MEXICO

Geography

Mexico is a generally mountainous country located in the south-western part of the North American continent. With an area in excess of 1.96 million km^2, Mexico ranks as the 15th largest country in the world.

Mexico's chief structural features are the Sierra Madre Occidental, the country's most extensive mountain system, which is an extension of the Rocky Mountains from northern North America and which runs parallel to the Pacific coast, and the Sierra Madre Oriental, which runs parallel to the Gulf coast. Between these ranges lies the large arid Meseta Central, consisting of highlands and basins. Another prominent structural feature is the Trans-Mexico Volcanic Belt in central Mexico, known as the Sierra Nevada, along which seismic activity is frequent.

Much of the Mexico's central and northern territories are located at high altitudes and the highest elevations are to be found in the Trans-Mexico Volcanic Belt: Pico de Orizaba (5700 m), Popocatépetl (5462 m), Iztaccíhuatl (5286 m) and the Nevado de Toluca (4577 m). In spite of the seismicity, valleys in this area contain a large percentage of the country's population, including Toluca, Mexico City and Puebla. A fourth mountain range, the Sierra Madre del Sur, runs from Michoacán to Oaxaca. Most of Mexico's major rivers are in the south. Deserts occupy much of the north-western and north central regions. Lowland areas are found along the Pacific coast, Gulf coast and Yucatan Peninsula.

Although at least half of Mexico is arid, both tropical and temperate climates are also represented, depending on elevation, winds and ocean currents. The rainy season extends from late May through October or November throughout most of the country, but rainfall is quite irregular and variable.

Mexico is exceptionally rich in minerals. In 2010, it was the world's second largest producer of silver, fluorspar and bismuth and the third largest producer of strontium, the fourth largest producer of wollastonite and diatomite, the fifth largest producer of lead, the sixth largest producer of oil, cadmium, molybdenum and zinc, the eleventh largest producer of gold and the twelfth largest producer of copper [1, 2].

Geology

Mexico extends at least 3000 km from NW to SE and has a highly varied and complex geology (Figure 1). Many areas have not been mapped and are little known, in part owing to very difficult access.

The geology of Mexico has been profoundly shaped by the presence and interaction of the Pacific, Rivera and Cocos Plates and the truncated end of the East Pacific Rise, all interacting along the western margin of the North American Plate. In addition, the major left-lateral fault between the North American Plate and the Caribbean Plate cuts east–west across the far south of the country. These major tectonic elements are responsible for the complex structural geology, as well as for the evolution and the variety of many of the rock types that occur in the country.

The active nature of the continental margin along the Pacific resulted in the uplift and associated vigorous erosion of the western and southern parts of the country, thereby creating large areas of exposure of metamorphic and plutonic strata from the deeper levels of the upper crust. In contrast, the continental margin along the Gulf of Mexico has generally been considered a gradually emergent passive margin over which sedimentation took place throughout the Cainozoic. Although there are exceptions to this broad generalization, the principal morphotectonic provinces recognized in mainland Mexico reflect this broad framework [3–5].

Reference [4] provides a comprehensive overview of the geology as well as an extensive reference list of geological work carried out throughout the country and to other sources of information.

Mexico's landmass may be divided into several major morphotectonic provinces: (i) Baja California Peninsula, (ii) Sonoran Basin and Range Province, (iii) Sierra Madre Occidental, (iv) Sierra Madre Oriental, (v) Gulf Coastal Plain Foreland and Yucatan, (vi) Trans-Mexico Neovolcanic Belt, (vii) Sierra Madre del Sur, and (viii) Sierra de Chiapas. A brief description of each geological province follows based on that published by de Cserna [4, 5].

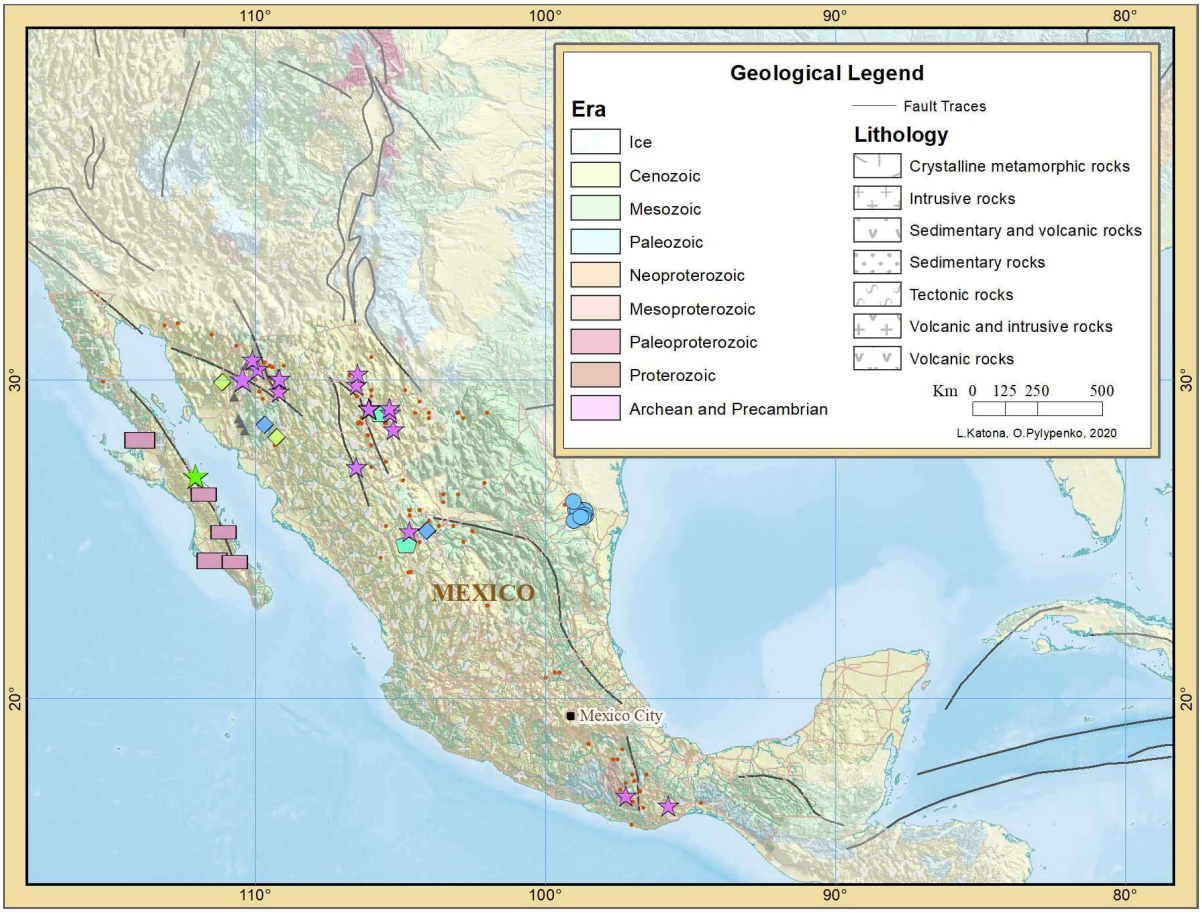

FIG. 1. Regional geological setting of Mexico showing the distribution of selected uranium deposits and occurrences. For the general uranium deposit and occurrence legend see World Uranium Geology, Exploration, Resources and Production, IAEA, 2020. A general global geological legend is shown although not all geological units necessarily occur on this particular map.

Baja California Peninsula

Baja California Peninsula, the westernmost tectonic province of Mexico, extends 1300 km SSE from the border with the United States of America to Cape San Lucas in the south. The Baja California Peninsula is bordered on the east by a complex structural depression whose floor lies below sea level and deepens towards the SE. The Peninsula is divisible from north to south into three morphotectonic subprovinces: (i) the Peninsula Ranges, (ii) the central region, and (iii) the Southern Cape region:

(i) *The Peninsula Ranges*: The poorly exposed eastern half of the Peninsula Ranges consists of the oldest rocks on the Peninsula and comprises weakly metamorphosed sandstone, shale, limestone and basic volcanics. Fossils date the sediments from Precambrian to Triassic. The next sequence of younger rocks on the western Peninsula comprises several thousand metres of metasedimentary and metavolcanic rocks of Middle Cretaceous age, which are intruded by numerous plutons. Of these, 387 have been mapped in the Peninsula Ranges with 250 identified

as 118 tonalites and quartz diorites, 87 granodiorites and 34 gabbro and diorite. Of the remaining 11, 5 are granites and 6 are adamellites. The total area of plutonic rock exposure is ~40% of the surface area of Baja California Norte. A post-batholithic marine sedimentary sequence of Late Cretaceous–Early Tertiary age forms a narrow belt along the west coast;

(ii) *The central region*: This consists of a near horizontal dissected volcanic plateau, the Sierra de La Giganta, flanked on the west by younger Tertiary sediments and Pliocene–Quaternary volcanics. A wide variety of other rock types ranging from sediments to volcanics occur in the area, most of which are metamorphosed and deformed;

(iii) *The Southern Cape region*: This consists of granitic and metamorphic terrain and includes a large granitic massif, which attains an elevation of just over 2000 m. The massif is flanked by metamorphic rocks and covered by a thin sequence of Miocene volcanics and Pliocene marine sedimentary rocks.

The dominant geological structures of the region are many N–NW trending high angle faults, some extending 15–20 km in length.

Large volumes of marine phosphorites occur in Tertiary uplifted sediments on the west coast of southern Baja California.

Sonoran Basin and Range Province

The Sonoran Basin and Range Province extends from the Arizona–Sonora segment of the international boundary to latitude 21° N. It extends from the Gulf of California in the west to the volcanic plateaux of the Sierra Madre Occidental. Between the international boundary and latitude 28° N, the region is characterized by NNW trending mountain ranges separated by valleys, which increase in width westwards. To the west, this forms a large desert region, the Altar Desert, which has moving sand dunes that emphasize the inselberg aspect of many of the mountain ranges. West of longitude 110° W, the region is very similar to the Basin and Range province of the USA.

South-east of Guaymas, the Range Province forms a narrow coastal plain on the Gulf of California. The oldest exposed rocks in Mexico occur in this morphogenic province and consist of quartz–muscovite schists, quartzite and quartzo–feldspathic gneisses intruded by calc–alkaline plutons dated at 1750 Ma. Various Precambrian rocks believed to form the basement occur widely throughout the province. Outcrops occur in widely spaced mountain blocks, making the interpretation of the regional geology difficult. Various strata of Late Precambrian–Palaeozoic age are found overlying the basement rocks. Upper Triassic continental and locally coal-bearing clastic deposits are primarily confined to the Sonoran Province. Various rocks types, including sediments and volcanics of Jurassic–Cretaceous age, are also distributed throughout the province.

Numerous granitic plutons are emplaced throughout the province and range in age from Late Cretaceous to Tertiary, with a tendency for the age to become younger from west to east. Deep fracturing of the northern part of the province throughout the Miocene and Pliocene reflects the Basin and Range tectonics of south-western North America. In Sonora, this resulted in block mountains oriented NNW and adjacent valleys controlled by high angle faults. In the western area, volcanic features are apparently related to faulting originating from the tectonic framework that resulted from the opening of the Gulf of California.

Sierra Madre Occidental

The geology of the Sierra Madre Occidental is very poorly known owing to difficult access caused primarily by the very rugged terrain. Only one railway and one highway cross the range. The Sierra Madre Occidental is a linear volcanic plateau elongated in a NNW direction along a distance of ~1200 km and varying in width in the range 200–300 km. The elevation averages 2000 m but attains a maximum height of 3348 m. The Sierra Madre Occidental is a broad anticlinal uplift with a gently dipping eastern flank and a more steeply dipping western flank.

The geology of the region is defined by a lower volcanic complex formed by batholithic intrusive and associated extrusive rocks whose ages are in the 100–45 Ma range, and an upper volcanic supergroup, formed mostly by ignimbrites, caldera complexes and small volumes of mafic lavas, with ages of 34–27 Ma. The extrusive rocks of the lower volcanic complex rest unconformably on deeply eroded terrain comprising Precambrian, Palaeozoic and Mesozoic metamorphic and plutonic rocks, as well as remnants of some sedimentary strata. The dominant rock is andesite with some intercalated rhyolitic ignimbrites. Water-borne pyroclastic material, as well as agglomerates and tuffs, are found at many places in the 1000–1400 m thick sequence. The plutonic rocks frequently intrude the lower volcanic complex. This sequence is characterized by intense alteration and the presence of mineral deposits, in contrast to the overlying upper volcanic supergroup.

The upper volcanic supergroup unconformably overlies the lower volcanic complex and consists primarily of rhyolitic and rhyodacitic ignimbrites. Some mafic lava flows occur near the top of the ignimbrite sequence, which is roughly 600–800 m thick. Numerous rhyolitic domes and calderas have been identified in this sequence [18.4]. However, significant uranium occurrences are not known.

Sierra Madre Oriental

The Sierra Madre Oriental extends south from the international border to roughly latitude 20° N. The western boundary is transitional to the main Sierra Madre Occidental and, in the east, it extends to the western margin of the low-lying Mexican portion of the Gulf Coastal Plain. The region is formed by a complex folded thrust sequence of Mesozoic carbonates with some interbedded shale, overlain by flysch, in which locally post-tectonic granitoid stocks are emplaced.

The province is elongated in a NNW direction and it extends to ~1500 km with a width varying from 200 km in Chihuahua to 400–500 km further south.

The major structures of this province are folds that have been modified by thrusting and later normal faults. These structures are formed principally in Lower Cretaceous carbonate and Upper Cretaceous flysch, although Upper Jurassic sandstone, shale and some carbonates of the lower parts of the deformed sequence are occasionally exposed. At isolated locations, exposure of both Palaeozoic and Precambrian strata occur.

Reference [5] notes that a tectonic model of the Sierra Madre Oriental, including large scale thrusts, is comparable to those of the southern Rocky Mountains of Canada or the Jura Mountains in Switzerland. The period of folding and faulting was followed by the emplacement of granitic, monzonitic and granodioritic stocks towards the end of the Eocene. These intrusives are widely distributed in the western two thirds of the Sierra Madre Oriental, whereas very few occur in the eastern frontal belt. The intrusives produced some important skarn mineralization and set the stage for hydrothermal activity and mineral deposition. The products of the Miocene volcanic activity of the Sierra Madre Occidental covered some of the western parts of this province. Widespread block faulting of Basin and Range tectonics accompanied the Pliocene uplifting of the entire province, as well as of the Sierra Madre Occidental.

Gulf Coastal Plain Foreland and Yucatan

The Gulf Coastal Plain Foreland and Yucatan morphotectonic province is adjacent to the eastern edge of the Sierra Madre Oriental, barely flanks the eastern termination of the Trans-Mexico neo-volcanic belt, and lies to the east of the Sierra Madre del Sur and NNE of the Sierra de Chiapas. This region represents the breakdown of the foreland in the Late Cretaceous–Early Tertiary, ENE directed folding and thrusting north of the Tuxtlas volcanic massif, and the burial and build-up of the present coastal plain by the products of erosion from the western, south-western and southern fold and thrust belt. In the north, the Rio Grande River supplied a considerable amount of clastic material. The coastal plain

between the Rio Grande in the north and the Laguna del Carmen in the SE may be divided into four palaeoembayments corresponding to the four principal depositional sites of the major rivers.

The Upper Eocene–Miocene, and at places even Pliocene and Pleistocene, sequence comprises sandstone and shale with some conglomerate and limestone. Most of these deposits are undisturbed, or are deformed by compaction, faulting and folding produced as drag along faults. However, in the northern parts of the Isthmus of Tehuantepec, numerous salt domes (the salt being of Middle Jurassic age) are emplaced in the Tertiary sequence, producing doming and associated faulting. The stratigraphy of the province is reasonably well known through oil and gas exploration. The basement for the Eocene and younger, primarily clastic sequence consists of deformed Mesozoic–Palaeocene sediments, which is in turn underlain by Palaeozoic metamorphics that are, in places, overlain by Permian flysch.

The Tertiary sequence varies in maximum thickness from 10 000 m in the Rio Grande embayment to 2000–5000 m in most other areas of the Gulf Coastal Plain. Another feature of the Gulf Coastal Plain is the presence of alkalic strata dated at 28–7 Ma in the Sierra de San Carlos and in the southern parts of the Sierra de Tamaluipas, as well as numerous basaltic volcanic rocks occurring as flows, volcanic necks and dykes. The alkalic volcanics have been likened to the Trans-Pecos Magmatic Province of Texas, which is considered by some to be the source of uranium in the south Texas sandstone-hosted deposits [6].

Yucatan is considered a stable platform with near surface strata consisting of Neogene and Palaeogene marine deposits. The deposits consist of marls and limestones of Miocene–Oligocene age with a combined thickness of ~2000 m, as well as underlying 1200 m of Upper Cretaceous interbedded limestone, dolomite and anhydrite.

Trans-Mexico Neovolcanic Belt

This province extends across Mexico from the Pacific coast to near the Gulf coast, roughly between latitudes 19° and 20° N. It is ~900 km long and up to 100 km wide. Morphologically, it is a broad, west sloping volcanic plateau, formed by polygenetic stratovolcanoes, monogenetic volcanoes and cinder cones, caldera complexes and explosion craters or maaren, with associated lava flows and pyroclastic deposits. Six of the stratovolcanoes constitute the highest peaks in the country.

The belt is thought to have developed in the central part throughout Late Miocene–Early Pliocene with the eruption of calc-alkaline andesite and dacite, with some small areas of rhyodacites and rhyolites. Magma generation was intimately related to the subduction process of the Rivera and Cocos Plates. The monogenetic volcano fields, which occupy large areas within this province, are formed by basalts (chemically basaltic andesites) and are interpreted as having originated from the mantle throughout subduction and without having incurred much contamination.

Sierra Madre del Sur

Were it not for the Trans-Mexico Neovolcanic Belt forming throughout the Pliocene–Quaternary, the Sierra Madre del Sur would comprise those strata that underlie Mexico north of latitude 19° N. It is located along and bounded by the Pacific Ocean in south-western Mexico. The morphology of this region has been governed by subduction processes along the Middle America Trench since the end of the Miocene, which has resulted in the truncation of the continent along the southern coast of Mexico. This uplift is recorded by the presence of onshore marine Cainozoic strata, the generation of magma and the occurrence of suitable tectonic conditions needed to form a natural dam across Mexico: the Trans-Mexico Neovolcanic Belt.

With the exception of a narrow coastal plain extending along the Pacific, the entire province is maturely dissected. The most prominent topographic feature is the segmented coastal cordillera, generally referred to as the Sierra Madre del Sur, which extends ESE from Bahía de Banderas for a distance of 900 km. Most of the highest elevations along this cordillera lie between 2600 and 3000 m, although the

highest peak is 4342 m. The area of the Puebla–Oaxaca upland has a very complex geology, which, is poorly understood. The oldest rocks are Precambrian granulites including quartzo–feldspathic gneiss, charnockite, paragneiss, marble and meta-anorthosite, among others. There is also a wide variety of Palaeozoic strata, many of them metamorphosed schists and gneisses. The area west of longitude 102° W is described as largely unknown, except for parts of Colima. Younger rocks include sedimentary sequences, as well as Upper Cretaceous and older granitic stocks that are widely distributed in the province. Early Tertiary deposition consists of continental clastics that are preserved in fault-controlled basins, while Middle Tertiary volcanic activity of andesitic composition is practically confined to the north central part of Oaxaca.

Sierra de Chiapas Province

The morphotectonic province extends from the Gulf Coastal Plain in the east to the Pacific Ocean and in the west, as far as southern Mexico. Bordering the Pacific is a coastal plain built by rivers flowing from the Chiapas Massif, which has an average elevation of 1500 m. Mesozoic deposits are adjacent to the coastal cordillera in the NE and form the NW elongated and fault-controlled Central Depression of Chiapas, as well as NE lying Chiapas Highlands. North and NE of the Chiapas Highlands is the Sierra de Chiapas proper, formed by a series of elongated mountain ranges and parallel valleys. The Chiapas Massif consists of the oldest strata found in this province and is a pre-Permian Palaeozoic, probably Devonian, batholith emplaced in Upper Precambrian metamorphic rocks. The Sierra de Chiapas is apparently separated from the Sierra Madre del Sur to the north by a transcurrent fault or shear zone marked by intense modern day seismic activity. The NE flank of the Chiapas Massif is overlain to the SE by 2700 m of black slates and ferruginous sandstones of either Carboniferous or Lower Permian age. The oldest Mesozoic rocks in Chiapas are continental red beds that are equivalent to, or underlie, Upper Jurassic and basal Cretaceous marine deposits. There is also a 12 000 m thick sequence of Palaeocene–Lower Miocene strata of shale, sandstone and limestone. Other strata in the area include a few granitic stocks of Late Triassic–Early Jurassic age, as well as Quaternary volcanics of andesitic composition. The area includes several recently active volcanoes and registers intense seismic activity [4–6].

Uranium exploration

Uranium exploration in Mexico began in 1957 and continued up to cessation in May 1983, with all work undertaken by governmental organizations. The areas explored, in order of importance, are in the States of Coahuila, Zacatecas, Chihuahua, Nuevo León, Queretaro, Puebla and Tamaulipas. Exploration included ground and airborne prospecting by geological and radiometric methods in addition to surface sampling, drilling and mining. Airborne and ground-based geochemical, emanometric and magnetometric techniques have also been used to a lesser extent.

Prior to 1970, exploration was conducted by the Mexican Nuclear Energy Commission, which, in 1971, became the National Nuclear Energy Institute. Following a major reorganization in 1979, the National Nuclear Energy Institute was split into the following organizations: the Atomic Energy Agency, whose activities were coordinated by Uranio Mexicano (URAMEX), which is in charge of all activities concerning the nuclear fuel cycle; the Mexican National Commission for Nuclear Safety and Safeguards and the National Nuclear Research Institute.

In February 1995, URAMEX was dissolved and its responsibilities transferred to the Mineral Resources Board (Consejo de Recursos Minerales) and to the Mining Development Commission (Comisión de Fomento Minero). Both organizations report to the Ministry of Energy, Mines and State-Owned Industry.

Through 1980, a total area of 260 000 km² were explored by airborne radiometric surveys at line spacings of 0.8–1.0 km. In addition, 35 000 line-km of car-borne surveys were undertaken.

By 1981, drilling totalled 1 243 170 m (including 200 000 m planned for 1981) at a cost of US $18.569 million [18.7]. In 1981, 1982 and 1983, drilling campaigns of 150 640 m, 136 330 m and 49 555 m, respectively, were conducted. The costs for the drilling campaigns completed in 1981, 1982 and 1983 are not available. A total of 14 643 holes were drilled through 1983. Holes were logged using electrical and gamma ray methods.

Throughout the period 1981–1983, URAMEX continued the exploration and evaluation of 19 prospects located in the States of Chihuahua (4), Durango (5), Zacatecas (2), San Luis Potosi (1), Nuevo León (3), Sonora (2) and Oaxaca (2). The geological environments of the prospects explored include acid volcanics (La Gloria, La Mesa, Majalca, Cerros Colorados, La Perla, Montosa, Teresa, Lajoy and El Refugio), Tertiary sandstones (La Diana, Santa Fe and Dos Estados), contacts between acid to intermediate intrusives and volcanics (Granaditas and El Picacho), pre-Jurassic gneiss and schist and Jurassic shale (San Juan Mixture and Tayata). Fifteen properties where drilled in 1981–1983 [8].

In 2009, the Mexican Geological Survey reactivated uranium exploration in order to validate or re-evaluate the resources previously reported by URAMEX.

During the 2013–2016 period, 16 442 m were drilled in 144 holes. In 2017– 2018, 5 164 m was drilled in 47 holes with core recovery.

Areas under study were Pena Blanca in Chihuahua State, Los Amoles in Sonora State, Buenavista, Chapote, La Diana, Peñoles, La Presita, La Coma, Trancas, Dos Estados and Santa Fe in Nuevo León State with geological and radiometric prospection works. In Durango State, exploration activities have focused on Santiago Papasquiaro area, where anomalies and evidence of surface and underground uranium minerals were defined.

Uranium resources

The principal deposits or districts and their recoverable resources are in Chihuahua, Nuevo León, Sonora, Oaxaca and Durango (Table 1).

TABLE 1. URANIUM DEPOSITS [8–10]

Deposit	Location	Type	Resource (tU)	Grade (%U)	Remarks
El Nopal	Chihuahua	Volcanic (breccia pipe)	306	0.25	Disseminations and veins in rhyolite and tuffs
Margaritas–Puerto III	Chihuahua	Volcanic at limestone contact	2542	0.10	Disseminations and veins in rhyolite and tuffs
Los Amoles	Sonora	Veins in fractured silicified andesite	403 (reserves), 485 (additional resources)	0.16	Occurs in roof pendant of intrusive body
Las Preciosa	Durango	Volcanic (breccia and intrusive)	368	0.05	
Santa Catarina Tayata	Oaxaca	Volcanic (tuff and conglomerate)	<424	0.04–0.08	
La Coma	Nuevo León	Sandstone (roll front)	1114	0.2	
Buenavista (La Sierrita(?))	Nuevo León	Sandstone (roll front)	1200	0.2	
El Chapote	Nuevo León	Sandstone (roll front)	672	0.07	

Past evaluation of these projects by URAMEX did not fulfil the international standards of evaluation. Potential was demonstrated, and the Mexican Geological Survey is now re-evaluating the resources following international standards. The first results of this programme are presented in Table 2:

Chihuahua

The Peña Blanca district, in Chihuahua State, is part of the Sierra del Cuervo and consists of a sequence of Cainozoic acid volcanics, Cretaceous limestones and basal conglomerates. The main portion of the uranium mineralization is generally related to both hydrothermal and supergene processes and occurs as breccia pipe fillings, fracture fillings and disseminations and in tabular orebodies in rhyolitic tuffs. The mineral association includes primary and secondary uranium and molybdenum minerals. Total recoverable resources in the RAR and EAR-1 categories at costs of <US $130/kgU reported in [8] amount to ~3220 tU.

TABLE 2. URANIUM DEPOSITS: RESOURCES EVALUATION BY THE MEXICAN GEOLOGICAL SURVEY [11]

Las Margaritas, Chihuahua State	597
El Puerto III, Chihuahua State	180
El Nopal I, Chihuahua State	422
Los Amoles, Sonora State	399
La Coma, Nuevo León State	852
Buenavista, Nuevo León State	1 455
El Chapote, Nuevo León State	1 104
La Diana, Nuevo León State	940
Peñoles, Nuevo León State	191
La Presita, Nuevo León State	185
Trancas, Nuevo León State	130
Dos Estados, Nuevo León State	169
Santa Fe, Nuevo León State	90

The La Sierrita district is situated in the State of Nuevo León, close to the border with Tamaulipas State. Geologically, the area is underlain by Oligocene–Miocene tuffaceous sediments of the Burgos Basin. Uranium mineralization, grading 0.05–0.12% U, includes coffinite and uraninite occurring in a roll front redox interface in carbonaceous sandstones of Oligocene age. Within this district, there are 8 deposits with combined uranium resources of up to 850 tU. These deposits include, in order of size, La Coma, Buenavista, La Diana and El Chapote, as well as Peñoles, La Presita, Dos Estados and Las Trancas.

Mexico's three defined roll front-type sandstone deposits (La Coma, Buenavista and El Chapote) are of Oligocene age and occur within the fluvial wedge of the Gulf Coastal Plain. The deposits are not described in detail in the published record, although the host is identified as fine- to coarse-grained sands of the Frio Formation. In addition to the above resources hosted in rhyolitic volcanics, uranium occurrences have also been found in Upper Cretaceous limestones in the areas of Domitila, Jales, Lotes, Valle de Aldama, Adargas and Lamentos.

Roughly 90% of these resources, with a grade of ~0.085% U, are located in five deposits: Margaritas, Puerto III, Nopal I, Nopal III and Laguna de Cuervos. The remainder occur in 10 small lower grade (0.019% U) deposits: Puertos I, II, IV, V, VIII, Laguna del Diablo, Cerva Amarilla, Peñon Blanco, Nopal II and La Gloria.

Nuevo León

The Frio Formation is of the same age, is equivalent to the Oligocene Catahoula Formation and it occurs to the north in the south Texas uranium province. The Catahoula Formation is a highly tuffaceous fluvial unit that was deposited in a marginal marine environment and serves as the principal host for uranium deposits in south Texas. In addition, the Mexican deposits are of a similar size and uranium grade as the south Texas deposits. The development of in situ leach production in south Texas has primarily taken place since the discovery of the Mexican deposits and much has been learned about this geological environment since work on the Mexican deposits was suspended.

Sonora

Los Amoles is the most important uranium deposit in Sonora State. The deposit consists of three orebodies: Amoles, Amoles II and Martin. The mineralization comprises primary and secondary uranium minerals and is associated with argentiferous galena and barite, which occur in fractures in altered trachyandesite that overlies a Mesozoic granite. The estimated uranium resources in [18.8] totals ~1050 tU RAR and EAR-I, recoverable at less than US $130/kgU. In addition, there appears to be a high potential for discovery of additional deposits, which would merit future exploration in the area surrounding the Los Amoles II and Martin deposits.

Additional uranium deposits in the Sonora State are Noche Buena, San Antonio de las Huertas, Granaditas, Santa Rosalia, Picacho, Yecora, Huasabas, Moctezuma and Los Caballos. Their total resources (RAR plus EAR-1 recoverable at <US $130/kgU) are estimated at 850 tU, hosted in the following geological settings:

(a) *Noche Buena*: Secondary uranium minerals associated with Ag, Pb and Zn minerals as fracture fillings in altered granite of Mesozoic age;
(b) *San Antonio de las Huertas*: Secondary uranium minerals associated with Ag, Pb, Zn and Cu minerals as fracture fillings in Jurassic sediments intruded by an acid to intermediate Cainozoic intrusive;
(c) *Granaditas–Santa Rosalla–Picache*: Uranium mineralization in acid to intermediate volcanics of Cainozoic age;
(d) *Yecora*: Uranium mineralization associated with W and Mo minerals in a brecciated granite of Mesozoic age. Although the known resources are small, the potential of this area is estimated by URAMEX to be around 500 tU;
(e) *Huasabas, Moctezuma and Los Caballes*: Secondary uranium mineralization in fractures in Cainozoic acid to intermediate volcanics as well as at the contacts of lava flows.

Oaxaca

The Tayata and San Juan Mixtepex deposits, located in the western part of Oaxaca State, were discovered sometime around 1980. The deposits are located in the Tlaxiaco Basin and host total resources (RAR), as reported in [18.6] in the US $80–130/kgU cost category, of ~470 tU [18.8]. Uranium mineralization is related to a structurally complex area underlain by conglomerates and tuffs of Cainozoic age in fault contact with Cretaceous limestone and silicified sandstone and schist of Jurassic age, occurring in fault contact with pre-Jurassic gneisses. It is reported that Tayata contains ~85% of the total resources of the area.

Durango

La Preciosa, El Mezquite, Coneto–Buenavista and Sierra de Coneto, all located in Durango State, are deposits and prospects with RAR and EAR-1 resources reported in the [8] as 840 tU in the US $80–130/kgU cost category and occurring in a variety of geological environments.

La Preciosa is the largest but lowest grade deposit in Durango, accounting for ~50% of the resources of in the State. The uranium mineralization is associated with a brecciated intrusive contact between Lower Cretaceous sediments and granitic rocks.

El Mezquite contains roughly tabular disseminated and fracture filling mineralization in a tuffaceous bed of probable Middle Tertiary age. The Coneto–Buenavista occurrence is hosted in a vein structure in a Cretaceous limestone host. Uranium minerals are associated with fluorite. The Sierra de Coneto deposit contains a number of other uranium occurrences in Cainozoic acid volcanics.
According to the 1999 Red Book [18.3], estimates of uranium resources were last prepared in 1982. Feasibility reports had been prepared for the Amoles and Peña Blanca deposits [8].

Known uranium resources total 2400 tU, which are recoverable in the US $80–130/kgU cost category. New undiscovered resources comprise 12 700 tU, of which 2700 tU are designated as EAR-II and 10 000 tU are speculative resources (Table 3) [8].

TABLE 3. REPORTED UNDISCOVERED CONVENTIONAL RESOURCES (tU)

Category	<US $130/kgU	Cost range unassigned
Prognosticated	3000	
Speculative resources		10 000

Identified resources

As of 1 January 2017, reasonably assured resources (RAR) and inferred resources (in-situ) totalled to 2540 tU and 4 264 tU respectively, in the <US$ 260/kgU cost category [18.9]. Resources are associated to sandstone-type deposits (RAR: 852 tU, IR: 4 264 tU) and volcanic related deposits (RAR: 1598 tU). The historical variation in identified resources is shown in Figures 2 and 3.

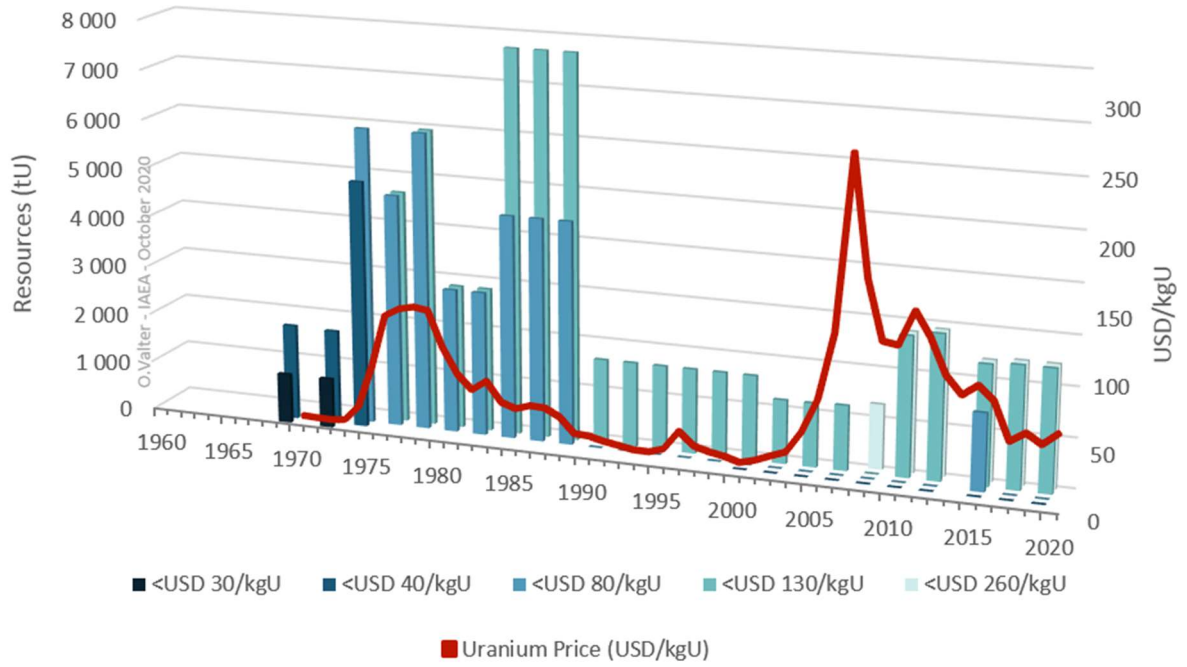

FIG. 2. Historical variation of recoverable reasonable assured resources within various cost categories in Mexico. Periods where no resources are shown in any cost categories are periods where resources were not reported, either by the Member State or as a secretariat estimate.

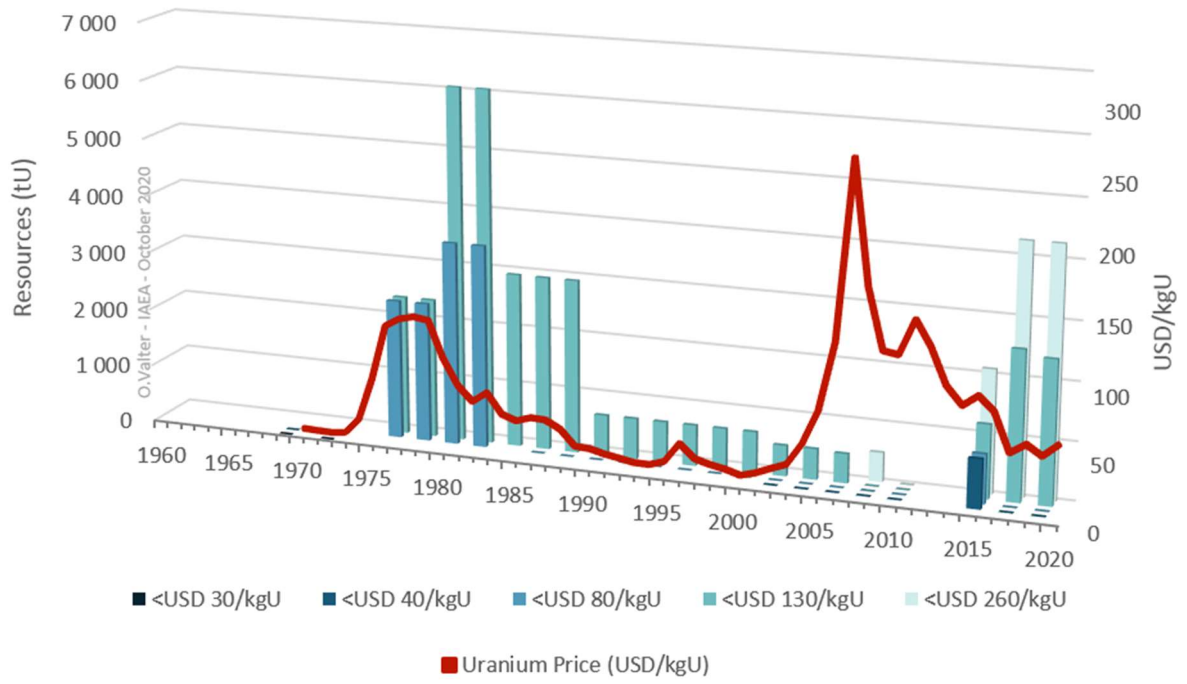

FIG. 3. Historical variation of recoverable inferred resources within various cost categories in Mexico. Periods where no resources are shown in any cost categories are periods where resources were not reported, either by the Member State or as a secretariat estimate.

Unconventional resources

Unconventional uranium resources in marine phosphates are reported for Baja California, totalling 150 000 tU. In addition, 1000 tU of unconventional resources related with hydrothermal non-ferrous mineralization in La Preciosa (Durango), Noche Buena (Sonora) and Tayata (Oaxaca) are reported. This resource was previously classified as a conventional resource (Table 4).

TABLE 4. REPORTED UNCONVENTIONAL RESOURCES

Deposit	State	Type	Resource (tU)	Grade (ppm U)	Source
San Juan de la Costa	Baja California	Phosphorite	6000	90–150	1999 Red Book
Santo Domingo	Baja California	Phosphorite	145 000	90–150	1999 Red Book
Tayata	Oaxaca	Non-ferrous mineralization	Total 1000	n.a.[a]	1986 Red Book
Noche Buena	Sonora				
La Preciosa	Durango				

[a] n.a.: not available.

Potential for new discoveries

The 1980 IUREP report [12] provides a description of uranium potential. Since 1980, very little uranium exploration has been conducted in Mexico. Therefore, except for the major advances in the use of in situ leach technology for the extraction uranium from roll front type sandstone deposits made since 1980, which may be applied to exploit the La Coma, Buenavista and El Chapote deposits, little else has changed.

IUREP reports that there are several areas that appear promising for the discovery of sandstone, vein and disseminated deposits. However, only limited exploration has been undertaken.

Large areas of Mexico are covered by volcanic rocks and many of these are of acidic composition. The Oligocene–Pliocene acid volcanics of the Sierra Madre Oriental are considered obvious targets. Volcanics of this type occur in the States of Chihuahua, Sonora, Durango, San Luis Potosi, Nayarit, Zacatecas, Queretaro and Hidalgo, with isolated outcrops in Baja California and Coahuila. Volcanics of the same age and composition also crop out in the Sierra Madre del Sur in the States of Guerrero and Oaxaca. Mesozoic acid volcanics occur as isolated outcrops in the States of Sonora, Sinaloa, Jayarit, Durango, Coahuila, Zacatecas, Michoacan and Guerrero. There are also many outcrops of these rocks in the States of Veracruz, Puebla, Oaxaca, Chiapas and Baja California. Palaeozoic acid volcanics occur along the Pacific Coastal Plain.

No occurrences of uranium are known in pegmatites, migmatites or metamorphic rocks in general. The potential for deposits in rocks of this type, plus granites, exists in the Sonoran Desert and Plains, the Sierra de la Baja California, the Sierra Madre del Sur, the Oaxaca Valley and the Sierra de Chiapas. In general, these areas contain Palaeozoic or older metamorphics, which have been, in places, intruded by Mesozoic or Tertiary granodiorites, granites, quartz monzonites and syenites.

The potential for vein uranium deposits occurs in many parts of Mexico, especially in areas hosting acid igneous intrusives, including Baja California, the Sonoran Desert and Plains, the Sierra Madre del Sur and the Oaxaca Valley, and in those areas where acid volcanics occur, as detailed above.

In addition to the Gulf Coastal Plain, there are several additional areas with potential for uranium deposits in sandstones. In the north-western part of Baja California, Lower Cretaceous tuffs are overlain by Palaeozoic and Eocene marginal marine and fluvial sediments and, throughout the Peninsula, there are Cretaceous–Pleistocene sediments interbedded with volcaniclastics. The Parras and La Popa Basins of southern Coahuila and western Nuevo León in the Sierra Madre Oriental contain terrigenous sediments of Late Cretaceous and Palaeocene age, the Difunta Group being of particular interest. Similar Upper Cretaceous deltaic sediments are also found in the Sabinas and Ojinaga Basins of eastern Coahuila and north-eastern Chihuahua, respectively, also within the Sierra Madre Oriental.

In the Maseta Central, the Late Triassic Nazas Formation was deposited in a lacustrine environment consisting of red to purple mudstones, siltstones and sandstones interbedded with andesitic to rhyolitic tuffs, flows and ignimbrites. In northern Zacatecas and adjacent Durango, the formation overlies highly folded and faulted schists, metavolcanics and metasediments of possible Palaeozoic age.

In the Sierra Madre del Sur, in the basin of the Balsas River and in the Oaxaca Valley, Tertiary continental beds are frequently interbedded with andesitic to rhyolitic volcanics. The Eocene–Oligocene Balsas Formation is a very attractive target in this area. Also in the Oaxaca Valley, the Middle Jurassic consists of continental conglomerate, sandstone, shale, siltstone and coal.

There exists the possibility of finding calcrete deposits in northern Mexico where surficial, unconsolidated fluvial sediments occur in the restricted basins of arid regions. There is also some potential for finding uranium deposits in petroliferous limestones in the Sierra Madre Oriental and the Gulf of Mexico Coastal Plain.

In summary, the potential for additional uranium resources in Mexico is moderate to high [12].

Uranium production

Mexico's Mining Development Commission operated an experimental uranium recovery plant (Planta de Beneficio de Uranio) at Villa Aldama, Chihuahua, in 1969–1971. The facility used alkaline leaching and had a capacity of 80 t ore/d. The operation recovered molybdenum and a total of 49 tU of by-product uranium from ores mined at the Domitilia (Peña Blanca), Sierra de Gomez and other

occurrences, all in Chihuahua State. Tailings from the operation were disposed of at Peña Blanca. The plant has been decommissioned.

National policies related to uranium

Government policy accords the State exclusive rights regarding activities related to nuclear matters, including uranium mining. Uranium exploration in Mexico ceased in May 1983 and URAMEX, the organization accountable for this activity, was disbanded in 1985. Some of URAMEX's accountabilities were assumed by the Mineral Resources Board (Consejo de Recursos Minerales). Under the Mexican Law on Mining (Art.5, II) exploration for, and exploitation of, radioactive minerals are controlled activities. This type of mineral is incorporated in the National Mining Reserve Zone System [3].

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