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Detrital zircon geochronology of Neoproterozoic to Middle Cambrian miogeoclinal and platformal strata: Northwest Sonora, Mexico

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RESUMEN

Ochenta y cinco circones detritales provenientes de estratos sedimentarios del Mesoproterozoico y/o Neoproterozoico al Cámbrico Medio del noroeste de Sonora, México, han sido analizados para determinar los terrenos fuente y delimitar las edades de deposición de las unidades. Los conjuntos de circones de la Formación El Alamo y la unidad El Aguila del Mesoproterozoico y/o Neoproterozoico tienen edades entre 1.06 Ga y 2.67 Ga, con predominio de edades de 1.1 a 1.2 Ga. Los circones de la Cuarzita Bolsa del Cámbrico Inferior y Medio muestra grupos de edades desde 525 Ma a 1.63 Ga, con un grupo dominante de 1.1 a 1.2 Ga. Minerales con edades más antiguas que 1.2 Ga, son probablemente provenientes del basamento y de granitos de ~1.4 Ga del suroeste de Estados Unidos y noroeste de México. También es posible que los sedimentos hayan sido transportados desde el sur, aunque posibles fuentes con la edad adecuada no están expuestas actualmente al sur del área de estudio en el norte de México. Existen tres posibilidades para explicar la fuente de los circones dominantes con edades de 1.1 a 1.2 Ga: (1) afloramientos del cinturón Grenvilliano en el sur de Norte América, (2) cuerpos de granito locales con edades de 1.1-1.2 Ga o (3) una fuente al sur, como el terreno de Oaxaca que experimentó posteriormente transporte tectónico. Estudios de unidades adicionales en el occidente de Estados Unidos y norte de México pueden ayudar a resolver la ambigüedad sobre la fuente de los circones de 1.1 a 1.2 Ga.

PALABRAS CLAVE: Circones detritales, geocronología U-Pb, noroeste de México.

ABSTRACT

Eighty-five detrital zircon grains from Mesoproterozoic and/or Neoproterozoic to Middle Cambrian sedimentary strata in northwest Sonora, Mexico, have been analyzed to determine source terranes and provide limiting depositional ages of the units. The zircon suites from the Mesoproterozoic and/or Neoproterozoic El Alamo Formation and El Aguila unit yield ages between 1.06 Ga and 2.67 Ga, with predominant ages of 1.1 to 1.2 Ga. Zircons from the Lower? and Middle Cambrian Bolsa Quartzite show age groups from 525 Ma to 1.63 Ga, with a dominant population of 1.1 to 1.2 Ga grains. Grains older than 1.2 Ga in the samples were most likely derived from basement terranes and ~1.4 Ga granitic bodies of the southwest U.S. and northwest Mexico. It is also possible that the sediments were transported from the south, although source rocks of the appropriate age are not presently exposed south of the study area in northern Mexico. Three possibilities for the dominant 1.1 to 1.2 Ga grains include derivation from: (1) exposures of the Grenville belt in southern North America, (2) local 1.1-1.2 Ga granite bodies, or (3) a southern source, such as the Oaxaca terrane, that was subsequently rifted away. Sampling of additional units in the western U.S. and northern Mexico may help resolve the ambiguity surrounding the source of the 1.1 to 1.2 Ga grains.

KEY WORDS: Detrital zircons, U-Pb geochronology, northwest Mexico.

INTRODUCTION

U-Pb geochronological analyses of detrital zircons have been completed on two Mesoproterozoic and/or Neoproterozoic feldspathic sandstones and one Lower? and Middle Cambrian quartzite in northwestern Sonora. This study was undertaken to determine source terranes for the three units and to provide limiting depositional ages on the two units suspected to be of Mesoproterozoic and/or Neoproterozoic age. Previous detrital zircon studies in Sonora included one sample of Cambrian miogeoclinal quartzite and several samples of Ordovician and younger miogeoclinal and eugeoclinal rocks (Gehrels and Stewart, 1998).

The Mesoproterozoic to Cambrian is an important time in the tectonic development of western North America. From about 1.1 to 0.7 Ga, western North America is considered to have been a part of the supercontinent of Rodinia, which was an assembly of most continents into one conterminous plate (Moores, 1991; Hoffman, 1991; Dalziel, 1992; Karlstrom *et al.*, 1999). In most reconstructions, the southwestern part of the United States and northern Mexico are adjacent to the Antarctic continent and the Kalahari region of Africa. In the reconstruction of Karlstrom *et al.* (1999), the western United States is adjacent to Australia, and Oaxaca (southern Mexico, in part comparable to Oaxaquia of Ortega-Gutiérrez *et al.,* 1995) lies between Laurentia and Australia. These tectonic reconstructions are important for this study because the Las Viboras Group and the El Aguila unit may have accumulated during the existence of Rodinia, and some detrital zircons in these units may have been derived from the vast continental area of Rodinia to the south.

Rodinia is considered to have existed until about 0.7 Ga, when it was fragmented by rifting (e.g. Burchfiel *et al.,* 1992; Lawlor *et al.,* 1999; Karlstrom *et al.,* 1999). This rifting established Laurentia as a separate continent and led to deposition of fringing Neoproterozoic and Paleozoic miogeoclinal deposits that include the Cordilleran miogeocline of western North America. The Cordilleran miogeocline extends along much of western North America, including the Caborca area of northern Sonora. Inland of the miogeoclinal fringe, the cratonal area of Laurentia was covered by relatively thin platformal strata. One of our samples, the Bolsa Quartzite, comes from this cratonal cover.

We use the term “miogeocline” as defined by Dietz and Holden (1966) for ocean-ward thickening, wedge-shaped, continental-terrace deposits along continental margins. They considered the Cretaceous and Cenozoic deposits underlying the continental shelf of eastern North America as a typical example. In more recent interpretations, miogeoclinal deposits form when rifting and continental separation forms a new continental margin, and an ocean-ward thickening wedge of sediment is deposited along the margin as a consequence of post-rift thermal contraction.

U-PB GEOCHRONOLOGY

Zircons were separated from ~20 kg samples taken from a narrow, stratigraphic interval in each unit. The samples were crushed, pulverized, separated on a Wilfley table, passed through a Frantz LB-1 magnetic separator, and separated further with heavy liquids. The zircons were separated into different size fractions, and individual crystals were analyzed by isotope dilution-thermal ionization mass spectrometry after abrasion to approximately 2/3 of their original diameter. The grains chosen for analysis were selected from all morphology and color groups with the intent to maximize the number of age groups recognized. Data reduction was completed with programs of Ludwig (1991a, b), with parameters listed in Table 1. A more detailed description of the analytical techniques used is described in Gehrels and Stewart (1998).

The projected age of each grain, which is the upper intercept of a discordia line projected from 80 ± 40 Ma, is listed in Table 1. These projected model ages are interpreted to be more reliable than ^{207}Pb*/^{206}Pb* ages, as 80 Ma is the likely age of isotopic disturbance in the region.

Grain color and morphology have the potential to distinguish, in general, zircon populations from different sources, however, no relationship between age and either color or morphology is present in our samples.

STRATIGRAPHY

The three samples we studied are from (1) the Mesoproterozoic and/or Neoproterozoic El Alamo Formation of the Las Viboras Group, (2) the informally named Mesoproterozoic and/or Neoproterozoic El Aguila unit, and (3) the Lower? and Middle Cambrian Bolsa Quartzite. As described below, each of these units has a different stratigraphic setting. Little information has been published on the stratigraphic nomenclature, lithology, age, and tectonic setting of the El Alamo Formation and El Aguila unit, which are the subject of ongoing studies by Stewart and Amaya-Martínez (2000). In addition, uncertainty exists about the true age and tectonic setting of these two units. We provide a summary of existing information about the El Alamo Formation and El Aguila unit so that the reader can better integrate the detrital zircon studies we present here with information on Mesoproterozoic and/or Neoproterozoic arenites elsewhere in North America.

El Alamo Formation

The El Alamo Formation was collected from the east side of Cerro Minas de Los Gambusinos at Lat. 29° 35.5’ N, Long. 110° 35.6’ W, about 4 km southeast of Cerro de Oro and 75 km northeast of Hermosillo (Figure 1). It is approximately 770 m thick and consists of reddish brown cross-stratified arkosic sandstone with minor amounts of interbedded siltstone. It is laminated to thin bedded with abundant small-scale trough cross strata. Stewart and Amaya-Martínez (2000) report that the strata were apparently deposited by a braided river that spread out across a broad coastal plain and encroached on the intertidal zone.

The El Alamo Formation lies between the El Tápiro Formation and the Año Nuevo Formation within the Las Víboras Group (Figure 2). The strata were originally referred to as the El Alamo unit of the La Palma Group by Castro-Rodríguez and Morfín-Velarde (1998a, b), but they have been elevated to a formation in the Las Víboras Group by Stewart and Amaya-Martínez (2000). Up to 2.4 km thick, the Las Víboras Group is exposed in an area of about 5000 km^2 centered near Cerro de Oro.

The Las Viboras Group is poorly dated. The basal unit (El Tápiro Formation) lies unconformably on Precambrian

Table 1

U/Pb geochronologic data

						Apparent ages (Ma)			
Grain type	Grain wt. (μg)	Pb_c (pg)	U (ppm)	$\frac{206c}{204}$	$\frac{206c}{208}$	$\frac{206*}{238}$	$\frac{207*}{235}$	$\frac{207*}{206*}$	Projected age (Ma)
EL ALAMO (Mesoproterozoic and/or Neoproterozoic)									
PR	23	10.9	224	5300	5.3	1088 ± 7	1096 ± 9	1111 ± 9	1112 ± 10
CR	13	5.9	93	2670	5.6	1204 ± 9	12 ± 11	1204 ± 10	1204 ± 10
CE	6	6.3	55	990	3.4	1065 ± 15	1108 ± 17	1194 ± 14	1204 ± 16
PE	5	7.1	171	1510	6.0	1180 ± 11	1188 ± 13	1203 ± 10	1205 ± 11
CR	45	9.5	53	2650	1.9	1207 ± 7	1209 ± 9	1212 ± 9	1212 ± 9
PE	150	6.8	0	3180	2.3	1208 ± 8	1208 ± 10	1209 ± 9	1209 ± 10
PE	110	13.6	69	690	2.7	1175 ± 13	1189 ± 18	1216 ± 19	1218 ± 20
PE	15	5.1	64	2680	6.2	1307 ± 12	1342 ± 14	1397 ± 9	1402 ± 10
PR	17	6.1	63	2630	4.3	1382 ± 11	1392 ± 6	1408 ± 9	1409 ± 9
CE	9	8.4	78	1550	5.8	1088 ± 14	1195 ± 16	1393 ± 10	1413 ± 15
CE	8	6.1	32	1610	4.8	1372 ± 12	1393 ± 15	1425 ± 11	1429 ± 11
PE	9	5.6	232	5900	5.2	1429 ± 8	1430 ± 10	1432 ± 8	1432 ± 9
CE	7	11.4	90	840	4.0	1414 ± 15	1424 ± 19	1439 ± 14	1440 ± 14
PR	22	13.1	283	6890	13.2	1391 ± 9	1477 ± 11	1602 ± 7	1612 ± 9
PE	9	5.6	189	5400	6.3	1606 ± 9	1619 ± 12	1635 ± 8	1637 ± 10
PE	7	7.4	59	970	3.0	1568 ± 22	1604 ± 25	1653 ± 12	1656 ± 13
PR	17	10.1	135	3620	4.0	1486 ± 8	1588 ± 11	1726 ± 8	1737 ± 10
CR	10	98	89	178	2.1	1707 ± 17	1738 ± 45	1776 ± 40	1778 ± 40
CR	6	5.8	42	800	4.2	1620 ± 35	1711 ± 38	1825 ± 12	1833 ± 13
CR	6	6.4	66	1200	4.8	1712 ± 23	1991 ± 28	2294 ± 8	2312 ± 12
PR	13	7.4	148	7100	5.8	2371 ± 14	2462 ± 17	2538 ± 6	2542 ± 6
EL AGUILA (Mesoproterozoic and/or Neoproterozoic)									
CE	9	5.6	112	2050	10.6	1057 ± 10	1057 ± 11	1057 ± 8	1057 ± 9
PR	19	9.7	176	3780	9.3	1053 ± 7	1055 ± 9	1060 ± 12	1060 ± 12
PR	11	5.7	246	5460	7.4	1081 ± 5	1082 ± 7	1084 ± 8	1085 ± 9
CR	12	10.1	95	1360	7.3	1140 ± 10	1142 ± 13	1148 ± 16	1149 ± 16
CR	11	7	40	1150	8.5	1111 ± 11	1127 ± 14	1159 ± 13	1161 ± 14
CR	16	9.5	53	1080	6.8	1141 ± 12	1148 ± 17	1161 ± 19	1162 ± 20
CE	8	6.7	96	2240	5.9	1143 ± 9	1150 ± 11	1164 ± 11	1165 ± 11
PR	12	5.6	120	5200	6.3	1171 ± 6	1177 ± 8	1188 ± 9	1189 ± 10
CR	12	12.8	49	650	5.8	1303 ± 16	1311 ± 21	1323 ± 18	1325 ± 19
PE	6	25	284	875	6.2	1225 ± 8	1287 ± 13	1392 ± 14	1402 ± 15
PE	9	6.8	161	3000	9.0	1313 ± 9	1348 ± 12	1404 ± 11	1409 ± 12
PE	9	7.1	153	4390	8.8	1364 ± 8	1382 ± 10	1410 ± 9	1412 ± 10
CE	5	6.2	206	3980	8.6	1334 ± 8	1368 ± 10	1422 ± 7	1427 ± 8
PR	17	6	120	4950	5.4	1350 ± 7	1379 ± 10	1424 ± 9	1428 ± 10
PR	12	6.6	151	2380	7.4	835 ± 7	1001 ± 9	1384 ± 9	1433 ± 29
CR	14	7.4	125	4070	4.5	1578 ± 8	1611 ± 11	1654 ± 9	1657 ± 10
PR	12	6.4	94	3250	2.5	1654 ± 11	1656 ± 15	1659 ± 11	1659 ± 12
CE	7	10.1	190	2250	7.5	1578 ± 11	1617 ± 14	1669 ± 8	1672 ± 9
CE	6	5.4	69	1500	9.4	1704 ± 22	1706 ± 24	1709 ± 11	1710 ± 11
CR	11	6.4	53	4300	4.2	2443 ± 18	2566 ± 20	2664 ± 5	2668 ± 45

BOLSA (Lower? and Middle Cambrian)

PR	70	5.8	14	898	5.3	504 ± 10	507 ± 11.1	521 ± 23	525 ± 28
CE	25	17	29	385	4	844 ± 15	910 ± 21	1074 ± 28	1096 ± 32
CE	29	8.2	32	1290	5.2	1076 ± 11	1083 ± 12.7	1098 ± 12	1100 ± 12
CE	20	8.5	44	1200	5.2	1078 ± 11	1086 ± 13.4	1103 ± 13	1104 ± 14
PR	120	5.3	5	1380	5.5	1106 ± 16	1105 ± 18.4	1104 ± 16	1104 ± 17
CR	28	10.2	26	3756	6	1095 ± 13	1099 ± 16.5	1106 ± 17	1107 ± 18
CR	190	9.6	5	1120	4.8	1108 ± 11	1108 ± 13.5	1107 ± 13	1107 ± 14
CR	48	8.4	39	2650	4.3	1110 ± 11	1109 ± 9.08	1107 ± 10	1107 ± 10
PR	150	5.6	5	1730	5.6	1112 ± 13	1111 ± 14.8	1109 ± 13	1108 ± 14
CE	9	7.8	23	330	3.8	1115 ± 42	1114 ± 45.9	1111 ± 32	1110 ± 34
CE	20	26	32	292	3.3	1111 ± 15	1111 ± 21.9	1112 ± 28	1112 ± 29
CE	13	5.7	10	445	4.8	1039 ± 38	1062 ± 42.2	1108 ± 32	1113 ± 34
CR	64	21	111	3780	4.9	1106 ± 6	1108 ± 9.48	1112 ± 12	1113 ± 12
CR	28	15	51	1075	4.6	1115 ± 9	1115 ± 11.9	1114 ± 14	1114 ± 14
PR	24	22	45	520	3.9	1004 ± 10	1039 ± 18.3	1115 ± 27	1124 ± 29
CR	39	9.2	40	2280	3	1255 ± 10	1259 ± 11.8	1265 ± 10	1266 ± 10
CR	33	9.7	33	1460	3	1207 ± 10	1228 ± 12.5	1266 ± 10	1270 ± 10
CE	26	16	154	3190	4.3	1226 ± 8	1247 ± 9.94	1283 ± 8	1286 ± 9
CR	44	8.7	41	3200	2.9	1424 ± 9	1426 ± 11.1	1430 ± 8	1431 ± 8
PR	200	14.2	5	1085	5.2	1562 ± 12	1579 ± 14.9	1602 ± 9	1605 ± 10
CE	20	77	40	167	2.4	1398 ± 16	1484 ± 37.1	1609 ± 39	1619 ± 40
PR	150	5.9	10	4800	8.2	1632 ± 9	1632 ± 10.7	1631 ± 7	1632 ± 7

* = radiogenic Pb
Grain type: CE = colorless euhedral, CR = colorless round, PE = pink euhedral, PR = pink round.
All grains abraded to ~2/3 of original diameter with air abrador.
(206/204)m is measured ratio, uncorrected for blank, spike, or fractionation.
(206/204)c and (206/208)c are corrected for blank, spike, and fractionation.
Concentrations have an uncertainty of up to 25% due to uncertainty of weight of grain.
Constants used: $\lambda^{235} = 9.8485X10^{-10}$, $\lambda^{238} = 1.55125X10^{-10}$, 238/235 = 137.88.
All uncertainties are at the 95% confidence interval.
Pb blank ranged from 2 to 10 pg. U blank was consistently <1 pg.
206/238, 207/235, and 207/206 ages are measured, projected ages are upper intercepts projected from 80 ± 40 Ma.

crystalline basement rocks (presumably 1.4 Ga or older) (Stewart and Amaya-Martínez, 2000), which places a maximum age on the strata. The minimum age is not well constrained, but Stewart and Amaya-Martínez (2000) suggest that the Las Víboras Group may be older than the Caborca succession and the Cordilleran miogeocline. This is based in part on similarities in stratigraphy and stromatolites with pre-miogeoclinal strata in the western United States (Stewart and Amaya-Martínez, 2000). The stratigraphy of the Las Víboras Group, composed of two lower thick quartzite units and an upper thin dolomite/quartzite unit, is also quite distinct from nearby miogeoclinal strata of the Caborca succession, which consist predominately of dolomite and siltstone with little quartzite. Given this Meso- and/or Neoproterozoic apparent age, it is likely that the El Alamo Formation was deposited on the supercontient of Rodinia prior to the rifting event that formed the Cordilleran miogeocline.

<u>El Aguila unit</u>

The informally named El Aguila unit (Stewart and Amaya-Martínez, 2000) was collected 2.8 km south-southeast of Cerro El Sotol at Lat. 29° 26.0' N, Long. 110° 32.6' W, about 50 km northeast of Hermosillo and 20 km south of Cerro de Oro (Figure 1). It is approximately 385 m thick where exposed in an incomplete, faulted section. It consists of very fine- to very coarse-grained quartzite, with interstratified metasiltstone and sparse dolomite. The El Aguila unit contains sparse amounts of granule conglomerate with siltstone and quartzite intraclasts as large as 25 cm. It was probably deposited in a fluvial environment.

Stratigraphically, the El Aguila unit is distinct from the Las Víboras Group and the Caborca succession. We inter-

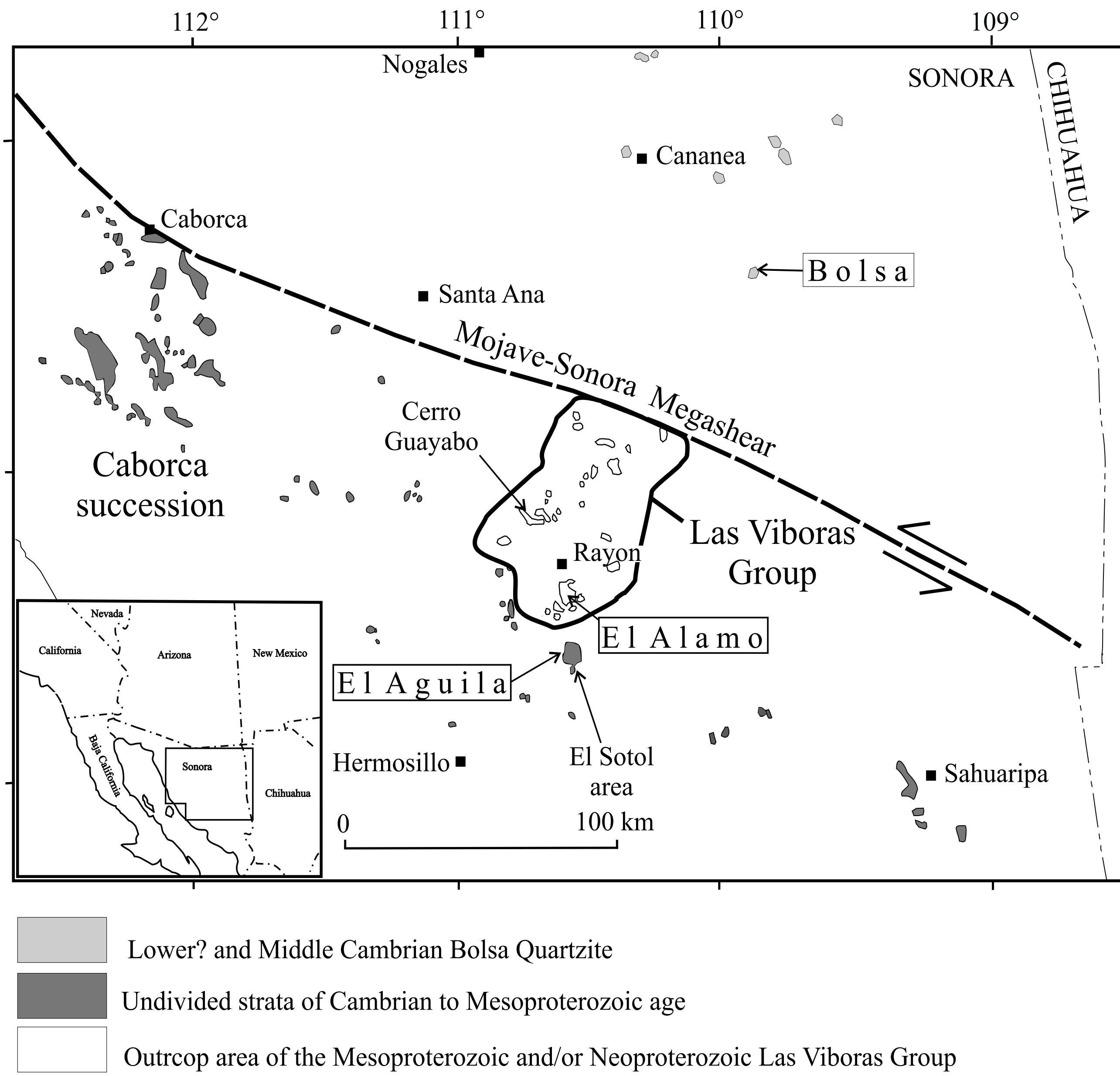

Fig. 1. Outcrop map of Cambrian and Neoproterozoic strata in Sonora, Mexico.

pret the El Aguila unit to be of Mesoproterozoic and/or Neoproterozoic age, and older than the Cordilleran miogeocline. This is based largely upon field relations which suggest that the El Aguila unit may be overlain by miogeoclinal strata on an angular unconformity (Stewart and Amaya-Martínez, 2000). Strata of the El Aguila unit appear more disrupted than strata below the unconformity, and different members of the El Aguila unit are present at different places along the apparent unconformity. Also, the El Aguila unit does not resemble any strata in the Caborca succession, and thus may be significantly older. The lower contact of the El Aguila unit is not exposed.

Bolsa Quartzite

A sample from the lower part of the Bolsa Quartzite was collected on the east side of Cerro La Cal at Lat. 30° 36.8’ N, Long. 109° 56.9’ W, approximately 3 km south-southwest of the village of Bacoachi and approximately 55 km southeast of Cananea, Sonora (Figure 1). The Bolsa Quartzite is a thin unit, generally less than 200 m thick, that generally lies unconformably on Precambrian Pinal Schist inland of the Cordilleran miogeocline. The Bolsa Quartzite crops out in northeastern Sonora and extends northward into Arizona. At our sampling location near Bacoachi, however,

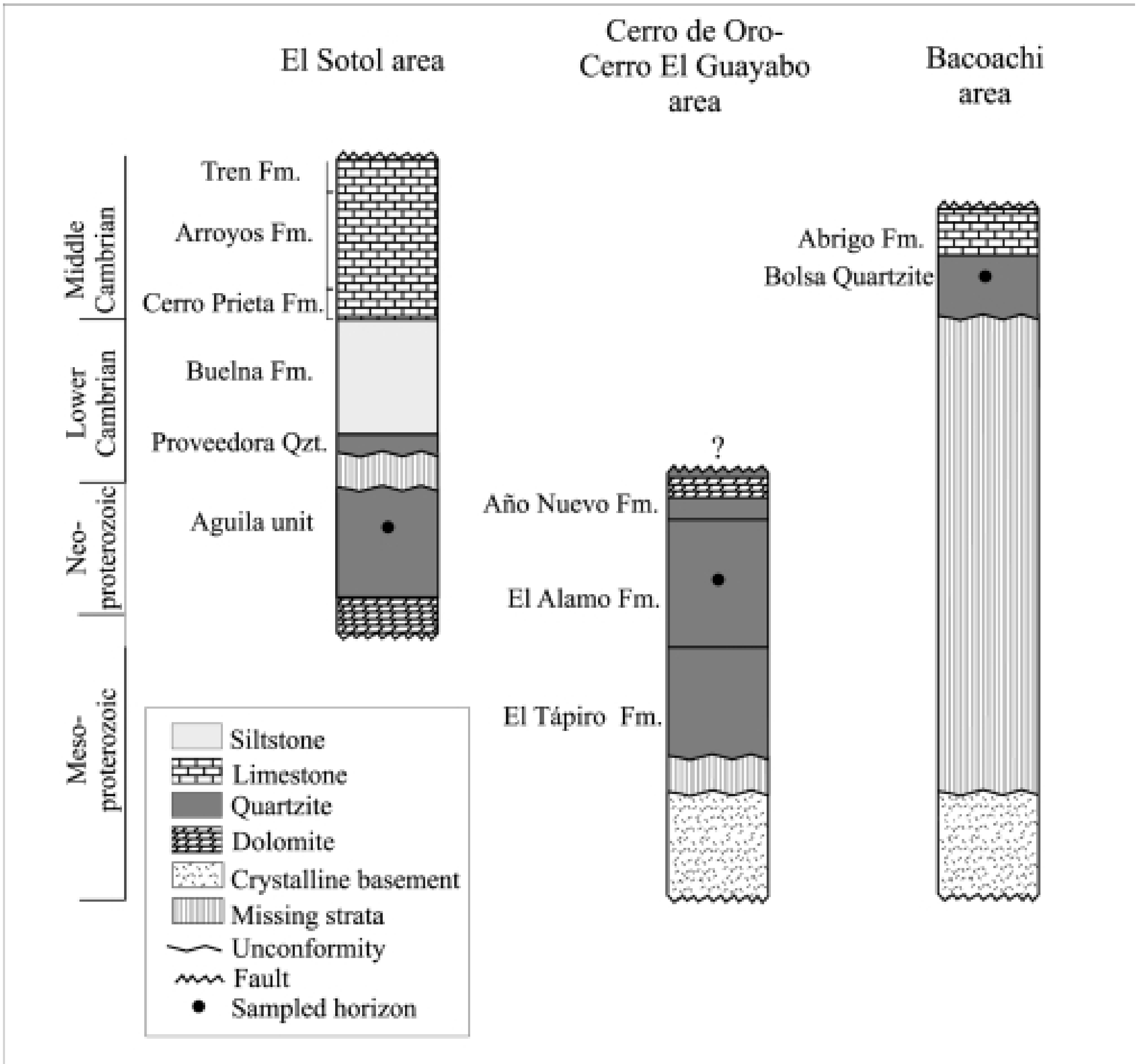

Fig. 2. Generalized stratigraphic columns of sample localities. Vertical scale is not actual stratigraphic thickness.

it overlies Precambrian porphyritic granite (Figure 1). The Bolsa Quartzite is composed of siliceous sandstone and quartzite, with subordinate conglomerate near the base of the unit and siltstone and shale near the top. The average grain size, feldspar content, and thickness of beds decreases upward in the unit. At the sample site, the Bolsa Quartzite contains U-shaped fossils, possibly *Monocraterion*. At other localities of the western United States, *Skolithos* tubes, animal tracks and trails, and mudcracks occur in the Bolsa Quartzite. The Bolsa Quartzite most likely accumulated in intertidal and shallow subtidal environments (Middleton, 1989).

The age of the Bolsa Quartzite is poorly known, as it does not contain age-diagnostic fossils (Hayes, 1975). It has generally been considered to be Middle Cambrian in age because it is conformable with, or intertongues with, the overlying Middle Cambrian Abrigo Formation (Hayes, 1975).

However, the Bolsa Quartzite is known to be time transgressive, and at least part of the Bolsa Quartzite is probably Early Cambrian in age (Hayes, 1975).

RESULTS

El Alamo Formation

The zircon grains from the El Alamo Formation are variable in morphology and color. The dominant population consists of light to dark pink grains that are elongate and highly rounded. Subordinate groups include pink euhedral, colorless rounded, and colorless euhedral grains. All zircons analyzed were between 100 and 150 μm prior to abrasion. Most of the El Alamo Formation zircons yield concordant to slightly discordant analyses, with a ~2312 Ma grain exhibiting moderate discordance (Figure 3; Table 1). Among the twenty-one grains analyzed, four intervals are recognized (Figure 7). Seven grains fall between 1112 and 1218 Ma, six between 1402 and 1440 Ma, six between 1612 and 1833 Ma, one at ~2312, and one at ~2542 Ma (Table 1).

El Aguila unit

Pink rounded, colorless rounded, and pink euhedral grains dominate zircons from this sample, with fewer colorless euhedral crystals. The grains were all elongate and between 100 and 150 μm prior to abrasion. Most grains yield ages that cluster into three groups, with one exception (Figure 4). There are eight grains between the ages of 1057 and 1189 Ma, seven grains between 1325 and 1433 Ma, four grains between 1657 and 1710 Ma, and one zircon is ~2668 Ma. (Table 1).

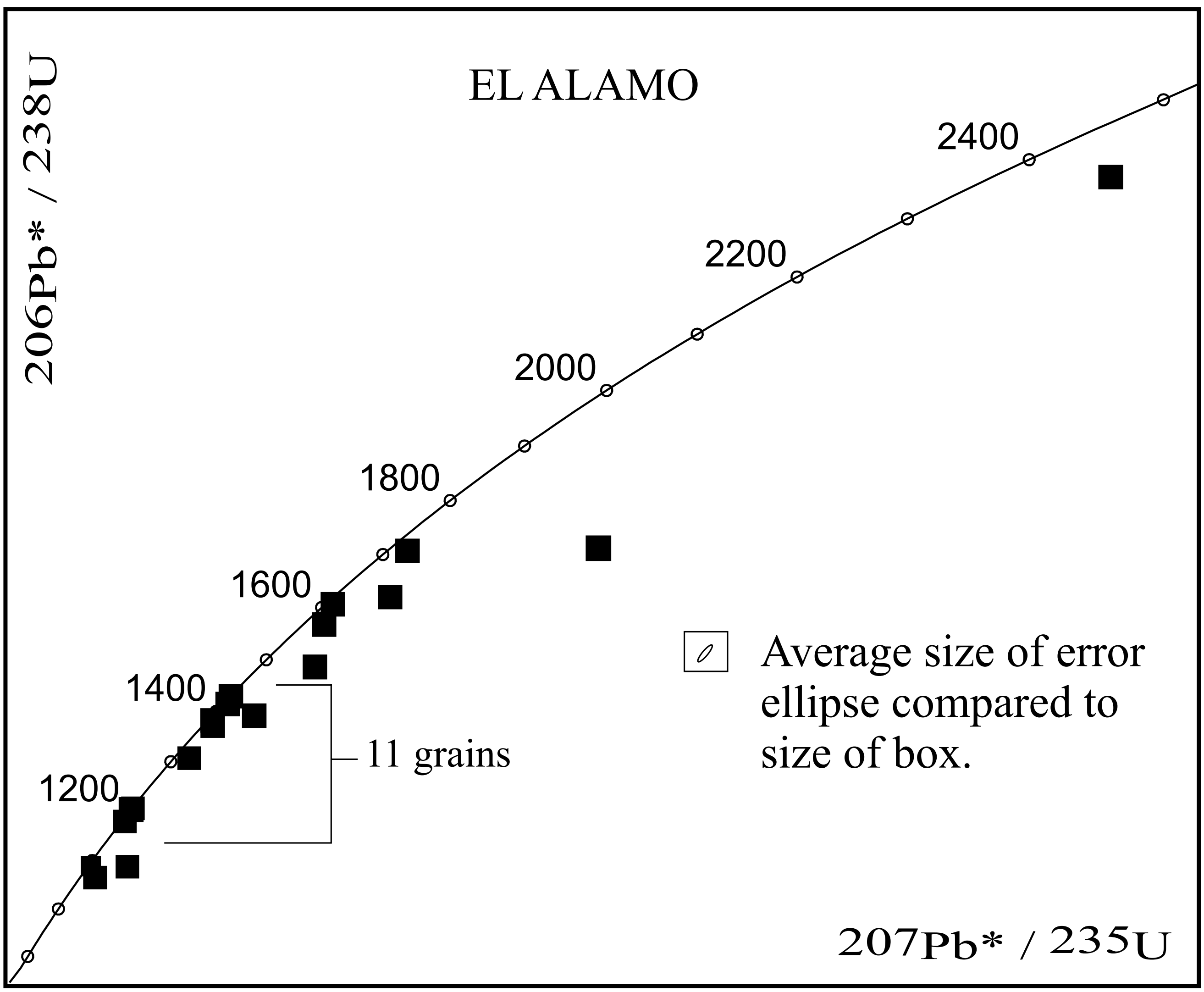

Fig. 3. Detrital zircon data for sample of El Alamo Formation (21 grains analyzed). As shown, uncertainty of each analysis is much smaller than the boxes. Some boxes overlap.

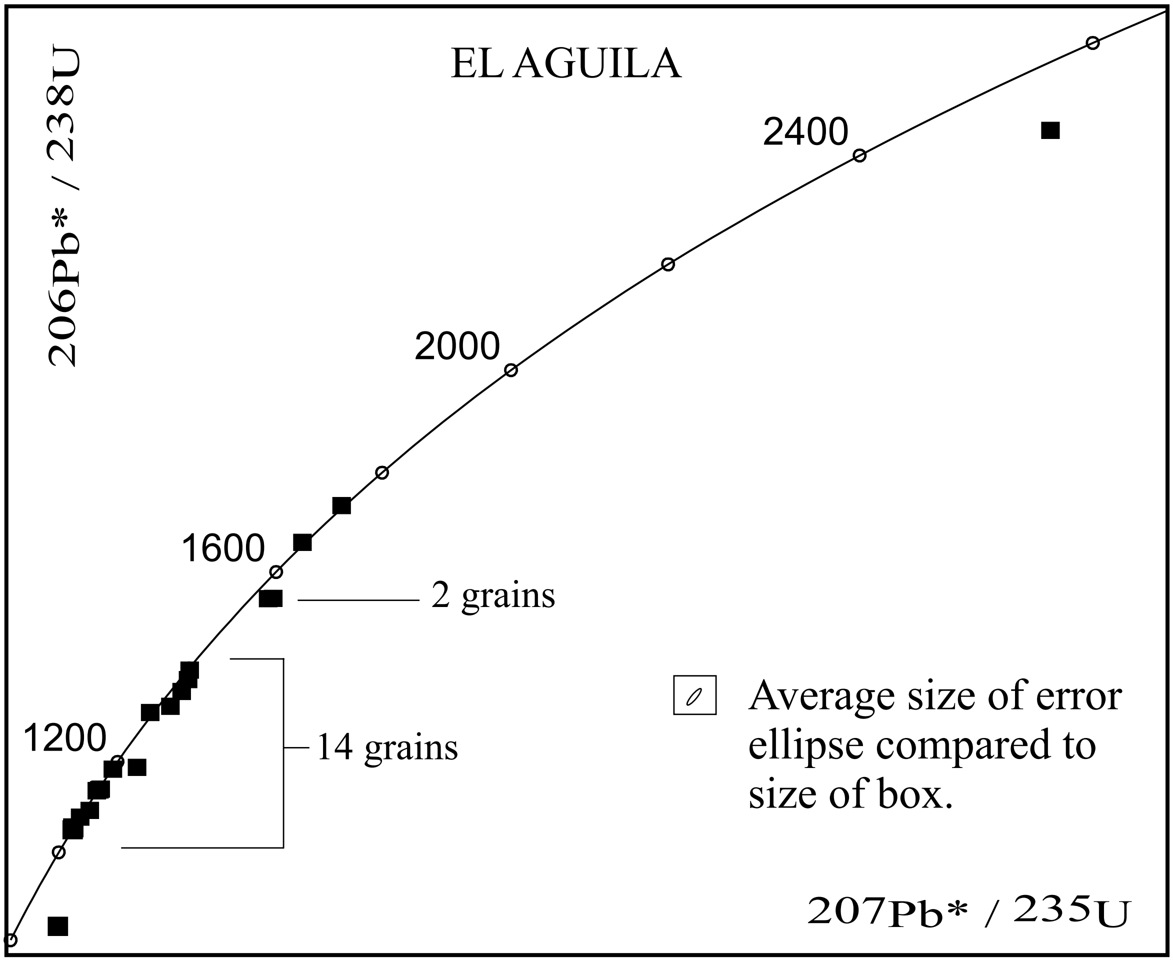

Fig. 4. Detrital zircon data for sample of El Aguila unit (20 grains analyzed). As shown, uncertainty of each analysis is much smaller than the boxes. Some boxes overlap.

Bolsa Quartzite

Zircons in the Bolsa Quartzite are relatively evenly split between colorless rounded, colorless euhedral, and pink rounded grains. Grains analyzed were all between 145 and 200 μm before abrasion. The zircon ages define five groups (Figure 5). One grain is 525 Ma, 14 grains range from 1096 to 1124 Ma, three grains are between 1266 and 1286 Ma, one grain is ~1431 Ma, and three grains range in age from 1605 to 1632 Ma (Table 1).

PROVENANCE

Paleocurrent data provide general information on transport directions of detrital material and thus of possible source areas. Sparse paleocurrent data is available from the units studied, however flow directions vary considerably even within the same unit. In the Las Víboras Group, including the El Alamo Formation, paleocurrents are generally toward the north (Stewart and Amaya-Martínez, 2000). This suggests that the Mesoproterozoic and/or Neoproterozoic strata in this study may have been shed from a source area to the south. In contrast, paleocurrent directions in the Bolsa Quartzite are to the west or southwest in southeastern Arizona (Seeland, 1969) and northern Sonora (Stewart and Amaya-Martínez, 2000), suggesting a source to the east or northeast. This is consistent with transport directions in Cambrian and Neoproterozoic quartzites in the southwestern United States and northwestern Mexico, which are generally away from the continental interior (Stewart, 1992).

Based upon our detrital zircon ages and this sparse paleocurrent data, the following options are proposed for sources of the zircons in the El Alamo Formation, El Aguila unit, and Bolsa Quartzite.

The single grain of 525 Ma in the Bolsa Quartzite was most likely shed from the Wichita uplift, located in northern

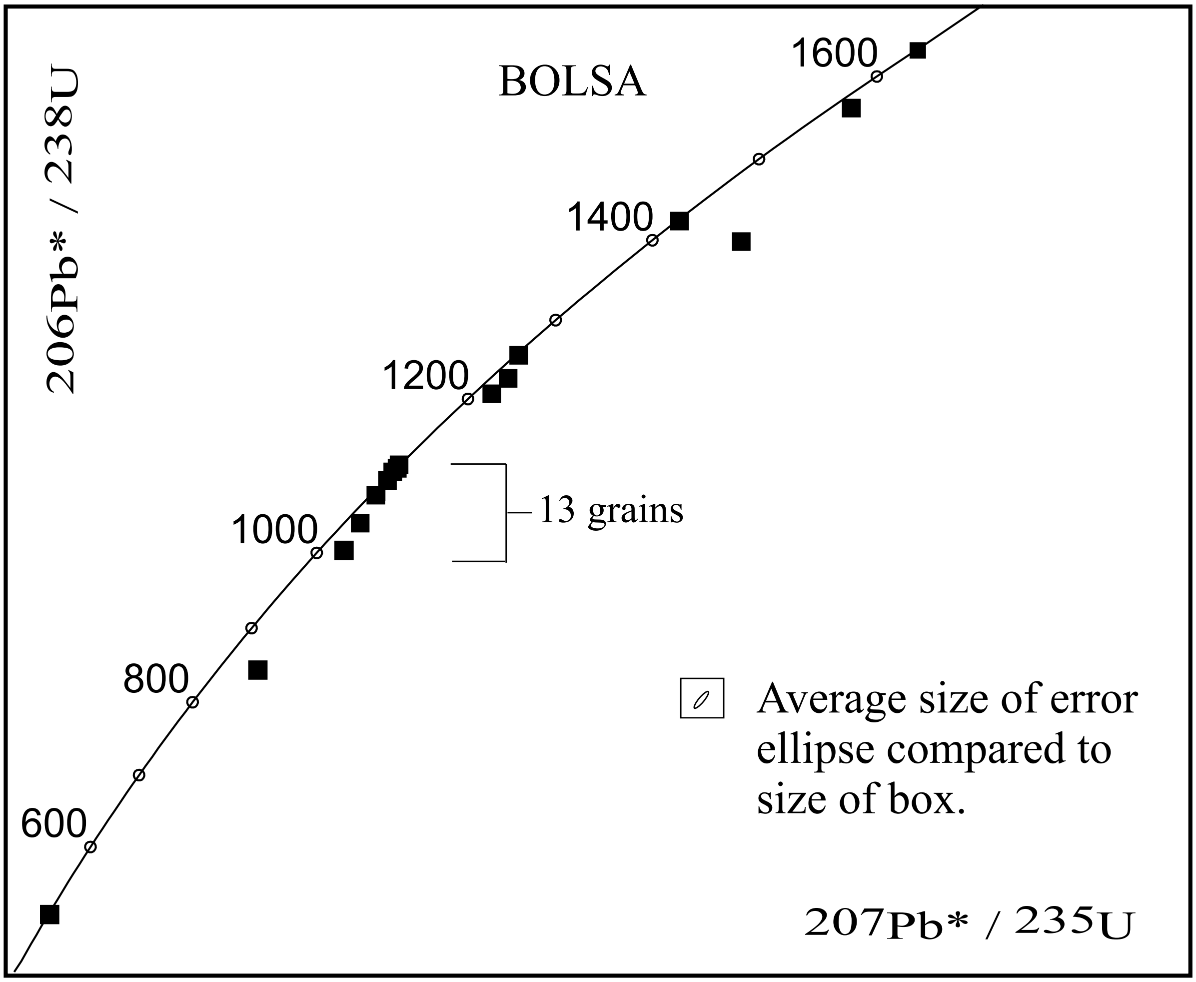

Fig. 5. Detrital zircon data for sample of Bolsa Quartzite (22 grains analyzed). As shown, uncertainty of each analysis is much smaller than the boxes. Some boxes overlap.

Texas and southwestern Oklahoma, where rocks of 530 and 535 Ma crop out (Hogan and Gilbert, 1997) (Figure 6). It is also possible that the grain was shed from the Coahuila terrane in northeastern Mexico, where ~579 Ma granitic boulders have been identified (Lopez *et al.*, 1998), although this age is a bit old.

The zircons ranging in age from 1.0 to 1.2 Ga, which are dominant in all three samples (Figure 7), could have come from three possible sources. One option is that the sediment was transported via fluvial systems from the Grenville belt that trends more or less east-west through present-day western and central Texas and into northeastern Mexico (Figure 6A). Rankin *et al.* (1993) and Mosher (1998) have reported zircons from the Llano uplift ranging in age from 1.1 Ga to 1.3 Ga. The Llano area shows a distinctive bimodality at 1.1 and 1.3 Ga, and although the Bolsa Quartzite shows a strong 1.1 Ga signature (Figure 7), 1.3 Ga grains are subordinate in our samples.

Another possibility is that these grains were transported by rivers from large granite bodies, now covered or eroded, in western North America (Figure 6B). Based on detrital zircon and ε_{Nd} data from the miogeoclinal Wood Canyon Formation in southern California, Farmer and Ball (1997) have proposed the existence of such a granite body in southwestern Utah, which they informally called the Wood Canyon granite. This granite, they suggest, may have provided 1.1 Ga zircon grains found in the miogeoclinal deposits, as well as account for the anomalous ε_{Nd} value found in the middle member of the Wood Canyon Formation. There is no known exposure of the Wood Canyon granite, it is simply a hypothetical body that could account for the data from the Wood Canyon Formation. However, a few plutonic rocks of 1.1 to 1.2 Ga are known in other parts of western North America (i.e., Aibo granite, San Gabriel terrane, and Pikes Peak granite) (Figure 6B), but these bodies are too small to supply the large amount of detritus needed to form the units.

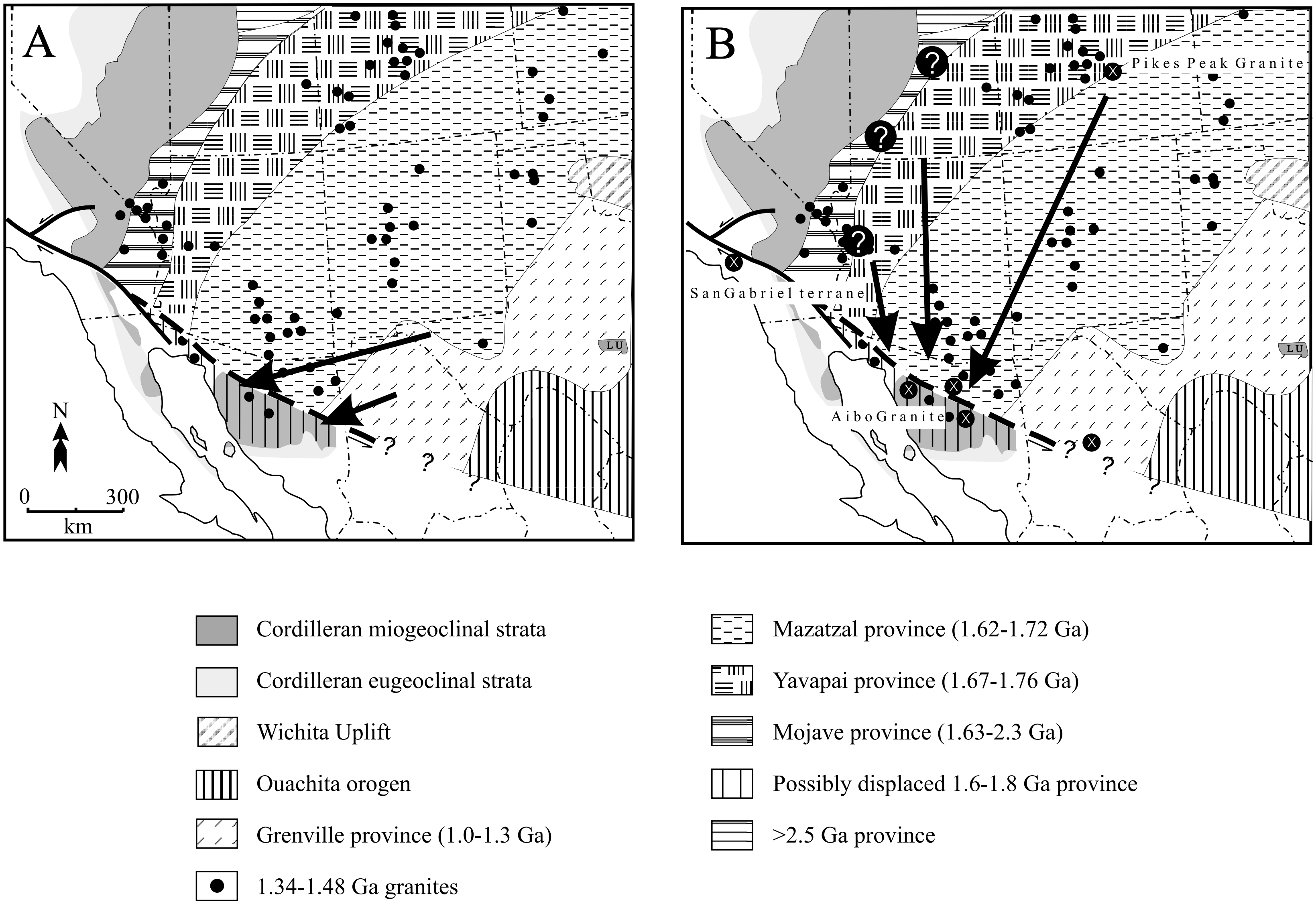

Fig. 6. Geological sketch maps showing basement terranes in southwestern U.S. and northwest Sonora, Mexico. Arrows represent hypothesized sediment transport. Dashed line represents hypothetical Mojave-Sonora Megashear. Map adapted from Gehrels and Stewart (1998), Hoffman (1989), Van Schmus *et al.* (1993), and Anderson and Morrison (1992). A) Derivation of most detritus from the Grenville belt in southern United States. B) Derivation of most detritus from mainly hypothetical granite bodies of Grenville age in southwestern United States. X's indicate known plutons of Grenville age. From Rodríguez-Castañeda (1994), Stephens *et al.* (1986), Anderson *et al.* (1979), Mauger *et al.* (1983), Blount (1982), Reed (1993), and Van Schmus *et al.* (1993). Question marks represent now covered or eroded Grenville age plutons that may have provided sediment. Southwestern Utah location from Farmer and Ball (1997). LU = Llano uplift.

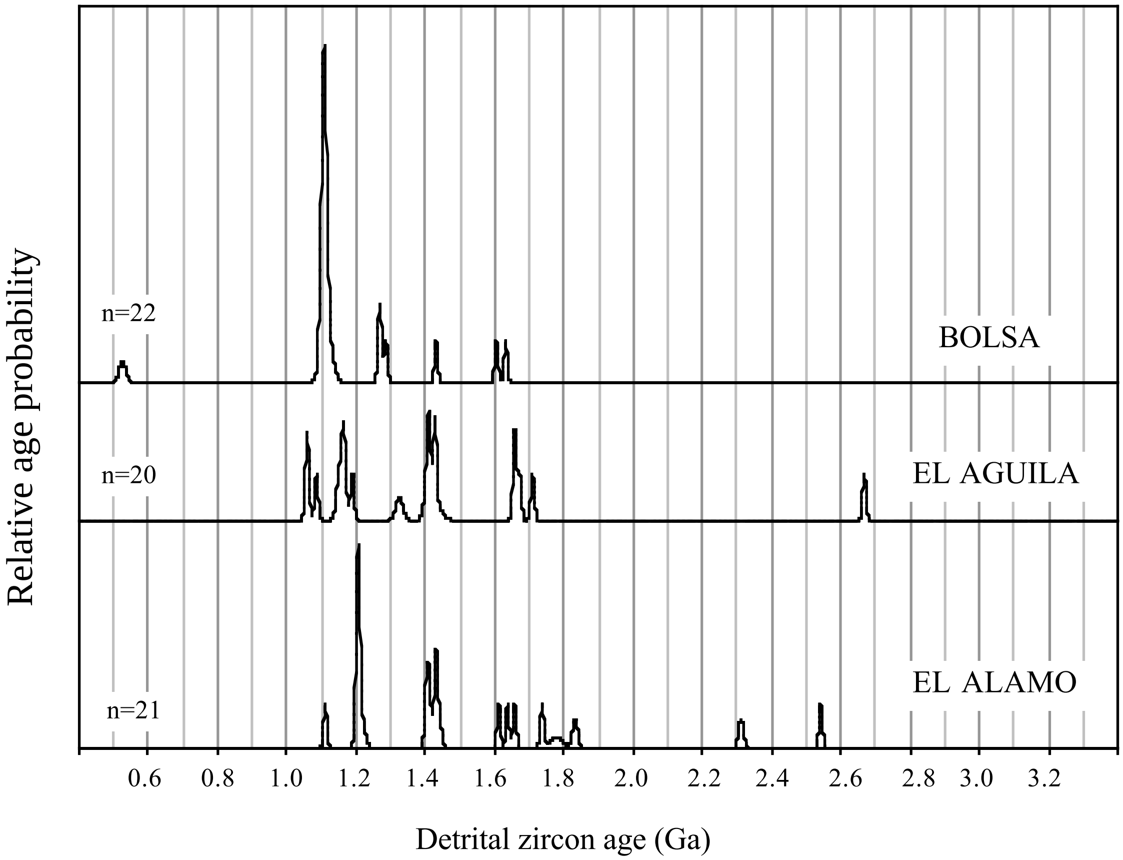

Fig. 7. Relative age probability plots of single-zircon ages from the Bolsa Quartzite, El Aguila unit, and El Alamo Formation. The plot shows the probability distribution (age and associated uncertainty) for each grain, summed for all grains within the sample. Height of peak indicates relative abundance of age in sample.

A third possibility is that the source of the 1.1 to 1.2 Ga zircons was to the south. The northerly transport direction indicated by paleocurrent data from the Las Víboras Group is suggestive of such a source. This idea is particularly attractive for 1.1 to 1.2 Ga detrital zircons in the El Alamo Formation and the El Aguila unit, both of which may be older than the Cordilleran miogeocline. Prior to rifting that formed the Laurentian continental margin and the Cordilleran miogeocline, the Las Víboras Group and El Aguila unit would have been in the interior part of the Rodinia supercontinent (Hanson *et al.*, 1998). If true, the 1.1 to 1.2 Ga zircons may have been derived from Grenville-age rocks in this supercontinent south of what is now central Sonora. Such Grenville-age rocks could have been a southwestern continuation of the Grenville belt of North America that was rifted away during the fragmentation of Rodinia. Another southern provenance possibility is the Oaxaquia terrane, which trends roughly northwest through southern Mexico (Ortega-Gutiérrez *et al.*, 1995, Lawlor *et al.*, 1999). However, it probably was not located in its current position during Mesoproterozoic to Cambrian time; it is thought to have originated in eastern North America and moved to eastern Mexico during late Paleozoic time (Ortega-Gutiérrez *et al.*, 1995).

Grains older than ~1.4 Ga do not aid in testing these scenarios, as they are equally likely to appear in all options (Figure 6A and B). The ~1.4 Ga grains could have come from any of the 1.4 Ga granitic plutons that populate much of the southern United States and northwestern Mexico (Anderson and Morrison, 1992). The grains between 1.6 and 1.8 Ga could have been derived from any of the three southwestern United States basement provinces; Mojave (1.63 to 2.3 Ga), Yavapai (1.67 to 1.76 Ga), or Mazatzal (1.62 to 1.72 Ga) (Figure 6). Grains older than 2.4 Ga could have been derived from the Archean-earliest Proterozoic provinces in the cratonal interior or from the Mojave province. Alternately, if a southern terrane provided the Grenville-age grains in these samples, the 1.4 to 1.8 Ga grains could have come from the south. This alternative is difficult to test, however, because there is much debate as to what landmass was located south of northern Mexico at the time of deposition.

CONCLUSIONS

Individual detrital zircon grains from Mesoproterozoic and/or Neoproterozoic to Middle Cambrian rocks in Sonora were analyzed by isotope dilution-thermal ionization mass spectrometry to identify potential source terranes. Most grains belong to four age groups: 1.0 to 1.2 Ga, 1.4 Ga, 1.6 to 1.8 Ga, and >2.4 Ga. An exception is one 525 Ma zircon found in the Bolsa Quartzite. The 1.0 to 1.2 Ga grains dominate, particularly in the Bolsa Quartzite and El Alamo Formation.

Zircons with ages of ~1.4 Ga could have been derived from granite plutons of this age that are widespread in southwestern United States and northwestern Mexico. Grains with ages between 1.6 and 1.8 Ga could have come from any of the three crystalline basement terranes of southwestern United States; the Mojave, Yavapai, or Mazatzal provinces. Grains older than about 2.4 Ga could have originated in Archean provinces of North America or in the Mojave Province. Conversely, if a southern source is favored, the possibility of transport from the landmass south of the rift is an option, however the identification of that landmass is debated.

The dominant age group in our samples is 1.0 to 1.2 Ga. Three hypotheses to explain the abundance of these grains are: (1) derivation from the Grenville belt in southern North America-northern Mexico, (2) derivation from now covered or eroded plutons located north of the Grenville belt in western North America, or (3) derivation from southern sources that were rifted away during the breakup of Rodinia.

Determining provenance terranes for these sedimentary units has proven to be non-unique, as there are difficulties with each of the hypotheses presented. Further sampling of age-correlative units throughout the western United States and northern Mexico may help determine the areal extent and origin of the dominantly 1.0 to 1.2 Ga detrital material.

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