

The Olivos Olistostrome: Remnant of a Late Permian Oceanic Basin along the Southwestern Margin of Laurentia, Chihuahua, Mexico

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Abstract

We report on the finding of an olistostrome containing Late Permian basalts (257 ± 7 Ma K-Ar, whole-rock) with MORB affinity embedded within deep-water Jurassic sediments (Upper Bajocian–Middle Callovian) in south-central Chihuahua, northern Mexico, at the southwestern margin of the North American craton (Laurentia). The largest Paleozoic outcrops in northern Mexico occur in the Chihuahua, Caborca, and Cortez terranes; the Los Olivos area is a small outlier with no discernible relation with either of those outcrops. Study of the Sierra de Olivos, in south-central Chihuahua, offers key elements to decipher the Late Paleozoic and Mesozoic evolution of the southern North American craton. Elements of oceanic crust in the olistostrome of Los Olivos are massive and pillowed basalts. Their chemistry shows that they are K-poor ($K_2O \sim 0.1\%$) and TiO_2 rich ($\sim 0.8\%$); they are extremely depleted in elements such as Rb, Sr, and Zr, and trace-element compositions place them in the N-MORB and IAT fields of tectonic discrimination diagrams. The basalts, together with associated granitic tectonic blocks exhibiting a well-developed mylonitic texture, lie at the southern margin of Laurentia, and south of the inferred trace of the Mojave-Sonora megashear. They also lie along one of the inferred traces of the Ouachita suture. The Permian basaltic slabs were tectonically emplaced within the Middle Jurassic sedimentary sequence, but we infer that they were deposited as gravity slides. Their contacts with less competent rocks were reactivated, facilitating tectonic displacement during the Hidalgoan orogeny. The deep-marine Middle Jurassic sequence is informally assigned to the Pelayo Formation, which is covered by deep-water Cretaceous sedimentary facies of the Mezcalera Formation and by Tertiary volcanic rocks of the Sierra Madre Occidental magmatic arc. If the radiometric age determination of the oceanic basalts correctly dates the emplacement of these lavas, our study provides evidence on the existence of a Late Paleozoic–Mesozoic oceanic plate, subducted collision of either Gondwanic or Pacific elements with Laurentia, or during accretion of the Guerrero terrane (e.g., the Mezcalera plate). Characteristics of the markedly epiclastic Middle Jurassic units that host the olistostrome supports the assumption of an active margin setting for Jurassic deposition at the southern extreme of the Laurentia craton.

Introduction

PANGAEA paleoreconstructions for the Gulf of Mexico and the central Atlantic Ocean result in a significant overlap of Mexico, Central America, and South

America, implying relative motion and different paleopositions for most of Mexico and nuclear Central America (Bullard et al., 1965; Pindell, 1985; Urrutia-Fucugauchi, 1984). In Mexico, studies of the basement and major tectonic features have identified several terranes with distinct tectono-

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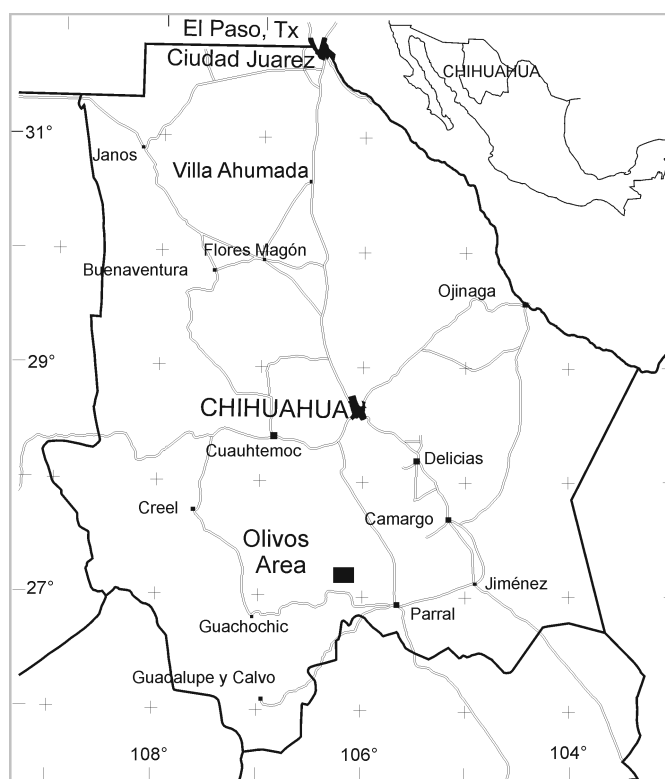


FIG. 1. Location of the study area.

stratigraphic records (Campa and Coney, 1983; Sedlock et al., 1993). Tectonic relationships and evolution of the terranes are not yet fully understood, despite advances in the past decades with new outcrops identified and more geochronological and paleomagnetic data available (e.g., Ballard et al., 1989; Sedlock et al., 1993; Urrutia-Fucugauchi et al., 1987; Keppie and Ortega, 1995; Ruiz et al., 1999; Stewart et al., 1999). This is partly due to the scarcity of Precambrian and Paleozoic basement and Paleozoic sedimentary cover exposures. In northern Mexico, the largest Paleozoic outcrops occur in the Chihuahua, Caborca, and Cortez terranes. The basement rocks of the Caborca and Chihuahua terranes are part of the North American craton, whereas the Cortez terrane belongs to the paleo-Pacific oceanic margin. Upper Paleozoic rocks of volcanic-arc affinity occur in the Coahuila block (Las Delicias Arc), east of the study area. Lower to Upper Paleozoic strata of the passive

margin of Laurentia occur in the Plomosas uplift, northeast of the study area.

Geological investigation of the Sierra de Olivos offers key elements to decipher the Late Paleozoic through Jurassic evolution of the southern North American craton. Valle de Olivos is located at the meridional sector of the state of Chihuahua, 155 km from the city of Chihuahua in northern Mexico (Fig. 1). According to Raisz (1959) the study area is located in the Sierra Madre Occidental province; the most important mountain ranges in the study area are Sierra de Olivos, Sierra La Cuchilla, and Sierra San Ignacio (Fig. 2). Previous investigations in the area were limited to ore prospecting reports such as those by Penoles Group (O. Comaduran-Ahumada, per. commun., 1999). Those studies proposed that some of the mineral deposits in this part of Chihuahua could be interpreted as sedimentary, and related to submarine volcanism (Comaduran-Ahumada and Melchor, 1996). Thus far, the most comprehensive published geological work related to

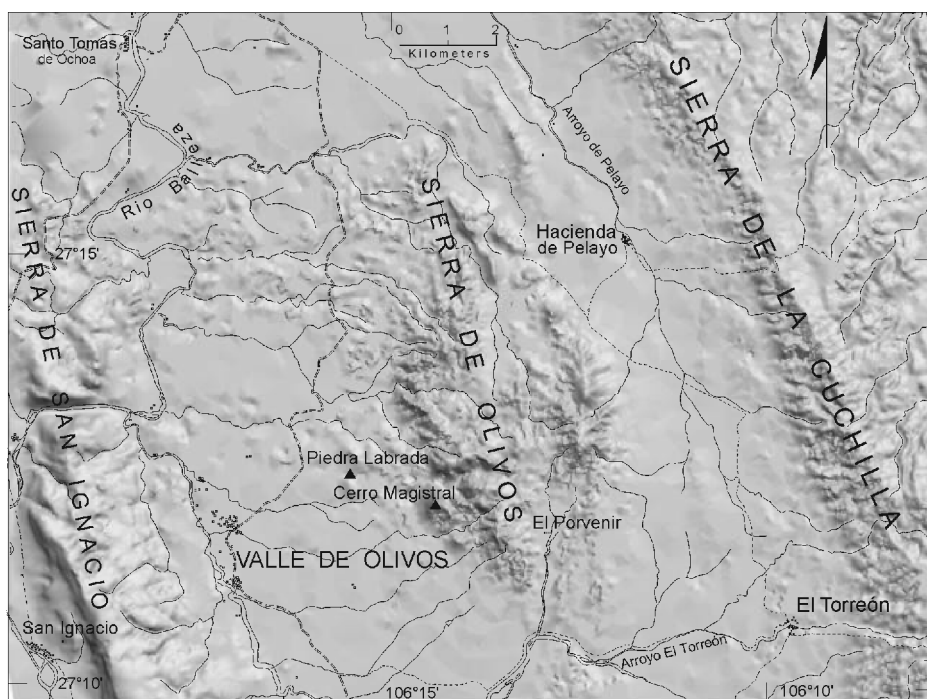


FIG. 2. Valle de Olivos area, showing the Sierra de San Ignacio range to the west, Sierra de Olivos range at the center, and Sierra de la Cuchilla range to the east. Tilting ranges attended generation of the Gulf of California aulacogen.

the Valle de Olivos region is that of Consejo de Recursos Minerales (COREMI, 2000), particularly the work included in the Carta Geológico-Minera Huejotitan. Considering that this region is of little economic interest due to the nonexistence of gas, oil, metallic ore, and industrial mineral deposits, and with a small population, its geology has been relatively little studied.

Here we report on the existence of Middle Jurassic flysch-type deposits, containing large blocks of both oceanic crust (fragments of Permian age basalt flows and pillow lavas) and mylonitic tectonic blocks of granitoids of unknown age. These rocks occur in the Valle de Olivos area covered by the Cretaceous Mezcalera Formation, the only marine unit described in the literature (COREMI, 2000; Araujo-Mendieta and Arenas-Partica, 1986; Fig. 3).

Regional Geology

Because of its position on the eastern part of the Sierra Madre Occidental Province, the Sierra de Olivos is surrounded by and partly covered by the Tertiary volcanic arc sequence. Underlying these

volcanic units, thick Cretaceous sedimentary deposits are exposed mainly in the northern and eastern part of the study area. The Cretaceous sequence is composed predominantly of thin-bedded calcareous rocks, and shows intense deformation characterized by tight isoclinal folds with axial planes (NW-SE strike) showing vergence to the east. Under the Cretaceous sequence, and below a regional detachment structure, dominantly epiclastic sedimentary rocks contain megablocks of basalt with pillow structures and mylonitized granitic tectonic blocks of unknown age.

Stratigraphy

In the study area, several sedimentary units with ages ranging from Middle Jurassic to Recent, are described as follows.

Pelayo Formation

This is the oldest sedimentary unit exposed in the study area (Figs. 3 and 4; see also Figs. 12 and 14). The name Pelayo Formation (Jpe) is used informally; it corresponds to a fossil locality (Arroyo Pelayo) that established the biostratigraphic age of

SYSTEM	SERIES	STAGE	TEXAS	CHIHUAHUA TROUGH 1	SABINAS BASIN 2	MAR MEXICANO 3	VALLE DE OLIVOS 4
Neogene	HOLOCENE						
	PLEISTOCENE						
	PLIOCENE						
	MIOCENE						
	OLIGOCENE						
Paleogene	Eocene						
	PALEOCENE						
CRETACEOUS	GULFIAN	Maastrichtian	Navarro Taylor	PICACHO	ESCONDIDO OLMOS	?	
		Campanian		SAN CARLOS	SAN MIGUEL		
		Santonian	Austin	OJINAGA	UPSON		
		Coniacian			AUSTIN		
		Turonian	Eagle Ford		Eagle Ford		
	COMANCHEAN	Cenomanian	Woodbine-Buda	CALIZA AURORA	BUDA	AURORA	?
		Albian	Fredericksburg		DEL RIO GEORGETOWN KIAMICI		
		Aptian	Trinity		TAMAULIPAS SUPERIOR		
	COAHUILAN	Barremian	Pearsall	CUCHILLO	LA PEÑA CUPIDO	MEZCALERA	MEZCALERA
		Hauterivian	Sligo	LAS VIGAS	LA VIRGEN LA MULA		
		Valanginian	Hosston	NAVARRETE	PADILLA		
		Berriasian			BARRIL VIEJO		
					MENCHACA		
JURASSIC	SABINAS	Tithonian	Cotton Valley	EVAPORITES	LA CASITA	LA CASITA	Pelayo
		Kimmeridgian	Buckner	LA CASITA			
		Oxfordian	Smackover		LA GLORIA / OLVIDO		
		Callovian	Norphlet			EQ. LA GLORIA	?
		Bathonian	Louann Werner		?		
		Bajocian			CONGLOMERADO BASAL	?	
						NAZAS	
TRIASSIC	UPPER	Rhaetian				?	
		Norian					
		Carnian					
Permian			Hueco Group				
Pennsylvanian			Magdalena Group				
Mississippian			Helms fm				
			Rancheria fm				
Devonian			Las cruces fm				
			Percha shale				
Silurian			Canutillo fm				
Ordovician			Fusselman dol.				
			Montoya group				
Cambrian-ordovician			El paso group				
			Bliss sandstone				

FIG. 3. Stratigraphic correlation table. References: 1 = Haenggi and Muehlberger, 2005; DeFord and Haenggi, 1970; 2 = Santamaría-O et al., 1991; 3 = Araujo-Mendieta and Arenas-Partida, 1986; 4 = present study.

this unit. This is the first report of a marine formation of Jurassic age in the region. Due to structural complexity, it was not possible to measure the actual thickness of this sedimentary sequence. We estimate a minimum thickness of 200 m. Its base is buried and the contact with the overlying unit, the Mezcalera Formation, is shown as a detachment structure. Within this sequence are several tectonically embedded blocks of basalt flows with pillow

structures typical of igneous material erupted under water. Also granitic bodies with mylonitic textures occur. The basalt and granitoid blocks are interpreted as parts of an olistostrome.

The Pelayo Formation is made up of an epiclastic marine section of argillaceous siltstones, sandstones, and minor conglomerates, with laminar to thin stratification in most parts. The sporadic occurrence of micritic thin strata of limestones with

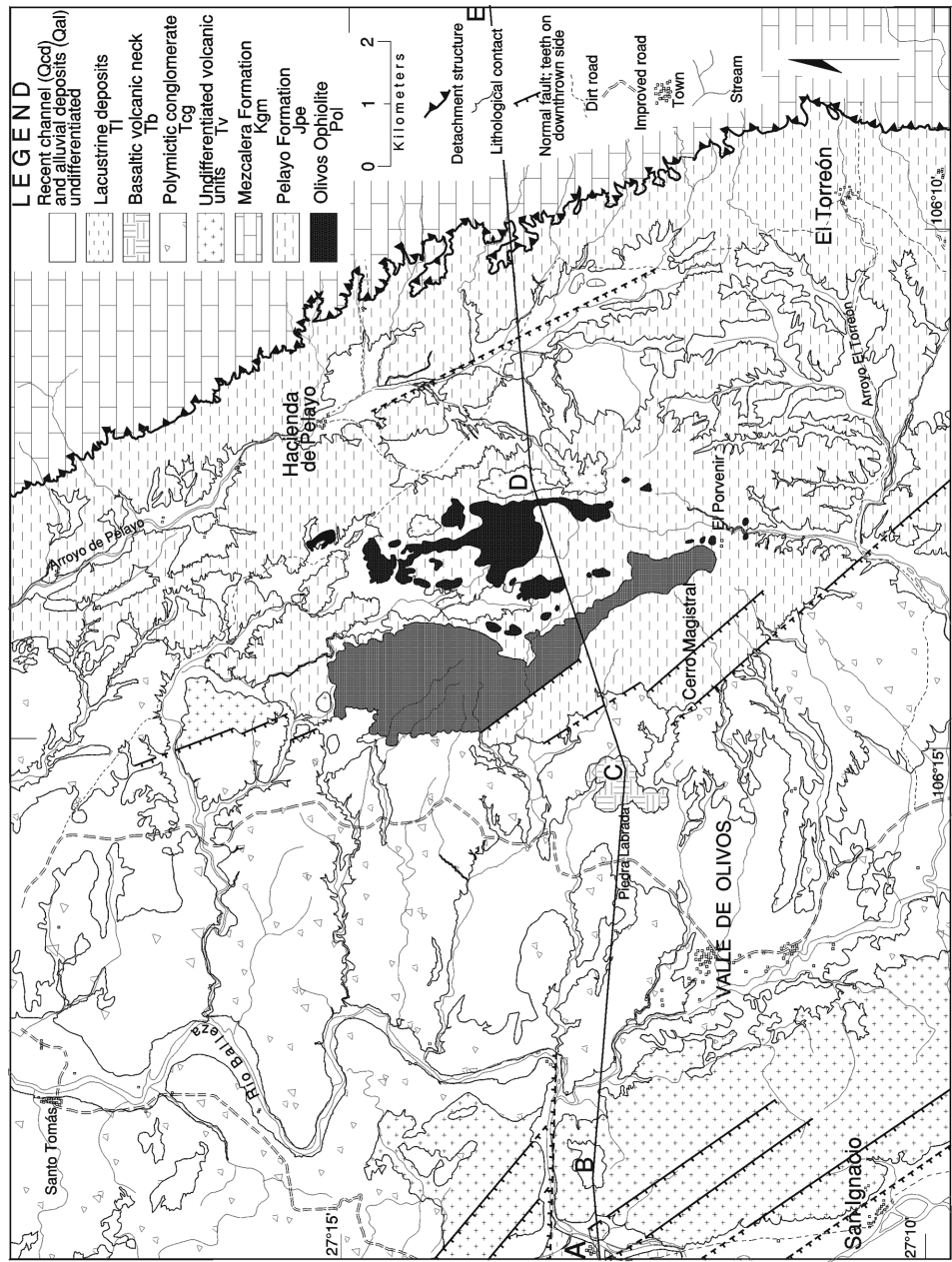


FIG. 4. Geologic map of the Valle de Olivos region (modified from COREMI, 2000).

scarce planktonic microfossils (calcisferulids?) suggests deposition in deep water above the calcium carbonate compensation depth. Transmitted light microscopy shows that the epiclasts consist of quartz and feldspar set in a green matrix reflecting the abundance of chlorite. Other clay types and calcium carbonate with gravel-size intraclasts also are present. The clasts and intraclasts are mostly feldspar crystals, scarce ferromagnesian minerals, biogenic remains, and quartz; feldspar is dominant.

XRF analyses of major elements of three samples from this unit (1007–1009) are presented in Table 1. Corroborating petrographic modal compositions, CIPW norms indicate feldspar and quartz as the main constituents. Most of the Pelayo Formation is considered as a hemipelagic deposit, with textures ranging from clay to silty and sandy clay, despite turbidites occurring interdigitated within the sequence. It is composed mainly of fine terrigenous quartz and feldspar, which is consistent with rock chemistry.

Along Arroyo de Pelayo, in the vicinity of the Hacienda de Pelayo (Figs. 2 and 4), we found ammonites contained in a concretion inside a calcareous-slaty limolite horizon in vertical position. Ammonites were grouped in five species, but only three were identified. R. Scott (pers. commun., 2006) described preliminary assessment of the three ammonites as follows: “The three genera tentatively identified are *Epistrenoceras* (Upper Bajocian–Upper Bathonian), *Eurycephalites* (Lower Callovian), and *Reineckeia* (Middle Callovian). Now, if these three fossils are present together in the same concretion and have not been transported, which does not appear to be the case, then either ranges need adjusting or identifications need adjusting. Because of the incomplete preservation, the unequivocal identification of these specimens may not be possible.” This paleontological identification allows assigning a Middle Jurassic age to this sequence.

Thus the primary stratification and lithological characteristics, with very scarce calcareous horizons, of this sequence are interpreted to reflect deposition presumably in a fore-arc region of an active continental margin. The scarcity of carbonate shows a depth of water close to the compensation level of carbonates, and sediments that were transported by density currents (forming turbiditic flysch-type deposits) and by gravity flows that carried the basalt and granitoid blocks interpreted as part of an olistostrome.

At least two compressional-tangential events have affected this sedimentary unit in approximately the same direction. Dynamic metamorphism is common, especially in the contiguous areas to the basalt blocks. Because of this, a slaty texture in the pelitic facies is ubiquitous; this is interpreted as evidence that the blocks were tectonically emplaced in the sedimentary sequence. Where this facies is found attached to the ophiolite, its metamorphic texture changes from phillite to schist.

Mezcalera Formation

The sedimentary unit located at the top of Sierra La Cuchilla, along the eastern portion of the study area (Figs. 2 and 4; see also Figs. 12, 13, and 14), is assigned to the Cretaceous Mezcalera Formation (Kgm). The type-locality is at the Arroyo La Mezcalera in the Valle de Zaragoza district with a section 1860 m thick (Tarango-Ontiveros, 1993; Araujo-Mendieta and Arenas-Partida, 1986; FYSPSA, 1979), 25 km east of the Los Olivos region.

The Mezcalera Formation is represented by a rhythmic sequence of, greenish grey to light grey argillaceous limestones, calcareous lutites, and fine-grained sandstones in thin- to medium-bedded strata. These latter rocks contain index planktonic microfossils that indicate an age that ranges from Hauterivian to Santonian (Tarango-Ontiveros, 1993). Similar to the underlying unit, complex structure makes it difficult to determine the actual thickness in the study area. The contact with the Pelayo Formation is marked by contrasting facies and independent styles of deformation above and below the contact zone. The contact is tectonic, showing brecciated material in some places (Fig. 5). The top of the Mezcalera Formation has been eroded and is covered discordantly by Tertiary volcanic units. This relation is observed to the north and southeast, outside of the Olivos area (COREMI, 2000).

Tertiary volcanic sequence

We identified several extrusive units (Tv) of acidic to intermediate composition. The interpreted emplacement mechanism agrees with the models proposed by Smith (1960). Between the igneous units, intraformational conglomerates separate distinct volcanic pulses. However, the thickness of the volcanic units is relatively small, probably due to a large distance to the volcanic source or to erosion. In some places, erosion resulted in the complete removal of the units of intermediate

TABLE 1. Un-recalculated Whole-Rock Chemistry of Igneous and Sedimentary Units from the Valle de Olivos Area, wt%¹

Sample: Rock or magma type2:	1000 N-Type MORB	1001 WPA	1002 Rhyolite	1004 N-Type MORB	1005 N-Type MORB	1006 N-Type MORB	1007 Sub-gray wacke	1008 Gray wacke	1009 Gray wacke	1010 Tonalite	1011 Granodiorite	1012 Tonalite	1013 Tonalite	1014 Rhyolite	1015 Rhyolite	1016 Rhyolite	1017 Dacite	1018 Rhyolite	1019 Quartz latite
SiO ₂	50.87	43.38	69.61	58.62	49.77	47.62	70.66	54.59	56.59	74.72	70.11	73.51	73.84	69.09	75.39	68.24	67.81	70.70	63.36
TiO ₂	%	0.78	2.15	1.04	0.87	0.79	0.44	0.37	0.41	0.23	0.72	0.18	0.20	0.40	0.13	0.33	0.55	0.27	0.47
Al ₂ O ₃	%	15.56	14.93	11.97	11.73	16.83	11.37	13.30	16.04	11.48	12.98	10.54	11.56	14.19	11.04	12.82	15.04	12.99	19.01
FeOT ₃	%	13.02	11.12	2.88	11.04	13.43	12.80	7.05	7.23	12.44	4.48	2.86	4.19	2.43	1.69	1.50	2.81	1.53	0.50
MnO	%	0.18	0.18	0.03	0.17	0.19	0.18	0.07	0.12	0.10	0.03	0.09	0.06	0.10	0.06	0.05	0.04	0.03	0.01
MgO	%	3.07	6.52	0.28	3.10	4.52	3.81	0.41	8.32	4.11	1.08	1.25	0.58	0.49	-0.02	0.28	0.20	0.23	0.55
CaO	%	8.72	10.66	0.64	4.38	7.35	10.33	0.90	5.77	0.17	0.24	0.90	1.61	0.35	1.54	0.12	3.57	1.06	0.97
Na ₂ O	%	2.78	3.58	3.39	3.15	3.34	2.12	5.45	3.24	3.65	3.73	5.05	5.40	2.72	2.85	3.01	4.09	4.13	4.67
K ₂ O	%	0.07	1.32	5.15	0.31	0.12	0.09	0.80	0.23	1.03	2.76	0.18	0.20	4.56	6.17	5.17	4.04	3.60	7.24
P ₂ O ₅	%	0.05	0.72	0.03	0.09	0.06	0.05	0.10	0.04	0.06	0.02	0.14	0.05	0.04	0.05	0.06	0.17	0.09	0.04
LOI	%	4.02	4.59	4.73	5.10	3.99	4.73	1.53	5.34	4.14	1.28	3.69	2.48	3.26	1.57	4.27	2.62	4.13	1.99
TOTAL	%	99.12	99.15	98.87	98.73	99.13	98.78	98.55	98.74	98.51	99.46	98.98	98.94	98.79	99.05	99.29	99.05	98.81	98.81
Rb	ppm	10	44	184	10	8	20	8	22	10	60	4	10	126	210	200	130	154	270
Sr	ppm	20	1015	10	40	38	14	60	34	42	52	40	36	140	12	104	222	102	180
Nb	ppm	2	106	30	2	-2	6	2	4	6	20	2	2	8	28	14	16	14	22
Zr	ppm	30	321	456	45	33	108	30	93	234	339	177	135	198	435	267	255	189	390
Y	ppm	16	22	68	22	16	34	16	16	50	54	74	68	30	72	38	42	40	40
Quartz (Q)	WN	5.60	0.00	29.09	20.33	0.48	1.90	7.32	17.37	40.86	34.07	39.33	39.65	32.51	35.52	26.25	25.06	31.66	5.89
Anorthite (An)	WN	31.27	21.96	2.37	18.08	28.23	38.14	3.91	22.60	1.11	3.70	5.84	1.52	7.66	0.00	6.48	7.51	4.90	4.70
Albite (Ab)	WN	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Dioptase (Di)	WN	11.81	23.83	0.70	3.76	8.12	13.22	0.00	6.33	0.00	0.00	1.82	0.00	0.00	0.30	3.59	0.00	0.00	0.00
Hyperssthene (Hly)	WN	22.32	0.00	3.25	23.22	28.56	7.73	30.82	30.80	5.83	6.37	5.19	5.72	3.25	1.83	0.00	2.58	1.90	1.42
Albite (Ab)	WN	24.71	12.61	30.46	28.43	29.70	18.95	47.30	32.58	44.59	32.49	44.76	47.30	24.03	22.98	26.82	35.88	36.89	40.79
Orthoclase (Or)	WN	0.41	8.21	32.27	1.95	0.77	0.53	4.85	1.48	6.44	16.78	1.12	1.24	28.19	37.41	32.15	24.76	22.46	44.20
Wollastonite (Wo)	WN	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	3.13	0.00	0.00	0.00
Olivine (Ol)	WN	0.00	14.93	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Nepheline (Ne)	WN	0.00	10.50	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Apatite (Ap)	WN	0.12	1.76	0.07	0.23	0.14	0.23	0.09	0.14	0.05	0.32	0.12	0.09	0.12	0.09	0.14	0.42	0.23	0.09
Ilmenite (Il)	WN	1.56	4.31	0.32	2.11	1.73	1.58	0.85	0.76	0.82	1.41	0.36	0.40	0.80	0.25	0.66	1.08	0.55	0.89
Corundum (C)	WN	0.00	0.00	0.00	0.00	0.00	0.14	0.00	0.23	2.19	2.61	0.00	1.99	2.20	0.00	0.00	1.32	0.63	1.88
Rutile (Ru)	WN	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.02
Magnetite (Mt)	WN	2.20	1.90	1.48	1.90	2.28	3.49	1.25	2.12	2.09	2.23	1.45	2.10	1.23	0.08	0.77	1.41	0.78	0.00
Hematite (Hm)	WN	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.11
Total	WN	100.00	100.01	100.00	100.01	100.00	99.99	99.98	100.00	100.01	99.99	100.00	100.01	99.99	99.97	100.00	100.01	100.00	99.99

¹Some immobile trace elements in ppm are displayed for discrimination diagrams. At the bottom, CIPW norms of the Olivos samples are presented. Analyses performed by Chemex Labs Ltd.
²Magma type determined by using immobile trace element discrimination diagrams, N-Type MORB = oceanic basalt from normal mid-ocean ridge environment; WPA = alkali basalts from within-plate environments (Meschede, 1986)
³FeOT = Total iron as FeO.



FIG. 5. Brecciated material at the contact between the Middle Jurassic Pelayo Formation and the overlying Cretaceous Mezcalera Formation is considered as a result of structural detachment. The big fragments belong to the Mezcalera Formation, which can be seen at the “Achicadero de Lucas” area near El Torreon Ranch.



FIG. 6. Basaltic pillows displaying ellipsoidal structure. On the left, the concavity of a pillow matches the convexity of another. These pillows represent one of the best outcrops located along the Arroyo La Mina, 3 km north of Cerro Magistral.

composition. COREMI (2000) provided an Oligocene age for the volcanic sequence in Valle de Olivos by correlation with dated units in other localities of the region. We note, however, that Eocene volcanism is also widespread in areas of central and southern Chihuahua, and thus an Eocene age cannot be discounted.

Seven samples from these volcanic units were analyzed for major and immobile trace elements (Samples 1002, 1014–1019; Table 1), for a volcanic rock classification. Dacite, rhyodacite, and rhyolite are the main rock type identified (Figs. 6 and 7A). The acidic volcanic rocks of the Valle de Olivos area fall within the calc-alkaline field (Fig. 7B). This is

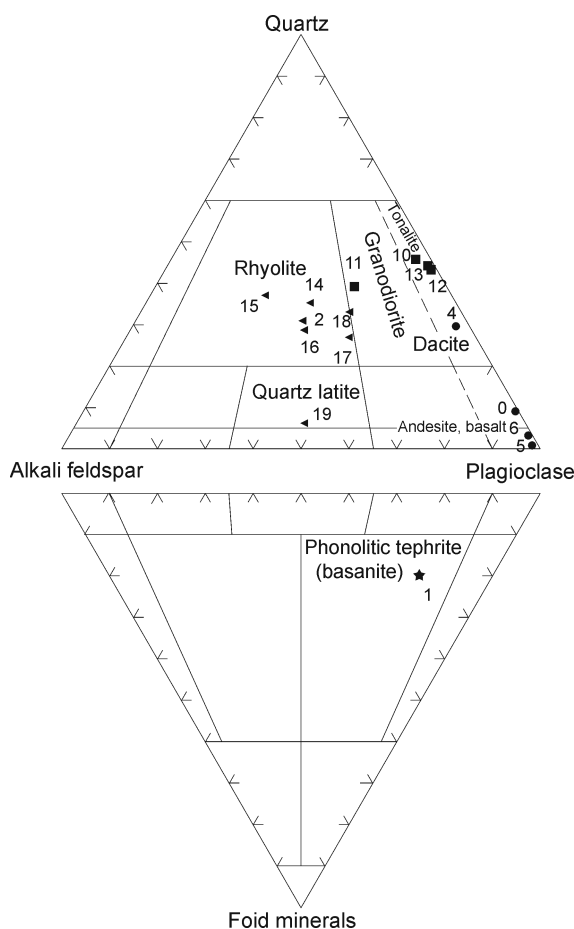


FIG. 7. Streckeisen's classification of igneous rocks. Phaneritic and aphanitic names together. Solid circles represent basaltic pillows, solid triangles Tertiary volcanic units; the solid star represents the 7.58 Ma basanite cinder cone; solid quadrangles indicate granitic tectonic blocks of unknown age associated with the Los Olivos ophiolite.

consistent with analyses of Eocene and Oligocene rocks both in Sierra Madre Occidental and central Chihuahua (McDowell and Clabaugh, 1979; Megaw, 1979).

On the western side of the Sierra de Olivos, an outcrop was identified as Piedra Labrada. This feature corresponds to a basaltic volcanic neck (Figs. 2 and 4), a relict cinder cone located over the trace of a normal fault. COREMI (2000) suggested a Late Miocene age (7.58 Ma) for columnar basalts from the Valle de Olivos area, which are correlated with other units of similar composition in the region, such as those of the Camargo volcanic field (Royo-Ochoa, et al., 2004). Using the compositional

diagrams of Figures 6 and 8, the Late Miocene basalt is classified as a nephelinic basanite.

Tertiary clastic sequence

Overlying the Tertiary volcanic sequence, and resting on erosional discordance, there is a thin section of epiclastic massive strata (Tcg) formed mostly by volcanic derived-material from older volcanic units (Figs. 4 and 12). Clasts of Jurassic and Cretaceous calcareous sequences are also present. Conglomerates are medium to well consolidated, light brown, forming a polymictic conglomerate. The age of this deposit is probably Oligocene–Miocene.

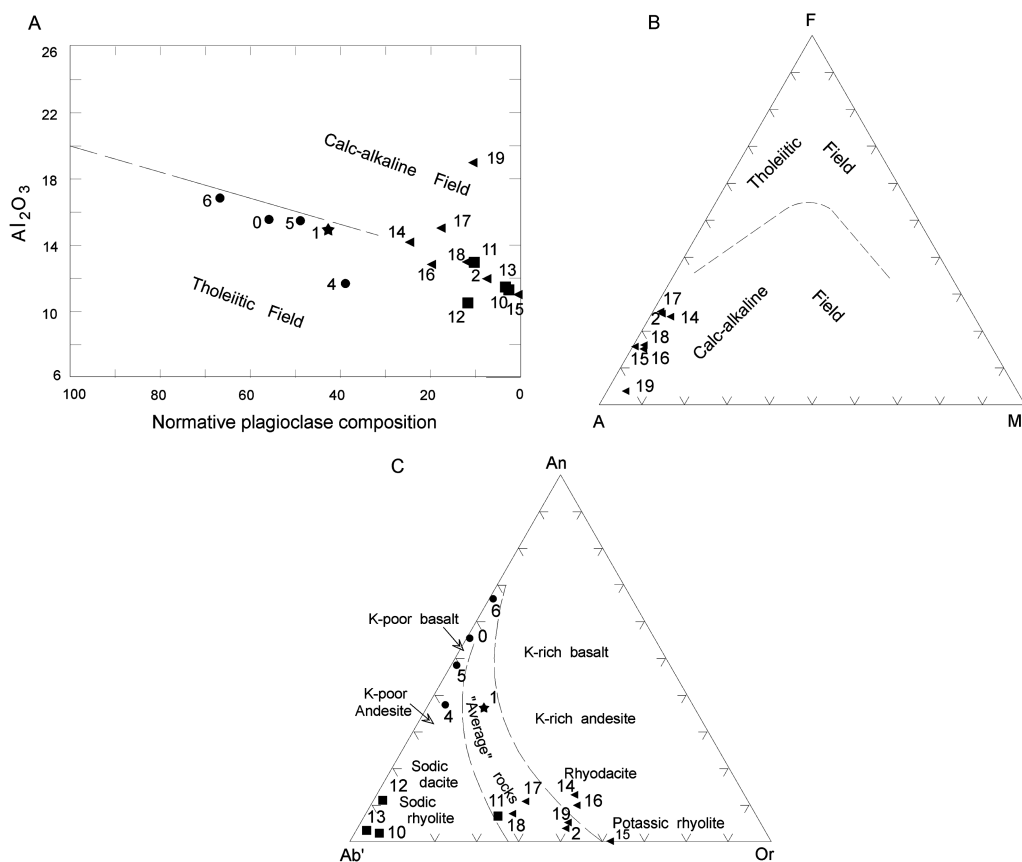


FIG. 8. Two- and three-component diagrams from Irvine and Baragar (1971), where 12 samples from the Valle de Olivos region, through the use of the CIPW norm and graphical plots, can be distinguished and named according to compositional fields. A. Plot of wt% Al_2O_3 versus normative plagioclase composition locates basaltic samples on the tholeiitic field. B. A-F-M ternary diagram for Tertiary volcanic units. C. An-Ab'-Or ternary diagram showing the K-poor area where the basaltic samples fall, whereas all others are considered as high K content. Plots in % cation equivalents.

On the western side of the study area (Fig. 4), white to light grey, nearly horizontal, thin- to medium-bedded calcareous and epiclastic strata (Tl) are exposed. The strata were deposited in lacustrine basins formed as a result of block tilting. There is no evidence for their age, although block tilting may be related to regional Neogene extension associated with the opening of the Gulf of California or to Basin and Range tectonics (Henry and Aranda-Gómez, 1992).

Quaternary epiclastic sequence

Weakly to moderately consolidated Quaternary sediments derived from all underlying units are

present in the region (Qal); they fill low-lying areas, forming piedmonts and alluvial fans. Sediments from the oldest eroded units, represented by unconsolidated sediments in river beds (Qcd), are considered as Holocene-age units.

Olivos Olistostrome

COREMI (2000) described a "sequence of Triassic-Jurassic schists tectonically underlain under thrust fault by pillow lavas and andesitic flows with sandstone, shale and limestone strata, intensely foliated of Neocomian age." The term Olivos olistostrome (Pol) is used here to designate oceanic

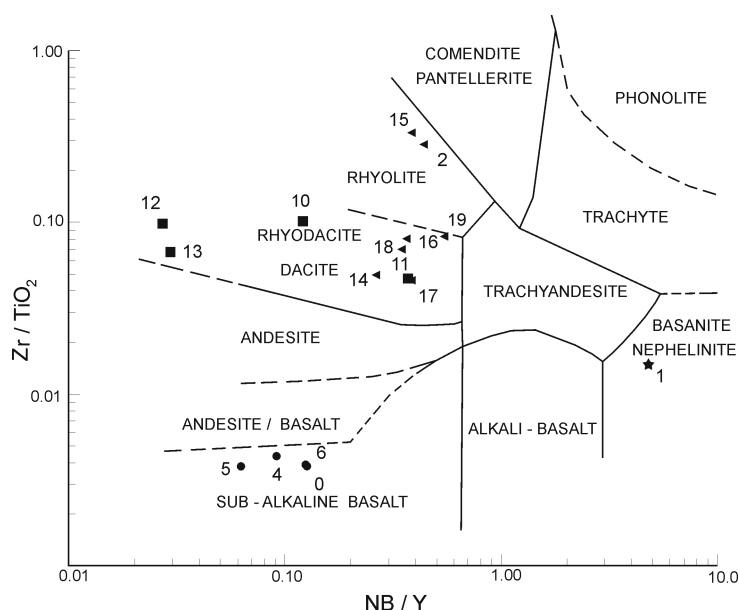


FIG. 9. Binary diagram after Winchester and Floyd (1977) for geochemical discrimination of different magma series, emphasizing types of mid-ocean ridge basalts using immobile elements. Solid circles represent the ophiolite samples; solid triangles Tertiary volcanic units. The solid star indicates the 7.58 Ma basanite cinder cone.

crust bodies that were emplaced as tectonic blocks in the Middle Jurassic sedimentary sequence of Sierra de Olivos, which we name the Pelayo Formation (Figs. 4 and 12).

On the west side of Sierra de Olivos (Figs. 2 and 4) several blocks associated with the olistostrome crop out. The largest block is a basalt slab with approximately 0.6 km² of surficial exposure and several minor blocks that together comprise about 0.244 km² (Fig. 4). All those blocks are intensely fractured and weathered. Primary structures in the megablocks can be perceived on unweathered rock from stream outcrops. Massive basalt lava flows make up almost entirely the Olivos olistostrome. On the other hand, basaltic pillow lavas (Fig. 9), dikes, monolithic breccias, and clastic sedimentary beds (turbidites) are recognized in a few widely separated outcrops. Siliceous rocks previously described by COREMI (2000) containing radiolarians, diatoms, or some other cherty precipitates were not found in our field mapping.

On the southern portion of Sierra de Olivos range along the El Porvenir Ranch area (Figs. 2 and 4), several tectonic blocks of granitoids associated with the olistostrome crop out. From Streckeisen's classification of igneous rocks (Fig. 6), the samples are

high-silica granites (samples 1010–1013; Table 1). The granites are relatively rich in Na (~5%), and according to the ASI versus SiO₂ diagram (Chappell and White, 1974), most fall in the S-type granite field (see Fig. 11). In thin section under cross-polarized light, they reveal a well-developed mylonitic texture, where most grains exhibit undulatory optical extinction, mainly in quartz crystals.

Radiometric K-Ar dating of pillow lava coming from the main body of the Olivos oceanic basalts yields a date of 251 ± 7 My (Geochron-Labs, 1999; sample R-12524), corresponding to the Late Permian. The material analyzed was whole-rock, using -80 ± 200 mesh, treated with dilute HF and HNO₃.

Rock Chemistry

Table 1 shows XRF analyses of major elements expressed in weight percent, CIPW norms, and ICP analyses of immobile trace elements in ppm for 19 samples from the Valle de Olivos area. Analyses were performed at Chemex Labs Ltd.

Nineteen representative rock samples from Valle de Olivos were analyzed. Sample 1001 comes from the Miocene Piedra Labrada volcanic neck (Figs. 2 and 4). Samples 1000, 1004–1006 belong to the

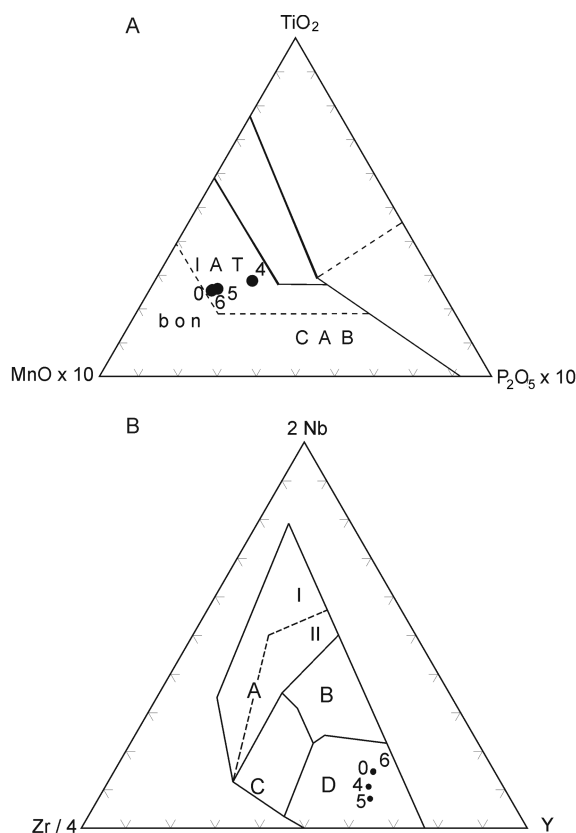


FIG. 10. A. Ternary minor-element discrimination diagram after Mullen (1983). B. Ternary diagram after Meschede (1986). Within-plate alkali basalts (WPA) = AI, AII; within-plate tholeiites (WPT) = AII, C; plume-type MORB = B; normal-type MORB = D; volcanic-arc basalts (VAB) = C, D.

Olivos pillowed basalts. Samples 1007–1009 are typical of the epiclastic Jurassic Pelayo Formation. Four samples (1010–1013) were taken from the El Porvenir Ranch area to characterize the granitic tectonic blocks in these outcrops. A suite of seven samples (1002, 1014–1019) represents rock units from the Tertiary acid volcanic sequence.

In Streckeisen's igneous rock classification (Fig. 6), phaneritic and aphanitic units are not separated. Samples from all tectonic blocks ascribed to the Olivos olistostrome are K-poor except for sample 1011, which falls at the center of the ternary diagram.

Al₂O₃ shows the most prominent chemical difference between the calc-alkali and tholeiitic series (Irvine and Baragar, 1971). The Al₂O₃ normative plagioclase composition diagram (Fig. 8A) indicates that all basaltic units are tholeiitic. Figure 7B con-

siders only the Tertiary volcanic units, which are grouped into the calc-alkaline field. On the ternary diagram (Fig. 7C), basaltic rocks are clearly concentrated into the K-poor area, whereas their counterpart acidic igneous rocks fall predominantly in the Ab'-Or region. Based on standard feldspar composition, a division into K-poor, K-average, and K-rich types is made using the An-Ab'-Or ternary diagram (Irvine and Baragar, 1971). Samples from the basalt slabs and granitic tectonic blocks show a markedly K-poor affinity, with the exception of sample 1011 which is positioned near the K-poor and K-average boundary. Sample 1001 falls within basanite-nephelinite field due to the olivine and nepheline contents, whereas acid igneous rocks classify into dacite-rhyodacite-rhyolite fields (Figs. 6 and 7C; Table 1).

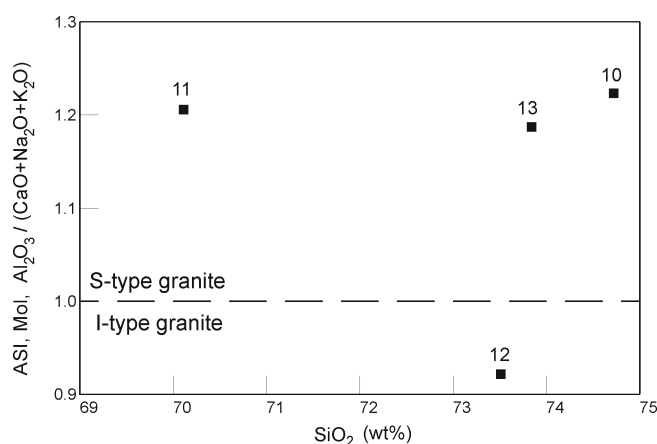


FIG. 11. ASI versus SiO₂ diagram of granitoid tectonic blocks from the El Porvenir area.

Major and immobile trace-element analyses were carried out on four samples of the Olivos basalt blocks (1000, 1004, 1005, and 1006; Table 1). One of the samples highly enriched in SiO₂ (1004, ~58% SiO₂) may not be representative. The rocks exhibit some alteration, as evidenced by high LOI values (~4%). According to the proposed classification suggested by Irvine and Baragar (1971), sampled units are subalkaline to tholeiitic k-poor basalts, with low Zr/TiO₂ and low Nb/Y ratios near 0.1 (Table 1, Fig. 8). The pillow basalt samples are extremely depleted in elements such as Zr, Sr, Rb, and Nb, showing a mantle-depleted signature. We plotted the immobile trace elements in a variety of tectonic discrimination diagrams. For the metamorphosed or extensively altered rocks, a binary chemical diagram for discriminating different volcanic rock types and magma series considering immobile minor and trace elements (Ti, Zr, Y, and Nb) proved to be more reliable than methods that utilize major elements for rock-type classification (Winchester and Floyd, 1977). Both the Nb/Y ratio and the Zr/TiO₂ ratio are indices of alkalinity, and only the Zr/TiO₂ ratio is considered as a differentiation index. Figure 8 exhibits a clear separation of the ophiolite group samples from other samples. In the diagram of Mullen (1983) (Fig. 10A), they fall in the field of island-arc tholeiites, whereas in the diagram of Meschede (1986) (Fig. 10B), they fall in the field of N-type MORB. The highly depleted compositions, together with the presence of pillow lavas, support

an origin directly related to oceanic basalt volcanism in an N-type mid-ocean ridge environment.

Application of the Nb-Zr-Y diagram for the Olivos ophiolite suite identifies these basalts as emplaced in a normal mid-ocean ridge environment. This is indicated by depletion of Nb content and relative enrichment.

Granitoids from El Porvenir tectonic blocks (Fig. 4) are characterized as S-type granite (Samples 1010, 1011, and 1013; Fig. 11), based on its whole-rock major-element chemistry, with data plotting near the I-type to S-type ASI line. Sample 1012 falls into the I type due to its relatively high CaO and low Al₂O₃ contents.

Structural Geology

Normal faults

Normal faulting affects all units in the Los Olivos area. Tertiary extension occurs from the Pacific margin to the U.S.-Mexico border, and from the surface to the brittle-ductile transition zone in the crust. This regional extensional regime results in volcanism that in places coincides with dikes coming directly from the asthenosphere (Moores and Twiss, 1995). The extensional tectonic and volcanic activity has been associated with the Gulf of California opening, suggesting that normal faults remain active while the separation continued (Henry and Aranda-Gómez, 1992). In the study area, the presence of normal faults is evident along blocks tilted

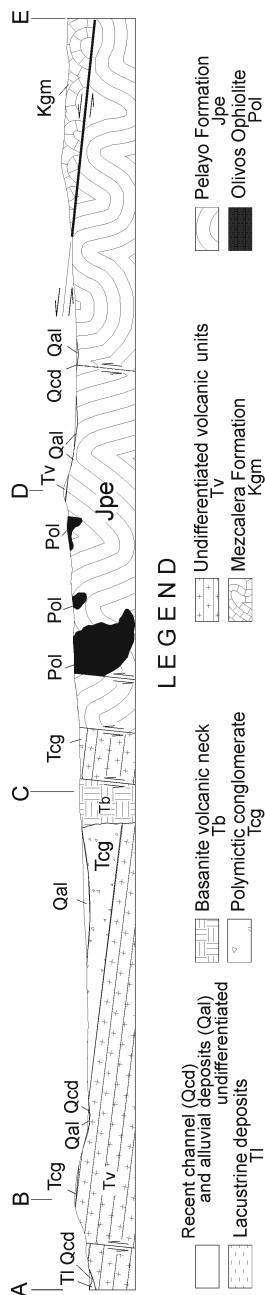


FIG. 12. Structural section along the A–B–C–D–E line, as indicated on Figure 4.

and forming the ranges of Sierra San Ignacio, Sierra de Olivos, and Sierra La Cuchilla (Figs. 2 and 4).

Reverse faulting

Low-angle reverse faulting affects the Cretaceous sedimentary sequence more than the older rocks. This is also observed in the Jurassic sedimentary sequence. The contact between the Pelayo and Mezcalera formations is considered as low-angle reverse faulting and is defined as a detachment structure (Figs. 4 and 12).

Hidalgoan deformation

We consider that Hidalgoan deformation is produced by tangential compression affecting only the Jurassic and Cretaceous sedimentary sequences. The anticlines and synclines in the Jurassic sequence are characterized by larger wavelengths than those developed in the Cretaceous sequence, where tight isoclinal folds are common with vergence to the east (Fig. 13).

Vertical uplift

This type of deformation typified by domal structures is defined in our study area by broad folds formed by vertical uplift, high-angle faults, and block-faulted terranes. The region of the Olivosolistostrome is also affected by vertical uplift, triggering the erosion of the Cretaceous sequences, exposing outcrops of the Jurassic sequence, over which the Tertiary volcanic units were deposited. Evidence of hydrothermal alteration of the Pelayo Formation through almost the entire Sierra de Olivos suggests the presence of a Tertiary intrusive body at depth formed by repeated magmatic pulses. This intrusive is responsible for the uplift as well as silicification and local hydrothermal mineralization.

Discussion and Conclusions

The stratigraphy of the Valle de Olivos study area is summarized in Figure 14. Our interpretation of fragments of the Late Permian Olivosolistostrome oceanic crust within Jurassic sediments (Upper Bajocian–Middle Callovian) reflects the existence of the Mezcalera oceanic plate. The Mezcalera plate was subducted during collision of the Guerrero superterrane with Laurentia. Characteristics of the Middle Jurassic markedly epiclastic units that host the Olivos oceanic basalts support the assumption of an active margin setting for the sedimentary deposition along the southwestern margin of the North American craton.



FIG. 13. Kink folds in the Cretaceous Mezcalera Formation, located in the Sierra La Cuchilla range.

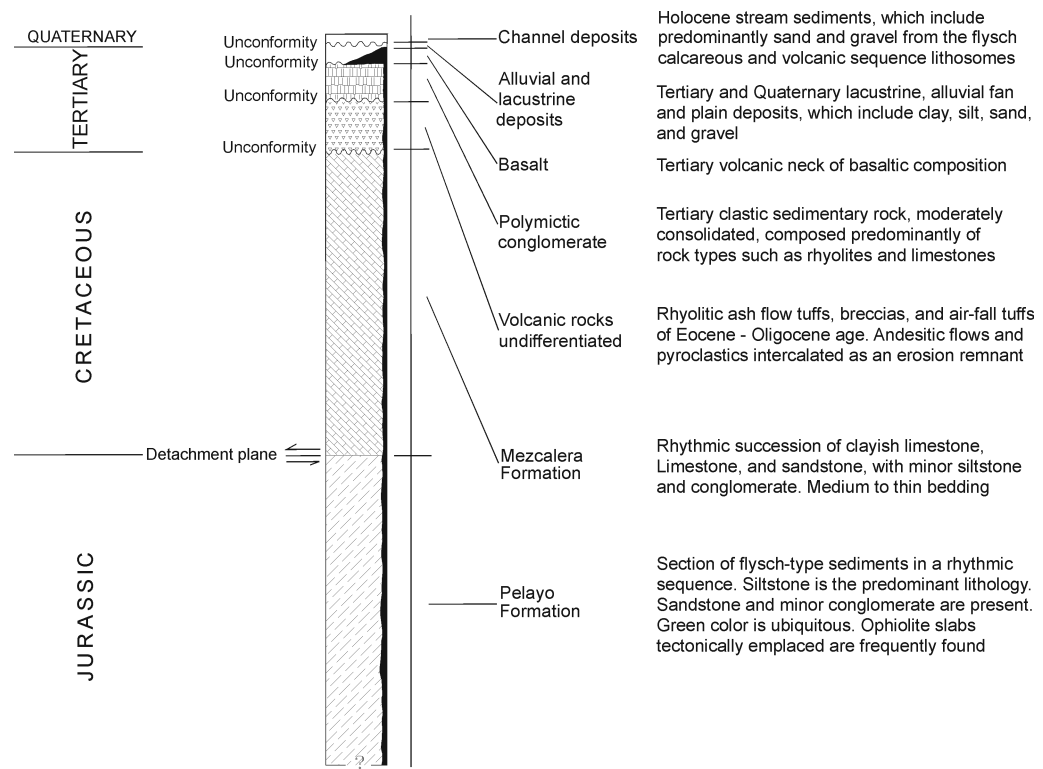


FIG. 14. Stratigraphy of the Valle de Olivos region.

Collision between Gondwana and Laurentia during the Early to Late Permian resulted in closure of the Ouachita–Marathon Basin, generating the Ouachita suture zone. Continental extension is represented by the East Mexican arc identified to the east of the study area (Bartolini et al., 1999; Torres et al., 1999), which resulted from the Mezcalera subduction. Later, during the Late Triassic–Middle Jurassic, and also contemporaneous with the intra-

continental extension that dismembered Pangea, and following truncation of the Laurentia craton margin along the California–Coahuila transform fault, the Mezcalera plate was subducted under Laurentia, forming the Middle Mesozoic magmatic arc, as shown in Figure 15 (Dickinson and Lawton, 2001).

As a consequence of this process, slabs of the Mezcalera oceanic crust were obducted and supplied to the continental margin sediments deposited

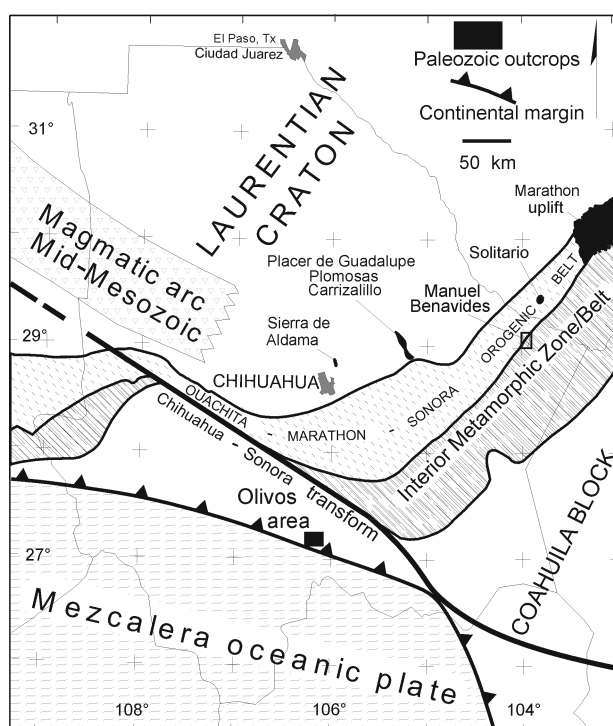


FIG. 15. Paleogeography suggested for the Late Triassic–Middle Jurassic geotectonic reconstruction of Mexico (redrawn from Dickinson and Lawton, 2001 and Poole et al., 2005).

during the Bajocian–Callovian. These units are deformed, contorted, and exposed in the mélange of the Sierra de Olivos region.

The term Mezcalera comes from an unpublished report of Petroleos Mexicanos (Araujo-Mendieta and Arenas-Partida, 1986) to designate a sequence of deformed turbidites in the vicinity of Valle de Zaragoza, Chihuahua. Dickinson and Lawton (2001) used the term because they interpreted the Mezcalera Formation as the record of collision of the Guerrero terrane with the mainland, representing a pro-foreland basin related to collision (T. Lawton, pers. commun., 2004). According to Lawton, supporting data for the Mezcalera plate hypothesis rest on two main lines: (a) Small outcrops of primarily Lower Cretaceous chert and greenstone were assigned to the Arperos basin by Freydier et al. (1997). Dickinson and Lawton (2001) proposed that these outcrops lie between the Guerrero arc terrane and mainland Mexico, and interpreted the rocks as remnants of the subducted Mezcalera plate. (b) Widespread Triassic–Jurassic arc magmatism took

place in the southwestern part of the United States, extending into Sonora, and connecting with the Nazas volcanic rocks in central Mexico, as described by Grajales-Nishimura et al. (1992).

An alternative interpretation, which is also supported by the presence of granitoids in the olistostrome, is that the oceanic basalts formed part of an unnamed oceanic plate that bordered western equatorial Pangea. The basalts were emplaced tectonically against a Pacific margin continental arc, represented by the Las Delicias arc (McKee et al., 1988) and late Paleozoic magmatism in eastern Mexico (Torres et al., 1999), in post-Triassic time. Both the granites and basalts were later emplaced as gravity slide deposits in the Jurassic basin represented by the Pelayo Formation.

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