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GUIDE TO KEY OUTCROPS FOR RECONSTRUCTION OF THE GEOLOGIC - TECTONIC HISTORY OF SIERRA DE CATORCE: NORTHEASTERN MEXICO

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Guide to Key Outcrops for Reconstruction of the Geologic-Tectonic History of Sierra de Catorce: Northeastern Mexico

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ABSTRACT

In the Sierra de Catorce, there is an uplifted block in the southernmost Basin and Range province in northern San Luis Potosí, where most of the oldest stratigraphic units of the region are well exposed. The succession includes Upper Triassic siliciclastics consisting of an alternation of fine-grained sandstone and shale layers, interpreted as lateral equivalents to deep marine turbidites, named the Zacatecas Formation, known from several localities to the west in the region. At Real de Catorce, the previously described deposits underlie coarse chaotic deposits which are products of flow events that change upwards in a marine marginal succession that includes the Triassic-Jurassic boundary. Upwards, the succession includes volcanic and volcaniclastic strata related to the Lower to Middle Jurassic Nazas Formation, underlying conglomerate-breccia and red sandstones of the La Joya Formation that represents an erosional or break-up unconformity related to the initial spreading in the Gulf of Mexico Basin. La Joya Formation changes up-section into limestones of the Zuloaga Formation, which resulted from the Middle-Late Jurassic marine transgression. Outcrops in the General Canyon, along the route Carretas-Real de Catorce include typical strata that allow interpretation of the tectonic-paleogeographic evolution of the Late Triassic-Early Jurassic Pacific margin of Mexico, which evolved into extensional to transtensional basins related to the Gulf of Mexico Basin and probably in part, a result of back-arc extension related to the Nazas volcanic arc. Upper Jurassic strata in the region represent the bottom of the marine sedimentary succession deposited in the Central Mexico Basin, a trough shaped subsiding paleogeographic element in Central Mexico during Late Jurassic-Cretaceous time. Finally, we describe some outcrops that illustrate structures produced by contractile deformation (Late Cretaceous-Paleogene) and post-deformational magmatism (Eocene) that occurred in the area.

Keywords: Real de Catorce, Triassic, Jurassic, stratigraphy, geochronology.

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RESUMEN

En la Sierra de Catorce, hay un bloque levantado en la porción meridional de la provincia de Cuencas y Sierras en el norte de San Luis Potosí donde la mayoría de las unidades estratigráficas más antiguas de la región están bien expuestas. La sucesión estratigráfica incluye rocas siliciclásticas del Triásico Superior en forma de una alternancia de capas de arenisca de grano fino y lutitas, interpretadas como equivalentes de turbiditas marinas más profundas conocidas como Formación Zacatecas en varias localidades al oeste de esta zona. En la Sierra de Catorce la parte superior de esta alternancia de areniscas finas y lutitas pasa a depósitos caóticos gruesos que son producto de eventos de flujo masivo que evolucionan en una sucesión marina marginal que incluye al límite Triásico-Jurásico. Hacia arriba, la sucesión incluye productos volcánicos y horizontes volcanoclásticos relacionados con la Formación Nazas, del Jurásico Inferior a Medio, la cual subyace a un conglomerado o brecha y areniscas rojas de la Formación La Joya, que representa una discordancia erosional o "break-up unconformity" relacionada con extensión durante la apertura del Golfo de México. La Formación La Joya pasa hacia arriba en la secuencia a calizas de la Formación Zuloaga, como resultado de la transgresión marina ocurrida durante el Jurásico Tardío. Afloramientos en el Cañón General, a lo largo de la ruta Carretas-Real de Catorce, incluyen estratos que permiten interpretar la evolución tectónica paleogeográfica del margen Pacífico antiguo de México durante el Triásico Tardío-Jurásico Temprano, que posteriormente evolucionó en las cuencas extensionales a transtensionales relacionadas con la apertura del Golfo de México y posiblemente en parte como una extensión tras-arco, relacionada con el magmatismo del llamado arco volcánico Nazas. Los estratos del Jurásico Superior en la región representan la parte inferior de la sucesión sedimentaria marina depositada en la Cuenca Mesozoica del Centro de México, un elemento paleogeográfico subsidente durante el Jurásico Tardío-Cretácico. Finalmente se describen algunos afloramientos que ilustran las estructuras producto de la deformación contractiva (Cretácico Tardío-Paleógeno) y el magmatismo post deformación (Eoceno) ocurridos en la zona.

Palabras clave: *Real de Catorce, Triásico, Jurásico, estratigrafía, geocronología.*

1. Introduction

The Mesozoic sedimentary cover in Eastern Mexico overlies a peri-Gondwanan Grenvillian block known as the Oaxaquia microcontinent (Ortega-Gutierrez *et al*., 1995). Westward from westernmost San Luis Potosí, there is no evidence of a major block of Precambrian-Paleozoic basement. In these areas, ancient oceanic crust and overlying Triassic pelagic sediments and turbidites constitute the sole of the Jurassic-Cretaceous marine volcanic and volcano-sedimentary successions, which make up the so-called composite Guerrero terrane (Figure 1). To the east, Precambrian-Paleozoic crystalline basement underlies a folded and thrusted sedimentary cover, which consists of Jurassic-Cretaceous limestones and evaporites as well as subordinate clastic rocks in the Sierra Madre Oriental province.

According to the distribution of the Precambrian-Paleozoic basement in Mexico, the ancient westernmost Pangea paleomargin can be interpreted to extend from southern Sonora and Chihuahua, along north-central and eastern Mexico, and southeastward to Puebla and western Guerrero. During early Mesozoic times, thick Triassic siliciclastic successions were deposited on an ancient passive margin of Pangea, (Silva-Romo *et al*., 2000) evolving to the west in the so called "Potosí submarine fan" (Centeno-García 2005, Centeno-García *et al*., 2008), while coeval continental fluvial deposits in Nuevo León and Tamaulipas are known as El Alamar Formation (Barboza-Gudiño *et al*., 2010).

After marine regression and deformation of the Triassic rocks caused by subduction at the western margin of Pangea, a continental volcanic arc, known as the Nazas Formation or Nazas arc (Pantoja-Alor, 1972, Lawton and Molina-Garza., 2014) evolved during Early to Middle Jurassic time. Moderately deformed subaerial volcanic rocks of the Nazas arc rest unconformably on tightly folded Triassic turbidites. Volcanic materials of the Nazas Formation are partly interlayered and covered by Lower Jurassic volcaniclastic "red-beds" (La Boca Formation; Mixon *et al*., 1959). Finally, in the Middle Jurassic La Joya Formation (Mixon *et al*., 1959), there is a fining upward siliciclastic

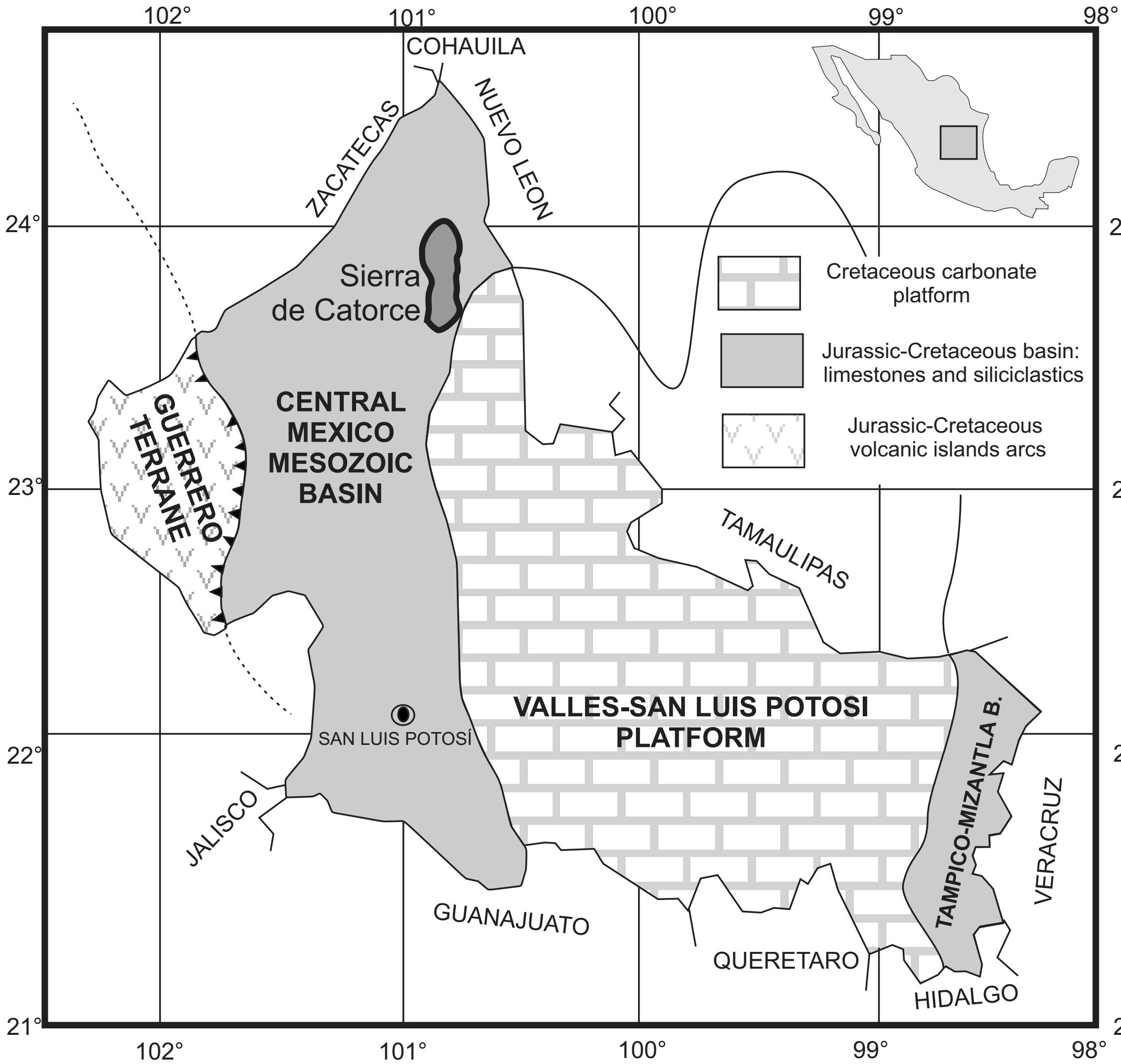

Figure 1. Major paleogeographic elements in the state of San Luis Potosí, north-central to northeastern Mexico and location of the Sierra de Catorce.

sequence, grades upward into marine evaporitic and carbonate beds of the Callovian-Oxfordian Zuloaga Group (Sandstrom, 1982) and the fossil-rich La Caja (Imlay, 1938) or La Casita Formation (Imlay, 1936) at the top of the Jurassic succession.

The Sierra de Catorce, which lies at the boundary between the Mesa Central and Sierra Madre Oriental provinces in northern San Luis Potosí, (Figure 2) as a strongly uplifted area offers the possibility to examine exposures of the oldest rocks in the region, including the above mentioned Triassic rocks and the Jurassic succession consisting of volcanogenic and non-marine sedimentary Lower to Middle Jurassic units. The Triassic-Lower Jurassic succession unconformably underlies the Upper Jurassic represented by a marine, first mostly calcareous (Zuloaga Formation) and then calcareous-siliciclastic (La Caja Formation) shelf sequence. Probably the most complete Jurassic succession in the Sierra de Catorce is exposed in Cañón General between the towns of Los Catorce and Real de Catorce, along a 5 km route in the Canyon (Figures 3, 4), where the base of the Jurassic succession is exposed east of Los Catorce, at an elevation of 2200 meters and the Jurassic-Cretaceous boundary at 2900 meters on the mountains around Real de Catorce.

Our goal is to describe and interpret several outcrops that illustrate the processes and geotectonic environments that have been associated over time with different lithostratigraphic units recognized and well exposed in Cañón General, along the road between Los Catorce and Real de Catorce. The present work can be taken as a field guide along a

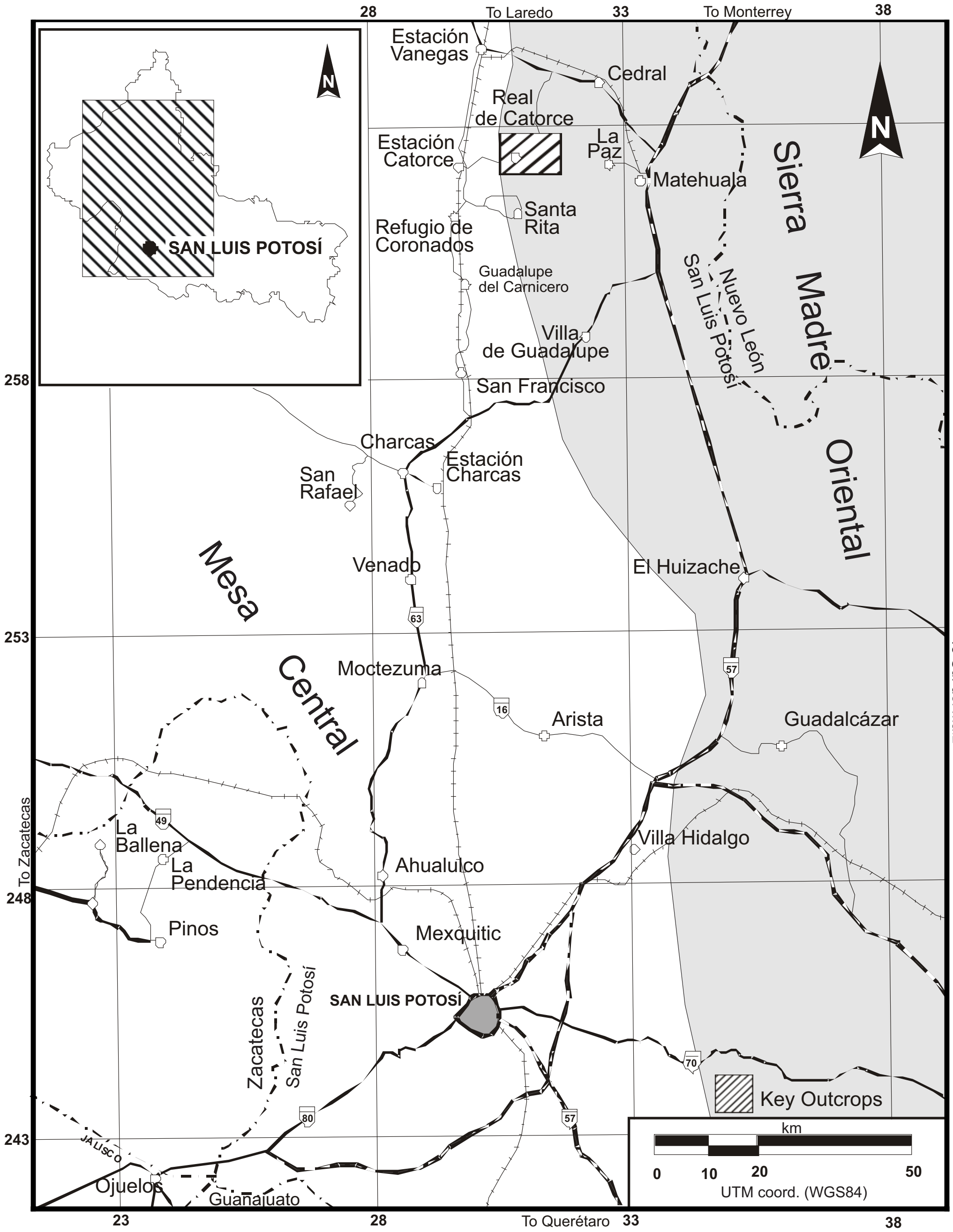

Figure 2. Regional map and access to the Sierra de Catorce, modified from Barboza-Gudiño *et al.*, 2012.

section through the mountain range, coming from the west along Cañon General and passing through Real de Catorce towards the northeast.

2. Upper Triassic Turbiditic Succession in the Mesa Central

Centeno-García (2005) gave the name Potosí fan to a widespread succession of deep-marine siliciclastic turbiditic deposits exposed in the Mesa Central in the states of San Luis Potosí and Zacatecas, and westward, in Guerrero and Michoacán. After the first report of Late Triassic fauna in the neighborhood of Zacatecas city (Burckhardt and Scalia, 1905), rocks of the Potosí fan were first named "Triassic of Zacatecas" (Gutiérrez-Amador, 1908) and later Zacatecas Formation (Martínez-Pérez, 1972). In the respective localities, different names are used

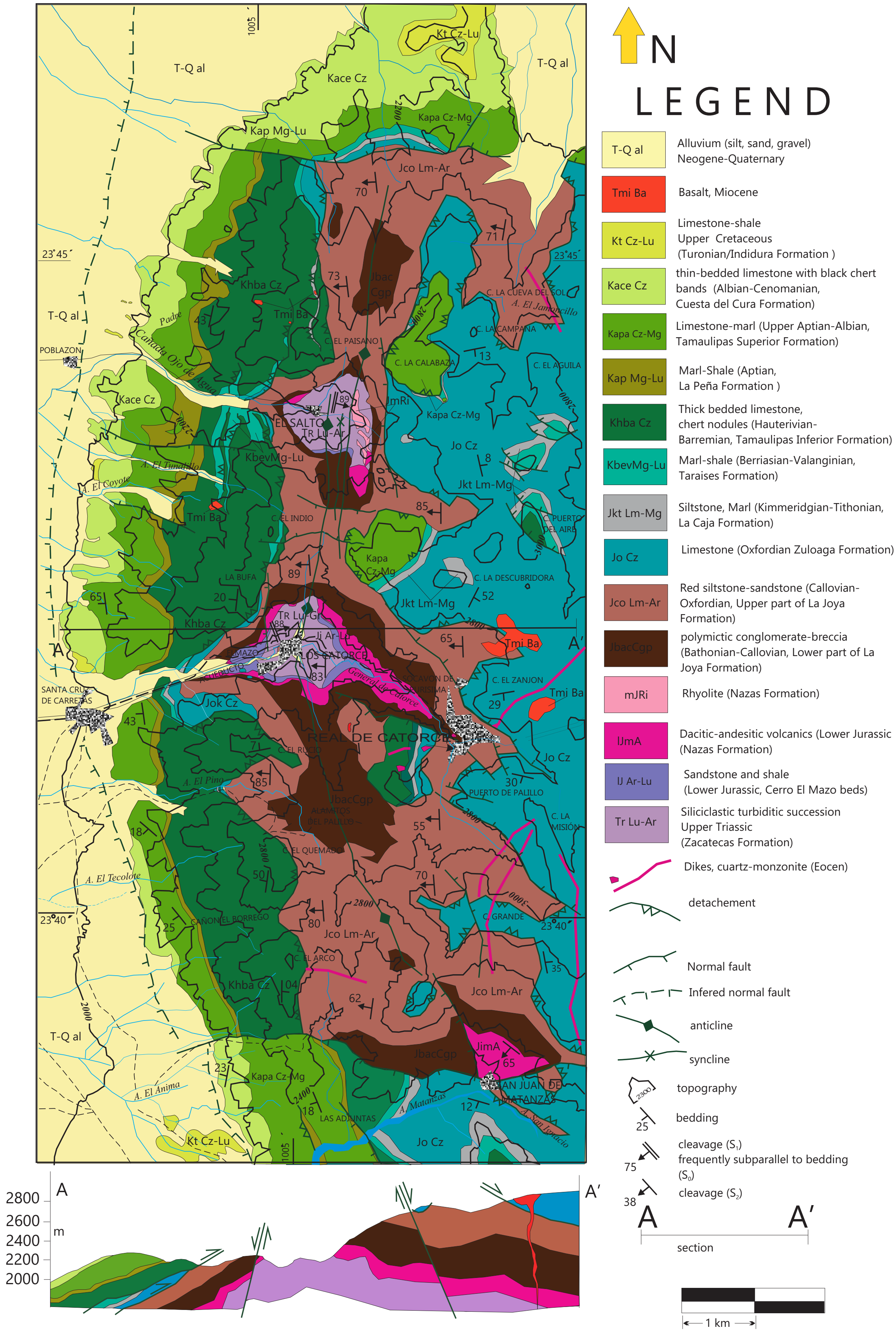

Figure 3. Geological map of the northwestern Sierra de Catorce (from Barboza-Gudiño *et al*., 2014, 2012).

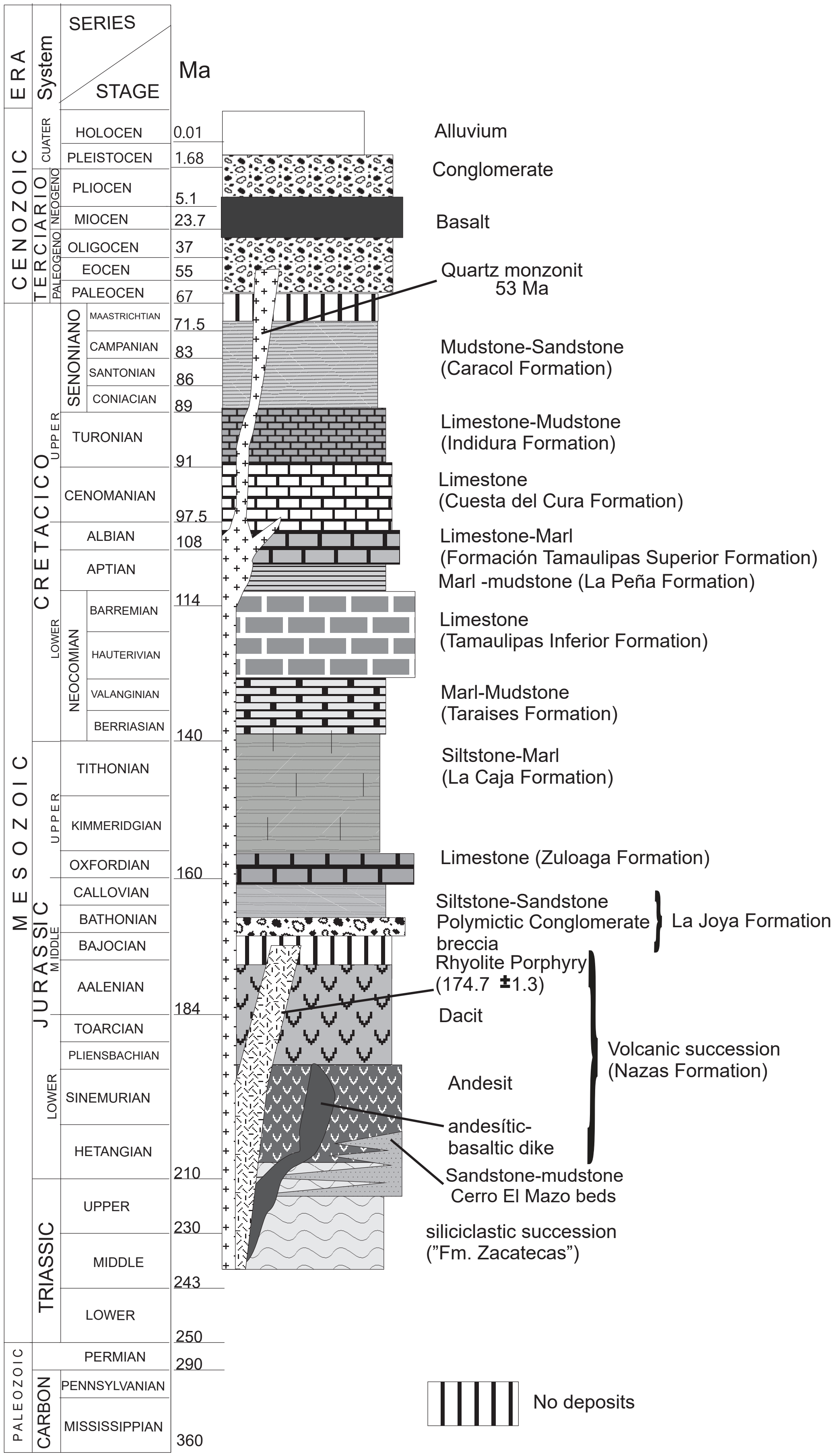

Figure 4. Stratigraphic column of the Sierra de Catorce (after Barboza-Gudiño *et al*., 2004, 2012).

for equivalent siliciclastic successions, such as La Ballena Formation proposed by Silva Romo *et al.* (2000) in the Sierra de Salinas, Zacatecas, while Córdoba-Méndez (1964) used the name Taray Formation in northern Zacatecas. The Zacatecas Formation outcropping in the Mesa Central province is the marine counterpart of the continental El Alamar Formation outcropping in the Sierra Madre Oriental (Barboza-Gudiño *et al.*, 2010, 2012). Generally, the Zacatecas Formation consists of interstratified sandstones, siltstones, shales and conglomeratic sandstones.

In the Cañón General area (for example outcrops at coordinates: 23°42.1'N; 100°54.5'W) the sequence of interlayered fine-grained sandstone beds and black shales, whose base is not exposed, crops out around the town of Los Catorce (Figure 5A), where it exhibits good stratification, mostly strongly folded with development of pervasive cleavage and vertical pencil structures parallel to common steeply-dipping fold axes. A Late Triassic age for this succession is determined through U-Pb ages of detrital zircons (Barboza-Gudiño *et al*., 2010) that are in concordance with correlations based on lithological similarities and stratigraphic positions of equivalent fossil-bearing strata in the other above-mentioned localities from the Mesa Central. To the top of the Triassic sequence exposed in the Cañón General area, slumping structures (Figure 5B) and debris flow,

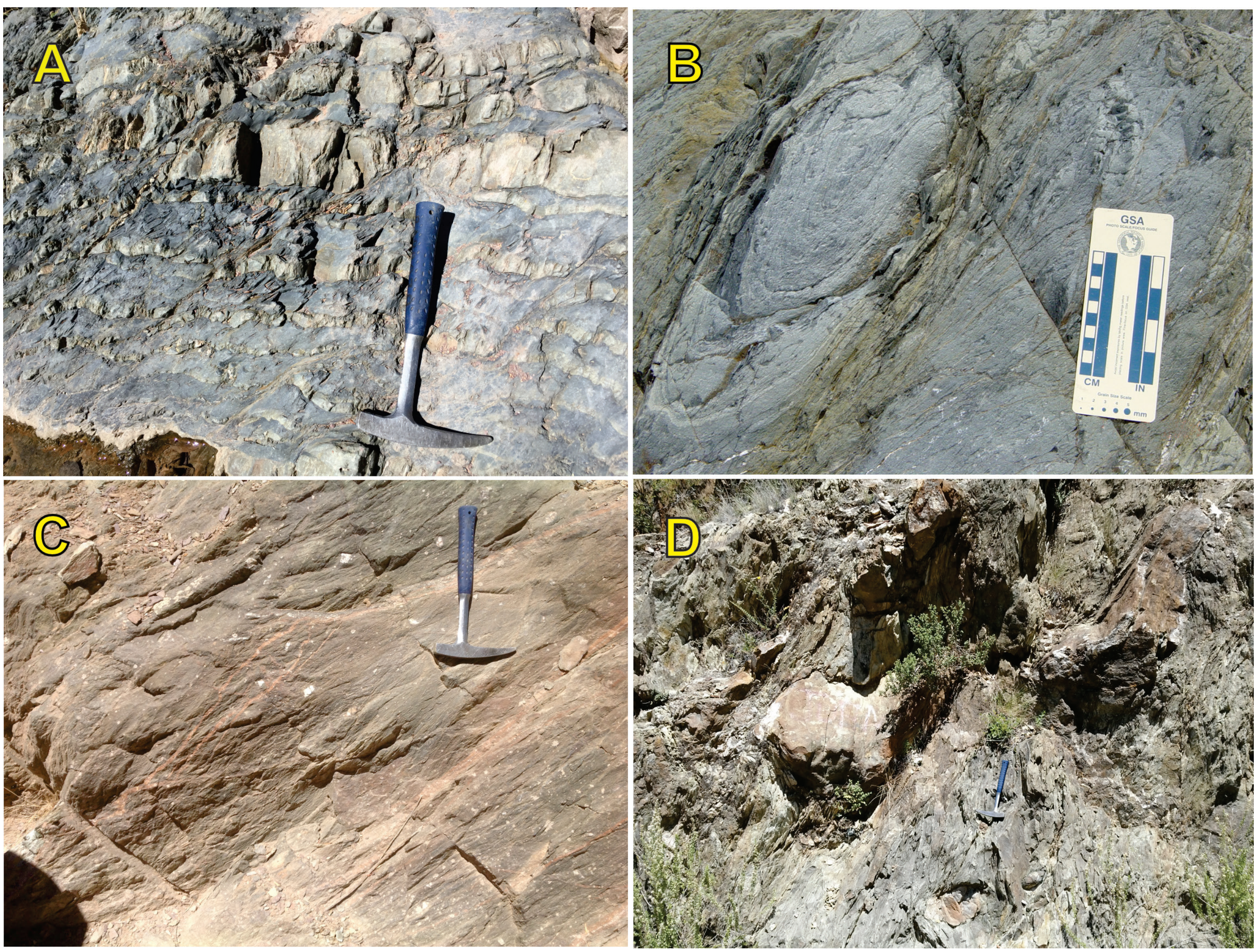

Figure 5. A. Deformed sandstone interlayered with black shale horizons in the Upper Triassic turbiditic succession (Zacatecas Formation) of Los Catorce; B. Slump folds in fine-grained sandstones layers of the Zacatecas Formation at Los Catorce; C and D floating quartz pebbles and carbonate cemented sandstone and cherty blocks in massive deposits corresponding to the uppermost part of the Triassic Succession of the informal unit named "Cerro El Mazo beds", exposed in the neighborhood of the town of Los Catorce.

as well as massive sandstone deposits containing floated pebbles (Figure 5C) to meter size blocks are very common (Figure 5D), and it appears to be a transitional change into the so-called Cerro El Mazo beds (Barboza-Gudiño *et al*., 2004). There are no reports of fossils in the Triassic turbidites of Sierra de Catorce and only the "Cerro el Mazo beds", that overlie the Zacatecas Formation, considered also in part latest Triassic in age (Wengler, 2014), contain plant fossils (see below). The facies associations in the Zacatecas Formation are generally interpreted as inter-channel deposits and subordinate supra-fan, levee, and channel deposits. Hoppe (2000) measured a ~213 m thick succession at Los Catorce, which is considered an incomplete section because the base of this unit is not exposed. In addition to the strong deformation, this unit changes gradually upwards in the siliciclastic and volcanogenic layers of the informal unit termed "Cerro El Mazo beds" (Barboza-Gudiño *et al*., 2004), which include the Triassic-Jurassic boundary (Venegas-Rodriguez *et al*., 2009, Wengler, 2014). The Cerro El Mazo beds in turn change into the volcanic arc succession known as Nazas Formation in north-central to northeastern Mexico.

3. "Cerro El Mazo Beds" Triassic-Jurassic Marine Marginal Succession

At Cerro El Mazo, two kilometers west of Los Catorce and along the first half of the way between Los Catorce and Real de Catorce, Barboza-Gudiño *et al*. (2004) and Venegas-Rodríguez *et al*. (2009) described the informal unit named "Cerro El Mazo beds". In the region, this unit is only recognized in the area of Real de Catorce and consists of more than 300 m of quartzite and conglomeratic sandstone, green, yellow and red shale, as well as interlayered andesitic "greenstone", including massive deposits composed of conglomeratic sandstone with floating quartz pebbles to blocks of quartzite and cherty rocks in a muddy-sandy matrix. The Cerro El Mazo beds rest with erosive contact on turbidites of the Zacatecas Formation. According to U-Pb data of detrital zircons reported by Venegas-Rodríguez *et al*. (2009) and new data by Wengler (2014), the lower part of this succession corresponds to the latest Triassic, and the Triassic-Jurassic boundary is located in the middle to upper part of the succession. To the top, the presence of nodular shales, flasher bedding and possible paleosols indicates a marginal marine sequence that contains interlayered volcanogenic materials interpreted as the base of the Lower Jurassic Nazas Formation.

Outcrops of the informal unit "Cerro El Mazo beds" (Barboza-Gudiño *et al*., 2004, Venegas-Rodríguez *et al*., 2009) occur west and east of the town "Los Catorce", along the road to Santa Cruz de Carretas, and along the road to Real de Catorce, for example at coordinates 23°42'N; 100°54.3 W. These sections represent, respectively, west-dipping and east-dipping flanks of a north-south trending antiform, the core of which shows along the canyon the oldest stratigraphic units known from the Mesa Central. The Cerro El Mazo beds are composed of quartzite or conglomeratic, compact litharenite which includes the Triassic-Jurassic boundary in the Cañón General succession (Figure 6A) containing remains of plants (Figure 6B), probably Cycadeoids like *Zamites* sp. (Bartolini *et al*., 1999), and interlayered red and green-yellow mudstone (Fig. 6C), as well as basaltic-andesitic dikes and lava flows that represent products of synsedimentary volcanic activity (Figure 6D). At least the upper part of the Cerro El Mazo beds is interpreted as shallow marine marginal facies. Upwards in the succession, interlayered andesitic to rhyodacitic lava flows and pyroclastic deposits represent the basal Early Jurassic volcanic succession known in the region as the Nazas Formation. On the east flank of the above-described Los Catorce Antiform, the Nazas Formation is thick, up to more than 200 m over the Cerro El Mazo beds, whereas southwest of Los Catorce, the thickness of the Lower Jurassic volcanic succession, markedly diminishes to only a few meters of green and red-purple colored tuffaceous layers. Some field verifications are required in order to determine the presence of a possible more voluminous volcanic edifice to the east of Los Catorce antiform as the origin of the thickness change, or the same as a result of a typical structure of an inverted half graben where the Nazas would have been deposited inside the sunken block and partially outside it, later this

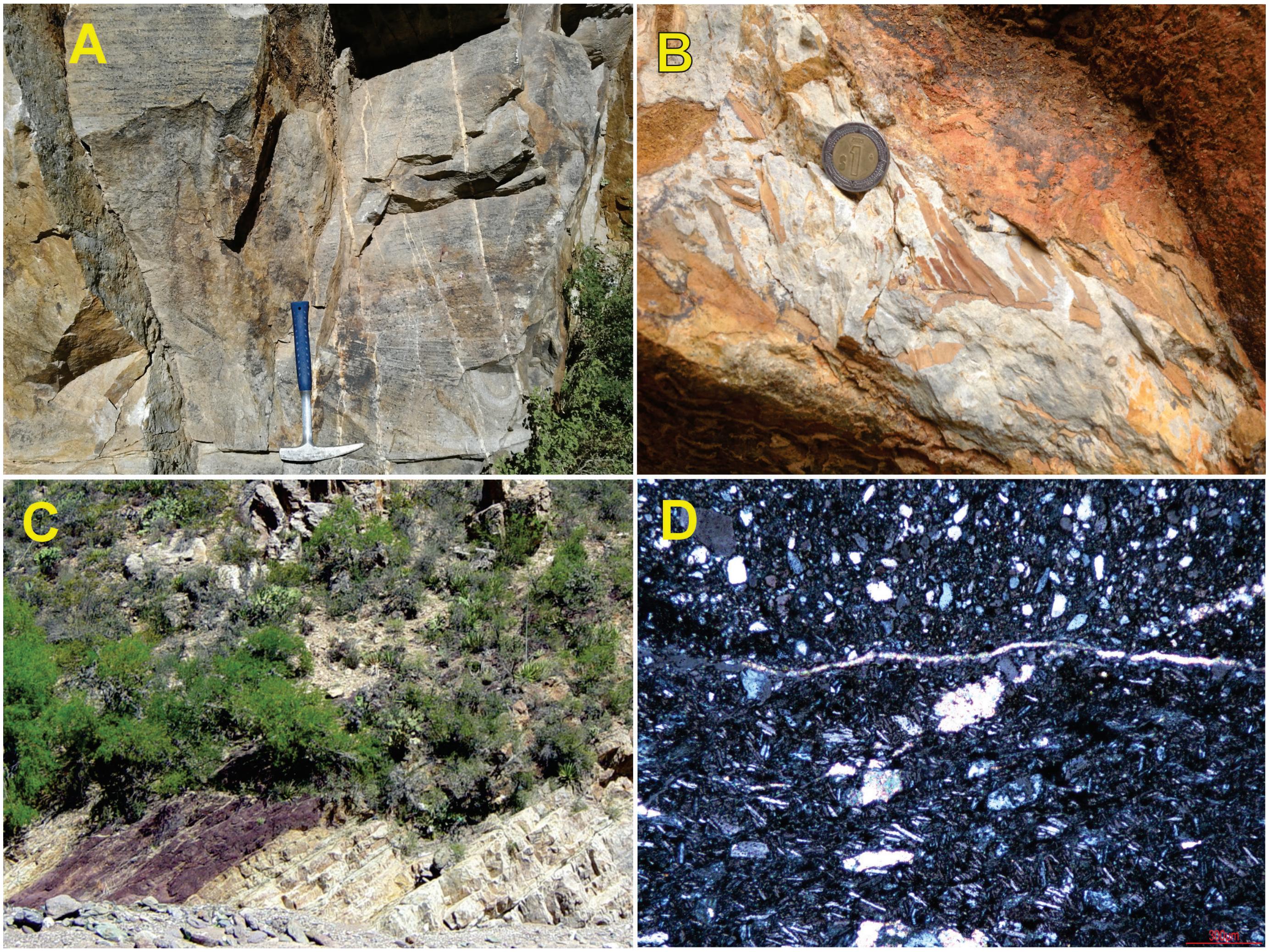

Figure 6. A. Thick bedded quartzite or conglomeratic litharenite showing internal cross-lamination in the Cerro El Mazo beds along the road from Los Catorce to Real de Catorce; B. Remains of plants, probably Cycadeoids similar to *Zamites* sp. in the basal sequence of Cerro El Mazo beds, east of Los Catorce. Coin is 2 cm in diameter; C. Thick bedded quartzite, and litharenite interlayered with red and yellowish mudstone layers; D. Chloritized products of mafic synsedimentary volcanic activity are interlayered in the marine marginal facies of the Cerro El Mazo beds. In the microphotography under XPL (magnification ×5) the lower half of the view is composed of laths of fine plagioclase and some carbonate patches and the upper half displays a clastic deposit with abundant fine-to medium-grained quartz fragments.

structure would have been inverted by contractive tectonics, originating the described antiform.

4. Nazas Formation: Lower Jurassic Volcanic Succession

The Nazas Formation (Pantoja-Alor, 1972) is a Lower to Middle Jurassic volcanic and volcano-sedimentary succession, composed at the type locality in the Villa Juárez Uplift, northeastern Durango of intermediary to felsic lavas, ash and tuffs, including several related epiclastic deposits. Other authors described pre-Oxfordian volcano sedimentary successions outcropping in several localities from north-central and northeastern to southeastern México (López-Infanzón, 1986; Grajales-Nishimura *et al*., 1992; Tristán-Gonzalez and Torres-Hernández, 1994; Jones *et al*., 1995; Blickwede, 2001; Bartolini *et al*., 2003; Barboza-Gudiño *et al*., 2004, 2008, 2012; Barboza-Gudiño, 2012; Godínez-Urban *et al*., 2011; Zavala-Monsiváis *et al*., 2012; Lawton and Molina-Garza, 2014). Most of these authors related the volcanic activity to the active continental margin of southwestern North America during the Early to Middle Jurassic, as well as partially to activity of a volcanic arc extending across southwestern north America and known in México as the "Nazas arc" (Bartolini *et al*., 2003). Martini and Ortega-Gutiérrez (2018), interpreted the volcanic activity as related to intrusion of magmas in the back-arc zone, forced by flat subduction of the Farallón plate during Early Jurassic time, and considered magmatic rocks outcropping in western Mexico as the true continuation of the western North American magmatic-arc. A recent review article by Busby and Centeno-García (2022) largely agrees with Martini and Ortega-Gutierrez (2018). U-Pb geochronology of detrital zircons shows that the volcanic activity in north central to northeastern Mexico was active for a period of *ca*. 30-40 Ma during the Early and Middle Jurassic, from *ca*. 195 Ma to 165 Ma BP (Barboza-Gudiño *et al*., 2008, 2012).

At the point known as La Purísima, on the road between Los Catorce and Real de Catorce, the volcanic succession of the Nazas Formation, consisting of rhyodacites and felsic pyroclastic rocks, rests on red siltstones, greenstones and quartzite of the "Cerro El Mazo beds" (Barboza-Gudiño *et al*., 2004; Venegas-Rodríguez *et al*., 2009). The pyroclastic rocks consist of ash-fall deposits or laminated ash; some locally contained welded tuff near the vent and unwelded tuff at a distance where smaller, cooler particles fell to the ground; also recorded are volcanic breccia horizons and marked pseudo-stratification at the base (Figure 7A), while bedded pyroclastic deposits grade up-section into massive deposits showing several intensely sheared zones containing sericite due to both? Dynamic metamorphism and associated hydrothermal alteration. Basaltic-andesitic lavas also occur in the volcanic succession exposed in the Sierra de Catorce. The lava contains fluidal porphyritic texture with highly altered, probable hornblende phenocrysts, scarce pyroxene, olivine, and plagioclase in a fine groundmass composed of acicular plagioclase, ferromagnesian minerals, and opaque grains (Figure 7B). Some lavas represent auto-breccias formed during flow emplacement. Similar basaltic-andesitic lavas crop out at Sierra de Salinas and Sierra de Charcas. The volcanic units are unconformably overlain by Middle to Upper Jurassic red beds of La Joya Formation (Figures 7C and D). The exposed succession along the road to Real de Catorce forms part of the eastern flank of Los Catorce Antiform.

U-Pb (zircon) ages of the volcanic rocks indicate an Early Jurassic age for the basal part of the Nazas Formation in the area. Now, a possible volcanic arc origin is doubtful for the layers of interstratified greenstone in the Cerro El Mazo beds, considered Upper Triassic-Lower Jurassic in age. To augment previously published U-Pb ages for Real de Catorce volcanic rocks (Barboza-Gudiño *et al*. 2008) and other localities of the Nazas Formation in the region (Jones *et al*., 1995; Barboza-Gudiño *et al*., 2008, 2012; Zavala-Monsiváis *et al*., 2012; Lawton and Molina-Garza, 2014), we present a new U-Pb age (zr) of the pyroclastic rocks at coordinates: 23°41.7'N; 100°53.6'W, on the La Purísima-Real de Catorce road. The dated sample is a light green pyroclastic rock with scarce ochre to gray aphanitic subangular lithoclasts. More than 50 zircons were separated from the sample, using standard mineral separation techniques and 43 of them were analyzed by the LA-ICP-MS technique, considering analytical errors and procedures as described by Gehrels *et al*. (2008). The geochronology studies were conducted in the LaserChron Laboratory at the University of Arizona at Tucson.

Zircon crystals were analyzed with a VG Isoprobe multicollector ICPMS equipped with nine Faraday collectors, an axial Daly collector, and four ion-counting channels. The Isoprobe is equipped with an ArF Excimer laser ablation system, with an emission wavelength of 193 nm. The collectors allow measurement of ^{204}Pb in the ion-counting channel while ^{206}Pb, ^{207}Pb, ^{208}Pb, ^{232}Th and ^{238}U are simultaneously measured with Faraday detectors. The analyses were conducted in static mode with a laser beam diameter of 35–50 µm, operated with an output energy of ~32 mJ (at 23 kV) and a pulse rate of 9 Hz. Each analysis consisted of one 20-s integration on peaks with no laser firing and 20 1-s integrations on peaks with the laser firing. The analysis was monitored by analyzing an in-house zircon standard, which has a concordant TIMS age of 564 ± 4 Ma (2σ). This standard was analyzed once for every five unknowns in detrital grains. The Pb isotopic ratios were corrected for common

Pb, using the measured 204Pb, assuming an initial Pb composition according to Stacey and Kramers (1975).

The concordia diagram and weighted mean calculations were made using the Isoplot/Excel v. 3.0 program (Ludwig, 2003). Uncertainties on individual analyses in data table are reported at a 1σ level and weighted mean ages were calculated at 95% of confidence. Zircon grains from the sample SC12-1 have Th, U contents of 35–1477 ppm, 118–1318 ppm respectively, and Th/U ratios of 0.15-1.55 (Table 1), indicating a magmatic origin (Hoskin and Schaltegger, 2003). In the $^{207}Pb/^{235}U$ - $^{206}Pb/^{238}U$ concordia diagram, 30 analytical spots concentrate close to the concordia line, 9 analyses have $^{206}Pb/^{238}Pb$ ages between 178 – 186 Ma, but have very high uncertainties; the other 21 analyses yielded a weighted mean $^{206}Pb/^{238}U$ age of 179.4 ± 2.1 Ma (MSWD = 0.38), which is interpreted as the crystallization age of the pyroclastic rock of La Purisima-Real de Catorce. Figure 8 shows a concordia diagram and a weighted mean age plot diagram.

5. La Joya Formation: Middle Jurassic Break-up Unconformity

Imlay *et al*. (1948) first described the red beds exposed in the Huizachal Valley, Sierra Madre

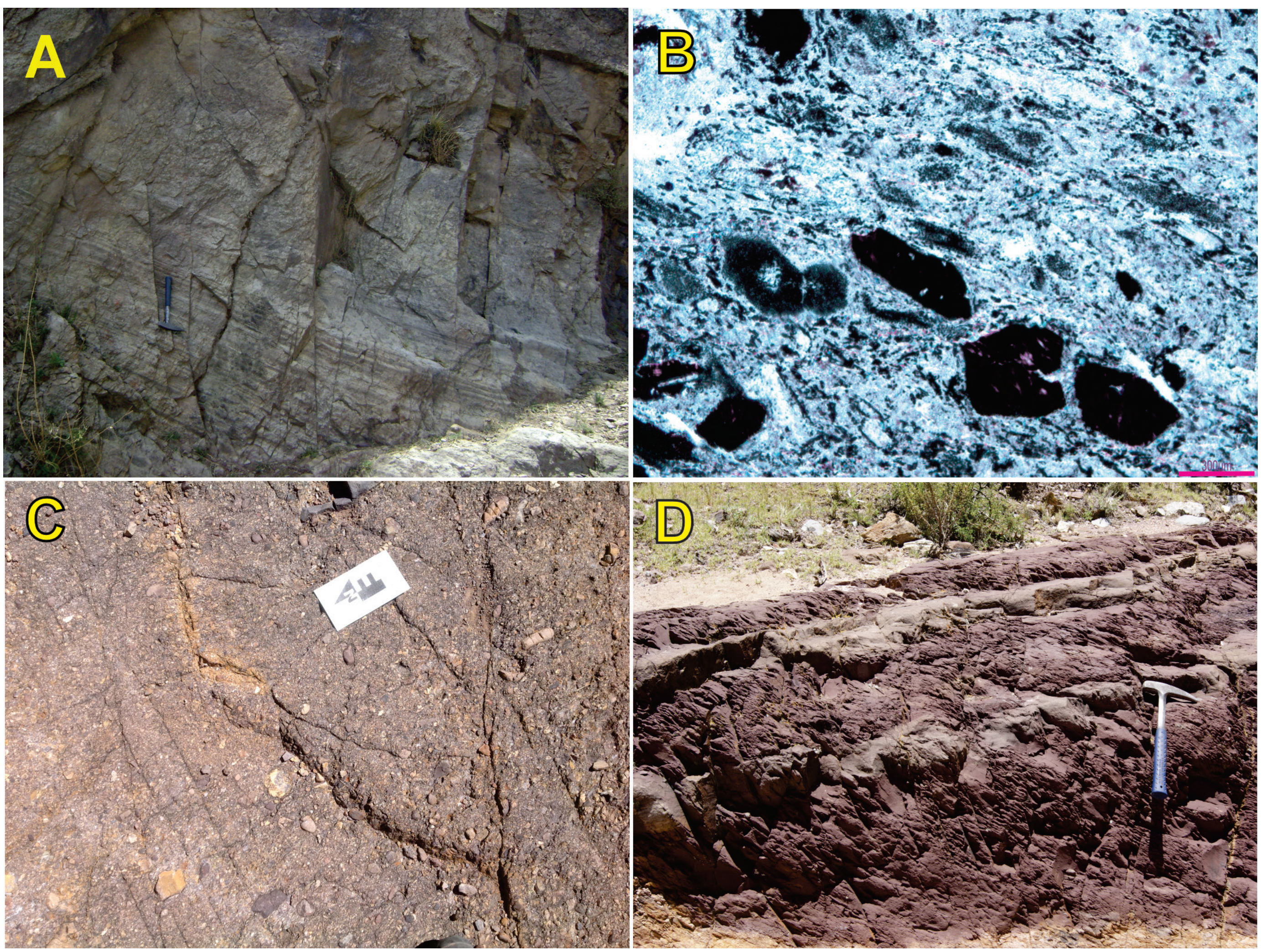

Figure 7. A. Pyroclastic layered rock at Socavón La Purísima, road Los Catorce-Real de Catorce; B. Mafic to intermediary lava flow in the neighborhood of Real de Catorce, shows under the microscope several possible pyroxene and olivine phenocrysts, according to the external form of crystals, because they are replaced by opaque minerals (XPL, 5X magnification); C. Conglomerate of the lower part of La Joya Formation west of Real de Catorce; D. Red siltstone and fine-grained sandstone layers in the upper part of La Joya Formation east of Real de Catorce.

Table 1. LA-ICPMS, U-Th-Pb analytical data for zircons of sample SC12-1 from Stop 3.

				Isotopic Rates						Aparents Ages							
Zircon	Th (ppm)	U (ppm)	Th/U	^{207}Pb/ ^{206}Pb	1σ	^{207}P /^{235}U	1σ	^{206}Pb /^{238}U	1σ	^{207}Pb/ ^{206}Pb	± (Ma)	^{207}Pb/ ^{235}U	± (Ma)	^{206}Pb/ ^{238}U	± (Ma)	Best Age	± (Ma)
SC12-_02	148	274	0.54	0.050	1.548	0.197	2.839	0.028	1.603	214	35.5	182	4.7	180	2.8	180	2.8
SC12-_03	324	264	1.23	0.05	1.404	0.272	2.702	0.040	1.579	195	32.3	244	5.8	250	3.9	250	3.9
SC12-_05	191	216	0.88	0.049	1.588	0.188	2.969	0.028	1.766	147	36.8	175	4.8	178	3.1	178	3.1
SC12-_06	129	161	0.8	0.050	1.787	0.188	3.145	0.028	1.764	169	41.2	175	5	175	3.1	175	3.1
SC12-_07	189	216	0.88	0.053	1.865	0.210	3.480	0.029	2.206	339	41.7	194	6.1	182	4	182	4
SC12-_08	513	460	1.12	0.051	1.420	0.207	2.704	0.029	1.561	259	32.3	191	4.7	186	2.9	186	2.9
SC12-_09	111	136	0.81	0.052	5.078	0.207	7.094	0.029	2.656	294	112	191	12.3	183	4.8	183	4.8
SC12-_10	684	494	1.38	0.051	1.346	0.197	2.591	0.028	1.472	224	30.8	183	4.3	180	2.6	180	2.6
SC12-_11	234	314	0.75	0.052	1.281	0.284	2.538	0.040	1.473	280	29.1	254	5.7	252	3.6	252	3.6
SC12-_12	270	256	1.06	0.051	1.579	0.202	2.884	0.029	1.635	216	36.1	187	4.9	185	3	185	3
SC12-_15	510	467	1.09	0.052	1.347	0.202	2.667	0.029	1.600	262	30.6	187	4.5	181	2.9	181	2.9
SC12-_18	59	131	0.45	0.052	2.038	0.205	3.372	0.029	1.745	288	45.9	189	5.8	182	3.1	182	3.1
SC12-_19	477	443	1.08	0.052	1.251	0.280	2.492	0.039	1.437	274	28.4	251	5.5	249	3.5	249	3.5
SC12-_20	423	562	0.75	0.05	1.303	0.196	2.562	0.029	1.483	194	30	182	4.3	181	2.7	181	2.7
SC12-_22	232	301	0.77	0.051	1.469	0.206	2.798	0.029	1.65	257	33.4	190	4.8	185	3	185	3
SC12-_23	201	1318	0.15	0.073	1.082	1.551	2.497	0.154	1.650	1019	21.8	951	15.3	923	14.2	923	14.2
SC12-_24	209	309	0.68	0.050	1.609	0.196	2.955	0.029	1.712	191	37	182	4.9	181	3.1	181	3.1
SC12-_26	122	166	0.73	0.051	2.437	0.201	3.803	0.029	1.831	234	55.3	186	6.4	182	3.3	182	3.3
SC12-_27	1477	954	1.55	0.051	1.061	0.269	2.319	0.038	1.479	259	24.2	241	5	240	3.5	240	3.5
SC12-_28	508	481	1.06	0.056	1.058	0.534	2.220	0.070	1.322	442	23.4	435	7.8	433	5.5	433	5.5
SC12-_29	97	150	0.65	0.050	2.013	0.198	3.260	0.029	1.62	212	46	184	5.5	181	2.9	181	2.9
SC12-_31	134	306	0.44	0.050	1.464	0.197	2.739	0.029	1.624	200	33.6	182	4.6	181	2.9	181	2.9
SC12-_32	237	253	0.94	0.049	1.712	0.189	2.907	0.028	1.514	130	39.8	176	4.7	179	2.7	179	2.7
SC12-_33	516	575	0.9	0.052	1.078	0.281	2.242	0.039	1.333	286	24.5	252	5	248	3.2	248	3.2
SC12-_34	215	274	0.78	0.049	1.440	0.190	2.584	0.028	1.388	164	33.3	177	4.2	178	2.4	178	2.4
SC12-_35	111	153	0.72	0.052	1.797	0.202	3.047	0.028	1.622	297	40.5	187	5.2	178	2.8	178	2.8
SC12-_36	35	201	0.18	0.078	1.013	2.092	2.179	0.194	1.313	1155	20	1146	14.9	1142	13.7	1142	13.7
SC12-_37	160	452	0.35	0.050	1.277	0.194	2.431	0.028	1.374	197	29.4	180	4	179	2.4	179	2.4
SC12-_38	123	178	0.69	0.05	1.559	0.194	2.789	0.028	1.562	197	35.8	180	4.6	179	2.8	179	2.8
SC12-_39	234	636	0.37	0.052	1.119	0.334	2.260	0.046	1.308	302	25.3	292	5.7	291	3.7	291	3.7
SC12-_40	436	598	0.73	0.050	1.207	0.193	2.420	0.028	1.457	187	27.9	179	4	178	2.6	178	2.6
SC12-_42	87	134	0.65	0.050	1.830	0.197	3.084	0.028	1.632	207	41.9	182	5.1	180	2.9	180	2.9
SC12-_43	112	187	0.6	0.050	1.484	0.190	2.683	0.028	1.497	186	34.2	177	4.3	176	2.6	176	2.6
SC12-_44	255	511	0.5	0.060	1.028	0.540	3.043	0.065	2.485	600	22.1	438	10.8	408	9.8	408	9.8
SC12-_46	538	847	0.63	0.054	1.339	0.266	2.563	0.036	1.511	380	29.8	239	5.4	225	3.3	225	3.3
SC12-_47	77	125	0.61	0.052	1.892	0.204	3.153	0.029	1.647	284	42.7	189	5.4	181	2.9	181	2.9
SC12-_48	151	525	0.29	0.050	1.190	0.190	2.339	0.027	1.343	209	27.4	177	3.8	174	2.3	174	2.3
SC12-_49	153	228	0.67	0.056	1.184	0.564	2.318	0.073	1.314	451	26.1	454	8.4	455	5.8	455	5.8
SC12-_50	420	837	0.5	0.051	1.154	0.201	2.479	0.029	1.616	230	26.4	186	4.2	182	2.9	182	2.9
SC12-_51	624	619	1.01	0.049	1.175	0.199	2.350	0.029	1.383	159	27.3	184	3.9	186	2.5	186	2.5
SC12-_52	151	118	1.28	0.074	1.072	1.733	2.273	0.169	1.393	1048	21.5	1021	14.5	1009	13	1009	13
SC12-_54	136	292	0.47	0.050	1.565	0.191	2.748	0.028	1.477	184	36	177	4.5	177	2.6	177	2.6
SC12-_55	93	130	0.72	0.052	2.128	0.201	3.499	0.028	1.859	263	48.1	186	5.9	180	3.3	180	3.3

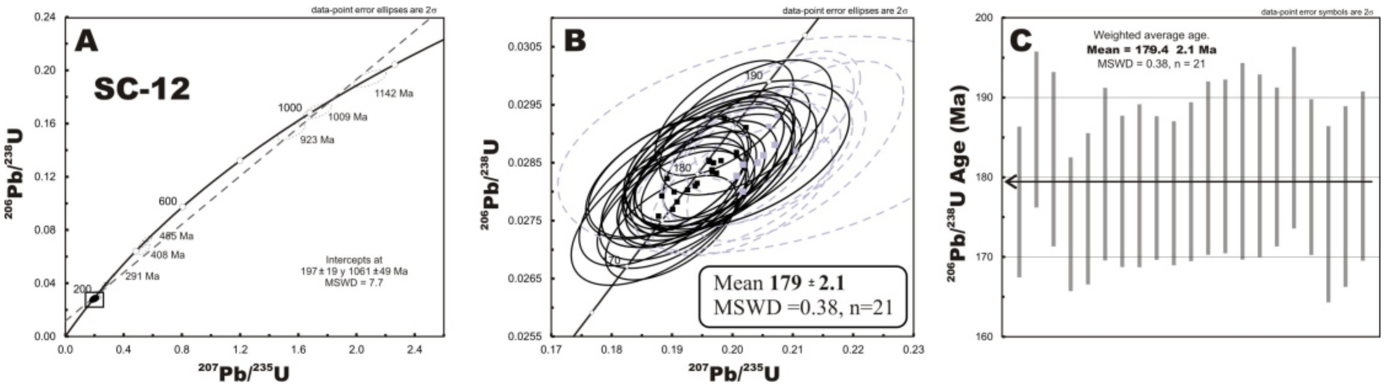

Figure 8. A. Wetherill concordia diagram (U-Pb, zr. LA-MC-ICP-MS technique) for sample SC12-1; B. Detail of youngest population in A, showing the most concordant zircons used for the age calculation as black-line ellipses and discordant zircons as gray-dashed line ellipses; C. The most concordant U-Pb zircon analyses used for the $^{206}Pb/^{238}U$ age calculation (n = 21) are plotted in a weighted mean age diagram with used $^{206}Pb/^{238}U$ ages as gray bars.

Oriental, in southern Tamaulipas, and named them Huizachal Formation. The separation in this region of two red-bed units by Mixon *et al*. (1959) into the older La Boca and younger La Joya formations led to a more detailed subdivision of the succession, assigning both units to the Huizachal Group. La Boca Formation is well exposed in the Huizachal-Peregrina anticlinorium in Tamaulipas, where it consists of more than 1500 m of red sandstone, siltstone, mudstone, and conglomeratic sandstone intercalated with volcanic products comparable to the Nazas arc volcanics (Barboza-Gudiño *et al*., 2012). Mixon *et al*. (1959) defined La Joya Formation as a sequence of conglomerates and red sandstones, which rest unconformably on red beds of La Boca Formation near the town of La Joya Verde, in the Huizachal Valley. La Joya represents a fining upward sequence composed of polymictic conglomerates and breccias that include clasts of volcanic, plutonic, and metamorphic rocks, as well as older sedimentary rocks (Rubio-Cisneros and Lawton; 2011, Barboza-Gudiño *et al*., 2012).

The La Joya Formation overlies a regional erosional unconformity (Barboza-Gudiño, 2012) and its thickness varies in northeastern Mexico from zero to over 500 m (Barboza-Gudiño, 2012; Barboza-Gudiño *et al*., 2014). Michalzik (1991) interprets these deposits to record an environmental change from terrestrial to marine conditions during Middle to early Late Jurassic Time, which agrees with several maximum depositional ages later reported for the La Boca and La Joya formations by Rubio Cisneros and Lawton (2011) and Barboza-Gudiño *et al*. (2012, 2014).

At "Puerta del Sol" west of Real de Catorce (23°41.8'N; 100°53.5'W) polymictic conglomerate (Figure 7C) and conglomeratic red sandstones of the basal member of La Joya Formation (Bathonian to Callovian) form a prominent cliff, and offer a panoramic view of the stratigraphic units exposed in the Canyon, which include, with only minor stratigraphic breaks or erosional unconformities, the most complete Jurassic succession exposed in the Mesa Central province (Figure 9). The conglomerates underlie red sandstones in the middle part of the succession (Figure 7D) that change up section to a thick mostly massive red siltstone unit. The complete La Joya section is more than 500 m in thickness. At Cerro El Mazo in the western flank of Los Catorce antiform, a 250 m thick fining upward sequence of La Joya Formation consists of a basal 80 to 100 m thick conglomerate-breccia member and an upper member of red sandstone-siltstone as much as 150 m thick.

6. Upper Jurassic Marine Transgression

The upper part of La Joya Formation grades into shallow marine deposits of the Zuloaga Formation (Imlay, 1938). The Zuloaga Formation consists of medium to dark gray limestone and local interlayered evaporites and marls. The limestones are frequently thick bedded, mudstones

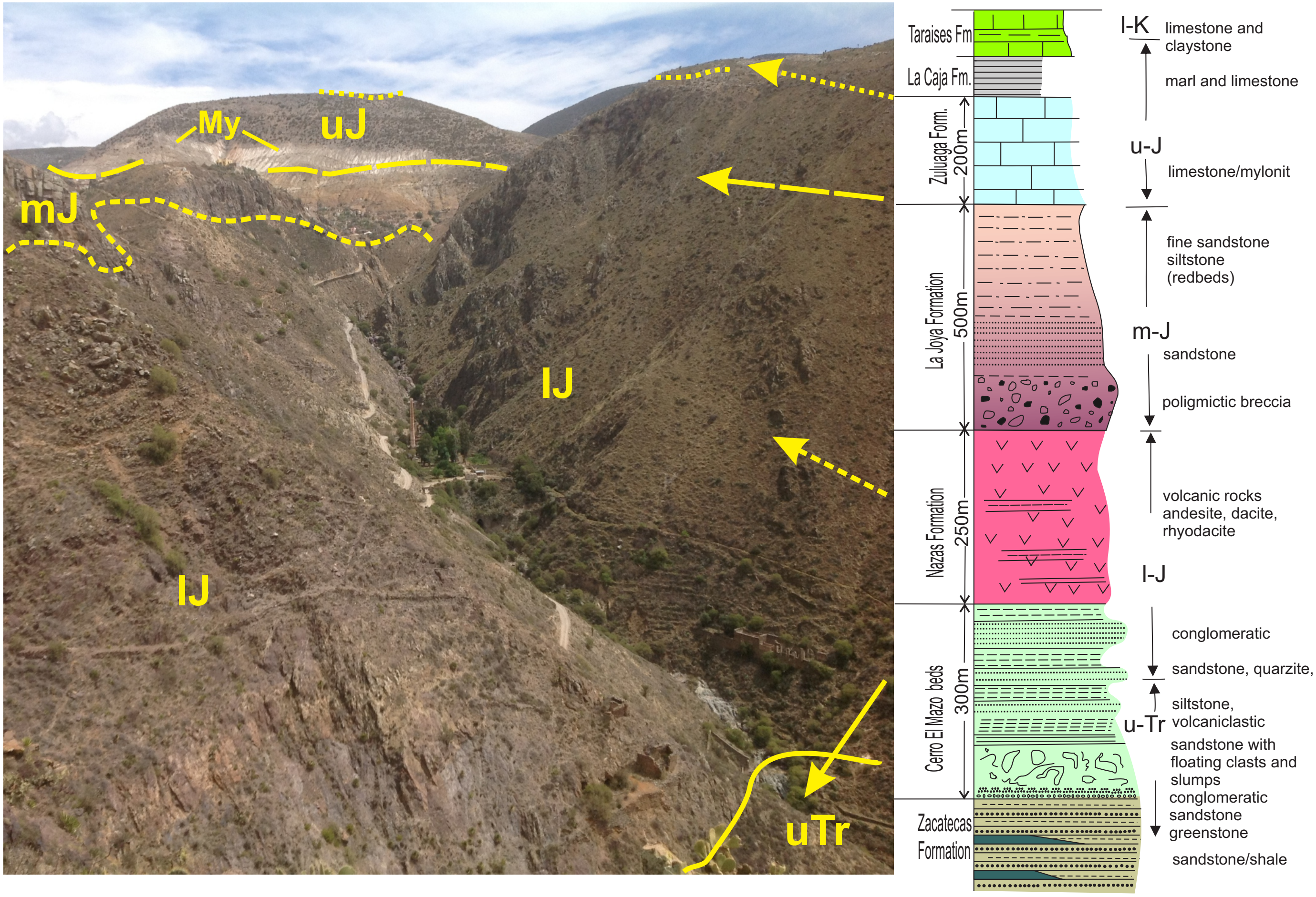

Figure 9. View of the Cañón General outcrops and stratigraphic column of the exposed units, which include the most complete Jurassic succession exposed in the Mesa Central province: Upper Triassic turbidites of the Zacatecas Formation and uppermost Triassic to Lower Jurassic marine marginal strata of the "Cerro El Mazo beds" (uTr); volcanic rocks of the Lower to Middle Jurassic Nazas Formation (lJ); continental to shallow marine conglomerate and red beds of La Joya Formation (mJ); limestones of the Zuloaga Formation and the uppermost Jurassic beds of the La Caja Formation (uJ), which includes also the Jurassic-Cretaceous boundary at the top. The boundary between red beds of La Joya Formation into limestone of the Zuloaga Formation is a detachment surface, developed in the limestones of the base of the Zuloaga Formation, which appear as a strongly foliated and scratched whitish zone (My).

to grainstones with stylolites and rare gray to brown chert nodules or bands, with a few fossils of *Nerinea* sp. and corals. The Zuloaga represents shallow marine sedimentation in an Oxfordian sea during the initial marine transgression in the area and probably represents a pelagic lime mud facies (Bacon, 1978; Oivanki, 1974). At Real de Catorce, the Zuloaga Formation is more than 300 m thick and, as all the overlying Upper Jurassic-Cretaceous rocks, is intensely folded, showing an abrupt upper contact concordant with the pink to gray thin bedded fine-grained marine clastics and marls of La Caja Formation. The La Caja Formation in San Luis Potosí and Zacatecas is an offshore basinal equivalent of the Kimmeridgian–Tithonian shallow-marine clastic sediments of La Casita Formation in Nuevo León and Tamaulipas.

7. Cretaceous–Paleogene Deformation

The Triassic–Early Jurassic sedimentary and volcanic rocks of the Sierra de Catorce exhibit folds and pervasive cleavage related to ancient pre-Late Jurassic compressive deformation. Late Jurassic–Early Cretaceous carbonates in turn are detached from the older units at the base of the Zuloaga Formation. Finally, in their external structure, the Sierra de Catorce is an uplifted block bounded by regional north-south-trending post-Laramide extensional faults. The extensional north-south faults cut northwest-trending sinistral faults and poor developed northeast-trending dextral faults. In turn, north-south and oblique faults are cut by west-northwest trending normal faults.

The Jurassic–Cretaceous carbonate sequence shows intense folding and imbrication (Figure 10). Cretaceous limestones west of Los Catorce rest direct upon La Joya Formation as a result of nappe thrusting (Hoppe, 2000; Barboza-Gudiño *et al*., 2004) showing strong shearing or tectonically depressed layers and omission of parts of the Upper Jurassic–Lower Cretaceous stratigraphic units such as the Oxfordian Zuloaga Formation and the Tithonian La Caja Formation.

In all the studied outcrops in the study area, the lower part of the Zuloaga Limestone consists of a mylonitic rock with strong foliation and extensional lineation, as a well-developed S-C fabric or sometimes appearing as a white colored horizon along the contact with the underlying fine grained red sandstone and siltstone beds of La Joya Formation (Figure 11A). In all the cases, tectonic transport was to the east-northeast (Gutierrez-Navarro, 2017). Cretaceous carbonate layers above the detachment show also folds and intraformational shear zones with a general transport to the East-Northeast.

The point known as "El Mirador" (23°42'N; 100°51.5'W) close to the entrance to the Ogarrio tunnel, coming from the road Cedral-Vanegas, north of the Sierra de Catorce, offers a good overview of the strongly deformed rocks of the detached Jurassic–Cretaceous cover. Cretaceous limestones, as well as Oxfordian medium-bedded limestones of the Zuloaga Formation (Imlay, 1938) and marls of the Kimmeridgian–Berriasian La Caja Formation (Imlay, 1938; Olóriz, *et al*., 1999), are well exposed along the road to Real de Catorce. They are intensely

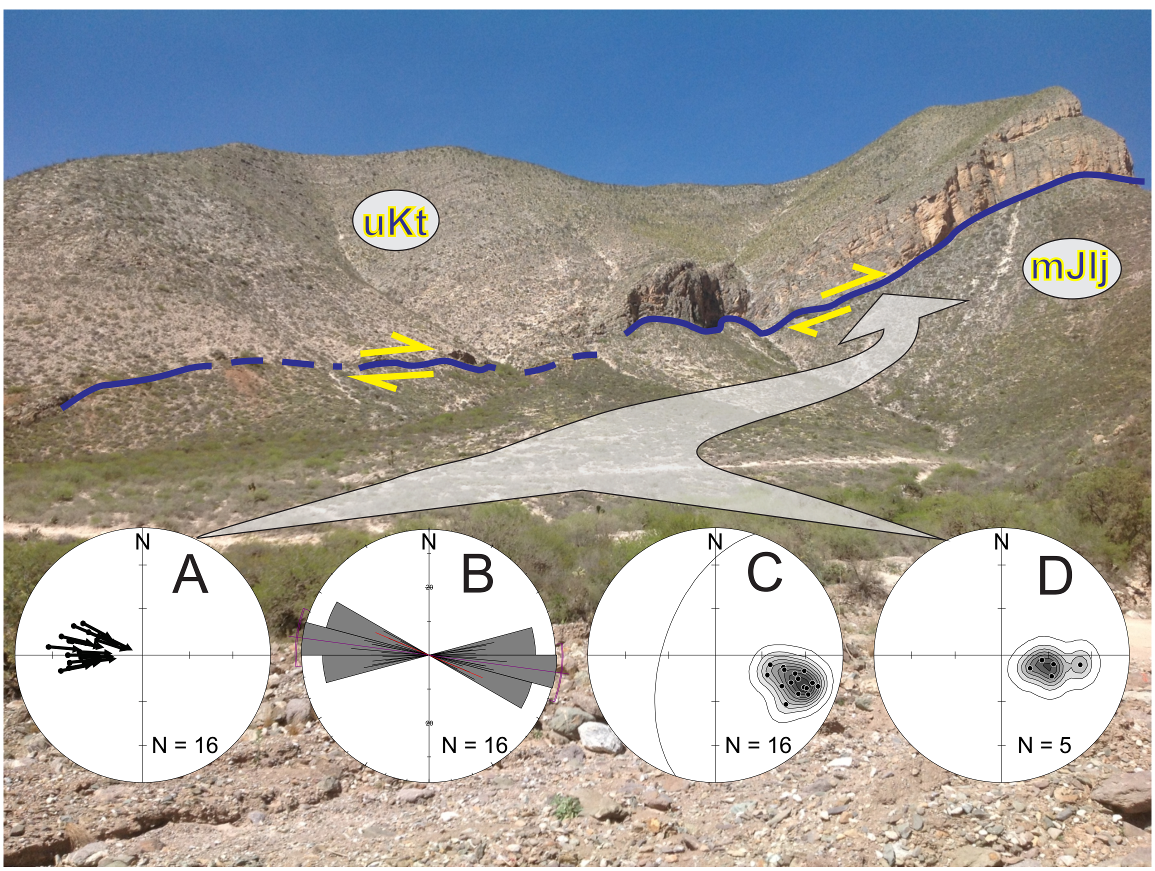

Figure 10. View of the northern wall of Cañón General, western flank of Los Catorce Antiform in front of Cerro El Mazo. Cretaceous limestones are resting directly on red beds of the Middle Jurassic La Joya Formation as a result of a lack of the Upper Jurassic Zuloaga and La Caja formations as well as the lowest Cretaceous strata. This stratigraphic relation is a result of a nappe structure that evolved during the earliest horizontal laramidic movements which were stopped probably against an uplifted block in the central part of the Sierra de Catorce for this time, resulting in thrusting and imbrications and folding within the calcareous Upper Jurassic-Lower Cretaceous cover in the region.

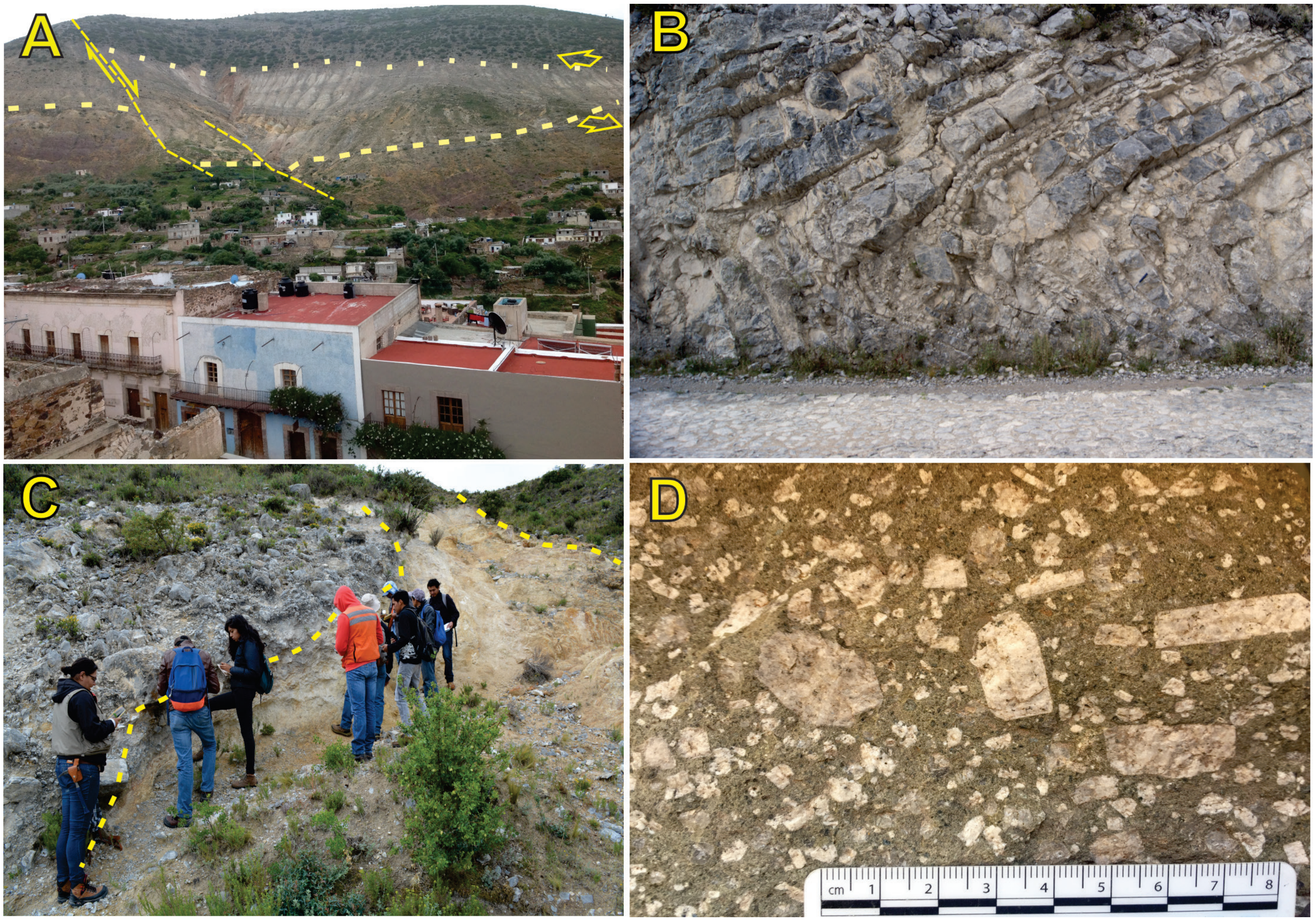

Figure 11. A. Detachment zone at the bottom of the limestones of the Zuloaga Formation against shale of the top of La Joya Formation. This weak zone allowed independent deformation of the mostly calcareous Upper Jurassic–Cretaceous cover, producing north-northwest-trending folds commonly asymmetric to recumbent to the east. B. Recumbent fold in the Zuloaga Formation at El Mirador, Potrero de Catorce; C. Outcrop of a strongly eroded granodioritic dike cutting cretaceous limestones of the Tamaulipas Inferior Formation close to El Mirador point; D. Fresh sample of a rock similar to the granodioritic dike of figure 10C is a porphyry, composed of phenocrysts of alkali feldspar, plagioclase and quartz in a fine-grained holocrystalline matrix.

folded, showing several minor thrust faults formed by Laramide shortening (Figure 12), which also produced uplift of Sierra de Catorce and the detachment of its mostly calcareous Upper Jurassic-Cretaceous cover. The detachment allowed independent deformation of the cover into north-northwest trending folds (Figure 11B). The age of folding in the area is constrained between Campanian–Maastrichtian folded sediments and undeformed middle Eocene quartz monzonite and granodiorite porphyritic intrusions dated at 48.6 ± 0.8 Ma (Huerta-Gonzalez, 2017) and 44.6 ± 0.1 Ma (Díaz-Bravo *et al*., 2021) (Figure 11C). $^{40}Ar/^{39}Ar$ dating of authigenic illite in detachment surfaces, shear zones and slip surfaces on the flanks of folds indicates three deformation episodes during the Cenomanian–Turonian (96 – 90 Ma), Campanian– Maastrichtian (80 – 69 Ma) and Paleocene–Lower Eocene time (62 – 52 Ma) (Gutiérrez-Navarro, 2017; Gutierrez-Navarro *et al*., 2021).

8. Magmatism and Mineralization

The described Mesozoic stratigraphic units were intruded by Eocene granodioritic dikes, which are considered apophyses of a main intrusion in Potrero de Catorce-Real de Catorce area, like a second stock exposed in Real de Maroma, in the southern Sierra de Catorce, consisting of a major stock with several radial associated dikes. Polymetallic Ag, Pb, Zn, Sb and Hg mineralization

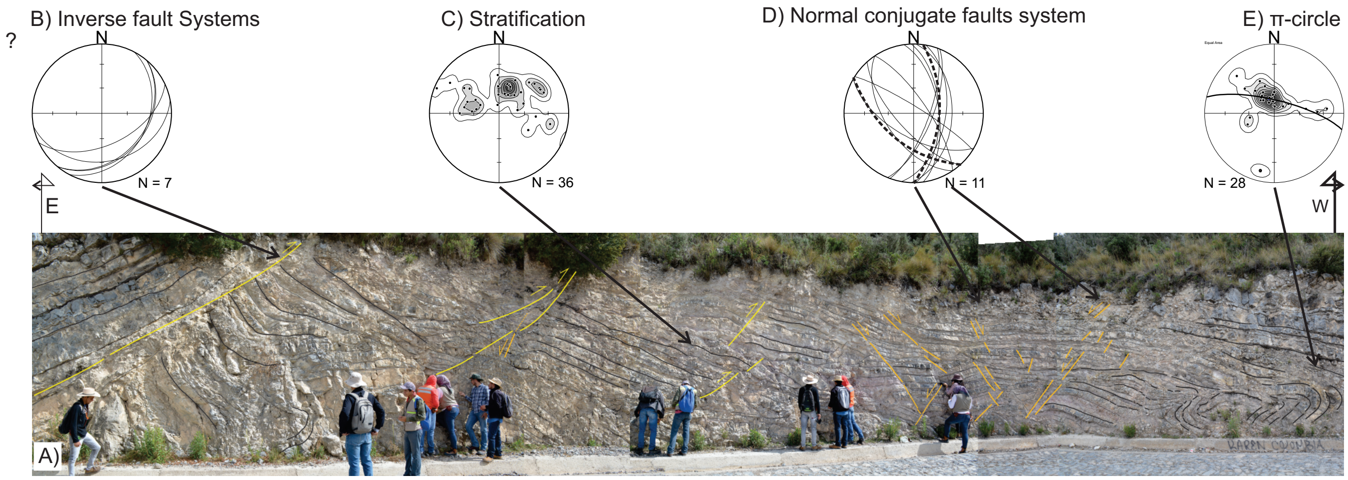

Figure 12. In A) a profile of the section is shown on the road La Luz-Túnel de Ogarrio, the view is from the north to the south and the section is East-West, it can be seen that towards the east part of it. There is a series of systems of inverse faults which have a vergence towards the Northwest, the inverse kinematics is observed in drag folds in the traces of the fault in yellow. B) The stratification is distorted by systems of inverse and normal faults. The geometry of the strata can be observed in C), which represents soft folds that were later deformed by systems of inverse faults with vergence towards the West (Cretaceous?) and extensional systems (Paleogene?). Normal faults form more recent conjugated systems in D); the conjugated main planes can be observed in dotted lines. The shortening deformation stage (Cretaceous?) is represented by reclined folds that present their vergence towards the Northwest as shown by the stereogram in E).

in the area is spatially and likely genetically related to such hydrothermal activity related to the magmatism. The rock shows idiomorphic white phenocrysts of feldspar, plagioclase and minor quartz in a microcrystalline gray-green to yellow matrix, usually very altered throughout the sierra with the exception of some outcrops *ca*. 3 km to the northeast of Potrero de Catorce town to the left (east) of the road to Cedral (Fig. 11D).

According to their geochemical and petrographic characteristics, the intrusives are of calc-alkaline character. They display the geochemical signature of a continental volcanic arc associated with a subduction environment; absence of deformation indicates emplacement during or after the final compressive phase of the orogeny. U-Pb (zr) ages from Mascuñano *et al*., (2013) vary between 40.8 ± 0.3 to 44.6 ± 0.8 Ma. In addition, Huerta-Gonzalez (2017) reported a U-Pb age (Zr by LA-MC-ICPMS) of 48.6 ± 0.8 for the intrusion outcropping north of Potrero de Catorce (23°44'N; 100°50.2'W).

In the epithermal districts Real de Catorce at the north and Real de Maroma at the south of the Sierra de Catorce, mineralization occurred in form of veins, stock works and strata bound bodies. Silver occurs in the oxidation zone as cerargirite-browargirite and minor cerussite; malachite and iron and mangan oxides are common. Deeper in the sulfide zone, lead, zinc and copper sulfides are present. Antimony is more common in the Tierras Negras District, 10 km south of Real de Catorce, in the form of strata-bound calcite, corps, with stibnite or in many cases in the oxidized zone as radial, stibnite pseudomorphs of cervantite and valentinite aggregates.

Discussion and Conclusions

The recognized stratigraphy of Sierra de Catorce includes Upper Triassic turbidites of the Zacatecas Formation; uppermost Triassic to Lower Jurassic slope up to marine marginal strata with interlayered andesitic greenstone dikes and flows of the informally named "Cerro El Mazo beds"; rhyolitic, dacitic, and andesitic volcanic rocks of the Lower to Middle Jurassic Nazas Formation; continental to shallow marine conglomerate and red beds of La Joya Formation; limestones of the Zuloaga

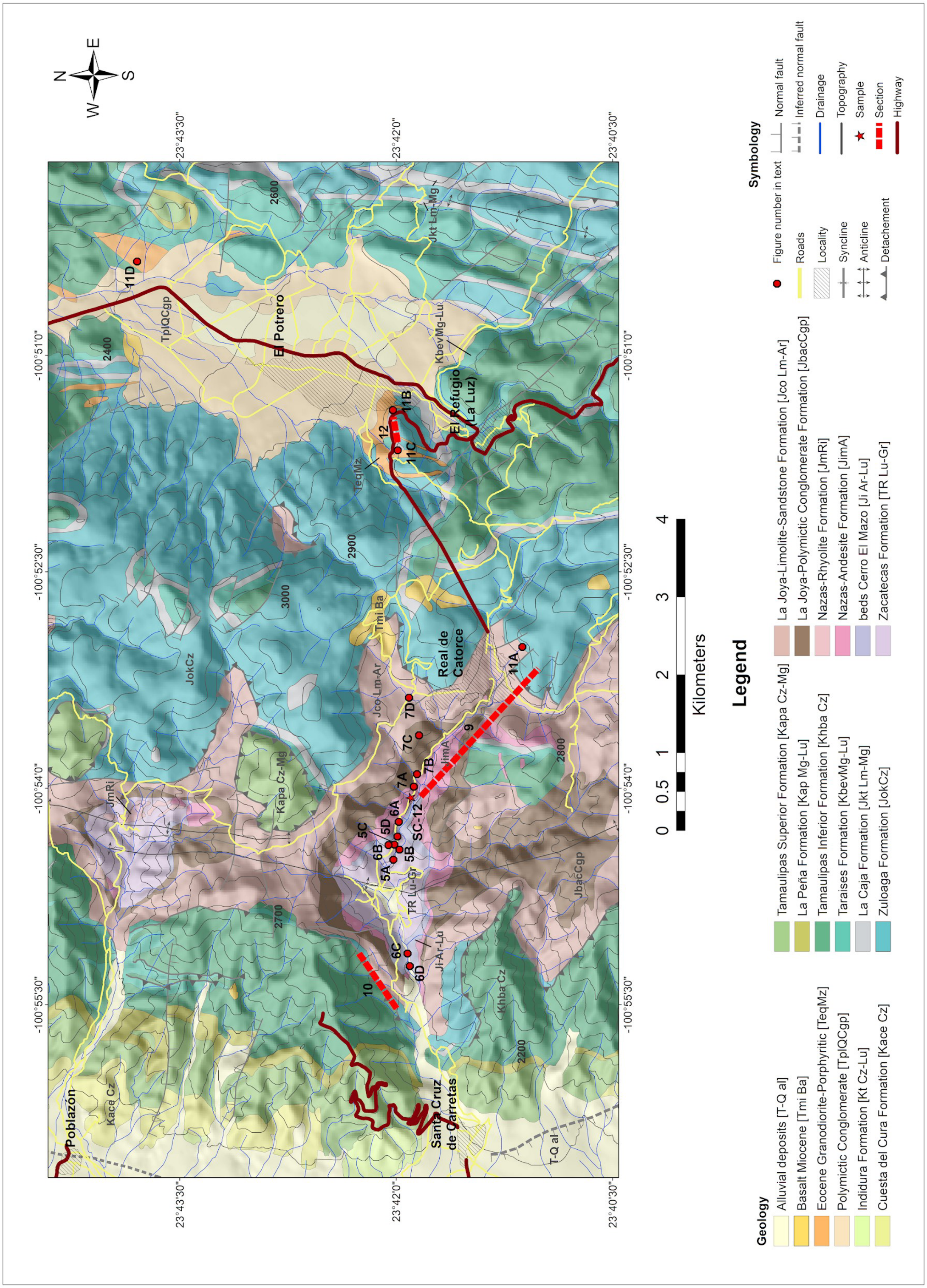

Figure 13. Geological map of the area, showing location of the most illustrative outcrops of lithology, structures and stratigraphic units. Numbers correspond to respective figures in the text.

Formation, and the uppermost Jurassic beds of the La Caja Formation, the top of which represents the Jurassic–Cretaceous boundary. The transition between red beds of La Joya Formation into limestone of the Zuloaga Formation is a detachment surface, or zone, where limestones of the Zuloaga Formation are strongly mylonitized and appear as a whitish zone, microbrecciated, with numerous shear bands.

In order to facilitate use of the present article as a field guide, in Figure 13 we present a detail of the geological map of the area, on which the most illustrative outcrops of the lithological structures and units described are indicated by the numbers corresponding to the respective figures throughout the text.

In the Sierra de Catorce, Upper Triassic strata of the Zacatecas Formation record submarine fan facies sedimentation that change upwards from turbiditic sandstones and shale into channelized conglomeratic sandstones and quartzite, with interlayered siltstone and volcanic-volcaniclastic rocks. The occurrence of slump structures and chaotic deposits with several intrabasinal floating clasts and blocks in the succession indicates mass flow events close to an ancient continental margin.

Upward in the section exposed near Real de Catorce, the presence of shales with carbonate nodules, flaser bedding and glauconite as well as possible paleosols indicates a shallowing of the basin and a transition from deep marine to a marginal-marine facies with red sandstones interlayered with volcanogenic materials that mark the bottom of the Lower Jurassic Nazas Formation.

All pre-Jurassic rocks are strongly deformed suggesting that a subduction zone was active in a low stress stage during latest Triassic time, producing deformation of Zacatecas Formation strata. In contrast, sedimentary and volcanogenic layers of the Nazas are notably less deformed than Zacatecas beds, related probably to a subsequent high-stress stage of subduction that provoked also the volcanic arc or subduction magmatism.

In accordance with our observations and specifically in the studied key outcrops of the Cañón General area, the Triassic to Lower Jurassic stratigraphic units represent remnants of paleogeographic elements that evolved close to the paleo-Pacific margin of western Pangea during early Mesozoic time. To the west, parts of the sedimentary pile consisting of deep marine turbidites were likely deposited on the continental slope and the adjacent oceanic floor. To the east, the continent Pangea began to disperse, and coeval fluvial and alluvial red beds of the Triassic El Alamar Formation (Barboza-Gudiño *et al.*, 2010) and the Lower Jurassic La Boca Formation (Mixon *et al.*, 1959), known also as the Huizachal Formation (Imlay *et al.*, 1948, Carrillo-Bravo, 1961), were deposited on the edge of the continent. Westwards, such continental Lower Jurassic sediments are interstratified with the Early Jurassic volcanogenic rocks of the Nazas Formation.

The La Joya Formation represents the sedimentation following development of a regional erosional unconformity recognized in several localities of northeastern Mexico. This regional unconformity was related to the opening of the Gulf of Mexico basin and thus represents a break-up unconformity (Michalzik, 1988). The La Joya Formation overlies in many localities the volcanic rocks of the Nazas arc, and a large proportion of its clastic components are eminently characterized as a product of subduction volcanism, which places the La Joya Formation and the Gulf of Mexico itself in a controversial back-arc position (Stern and Dickinson, 2010).

In addition to Early Jurassic volcanic rocks in San Luis Potosí and northeastern Mexico, correlative calk-alkaline granitoids are exposed in Sonora, Baja California, Marias Islands and in southern México State, suggesting also a Lower–Middle Jurassic subduction in this region more than 600 km far away at the actual pacific coast. Martini and Ortega-Gutiérrez (2018) proposed regional extension imposed by North America-South America divergence that allowed the emplacement of magmas that were clearly influenced by the subduction of the Farallon Plate from the Pacific. Those authors interpreted the Nazas arc as a hybrid domain that reflects the superposition of the Atlantic and Pacific tectonic processes.

The Sierra de Catorce stratigraphy, and the nature and regional distribution of the several described Triassic and Jurassic lithostratigraphic units, suggest the occurrence of a continental margin in central Mexico that evolved from a passive to an active margin during Late Triassic-Early Jurassic time.

Late Jurassic Early Cretaceous carbonates in the Sierra de Catorce are detached from the older units at the base of the Zuloaga Formation. Cretaceous limestones west of Los Catorce structurally overlie the Middle Jurassic La Joya Formation because of nappe thrusting and tectonically omitted Upper Jurassic–Lower Cretaceous layers in the succession. The age of folding in the area is constrained between Campanian–Maastrichtian folded sediments and undeformed middle Eocene quartz monzonite, and granodiorite porphyritic intrusions (Mascuñano *et al*., 2013). Mineralization in the area is spatially and probably genetically related to hydrothermal activity associated with the same magmatism (Huerta-Gonzalez, 2017).

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