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From Rheic ocean opening to Pangea breakup: a chronostratigraphic and isotopic database of key localities in Mexico☆

De la apertura del océano Rheico a la ruptura de Pangea: una base de datos cronoestratigráfica e isotópica de localidades clave en México.

Luigi A. Solari[a], Michelangelo Martini[b], Pilar Navas-Parejo[c], Mildred Zepeda-Martínez[a], Guillermo Espejo-Bautista[a], Roberto Maldonado[b], Sandra Guerrero-Moreno[a], Mónica Ramírez-Calderón[a], Luis Elizondo-Pacheco[a], Francisco Javier Osorno-Covarrubias[d]

[a] *Centro de Geociencias, UNAM, Campus Juriquilla, 76230, Querétaro, Qro., México*
[b] *Instituto de Geología, UNAM, Ciudad Universitaria, 04510, Ciudad de México, México*
[c] *Estación Regional del Noroeste, Instituto de Geología, UNAM, 83000, Hermosillo, Sonora, México*
[d] *Instituto de Geografía, UNAM, Ciudad Universitaria, 04510, Ciudad de México, México*

Abstract

This database includes a wealth of geochronologic, isotopic, and provenance data, published or in publication, which constitutes an effort to unravel the evolution of Mexican, pre-Cretaceous geological units that are key in reconstructing the history of the Rheic Ocean, from its opening to its closure, and the initial breakup of Pangea. The database is built on reference geological maps, that the authors compile from published works and that locally, contain novel cartographic data. Since the localities studied in this work contain successions that are different in age, P-T conditions, lithology, and geologic significance, and given that each stand-alone work (research, undergraduate and graduate theses, etc.) focused on resolving the central theme of the Rheic ocean evolution and Pangea amalgamation and breakup, we generate an open database that will be continuously updated, as soon as new data are available. Initially intended as a database to present the results of several present and previous grants obtained by the authors, and make them available to collaborators, this contribution evolved to be an open source for all the researchers that are interested in the Paleozoic–early Mesozoic Mexican tectonic evolution and the pre-Mesozoic basement characterization.

Keywords: Rheic ocean; Pangea; Paleozoic–early Mesozoic time; geochronology; Mexico.

Resumen

Esta base de datos incluye principalmente datos geocronológicos, isotópicos y de procedencia, en parte publicados y en parte en publicación, entendida como un esfuerzo para caracterizar, describir y entender algunas de las unidades geológicas de México que tuvieron un papel activo en la evolución tectónica que va de la abertura del océano Rheico, su cierre, la consecuente amalgamación del supercontinente Pangea y su ruptura durante el Mesozoico temprano. La base de datos está construida sobre mapas geológicos de referencia, compilados por los autores desde trabajo previos y, cuando disponibles, incluyendo también datos e interpretaciones cartográficas propias. Dado que esta base de datos incluye estudios realizados en localidades diferentes, con características geológicas propias que varían desde unidades de basamento como de coberturas, con sus características de edad, condiciones P-T y litología, su contenido está actualizado constantemente, en cuanto nuevos datos estén disponibles. Aunque inicialmente se ha construido esta base de datos con el intento de presentar los resultados analíticos de diferentes proyectos presentes y pasados a cargo de los autores, y hacerlos disponibles para la comunidad, esta contribución ha evolucionado como un repositorio de datos, abierto y disponible para todos aquellos interesados en la evolución tectónica de México, durante el Paleozoico y el comienzo del Mesozoico, y la caracterización de su basamento pre-Mesozoico.

Palabras clave: Océano Rheico; Pangea; Paleozoico y Mesozoico temprano; geocronología; México

1. Introduction

Recognizing that the history of the Earth has been punctuated by the cyclic assembly and breakup of supercontinents (e.g., Superia, Columbia, Rodinia, and Pangea; Murphy and Nance, 2013; Mitchell et al., 2021) is definitively one of the most outstanding developments in Earth Sciences since the discovery of plate tectonics. The repeated consolidation and dispersion of supercontinents fundamentally influenced the evolution of geography and topography, leading to continuous changes in the hydrographic pattern, as well as in the oceanic and atmospheric circulation, which produced the diversification of climatic conditions, natural environments, and life over the time (Hay, 1996; Donnadieu et al., 2006). Based on this premise, reconstructing the supercontinent cycle remains a key issue for our understanding of the origin of modern Earth. Pangea is the most recent supercontinent formed on Earth and, for that reason, is less difficult to reconstruct. Its assemblage took place during the late Paleozoic time (e.g., Nance et al., 2012), whereas its breakup is bracketed by most authors to early Mesozoic time (Schettino and Turco, 2009; Labails et al., 2010), although a few authors proposed that, locally, it may have initiated to break up by latest Paleozoic time (Valentino and Gates, 2001; Martini et al., 2022). Despite the late Paleozoic–early Mesozoic paleogeographic position of the major continents that formed Pangea has been solidly reconstructed (e.g., Schettino and Turco, 2009), the location of smaller blocks, as well as their connection with surrounding continental masses, remains poorly constrained. This lack of information has led to an incomplete understanding of the kinematics and dynamics of the consolidation and breakup of Pangea. Mexico is one of those sectors where the late Paleozoic–early Mesozoic paleogeography is not yet completely defined. Uncertainty in the Mexican paleogeography at the time of Pangea formation is the result of two main reasons: 1) the upper Paleozoic–lower Mesozoic geological record of Mexico is poorly explored, recognized, and understood; 2) most works that focused on the upper Paleozoic–lower Mesozoic stratigraphic and structural record analyzed and discussed the results only in the local tectonic context (Michalzik, 1991; Ochoa-Camarillo et al., 1998; Campos-Madrigal et al., 2013; Martini et al., 2016; Ramírez-Calderón et al., 2021). Only a few works have proposed more regional reconstructions (Anderson and Schmidt, 1983; Boschman et al., 2014; Martini and Ortega-Gutiérrez, 2018; Frederick et al., 2020; Pindell et al., 2021), which, however, differ substantially from each other in several aspects. Discrepancies between the various reconstructions mainly derive from the lack of published information in critical areas of the circum-Gulf of Mexico region, which has led to the development of substantially different points of view on how western equatorial Pangea was assembled and, successively, broke up. These different scenarios are the subject of a constructive debate that escalated during the last few decades.

Generating a database that compiles, homogenizes, and synthesizes different types of data obtained during the last decade from various areas of Mexico would benefit the international geological community aimed at the reconstruction of Pangea. In this regard, we take the initiative to create a comprehensive database of all the results we have obtained in the last decade, during the development of various projects focused on reconstructing the consolidation and breakup of Pangea. Data compiled in the database include stratigraphic, U-Pb geochronologic, Hf isotopic, fission track, and provenance results, which have been previously published by the authors of this work, and that have been obtained from many key areas in southern Mexico (Figure 1). The database will be constantly updated over time, to represent a reference for the geological community interested in consulting the most recent results obtained by our working group.

2. Geological Background

The areas that have been the object of our research during the last decade, and of which we synthesize the results to generate the first progress of the database, are in the states of Oaxaca, Puebla, and Guerrero, in southern Mexico (Figure 1). The stratigraphic record of these areas mainly consists of various basement complexes of Proterozoic and Paleozoic age, which were assembled during the final consolidation of Pangea, and were successively overlapped by early Mesozoic, continental to marine successions formed during Pangea breakup.

The ~0.95–1.3 Ga Oaxacan Complex (OC; Figures 1 and 2) comprises metaplutonic and metasedimentary rocks, which experienced granulite-facies metamorphism during the ~970–990 Ma Zapotecan orogeny (Solari et al., 2003 and 2014; Keppie et al., 2003). Most authors interpret the ~1.15–1.2 Ga metaigneous rocks of the OC either as a juvenile, intra-oceanic arc or a rift assemblage (Ortega-Gutiérrez et al., 1995; Keppie et al., 2001 y 2003; Keppie and Dostal, 2007; Solari et al., 2014; Weber and Schulze, 2014; Ortega-Gutiérrez et al., 2018). A younger, anorthosite-mangerite-charnockite-granite suite intrudes the ~1.2 Ga metaigneous assemblage right before the granulite-facies metamorphism. The OC Paleozoic sedimentary cover is scattered and is exposed only at two localities: Santa María Tiñu and Santiago Ixtaltepec (see the geological maps on the Interactive Map). Although they

**E-mail address:* solari@unam.mx

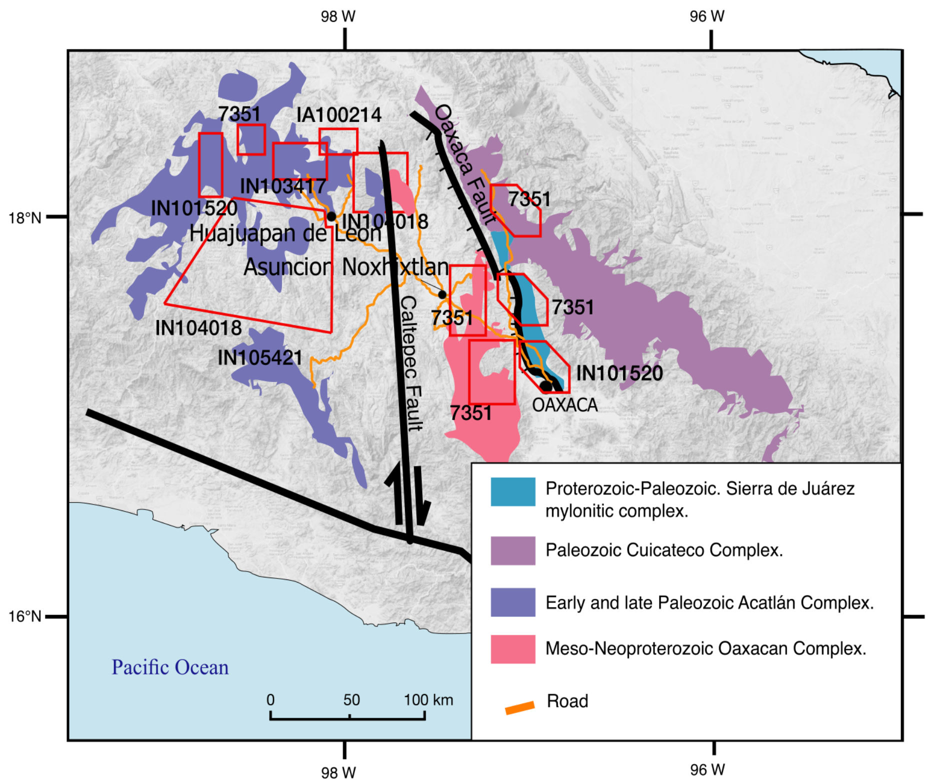

Figure 1. Sketch map of southern Mexico, where the main crustal blocks, which data are reported in this database, are shown. Red rectangles indicate the studied areas depicted in the geologic maps contained in the database. The accompanying codes refer to the grants that funded each study (7351: Conacyt Ciencia de Frontera; IA100214, IN104018, IN105421, IN103417, IN101520: PAPIIT-DGAPA) / Figura 1. Mapa croquis del sur de México, donde se muestran los principales bloques de la corteza terrestre, cuyos datos se reportan en esta base de datos. Los rectángulos rojos indican las áreas estudiadas, representadas en los mapas geológicos, contenidos en la base de datos. Los códigos adjuntos se refieren a los proyectos que financiaron cada estudio (7351: Conacyt Ciencia de Frontera; IA100214, IN104018, IN105421, IN103417, IN101520: PAPIIT-DGAPA).

are known since the ’60s and represent critical stratigraphic units for the reconstruction of the Paleozoic paleogeographic position of their underlying basement rocks, these sedimentary successions have neither been studied with enough detail, employing modern isotopic techniques nor have never been the object of exhaustive sedimentologic and petrologic studies so far.

The Acatlán Complex (AC; Figures 1 and 2) is the classic Paleozoic orogen of Mexico, studied since the seminal work of Ortega-Gutiérrez (1978). It records a complex and polymetamorphic history, ranging from Cambrian–Ordovician to Permian time, with some lithological units (Magdalena and Chazumba lithodemes) that seem to be related to a more recent Jurassic tectonothermal event (e.g., Yañez et al., 1991; Ortega-Gutiérrez et al., 1999; Talavera-Mendoza et al., 2005; Keppie et al., 2008; Vega-Granillo et al., 2007; Ortega-Obregón et al., 2009; Helbig et al., 2012; Estrada-Carmona et al., 2016). Previous works recognized that the history of the AC was punctuated by magmatic episodes during Ordovician, Permian and, after its amalgamation with the OC, during Jurassic time (eastern Sector, Ayu Complex of Helbig et al., 2012), as well as high-pressure metamorphism during Carboniferous time, and different episodes of sedimentation associated with the opening of an oceanic basin (either the Rheic or Iapetus oceans, or both) during Cambrian–Silurian time, as well as with the Devonian–Permian collisions with the OC during the final assembly of Pangea. The pertinence of the AC to either the Iapetus or Rheic oceans is still a matter of debate (e.g., Ortega-Gutiérrez et al., 1999; Vega Granillo et al., 2009; Nance et al., 2008; Keppie et al., 2008; Weber et al., 2018; Juárez-Zúñiga et al., 2019). Two units are currently highlighted in this database, namely the Patlanoaya Group and the Esperanza granitoids (see the geological maps on the Interactive Map). The Carboniferous–Middle Permian Patlanoaya Group is composed of fluvial and marine deposits (Flores de Dios et al., 1998; Vachard et al., 2000; Ramos-Arias et al., 2008) and constitutes one of the few parts of the AC that did not experience metamorphism and penetrative deformation. Whole-rock sandstone petrography and U-Pb detrital-zircon geochronology document that the basal stratigraphic record of the Patlanoaya Group was deposited in an extensional basin developed during the Carboniferous exhumation of Cambrian-Silurian metasedimentary and metaigneous rocks from low-to medium-grade metamorphic facies, as well as Ordovician plutonic rocks, presumably related to the exhumation of the AC high-pressure/low-temperature metasedimentary and metaigneous rocks (Zepeda-Martínez et al., 2022).

The AC high-pressure metamorphism records a collision-subduction event related to the closure of the Rheic Ocean, manifested by the occurrence of eclogites and other associated high-pressure rocks. The Esperanza granitoids constitute a N–S-oriented stripe, possibly associated to the high-pressure Piaxtla suite, with variable degrees of deformation. Our studies demonstrate how this (meta)granitoid belt crystallized between 469±3.5 and 465±3.3 Ma, with a later intrusive event of pegmatitic facies with a crystallization age of 461.6±3.3 Ma (all zircon ages, Flórez-Amaya, 2020). Apatite U-Pb ages in the 366±19 to 333±9 Ma range are instead indicative of the high-pressure metamorphic re-equilibration that the Esperanza granitoids suffered in the Carboniferous. The integration of petrological and geochronological information suggests that the metamorphism of the metasedimentary portion of the Piaxtla Suite records a Pacific-type subduction process during the Mississippian, possibly related to the interaction between Gondwana and the paleo-Pacific, before the collision of western Gondwana with Laurentia (Ramos-Arias and Keppie, 2010; Ramos-Arias et al., 2008 and 2012).

The OC and AC constitute peri-Gondwanan continental blocks that were located at the western equatorial margin of Pangea during the late Paleozoic time. In southern Mexico, the manifestation of Pangea consolidation is represented by a kilometer-scale, ductile, dextral fault named the Caltepec fault, which developed by the transpressive collision between the OC and AC at ~270 Ma (Figure 1; Elías-Herrera and Ortega-Gutiérrez, 2002; Elías Herrera et al., 2007).

The oldest succession that unconformably overlies both the OC and AC, thus postdating the assembly of Pangea in southern Mexico, is the Matzitzi Formation (Figure 2). This unit is composed of fluvial deposits (Centeno-García et al., 2009) with an abundant fossils flora. Fluvial deposits of the Matzitzi Formation are interlayered with rare rhyolitic volcanic deposits and cut by subvolcanic bodies with peperites along their borders (Martini et al., 2022). The age of these igneous rocks indicates that the Matzitzi Formation was deposited at least between the latest Permian and Middle Triassic time (Martini et al., 2022). The tectonic setting under which the Matzitzi Formation was deposited is controversial. Some authors interpreted the Matzitzi Formation as a unit associated with the evolution of a continental arc developed along the western equatorial margin of Pangea (Centeno-Garcia et al., 2009). Other authors suggested that the Matzitzi Formation was deposited in an extensional basin, representing the early manifestation of the Pangea breakup (Martini et al., 2022).

The most iconic stratigraphic record of Pangea breakup in southern Mexico is represented by Jurassic and Lower Cretaceous continental to marine successions, which were deposited in three main extensional to transtensional basins that, from south to north, are: the Tlaxiaco (Zepeda-Martínez et al., 2021), Ayuquila (Campos-Madrigal et al., 2013), and Otlaltepec basins (Martini et al., 2016; Figure 1). The internal architecture of these basins is complex and is dominantly controlled by the exhumation of the surrounding fault-bounded basement highs, which are composed of Proterozoic and Paleozoic rocks of the OC and AC (Martini and Ortega-Gutiérrez, 2018). Identifying the main faults that accommodated Pangea breakup and controlled the evolution of the Jurassic–Early Cretaceous basins is not an easy task, mostly because of the complex deformational overprinting by successive deformation events during Late Cretaceous and Cenozoic time. To date, two major structures have been recognized and documented in the field: the Salado River-Axutla fault and the Sierra de Juarez Mylonitic Complex (Figure 1). The brittle-ductile Salado River-Axutla fault represents the northern boundary of the Tlaxiaco basin (Martiny et al., 2012; Zepeda-Martínez et al., 2021; Figure 1). Available biostratigraphic and 40Ar-39Ar isotopic data indicate that this fault is an Early–Middle Jurassic fault, which was later reactivated during Cenozoic time (Martiny et al., 2012; Zepeda-Martínez et al., 2021).

The Sierra de Juárez Mylonitic Complex and the Mazatecan Complex constitute an assemblage of metaigneous and metasedimentary rocks, extending from east of Oaxaca City, farther to north, east of Tehuacán (Puebla) that are interpreted as the exposed basement of the Cuicateco terrane. While the Sierra de Juárez Mylonitic Complex was interpreted as a Mesozoic ductile structure, who reactivated a Paleozoic (?) shear zone (e.g., Alaníz-Álvarez et al., 1994 y 1996), new findings (Espejo-Bautista et al., 2021; in press; and accepted) allow to assess several main geologic events synthesized as follows: (1) development of a Lower to Middle Paleozoic sedimentary belt along the southern margin of the Rheic Ocean derived from Gondwanan sources with maximum depositional ages of ca. 468 and 392 Ma, affected by medium-grade metamorphism during the Late Permian-Middle Triassic after the Pangea assembly; (2) volcanic activity dated at 292±1.8 Ma coeval with sedimentation (with a maximum depositional age of ca. 293 Ma) related to a large Upper Mississippian-lower Permian magmatic belt along NW Gondwana during the Rheic Ocean closure; (3) contractive flat-slab subduction-related metamorphism at 246±1.9 Ma postdating the Pangea assembly; and (4) Late Early Jurassic anatexis coeval with shear deformation at 176±1 Ma and intermediate magmatism dated at 175±1 Ma. These events were likely produced by arc-related magmatism influenced by transtensional tectonics along eastern peninsular Mexico during the Pangea breakup and the opening of the Gulf of Mexico. Farther to north the Mazatecan Complex comprises similar lithologies (schists tentatively interpreted as Paleozoic by Ángeles-Moreno, 2006) that were affected by an Early Cretaceous migmatitic event.

The thermochronometric data obtained from samples located in different localities of those studied in this work

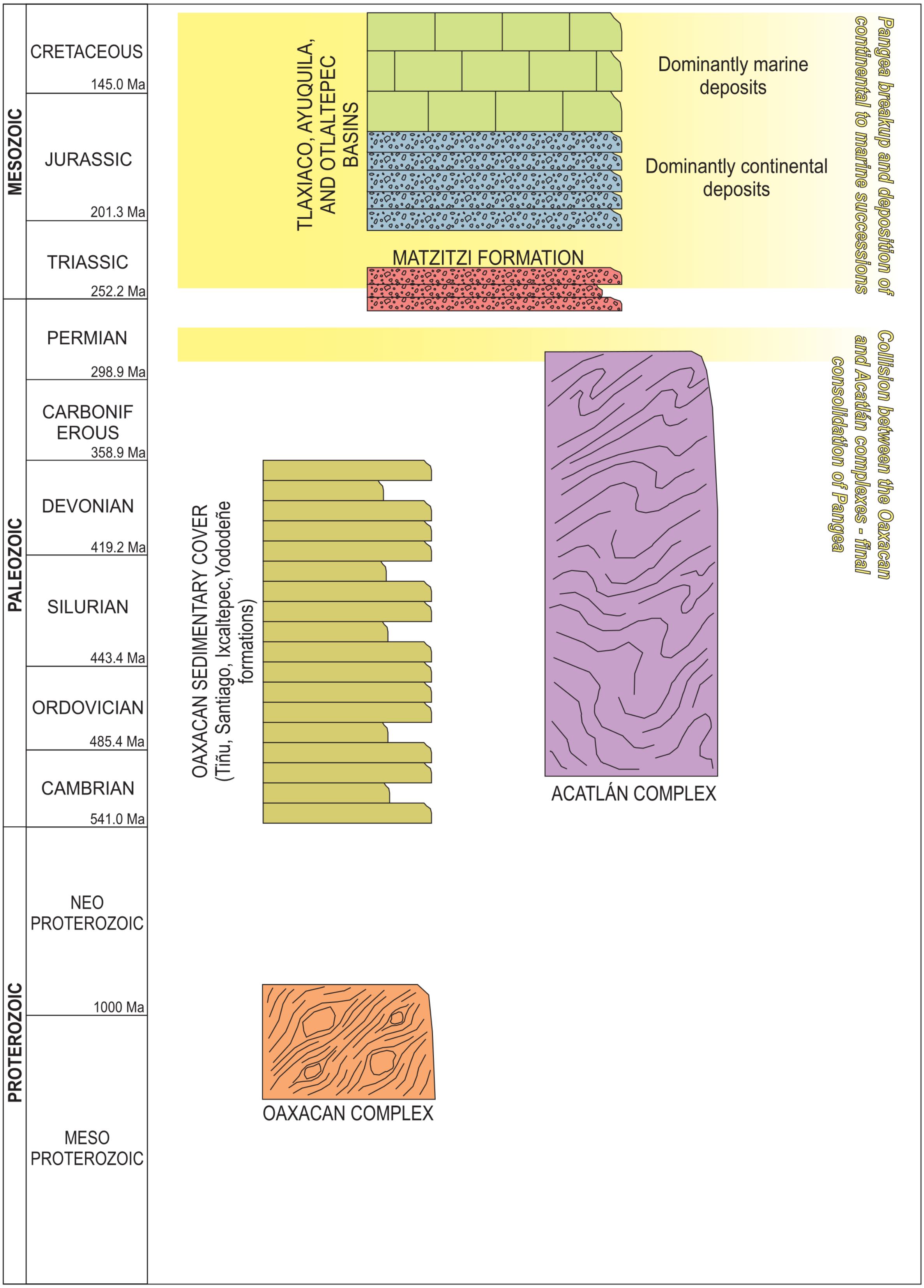

Figure 2. Chronostratigraphic column illustrating the main stratigraphic units exposed in the states of Puebla, Oaxaca, and Guerrero, southern Mexico. The time scale is according to Gradstein et al. (2012) / Figura 2. Columna cronoestratigráfica que ilustra las principales unidades estratigráficas expuestas en los estados de Puebla, Oaxaca y Guerrero, sur de México. La escala de tiempo es según Gradstein et al. (2012).

suggest a differential exhumation: 1. two episodes of cooling and exhumation in the Oaxacan Complex, the first during the Late Triassic-Middle Jurassic, probably associated to the initial stages of Pangea breakup; the second occurred during the Early Cretaceous, and is associated to the late stages of the Gulf of Mexico opening; 2. a Late Cretaceous–middle Eocene cooling period is recorded within the Sierra Madre del Sur and this is interpreted as resulting from exhumation, a tectonic activity which is contemporaneous with the shaping of the Mexican orogeny (Fitz et al., 2018; Abdullin et al., 2021; Ramírez Calderón et al., 2021; Florez-Amaya et al.,2022).

3. Methods

3.1. Generation of the field and analytical data

Data compiled in this database are already presented in scientific publications or will be available in papers submitted or in publications; therefore, in this document, we refer to the original publications for details on the analytical methods. In the following section, we present only a brief description of the main methods used to generate the data used in the database. Unless otherwise noted in the database, all the U-Pb geochronological and Hf-isotopic data have been processed and analyzed in laboratories and facilities of the Universidad Nacional Autónoma de México (UNAM), mostly at Centro de Geociencias (CGEO), following the mineral separation procedures reported in Solari et al. (2007). U-Pb geochronology was carried by laser ablation inductively-coupled plasma mass spectrometry (LA-ICPMS), while zircon Hf isotopic analyses were measured by laser ablation multicollector inductively-coupled plasma mass spectrometry (LA-MC-ICPMS) at Laboratorio de Estudios Isotópicos (LEI), CGEO-UNAM, according to the methodology reported in Solari et al. (2010 and 2018) and Ortega-Obregón et al. (2014). All the U-Pb graphics in the database were produced using the IsoplotR software (Vermeesch et al., 2018).

Regarding the provenance analysis, sandstone point-counting was performed by using the Gazzi-Dickinson method (Gazzi 1966; Dickinson 1970), to reduce the influence of grain size on the composition. Volcanic lithic grain categories are according to Dickinson (1970). Metamorphic lithic grains categories are according to the Garzanti and Vezzoli (2003) scheme. Heavy minerals concentrates were obtained according to the guidelines of Andò (2020), and were also point-counted by using the Gazzi-Dickinson method, as recommended by Garzanti and Andò (2019).

3.2. Database construction

The database is constructed to facilitate the visualization of a big amount of chronologic data on a georeferenced geologic map. An Open Street Map topographic database is used to georeference the studied localities. In contrast, the geology is mostly a combination of field work performed by the authors, integrating some previously published maps (mostly by Servicio Geológico Mexicano and, in some cases, local mapping referred to in the original papers). During fieldwork, particular care was taken in selecting samples for further geochronological, petrological, and paleontological studies, which would help to correctly fit the studied localities in the Rheic Ocean to Pangea evolution, with a special focus on characterizing the involved basement, mostly of Precambrian to Paleozoic age. The database contains the name of the stratigraphic unit studied, a simplified sample description, as well as sample coordinates and the name of the locality (municipality) in which the sample was collected. Where available, we included a field picture from where the sample was collected and, if considered useful for the interpretations, photomicrographs taken under the microscope. The referred ages are mostly calculated by U-Pb on zircon crystals or other accessory minerals such as apatite, and rutile. Several ages are reported, depending upon the interpretations: igneous, metamorphic, or maximum depositional age. In the case of high-grade (amphibolite to granulite facies) metasedimentary rocks, the maximum depositional age corresponds to the age of the youngest concordant crystal. A single age uncertainty, expressed at 2SE (standard error) uncertainty, is reported, since for each sample only one age is reported, to avoid confusion. Once again, we stress the need to refer to the original paper for deeper interpretations of the data reported in this database, especially in those cases where complicated samples (for instance, high-grade gneisses that can have an igneous crystallization age, and metamorphic overprints) were studied. An excel file is linked to each sample, containing the analyzed data (mostly zircon elemental concentrations, isotopic ratios, and uncertainties, and the calculated ages). One concordia file is also included, to have a general and visual approach to the produced ages. Finally, for detrital data, we provide the kernel density estimator to quickly represent the age distribution of the studied samples, some point-counting data. Where Hf isotopic data have been obtained, we also include those, as mean εHf, T_{DM} age, providing an Excel data table that includes the numerical data obtained for each sample. The reader can refer to the provided Excel data (reduced and recalculated, including propagated standard and internal errors, as briefly explained above and, more in detail, in the original papers) to produce his plots, if needed, and to compare to other data and graphs.

4. Conclusions

Several localized data contribute to the buildup of the current database, which will be expanded as more data will be produced and added to it. The partial results presented as part of the Geologic Setting, subdivided by chronologic and geographic order, are those available and published at the end of 2022. It is thus feasible that the reader will find, in the database, more data than those presented and interpreted here. Together with the database growth, the bibliographic references will also be updated to allow the reader to find the original data and the paper in which those will be presented and discussed.

While an overall conclusion is outside the scope of this database, the individual interpretations drawn by each studied sample can be found in the original papers referred together with the other inherent information that can be found in the interactive system and, at least for those available at this moment, reported here in the reference section. This database is aimed to constitute an example of how a large and growing amount of geochronologic, isotopic, and provenance data can be integrated at the regional geologic scale, to allow showing the evolution of improved geologic interpretations as more studies are concluded.

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