Late Paleozoic fusulinids from Sonora, México: Importance for interpretation of depositional settings, biogeography, and paleotectonics

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ABSTRACT

Three sets of fusulinid faunas in Sonora, Mexico, discussed herein, record different depositional and paleotectonic settings along the southwestern margin of Laurentia (North America) during Pennsylvanian and Permian time. The settings include: offshelf continental rise and ocean basin (Rancho Nuevo Formation in the Sonora allochthon), shallow continental shelf (La Cueva Limestone), and foredeep basin on the continental shelf (Mina México Formation). Our data represent 41 fusulinid collections from 23 localities with each locality providing one to eight collections.

Reworked fusulinids in the Middle and Upper Pennsylvanian part of the Rancho Nuevo Formation range in age from Desmoinesian into Virgilian (Moscovian-Gzhelian). Indigenous Permian fusulinids in the La Cueva Limestone range in age from middle or late Wolfcampian to middle Leonardian (late Sakmarian-late Artinskian), and reworked Permian fusulinids in the Mina México Formation range in age from early to middle Leonardian (middle-late Artinskian). Conodonts of Guadalupian age occur in some turbidites in the Mina México Formation, indicating the youngest foredeep deposit is at least Middle Permian in age. Our fusulinid collections indicate a hiatus of at least 10 m.y. between the youngest Pennsylvanian (Virgilian) rocks in the Sonora allochthon and the oldest Permian (middle Wolfcampian) rocks in the region.

Most fusulinid faunas in Sonora show affinities to those of West Texas, New Mexico, and Arizona; however, some genera and species are similar to those in southeastern California. As most species are similar to those east of the southwest-trending Transcontinental arch in New Mexico and Arizona, this arch may have formed a barrier preventing large-scale migration and mixing of faunas between the southern shelf of Laurentia in northwestern Mexico and the western shelf in the southwestern United States.

The Sonora allochthon, consisting of pre-Permian (Lower Ordovician to Upper Pennsylvanian) deep-water continental-rise and ocean-basin rocks, was thrust northward 50–200 km over Permian and older shallow-water carbonate-shelf rocks and Permian deep-water foredeep rocks of southern Laurentia. As Triassic rocks unconformably overlie the Sonora allochthon, we conclude that terminal movement of the allochthon was in Late Permian time.

Key words: fusulinids, sedimentation, stratigraphy, biogeography, tectonic framework, Pennsylvanian, Permian, Sonora, Mexico

RESUMEN

Tres grupos de faunas de fusulínidos discutidos en este artículo documentan diferentes ambientes de depósito y tectónicos a lo largo de la margen suroeste de Laurentia (Norte América) durante el Pérmico y Pensilvánico. Estos ambientes incluyen: talud continental y cuenca oceánica (Formación Rancho Nuevo en el alóctono de Sonora); plataforma de agua somera continental (Caliza La Cueva) y cuenca del tipo "foredeep" sobre la plataforma continental (Formación Mina México). La información obtenida representa 41 colecciones de fusulínidos provenientes de 23 localidades, en las cuales se obtuvieron de una a ocho colecciones por localidad.

Los fusulínidos retrabajados contenidos dentro del Pensilvánico Medio y Superior de la Formación Rancho Nuevo varían en edad desde el Desmoinesiano hasta el Virgiliano (Moscoviano-Gzheliano). Los fusulínidos in situ del Pérmico en la Caliza La Cueva de la plataforma varían en edad desde al menos el Wolfcampiano medio o tardío hasta el Leonardiano medio (Sakmariano tardío-Artinskiano tardío) y los fusulínidos retrabajados dentro de la Formación Mina México indican rangos de edad entre el Leonardiano temprano a medio (Artinskiano medio-tardío). Conodontos de edad Guadalupiano contenidos en estratos de turbiditas en la Formación Mina México indican que la edad de depósito más joven dentro de la cuenca "foredeep" es al menos Pérmico Medio. Las colecciones de fusulínidos indican un hiatus de al menos 10 Ma entre las rocas más jóvenes del Pensilvánico (Virgiliano) en el alóctono de Sonora y las rocas más antiguas del Pérmico (Wolcampiano medio) en la región.

La mayoría de las faunas fusulínidos en Sonora muestran afinidades con aquellas del oeste de Texas, Nuevo México y Arizona; sin embargo, algunos géneros y especies son similares a aquellos de la porción sureste de California. Debido a que estas especies son similares a las reportadas hacia el este del arco Transcontinental, que muestra una orientación suroeste en Nuevo México y Arizona, se interpreta que este arco puede haber formado una barrera que impidió la migración a gran escala y la mezcla de faunas entre el extremo sur de la plataforma de Laurentia en el noroeste de México y el extremo oeste de esta misma plataforma en el suroeste de Estados Unidos.

El alóctono de Sonora, constituido por rocas anteriores al Pérmico (Ordovícico Inferior a Pensilvánico Superior) y depositadas en ambientes de talud continental de aguas profundas y cuenca oceánica, fue transportado tectónicamente hacia el norte una distancia estimada entre 50 y 200 km, cabalgando a secuencias de la plataforma carbonatada

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de aguas someras del Pérmico y más antiguas; así como también a las rocas pérmicas de aguas profundas, depositadas en las cuencas "foredeep" del sur de Laurentia. Debido a que rocas triásicas sobreyacen discordantemente al alóctono de Sonora, se concluye que el movimiento final del alóctono fue en el Pérmico Tardío.

Palabras clave: fósiles, fusulínidos, estratigrafía, marco tectónico, Pensilvánico, Pérmico, Sonora, México.

INTRODUCTION

Pennsylvanian and Permian fusulinids from the southwestern margin of cratonal North America in the State of Sonora, Mexico, occur in three principal depositional settings—continental rise-ocean basin (Sonora allochthon), continental shelf (Laurentian carbonate shelf), and foredeep (Mina México basin). Figure 1 shows the present distribution of the three depositional and tectonic settings. Figure 2 is a schematic north-south cross section showing pre-Mesozoic stratigraphic and structural relationships of rock units in the study area. The fusulinids occur in strata of Pennsylvanian and Permian ages (Figure 3). Of the fusulinid faunas discussed here, one set occupied shallow-marine environments on the continental shelf; the two other sets consist of displaced and reworked specimens, one deposited in a deep-marine foredeep developed on the continental shelf, and the other in deep-marine environments in continental-rise and ocean-basin settings along the southern margin of Laurentia.

Fusulinid samples collected by Poole and co-workers in the 1980s and 1990s, and by Poole and Amaya-Martínez in the early 2000s were taken during geologic mapping and stratigraphic studies. Raymond C. Douglass (U.S. Geological Survey) identified the fusulinids collected in the 1980s and Stevens identified the fusulinids collected after 1990. For this report, Stevens re-examined the collections studied by Douglass. Fusulinid faunas reported herein are listed in Tables 1 and 2 and illustrated in Figures 4–8.

The stratigraphic position of the fusulinid collections from the shelfal La Cueva Limestone can be determined, but collections from the Sonora allochthon and most of the foredeep unit (Mina México Formation) cannot because of severe disruption, and limited exposures and structural complications, respectively. Investigations of the fusulinid faunas provide significant information concerning biogeographic affinities and depositional and paleotectonic settings on the southwest margin of Laurentia (Figures 1, 2, and 3). Distribution of our fusulinid samples shown on Figure 1 ref1ects the scattered exposures of upper Paleozoic strata in Sonora.

Fusulinid faunas and their depositional environments are discussed

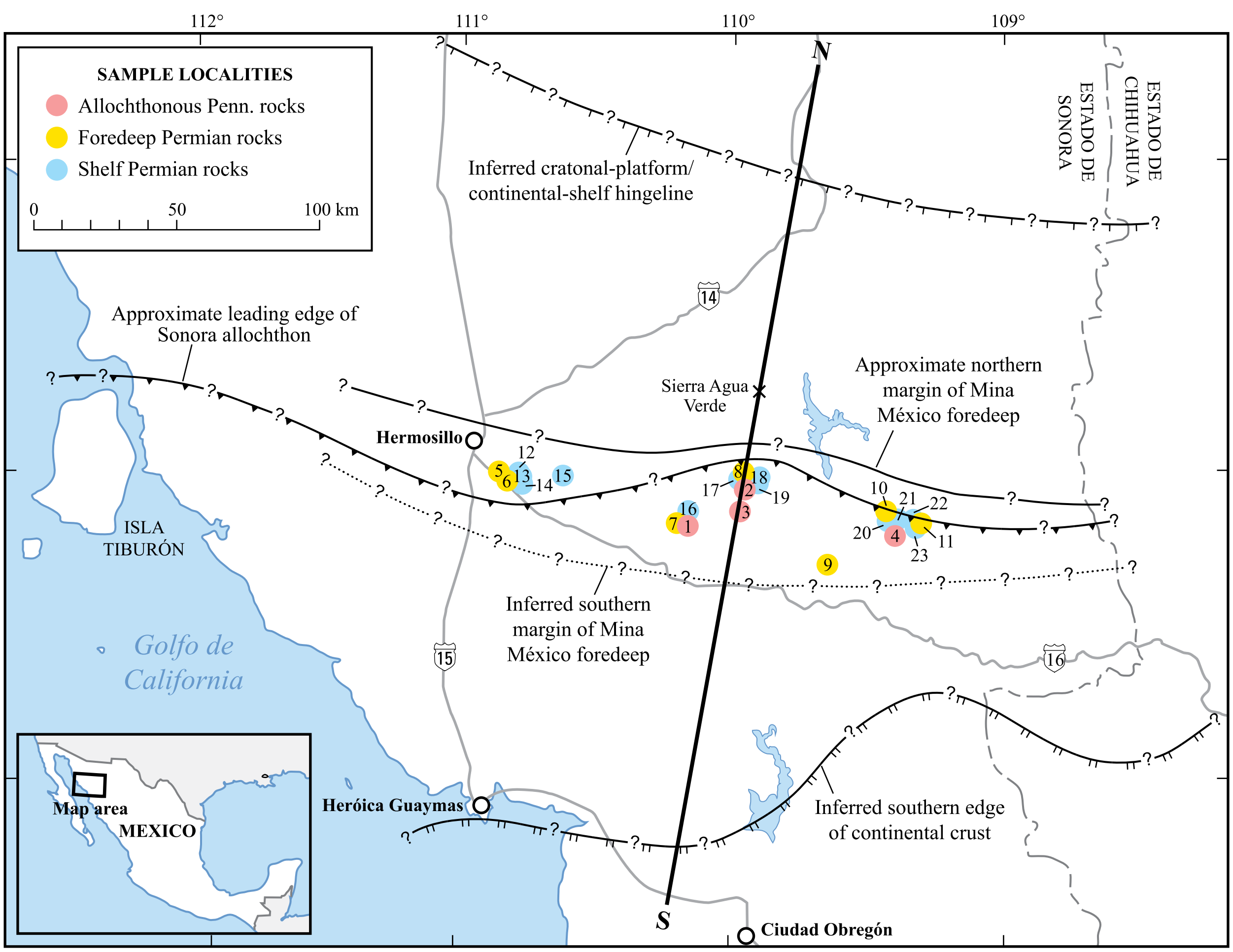

Figure 1. Index map showing depositional and tectonic setting of 41 samples from central and east-central Sonora. Twenty-three sample localities (colored dots) and 41 faunas are discussed in the text and listed in Tables 1 and 2. Tectonic features include cratonal-platform/continental-shelf hingeline, leading edge of Sonora allochthon, northern and southern margins of Mina México foredeep, and south edge of continental crust. N-S bold line is position of line of schematic cross section shown in Figure 2.

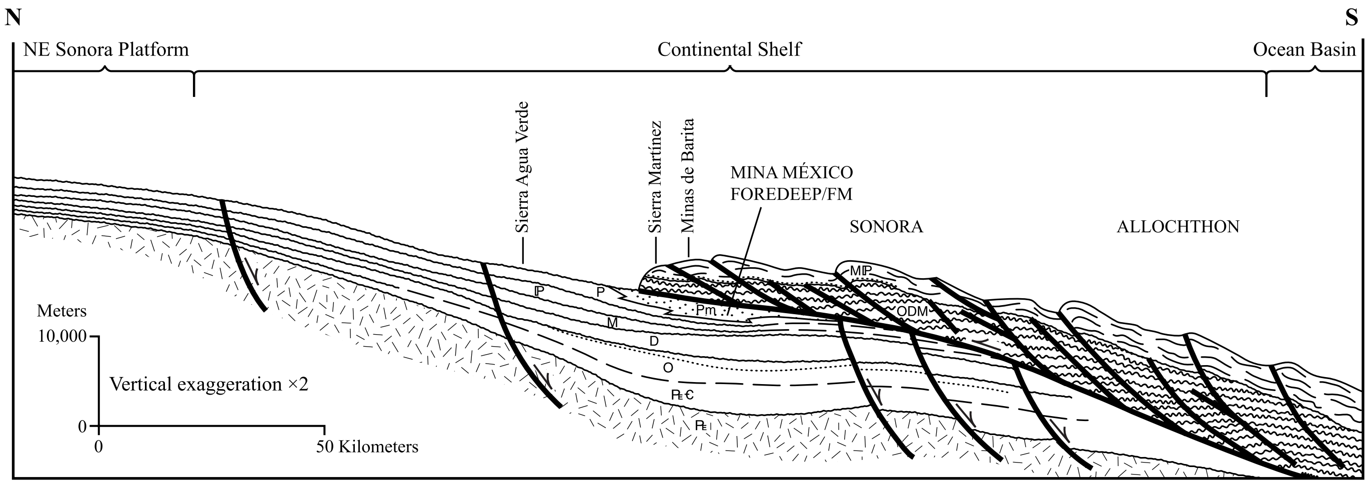

Figure 2. Schematic cross section (2× vertical exaggeration) showing stratigraphic and structural relationships of pre-Mesozoic rocks from the northeast Sonora platform to the south Sonora shelf margin. Location of the cross section is shown on Figure 1. Sierra Agua Verde section is from Stewart *et al.* (1999). Standard geologic/letter symbols are used for rock ages. Wavy lines indicate major unconformities and dots indicate prominent clastic beds within the Paleozoic sequence.

in ascending stratigraphic age, that is, from allochthon to shelf, to foredeep.

LATE PALEOZOIC FUSULINID FAUNAS IN CENTRAL SONORA

Previous work

Fusulinids have been known in Sonora since the 1930s when King (1939) and Dunbar (1939a) reported species generally resembling those in West Texas. In more recent times, Pérez-Ramos (1992) studied Permian fusulinids near Hermosillo and Arivechi in central and east-central Sonora, and compared them to species in southeastern Arizona. Pérez-Ramos and Nestell (2002) described Permian fusulinids near Cobachi in central Sonora, and Gomez-Espinosa *et al.* (2008) and Buitrón-Sánchez *et al.* (2012) described Pennsylvanian fusulinids at Cerro El Tule in northernmost Sonora and Sierra Agua Verde in east-central Sonora. The Cerro El Tule section contains fusulinids representing all stages of the Pennsylvanian.

Fusulinid faunas reported herein are listed in Tables 1 and 2 and illustrated in Figures 4–8.

Pennsylvanian fusulinids in Sonora allochthon

The eugeoclinal deep-marine Ordovician through Pennsylvanian rocks in the Sonora allochthon (Figure 3), deposited in a deep-water environment along the southern margin of Laurentia, consist of turbiditic mudstone, siltstone, sandstone, conglomerate, and limestone, containing *Nereites* (*e.g., Cosmorhaphe* and *Scalarituba*) and *Zoophycos* ichnofacies fossils, which indicate deposition in bathyal water depths (200–2000 m). The Pennsylvanian fusulinid faunas within the Sonora allochthon occur within lime-grainstone turbidites in the Rancho Nuevo Formation.

Permian fusulinids in Laurentian carbonate shelf

Permian fusulinid faunas within the autochthonous Laurentian carbonate shelf (La Cueva Limestone) occur within shallow-marine lime mudstones to packstones that commonly contain pelmatozoans, brachiopods, and other megafossils. Locally, peritidal limestone units occur in shallowing-upward cycles beginning with fossiliferous shallow subtidal limestone and ending with supratidal algal laminites.

Permian fusulinids in Mina México foredeep

Permian fusulinid faunas in the autochthonous Mina México Formation occur in synorogenic lime-grainstone turbidites overlying the carbonate shelf (Figures 2 and 3). The Mina México Formation intertongues with and has a gradational contact with the subjacent carbonate shelf La Cueva Limestone (Figure 3), and contains fusulinids transported from the shelf.

This deep-marine turbiditic sequence contains abundant *Nereites* (*e.g., Cosmorhaphe*, *Scalarituba*, and *Lophoctenium*) and *Zoophycos* ichnofacies fossils.

FUSULINID IDENTIFICATIONS AND AGES

Fusulinid identifications and ages are listed in Tables 1 and 2, and the geographic locations of samples are shown in Figure 1. Stratigraphic positions of formations from which samples were collected are shown in Figure 3. North American Series names for both the Pennsylvanian and Permian are employed herein. The depositional sequence nomenclature of Ross and Ross (2003) for the Lower Permian Series in the Glass Mountains of West Texas also is used. These sequences include lower Wolfcampian Nealian Substage (NR-1 through NR-16); upper Wolfcampian Lenoxian Substage (LH-1 through LH-3); lower Leonardian lower Hessian Substage (H-1 through H-4); middle Leonardian upper Hessian Substage (H-5 through H-7), and upper Leonardian Cathedralian Substage (C-1 and C-2).

Samples from the Rancho Nuevo Formation within the Sonora allochthon range in age from Desmoinesian into the Virgilian. Most samples are Missourian in age. Species represented in these samples previously have been reported primarily from the southern United States, especially the cratonal platform of southern New Mexico.

Fusulinids in the autochthonous Permian Laurentian carbonate shelf range in age from middle Wolfcampian through Leonardian, although most of the samples studied are Leonardian. Three carbonate-shelf samples contain *Eoparafusulina linearis*, a late Wolfcampian species. About one-half of the species in the carbonate-shelf rocks also occur in Texas, with most other forms described previously from northern Mexico or southeastern California.

Samples from the foredeep fill (Mina México Formation) contain fusulinids of Leonardian age. This unit probably is as young as Middle

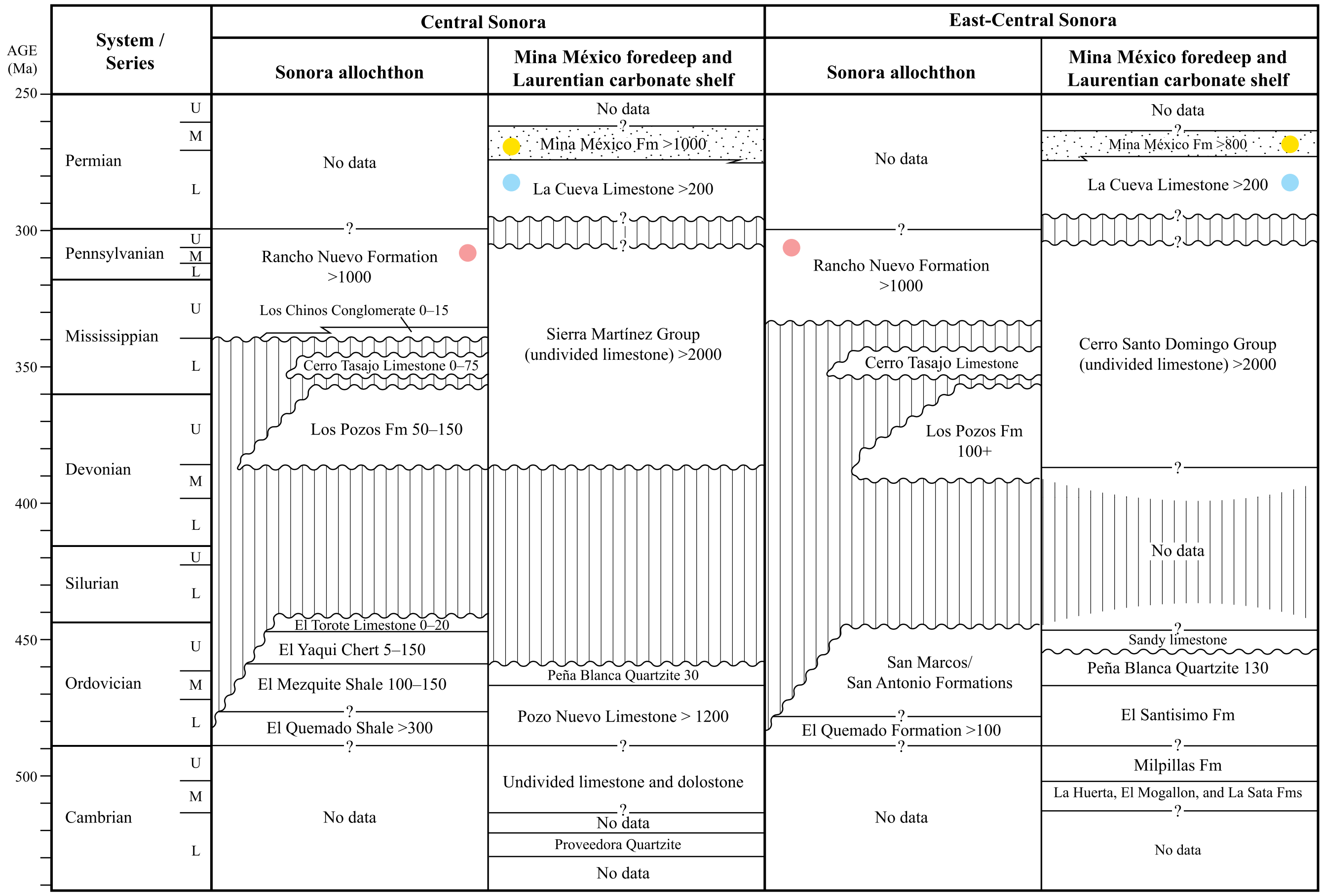

Figure 3. Generalized stratigraphic chart of Paleozoic strata in central and east-central Sonora within the Sonora allochthon, Mina México foredeep (stipple pattern), and Laurentian shelf. Sampled units indicated by colored dots. Time scale modified after Walker and Geissman (2009). Unit thicknesses are in meters.

Permian (Guadalupian), an age based on conodonts found in some lime-grainstone turbidite beds in the foredeep (C.A. Sandberg and F.G. Poole, work in progress). In the foredeep, an equal representation of Texas and California species is present, with slightly fewer species described previously from northern Mexico and Nevada.

The lack of typically Wolfcampian genera, especially *Pseudoschwagerina* and *Stewartina*, suggest that strata of this age, except for late Wolfcampian strata, as indicated by the presence of *Eoparafusulina linearis*, are rare or the appropriate facies are lacking in this region. Initial studies of redeposited conodonts in some lime-grainstone turbidites in the Rancho Nuevo Formation may be as young as late Virgilian in age (C.A. Sandberg and F.G. Poole, work in progress). The lack of early Wolfcampian samples may ref1ect incomplete sampling of the complexly deformed calciclastic turbidites in the region. However, numerous unconformities have been documented within the carbonate-shelf sequence in many Paleozoic sections in Sonora (Figures 2 and 3), so the apparent hiatus may represent a major stratigraphic gap within the upper shelf section.

DEPOSITIONAL ENVIRONMENTS

Continental rise – ocean basin

The Rancho Nuevo Formation consists of a deep-marine Upper Mississippian and Pennsylvanian turbiditic sequence within the upper part of the Sonora allochthon, which was emplaced during late Paleozoic time along the southern margin of Laurentia (Figures 2 and 3). It includes many complexly deformed beds of argillite, quartzite, conglomerate, limestone, and barite deposited in a deep-water continental rise-ocean basin setting. Trace fossils indicating deposition in bathyal water depths are common throughout the allochthon. Several interbedded lime grainstone turbidites were sampled for fusulinids and conodonts. The lime grainstones contain transported fossils representing all epochs of the Pennsylvanian Period. Individual turbidites contain reworked fusulinids derived mainly from exposed limestones on the carbonate shelf to the north, and the reworked conodonts in many turbidites were derived from many different-aged Paleozoic rocks also exposed on the shelf to the north. Therefore, it is likely that the fusulinids do not always represent the depositional age of the turbidite bed sampled, but rather an older source.

Carbonate shelf

The name La Cueva Limestone is used herein for the widespread Early Permian limestone in central and east-central Sonora that forms the highest unit in the Laurentian carbonate shelf (Figure 3). This name was first applied by Hewett (1978) and Schmidt (1978) to the upper member of their El Tigre Formation in east-central Sonora; however, their El Tigre Formation includes strata of the thick Cerro Santo Domingo Group of Poole *et al.* (2005, tab. 1, locality 40), which ranges in age from Ordovician to Permian. Poole *et al.* (2005) proposed abandoning the name El Tigre and retaining the name La Cueva Limestone, but restricting it to the Lower Permian fossiliferous

Table 1. Fusulinid sample data include catalog and field numbers, latitude and longitude from Mexican quadrangle maps (Transverse Mercator projection 1:50,000 scale), and general locality information. Sample localities are shown as colored dots on Figure 1.

Locality number	Catalog number*	Field number	Latitude – longitude	General locality
Allochthonous Pennsylvanian rocks *(Rancho Nuevo Formation)*				
1	f14531	82FP-6F	28°48'40" – 110°10'38"	Rancho El Guayacán area
	f14532	82FP-7F	28°48'42" – 110°10'37"	Rancho El Guayacán area
2	f14956	83FP-5F	28°55'10" – 109°58'23"	1.4 km ESE of mine office bldg.
	f14657	83FP-34F	28°55'23" – 109°57'47"	SSW of Cerro Las Rastras
	S-1988	06FP-35F	28°55'29" – 109°57'40"	SSE of Rancho Las Rastras
	f14534	82FP-59F	28°55'29" – 109°57' 19"	S of Cerro Las Rastras
	f14538	82FP-70F	28°55'29" – 109°57'38"	SSW of Cerro Las Rastras
	f14658	83FP-78F	28°55'06" – 109°58'24"	1.45 km ESE of mine office bldg.
	S-2051	07FP-229F	28°55'27" – 109°57'01"	Arroyo Los Chinos
	S-2053	07FP-229FA	28°55'27.1" – 109°57'00"	Arroyo Los Chinos
3	f14539	82FP-136F	28°52'28.5" – 109°58'38"	SW of Rancho Los Pozos
	S-2105	05FP-284F	28°52'28.5" – 109°58'38"	SW of Rancho Los Pozos
4	S-2109	09FP-101F	28°46'28" – 109°57' 40"	S of Arroyo El Cochi
Carbonate-shelf Permian rocks *(La Cueva Limestone)*				
5	S-1628	JS-92-59B	28°58'52" – 110°46'48"	NE part of Sierra Santa Teresa
6	S-1626	JS-92-48	28°58'00" – 110°47'06"	Main ridge of Sierra Santa Teresa
7	S-1624	JS-91-126	28°57'7.8" – 110°47'54"	Cerro Prieto, Sierra Santa Teresa
	S-1935	04FP-387F	28°57'24.8" – 110°48'21"	Cerro Prieto, Sierra Santa Teresa
8	S-1806	00RPLN-14	28°57'56.5" – 110°38'00"	Cerro El Diente, S of R. Las Norias
9	f14533	82FP-13F	28°50'16" – 110°10'55"	S end of Picacho Colorado
10	S-1779	99FP-34F	28°56'43" – 109°56'17"	NE of Cerro Las Rastras
	f14535	82FP-63F	28°55'35.5" – 109°57'09"	S end of Cerro Las Rastras
	f14536	82FP-64F	28°55'36" – 109°57'08.5"	S end of Cerro Las Rastras
	f14537	82FP-65F	28°55'36.5" – 109°57'08"	S end of Cerro Las Rastras
	S-1989	06FP-64F	28°55’42” – 109°56’59”	E base of Cerro Las Rastras
11	S-1691	96FP-237F	29°57’18.5” – 109°53’39”	Southern part of Sierra Martínez
12	S-2103	05FP-346F	28°56’32.5” – 109°52’47.5”	Southern end of Sierra Martínez
13	S-1879	03FP-204F	28°49’13.6” – 109°25’58.4”	El Torreoncito area
14	S-1880	03FP-232F	28°48’50.4” – 109°24’13”	1.3 km WSW of Cerro La Zacatera
15	S-1972	05FP-274FA	28°49’56.5” – 109°20’35.7”	Float from Cerro Santo Domingo
16	S-2104	05FP-270FA	28°49’50.65” – 109°22’28”	Cañón del Río Bacanora
Foredeep Permian rocks *(Mina México Formation)*				
17	S-1936	04FP-405F	28°59’13” – 109°53’10”	Southern Sierra La Flojera
18	S-1933	04FP-384F	28°57’23.4” – 110°48’20”	Cerro Prieto, Sierra Santa Teresa
	S-1934	04FP-385F	28°57’23.2” – 110°48’20”	Cerro Prieto, Sierra Santa Teresa
19	f14530	82FP-3F	28°49’44” – 110°11”05”	~700 m SE of R. La Vuelta Colorada
	f14529	82FP-4F	28°49’54” – 110°11’10”	~450 m E of R. La Vuelta Colorada
	f14540	82FP-226F	28°50’34” – 110°11’42”	1.3 km N of R. La Vuelta Colorada
20	S-1690	93FP-153F	28°55’19.5” – 109°56’47.5”	Arroyo Los Chinos
	S-1985	06FP-65F	28°55’43” – 109°56’58”	E side of Cerro Las Rastras
21	S-2093	08FP-43F	28°42’36” – 109°38’14.5”	Cerro Real Viejo, Sierra El Aliso
22	S-1940	04FP-347F	28°52’00.3” – 109°25’01”	Cañón del Arroyo El Dipo
23	S-2101	05FP-274F	28°49’56.5” – 109°20’35.7”	Float from Cerro Santo Domingo

*All samples are reposited at the Smithsonian National Museum of Natural History in Washington, D.C. Catalog/register numbers prefixed with “S” were processed and studied by Stevens at San José State University in San José, CA, and numbers prefixed with “f” were processed and studied by R.C. Douglass at the Smithsonian in Washington, D.C.

Table 2. Fusulinid identifications and ages.

Sample	Location	Species	Age
Permian shelf samples			
JS-91-126 (S-1624)	Cerro Prieto, S. Santa Teresa (Stewart *et al.,* 1997)	*Parafusulina vidriensis* Ross, 1960	Middle Leonardian
JS-92-48 (S-1626)	Main ridge of S. Santa Teresa (Stewart *et al.,* 1997)	*Parafusulina* aff. *P. brooksensis* Ross, 1960	Middle Leonardian
JS-92-59B (S-1628)	Northeast part of S. Santa Teresa (Stewart *et al.,* 1997)	*Parafusulina* cf. *P. apiculata* Knight, 1956; *Parafusulina multisepta* Magginetti, Stevens, and Stone, 1988	Early or middle Leonardian
96FP-237F (S-1691)	Southern S. Martínez	*Eoparafusulina* cf. *E. linearis* (Dunbar and Skinner, 1937)	Late Wolfcampian
99FP-34F (S-1779)	Northeast of Cerro Las Rastras	*Parafusulina* cf. *P. leonardensis* Ross, 1962; *Parafusulina* cf. *P. multisepta* Magginetti, Stevens, and Stone, 1988	Early Leonardian
00RPLN-14 (S-1806)	Cerro El Diente south of R. Las Norias (Page *et al.,* 2003)	*Parafusulina leonardensis* Ross, 1962; *Parafusulina* cf. *P. multisepta* Magginetti, Stevens, and Stone, 1988; *"Schwagerina* "? sp.	Early Leonardian
03FP-204F (S-1879)	Float from El Torreoncito area east of Arroyo Los Alisitos	*Parafusulina* aff. *P. allisonensis* Ross, 1960; *Skinnerella* cf. *S.* sp. A Pérez-Ramos, 1992	Early Leonardian
03FP-232F (S-1880)	1.3 km west-southwest of Cerro La Zacatera	*Eoparafusulina* sp.; *Parafusulina* cf. *P. multisepta* Magginetti, Stevens, and Stone, 1988	Early Leonardian
04FP-387F (S-1935)	Cerro Prieto, Sierra Santa Teresa	*Skinnerella gruperaensis* (Thompson and Miller, 1944); *Parafusulina multisepta* Magginetti, Stevens, and Stone, 1988	Early or middle Leonardian
05FP-274FA (S-1972)	Float west base of Cerro Santo Domingo	*Eoparafusulina linearis* (Dunbar and Skinner, 1937)	Late Wolfcampian
06FP-64F (S-1989)	East base of Cerro Las Rastras	*Skinnerella* cf. *S. gruperaensis* (Thompson and Miller, 1944); *Skinnerella* aff. *S. figueroai* (Thompson and Miller, 1944); *Skinnerella* cf. *S. australis* (Thompson and Miller, 1944)	Middle Leonardian
05FP-346F (S-2103)	South end of S. Martínez	*Pseudochusenella hazzardi* Stevens, and Stone, 2007	Middle? Wolfcampian
05FP-270FA (S-2104)	Cañón del Río Bacanora	*Skinnerella* cf. S. *cobachiensis* Pérez-Ramos and Nestell, 2002	Middle Leonardian
82FP-13F (f14533)	South end of Picacho Colorado	*Chalaroschwagerina?* sp.; *"Schwagerina"* cf. *"S." hawkinsi* Dunbar and Skinner, 1937; *"Schwagerina"* aff. *"S." youngquisti* Thompson and Hansen, *in* Thompson, 1954	Early Leonardian?
82FP-63F (f14535)	South side of Cerro Las Rastras	*Praeskinnerella crassitectoria* (Dunbar and Skinner, 1937); *Praeskinnerella guembeli* (Dunbar and Skinner, 1937)	Early Leonardian
82FP-64F (f14536)	South side of Cerro Las Rastras	*Praeskinnerella crassitectoria* (Dunbar and Skinner, 1937); *Praeskinnerella guembeli* (Dunbar and Skinner, 1937)	Early Leonardian
82FP-65F (f14537)	South side of Cerro Las Rastras	*Chalaroschwagerina* cf. *C. nelsoni* (Dunbar and Skinner, 1937); *Chalaroschwagerina*? sp.; *Eoparafusulina linearis* (Dunbar and Skinner, 1937); *"Schwagerina"* sp. aff. *"S." gracilitatis* Dunbar and Skinner, 1937	Latest Wolfcampian
Permian foredeep samples			
93FP-153F (S-1690)	Arroyo Los Chinos	*Parafusulina leonardensis* Ross, 1962	Early to middle Leonardian
04FP-384F (S-1933)	Cerro Prieto, S. Santa Teresa	*"Schwagerina" dugoutensis* Ross, 1962	Early Leonardian
04FP-385F (S-1934)	Cerro Prieto, S. Santa Teresa	*Parafusulina multisepta* Magginetti, Stevens, and Stone, 1988	Early to middle Leonardian
04FP-405F (S-1936)	Southern S. La Flojera	*Parafusulina* cf. *P. multisepta* Magginetti, Stevens, and Stone, 1988	Early to middle Leonardian
04FP-347F (S-1940)	Cañón del Arroyo El Dipo	*Parafusulina* cf. *P. vidriensis* Ross, 1960; *Parafusulina* cf. *P. multisepta* Magginetti, Stevens, and Stone, 1988	Middle Leonardian
06FP-65F (S-1985)	East side of Cerro Las Rastras	*Skinnerella cobachiensis* Pérez-Ramos and Nestell, 2002; *Skinnerella gruperaensis* (Thompson and Miller, 1944); *Parafusulina* cf. *P. multisepta* Magginetti, Stevens, and Stone, 1988	Middle Leonardian
08FP-43F (S-2093)	Fault block, Cerro Real Viejo, Sierra El Aliso	*"Schwagerina"* aff. *"S." dugoutensis* Ross, 1962; *Praeskinnerella* aff. *P. crassitectoria* (Dunbar and Skinner, 1937); *"Schwagerina"* sp.	Early Leonardian
05FP-274F (S-2101)	Float from west base of Cerro Santo Domingo	*Skinnerella cobachiensis* Pérez-Ramos and Nestell, 2002 ; *"Schwagerina"* cf. *"S." menziesi* Williams, 1963; *Parafusulina guatemalaensis* Dunbar, 1939b; *Parafusulina* cf. *P. apiculata* Knight, 1956; *Parafusulina* cf. *P. multisepta* Magginetti, Stevens, and Stone, 1988	Middle Leonardian
82FP-3F (f14530)	700 m southeast of Rancho La Vuelta Colorada	schwagerinid	Early Permian
82FP-4F (f14529)	Rancho La Vuelta Colorada área	*Parafusulina*? sp.	Probably middle Leonardian
82FP-226F (f14540)	North of Rancho La Vuelta Colorada	*Parafusulina* cf. *P. brooksensis?* Ross, 1960	Middle Leonardian

continues

Table 2 (continued). Fusulinid identifications and ages.

Sample	Location	Species	Age
Sonora allochthon samples			
06FP-35F (S-1988)	South-southeast of Rancho Las Rastras	*Protriticites* sp. (primitive form) ; *Fusulina* cf. *F. haworthi* (Beede, 1916)	Middle to late Desmoinesian
07FP-229F (S-2051)	Arroyo Los Chinos	*Triticites traceeae* Wilde, 2006; *Triticites birdspringensis* Cassity and Langenheim, 1966; *Triticites* aff. *T. muscerda* Myers, 1967	Missourian
07FP-229FA (S-2053)	Arroyo Los Chinos	*Eowaeringella* sp.; *Triticites* aff. *T. muscerda* Myers, 1967	Missourian
05FP-284F (S-2105)	Southwest of Rancho Los Pozos	*Triticites leeannae* Wilde, 2006	Missourian
09FP-101F (S-2109)	South of Arroyo El Cochi	*Triticites* cf. *T. leeannae* Wilde, 2006	Missourian?
82FP-6F (f14531)	Rancho El Guayacán area	*Triticites* cf. *T. cameratoides* Ross, 1965; *Eowaeringella?* sp.	Virgilian
82FP-7F (f14532)	Rancho El Guayacán area	*Triticites* sp.; *Eowaeringella*? sp.	Late Pennsylvanian
82FP-59F (f14534)	South of Cerro Las Rastras	*Triticites celebroides* Ross, 1965; *Triticites* aff. *T. acutuloides* Ross, 1965	Missourian
82FP-70F (f14538)	South-southwest of Cerro Las Rastras	*Triticites* cf. *T. acutuloides* Ross, 1965	Missourian
82FP-136F (f14539)	Southwest of Rancho Los Pozos	*Triticites* cf. *T. marathonensis* Ross, 1965; *Triticites* aff. *T. elegantoides* Ross, 1965	Virgilian
83FP-5F (f14656)	~1.4 km east-southeast of barite mine office and north of highway near transmission tower	*Eowaeringella* aff. *E. zelleri* Stewart, 1968; *Pseudofusulinella?* sp.	Missourian?
83FP-34F (f14657)	South-southwest of Cerro Las Rastras	*Beedeina* aff. *B. clarkensis* (Cassity and Langenheim, 1966)	Desmoinesian
83FP-78F (f14658)	~1.4 km east-southeast of barite mine office at highway road cut on axis of syncline	*Triticites* aff. *T. celebroides* Ross, 1965	Missourian

shallow-water limestone at the top of the carbonate shelf.

The La Cueva Limestone consists mainly of shallow-marine shelfal lime mudstones to packstones containing fusulinids and other megafossils. Locally the La Cueva consists of shallowing-upward cycles composed of units deposited sequentially in subtidal, intertidal, and supratidal environments. For example, outcrops of La Cueva Limestone at the south end of Cerro Las Rastras expose a series of shallowing-upward cycles composed of lower units of shallow-subtidal limestone (0.2–8 m thick), containing fusulinids and other fossils; middle units of intertidal limestone (90± cm thick); and upper units of supratidal gypsiferous limestone (15± cm thick). Calcite has replaced gypsum crystals in the original gypsiferous limestone. The interval of cycles studied at Cerro Las Rastras is estimated to be 150–170 m below the top of the formation.

Foredeep on carbonate shelf

The Mina México foredeep developed on the carbonate shelf of Laurentia as a result of crustal f1exing and isostatic loading associated with the collision of the Gondwanan and Laurentian continents (Figures 1–3 and Poole *et al.*, 2005). It was filled with turbiditic siltstones, fine sandstones and sparse turbiditic lime grainstones containing transported fusulinids, pelmatozoans and other megafossil fragments. The foredeep-fill rocks in east-central Sonora were informally named Mina México Formation by Hewett (1978) and Schmidt (1978). The name Mina México Formation is now an accepted formal name for sediments filling the Permian foredeep. The predominately siliciclastic turbidite sequence contains abundant deep-marine trace fossils.

The contact between the La Cueva and Mina México formations is gradational and the two units intertongue through a transitional interval as thick as 50 m (Figure 3; Poole *et al.*, 2005). Our fusulinid data indicate that intertonguing between the two formations occurred during a 2–3 m.y. period ranging from early to middle Leonardian time.

Dating the time of deposition of the bioclastic lime-grainstone turbidites of the Mina México Formation is difficult because of the unknown source of the sediment transported into the foredeep. In some cases, the age of the transported fusulinids and other fossils in the turbidites may ref1ect the age of contemporaneous deposits on the shelf, but it is likely that many of the fossils came from a variety of source rocks as indicated by a mixture of different-age fossils, especially conodonts.

U-Pb isotopic dating of detrital zircons (Mesoarchean-Neoproterozoic and subordinate Cambrian-Pennsylvanian) from turbiditic sandstones filling the Mina México foredeep in central Sonora suggests that most of the detritus was derived from Laurentia, but some detritus clearly came from the evolving Sonora allochthon and/or peri-Gondwana terranes to the south (Poole *et al.*, 2008; Amaya-Martínez *et al.*, 2010).

PALEOTECTONIC SETTING

Previous work (summarized in Stewart, 2005, and Poole *et al.*, 2005) showed that Sonora comprised the southern part of Laurentia. The remainder of Central America south of Sonora, however, is composed of allochthonous terranes, which according to Vachard *et al.* (2000a) were located somewhere between Laurentia and Gondwana in the Pennsylvanian with the exception of the Chortis block, which was still drifting towards Pangaea in the Early Permian. By the end of the Middle Permian, most of the Mexican terranes were amalgamated to one another and /or accreted to Laurentia (Vachard *et al.*, 2004). These Central American terranes probably represent fragments of northwest Gondwana.

The above scenario seems to be validated by various studies of Mexican fusulinids. The similarity of most of the Pennsylvanian

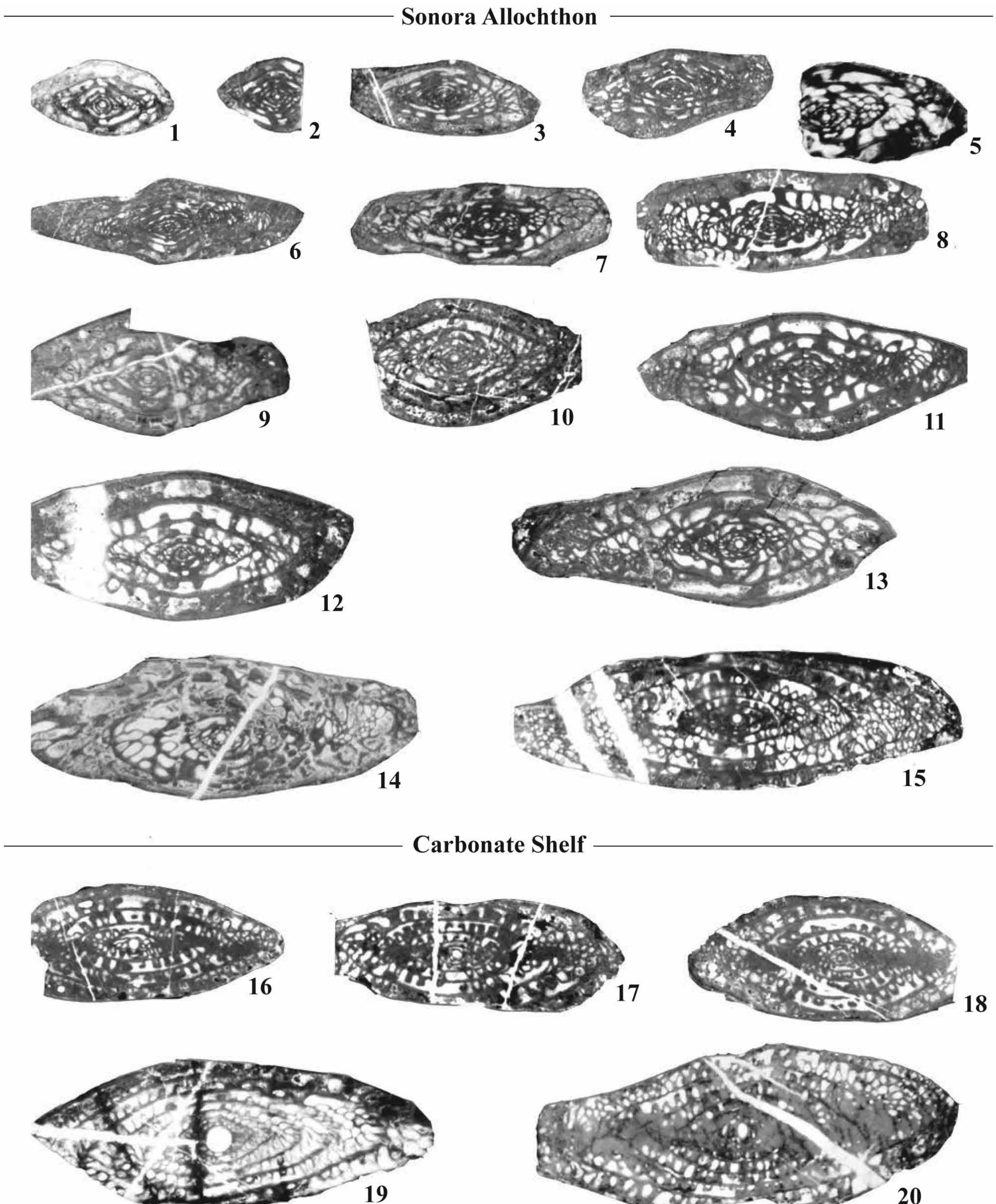

Figure 4. 1-15: Fusulinids from Pennsylvanian lime-grainstone turbidites in the Sonora allochthon. Figures 16-20: Fusulinids from Permian limestones in the Laurentian carbonate shelf. Sonora Allochthon Fusulinids: 1- *Protriticites* sp. (primitive form), S-1988, slide 379f, ×18; 2 -*Pseudofusulinella?* sp., f14656, ×10; 3 - *Triticites* aff. *T. acutuloides,* f14534, ×10; 4 - *Eowaeringella zelleri?,* f14556, ×10; 5 - *Triticites* cf. *T. leeannae,* S-2109, slide 380f, ×14; 6 - *Eowaeringella* sp., S-2053, slide 381f, ×10; 7- *Triticites celebroides,* f14534, ×10; 8 - *Triticites marathonensis,* f14539, ×10; 9 - *Triticites leeannae,* S-2105, slide 382f, ×14; 10 - *Triticites* aff. *T. elegantoides,* f14539, ×10; 11 - *Triticites traceeae,* S-2051, slide 383f, ×14; 12 - *Triticites birdspringensis,* S-2051, slide 384f, ×14; 13 - *Triticites* aff. *T. muscerda,* S-2051, slide 385f, ×14; 14 - *Triticites* aff. *T. muscerda,* S-2053, slide 386f, ×14; 15 - *Fusulina* cf. *F. haworthi,* S-1988, slide 387f, ×10. Permian Shelf Fusulinids: 16 - *Praeskinnerella crassitectoria,* f14536, ×10; 17 - *Praeskinnerella crassitectoria,* f14536, ×10; 18 - *Praeskinnerella guembeli,* f14536, ×10; 19 - *"Schwagerina"*? sp., S-1806, slide 388f, ×10; 20 - *Skinnerella* cf. S. *cobachiensis,* S-2104, slide 389f, ×10.

Carbonate Shelf

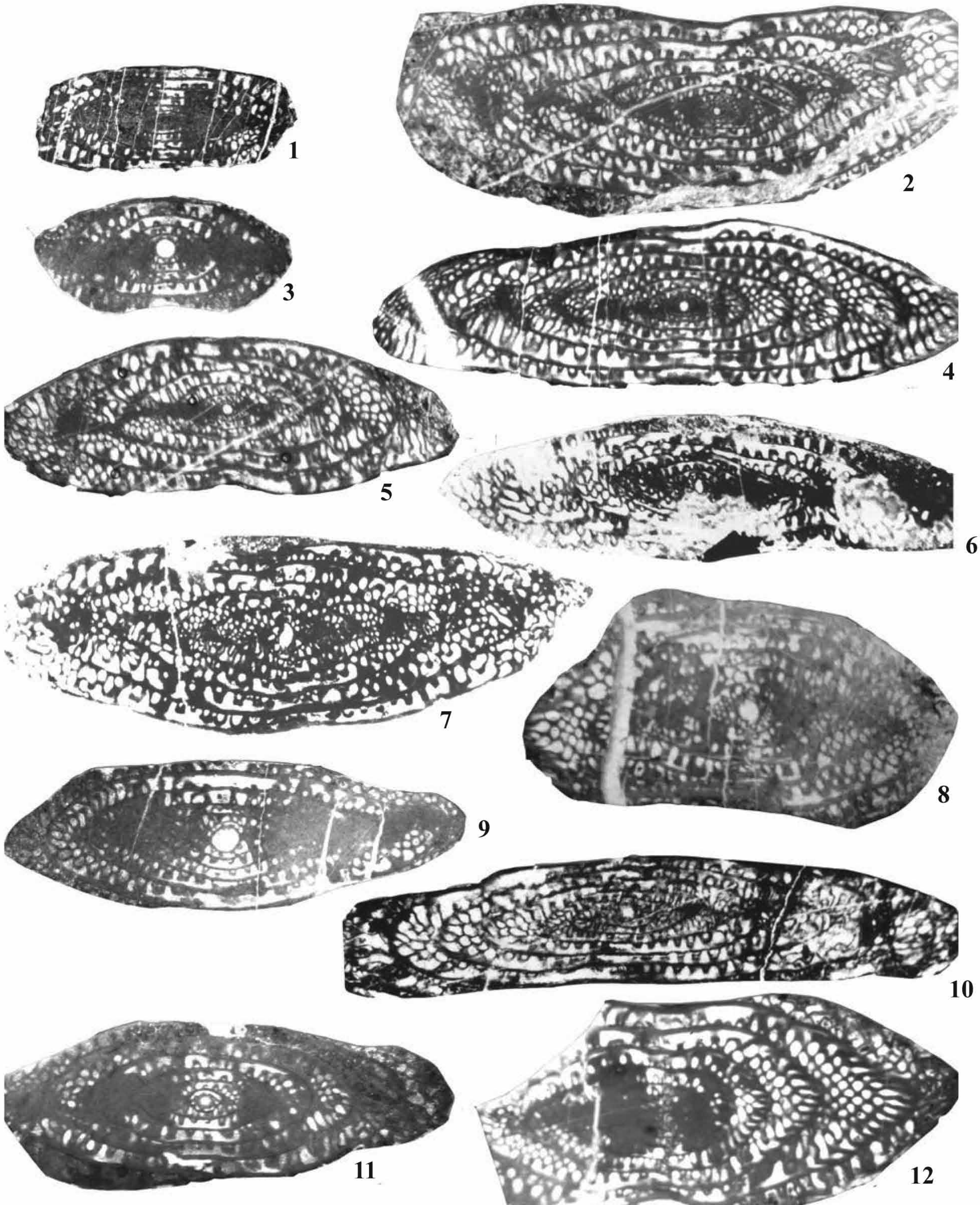

Figure 5. 1-12: Fusulinids from Permian limestones in the Laurentian carbonate shelf (all figures ×10). Permian Shelf Fusulinids: 1 - *Pseudochusenella hazzardi,* S-2103, slide 390f; 2 - *Parafusulina multisepta,* S-1628, slide 391f; 3 - *Skinnerella* cf. S. *gruperaensis,* S-1989, slide 392f; 4 - *Parafusulina* cf. *P. apiculata,* S-1628, slide 393f; 5 - *Parafusulina apiculata?,* S-1628, slide 394f; 6 - *Parafusulina* aff. *P. allisonensis,* S-1879, slide 395f; 7 - *Skinnerella* sp. A (of Pérez-Ramos, 1992), S-1879, slide 396f; 8 - *Skinnerella gruperaensis,* S-1935, slide 397f; 9 - *Skinnerella* aff. S. *figueroai,* S-1989, slide 398f; 10 - *Parafusulina leonardensis,* S-1806, slide 399f; 11 - *Skinnerella* cf. S. *australis,* S-1989, slide 400f; 12 - *Parafusulina multisepta,* S-1935, slide 401f.

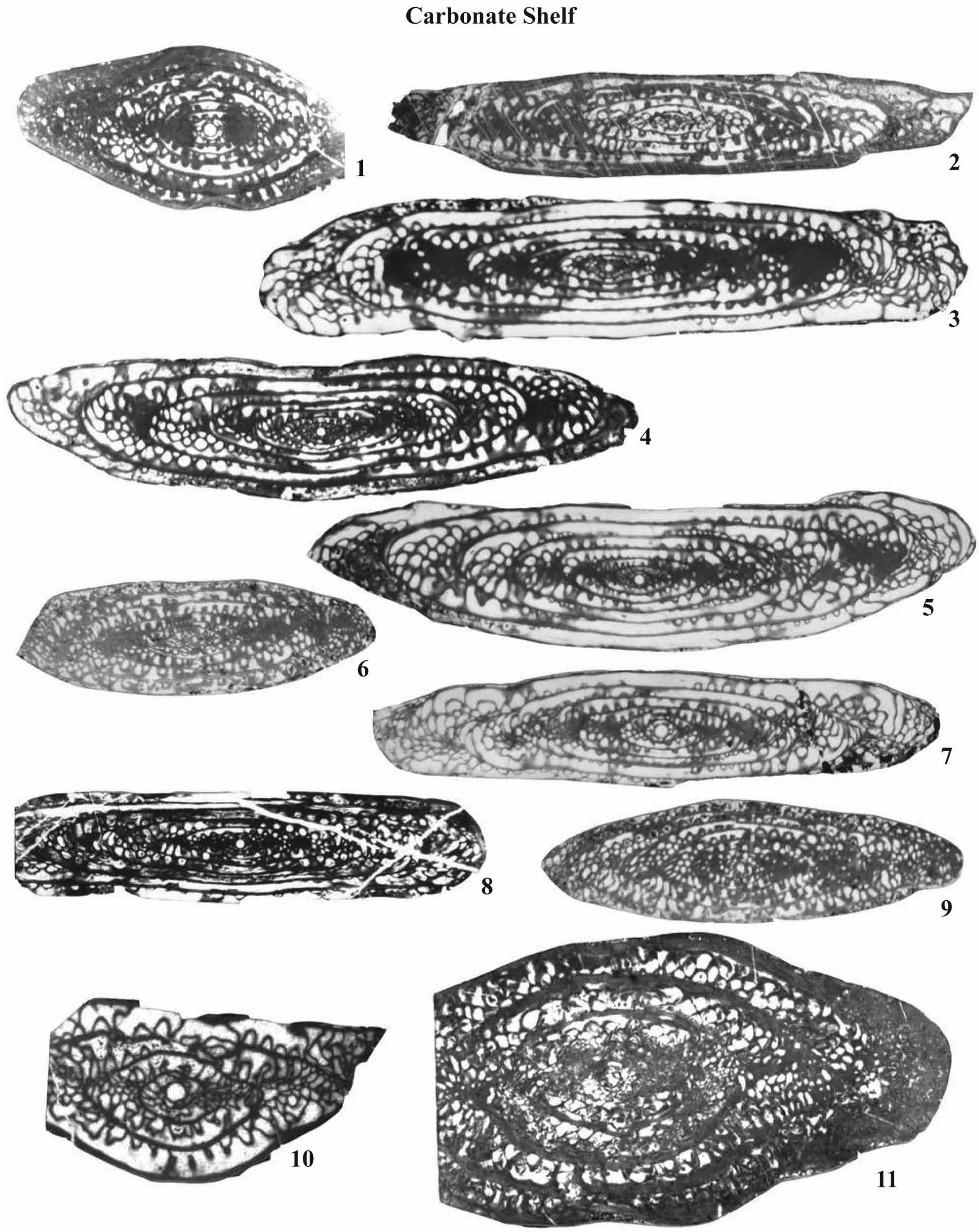

Figure 6. Figures 1-11: Fusulinids from Permian limestones in the Laurentian carbonate shelf (all figures ×10). Permian Shelf Fusulinids: 1 - *Praeskinnerella guembeli,* f14535; 2 - *Eoparafusulina linearis,* f14537; 3 - *Eoparafusulina linearis,* S-1972, slide 402f; 4 - *Eoparafusulina linearis,* S-1972, slide 403f; 5 - *Eoparafusulina linearis,* S-1972, slide 404f; 6 - *Parafusulina* aff. *P. brooksensis,* S-1626, slide 405f; 7 - *Eoparafusulina linearis,* S-1972, slide 406f; 8 - *Eoparafusulina* cf. *E. linearis,* S-1691, slide 407f; 9 - *Parafusulina* aff. *P. brooksensis,* S-1626, slide 408f; 10 - *Chalaroschwagerina* cf. C. *nelsoni,* f14537, 11 - *Chalaroschwagerina?* sp., f14533.

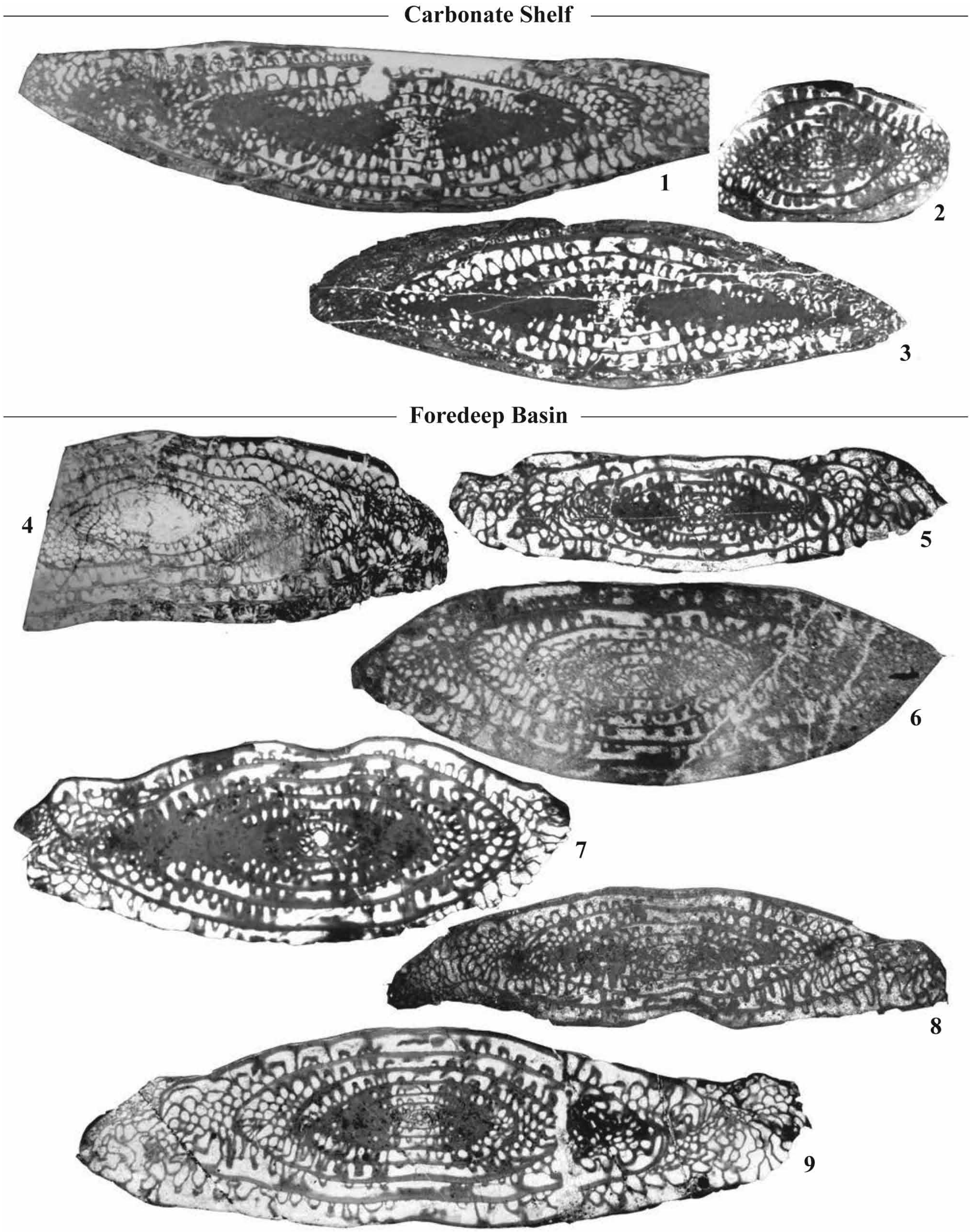

Figure 7. 1-3: Fusulinids from Permian limestones in the Laurentian carbonate shelf. 4-9: Fusulinids from Permian lime-grainstone turbidites in the Mina México foredeep. All figures ×10. Permian Shelf Fusulinids: 1 - *"Schwagerina""* aff. "*S.*" *youngquisti,* f14533; 2 - *Praeskinnerella guembeli,* f14535; 3 - *"Schwagerina"* aff. "*S." youngquisti,* f14533. Permian Foredeep Fusulinids: 4 - *Parafusulina* cf. *P. multisepta,* S-1940, slide 409f; 5 - *"Schwagerina" menziesi?,* S-2101, slide 410f; 6 - *Parafusulina* cf. *P. multisepta,* S-1985, slide 411f; 7 - *Skinnerella* cf. *S. cobachiensis,* S-2101, slide 412f; 8 - *Parafusulina guatemalaensis,* S-2101, slide 413f; 9 - possibly a microspheric form of *Parafusulina multisepta,* S-2101, slide 414f.

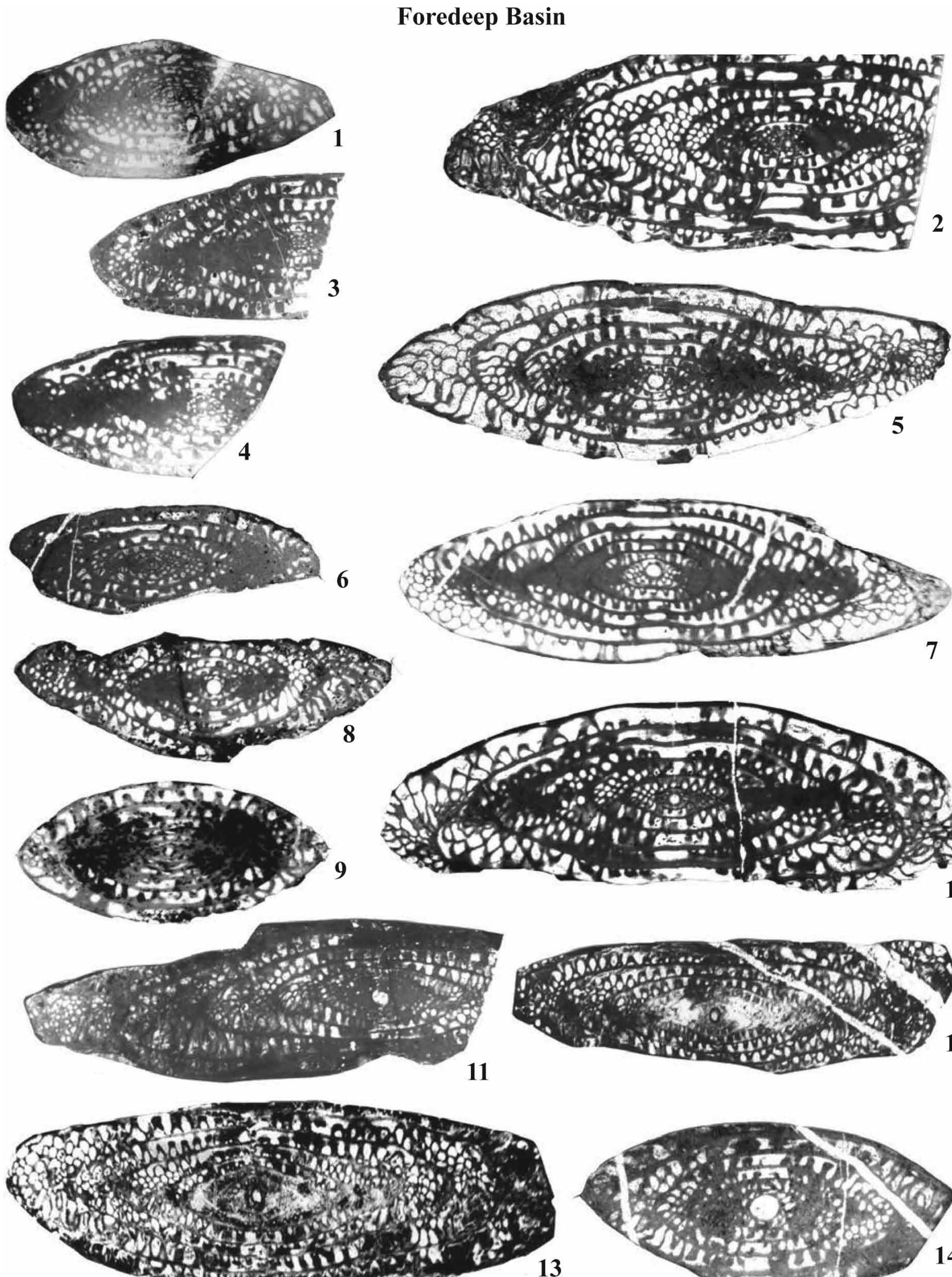

Figure 8. 1-14: Fusulinids from Permian lime-grainstone turbidites in the Mina México foredeep. All figures ×10. 1 - *"Schwagerina" dugoutensis,* S-1933, slide 415f; 2 - *"Schwagerina" dugoutensis,* S-1933, slide 416f; 3 - *"Schwagerina" dugoutensis,* S-1933, slide 417f; 4 - *"Schwagerina" dugoutensis,* S-1933, slide 418f; 5 - *Skinnerella cobachiensis,* S-2101, slide 410f; 6 - *"Schwagerina"* sp., S-2093, slide 420f; 7 - *Skinnerella cobachiensis,* S-1985, slide 421f; 8 - *Praeskinnerella* aff. *P. crassitectoria,* S-2093, slide 422f; 9 - *"Schwagerina"* aff. "S." *dugoutensis,* S-2093, slide 423f; 10 - *Parafusulina* cf. *P. apiculata,* S-2101, slide 424f; 11 - *Parafusulina leonardensis,* S-1690, slide 425f; 12 - *Parafusulina* cf. *P. vidriensis,* S-1940, slide 426f; 13 - *Parafusulina vidriensis,* S-1940, slide 427f; 14 - *Skinnerella gruperaensis,* S-1985, slide 428f.

and Permian fusulinid faunas on the Laurentian carbonate shelf in Sonora to those of the cratonal platform to the north (*i.e.,* in Texas, New Mexico, and Arizona), as indicated by the work of Pérez-Ramos (1992), Pérez-Ramos and Nestell (2002), and Buitrón-Sánchez *et al.* (2012), demonstrates a close geographic proximity. The fusulinids in the Mina México Formation are also similar to those on the Laurentian carbonate shelf. Therefore, it seems unlikely that many, if any, fusulinids were derived from the Central American terranes. However, it must be recognized that fusulinid faunas similar to those in Sonora occur elsewhere in Central America, for instance in the Missourian through middle Leonardian sequence in the Mixteco terrane in southwestern Mexico (Vachard *et al.*, 2000b). Farther south in Guatemala in rocks associated with the Chortis terrane, the Leonardian–Roadian fusulinids are similar to those in West Texas (Vachard *et al.*, 1997). Also from the earliest Pennsylvanian (Bashkirian) to Early Permian late Wolfcampian faunal similarities exist as far south as Lake Titicaca (Bolivia-Peru border) indicating communion between these areas. Similar Pennsylvanian and Permian faunas in Central America and Sonora indicate proximity of Gondwana and Laurentia in late Paleozoic time.

CONCLUSIONS

Although most fusulinid faunas along the southern margin of Laurentia show affinities to those of West Texas, New Mexico, and Arizona, some genera and species are similar to fusulinids in southeastern California (*e.g.,* Magginetti *et al.*, 1988). Stevens (2010) showed that some distinctive late Wolfcampian and Leonardian fusulinids and corals were able to disperse or migrate presumably from Nevada-California to Sonora and West Texas. Even so, most species in Sonora are similar to those east of the southwest-trending Transcontinental arch in New Mexico and Arizona (position of arch shown on fig. 1 in Poole *et al*., 2005), suggesting the arch may have formed a barrier preventing large-scale migration and mixing of faunas between the southern shelf of Laurentia in Sonora and the western shelf in the southwestern United States.

The Permian Sonora allochthon (Figures 1 and 2), consisting of Ordovician to Pennsylvanian deep-water continental-rise and ocean-basin rocks (Figure 3), was thrust 50–200 km onto shallow-water carbonate-shelf rocks (La Cueva Limestone) and overlying Permian foredeep f1ysch (Mina México Formation) of southern Laurentia (Poole *et al.*, 2005). No evidence of major strike-slip offset of Paleozoic rocks has been observed in the study area, as advocated by proponents of several hypothetical megashears in Sonora (see papers in Anderson *et al.*, 2005, for other interpretations).

Our fusulinid collections indicate a hiatus of at least 10 m.y. (see time scale of Walker and Geissman, 2009) between the youngest Pennsylvanian (Virgilian) rocks in the Sonora allochthon and the oldest Permian (middle Wolfcampian) rocks in the La Cueva Limestone. In addition, neither detrital fusulinids nor conodonts of early Wolfcampian age have been recognized in the lime-grainstone turbidites of the Mina México Formation. Thus far, the youngest transported fossils identified in Mina México turbidites are conodonts of Middle Permian (Guadalupian) age. The Sonora allochthon overrides part of the Mina México foredeep deposits, but as Triassic deposits depositionally overlie the Sonora allochthon, movement of the allochthon in Sonora probably ceased in the Late Permian. Therefore, the Sonora allochthon evidently was actively moving onto the Laurentian continental margin leaving no conspicuous depositional record. These data are interpreted as dating emplacement of the allochthon from Early to Middle Permian (a time period of 30–40 m.y.).

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