation. In several publications (Jacques-Ayala et al., 1990; Jacques-Ayala and De Jong, 1996; Jacques-Ayala, 2000), this belt of metasedimentary strata is viewed as an Upper Cretaceous foreland deposit. According to that model, the Altar Formation accumulated in front of a rising thrust front composed of Neoproterozoic and Paleozoic strata of the Caborca block, then was buried and metamorphosed in the footwall of this thrust system. A number of K/Ar dates (Damon et al., 1962; Hayama et al., 1984) support a late Paleocene age of metamorphism. Nevertheless, the presumption that the conglomerate beds of the Altar Formation are syndepositional with respect to Late Cretaceous thrusting requires a very complex fold geometry (Fig. 9a) in which a conformable section of Bisbee Group and Altar Formation in the northeastern Cerros El Amol is overturned, with the fold hinge nowhere exposed. Previous studies also fail to explain why rocks of the Altar Formation are consistently more metamorphosed than presumably deeper strata of the Bisbee Group.

I argue that the Altar Formation occupies a stratigraphic position similar to the Glance Conglomerate (Fig. 1b). While this Mesozoic stretched-clast conglomerate belt does record important Late Cretaceous–Early Tertiary contraction and metamorphism, the stratigraphic relations and structural geometry are more compatible with a scenario in which deposition occurred in a Late Jurassic–Early Cretaceous rift basin. Several independent criteria require revision of the Late Cretaceous age assignment previously postulated for the Altar Formation. Principal evidence is based on recognition of conformable depositional contacts with overlying Bisbee Group strata (Figs. 3 and 4), distinct clast characteristics and provenance variations (Table 1), and regional structural considerations that make it possible to draw simpler cross sections through the metaconglomerate belt and adjacent Bisbee strata (Figs. 4 and 9b).

The Morita Formation conformably overlies the upper part of the Altar Formation. The observed gradational transition implies that highlands that initially bounded the conglomeratic basin had subsided by the time the Bisbee Sea transgressed into northwestern Mexico. Variations in composition and size of conglomerate clasts (Table 1) support this interpretation. In general, the prominent Jurassic arc source had mostly disappeared before deposition of the Morita Formation, and smaller pebbles contributed from the Neoproterozoic–Paleozoic miogeoclinal source indicate lower relief to the southwest. Conglomerate clasts in higher parts of the Bisbee Group record erosion of local andesite sources in the upper part of the Altar Formation as well as a significant contribution from the Morita Formation.

Complications involved with reconstructing the deformed Upper Jurassic and Cretaceous strata are alleviated when the Altar Formation is positioned stratigraphically beneath the Bisbee Group. This interpretation is consistent with the observed higher metamorphic grade in the Altar Formation compared with the Bisbee Group and El Chanate Group. Correlation of the andesite porphyry stocks of Sierra El Batamote (map unit Kap) with Upper Cretaceous andesite flows of the El Carro volcanic complex is also permitted. Bedding/cleavage relationships demonstrate that a northeast-vergent fold and thrust belt dominates the structure and disrupts the proposed stratigraphy in a simple fashion (Figs. 2, 4 and 9b). Structural and metamorphic discordance between Sierra El Batamote and Sierra El Chanate was later enhanced by Tertiary normal faulting that caused uplift of Sierra El Batamote and rotation of the Sierra El Chanate syncline such that its axial plane dips northeast.

5.2. *Inferred depositional setting of the Altar Formation*

The Upper Jurassic –Lower Cretaceous Altar Formation accumulated in an elongate, northwest-trending basin bounded on the southwest by highlands composed of Upper Proterozoic–Paleozoic miogeoclinal strata and on the northwest and northeast by the Jurassic volcanic arc. Coarse-grained, subangular, boulder–cobble-rich beds in the lower part of this section suggest close proximity to sources with steep relief, possibly uplifted fault blocks. One likely candidate fault, located near Rancho El Zoquete (Fig. 2), forms a northeast-striking boundary between Middle Jurassic volcanic strata of Sierra La Gloria and Upper Jurassic polymict conglomerate of the northwestern Cerro El Alamo (Corona, 1979). Further work is needed to assess whether the conglomerate is syndepositional with respect to movement on this fault. Another possible boundary structure is the northwest-trending Mojave-Sonora megashear (Figs. 1 and 2), a postulated Late Jurassic transform fault (Silver and Anderson, 1974; Anderson and Silver, 1979). This fault offers a mechanism to expose local sources Neoproterozoic miogeoclinal clasts directly southwest of Caborca and Altar.

Lacustrine sediments and interstratified volcanic rocks distinguish the upper Altar Formation. Clastic strata in this part of the section are generally finer grained, for example, medium-grained sandstone and pebble conglomerate interbedded with siltstone and shale. Brown lacustrine(?) carbonate layers or nodules and felsite layers (rhyolite tuffs?) are commonly associated with the mudstone horizons. Porphyritic andesite flows and flow breccias of highly variable thicknesses interfinger with conglomerate beds that contain volcanic pebbles of similar composition.

The stratigraphy of the upper part of the Altar Formation is compatible with a depositional setting in which lakes intermittently received coarser sandy and pebbly detritus from highlands of subdued relief. In contrast to the paleogeography during deposition of the lower Altar Formation, the topography was peneplained or eroded to a low level, such that fluvial transport mechanisms systems had lost much of their energy. The lake sediments were in close proximity to andesitic volcanoes that contributed lava flows and breccias to the basin.

The gradational transition between the Altar Formation and the overlying Morita Formation suggests a period of regional subsidence that preceded deposition of the Bisbee Group and permitted the entrance of the Bisbee Sea into northwestern Mexico. During deposition of the Morita Formation, the Jurassic arc source disappeared and the southwesterly source of quartzite, chert, and carbonate clasts was more subdued. Andesitic detritus in Morita conglomerate records fluvial reworking of remnant Late Jurassic volcanoes.

The tectonic setting of the narrow basins in which Glance Conglomerate accumulated in southern Arizona has been variably attributed to rifting within the Jurassic arc (Krebs and Ruiz, 1987), formation of extensional half-grabens behind the Early Cretaceous arc (Bilodeau and Lindberg, 1983), and development of pull-apart basins along releasing bends of the Mojave-Sonora megashear (Anderson et al., 1995). In the Altar–Caborca region, very thick Upper Jurassic–Lower Cretaceous sequences of upward-fining, locally derived clastic beds interstratified with andesitic volcanic and lacustrine rocks are broadly compatible with all of these hypothetical tectonic scenarios. Here and in other parts of Sonora, however, consistent asymmetries in the configuration of conglomerate boundaries with older rocks reveal striking regional patterns supporting a sinistral transtension (pull-apart basin) model (Nourse, 1995; Anderson et al., 1995). Additional studies are needed to establish convincing facies patterns near proposed boundary faults in Mexico, and to document syngenetic relations between conglomerate deposition and Late Jurassic faulting.

5.3. Importance of the 'Laramide' orogeny in northern Sonora

The structural relationships documented in this paper demonstrate Laramide age compression in the Caborca–Altar region. Northeast–southwest or east–west shortening created folds and associated cleavage between 71 and 51 Ma. These folds were linked kinematically to southwest-dipping thrusts postulated in the vicinity of Cerros El Amol. Consistent asymmetries recorded by axial planar cleavage, reverse fault orientations, and locally overturned folds consistently indicate northeast vergence. The age of this contraction falls within the time interval (sensu lato 90–50 Ma) specified for the Laramide orogeny in the Rocky Mountains region (Ransome, 1904; Gilluly, 1956; Cooper and Silver, 1964). The geometry and scale of the Altar–Caborca fold-thrust belt compares well with Laramide structures described in southeastern Arizona (Davis, 1979).

The Laramide orogeny has been recognized elsewhere in Sonora. South of the study area, Upper Proterozoic and Paleozoic miogeoclinal strata of Sierra La Vibora compose the hanging wall of an east-vergent thrust (De Jong et al., 1988). This fault deforms Lower Cretaceous(?) sediments in its footwall, and is intruded by a Late Cretaceous (80 Ma) granodiorite (Fig. 2). In the Sierra San Antonio region (Fig. 1a), a reverse fault places Bisbee Group strata over Upper Cretaceous conglomerate of the El Tule Formation (Rodríguez Castañeda, 1997). This fault, which is overlapped by Tertiary volcanic rocks, may have a strike length of 30 km or more (Rodríguez Castañeda, 1997). Laramide strain may also be recorded in the Magdalena–Madera metamorphic core complex (Nourse, 1990, 1995; Fig. 1). In this area, a lower plate containing Middle and Upper Jurassic protoliths preserves ductile fabrics that predate mid-Tertiary extension, and folded Bisbee Group strata in the upper plate discordantly underlie Oligocene–Miocene volcanic rocks.

5.4. Distinctions between Upper Jurassic and Upper cretaceous conglomerates in northern Sonora

Throughout northern Sonora, conglomerates of both Late Jurassic and Late Cretaceous age exist in the same general areas (Fig. 1a). For example, directly northeast of Sierra El Batamote the Upper Cretaceous El Chanate Group unconformably overlies the Cintura Formation of the Bisbee Group (Jacques-Ayala, 1993). Like the Altar Formation of Sierra El Batamote, the El Chanate Group contains conglomerate and sandstone interstratified with andesite flows. In the Cabullona basin of northeastern Sonora, conglomerate and sandstone containing Upper Cretaceous dinosaur bones and interstratified andesite occur close to a section mapped as Glance Conglomerate (Taliaferro, 1933; Imlay, 1939; González-León and Lawton, 1995). North of Sierra San Antonio, conglomerate and andesite of the Upper Cretaceous El Tuli Formation occupy the stratigraphic interval between Bisbee Group and a Tertiary volcanic section (Rodríguez Castañeda, 1997). Along strike to the northwest are extensive exposures of Upper Jurassic Cocospera Conglomerate (Nourse, 1995). The Altar Formation, El Chanate Group, Cabullona Group, Cocospera Conglomerate, and El Tuli Formation all contain high-energy debris-flows and channel deposits formed in colluvial and alluvial environments. However, the Altar Formation and Cocospera Conglomerate lack clasts of light gray, fossiliferous Mural Limestone present in the other conglomeratic sections.

In places where both Upper Jurassic and Upper Cretaceous sections exist and depositional relationships to the Bisbee Group are unclear, clast composition analyses offer the easiest way to distinguish between the conglomerates. Those conglomerate beds that include the distinct clast assemblage of red siltstone or shale, reddish-purple sandstone, and Mural Limestone (all components of the Bisbee Group) should be assigned Upper Cretaceous or younger ages. Conglomeratic sections characterized by Jurassic and older clasts and lacking clasts derived from the Bisbee Group probably correlate with the Glance Conglomerate. Geochronological work on interstratified volcanic units is needed to further constrain these age designations.

6. Conclusions

The Caborca–Altar stretched-clast conglomerate and associated finer clastic and volcanic strata (Altar Formation) accumulated in a northwest-trending, fault-bounded basin during Late Jurassic–Early Cretaceous time. Because this section contains clasts of the Middle Jurassic volcanic arc and is depositionally overlain by the Lower Cretaceous Bisbee Group, its stratigraphic age is broadly correlative with the Glance Conglomerate. Prominent highlands composed of the Jurassic arc and the Neoproterozoic–Paleozoic miogeocline shed coarse debris into this basin early in the deposition of the Altar Formation. Locally thick andesite flows and breccias entered the basin during deposition of the upper Altar Formation. The Jurassic highlands appear to have subsided prior to deposition of the Morita Formation, such that lower energy fluvial channels were dominated by miogeoclinal quartzite, quartz arenite, or chert pebbles and andesitic clasts locally derived from the upper Altar Formation. The Altar Formation lacks clasts derived from the Bisbee Group and does not exhibit the red colors that distinguish finer-grained beds of the overlying Cretaceous sections. In contrast, intraformational red siltstone and purple sandstone clasts characterize in conglomerate beds of the Bisbee Group, and Mural Limestone clasts first appear in the Upper Cretaceous El Chanate Group.

The region experienced significant northeast–southwest contraction between 71 and 51 Ma. Northwest- or north-trending folds, locally overturned, and northwest-striking thrusts deform the Upper Jurassic and Cretaceous strata over a strike length of 60 km. Penetrative southwest-dipping cleavage is associated with these consistently northeast-verging structures. Lower greenschist-facies metamorphism that accompanied shortening of the Altar Formation may have derived its thermal energy from the emplacement of pre-orogenic Late Cretaceous andesite or dacite porphyry stocks. The present-day juxtaposition of the higher grade, northeast-vergent anticline of Sierra El Batamote with the lower grade, southwest-vergent syncline of the Sierra El Chanate is explained by uplift and horizontal-axis rotation along mid-Tertiary normal faults.

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