Evolution of metallic deposits in time and space in Mexico

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Abstract

Politically, the development of the Mexican Minerals industry has been divided into six intervals: (1) Pre-Colonial, (Prior to 1521), (2) Colonial (1521-1821), (3) Post Colonial (1821-1911), (4) Post-Revolution (1917-1961), (5) Mexicanization (1961-1992), and Post-Mexicanization (1992- onwards). Production of gold and silver, traced from 1500 to the present day, reflects these six intervals with important variations following Independence in 1821, and the Mexican Revolution (1910-1917) which overlapped World War I. Another diminishment in production of these two metals occurred during the Mexicanization of the minerals industry during 1961-1992. From 1521 to 2010 it is estimated that 74.3 million oz of gold and 10.6 billion oz silver have been produced.

Geologically, and using available age determinations made in approximately the last half century, plus compiling stratigraphic evidence where isotopic determinations are unavailable, six metallizing epochs are recognized: (1) Late Proterozoic (1.1-1.0 Ga), (2) Early Paleozoic (470-397 Ma), Permo-Triassic (265-228 Ma), (4) Jurassic-Early Cretaceous (190-130 Ma), (5) Late Cretaceous-early Miocene (100-16 Ma), and (6) late Miocene-Present Day (<16 Ma). The areal distribution of these deposits in places is constrained by individual tectonostратigraphic terranes but more commonly occurs throughout regions covering several terranes that have been subject to tectonic events along an active margin of western Mexico.

The Late Proterozoic epoch is characterized by Ti, and U, Th and REE deposits in the Oaxaca Complex.

The Early Paleozoic epoch contains few known economic deposits, although pods of Cr and Ni occur in metamorphosed host rocks, in Southern Mexico.

Permo-Triassic time, that embraces the latter part of compressive tectonics accompanying the formation of Pangea, is similarly poor in metallic deposits, however polymetallic Pb-Zn-Cu-(Ag-Au) deposits are associated with the Chiapas batholith complex and the oldest of the massive sulfides occurs in weakly metamorphosed strata and intercalated basic volcanic rocks of the Sierra Madre terrane.

The Jurassic-Early Cretaceous epoch contains numerous massive sulfide deposits, contained primarily in the Guerrero terrane of western mainland Mexico. This terrane has been divided into the Teloloapan (Zn-Pb-Cu) and Zihuatanejo (Zn-Pb-Cu) and Northern Guerrero (Zn-Cu) subterrane. The oldest porphyry copper deposits occur in this time span, one of which is located in the Maya terrane of Southern Mexico. Additionally, two red-bed copper deposits are located in Early Cretaceous strata of the Chihuahua terrane and a world-class manganese deposit is situated in oxidized upper Jurassic strata of the Sierra Madre terrane.

There is a large increase of metallic mineral deposits in the Late Cretaceous-early Miocene epoch, primarily located in the western margin and also in Central Mexico north of the Trans-Mexican Volcanic Arc. Much of Mexico’s mineral wealth comes from these ores and can be attributed to hypogene concentration of metals associated with a subduction regime which resulted in orogeny, ground preparation, intrusive and extrusive magmatism. A porphyry Cu-Mo-(W-Au) belt lines the western margin of mainland Mexico, covers several terranes, and there is limited spatial overlap with Fe and other metals in Southern Mexico. The largest deposits occur in the Chihuahua terrane, underlain by cratonic crust. Polymetallic (Pb-Zn-Ag) skarn, replacement, manto and chimney deposits, are found in several terranes but further inland than the porphyry Cu deposits, and located in the northern Central plateau. Other Fe and U deposits are found in or near the southern edge of the Chihuahua and Caborca terranes with the exception of the Cerro de Mercado Fe ores that are located in a caldera environment overlying the Parral terrane. Sandstone-U mineralization forms a cluster of deposits in the Coahuila terrane adjacent to Texas. There is considerable geographic overlap between Sn, Hg, and Sb deposits in central Mexico north of the Trans Mexican volcanic Arc, and Hg and Sb concentrations are found in southern terranes south of the volcanic arc. Each element occurs in characteristic host rocks. Manganese is widespread throughout many terranes although few deposits have a specific age assignment. The bulk of W ores are restricted to granitoid terranes of Northwestern Mexico. The much sought after fissure-vein, epithermal, precious-metal deposits are located primarily in the occidental volcanic arcs, whereas mesothermal Au-(Ag) deposits occur along the trend of the Mojave-Sonora Megashear that separates the Chihuahua and Caborca terranes in Northern Sonora, and these have been related to the Laramide Orogeny. A small number of disseminated Au-(Ag) deposits are found in this region, distributed in sedimentary, volcanic, intrusive, or metamorphosed host rocks and also in structurally controlled deposits as in southernmost Baja California in the La Paz terrane. The remaining deposits of this epoch include REE and Th concentrations in carbonatites in the Chihuahua terrane and in an alkaline complex in southeastern Coahuila terrane. A small number of Mississippi Valley-type deposits also occur in this region.

The youngest metallizing epoch displays porphyry copper and contact metamorphic Fe deposits in southernmost Mexico, bordering subduction along the Middle America Trench, and stratabound Cu and Mn ores are present in the Vizcaino terrane of the recently formed Baja California peninsula. The youngest Au-(Au) deposits are located in the widely separated Maya and Cortez terranes, the latter bearing hot-spring deposits and the Cerro Prieto geothermal field in northernmost Baja California and within the environment of the San Andreas fault system. Other geothermal fields are located in tectonically active Pliocene and younger volcanic fields mostly in the Trans-Mexican Volcanic Arc. Placer Au and Sn accumulations in Western Mexico, derived from hypogene mineralization of earlier epochs is widespread. The youngest and still-ongoing metallization events are associated with black and white smokers in the East Pacific Rise and Guaymas Basin and near-shore, shallow-water hydrothermal vents in western Mexico.

Some terranes are characterized by specific metals, whereas other provinces display metal assemblages that straddle several terranes, especially where subduction and related tectonism have occurred in western Mexico since at least Jurassic time. This tectonism appears to be the triggering mechanism that spawned tectono-magmatic-hydrothermal processes that produced the bulk and increasingly diverse metallization as 1.0 Ga of geologic time elapsed.
INTRODUCTION

Historical

Discovery, development, and production of Mexico’s mineral wealth, particularly the metallic resources can be conveniently divided into six time intervals each with singular characteristics, (1) Pre-Colonial (pre-1521), (2) Colonial (1521-1821), (3) Post colonial (1821-1911) including the Porfirio Diaz era of foreign investment (1876-1911), (4) Post Revolution with further foreign participation (1917-1961), (5) Mexicanization of the minerals industry and cessation of foreign investment (1961-1992), and (6) Post Mexicanization with renewed foreign investment, particularly by Canadian companies (1992 onwards).

Mexico’s documented metallic mineral production stems from the 800’s with the recovery of gold during the classical period at Monte Alban, Oaxaca, possibly from placer deposits at Tepeuclla (Ordoñez, 1986). Thereafter other metals were exploited, particularly gold and silver during the colonial period, and discoveries were made with increasing frequency throughout what was to become the Republic of Mexico (see Ordoñez, 2009). The start of the colonial period began with the smelting of iron ore in the state of Veracruz (Fig. 1) to provide arms for the newly arrived Spanish conquerors. But the predominance of silver production was furthered in 1521 with discoveries at Taxco, Guerrero, a district that is still in production. Other important discoveries quickly followed at Sultepec, Mexico state; Pachuca, Hidalgo; Tlalpujahua, Michoacán; and at Zacatecas, Zacatecas. Further to the north, and accompanying the Spanish expansion, significant discoveries of silver-lead ore were made at Santa Barbara, in 1544, and at nearby Parral in 1600, both in Chihuahua. Elsewhere, the famous Veta Madre, Guanajuato district yielded the first of its prodigious wealth in 1550. Large iron deposits were identified at Cerro de Mercado, Durango, in 1551 and the patio process for the treatment of precious metal ores by amalgamation with mercury was devised by Barholome de Medina in 1554 at Pachuca.

During the 17th century important discoveries of native silver were made at Batopilas (1630), and silver and gold at Cusihuiriachic, again both in Chihuahua; La Plomosa, Sinaloa (1722); and a bonanza at Taxco, Guerrero (1752) which is said to have produced 168 kg/t silver. Later, important mining commenced at Tayolitita, Durango in 1757 and at Catorce, San Luis Potosi in 1773.

The first of notable scientific enquiries took place in 1570 when Francisco Hernandez published La Nova Plantarium, Animalium, et Mineralium Mexicanarum in Rome, Italy, followed by Juan de Torquemada who produced Veintium Libros Vibrales y Monarchia Indiana in 1723, a compilation of mines, volcanoes, earthquakes, geothermal waters, and minerals (Ordoñez, 1986). Subsequently Baron Von Humboldt in 1804 described 37 mineral districts in New Spain. Later, in 1823, von Humboldt presented in Paris, France, one of the first descriptions of rocks in Mexico in his Essai Georistique Sur le Gisement des Roches dans les deux Hemispheres. Also, his observations of the veins at Guanajuato were of sufficient detail and clarity to place them at the forefront of geologic investigations at that time. The educational field was enhanced by the foundation of the School of Mines and Metallurgy in Guanajuato in 1786, and this was followed by a tax in 1792 on mines in the republic to pay for construction of a building to house the School of Mines in Mexico City (Ordonez, 1986). Thus, by the time Mexico was gaining independence from Spain in 1821, a wealth of metallic deposits, a few of which are mentioned here, had been found, exploited, studied and documented at least in rudimentary fashion.

According to Bernstein (1964), the quantity of gold and silver extracted by the Spaniards in Mexico will never be known with certainty. But during the first two decades of the 18th century, Mexico’s annual output of gold averaged 524 kg and of silver 163,800 kg; and in the first decade of the 19th century output reached 1,763 kg of gold and 553,800 kg silver. However, following the war of Independence 1810-21, mining and related activities fell into disrepair as the Spaniards were either expelled or discriminated from owning land, thus making capital scarce.

In 1823 when legal prohibitions against foreigners owning mines were reduced, it allowed infusion of British, German, and United States investments and the post-colonial period saw continuation of discoveries, several of which were in the more inaccessible mountain ranges, for example, at Moris (1826) and the rich Nuestra Señora de Rosario mine in the Guadalupe y Calvo district (1835), both in Chihuahua. The latter is said to have values ranging up to 7,910 g/t gold. Other important districts were identified by Saint Clair DuPort (1843) in his book entitled La Production de Metaux Precieux au Mexico. However, war with the United States, terminating with the treaty of Guadalupe Hidalgo in 1848, the instability of “The Reforma” and the period of French intervention and Maximillians’s empire, throttled new investment. Eventually, Benito Juarez came to power in 1867 and the roots of the Mexican Steel industry were promoted in Las Truchas, Michoacán, and at Peña Colorado, Colima. Subsequently, the well known weekly paper El Minero Mexicano that documented mining activities was published from 1873-1903.

The Diaz era spanned 1876-1911, except for a gap of four years and produced tremendous growth in European and United States investments in Mexico, a trend that had been started by Juarez (Bernstein, 1964). The latter part of the 19th century saw an increasing participation of foreign companies exploiting Mexican metallic wealth: the Boleo Company of France operated the copper mines at, Santa Rosalia, Baja California Sur in 1885, and the Peñoles Company began operations at Ojuela, Durango as a subsidiary of the American Metals Co. Ltd. of New York in 1887; the Mazapil Copper Company was organized in 1896 in England to work the copper mines in Concepcion del Oro in northern Zacatecas; La Palmarejo and Mexican Gold Fields of London formed in 1898 to exploit the mines in Chiniapas, Chihuahua; and the Dos Estrellas mine of French capitalization started operations in the gold and silver lodes at Tlalpujahua in Michoacán in 1898. At the turn of the century, the Mexico Mines of El Oro in 1904 in the state of Mexico and the San Francisco Mines of Mexico which acquired the gold-silver-lead-zinc properties at San Francisco del Oro, Chihuahua; were both British ventures. The American presence was felt by the formation of the Green Gold and Silver Company for exploration of precious metals and copper deposits in Chihuahua and Sonora, leading to discovery of the huge copper and molybdenum deposits at Cananea, Sonora, at Real del Monte and Pachuca, Hidalgo, following earlier British ownership, the United States Smelting, Refining and Mining Company initiated operations in 1906 (Ordoñez, 1986; Fig. 1).

By 1908 there were 1,030 mining companies registered in Mexico during the latter part of the promotional period of President Porfirio Diaz and some of them were documented in the book Minas de Mexico by J.R. Southworth (1905), the text being written in Spanish and also English. Thus by the start of
Figure 1. Index to states and deposits in Mexico cited in the historical review (from Clark and Fitch, 2009).
the Mexican revolution in 1910 there were 31,988 mining concessions covering 450,371 hectares, and operated by 67,987 active mines.

However, in 1914 as the revolution continued, all acts and decrees of the federal government, including those related to mining, were annulled and this severely damaged the mining industry. After the conclusion of the revolution in 1917, Article 27 in the new constitution exercised Mexico's inalienable rights to the subsurface, and led to the concept of federal concessions to obtain mining rights (Bernstein, 1964). Nevertheless, geological and mining investigations had sporadically continued and were brought to fruition shortly thereafter in formal publications, as for example, at El Oro-Tlalpujahua (Flores, 1920; see also Rivera-Ledesma (2009).

The post-revolution period in 1926 was accompanied by a limit of 30 years life for a mining concession with a minimum production schedule, which, if not achieved, led to closure of mines undergoing development. Increase of metal prices at this time led to a 9.5% contribution in 1930 to the gross domestic product, (GNP), as the world prepared for WW II. By 1934 the Comisión de Fomento Minero was established as a Federal Agency to promote mining. The first large open pit was developed at Cananea in 1944 and the Instituto Nacional para la Investigación de Recursos Minerales (later Consejo de Recursos Minerales and presently Servicio Geologico Mexicano) was formed in 1949 to explore for mineral deposits.

In 1961 the Mexicanization of the industry, whereby 51 percent of shares had to be in Mexican hands, private or government, produced stagnation in investment and consequently exploration. Mexicanization was applied to the Peñoles, Frisco, and ASARCO companies, among others. Nevertheless a few major discoveries were made at this time, including Las Torres silver property, in the Guanajuato district in 1968; and La Caridad copper deposit, Sonora, 1975. In 1972 the Hercules iron mine in Coahuila began production and the open pit silver-lead-zinc-(cadmium) mine at Real de Angeles, Zacatecas a decade later. However by 1970 the Mexican mining industry generated only 1.5% GNP and 1.3% in 1980, (Ordoñez 1986; Ordoñez, 2009).

In 1990, new regulations were passed to the existing mining law. The new regulations provided for greater than 49% foreign ownership of mining projects. This change sent a clear message to foreign investors that they would be welcome. In 1992 a new Mining Law was passed as a Constitutional Amendment to Article 27 (Miranda and Lacy, 1993). The new Mining Law provided for staking a 6-year exploration concession that could be converted to a 50-year exploitation concession renewable for a second term. There was no size limit for a concession. The law required annual rentals and work commitments for a concession. In 1990 New Regulations were made to conform to the New Mining Law. Then, in 1993, a New Foreign Investment Law was passed that allowed 100% foreign ownership of mining projects and immediately exploration increased together with subsequent development and production.

Thus, the Mexicanization policy was scrapped and the law was again amended in 1996 (Torres, 2002). Many of the older districts that had been idle since the revolution, and, or through lack of investment and modern technology during the 1961-1992 period, for fear of total nationalization akin to Mexico's petroleum industry, came to life again. Gold and silver targets were predominant, and a few examples illustrate this point: La Colorada, Sonora, 1993; Ocampo, Chihuahua, (2003) and La Herradura, Sonora (1998) to name but a few. Simultaneously, exploitation of micron-size gold deposits by open-pit mining and heap leach recovery led to the development of new properties in the Sonora gold belt (Clark, 1998), La Herradura mine being the largest when discovered, began production in 1998. In the same belt, the separation of gold particles by a modern air separation method (Piggot, 2000) at El Boludo a year earlier revived interest in placer deposits. New discoveries of massive sulfides were made in Zacatecas, of which the San Francisco I. Madero deposit, possibly of sedimentary exhalative origin, is the best known with production starting in 2001 (see Gonzalez-Villalvaso and Lopez-Soto, 2009). One of the latest discoveries brought about by pure geological exploration in virgin territory is the El Sauzal, micron-size gold deposit in Chihuahua, production beginning in 2004. Some of the more recent discoveries being brought into production include Los Filos, Guerrero, 2007 (see Rivera Abundis et al., 2009), Peñasquito, Zacatecas (see Turner, 2009), and Dolores, Chihuahua (see Melendez-Castro, 2009). In short, with significant increases in several metal prices, exploration, development, and production are enjoying a new wave of activity in Mexico at least until the global financial crisis that began in late 2008.

Production History

An estimate of Mexico's total mine production of gold, silver, copper, lead and zinc from 1521 through 2010 is shown in Table 1a. The production of gold and silver by year is shown in Figures 2a and 2b. Figure 2a covers the total interval of 1521-2010. Figure 2b expands Figure 2a to show the interval 1880-2010. Sources of the data are Gonzalez-Reyna (1956a), Martino et al. (1992) and U.S. Geological Survey Minerals Information Surveys for the period 1955 through 2008. Data for silver production is reported back to 1521 by Gonzalez-Reyna (1956a), however data for gold production is fragmented for the period 1521 to 1880 with totals reported for the period 1521-1890. Production data for copper and lead are shown as totals for 1521-1890 and then annually afterward (Gonzalez-Reyna,1956a). Production data for zinc is shown for 1893 and annually afterward (Gonzalez-Reyna,1956a).

Mexico's total production of 74.3 million ounces of gold and 10.6 billion ounces of silver places it as the highest of Latin American countries for both gold and silver production.

An examination of Figures 2a and 2b, including the notation of events, leads one to the conclusion that political events had a major effect on production increases and decreases of gold and silver production throughout the 490-year history represented by the data. Two periods of tremendous increase in both gold and silver production are evident. The first period began in 1892 and the second in 1992 (for silver 1876, 1992), both created by favorable mining laws. The first period began with the great railroad boom 1880-1884, and the new Codigo Minero in 1884 with provisions favorable for foreign investors. This was followed by the Tax Law of 1887, the 1892 Mining Law, and the introduction of the cyanidization process in 1892 for the recovery of gold and silver. The second period of dramatic growth began with the New Mining Law of 1992, described previously.

Present production

The modern Mexican mining industry produces significant quantities of 14 metallic commodities. Ten of these are listed below in tabular form for 2006 through 2010, the latest years for
which reliable data are available (Table 1b). Another element, namely aluminum, is not shown as it is derived from imported ores. Also, part of the tin production is due to imports. In a later section, the distribution of deposits will be discussed that contribute to the individual element totals shown therein.

Thus, Mexico ranked among the top world producers in several metals (Perez, 2011): it was the world’s second leading producer of silver. In addition, Mexico ranked high in other metal production including cadmium, lead, zinc, molybdenum, manganese, copper, and gold. In 2009 the total value of Mexico’s mineral production excluding petroleum and natural gas was valued at $10.21 billion US of which metals contributed 93% of the total. Considering the total mineral industry production in Mexico for 2009, gold amounted to a 22.9% share of the total value followed by silver 18.3%; copper 16.6%, zinc 9.0%; iron 5.1%; molybdenum 3.5%; and lead 2.5% (Perez, 2011).

Mining investment in 2009 was $2.9 B US which was a 22% decrease compared to 2008 (Perez, 2011). In 2009, a total of 279 mining companies with direct foreign investment were working on 718 projects (Instituto Nacional de Estadística y Geografía, 2010). Mineral commodity prices fell during 2008-2009 and the mining part of Mexican GDP in 2009 was 1.6%. More details of Mexico’s mining industry are given in Lee-Moreno (2009).

Previous Investigations
Despite the long history of metals production in Mexico plus the impressive present day production and corresponding monetary value, relatively few studies have been made of the distribution of mineral deposits throughout the republic. This in spite of a sizeable geologic literature in Spanish, English, French and German, listed in decreasing order of importance. The first attempt to describe the mineral riches of Mexico, apart from those mentioned above, was made at length by Ramirez (1884). Investigations by the Instituto de Geología at the turn of the century included the first time-space considerations of mineral deposits (Aguilera, 1896, 1901). The 20th century produced additional research on the distribution of a variety of individual metallic elements in a series entitled Cartas de la República Mexicana de yacimientos minerales metalicos, a total

Table 1a. Mine production of gold, silver, copper, lead and zinc in Mexico 1521-2010 (after Clark and Fitch, 2009).

<table>
<thead>
<tr>
<th>Year</th>
<th>Gold (M oz)</th>
<th>Silver (M oz)</th>
<th>Copper (mt)</th>
<th>Lead (mt)</th>
<th>Zinc (mt)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1521-1890</td>
<td>8.8</td>
<td>2,840</td>
<td>80,000</td>
<td>300,000</td>
<td>-</td>
</tr>
<tr>
<td>1891-2010</td>
<td>65.5</td>
<td>7,780</td>
<td>13,567,700</td>
<td>21,245,100</td>
<td>22,546,486</td>
</tr>
<tr>
<td>Total</td>
<td>74.3</td>
<td>10,620</td>
<td>13,647,700</td>
<td>21,545,100</td>
<td>22,486,500</td>
</tr>
</tbody>
</table>

M – million, mt - metric ton

Table 1b. Important metals production in Mexico 2005-2010 (from Pérez, 2009).

<table>
<thead>
<tr>
<th>Year</th>
<th>Precious Metals (Kg)</th>
<th>Industrial Metals (mt)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Gold</td>
<td>Silver</td>
</tr>
<tr>
<td>2006</td>
<td>38,961</td>
<td>43,710</td>
</tr>
<tr>
<td>2007</td>
<td>43,710</td>
<td>3,135,430</td>
</tr>
<tr>
<td>2008</td>
<td>50,365</td>
<td>3,236,312</td>
</tr>
<tr>
<td>2009</td>
<td>51,393</td>
<td>3,553,841</td>
</tr>
<tr>
<td>2010 est.</td>
<td>60,000</td>
<td>3,500,000</td>
</tr>
</tbody>
</table>

Figure 2a. Gold and silver production in Mexico 1521-2010 (from Clark and Fitch, 2009).

Figure 2b. Gold and silver production in Mexico 1880-2010 (from Clark and Fitch, 2009).
of 13, which appear in the catalog of publications of the Instituto de Geología, Universidad Nacional Autónoma de México (UNAM), p. 36. They were compiled by González-Reyna (1967). In addition to these maps, tin was also investigated by Foshag and Fries (1942) and again by Pan (1974). Other individual element studies were made by Gonzalez-Reyna as follows: for lead and zinc (1948, 1950); silver (1956), and all mineral deposits (1947, 1956a). Iron deposits were described by Flores (1951), Pesquera et al. (1979), and Cabrera et al. (1983). Manganese was discussed by Trask and Rodriguez-Cabo (1948) and again in a symposium of the International Geological Congress held in Mexico by Park (1956). Other papers on manganese in the same year were authored by Mapes (1956) and Gonzalez-Reyna (1956a). An important compilation of epithermal gold and silver deposits in northwestern Mexico was published by Wisser (1966).

Publications of a more regional nature that considered multiple metallic elements include Behre (1957), Burnham (1959), Wilson (1968), Gabelman and Krusiewski (1968), Salas (1970), and de Cserna (1976).

The latest geologic maps of Mexico include Ortega-Gutierrez et al. (1992), and Servicio Geológico Mexicano (2007), both at 1:2,000,000 scale.

Salas (1975a) published a 1:3,500,000 scale metallogenetic map of Mexico using the international code of symbols and accompanied by a report Salas (1975b). Later he compiled Geología Económica de Mexico (Salas, 1988), and this was translated into English (Salas, 1991). Mexican deposits were also included in the prodigious compilation of the northeast quadrant of the Circum-Pacific Region by Guild et al. (1985).

The first introduction of tectonostratigraphic terrane analysis as it affects the distribution of gold-silver and lead-zinc deposits in Mexico was made by Campa and Coney (1982, 1983) and later modified by Sedlock et al. (1993). The distribution of tin-bearing rhyolites that straddle several terrane boundaries of north-central Mexico was depicted by Ruiz (1988).

In contrast, the literature of the precise dating of metaliferous deposits by isotopic methods on a national scale is more sparse than the geographic distributions cited above and in this paper. This is particularly apparent for deposits that are older or younger than the prolific Late Cretaceous-Early Tertiary mineralizing epoch. There is no modern study, to date, that has attempted to deal with the age of all important metallic deposits in Mexico, although numerous individual deposit descriptions increasingly provide radiometric data. Nevertheless, a few studies are worthy of mention here.

The first attempt was made by Stillitoe (1976) with his description of Mexican porphyry deposits, and this theme was followed up by Damon et al. (1981, 1983), Barton et al. (1995), and Valencia-Moreno et al. (2000, 2006). A publication that dealt with various elements in different classes of deposits for northern Mexico was compiled by Clark et al. (1979a, 1982). A volume containing many important Mexican deposits, mostly metallic, was edited and published by Clark and Salas (1988). Megaw et al. (1988, 1997) firmly established the age of carbonate-hosted Pb-Zn-(Ag-Cu-Au) deposits in northern Mexico. Controls on the formation of low-sulfidation epithermal deposits using fluid inclusion and stable isotope data were discussed in detail by Albinson et al. (2001), and this was followed by Campbru et al. (2003) who described the ages of epithermal deposits in Mexico with links to Tertiary volcanism. The first attempts to recognize provinces and epochs of mineralization in Mexico as a whole were made by Clark (1989, 1997), and these were followed by Clark and Fitch (2005).

In a volume celebrating the centennial of the Sociedad Geológica Mexicana, Valencia-Moreno et al. (2007) revisited the porphyry copper deposits whereas the epithermal deposits were reclassified by Campbru and Albinson (2007). The latest deposit descriptions on a national scale are to be found in the Geología de Mexico, that also celebrates the Centenary of the Geological Society of Mexico, and includes descriptions of low-temperature, carbonate-hosted deposits in Mexico by Tritlla et al. (2007), whereas the mineral deposits of the more limited area of the Mesa Central are described by Nieto-Samaniego et al. (2007). Finally, Clark and Fitch (2009) addressed the distribution of all metallic deposits in Mexico in time and space.

Objectives and Methodology

Given the wealth of metallic deposits briefly alluded to above in terms of longevity of production and present day economic importance, plus the lack of a comprehensive study that embraces the distribution of all important metallic commodities in space and time, this article attempts to provide the foundation for a compilation of all significant metallic deposits in Mexico in the modern plate tectonic-tectonostratigraphic terrane context. This article presents the information by first summarizing the geological framework leading up to and including each of the six major time slices considered. This is accomplished by drawing freely on the published literature of which the prodigious compilations of Sedlock et al. (1993) and Alainz-Alvarez and Nieto Samaniego (2007) are foremost. However, we do not attempt to examine every possible aspect of this evolution contained in these and other references, but choose a generally accepted sequence of events. Finally, as the tectonostratigraphic terranes of Mexico, first described by Campa and Coney (1982, 1983), and Coney and Campa (1984), were modified and renamed to a large extent by Sedlock et al. (1993). Where there is ambiguity in terrane designation the later nomenclature is given in parentheses.

In this context only two tectonostratigraphic reconstructions are made: the inclusion of the Mojave-Sonora Megashear (Figs. 5-16) and the formation of the Baja California Peninsula (Fig. 16).

Six time slices that contain the important deposits (Table 2) will be described whereas the geographic distribution of various classes of ore will be presented in a series of figures. The choice of the six time intervals is dictated by consideration of major tectonic, metamorphic, igneous, and, or dispositional events, plus the reconstruction of tectonostratigraphic terranes. We do not describe the individual classes of deposit, assuming that the reader already is aware of their salient characteristics, nor do we repeat tables of age determinations that have been published elsewhere. Precious metal grades are given in grams per ton (g/t), and diagrams showing the distribution of deposits are indexed by acronyms listed alphabetically.

In spite of this comprehensive approach, there are limitations to the data presented, the most obvious of which is that there are more deposits known than there are corresponding data relative to their age. We limit the deposits included in this report to those for which age determinations have been presented, or for which geological evidence of their age is compelling. This is particularly necessary when considering those deposits that were exploited and depleted before radiometric dates began to be widely produced a little more than 50 years ago.
Table 2. Summary of metallic deposit formation in six epochs from Proterozoic to Present, host rocks, tectonic framework, and references (from Clark and Fitch, 2009).

<table>
<thead>
<tr>
<th>Interval</th>
<th>Mineral Deposit</th>
<th>Principal Host Rocks</th>
<th>Tectonic Environment</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>Late Miocene</td>
<td>Au, Ti, Placer</td>
<td>Surficial and beach deposits</td>
<td>Weathering, transportation, concentration</td>
<td>Wilson et al. (2003); Barajas (1987)</td>
</tr>
<tr>
<td>Present &lt; 16 Ma</td>
<td>Au, Hot Spring</td>
<td>Silica wining and flooding</td>
<td>Volcanism, high heat flow</td>
<td>Sharp (1982); Fisheres-Walt-Gold (1991)</td>
</tr>
<tr>
<td></td>
<td>Cu Mn, Stratiform</td>
<td>Conglomerates, sands, tillis</td>
<td>Sedimentation in Gulf of California exoremetal basin</td>
<td>Batie et al. (1999); Wilson and Veis (1949)</td>
</tr>
<tr>
<td></td>
<td>Fe, Au, carbonaceous, hrs pipe</td>
<td>Granodiorite: limestone, andesite, basalt</td>
<td>Subduction related in southwestern Mexico</td>
<td>Castro-Mora (1999); Miranda-Gutierrez (2005)</td>
</tr>
<tr>
<td></td>
<td>Cu porphyry</td>
<td>Dissolutions in intrusion</td>
<td></td>
<td>Castro-Mora (1999)</td>
</tr>
<tr>
<td></td>
<td>REE, MVT</td>
<td>Carbonates: alkaline immersions</td>
<td>Subduction related</td>
<td>Nandigam et al. (1999); Ramirez-Fernandez (2006)</td>
</tr>
<tr>
<td></td>
<td>Au-Ag, Epithermal; Mesothermal</td>
<td>Tertiary volcanics: variable, (placers)</td>
<td>Subduction related</td>
<td>Camps and Albais (2007); Perez-Segura (2008)</td>
</tr>
<tr>
<td></td>
<td>W, Hydrothermal</td>
<td>Tetratitic, carbonate replacement, pegmatite, quartz veins</td>
<td>Subduction related</td>
<td>Frics and Schmitter (1945); Dong and Burt (1979)</td>
</tr>
<tr>
<td></td>
<td>Mn, Hydrothermal, exhalative</td>
<td>Carbonates, turf, volcanics</td>
<td></td>
<td>Trask and Rodriguez-Capó (1948); Gonzalez-Reyna (1935); Okita (1922)</td>
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<tr>
<td>Late Cretaceous</td>
<td>Sb, Hydrothermal</td>
<td>Carbonate, silicate, (placer)</td>
<td>Directly or indirectly related to subduction</td>
<td>White (1946); White and Gonzalez (1946); White and Guiza (1949)</td>
</tr>
<tr>
<td>Early Cretaceous</td>
<td>Hg, Hydrothermal</td>
<td>Fractured carbonates, silicate volcanics</td>
<td>Magnatism, increasing alkalinity to the east and</td>
<td>White (1946); White and Gonzalez (1946); White and Guiza (1949)</td>
</tr>
<tr>
<td>100-16 Ma</td>
<td>Sn, Volcanogenic</td>
<td>Granite, nepheline, (placers)</td>
<td>Associated accretion and Lunzinoi ophiolites</td>
<td>White (1946); White and Gonzalez (1946); White and Guiza (1949)</td>
</tr>
<tr>
<td></td>
<td>U, volcanogenic</td>
<td>Tertiary silicate volcanics</td>
<td></td>
<td>Tatu et al. (1987)</td>
</tr>
<tr>
<td></td>
<td>Fe, replacement magmatic</td>
<td>Carbonates, Periclin magmas</td>
<td></td>
<td>Fosberg and Fries (1942); Lee-Moreno (1972); Pan (1974)</td>
</tr>
<tr>
<td></td>
<td>Pb-Zn-Ag (~ Au, skarn, replacement,</td>
<td>Mesozoc Carbonates</td>
<td></td>
<td>Goodell and Waters (1981); Corina-Eraquero-Herruzco (2004)</td>
</tr>
<tr>
<td></td>
<td>manto, breccia pipe</td>
<td>(Fig. 7)</td>
<td></td>
<td>Megaw et al. (1981); Hettler (1986)</td>
</tr>
<tr>
<td></td>
<td>Co-Mo (~W, Au, porphyry)</td>
<td>Dissolutions, stockworks, bauxites</td>
<td></td>
<td>Barton et al. (1985); Valencia-Mora et al. (2007)</td>
</tr>
<tr>
<td>Jurassic-Early</td>
<td>Cu, Rod Bod</td>
<td>Sandstone, siltstone</td>
<td>Marine platform</td>
<td>Price et al. (1988)</td>
</tr>
<tr>
<td>Cretaceous</td>
<td>Pb-Zn-Cu-Ag, YMS</td>
<td>Sedimentary and submarine volcanics</td>
<td>Subduction at western margin of Mexico,</td>
<td>Sedlock et al. (1993); Miranda-Gutierrez (1995)</td>
</tr>
<tr>
<td>191-110 Ma</td>
<td>Cu porphyry</td>
<td>Silicate plateau</td>
<td>Subduction related</td>
<td>Dinnon et al. (1983)</td>
</tr>
<tr>
<td></td>
<td>Cr, Ni, Cu, Fe, ultra basic</td>
<td>Serpentinite, diabase</td>
<td>Continental or island accretion and formation of</td>
<td>Ortiz-Herruzco et al. (2003)</td>
</tr>
<tr>
<td></td>
<td>(Fig. 5)</td>
<td></td>
<td>Mesozoc Sonora-Megaschre</td>
<td></td>
</tr>
<tr>
<td>256-228 Ma</td>
<td>Ni, Co, Cu), disseminated</td>
<td>Serpentinite, metagabbro</td>
<td>Disconformable ophiolite</td>
<td>Castro-Mora (2009); Ortiz-Herruzco et al. (2003)</td>
</tr>
<tr>
<td></td>
<td>(Fig. 4)</td>
<td></td>
<td></td>
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</tr>
<tr>
<td>Early Paleozoic</td>
<td>Ca-Zn-Pb-Ag, YMS</td>
<td>Schist, phylite and basic metavolcanics</td>
<td>Metamorphism and deformation caused by continental</td>
<td>Chavez-Martinez et al. (1999); Sedlock et al. (1993)</td>
</tr>
<tr>
<td>470-397 Ma</td>
<td>Ti veins and less</td>
<td>Anorthosite, Gropee Chacusal</td>
<td>Convergence from ~49436-318 Ma</td>
<td>Yuen et al. (1991); Ortigz-Gutierrez et al. (1999)</td>
</tr>
<tr>
<td></td>
<td>Ni, Cr, Co, Pt (trace amounts)</td>
<td>Serpentinite</td>
<td>Pre-Mississippian metamorphic sequence</td>
<td>Castro-Mora (1999); Ortiz-Herruzco et al. (2003)</td>
</tr>
<tr>
<td></td>
<td>(Fig. 4)</td>
<td></td>
<td>Allochonic juxtaposed after formation of</td>
<td>Ortiz-Herruzco et al. (2003)</td>
</tr>
<tr>
<td></td>
<td>Early Paleozoic</td>
<td></td>
<td>Nwiutle Gouves (1,440-744 Ma)</td>
<td></td>
</tr>
<tr>
<td>Proterozoic ~1.1-1.0 Ga</td>
<td>Ti, disseminated, lenses</td>
<td>Anorthosite, nepheline</td>
<td>Metagendritic sediments and bimodal volcanics of</td>
<td>Ortiz-Herruzco et al. (1995); Ortigz-Gutierrez (1981, 1984)</td>
</tr>
<tr>
<td></td>
<td>Au-Ag veins</td>
<td>Quartz veins in Gouves</td>
<td>all metamorphosed in Gropee Chacusal to gneiss at</td>
<td>Equiliz de Atunes (2004)</td>
</tr>
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<td></td>
<td>(Fig. 3)</td>
<td></td>
<td>0.23 Ma followed by pegmatite emplacement</td>
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</table>
PROTEROZOIC

The tectonic evolution of Mexico will be briefly summarized from Proterozoic through Recent time, giving special attention to the six principal metallizing epochs for which data is available.

In general, we subscribe to the fundamental premise of Coney et al. (1980), Coney (1981, 1983), and Sedlock et al. (1993) that the tectonic evolution of Mexico is that of an agglomeration of terranes accreted to the southern margin of North America. However, we do not enter into the multidisciplinary data that contributes to this evolution, rather choose a history that best fits the literature to explain the distribution of deposits within the geologic framework.

Distribution of Proterozoic lithologies

Precambrian rocks are exposed in Mexico in five regions; in the northwest, north, northeast, south central and southern parts of the Republic. Thus, in four of these regions metasedimentary and metavolcanic rocks of the Grenville province (~1.0 Ga) are inferred to continue southwestward into northern Mexico, and are known to occur in northern Chihuahua, and near Ciudad Victoria, Moloango as well as in the Oaxaca complex. Immediately the question arises as to whether there is a continuous distribution of the Grenville in the concealed areas between the widely scattered outcrops (Ruiz et al., 1988), or if the Grenville terrane occurs as fault-bounded blocks of basement that are allochthonous with respect to one another and to the North American craton (Sedlock et al., 1993). This question does not arise in the case of the Early- to Middle Proterozoic rocks of northern Sonora that are closely linked to terranes in the adjacent North American craton.

Oaxaca terrane

The Oaxaca terrane of Campa and Coney (1983), or Zapoteco terrane of Sedlock et al. (1993), is regarded as a fragment of Proterozoic continental crust and consists of crystalline rocks of Grenville age. The oldest unit in this terrane is the Oaxaca Complex (~10,000 km² outcrop) that consists of meta-anorthosite, quartzofeldspathic orthogneiss, paragneiss, calcsilicate metasedimentary units, and charnockite. It was formed by metamorphism of miogeoclinal or continental rift deposits and plutonic rocks (Ortega-Gutiérrez, 1981; 1984). Pantoja-Alor et al. (1974) have advanced evidence of Proterozoic aged metamorphic rocks that they interpreted as evidence of a seaway in adjacent Chiapas, extending northwards through Oaxaca and beyond. Peak metamorphism of granulite facies took place at a temperature of 710 ± 50°C and pressures of 7 kbar (Mora et al., 1986), and occurred between 1,100-1,000 Ma (Robinson, 1991; Anderson and Silver, 1971, Ortega-Gutiérrez et al., 1977).

The northern Oaxaca complex has been investigated by Solari et al. (2004) who recognized metamorphic conditions of 735 ± 5°C and 7.7 ± 0.1 kbar in the granulite facies, which was dated between ~998 and ~979 Ma using U-Pb isotopic analyses of zircons. These ages are similar to those found in the southern Oaxaca Complex, the Guichicovi Complex and the Novillo Gneiss of east-central Mexico.

The Guichicovi Complex is located near the western edge of the Maya terrane, and consists of paragneisses and igneous rocks metamorphosed under granulite facies conditions. It is separated from the adjacent Juárez (Cuicateco) terrane by the Vista Hermosa fault. The age of a felsic orthogneiss (1.23 Ga) dates the primary emplacement of this granite body, and the petrography of the 400 km² Guichicovi complex shows that it is related to other granulite exposures in Mexico that pertain to the Oaxaquia microcontinent (Weber and Köhler, 1999). During subsequent breakup of Rodinia in Eocambrian-Cambrian time, Oaxaquia, including the Guichicovi complex, was interpreted as remaining with Gondwana, but a later collision of Gondwana and Laurentia led to the present position of the Grenville fragments in Mexico.

Mineral Deposits in Oaxaca Complex (~1.1-1.0 Ga)

Titanium

The principal metaliferous deposit, for which a Proterozoic age has been established, occurs at Pluma Hidalgo (Tisur mine), located in the southernmost part of the complex (Table 2, Fig. 3). The titanium content of this high grade titanium deposit is taken from Force (1991), taking into account Paulson (1964) and an unpublished report (1957) by Thayer. An overlying gneiss, composed of finely banded quartz-orthopyroxene-garnet-graphite-ilmenite rock assemblage, contains numerous thin sills of quartz-feldspar. Structurally below, the gneiss is intruded by concordant and discordant bodies of impure anorthosite that contain the titanium deposits. These impure anorthosites contain 2 to greater than 50 percent rutile. Rutile-bearing intervals average 20 to 40 m in width over a strike length of 600 m or more. Wall rocks are mostly gneiss, but locally, impure anorthosite occurs with smaller amounts of rutile. Ilmenite is also present in the deposit. Force (1991) concludes that a contact-metasomatic origin is plausible to explain the deposit, but is probably not the only process of formation. Later, Schulze et al. (2000) provided dates of 1,010 Ma for anorthositic gabbro, and 998 Ma for anorthosite at Pluma Hidalgo. For the latest report on this locality, see McNulty et al. (2009), who conclude that rutile occurs interstitially associated with feldspars in the monzodiorite and alkaline anorthosite and appears to be the result of late magmatic concentration of residual fluids rich in titanium.


Gold

Elsewhere in Oaxaca, gold has, from time to time, been considered to have a Precambrian origin (Capilla, 1909), but to date, this has not been verified. Among the better known auriferous localities, is the San Miguel Peras district. It contains numerous thin sills of quartz-feldspar. These localities are closely associated with fault zones, subhorizontally to the southwest, containing milky quartz with sulfides and native gold, hosted by granite facies ortho-and paragneisses, pegmatitites, and micaceous marble, part of the Oaxaca Complex (Castror-Mora and Arceo y Cabrilla, 1996; Egüíluz de Atuñano et al., 2004).

Uranium, thorium and rare earth elements (REE)

Uranium, thorium and rare earth elements have a north-south distribution through the central part of Oaxaca. There is a lithologic control to these deposits, represented by metamorphic rocks of the Oaxaca Complex. These elements are contained in...
Figure 3. Tectonostratigraphic terranes of Mexico from Campa and Coney (1983), and Instituto Mexicano del Petroleo (1984). Diagram has been adapted from Ruiz et al. (1988) and shows lower crustal xenolith localities. Sonoran Proterozoic terranes are taken from Anderson and Silver (1979). Proterozoic mineral localities are confined to the Oaxaca Complex (after Clark and Fitch, 2009).
allanite and fergusonite, in the Santa Ana and La Crisis pegmatities in the Telixtlahuca area (Castro-Mora and Arceo y Cabrilla, 1996). At this locality, Gomez-Caballero (1990) notes that the high grade metamorphism in this region was able to remobilize dispersed incompatible elements (lanthanides) and deposit them in pegmatities. Another pegmatite in this area that contains REE is the compositionally zoned, granitic, El Puerto body that varies from meta-to peraluminous composition. This pegmatite contains high concentrations of Nb, U, Th, Zr, and REE (Morales-Alvarado et al., 1999). Additionally, the marbles of the complex that were mobilized by anatexis (carbonatites?), see Ortega-Gutiérrez (1977), have been considered as another lithology potentially favorable for REE concentration.

Molango area, Hidalgo
North of Molango, Hidalgo, the Huiznopala gneiss is exposed, and also in the core of the nearby Huayacocotla anticline, Veracrutz (Fries and Rincón-Orta, 1965; López-Ramos, 1980), and a Grenville age has been confirmed by Pachett and Ruiz (1987). The Huiznopala gneiss, with a total outcrop area of (~25 km²) is the smallest of four exposures of Grenvillian granulites in eastern and southern Mexico, the other localities being the Novillo gneiss, near Ciudad Victoria, Oaxaca Complex, and the Guichicovi Gneiss. Lithologically, three units are recognized by Lawlor et al. (1999): main series orthogenesis, anorthosite-gabbro complex, and layered paragneiss. The oldest stage included arc magmatism from ~1,200 to ~1,150 Ma, followed by granulate facies metamorphism with a peak at ~725 ± 50°C and 7.2 ± 1 kbar, and possible emplacement of the anorthosite-gabbro complex at ~1,000 Ma. Ductile deformation and granulate-facies metamorphism in this area closely corresponds to final thrusting and deformation in the Grenville Province.

However, neither in the Molango area, a small outcrop area of 5 km², nor in the Huayacocotla anticline, have economic metallic deposits been found. Nevertheless, a small, decimeter scale pegmatite that cuts the ductile fabric of the paragneiss has been found, and it consists of about 65% ilmenite, 20% plagioclase, 10% zircon and the remaining phases are rutile and an altered mafic mineral (Lawlor et al., 1999).

Novillo area, Tamaulipas
Further north in the Sierra Madre Oriental, Precambrian rocks are exposed in the Huizachal-Peregrina anticline. The important unit is the Novillo Gneiss, composed of garnet and pyroxene-bearing granulite, later subject to retrograde reactions (Ortega-Gutiérrez, 1978). Sm-Nd dates for the Novillo gneiss are about 1,000 Ma (Patchett and Ruiz, 1987). Strongly zoned garnets yielded higher temperatures and pressures in cores (729-773°C, 8.9-9.7 kbar) than in rims (642 ± 33°C, 7.9 ± 0.5 kbar), according to Orozco (1991).

At this locality, native gold occurs in veinlets. Fractures are oriented N10-12°W and inclined 25 to 34°NE, coinciding with the plane of foliation of the host rock. The gneiss is cut by numerous sulfide-bearing anodesite dikes, striking N80-90°E, inclined 80°SE. The gold is not disseminated in the gneiss (Eguiluz de Atuñano et al., 2004), and it is assumed by the authors that the gold was generated in a post-Grenvillian phase of extension.

Los Filtrus, Chihuahua
Several tectonic blocks of metagranite and amphibolites and minor gneisses are found within the Rara Formation of early Permian age (Ramirez and Acevedo, 1957), located in the Sierra del Cuervo, 30 km NNE of Chihuahua City. Hornblende from two amphibolite dikes gave ages of 1,024 and 1,037 Ma (Mauger et al., 1983). These Grenville ages are similar to those of intrusive granites in the Llano region of Texas (Zartman, 1964), and to hornblende ages in the Van Horn area (Denison, 1974), and Red Bluff Granite of the Franklin Mountains (950 Ma, Dennison and Hetherington, 1969). To date, no metal deposit is known at Los Filtrus, nor in subsurface lithologies tapped by PEMEX wells in northern Chihuahua.

Northern Sinaloa
The presence of Grenvillian basement beneath the northern part of the Guerrero terrane in northern Sinaloa has been invoked by Keppie et al. (2006), and is based on geochemical data including a recalculated TDM model age of 1238.4 Ma that is consistent with partial melting of the underlying basement. They further deduced that migmatized amphibolite-facies gneisses and amphibolites of the Francisco gneiss resulted from Miocene exhumation in a core complex of high grade metamorphic rocks.

Northern Sonora
Exposures of Precambrian rocks in northern Sonora were divided into two major regions by Anderson and Silver (1979), see Figure 3. The northeastern region was determined to have a 1.7-1.6 Ga age, whereas the southwestern terrane fell into the 1.8-1.7 Ga range (Paleoproterozoic). The oldest rocks are found in the Caborca terrane (Campa and Coney, 1983) or the Seri terrane of Sedlock et al., 1993. In the La Berruga hills, Anderson et al. (1979) recognized an assemblage of quartzite, schist, gneiss, and amphibolite, intruded by hornblende diorite and quartz latite, all overlain discordantly by orthogneiss. Quartz monzonite and granodiorite have suffered metamorphism and been converted to faser gneiss and generated segregations and pegmatities. Mineral assemblages characteristic of the amphibolite facies are widespread but greenish grade also occurs in the southwest part of the Berruga hills.

In northeastern Sonora, lithologies are commonly schistose or slaty and of greenschist grade and are correlatives of the Pinal Schist, Arizona (Anderson and Silver, 1979). However, both terranes have been intruded by anorogenic granites in the 1,500-1,400 Ma interval and by local micrographic granite of 1,100 Ma age, such as the Aibo granite of the Caborca area.

Moreover, the distinction of the two regions based solely on U-Pb zircon geochronology of igneous rocks has been criticized by Iriondo et al. (1999). They point to a continuity of Early Proterozoic magmatism from approximately 1.8 to 1.6 Ga, a ubiquitous ~1.4 Ga magmatic pulse followed by Grenvillian age (1.1 Ga) magmatic pulse in both regions, thus promoting the concept of a common magmatic evolutionary history during the Proterozoic.

The two terranes were thought to be separated by the controversial Mojave-Sonora Megashear (Silver and Anderson, 1974, Anderson and Silver, 1981), along which there is 700-800 km left lateral displacement, which occurred after middle Jurassic time. Evidence for lateral displacement comes from similarities between cordilleran miogeoclinical rocks in eastern California and those in the Caborca region, located on opposite sides of the megashear (Stewart et al., 1990). At the same time it can be noted that the younger terrane is continuous with cratonic rocks of adjacent parts of Arizona (Anderson and Silver, 2005). Recently, Premo et al. (2003) have used U-Pb zircon
chronology of the Paleoproterozoic basement of Sonora to show affinity with pulses of magmatism in the Yavapai and Mazatzal provinces of central Arizona.

Finally, a complete Late Proterozoic through middle Cambrian sequence of miogeoclinal strata has been recognized at Cerro Rajon, southeast of Caborca. It rests unconformably on the crystalline basement (Arellano, 1956; Stewart et al. 1984).

Within the Proterozoic of Sonora several mineral deposits are hosted by older crystalline rocks. In particular, and along the Sonora gold belt (Clark, 1998), several localities are worthy of mention, including the economic deposits at San Francisco and La Herradura. But at San Francisco, Pérez-Segura et al. (1996), using $^{40}\text{Ar}/^{39}\text{Ar}$ determinations, found that sericite alteration envelopes gave ages around 40 Ma, and the age of mineralization at La Herradura is also Tertiary (Pérez-Segura, 2008).

In reviewing fluid inclusion characteristics of several mesothermal gold veins in the gold belt, including Carina, Mina Grande, and El Tiro, Albinson (1989) notes the presence of significant amounts of CO$_2$ (up to 15% molar) which was taken into account in depth calculations of up to 4 km. In some places, veins truncate the regional metamorphic foliation, thus suggesting an age later than peak metamorphism. Nevertheless, the Sonoran Proterozoic basement is believed to be either the primary source or indirectly contributing to the CO$_2$ rich mineralizing fluids; gold and other metals being remobilized by post-Proterozoic metamorphic processes at a depth of 4 km at the El Tiro and Carina deposits, and consistent with a mesothermal temperature range. Also, the pH change due to CO$_2$ loss during boiling is important in mineral deposition (Hedenquist and Henley, 1985).

Other gold-bearing veins at La Joya, Sierra de Alamo, Cruz de Pino, and Jenoyema were emplaced in Mesozoic or Cenozoic host rocks at depths that vary from 2,000-1,500 m due to repetitive remobilization of CO$_2$-bearing fluids (Albinson, 1989). Recently, several gold deposits in the Sonoran gold belt have been dated and fall within the 60-40 Ma range (Pérez-Segura, 2008), and will be discussed later. In reviewing the compilations of all metallic deposits in Sonora by Pérez-Segura (1985) and Cendejas-Cruz et al. (1992), no deposits of confirmed Precambrian age have been identified.

Not found to date, as in adjacent parts of the United States, are volcanogenic copper-zinc massive sulfide deposits of Precambrian age, found in the Yavapai series in central Arizona. These include massive sulfide deposits in the Jerome area including the United Verde and Iron King deposits, and at Bagdad, located further to the west (Anderson, 1968). Mauger et al. (1965) obtained lead isotope model ages of 1,750 Ma and 1,640 Ma for the United Verde and Iron King deposit respectively. Later, the Old Dick deposit in the Bagdad area revealed a model age of 1,700 Ma (Doe, 1966).

**Proterozoic-Paleozoic tectonic evolution**

Based on paleontological inferences, McMenamin and McMenamin (1990) postulated a pre-Gondwana supercontinent and named it Rodinia (also known as Paleopangaea). The configuration of this supercontinent was ascertained by noting that at ~1.0 Ga and slightly older, a period of major orogeny occurred in widely separated parts of the world (Rogers and Santosh, 2004). Rodinia was broken up at about 0.7 Ga (Hoffman, 1991), and parts of the original continuous Grenville orogenic belt became attached to various continents. The orogenic belts at that time included the Grenville province of eastern Canada and its correlatives in Appalachia, Llano and west Texas, and Oaxaquia. However, in Mexico as noted earlier, it is still not entirely clear whether the Grenville localities of northern and eastern Mexico are continuous (Ruiz et al., 1988) or isolated allochthonous blocks (Sedlock et al., 1993).

Xenoliths associated with basic alkalic volcanic centers of Quaternary age in San Luis Potosi state, have been derived from the mantle and base of the crust (Aranda-Gómez, 1993). The Moho discontinuity in the region was calculated to be present at a depth between 33 and 46 km. By using isotopic data obtained from xenoliths in San Luis Potosi and El Toro in Zacatecas in central Mexico (Fig. 3), Ruiz et al. (1988) concluded that concealed lower crust exists in central Mexico that is similar to exposed Grenville localities. Furthermore, they inferred that phaneroczoic crustal genesis must have created part of the basement under central Mexico, probably of Paleozoic age. Also, they noted that west of the Precambrian exposures the basement contains significant amounts of Phanerozoic (probably Paleozoic) crust. Ruiz et al. (1988) suggested that the Paleozoic crust may have had it origins as one or more suspect terranes as suggested by Coney (1981), referred to as the Cordilleran model. An alternative interpretation is the Appalachian – Caledonian model that embraces continuity of Grenville and Paleozoic age rocks though Appalachia and Texas, southward through eastern Mexico to link with the Oaxacan and Acatixl complexes respectively, both models being offset in northern Mexico by the Mojave-Sonora megashear (see Ruiz et al., 1988, figs. 5a, 5b).

The Cordilleran model was discarded by Yanez et al. (1991) after assessing isotopic data from the Acatixl complex. Specifically neodymium model ages are unlike those of accreted crustal blocks of the Pacific margin.

The existence of a Mesoproterozoic Grenvillian microcontinent along the axis of the foregoing Appalachian-Caledonian model has been proposed by Ortega-Gutiérrez et al. (1995). The extent of this microcontinent is such that it stretches from the Oaxacan Complex northwards to Molango, Ciudad Victoria and beyond with possible extensions to the northwest (Solari et al., 2004). Its origins are considered to be in eastern North America and it is assumed to have taken up its present geographic location in late Paleozoic time.

The Proterozoic - Paleozoic lithologic record in southern Mexico was based on two tectonic cycles. The pre-Mississippian tectonic evolution of southern Mexico has been elicited as follows. In the Oaxacan Complex, miogeoclinal sedimentation, took place during the opening of a seaway in Mesoproterozoic time. It was followed by the emplacement of anorhhotic that forms the lower part of the complex (Ortega-Gutiérrez, 1981). Thereafter, these protoliths were subject to the Grenville orogeny with the production of granulite facies at 1,025 Ma, resulting in the formation of para- and othogneisses. Later pegmatites were intruded and uplift took place in Neoproterozoic time.

In contrast, the adjacent Acatixl Complex protoliths were developed by sedimentation in Cambro-Ordovician time in a pre-Atlantic (latanus) ocean simultaneously with the appearance of ophiolite. The consumption of this plate by convergence induced subduction probably ended in the Devonian as continental masses collided and produced a suture, today represented by a dismembered and eclogitized ophiolite of the present day Acatixl Complex (Ortega-Gutiérrez, 1981). This crustal thickening resulted in intense metamorphism and plutonism in
the Devonian (Acadian ?) orogenesis. The accreted protoliths appear to be underlain by Precambrian basement due to the presence of high-grade xenoliths in Cenozoic stocks up to 400 km to the west of the Caltepec fault zone that separates Mesoproterozoic rocks of the Oaxacan Complex from Paleozoic lithologies of the Acatlán Complex (Elías-Herrera and Ortega-Gutiérrez, 2002; Keppie et al., 2003). Subsequently, the Acatlán complex was overlain unconformably by unmetamorphosed strata of Mississippian through Permian age (Sedlock et al., 1993, Keppie et al., 2003), but there are deformed, metamorphosed rocks of late Paleozoic ages at the southern margin of the Mixteco terrane.

Tectonically, in early to mid-Devonian, the Oaxaca terrane collided with the Acatlán Complex and basement of the Mixteco terrane. The age of the collision according to Ortega-Gutiérrez (1981), Yanez et al. (1991), is indicated by metamorphic and deformation ages in the Acatlán Complex, ages of granite intrusion in both terranes, and the presence of clasts of both terranes in overlying Late Devonian marine strata.

Isotopic studies in the Acatlán Complex reveal three tectonothermal events, the first being at 400-380 Ma. This Devonian event has been interpreted as a Laurentia-Gondwana collision (Yanez et al., 1991). Later in Carboniferous time another event caused deformation in the complex, plutonic activity in southern Mexico and deformation in the Ouachita, Marathon and Appalachian belts, due to a second Laurentian-Gondwana collision (Yanez et al., 1991).

Subsequent to the foregoing tectonic scenarios Ortega-Gutiérrez et al. (1999) produced evidence of an earlier event based on new age, petrologic and field data. This event, named the Acatecan orogeny, appears to be the earliest manifestation of Gondwana-Laurentia collision and has been interpreted to have taken place in late Ordovician-Early Silurian time as the Oaxaquia microplate overrode the eastern margin of Laurentia.

Recently, the oblique collision between the Oaxaca and Acatlán complexes has been described along the Caltepec fault zone. This fault zone is regarded as a major terrane boundary and is characterized by dextral transpression (see Elías-Herrera and Ortega-Gutiérrez, 2002, fig. 11). The anatectic leucosome and the resulting syntectonic Cozahuico granite in the fault zone yielded Early Permian U-Pb zircon ages. Initial 87Sr/86Sr ratios and Sm-Nd model ages for the granite and leucosome indicate a migmatic mixture that originated from melted Proterozoic crust and a component of depleted mantle (Elías-Herrera et al., 2007). This event is related to the collision between Gondwana and Laurentia respectively and relates to the final consolidation of Pangaea. The overlying Matzitza Formation of Leonardian (Early Permian) age implies high cooling and uplift rates during the Permian. There has been tectonic reactivation along the Caltepec fault during the Early Cretaceous, Paleogene, and Neogene.

To the south of the Acatlán complex is the Xolapa complex that parallels the Pacific coastline, some 600 km long and 50-150 km wide (Ortega-Gutiérrez, 1981). It forms the basement of the Xolapa (Chatino) terrane. Essentially it comprises metasedimentary and metaigneous lithologies exhibiting amphibolite facies (Were-Keeman and Bustos-Díaz, 2001). The northern limit is marked by mylonites and cataclastic rocks that separate migmatites and granites of the complex from the adjacent Guerrero, Mixteca, and Oaxaca terranes. The age of the protolith is Proterozoic-Paleozoic (Herrmann, 1994) but the age of migmatization is Late Cretaceous-Early Tertiary. More recently, the more limited areal contact between the Xolapa Complex, which was intruded by granitoid igneous rocks of Paleogene to Miocene age, and the Oaxacan Complex, has been described along the Chacalapa fault. The age of the shear zone is late Oligocene (Tolson, 2007). The complex is overlain by Tertiary volcanic rocks.

A fourth metamorphic complex in southern Mexico is referred to as Tierra Caliente (Ortega-Gutiérrez, 1981), and is located in the Balsas River basin and south of the Trans Mexican Volcanic Arc, and is part of the extensive Guerrero terrane (Ortega-Gutiérrez, 1981). Low grade metamorphism in the complex permits identification of the original interbedded eugeosyncinal, sedimentary and volcanic units. Included here are informally named units such as the Taxco schist, Taxco Viejo greenstone and the volcano-sedimentary metamorphic sequence of Teloloapan-Ixtapan de la Sal, the latter being thrust eastwards over Cretaceous shelf carbonates of the Mixteca terrane platform. The age of various lithologic units based on paleontologic and limited radiometric data suggests an evolution that began in the late Paleozoic and continued through the Cretaceous (Ortega-Gutiérrez, 1981). The complex may have been accreted to the continental margin of Mexico by Late Jurassic time (Sedlock et al., 1993). In contrast, Cabral-Cano et al. (1993) conclude that thrusting at the eastern margin of the Guerrero terrane is related to the later Laramide orogeny without invoking accretion and the allochthonous nature of the Tierra Caliente metamorphic complex.

Elsewhere in Mexico, marine Paleozoic strata are found in several basins in Sonora, Chihuahua (Pedregosa), the main Chihuahua basin, and what Lopez Ramos (1969, 1979), has called the main geosyncline that stretches southward from Coahuila and Tamaulipas through Zacatecas, San Luis Potosi, Querétaro to the Huaycocotla anticline, Veracruz, and the Tlaxiaco basin in northern Oaxaca. The southernmost outcrops occur in the Chiapas-Guatemalan basin, but their relation to the main seaway is obscure. This was a narrow seaway, possibly linked to the Oauchita geosyncline.

The Cambrian section is best developed in the Caborca region of Sonora. Generally, Ordovician strata are less than 300m in thickness and have platform characteristics. The Silurian, according to López Ramos (1969) is poorly represented but is known at Placer de Guadalupe, Chihuahua (Bridges and Deford, 1961), and in the Ciudad Victoria area of Tamaulipas. The principal outcrops of Devonian strata occur in Sonora, Chihuahua and Tamaulipas.

The Mississippian units however, have wider distribution than any of the previous systems and are recognized from north to south in Mexico, as are the succeeding Pennsylvanian sequences. Nevertheless, it is the Permian outcrops that are the most widespread in Mexico. They are thickest in the main geosyncline that is bordered to the west by a positive area that would later be covered by much of the Sierra Madre Occidental volcanic plateau. To the northeast, there is another widespread emergent region.

In south-central Mexico, the most complete Paleozoic section crops out north of Nochistlán, Oaxaca, (Pantoja-Alor, 1970), and is unconformably overlain by Cretaceous rocks.

The late Paleozoic history of Mexico has been summarized by Vachard and Pantoja (1997), and subdivided into five intervals starting with Early Mississippian strata developed as a consequence of rifting after the Mixteca and Oaxaca terranes were joined. Osagean faunas are widespread at many localities throughout Mexico. The final interval considers a complex
paleogeography during late Permian time and the near complete emergence of Mexico thereafter except for a limited number of areas.

In northwestern Mexico, a passive margin existed at the southwestern edge of North America from latest Proterozoic to middle or late Paleozoic time, and was the site of cratonic and shelfal miogeoclinal strata. Basinal, eugeoclinal units were deposited in deeper water to the south and west (Sedlock et al., 1993). Cratonic sediments are found in northern Chihuahua and Sonora from Ordovician until the Mississippian and they are fringed peripherally to the south and west by shelfal strata in Sonora and Baja California (Seri terrane). The shelfal strata are overthrust by basinal rocks of Ordovician to Mississippian age that had been deposited on the ocean floor further to the south and west of the North American continent (Stewart et al., 1990; Sedlock et al., 1993).

**Limited metallization in Early Paleozoic time (470-397 Ma)**

In the large area of the Paleozoic, that includes metamorphosed, continental, and marine lithologies from Cambrian through Permian time, the documentation of metallic deposits of corresponding age is scant. This statement is based on an exhaustive search of the literature including the mining monographs of Oaxaca (Castro-Mora and Arceo y Cabrilla, 1996) and Sonora (Cendejas Cruz et al., 1992). However, summarizing the tectonic and metallogenetic potential of ultramafic-mafic complexes in Mexico, Ortiz-Hernández et al. (2003) note rocks of this affinity at the Novillo Canyon, Tamaulipas; El Fuerte, Agua Caliente, and Mazatlan, Sinaloa; and at Tehuitzingo-Tecomatlan, Puebla. At Novillo the values of Ni, Cr, Co and Pt in serpentinite are in trace amounts, and merit no further discussion. Of the three localities in Sinaloa, the El Fuerte and Mazatlán localities, while not dated isotopically, appear to be of Mesozoic age and will be discussed later. No mineralization is reported at Agua Caliente.

In southern Mexico, Puebla state, the Tehuitzingo-Tecomatlán complex is part of the Mixteco terrane characterized by Paleozoic basement (Acatlán Complex). The underlying Petlatingo Group is overthrust by the Piaxtla Group that contains thrust slices that represent obducted oceanic and continental lithosphere. The Piaxtla Group represents an accretionary prism that was possibly assembled in Siluro-Devonian time, unconformably overlain by the Tecomate Formation of Pennsylvanian-Early Permian age, and overprinted by Permo-Carboniferous deformation (Keppie et al., 2003). The lower part of the Piaxtla Group is represented by the Xayacatlán Formation that contains eclogitic mafic and pelitic rocks. The Xayacatlán Formation is considered to be older than Silurian (Meza-Figueroa et al., 2003) and has been intruded by Esperanza granitoids at 440-425 Ma. At Tehuitzingo and Tecomatlan, Ortiz-Hernández et al., (2003, 2006) note pods of chromite in serpentinitized host rocks with values of Cr (0.32%) and Ni (0.19%). Furthermore, the Tehuitzingo chromitites have low PGE contents, ranging between 102 and 203 ppb, typical of ophiolitic chromitites (Proenza et al., 2003). Thus the age of Tehuitzingo and Tecomatlan deposits is uncertain and although they have been assigned to the Late Paleozoic by Ortiz-Hernández et al. (2003, 2006), the protolith appears to be Early Paleozoic.

In the Tacaná region, located in southeastern Chiapas, adjacent Guatemala, in the Mazapa de Madero mineralized zone, a metamorphic complex that comprises anorthosites of the Chucúcs Group of (?) Early Paleozoic age Castro-Mora, 1999). They have been subjected to low grade metamorphism by Permian age (374 Ma) granite bodies of the batholith. In this mineralized zone, there are outcrops of titaniferous ore (ilmenite) with trace contents of chromium and nickel, mainly hosted in anorthositic rocks. These deposits form lenses and veinlets of ilmenite, the pods being up to 4.4 m long and 1.50 m wide, with irregular distribution (Castro-Mora, 1999; Castro-Mora and Ortiz-Hernández, 2000b).

**Creation of Pangea.**

Due to the convergence between Gondwana (which became a coherent supercontinent at ~500 Ma (Rogers and Santosh, 2004)), and North America (part of Laurasia), the intervening oceanic lithosphere was consumed as collision between two continents took place from the Mississippian to mid-Permian, resulting in the creation of Pangea at about 250 Ma. This collision produced the Ouachita-Marathon orogen in southwestern United States and the Tarahumara terrane that contains deformed basinal sedimentary rocks that were obducted onto the North American shelf (Sedlock et al.,1993). The Tarahumara terrane is not shown in Figure 4, but straddles the Chihuahua-Coahuila state line. The Ouachitan orogeny in eastern Mexico is known as the Coahuilan orogeny (de Cerna, 1960). In Pennsylvanian to Permian time, the western edge of the southern cordillera may have been truncated by an inferred sinistral fault system, which also terminated the Tarahumara terrane, its suspected trace being along the line of the future Mojave-Sonora Megashear (see Sedlock et al., 1993, fig. 32).

The latest reconstruction of the Gondwana-Laurentia collision is based on the models presented by Dickinson and Lawton (2001) followed by Elias-Herrera and Ortega-Gutiérrez (2002). The tectonic boundary between the Grenville-age Oaxacan Complex and the Paleozoic Acatlán Complex has been described above as an Early Permian event as the leading edge of Gondwana closed on Laurentia along the Marathon-Ouachita suture to form Pangea. The older Acadian (Early to Middle Devonian) orogeny previously described, has been discarded by Elias-Herrera and Ortega-Gutiérrez (2002) because Devonian deformation, metamorphism and intrusion by syntectonic plutons in the Acatlán Complex are unknown in the Oaxacan Complex.

Evidence from the Caltepec fault zone suggest oblique interaction between the Acatlán and Oaxaca blocks outboard of Gondwana during the final assembly of Pangea in early Permian time. Other consequences of this assembly include a Late Mississippian tectonic event with coeval silicic volcanism in the Ciudad Victoria area and the Late Mississippian-Early Permian Las Delicias arc in the Coahuila block. A similar reconstruction by Weber et al. (2006) emphasizes the position of the southern Maya block, including the Chiapas massif, relative to Gondwana.

**PERMO-TRIASSIC**

**Lithologies in Southern Mexico**

The lithologies associated with metallic mineral deposits of Permo-Triassic age are primarily located in southern Mexico, especially in the Maya tectonostratigraphic terrane (Fig. 4). In southwestern Chiapas and eastern Oaxaca, the Chiapas massif comprises metaplutonic and metasedimentary rocks. These lithologies have been derived from plutonic and sedimentary protoliths of inferred Neoproterozoic to early Paleozoic age (Sedlock et al., 1993). This massif contains granitoids of Permian, Triassic, Jurassic, and Cenozoic age. Pegmatite and
Figure 4. Paleozoic and Permo-Triassic metallic deposits in Mexico (after Clark and Fitch, 2009).
granitic bodies of latest Proterozoic age have been reported by Pantoja-Alor et al. (1974), López-Infanzon (1986), and Pacheco-G. and Barba (1986), whereas Burkart (1990) recognized Late Cretaceous intrusions. Older units are overlain unconformably by undeformed Carboniferous to Permian (?) strata according to Dengó (1985), and are probably correlatives of the Santa Rosa and Chochal formations respectively. Finally, in the eastern part of the Sierra de Juarez of northeastern Oaxaca, there are metamorphic rocks that consist of multiple deformations, gneisschist facies metasedimentary and metagneous rocks (Ortega-Gutiérrez et al., 1990) that have yielded late Paleozoic K-Ar dates.

The Chiapas massif is located in the southern part of a plutonic arc that has been identified also in eastern and northern Mexico (Damon et al. 1981; Torres et al., 1993). This is a calcalkaline belt located on the western margin of Pangea in northwestern South America in Early to late Permian time, being documented not only in Mexico but also in southwestern United States during the Late Permian-Early Triassic (Sedlock et al., 1993, fig. 31). Temporally, this overlaps with the mid-Permian cessation of Gondwana-North America convergence. The Chiapas batholith comprises biotite granite, and granodiorite (Castro-Mora and Ortiz-Hernández, 2000b). Batholithic phases intrude schists and quartzites of the Chucuar Group and younger phases invade the Santa Rosa Formation.

However, later investigations by Weber et al (2006) show that the Chiapas massif (~20,000 km²) is composed of deformed granitoids and orthogneiss with inliers of metasedimentary rocks, and so the term ‘batholith’ is no longer used. Data from orthogneiss reveal that the massif was part of an active continental margin of western Gondwana during the Early Permian (~272 Ma). Thereafter, latest Permian (254-252 Ma) metamorphism and deformation affected the whole massif and resulted in anatectic and intrusion of syntectonic granitoids. Also, data from a metapelitic yielded a Grenvillian source for the sediments, but para-amphibolite yielded 1.0-1.2 or 1.4-1.5 Ga sources and suggest South American provenances.

Mineral deposits in southern Mexico (265-228 Ma)

The Chiapas batholith complex, (Damon and Montesinos, 1978) is associated with polymetallic deposits, which Castro-Mora and Ortiz-Hernandez (2,000a) have divided into two assemblages, although in general, they both contain Pb-Zn-Cu-Ag-Au, for example, at Escuinilla-Pijijiapan (Fig. 4) and Las Palmas (Mapastepec). These intrusion-related deposits have not been directly dated; thus their inclusion in the Permo-Triassic mineralizing event should be treated with caution.

At the Teziutlán, Puebla, massive sulfide deposit (Fig. 4), the Cu-Zn assemblage is hosted by sericitic schist, phyllites, and basic metavolcanic rocks. The protolith consisted of Late Paleozoic (262-207 Ma) mudstones, sandstones, and basic lava flows (Chavez et al., 1999), as opposed to an Early Paleozoic age envisaged by Edelen and Lee (1941).

Permo-Triassic rocks of Eastern and Northern Mexico

In synthesizing the distribution of Permo-Triassic magmatic rocks in eastern and northern Mexico, Sedlock et al. (1993) concluded that magmatic arc rocks are present in a roughly linear swath that extends from Coahuila southwards to Chiapas, and, in fact, continues further south into neighboring Belize and Guatemala. These rocks have been penetrated by numerous petroleum wells drilled in the states of Veracruz, Nuevo Leon, and Tamaulipas (Fig. 1), along the Gulf of Mexico plain and their ages span 275-219 Ma. Surface outcrops occur in Coahuila in the Valle de San Marcos (242 Ma) and Potrero de La Mula (213 Ma). According to Sedlock et al. (1993) this arc, which extends into southwestern United States and southwestern South America, probably formed on the western margin of Pangea above an east-dripping subduction zone that consumed oceanic lithosphere located west of Pangea. The Mexican part of the arc may have been partially disrupted by later tectonic events, although initially it may have been laterally continuous. In Coahuila, the Las Delicias arc as portrayed by McKee et al. (1999), is known for the debris shed into the Las Delicias basin and preserved as the Las Delicias Formation. The basin and arc were active from Mid (?) -Pennsylvanian throughout most of the Permian (McKee et al., 1998). Las Delicias arc is also characterized by shallow, syndepositional plutons as old as the Rancho Pesuña rhylolite (331 Ma) and the Coyote pluton (220 Ma), the latter possibly representing late arc magmatism, a view not shared by López (1997).

Absence of Permo-Triassic metallic deposits in Northern Mexico

The Permo-Triassic metamorphic and metasedimentary rocks within Coahuila do not contain metallic deposits of economic interest (Duran-Miramontes, et al., 1993), and apparently this also holds for the magmatic arc rocks. In neighboring Chihuahua at Placer de Guadalupe, Bridges (1964) has described an overturned sequence of Ordovician through Permian sedimentary sequence, including a rhyolite flow of early Permian age (de Cserna et al., 1968). However, the age of the nearby Plomosas mine manto deposit (Escandon, 1971) is interpreted as Oligocene by Megaw et al. (1968).

Elsewhere in Chihuahua, Clark and de la Fuente (1978), and Duran-Miramontes et al. (1994) were unable to successfully document metallic deposits of Permo-Triassic age or older. Further west in Sonora, after an hiatus in deposition that spanned much of the Late Permian to middle Triassic time, deposition resumed in the Late Triassic (Stewart et al., 1990), and consists of two contrasting facies. Marine strata are located west of Caborca (Gonzalez-Leon, 1980), whereas the Barranca Group of east-central Sonora has been interpreted as siliciclastic deposits in a rift basin that contains a few thin layers of tuff (Stewart and Roldan, 1991). However, there are no known metallic deposits of Permo-Triassic age in Sonora (see Pérez-Segura, 1985, p.60).

Thus, there are no known analogous lead-zinc deposits of the Mississippi Valley-type (MVT) of the United States mid-continent region, where host rocks are Paleozoic in age, possibly because of limited intracratonic basins covered with relatively thin sequences of sedimentary rocks. In southeastern and central Missouri and also in the Arkansas-Tri State area, MVT ores have several similarities (Leach and Rowan, 1986), and subsequently their Permian age of mineralization was determined by paelomagnetic methods (Simons et al., 1997). Metallization corresponds to uplift during the Ouachita orogeny, when the outboard Lanorian plate impacted the North American plate, a scenario that may have analogous potential in Mexico.

Ophiolitic rocks are found in the Vizcaino peninsula and have been interpreted as being remnants of island arcs formed on Late Triassic oceanic crust and subsequently accreted to the continent in Late Jurassic or Early Cretaceous time (Ortiz-Hernandez, et al., 2003). At El Tigre (Fig. 4), lenses of chrome
contain up to 48.7% Cr₂O₃ and there are indications of Ru-Os-Ir (Vatin-Perignon et al., 2003). During 1982-1993, 13,000 t of chromite ore were extracted. Finally, the ophiolite and volcanic arc assemblages on the Vizcaino peninsula and nearby Cedros Island are interpreted by Kimbrough and Moore (2003) as autochthonous or parautochthonous forearc lithosphere constructed outboard of the Mesozoic continental margin arc, that correlate with ophiolitic terranes in western California and Oregon.

**JURASSIC-EARLY CRETACEOUS**

The breakup of Pangea began in the Late Triassic, although the formation of the Caribbean basin did not begin until the Earliest Cretaceous (Sedlock et al., 1993). This was accomplished by pre-Cretaceous rifting in two stages (Buffler and Sawyer, 1983). First, Late Triassic to Early Jurassic rifting took place in the Gulf region of eastern Mexico, and the depressions were filled with red beds and volcanic rocks. Later, in middle- to- late Jurassic time, a thin, transitional crust formed around what would become the Gulf of Mexico with Late Jurassic spreading in the deeper part of the basin. Whether or not displacement along the Mojave-Sonora Megashear was linked to the opening in the Gulf of Mexico, as envisaged by Pindell and Dewey (1982) and Anderson and Schmidt (1983), or was due to transpression in the Cordillera, as favored by Sedlock et al. (1993), has yet to be resolved.

In the cordilleran region, Late Triassic to Late Jurassic eastward subduction generated magmatic arcs that occur in southwestern North America and northwestern South America (Sedlock et al., 1993). In Mexico two groups are recognized. The first group formed Jurassic arc magmatism approximately concordant with the Permo-Triassic arc in Mexico in the southern Maya terrane, but was located southwest of the Permo-Triassic arc in the northern Maya and Coahuila terranes. A second group formed a continental arc further west or an island arc west of the continental margin (Sedlock et al., 1993), as terranes comprising continental blocks and island arcs were accreted to the western margin of Pangea in the Mexican region.

The first group is part of a Late Triassic-Jurassic arc stretching from southwestern United States to northwestern South America (Damon et al. 1984). This arc was cut by the Mojave-Sonora Megashear along the trend of the arc in northern Sonora where continental volcanic rocks (>180 to 170 Ma) were intruded by 175 to 150 Ma plutons (Anderson and Silver, 1979) and are correlated with rocks in southern Arizona. Sedlock et al. (1993) provide evidence of magmatism associated with the first group of arc rocks in the Acatlan, Chatino, and Yuma terranes. Plutonic rocks in the northwest and volcanic rocks in the northeastern parts of their Tepehuano terrane, and middle Jurassic rocks in the Caborca terrane, are probably parts of the arc that were displaced southeastward from the Mojave region or northwestern Sonora in Late Jurassic time. In the east-central part of the Guerrero (southern Tepehuano) terrane, the upper Jurassic Chilitos Formation may have been part of a continental arc. In the northern and southern parts of the Sierra Madre terrane, volcanic and plutonic rocks, penetrated by wells (Lopez-Infanzon, 1986), gave Jurassic ages, and in the Chiapas Massif there are early- to- middle Jurassic granitoids and Late Jurassic or older andesites.

The second group includes all other Late Triassic to Late Jurassic magmatic rocks in Mexico. Early Cretaceous plutonic, volcanic, and volcanoclastic rocks that were probably parts of oceanic island arcs, later accreted to North America by earliest Cretaceous time (Sedlock et al. 1993). Additionally, both the eastern and western parts of the Vizcaino (Yuma) terrane contain minor volcanic rocks, and the western region consists mainly of Late Jurassic and more abundant Early Cretaceous volcanic rocks. Further south in the southern part of the Guerrero (Nahuatl) terrane, intermediate composition volcanic rocks are widespread. Thus the apparent absence of continental crust in the Vizcaino (Cochimi and Yuma) terrane, La Paz (Pericu) and southern Guerrero (Nahuatl) terranes, is interpreted by Sedlock et al. (1993) as indicating that Jurassic magmatic rocks in these regions were formed in an island arc environment. The net result of piecing together these various Jurassic-Early Cretaceous magmatic locales is to produce a widespread arc rocks that is continuous from the northern Caborca (Seri) terrane, to the Chiapas Massif (see Sedlock et al. 1993, fig. 36).

**Jurassic-Early Cretaceous metallic deposits (191-110 Ma)**

**Porphyry copper deposits**

The number of positively identified metallic deposits of proven Jurassic-Early Cretaceous age is limited, particularly in comparison with the succeeding Late Cretaceous-early Miocene interval. Nevertheless, more mineralization diversity is apparent including a porphyry copper deposit that has been recognized at El Arco in Baja California described by Barthemly (1974, 1975). This deposit (Fig. 5) was interpreted to be associated with a granodiorite porphyry dated at 107 Ma, and is located within the batholithic zone that stretches from southern California and northern peninsula California in the Guerrero (Yuma) terrane throughout a large part of western Mexico, a distance of at least 2,700 km as envisaged by Gastil et al. (1976). However, more recent Re-Os are U-Pb dates of the El Arco deposit give a Middle Jurassic age of 164.7 ± 6.5 Ma from a granodiorite porphyry that hosts Cu-Au-(Mo) mineralization (Valencia-Moreno et al., 2006). Thus the volcanic-plutonic rocks of the El Arco-Calimali area are probably associated with the San Andres-Cedros volcanic-plutonic complex (~166 Ma), and likely part of an intraoceanic arc system which was accreted to the continent during the Cretaceous (110-98 Ma).

In southern Mexico in the Maya terrane, the San Juan Mazatlán porphyry copper prospect has been dated at 191 Ma (Damon et al., 1983a), and in Michoacán, the Inguaran mine, located near the southern limits of the Trans-Mexican Volcanic Belt where it overlaps the southern Guerrero (Nahuatl) terrane, was cited by Sillitoe (1976) as having an age of 100 ± 10 Ma. But later K-Ar determinations at Inguaran by Damon et al. (1983a) on biotite and sericite in brecciated rock gave 35.6 and 32.1 Ma respectively. Another porphyry copper deposit worthy of mention is Bisbee, Arizona, located approximately 10 km north of the Sonora-Arizona, line (Bryant and Metz, 1966). The age of the Bisbee deposit, first determined by Creasy and Kistler in 1962 at 178-163 Ma, was assigned to the Jurassic magmatic arc by Clark et al. (1979a).

There are several deposits in Baja California state that probably are pre-Laramide in age including from west to east mesothermal iron and copper related to granite intrusives; gold in metasedimentary rocks; and tungsten at deep-seated contacts in carbonate-bearing metasedimentary rocks (Gastil et al., 1975). Several of these deposits had been reported on from the 18th century onwards, including Wisser (1954) who remarked on the presence of small, mineable gold deposits within the plutonic massif (batholith) of the peninsula, and the magnetite-hematite deposits and the minor stocks with which they are associated.
Figure 5. Volcanic massive sulfide, porphyry copper, red-bed copper, and mafic-ultamafic rock deposits of the Jurassic-Early Cretaceous interval (from Clark and Fitch, 2009).
that lie in the Alisitos Formation of Albian-Aptian age. At the south end of the peninsula there are several gold deposits associated with the batholithic rocks of the La Paz (Pericu) block, but these are predominantly of Late Cretaceous age (Sedlock et al., 1993), and will be discussed in a later section.

An Early Cretaceous continental magmatic arc was active along the southwestern margin of Mexico, stretching from the Caborca (Seri), La Paz (Pericu), Vizcaino (in part Yuma) and western and southern parts of the Guerrero (Tahue and Nahuatl) terranes. This arc includes volcanic and plutonic phases, but in the Xolapa (Chatino) terrane, orthogneiss that yield 160-128 Ma dates, may represent granitoid intrusions prior to deformation and metamorphism. In the southern part of this widespread arc, several volcanicogenic massive sulfide deposits occur.

Volcanogenic massive sulfide deposits
The volcanicogenic massive sulfide and sedimentary exhalative deposits have been exploited in southern Mexico since the 19th century, (Clark, 1999), with mining initiated at El Rubi in the Zihuatanejo subterrane in 1850 (Miranda-Gasca, 1995). The deposits (Fig. 5) are primarily in Guerrero, Jalisco, Mexico, Michoacán, and Puebla states. The principal group of deposits containing the Zn-Pb-Cu-(Ag) assemblage is in the southern part of the Guerrero terrane. Limited gold values are found in the Campo Morado, (Oliver et al., 1997, 1998), Campo Seco, and Rey de Plata deposits (Chavez et al., 1999).

In general, this region consists of variably deformed and metamorphosed sedimentary and volcanic rocks of Jurassic to Cretaceous age. Mid-Cretaceous and Tertiary plutons intrude the volcanosedimentary sequences, and Tertiary volcanic rocks cover parts of the subterrane that host massive sulfide deposits.

Various hypotheses have been advanced for the development of the southern Guerrero terrane. They include plate-tectonic scenarios of Campa and Ramirez, 1979; Coney, 1983; and Ramirez et al., 1991. More recently Centeno-Garcia et al. (1993), using REE and Nd isotopic data concluded that there were two stages in the development of the southern Guerrero terrane. The first stage is recorded in the Arteaga Complex subterrane that may represent an accreted oceanic sequence, whereas the second stage was the development of an intraoceanic island arc above the Arteaga Complex. Basaltic pillow lavas of the Arteaga Complex indicate Mid-Oceanic Ridge Basalt (MORB) affinity, and were considered to be part of an oceanic basin that received sediments derived from a continental source (Acatlán and Oxaca Complexes?). The overlying Jurassic-Cretaceous arc-related rocks have initial $\Sigma$Nd and REE patterns similar to those of evolved intra-oceanic arcs.

The Guerrero terrane has been subdivided into several subterranea that border the southwestern coastline of Mexico, and are located to the north and south of the Trans-Mexican Volcanic Axis. The Teloloapan (Ixtepan), Huetamo, and Zihuatanejo sub-terranea were first described by Campa and Coney in 1983, and subsequently other subterranea have been recognized.

Miranda-Gasca (1995) has described over 60 VMS deposits in the Guerrero terrane, varying in tonnage from less than 100,000 t up to 6 Mt. Most of the deposits are of the Kuroko type (Zn-Pb-Cu) and are located in the Zihuatanejo and Teloloapan subterranea. The Guanajuato and Calmalli deposits contain the Zn-Cu assemblage.

Recently, Mortensen et al. (2008) have dated several VMS deposits in the Guerrero terrane by U-Pb methods and find that they are in a restricted time interval from latest Middle Jurassic to Early Cretaceous. The oldest age was obtained in the Cuale district (157.4 Ma) and the youngest is recorded from the Tlalnipe-Azulaquez district (139.7 Ma).

Teloloapan subterrane
The Teloloapan subterrane is characterized by calc-alkali basalt, andesite, and scarce rhyolite (Talavera 1993), all of which are interbedded with greywacke, shale, and limestone. The rocks have been strongly deformed and metamorphosed to zeolite and greenschist facies. Three lithological facies have been recognized by Heredia-Barragán y Garcia-Fons (1989): (a) volcanic, characterized by submarine extrusions with interfingeringsubordinate amounts of sediment; (b) pelitic, with minor amounts of submarine volcanic rocks; and (c) transitional facies, in which neither rock type predominates. Major volumes of massive sulfide are linked to possible exhalative sources with mill rock, a product of explosive phases of siliceous volcanism and characterized by quartz-sericite-pyrite alteration (Heredia, 1997). In the Campo Morado group, there are 12 deposits of which La Reforma is the most important, followed by Suriana and El Naranjo (Miranda-Gasca, 1995; Cluff et al., 2009). Most of the volcanicogenic massive sulfide deposits occur in a felsic volcanic unit of Early Cretaceous age and calc-alkaline affinity, near the contact with the stratigraphically overlying, fine-grained sedimentary strata. Heterolithic fragmental rocks occur in the main felsic volcanic unit (Oliver et al. 1997), see also Cluff et al. (2009). Mortensen et al. (2008) indicate that the Campo Morado deposits formed between 146.2 and 142.3 Ma.

Other deposits in the Teloloapan subterrane include Rey de Plata, the Azulaquez group, Santa Rosa, and the Tizapa group. The $^{206}\text{Pb}/^{238}\text{U}$ ages in the Tlanilpa-Azulaquez district are 139.7 Ma (Mortensen et al. (2008). These deposits form a north-trending belt some 115 km in length and 50 km wide (Heredia, 1997). The deposits contain up to 6 Mt of ore, with Campo Morado, Tizapa, and Rey de Plata the most significant (Miranda-Gasca 1995). Overall, along the eastern margin of the subterrane in Guerrero state, the Teloloapan assemblage is thrust eastward over Cretaceous shelf carbonates of the adjacent Mixteca terrane (Campa et al. 1976). Both proximal and distal volcanicogenic deposits occur within an island-arc regime bordering the Morelos platform (Heredia, 1997).

Zihuatanejo subterrane
The Cuale deposit contains several orebodies that occur in shale and volcanoclastic rocks of Late Jurassic-Early Cretaceous age that overly porphyritic rhyolite domes (Miranda-Gasca,1995).They have been described in detail by Macias-Romo and Solis-Pichardo (1985) and Berrocal and Querol (1991). The Cuale deposit, that contains high Ag ± Au grades when compared to similar deposits in western Mexico, has been dated at 157.2 to 154.0 Ma by Bissig et al. (2008) who employed zircons and the U-Pb method. The ages of other deposits in the Cuale region (El Rubi, El Desmoronado, La America, and El Bramador), are less well constrained than at Cuale. Similarly, a precise age of the host rocks is unknown at La Minita in northwestern Michoacán, but may be Early Cretaceous (Gaytan-Rueda et al., 1979). The lead-rich Arroyo Seco deposit, located in the southern part of Michoacán, was considered to be a sedex type by Chavez et al. (1999), and is located in the Tepalcatpec Formation which lies above the contact with the Arteaga Complex (Mortensen et al., 2008). This formation contains Albian to Cenomanian fossils which suggest that Arroyo Seco is no
older than late Early Cretaceous. At the El Encino iron mine in southernmost Jalisco, Chavez et al. (1999) list this deposit as a VMS type, hosted in Early Cretaceous rocks.

Northern Guerrero terrane

Three occurrences of stratiform sulfides have been located close to Guanajuato city. The San Ignacio, (Cu-Zn), Yolanda, and Arroyo de Cata deposits are small lenses hosted in black slates interbedded with propylitized and andesitic and basaltic flows and rhyolite plugs (Macias-Romo et al., 1991). Miranda-Gasca (1995) notes the igneous rocks dated by K-Ar methods have ages from 157-114 Ma. However, precise age determinations have only been made at El Gordo from a rhyolite flow in the footwall of the deposit which gave 146.1 Ma (Mortensen et al., 2008).

In northeastern Baja California, there is a part of the Guerrero terrane that presumably has been translated to the northwest as the peninsula developed. The Calmalli deposit is a stratiform sulfide deposit identified by Echavarri and Rangin (1978). It is hosted by basaltic flows in thin shales that have been subjected to greenschist metamorphism (Miranda-Gasca 1995), and like the deposits at Guanajuato, contains <1.0 Mt of resources.

The Olivos deposit, a small sulfide body in southern Chihuahua, occurs in a volcanosedimentary sequence near the junction between the Parral and Cortez terranes (Fig. 5). Mineralization is associated with carbonaceous shales and intercalations of andesite and rare felsic beds, all exposed in an erosional window and metamorphosed to greenschist facies (Comaduran, 1996; Gastelum-Morales y Comaduran-Ahumada, 1997).

More recently and by far the largest discoveries have been made in Zacatecas state, and north of the Trans-Mexican Volcanic Belt. This region, a high plateau (altiplano) to the southwest of the carbonated-hosted deposits in the Sierra Madre (Oriental) terrane (Megaw et al., 1996), is separated by a major tectonostratigraphic terrane boundary (Fig. 5). Traces of Bi, and possibly also Te, are characteristic metals associated with the Guerrero terrane, but are not found in the Sierra Madre Terrane (Yta and Barbanson 1993). The Zacatecas region is also well-known for its younger skarn and vein deposits.

In Zacatecas, beneath the wide basins covered by Quaternary deposits, and in outcrops at other localities, there are Late Jurassic-Cretaceous sedimentary and volcanic rocks in a lobe of the Guerrero terrane. This region is underlain in part by Triassic and possibly Paleozoic crust. The volcanosedimentary sequence has been recognized from the Fresnillo mining district in the northwest to just east of Noria de Angeles in the southeast, a distance of approximately 140 km.

In the Francisco I. Madero area the coexistence of synsedimentary sulfide deposits of Mesozoic age that host Tertiary veins that are found between Guanajuato and Fresnillo was recognized by Gómez-Caballero in 1985 (Arturo Gómez-Caballero, written personal communication, March, 2009). The veins are easily identifiable by their 200-600 g/t Ag and up to 6% Cu content, and include rare minerals containing Cu and Bi.

In the Francisco I. Madero (Madero) deposit, a lower lithological unit is composed of sericite-chlorite schist overlain by a pelitic-carbonate sequence, followed upwards by calcareous units, locally containing lavas, volcanoclastics, and siltstone of early Cretaceous age (Yta 1993). This deposit has been interpreted to be of sedimentary exhalative origin, by Miranda-Gasca (1995) and contains 36 Mt of Zn-Pb-Ag-(Cu)

mineralization, part of which includes sulfides of epigenetic origin. However, Yta (1993) postulated a high-temperature replacement origin because of the presence of granite apophyses and the metamorphic minerals garnet and diopside, that coexisted with ore minerals. Synsedimentary, non-economic pyrrhotite mineralization was, nevertheless, recognized. See also Gonzalez-Villalvazo and Lopez-Soto (2009).

Later, other discoveries in the same volcanosedimentary sequence have been made at San Jeronimo, which is 20 km south of the city of Zacatecas ( Western Copper Holdings,1998a). Two drillholes have resulted in the identification of massive sulfide and high-grade vein-silver potential (Western Copper Holdings, 1998a).

Further southeast and to the north of Noria de Angeles, are the El Salvador and San Nicolas massive sulfide deposits that contain a Zn-Cu-(Ag-Au) assemblage (Western Copper Holdings, 1998b). The El Salvador Cu-oxide zone, discovered in mid-1996, is a relatively flat-lying, massive sulfide body that varies from 1 to 13 m in thickness. The San Nicolas deposit described by Johnson et al (1999), is reported to contain 83.4 Mt of sulfide resource. These deposits are latest Jurassic in age and are associated with mafic and felsic volcanic flows. Four U-Pb ages from the San Nicolas and El Salvador deposits show that felsic volcanic units adjacent these deposits formed from 151.3 to 147.9 Ma (Mortensen et al., 2008).

Other VMS deposits

Of the remaining deposits, Kless (1970) considered the copper-rich La Dicha deposit to be Paleozoic in age but later, Sabanero-Sosa (1990) assigned the Ixcinatoyac Formation, which contains La Dicha deposit, to the Late Jurassic-Early Cretaceous interval, which would be similar to the majority of VMS deposits described above, albeit that La Dicha occurs in the Mixteca terrane (Fig. 5).

The Copper King deposit that also contains the Cu-Zn assemblage is located in a basaltic sequence of Las Ollas Complex and is thought to be of early to middle Mesozoic age (Mortensen et al., 2008), and 40Ar/39Ar ages of gabbroic dikes that cut the Las Ollas Complex vary from 112± 3.0 to 96.3 ± 25.5 Ma (Ortiz-Hernandez et al., 2006), and consequently suggest a pre-late Early Cretaceous age. However, stratigraphically below the Copper King deposit, intrusions of gabbro and leucomonzonite yielded a Rb-Sr isochron age of 311 ± 30 Ma (Pennsylvanian), see de Cserna et al. (1978), which may indicate a possible older age of the deposit.

Red-bed copper deposits

Stratiform copper deposits in northeastern Chihuahua were first identified by Weed (1902). Subsequently, they have been studied by King and Adkins (1946), de la Fuente (1973), Giles and Garcia, (1973) and Clark and de la Fuente, (1978) who recognized their distribution relative to other deposits in Chihuahua. More recently, Price et al. (1988) provided more details of these deposits, particularly their geochemical characteristics.

The copper ores occur in fine-grained, marine sandstones of the Early Cretaceous La Vagas Formation, deposited in the Chihuahua trough over an area of 12,000 km² in a sedimentary basin filled with Jurassic and Cretaceous deposits of evaporites overlain by clastics and limestones. The copper deposits display characteristics typical of red-bed copper ores including discontinuous lenses, with copper sulfides cementing sand
grains. De la Fuente (1973), recognized 10 mantos in the Las Vigas Formation with an average thickness of 1.0-1.5 m, containing as much as 3 percent Cu, of which 58 percent is sulfide ore. Oxidation products include malachite, azurite, and tenorite. Significant alteration halos are absent. Silver values are less than 24 g/t, the highest of 9 samples, and gold was less than 0.0049 g/t a marked contrast with silver-copper veins in red-bed sequences in adjacent parts of Texas (Price et al., 1988), that are notably enriched in silver.

In addition to the deposits in Las Vigas area, a similar stratiform copper deposit has been described at Samalayuca (Bruno, 1995), but the age of the deposit is problematical (Molina, 1997). Finally the arkosic San Marcos Formation of earliest Cretaceous age, in neighboring Coahuila state contains disseminated copper (Durán-Miramontes et al., 1993).

Manganese deposit

Exploration and development of the Molango district ores began in the 1960’s. This deposit is by far the largest in North America (Okita, 1992, see also Pérez-Tello (2009). Sedimentary manganese occurs at the base of the Chipoco facies of the Taman Mixto Formation of Late Jurassic age (Duenas-Garcia et al., 1992), in the form of rhodochrosite and manganano calcite. The deposit formed in a restricted marine environment (Okita, 1992), perhaps related to fluvial sediment loads or sea-floor hydrothermal activity associated with the development of the Gulf of Mexico. Manganese oxides were subsequently derived directly from the carbonate facies by secondary oxidation and leaching to form weathering products (Alexandri and Martinez, 1991). This deposit has been assigned to the Jurassic-Early Cretaceous interval (see Fig. 5), based on the age of the formation.

Mafic-ultramafic rock deposits

As seen in Figure 5, there is a cluster of mafic-ultramafic rocks in Sinaloa located in part of the Guerrero (Tahue) terrane. These include, from north to south the Macochin and El Realito occurrences (Mullan, 1978). The larger Macochin intrusion is interpreted as a lopolith, 50 km in diameter and at least 1 km thick. In both intrusions, gravity-layered hornblende cumulate forms a basal ultramafic zone, and the opaque phase is ilmenite, partly altered to sphenite.

At Bacubirito, ophiolite (Servais et al., 1986), there are anomalous values of Pt and Pd (Bustamante-Yanez et al., 1992). It was first described by Ortega-Gutiérrez et al. (1979). This locality was further investigated for platinum group minerals by Consejo de Recursos Minerales, which revealed that mineralization was a surficial phenomenon and not disseminated throughout the body (Arturo Gómez-Caballero, written communication, March, 2009). The relation of this mineralization to the impact of the largest metallic meteorite in Mexico at Bacubirito (Ward, 1902; Haro, 1931) remains a possibility.

At the Alisitos locality, the first report of Ni and Au was made by Kreigner and Hagner (1943), and this was followed by another report by Clark (1973). Later, Ortiz-Hernandez et al. (2003) report Ni-Au mineralization in peridotite and latite represented by native gold, nicolite, maucherite and gersdorffite. Ni values are 0.096-0.34% and Co is from 37-45 ppm.

The mina Culiacán locality is located 27 km northeast of the capital of Sinaloa and comprises a troctolitic rock pendant 4 x 7 km in size above granodiorite of batholithic proportions found throughout the state (Clark, 1973). Hydrothermal mineralization is fracture controlled, and the brecciated host rock contains the assemblage Fe-Ni-Co-As (Ortiz-Hernández et al., 2003). Nicolite is the principle Ni-bearing mineral and selected samples contain up to 4.9% Ni, and an average value of 20 ppm Pt. Cerecero-Luna et al., (1984) estimate potential reserves at 200,000 t grading 0.4-1.0% Co, 2 g/t Au, and 0.5% Ni.

Two outcrops of Jurassic (?) age gabbro were mapped by Fredrikson (1974) and occur approximately 20 km north of Mazatlán. Plagioclase – clinopyroxene ± hornblende gabbro is the dominant rock type in both bodies (Henry et al., 2003). Cumulus layering parallels contacts, bedding, and schistosity in the surrounding metasedimentary rocks. Rodríguez-Torres (2000) reported on platinum-group metals in this area, and Ortiz-Hernández et al. (2003) note indications of Ni and Cr in ultramafic phases.

South of the Trans-Mexican Volcanic Belt four serpentinitized mafic-ultramafic rock localities are found along the coast of Guerrero (Ortiz-Hernández et al., 2006; Fig. 5). At Camalotitio, scarce disseminations of chromite and pentlandite are replaced by bravoite and violarite (Morales-Velasquez et al., 1985).

The mineralized rocks at Loma Boya occur as a roof pendant on granitic batholith rocks. Values of Cr are as high as 18%, whereas Ni content is up to 1400 ppm.

At El Tamarindo, Cr values vary from 2.7-8.0% and Ni varies from 2,900-3,600 ppm (Ortiz-Hernández et al., 2003).

The fourth locality at Las Ollas, located to the south of the El Tamarindo occurrence in southernmost Guerrero (Nahautli) terrane, although barren of mineralization has been dated at 112 ± 3.0 – 96.3 ± 2.5 Ma (Early Cretaceous) according to Ortiz-Hernández et al. (2003). Further inland and in southernmost Mexico State serpentinitized mafic-ultramafic rocks host indications of Cr, Ni, and Co at Palmar Chico – San Pedro Limon, where Early Cretaceous isotopic age determinations have been made by Deigado-Argote et al. (1992).

In central Mexico, in Guanajuato State, at San Juan de Otates, a complete section of allochthonous oceanic arc rocks (Ortiz-Hernández et al., 1989b; Lapiere et al., 1992) have been dated at 113-112 ± 7.0 Ma. Values of Cr vary from 105-499 ppm, whereas Ni varies from 49-135 ppm.

LATE CRETACEOUS – EARLY MIOCENE Tectonic Evolution

This interval is characterized by the amalgamation of various terranes along the western flank of Mexico which subsequently became part of the North American plate (Sedlock et al., 1993). All these terranes were inboard of a trench along which oceanic lithosphere of the Farallon plate was subducted during Cretaceous-Paleogene time. Subduction was accompanied by magmatism, accretion and the Late Cretaceous-Paleogene Laramide orogenesis.

In Sonora and Sinaloa the resultant lithologies of the foregoing tectonic events were the emplacement of granitoid batholiths and other plutons, and also the formation and widespread distribution of two major volcanic sequences, all of which became host rocks for a variety of mineral deposits as described below. The Sierra Madre Occidental (SMO) continental volcanic arc had been divided into two great calcalkaline volcanic sequences by (Wisser, 1966), who referred to them as the lower andesite series and the overlying rhyolitic sequence (caprock). Later, Clark et al. (1976, 1979a,b) referred to these two groups of volcanic rocks as the Lower and Upper Volcanic Series, also known as the Lower Volcanic Complex and the Upper Volcanic Supergroup of McDowell and Keizer (1977) and McDowell and Clabaugh (1979). The latest subdivisions in SMO are taken from Ferrari et
that is, north of the Trans-Mexican Volcanic Belt. Among the
classes were emplaced primarily in northern and central Mexico,
years, from Late Cretaceous through early Miocene time a
sinistral lateral faulting activated NW-SE and N-S faults during
granodioritic and tonalitic compositions predominate.
Including batholiths (Moran-Zenteno et al., 2007), in which
southwestern Mexico is characterized by numerous plutons
coastal Michoacán to Oaxaca. Thus, the Pacific coast of
Oligocene age developed along the continental margin from
northwestern Oaxaca.
Later volcanism, including compositions
2007). Latest Cretaceous to Early Paleocene plutonism in the
with time, generally with easterly vergence (Moran-Zenteno et al.,
deformation included E-W shortening that migrated to the east
in Tamaulipas (Bloomfield and Cepeda, 1973) to
San Andres Tuxtla (Cantegral and Robin, 1979), and coincide
with intraplate extension in northern Mexico (James and Henry,
1991). In Veracruz, Hidalgo and Puebla, Miocene and younger
rocks were formed in arc or backarc environments. Mid-Miocene
rocks are calc-alkalic and are probably related to subduction of
the Cocos plate in southern Mexico, whereas late Miocene to
Recent rocks are alkalic and calc-alkalic and were erupted in an
extensional back arc regime (Sedlock et al., 1993).
In eastern Mexico, alkaline rocks decrease in age southwards from
Oligocene in Tamaulipas (Bloomfield and Cepeda, 1973) to
San Andres Tuxtla (Cantegral and Robin, 1979), and coincide
with intraplate extension in northern Mexico (James and Henry,
1991). In Veracruz, Hidalgo and Puebla, Miocene and younger
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rocks are calc-alkalic and are probably related to subduction of
the Cocos plate in southern Mexico, whereas late Miocene to
Recent rocks are alkalic and calc-alkalic and were erupted in an
extensional back arc regime (Sedlock et al., 1993).
In southwestern Mexico, as far south as Oaxaca, orogenic
deformation was initiated in the Late Cretaceous. Laramide
deformation included E-W shortening that migrated to the east
with time, generally with easterly vergence (Moran-Zenteno et al.,
2007). Latest Cretaceous to Early Paleocene plutonism in the
Jalisco block is contemporaneous with that in the central part of
Sierra Madre del Sur. Later volcanism, including compositions
from andesite to rhyolite, Paleocene to middle Eocene in age, is
located in the Presa Del Infernillo area in the states of
Michoacán and Guerrero, Taxco and localities further east in
northwestern Oaxaca.
However, the main axis of magmatism of middle Eocene and
Oligocene age developed along the continental margin from
coastal Michoacán to Oaxaca. Thus, the Pacific coast of
southwestern Mexico is characterized by numerous plutons
including batholiths (Moran-Zenteno et al., 2007), in which
granodioritic and tonalitic compositions predominate.
Sinistral lateral faulting activated NW-SE and N-S faults during
Eocene and early Oligocene time. The NW-SE faults extend as
far south as Oaxaca but the N-S set are located in northern
Sierra Madre del Sur (Moran-Zenteno et al., 2007).

Mineral Deposits (100-16 Ma)
From the foregoing summary of tectonic events in late
Cretaceous-Paleogene time, the newly accreted conglomeration
of terranes in Mexico had been structurally prepared on a
widespread scale in northern and southern Mexico for the
mineralizing fluids associated with the accompanying
magmatism. Thus, within a span of approximately 80 million
years, from Late Cretaceous through early Miocene time a
prodigious number of metaliferous deposits of several different
classes were emplaced primarily in northern and central Mexico,
that is, north of the Trans-Mexican Volcanic Belt. Among the
major classes of deposits are porphyry copper, skarns, mantos,
tin in rhyolites, disseminated gold in various host-rocks, and a
wealth of fissure-vein deposits including precious metal,
polymetallic, and manganese; stratabound and breccia pipe
uranium. The majority of these deposits coincide in space and
time with a subduction-related envelope of magmatism that
progressed eastward several hundreds of kilometers as far east
as the meridian of Coahuila, from the trench position paralleling
the west coast of Mexico, and then regressed towards the west
coast by early Miocene time (Clark et al. 1979a; 1982).

Porphyry copper deposits
Individually, porphyry copper deposits were being discovered,
evaluated, and brought into production, primarily in a span of
about 25 years through the early 1960's to the mid-1980's. A few
ore bodies of the larger systems had previously been mined of
which La Colorada and El Capote breccia pipes in the Cananea
district (Kelley, 1935, Perry, 1961) and Pilares breccia pipe
(Emmons, 1906, Wade and Wanke, 1920) in the Nacozari
district, both in Sonora, are examples (Fig. 6). Following the
investigation of numerous deposits along the west coast of
Mexico, several reports were produced that dealt with various
aspects of these deposits. Among these are Sillitoe (1976) who
provided basic information on location, mineralogy and alteration;
Damon et al. (1983a), who provided K-Ar age determinations for
all deposits; Barton et al. (1995) who added details on petrologic,
mineral assemblage, and geochemical characteristics of these
deposits; and Clark (1996) who related porphyry copper mineralization to tectonostratigraphic terranes.
The eastward shift in magmatism in northern Mexico has been
documented by Anderson and Silver (1974) and Henry (1975).
This was accompanied by changes in alkalinity. Cameron et al.
(1978, 1980) have shown the variation in alkalinity across
Chihuahua from southwest to northeast from calc alkalic,
moderate-K facies to a high-K facies in the eastern part of the
state. This scenario was further amplified geographically by
McDowell and Clabaugh (1979) who recognized three distinct
alkalinity zones across northern Mexico and adjacent parts of
west Texas.

Porphyry copper deposits have a common association with
Laramide calc-alkaline intrusive centers in northwestern Mexico
and younger intrusions in the southwestern part of the Republic.
Intrusion-related copper deposits are associated with intermediate and felsic magmas and characteristically contain the
Cu-(Mo-Zn) assemblage. Copper mineralization is closely
associated with strongly porphyritic quartz-feldspathic
intrusions. Dioritic rocks, according to Barton et al. (1995),
apear to be more closely associated with a Cu-(Fe-Au)
assemblage and alkaline igneous intrusions are not associated
with copper, but with fluorine-rich deposits. Diorite related
porphyry systems are less common in Mexico but are
represented at La Verde, Michoacán, and in other copper
occurrences in southern Mexico. Association with mid-to-late
Cretaceous batholiths has been noted in Sinaloa and in the
southwestern Guerrero terrane in weakly porphyritic granitoid phases.
Breccia pipe mineralization occurs in Guerrero and Michoacán in
the southern Guerrero terrane at Inguanar and La Verde (Solano-
Rico, 1995), and also in northern Sonora where the largest
deposits are located in the Chihuahua terrane in the Cananea
and Nacozari districts (see Valencia-Moreno et al., 2007 and
Ayala-Fontes, 2008, respectively).

Barton et al. (1995) have drawn attention to the role of igneous
rock compositions that exert a basic control on the nature of
Figure 6. Porphyry-copper deposits of the Late Cretaceous-early Miocene interval. From Sillitoe (1976), Damon et al. (1983), Valencia-Moreno et al. (2006), Clark and Fitch, (2009).
related hydrothermal systems through a combination of original element abundance and chemical equilibria. They conclude that most metals will become substantially more soluble with increasing activity of alumina (in metaluminous and peraluminous rock). Thus, base metals are commonly associated with peraluminous and modestly calcic aluminous systems and there is virtual absence of base metals associated with peralkaline systems. This, in itself, explains the relative paucity of predominantly copper-bearing systems in eastern Mexico.

Many characteristics of the Mexican copper belt are also controlled by basement lithology, subduction regime, and existence of a protective capping of dominantly volcanic rock, uplift and subsequent erosion. As the calc-alkalic Occidental Volcanic Arc, that produced the porphyry copper deposits, progressed eastward (Clark et al., 1979a, 1982), associated magmas became more calcic and copper poor (Damon et al., 1983a). Thus, enrichment to ore grade became increasingly improbable to the east.

Along the belt, as a whole, Damon et al. (1983a) showed that subduction related magmatism varied with latitude. Specifically, they contrasted initial strontium isotope ratios ($^{87}$Sr/$^{86}$Sr) of intrusions associated with these deposits, by comparing the low values that occurred in the accreted Guerrero terrane of Campa and Coney (1983), with those that occurred in the cratonic regime in northern Sonora, and adjacent parts of the southwestern United States. Ratios were plotted against latitude by Damon et al. (1983a), and fall in three distance groups, the highest being in the North America terrane (>0.7063), whereas mineralized porphyries in the Guerrero terrane of Campa and Coney (1983) (Tahue, Tepehuano, and Nahuatl terranes of Sedlock et al., 1993) have lower values and fall into two distinct geographic groups. The corresponding interpretation suggests that magmas originally had low initial $^{87}$Sr/$^{86}$Sr ratios, but the radiogenic component increased during magma residence and assimilation in the cratonic crust to the north. In the Cananea district, Wodzicki (1995) used Nd and Sr isotope data combined with major and trace element data to conclude that the Laramide rocks evolved from a mantle-derived parent melt by coupled assimilation and fractional crystallization.

In this regard, Titley (1992) has presented evidence of the importance of crustal lithologic contribution to magmas of Laramide age that relate to porphyry copper formation in Arizona. Subduction mechanisms in this scenario are regarded as triggering mechanisms, leading to the evolution of these ores, but crustal composition was considered to be a more profound influence on metallogenesis. In contrast, in his detailed synthesis of giant porphyry copper deposits in the Andes, Clark (1993) notes there is no anatomical distinction in the unusually large porphyry copper deposits, and tentatively suggests that very large deposits may owe their origin to a protracted and consistent magmatic history in the course of which only limited migration of the main subduction-related arc occurred.

Copper deposits are located in a zone paralleling the west coast from Sonora and Baja California (including the older El Arco deposit), southwards to Chiapas, a distance of 2,600 km (Fig. 6), in which they become younger from north to south. However, the zone becomes wider if other intrusion related mineral deposits are included, especially those deposits where copper is only a minor component of the system or in other deposits where copper is absent (see Barton et al., 1995, fig. 2 and table 2). As a result, over 600 copper-bearing intrusion related systems have been recognized, of which about 100 can be documented with some degree of certainty. But in this report, we separate those deposits that are skams if they do not contain disseminations in the intrusive body or breccia pipe mineralization. Neither do we include those deposits that do not contain copper. Some deposits predominantly contain molybdenum (Cerro Colorado, Los Chicharrones, San Judas), whereas the La Guadalupana locale is rich in tungsten (Schultz, 1953).

Figure 6 shows the location of 37 porphyry copper deposits for which radiometric age determinations are available. These data are taken from Sillitoe (1976), and Damon et al.(1983a). But the older El Arco and San Juan Mazatlan deposits have been eliminated from this mineralizing epoch as well as the younger Toliman and Santa Fe occurrences in Chiapas. Also, removed from consideration are those deposits that are primarily fissure-vein, skarn or replacement deposits which will be considered separately. One addition, Satevo in Chihuahua, has been added from Barton et al (1995). Considering all deposits, 13 fall in the Chihuahua (North American) terrane, 7 in the Caborca terrane, 5 in the Cortez terrane, and 11 in the Guerrero terrane. From this we agree with Damon et al. (1983a) and Clark (1996), that the occurrence of these deposits appears to be independent of the terrane intruded, and in Sonora and Sinaloa several deposits are associated with batholiths or penecontemporaneous volcanic rocks. However, the largest and richest deposits are located in the cratonic Chihuahua terrane.

The most recent age determinations are found in Barra et al. (2005) and Valencia-Moreno et al. (2007). By using Re-Os molybdenite ages for nine porphyry copper-molybdenum deposits from northwestern Mexico, Barra et al. (2005) show that the ages of this sample of the deposits shown in Figure 6, stretches from Maria, Sonora in the north to Malpica, Sinaloa in the south, and spans the interval 61-50 Ma (Paleocene to Eocene), and is associated with the Laramide orogeny. The Tameapa deposit (Chrisinger, 1975), has a protracted hydrothermal history brought about by four molybdenite mineralization events between 57 and 50 Ma (Barra et al., 2005).

In contrast, Valencia-Moreno et al. (2007) provide ages of all of the deposits shown on Figure 6, and many were formed during the interval 75 and 50 Ma. Metal distribution of these deposits was separated into three domains according to basement of emplacement. The northern domain is characterized by Proterozoic crystalline rocks of North America; the central-domain is composed of Paleozoic marine strata underlain by Proterozoic North American terrane, whereas the southern domain consists of Mesozoic island-arc sequences of the Guerrero terrane. The northern and central domains include Cu-Mo-W assemblages whereas the southern domain is dominated by Cu-Au mineralization, and with the exception of El Arco (~3.6 Mt Cu) and Santo Tomas (~1.1 Mt Cu) are relatively small deposits. The lessening of age of these deposits from north to south is striking. Including El Arco, Baja California, and Toliman, Chiapas, the variation in age is from 165 to approximately 6 Ma, a span of 159 Ma over a distance of 2,600 km or a younging on average of about 1.0 Ma per 16 km. This rate is much higher than the convergent rates between the Farallon-North American plates (Atwater, 1970; Coney, 1976; Clark et al., 1982), and is probably due to oblique subduction of the Farallon plate under southwestern North America.
Polymetallic skarn, breccia pipe, manto and vein deposits

The geographical and terrane distribution of 22 deposits that are skarns, replacements, or mantos, or some combination thereof, for which age determinations are available, is shown in Figure 7. Many more deposits, less precisely dated, are known but are not included here. In most cases, the age of the mineralization is assumed to be approximately the age of the associated intrusion that varies in composition from diorite to granite. Using the schematic representation of Megaw et al. (1988), to describe the spectrum of these deposits, San Martín, Charcas, Velardena, Providencia, Concepción del Oro, and Zimapán are proximal stock contact varieties, whereas Santa Eulalia, Naica, Mapimí (Ojuela), and La Encantada represent dike or sill contact skarns, through massive sulfides, to chimney and mantos and distal massive sulfide mantos. Of the remaining Pb-Zn-Ag bearing deposits, La Reforma, Cosala, San Felipe, Tronco de Peras, Los Reyes, and Dinamita are regarded as intermediate between the proximal contact skarn and distal massive sulfides, the latter having no known relation to an intrusion as at Los Lamentos. In contrast, the Pb-Zn-Ag bearing skarn at San Carlos in northeastern Chihuahua is related to a granite pluton emplaced during caldera development at 31 Ma (Immitt and Kyle, 1981, Immitt, 1987).

Replacement of country rock carbonates is common, and the high temperature carbonate hosted Ag-Pb-Zn-Cu deposits of northern Mexico, described by Megaw et al. (1988), occupy a zone running parallel to the paleotrench position but generally well east of the porphyry copper province referred to above (Clark et al., 1979a). These deposits are located within the Caborca (2) Chihuahua (4), Coahuila (3), Sierra Madre (7), Cortez (1), Parral (3), Toliman (1), and Guerrero (2) terranes, and thus appear to be independent of terrane lithologies. Two deposits are located west of the main belt of these ores and include Cosala (Pb-Zn-Ag), Sinaloa, hosted by Cretaceous carbonates. The El Tecolote Zn-Cu replacement deposit in Sonora is also included here rather than under porphyry copper deposits because of its replacement characteristics (Farias, 1973, and the fact that zinc is the principal metal (Cendejas-Cruz et al., 1992). Thus, the foregoing demonstrates a key circumstance controlling the formation of these deposits, namely, the interaction of calcalkaline intrusions developed above a flattening and eastward migrating subduction zone and associated magmatic arc and the widespread Mesozoic carbonates, primarily of Cretaceous age, that covered much of northern Mexico. However, the role of limestone host rocks in Mexico in this context had been previously noted by Prescot (1926), and Fletcher (1929), and in North America as a whole by Callahan (1977).

In general, the age of the skarn, replacement, and manto deposits is younger than the porphyry copper deposits within a southwest-northeast transect approximately perpendicular to the paleotrench position as they are inboard of the porphyry copper belt. Their age span, as a whole in this mineralizing epoch varies from about 80 Ma at La Parrilla, Durango to 27 Ma at La Encantada, Coahuila (Clark et al., 1979a). There appears to be an overall younging to the south from 59 Ma at La Reforma to 2 Ma at Santa Fe (Damon and Montesinos, 1978), if the latest mineralizing epoch is taken into account. Likewise, there is a younging of age from southwest to northeast from 59 Ma at La Reforma to 27 Ma at La Encantada.

Iron Deposits

Three genetic types of iron deposits were recognized by Flores (1951), namely, 1) replacement; 2) contact metasomatic; and 3) residual, totaling 63 localities. Subsequently, an inventory of 134 deposits was made by Pesquera et al. (1979), grouped into four sizes of reserves with a small number having tonnages greater than 10 Mt, and a large number with the smallest tonnage of less than 1 Mt. Of these, 9 deposits were considered to be of volcanogenic origin, some others were thought to be of magmatic injection, and the remainder contact metasomatic. Later, the result of the first symposium on the exploration for iron in Mexico was held in Monterrey, and a resume of the proceedings was elaborated by Estrada et al. (1988). Fourteen of the most significant iron deposits were divided into two groups, nine of which occur in the Mesozoic island-arc environment in the Sierra Madre del Sur of southwestern Mexico. Included here are Peña Colorada and Cerro Nahualtl, Colima; Las Truchas, Aguila, La Guayabera and Los Pozos, Michoacán; El Encino, and La Huerta, Jalisco; and El Violín, Guerrero (Fig. 8). These magnetite rich deposits were thought to be primarily of contact metasomatic origin the largest of which are situated in calcareous pelitic host rocks, as at El Encino, Peña Colorada, and Las Truchas. The second group of deposits is located in volcanic environments on the eastern flank of Sierra Madre Occidental in north-central Mexico, and is described separately below. The possibility of finding sedimentary origin iron ore deposits of Precambrian (Bazzan-Barron, 1980), Paleozoic, or Jurassic age has not been confirmed to date.

Contact metasomatic iron deposits

In southwestern Mexico (Fig. 8), several deposits are considered to have a metasomatic-hydrothermal origin, based on their association with Tertiary granite intrusives, and the metamorphic minerals formed at the contact with the host rocks. However preliminary observations at some of these deposits by Corona-Esquível (2000) suggest similarities with the volcanogenic group, for example Peña Colorada in Colima. The youngest iron deposit occurs at Cerro Colorado (18 Ma, Damon and Montesinos, 1978) and is located in the northwestern part of Chiaapas. Although it has characteristics of a typical porphyry copper contact zone, Castro-Mora (1999) stresses the importance of iron in this skarn deposit. Elsewhere, and further north in Sinaloa, two deposits are worthy of mention, namely Cerro Mazomique and Los Vasitos. Both are of contact metasomatic origin, formed by Laramide age granitoids of the Sinaloa batholith being intruded into early Cretaceous calcareous rocks (Bustamante-Yañez et al., 1992). At Mazomique, in the Choix district of northern Sinaloa, Davidge (1973), and Clark et al. (1979a) note the presence of iron oxide copper sulfide mineralization in the contact zone of three small mines. Further south, at Los Vasitos, the granodiorite intrusion was dated at 25 Ma (Clark et al., 1979a).

In Sonora, there are numerous small magnetite-hematite-bearing skarn deposits and two more are associated with volcanic rocks, one of which is located in a volcanic-sedimentary environment (Pérez-Segura, 1985). The three largest deposits are 1) San Miguelito dike is associated with volcano-sedimentary host rock intruded by a monzonite of likely Laramide age, 2) the San Marcos skarn mineralization which occurs at the contact of Permian (?) limestone and a Laramide monzonite body, and 3) El Violín which is located in a subaerial Tertiary rhyolite
Figure 8. Volcanogenic and other iron deposits; volcanogenic, sandstone, and other uranium localities, all of Late Cretaceous-early Miocene age including the marine phosphate deposits in Baja California Sur. (From Clark and Fitch, 2009).
environment. A fourth deposit, also noted by Pérez-Segura (1985), is El Volcan, situated some 50 km NE of Ciudad Obregon. It was brought into production in 2007 by exploiting a predominantly magnetite-rich ore body within a quartz monzonite-diorite intrusion near the contact with andesite volcanic rocks. Its origin is possibly of magmatic injection, although this interpretation is preliminary (Arroyo-Dominguez, 2009).

In Baja California numerous small iron-copper deposits form a north-south belt, the majority of which are related to granitoid bodies of probable mid-to-late Cretaceous age that have intruded volcanic rocks. Mineralization is in tabular bodies, either veins or mantos (Amaya-Martinez, 1977; Gastil et al., 1975). This belt is located in the Guerrero terrane of the northern peninsular region. The Santa Ursula deposit contains about 4 Mt and is the largest in this region according to Pesquera et al. (1979).

In Chihuahua three other deposits, for which data are available, show that contact metasomatic iron deposits also occur in the north-central part of the country. For example, La Negra located 20 km southeast of La Perla is associated with a quartz monzonite stock, and the ore occurs in a lenticular body surrounded by stockworks and veins of iron oxides. This deposit is assumed to have a similar age as the El Anteojo mine located 70 km northwest of La Perla, where iron mineralization occurs in a skarn adjacent a quartz monzonite dated at 35 Ma (Clark et al., 1979a). In adjacent northeastern Chihuahua, at San Carlos, magnetite is found in a contact metasomatic deposit formed where a granitic pluton invades early Cretaceous limestone. The pluton is related to caldera development at 31 Ma (Immitt and Kyle, 1981). Within the metasomatic zone a Pb-Zn assemblage has also formed, and epithermal veins containing a zinc-copper-fluorite assemblage occur near the northwestern margin of the caldera.

Finally, the reader is referred to papers on several of these deposits by Corona-Esquível et al. (2009a, c), who also remark on their genesis.

Volcanogenic Iron Deposits

Within this group are three deposits in northern Mexico: La Perla in Chihuahua; Hércules, Coahuila; and Cerro de Mercado, Durango (Fig. 8), all of which have been assigned to a continental magmatic arc environment. These deposits are in contrast to 9 major contact metasomatic deposits of southern Mexico that are located within an island-arc environment of Cretaceous age described in the Jurassic-Early Cretaceous epoch. The southern deposits are Peña Colorada, Las Truchas, El Encino, La Huerta, Aquila, Cerro Nahuatl, La Guayabera, Los Pozos, and El Violin.

However, in the last few years, the interpretation of origin of iron deposits in southwestern Mexico has changed. In previous years they have been interpreted as metasomatic because of the presence of intrusives in the region. However, several of these deposits have geologic and geochemical characteristics similar to Cerro de Mercado, briefly described below, and to El Laco in Chile, or Kiruna in Sweden. Thus, Aquila and El Encino show magmatic characteristics, whereas the Cerro Nahuatl deposit was formed by metasomatic replacement, and Las Truchas is mostly of replacement origin (Rodolfo Corona-Esquível, written communication, March, 2009).

La Perla has been described by several investigators, among them Crockett (1953); Cardenas-Vargas and Castillo-G. (1964); Campbell (1977); Van Allen (1978); and Corona-Esquível et al. (2003). The deposit is contained in the La Perla Formation, the lower part of a sequence of rhodacite lavas in the Sierra de Mestenes (Campbell, 1977). K-Ar age determinations of these volcanic rocks cluster around 30 Ma, and their alkalinity varies from peralkaline to peraluminous in the host rock. The ore body is lenticular and comprises specular hematite, martite and some magnetite (Van Allen, 1978), with gradational contact with the host rock. The various origins that have been suggested for the deposit have been reviewed by Corona-Esquível et al. (2009a) who conclude that the iron is of magmatic origin, promoted by F, P, and S volatiles that produced the massive iron oxide body by liquid immiscibility, which partitioned it from the remaining silicate melt.

Hércules, Coahuila consists of 12 ore bodies in varying stages of exploitation and 3 areas of geophysical anomalies where ore awaits development. The published literature includes Velasco-Hernandez (1964), Prado-Ruiz (1971), Cazares (1973), Ruvalcaba-Ruiz (1989), Hoyt (1990); and Hernández-Ontiveros (2009). In addition, a general introduction is given by Duran-Miramontes et al. (1993) that show many of the individual deposits are hosted by igneous rock and that the contact between ore and host rock is generally sharp but may be brecciated. The general geology of the area consists of Cretaceous carbonates overlain by subvolcanic rocks that have been dated by Ruvalcaba-Ruiz (1989) at 33.7 to 30.7 Ma, although the age of mineralization may be as young as 28 Ma (Hernández-Ontiveros, 2009). Ore bodies are located in andesite and many are fault controlled with metamorphism of the host rock. Hoyt (1989) produced a conceptual model of lenticular ore bodies in a fracture at a depth greater than 500 m containing high temperature (500-400°C) mineralization, surrounded by metamorphically altered porphyritic syenitic or trachytic host rock. Lower temperature deposits and altered host rock occur at shallower depths up to the surface where hot spring sinters are visualized.

Cerro de Mercado, Durango is an iron deposit that has been studied for about 150 years. Among the literature are reports by Weidner (1858); Birkinbine and Palacio y Tebar (1883); Foshag (1929); Labarthe-Hernández et al. (1987); and Lyons (1975, 1988). Labarthe-Hernández et al. (1987) note that a rhodacite flow was intruded by monzonite to quartz monzonite porphyry, producing a calcic-rich alteration zone, which was replaced by magnetite, later oxidized to hematite. Iron oxide ore bodies were controlled by fractures, resulting in subhorizontal ores which at depth became tabular and steeply inclined. Around the massive ore are hydrothermal breccia zones. Previously, Lyons (1975) had recognized the 30 Ma Chupaderos caldera, but stressed that formation of much of the iron deposits was by subaerial volcanic processes during an hiatus between two eruptive cycles of the caldera forming process. The resulting pulverulent deposits have also been recognized to a minor extent at La Perla and Hércules, but a subaerial origin has not been invoked. Lyons (1988) recognized late stage hematite-magnetite dikes that cut the entire system and fed flows. Both hypotheses entail the eruption of a magmatic iron, fluorine and other volatiles. Peña Colorada, situated like many of the other deposits in southwestern Mexico in the Guerrero terrane, is formed at the contact with a 68 Ma diorite body that intrudes mid-Cretaceous volcano-sedimentary rocks. The volcanic rocks have tholeiitic affinity and REE values are consistent with a primitive arc environment (Zurcher et al., 2001). This massive iron oxide replacement deposit, one of the largest in Mexico, contains 200 Mt with a grade of 60 percent magnetite.

Peña Colorada perhaps has the most complex mineralization. The middle and upper parts contain mineralogy typical of replacement including the presence of garnet, and in the highest part there are veins containing hydrothermal magnetite that cut part of the volcanic sequence and also the upper conglomerate. But in the lower part of the deposit, in the area known as “La Chula”, there are breccias cemented with magnetite, pyroxene, and apatite, typical of magmatic origin and similar to that of Cerro de Mercado (Rodolfo Corona-Esquível, written communication, March 2009).
For the latest descriptions of La Perla, Cerro de Mercado, Peña Colorada, and many deposits in southwestern Mexico, see papers by Corona-Esquivel et al. (2009 a, b, c, d).

Volcanogenic uranium deposits

Although there has been no commercial production of uranium in Mexico, exploration for and development of deposits in Chihuahua took place in the 1970's and 1980's, by the now defunct Mexican government agency URAMEX and later by Consejo de Recursos Minerales. Several occurrences of uranium minerals at the surface and in radioactive anomalies occur in the Chihuahua City area (Fig. 8), a region that extends for 200 km in a north-south area around the city, thus leading Goodell (1983, 1992; Goodell et al., 2009) to refer to this area as the Chihuahua City uranium province. The most important locality is Sierra Peña Blanca, located 45 km north of the city (Fig. 8), where uranium is found in fault zones and stratabound concentrations in volcanoclastic rocks of a distal facies of a 44 to 35 Ma old ignimbrite sequence (Goodell, 1981, 1982). Uranium is considered to have originally been dispersed in glassy tuffaceous rock in the Sierra Del Nido to the west, leached and then transferred in hydrothermal systems that formed concentrations in the Sierra Peña Blanca sequence.

The mineralogy of these deposits includes hexavalent margaritasite, (a Cs-rich analog of carnotite, Wenrich, 1983), uranophane, betauranophane, carnotite, weeksite, and metatyuyumunite (Cárdenas-Flores, 1983). Molybdenum is found in some of the uranium concentrations. In Sierra Peña Blanca, the deposits are limited to the Nopal Formation (43.8 Ma) and the overlying Escudura Formation (38.3 Ma), both having been dated by Alba and Chavez (1974). Important localities include the Nopal 1 breccia (pipe?), Margaritas stockwork in the Escudura Formation, and Puerto 3 stratabound prospect, mostly in the Escudura Formation.

Another uranium deposit of probable magmatic origin, located 30 km northwest of Chihuahua City, and closely associated with a Tertiary caldera, is San Marcos. The Quintas ignimbrite (46 Ma), the result of a second stage of plinian eruptions, is cut by the two curvilinear rhyolite dikes, the later one is within 200 m of the uranium prospect (Ferriz, 1981).

The Sierra de Gómez is situated 50 km east of Chihuahua City, and contains uranium associated with nickel that occurs in carbonates of Cretaceous age. This low-temperature mineralization is located in thrust faults and karst fillings (Goodell, 1992). Some 90 km further east of the Sierra de Gómez at Placer de Guadalupe, Antunez (1954) noted that uraninite occurs in hydrothermal veins with quartz and native gold, associated with dactitic intrusions. This mineralization has been has been dated at 32 Ma (Goodell, 1992).

Elsewhere in northern Mexico, Yza-Dominguez (1965) has reported on the Noche Buena uranium mine in Opodepe municipality, Sonora and Chavez-Aguirre and Cruz-Rios (1987) have drawn attention to the Los Amoles deposit in Late Cretaceous trachyandesite in the Sierra Aconchi, Sonora. Some 20 km to the southeast is the San Alejandro prospect, a vein that cuts Late Cretaceous-Early Tertiary volcanic rocks and contains uranium and gold values (Cendejas-Cruz et al., 1992).

At Granaditos (Fig. 8), Marquina-Martinez (1981, 1983) described mineralization in dactitic ignimbrite which included dissemination and breccia control. In other parts of north-central Sonora uranium is disseminated in ignimbrite in small veins at San Pedro de la Cueva; in fractures, disseminations, and hydrothermal breccia located in ignimbrite at Picacho; and in a chimney located in a series of pyroclastic and agglomeratic andesites and latites at Santa Rosalia. Other uranium occurrences in Sonora reported by Marquina-Martinez (1983) include localities near Moctezuma and Huasabas.

Other uranium deposits worthy of mention include the Coneto-Buenavista district in Durango; and El Chapote - Diana, Presita-Trancas-Peñoles in the state Nuevo Leon (Corona-Esquivel, written communication, March, 2009).

La Coma, a sandstone-uranium deposit in Nuevo Leon has been described by Pérez (1973). Other similar deposits located in the Oligocene Fri No Marino Formation include Buenavista, El Chapote-Diana and Presita-Trancas-Peñoles, all located in the Burgos Basin (Salas and Castillo-Nieto, 1991; Sanchez-Ramirez, 2011).

In the Baja California Sur marine phosphate deposits of late Oligocene-early Miocene age, uranium has been reported in minor amounts at San Juan de la Costa and San Hilario.

The remaining deposits referred to by Salas and Castillo-Nieto (1991), are located in the states of Zacatecas, San Luis Potosi, and Oaxaca (Santa Catarina Tayata), but because their age assignments are unclear they are not shown in Figure 8.

Finally other localities not mentioned above can be found in maps published by Instituto de Geologia (M-18) that show distribution of uranium, beryllium, lithium and thalium.

Volcanogenic tin deposits

There are numerous reports on tin in Mexico, one of the first being written by Ramirez (1885), followed by Kempton (1896) who reported occurrences in Durango and Zacatecas respectively, two of the important former producing states. In 1942, Foshag and Fries reported on tin deposits in Mexico as a whole and Smith et al. (1950, 1957), supplied more details on Durango localities. Two of the more recent and complete geological investigations were made by Lee-Moreno (1972), and Pan (1974), that dealt with exploration and geochemical characteristics, of these deposits. Figure 9 shows the deposits examined by Foshag and Fries in 1942 and these are presumably the more important localities and in which there has been some production.

Foshag and Fries (1942) identified tin deposits in 6 states; Hidalgo, Guanajuato, Aguascalientes, Jalisco, Durango, and Zacatecas (Fig. 9), and noted that tin had been found in 13 other states. They divided deposits into three classes, 1) associated with granite, 2) associated with silver ores, and 3) associated with extrusive rocks, but only types 2) and 3) have been economically productive. Another class, which they recognized, are placer accumulations.

The only district in which tin is associated with granite is Guadalcazar, San Luis Postosi. At this locality, Ruiz (1988) remarks on the similar chemistry of the Guadalcazar granite to the tin-bearing rhyolites in terms of major element characteristics, age that was determined isotopically at ~28 Ma, and also an initial strontium isotope ratio of 0.7070. Tin associated with lead-zinc-silver ores is only known at the San Antonio mine in the east camp of the Santa Eulalia district, Chihuahua, (Hewit, 1943, 1951). This mine produced about half of Mexico's tin production up to 1939, when tin-bearing ore was exhausted.

There are probably 1,000 tin localities associated with volcanic rocks, most of them located in small veins and in some placer deposits in the central plateau, and most importantly in the states of Durango, Zacatecas, and Guanajuato (Foshag and Fries, 1942). The common host rock is rhyolite, but a few deposits occur in underlying latite and andesite. Specularite commonly accompanies cassiterite or wood tin. Figure 9 shows the distribution of deposits that were investigated by Foshag and Fries (1942), with additions from Smith et al. (1957), and Tuta et al. (1988).

The northern Mexican tin belt contains deposits in 32-30 Ma age rhyolites flows and domes that are overlain by rhyolitic ignimbrites (Huspeni et al., 1984). This is a more restricted age range than that cited by Ruiz (1988) who considered that all
Figure 9. Late Cretaceous-early Miocene tin deposits, the majority of which are of volcanogenic origin, the exceptions being Santa Eulalia (SE), and Guadalcazar (Gu). After Clark and Fitch (2009).
Mexican tin-bearing rhyolites were emplaced from 32-26 Ma. Crystalization temperatures obtained from feldspar compositions are $700 \pm 50^\circ$C in the host rhyolites (>74% SiO$_2$), that are metaluminous and slightly peraluminous. In reviewing the elemental and trace element content of these rocks, Huspeni et al. (1984), conclude that the tin-bearing rhyolites were formed as extreme differentiates in high level magma chambers closely associated with caldera development. As most tin-bearing localities in the world are commonly associated with a cratonic basement, the interpretations of Ruiz et al. (1988), referred to previously in regard to the likelihood of Precambrian and Paleozoic crust existing in north-central Mexico, are important. Ruiz (1988), points out the Mexican tin province coincides where Bouguer anomalies are greatest (>200 Mgals). The lead-isotope data of Cumming and Kesler (1979) has also been interpreted by some as indicating that part of the North American craton underlies the region of the Mexican tin belt. Thus, tin values in the rhyolite magma may have a crustal component which was later followed by differentiation, as indicated by deep negative europium anomalies (Huspeni et al., 1984). Tin abundances in the host rocks are enriched with respect to Sierra Madre Occidental lavas much of which overlies the accreted Guerrero terrane. Also, initial strontium ratios are more radiogenic than in Occidental lavas much of which overlies the accreted Guerrero terrane.

Tin comes into the host rocks as xenoliths examined by Ruiz et al. (1988) from the Sierra Madre Occidental terrane have similar isotopic compositions to the tin rhyolites. Additionally, the timing of tin-bearing rhyolite emplacement may have coincided with a change of tectonic regime on the eastern flank of the Sierra Madre Occidental volcanic province from compression to extension. Figure 9 shows the location of 22 important tin deposits that are districts or individual mines. Many mines and deposits are indicated by Foshag and Fries (1942), and the names of those in Durango are identified by Smith et al. (1950, 1957). Thus, the limits of the tin province, as drawn on Figure 9 include only major deposits for which ages are available. Examination of the tin province clearly shows that the post-accretion-terrane deposits are overprinted by Oligocene age volcanic rocks, and those bearing tin in significant concentration occur either in the Chihuahua (North American) terrane, or where the largest concentration of important deposits is clustered in parts of the Parral, Guerrero, and Toliman terranes, close to the suspected region that may be underlain by Proterozoic and Paleozoic basement lithologies.

Mercury deposits

Many mercury deposits of northern Mexico are located near the contact of Mesozoic sedimentary strata and overlying volcanic rocks (Tuta et al., 1988). Small deposits are found in Chihuahua, Durango, Jalisco, and Zacatecas, and the location of mercury deposits, in general, is given in maps published by Instituto de Geologia (M-7), see also Figure 10.

The geochronology of these deposits has been given by Tuta et al. (1988) as follows. In the Canoas district, Zacatecas, mineralization occurs in a latite dome (Gallagher, 1952) and formed from 27-26 Ma. At Sain Alto, Zacatecas, adjacent the Sombreroite tin district, deposits are found in rhyolite and the age is post-37 Ma. At El Cuarenta, Durango, mercury is disseminated in granite, an overlying conglomerate (Gallagher and Perez, 1946), and in overlying rhyolites the deposits are probably in post-rhyolite faults, and their age is post-40 Ma.

Other smaller deposits are found at Cuencame, Durango (Salas, 1975a), but at Nuevo Mercurio in northeastern Zacatecas, the most important mercury district, mineralization is largely hosted by sedimentary rocks (Perez and Gallagher, 1946). The Nuevo Mercurio (San Felipe) deposits were identified in 1935, and are located in the Indidura Formation of Late Cretaceous age, that consists of thin-bedded limestone, marl, and shale. The cinnabar oxides occur in faults and fault-related breccias located in an overturned anticlinal structure, vergent to the northeast. There are two main fracture systems that were invaded by hydrothermal solutions that also deposited silica and siderite (Parga-Pérez et al., 1992). No igneous rock affiliation is apparent, and the age of the deposits is Late or post-Late Cretaceous.

There are two important mercury areas in the Sierra Gorda, Queretaro state. These are the San Joaquin and Plazuela-Bucareli localities, each one represented by several former producing mines (Rodríguez-Medina et al., 1992). At Plazuela-Bucareli cinnabar and metacinnabar mineralization occurs in veins, fractures, and cavity fillings. The host rock is the El Doctor limestone of Early Cretaceous age at Bucareli, whereas the host rocks are the Soyatal-Mezcala shales of Late Cretaceous age at Plazuela. Production from the Plazuela area from 1966 to 1984 is reported to total 812,000 kg Hg.

In the San Joaquin area similar mineralization occurs in the El Doctor Formation, and production from 1970 to 1974 totaled 1,051,000 kg Hg. There are seven mines in this area of which Calabacillas appears on Figure 10.

In southern Mexico, the Huauxtla mercury district is located in Guerrero state, where cinnabar was discovered in 1923. The ore is mainly cinnabar that inverted without change of color from metacinnabar (Gallagher and Pérez 1948). The deposits are found in limestones of Late Cretaceous age. The principal ore shoots are found along the Huauxtla fault and controlled by breccia and ribs of limestone.

The quicksilver and antimony deposits of nearby Huitzuco, Guerrero have been described by McAllister and Hernández-Ortiz (1945). The dominant rock is limestone, probably of Cretaceous age, broken by compressional faults, producing breccia and isoclinal folding. Small bodies of granite intruded the limestone and are located in the peripheral parts of the district. Solutions carrying mercury and antimony invaded the dolomitized breccia; replacing some of the dolomite with stibnite and livingstonite (HgS.2Sb$_2$S$_3$). McAllister and Hernández-Ortiz speculate on a Pleistocene age of mineralization, but this has not been confirmed and seems unlikely. Weathering of livingstonite and stibnite produced cinnabar and oxides of antimony.

The Atarega, San Luis Potosi, and San Joaquin, Queretaro, deposits, assigned an Oligocene-Pliocene age by Salas (1975a) are more likely to have a Late Cretaceous-Early Miocene age based on other mercury deposits where ages are based on more plausible information.

Antimony deposits

There are important deposits of antimony in Sonora, Queretaro, and San Luis Potosi states. Most of the original descriptions were made by United States Geological Survey personnel working with Mexican geologists.

The El Antimonio district of northwestern Sonora (Fig.10), contains numerous veins hosted by Triassic siltstones and sandstones that have been thrust faulted and intruded by igneous rocks that consist of quartz porphyry, diorite and trachyte, all of which form dikes and sills (White and Guiza, 1949). This district also produced antimony from placer deposits. Apparently the veins are not productive when hosted by
Figure 10. Distribution of important mercury and antimony deposits of Late Cretaceous-early Miocene age. From Clark and Fitch, (2009).
limestone. The age of these deposits is possibly Late Cretaceous or post Cretaceous inasmuch that the Triassic Antimonio Formation upper member is Early Jurassic age and overlying it is a thick sequence of volcanic rocks of possible Cretaceous age (Gonzalez-Leon, 1980). The intrusive rocks, referred to above, cut the entire sedimentary and volcanic sequence, and it is with these that the antimony mineralization is likely to be associated.

Another district containing antimony is Caborca, which is shown on the Salas (1975a) metallogenic map as consisting of veins and shears in sedimentary host rocks. Possibly these are the same deposits noted by Halse (1894), but their assigned age of Oligocene-Pliocene appears doubtful when compared to other deposits in Mexico.

Soyatal, Queretaro is the third largest antimony district in Mexico, and was discovered in 1905. The sedimentary rocks at Soyatal have been divided into three formations. The lower formation is mostly limestone, the middle formation is characterized by cherty limestone and is of Early Cretaceous age, and the upper formation is conglomerate at its base grading upwards through limestone and shale (White, 1948). The mineralogy of the deposits is simple and stibnite is the principle hypogene mineral, although many of the ore bodies have been oxidized, and on occasion, there are traces of mercury. Apparently stibnite was deposited from fluids that invaded faults and fractures and may have originated from the same source as the andesite extrusions in the district. The fluids were unable to penetrate the shale horizons, and White (1948) notes that antimony ores are preferentially deposited near the crests of major anticlinal structures. The age of the antimony mineralization is questionable, but appears to be post-Early Cretaceous.

The Sierra de Catorce, San Luis Potosi, has three well-known mining districts: San Jose (Tierras Negras) or Wadley (Sb); Real de Catorce (Ag-Pb-Zn); and Santa Maria de La Paz (Cu-Pb-Zn-Ag-Au). The San José antimony deposits were discovered in 1898 (White and Gonzalez-Reyna, 1946). Mantos are located in the Santa Emilia Formation of Late Jurassic age. Most of the ore in mantos occurs near faults and some is localized in antclinal axes. Migrating mineralizing solutions (Querol-Suné, 1974) caused selective recrystallization in beds that originally may have been more permeable. In reviewing these deposits, Martinez-Ramos and Maldonado-Ramirez (1975), noted that intrusions of quartz monzonite, granodirite and andesite porphyry are important in the formation of veins in the Zuloaga limestone, also of Late Jurassic age. They interpret the emplacement of the igneous rocks as a Tertiary event in which the andesite porphyries are youngest. Replacement of limestone is characteristic of mantos, and cavity filling marks the veins. The antimony-bearing mantos are associated with mercury, whereas the veins are associated with silver and lead (Duran-Miramontes et al., 1992). More recently, Zarate-Del Valle (1997) has reiterated his earlier interpretation of the source of the antimony in these deposits, namely from the underlying Trias-Jurassic red beds by lixiviation, followed by precipitation in lagoonal-neritic carbonate facies. This scenario is completed with remobilization from stratiform deposits and deposition in anticlinal structures during Miocene tectonic activity.

The La Maroma district discoveries were made in the 1770's and reveal an anticlinal structure in which the oldest rocks exposed comprise the Huizachal Formation, being overlain by the Zuloaga and La Caja Formations of Jurassic age, and finally by Lower Cretaceous units of limestone and shale. All sedimentary units have been intruded by a granodiorite of Tertiary age that displays apophyses and dikes up to 2 km length. Mineralization is in fissure-veins of which the Señor de la Humildad is 2-5 km in length. As a whole, the district has produced Pb-Zn-Ag and also Sb the latter being found in the eastern part of the district and closer to a smaller antcline formed in the same Mesozoic stratigraphic units and intruded by two small granodiorite stocks. The district is regarded as having great potential for future exploitation of silver and antimony-bearing lodes (Duran-Miramontes et al., 1992).

Los Tejocotes mines, Oaxaca (Fig. 10) were the largest producers of antimony from 1938 to 1943. Average annual production was 4,300 t of shipped ores containing 56-58% metallic antimony (Guiza and White, 1991). Deposits are found in a mid-Jurassic complexly folded limestone and shale sequence, near contacts with a porphyry intrusion. Ores occur in irregular shaped bodies, fracture-filling veins, and disseminations. Stibnite is the main mineral but is oxidized in near surface deposits.

Of the remaining antimony districts shown on Figure 10, Albino Zertuche, Caborca, and Villa Hidalgo were assigned an Oligocene-Pliocene age by Salas (1975a) as were El Antimono and Soyatal which have now been included in the late Cretaceous-early Miocene epoch, so it appears these three deposits are likely to be somewhat older than previously envisaged.

**Manganese deposits**

There are several well-known manganese districts in Mexico and numerous less important localities: the literature that covers the entire republic is found in Trask and Rodriguez-Cabo (1948), and the symposium on manganese deposits in Mexico, XX International Geological Congress, volume III (edited by Gonzalez-Reyna, 1956b). Several other bulletins and unpublished reports were made by Consejo de Recursos Minerales and will be cited below, and an inventory of manganese deposits has been published by the Instituto de Geologia (M-12).

In general, four types of deposits have been described by Trask and Rodriguez-Cabo (1948), 1) fissure deposits, which consist of manganese oxides and calcite in fissures in volcanic rocks, found mainly in Chihuahua and Sonora; 2) silicified replacement deposits, that contain manganese oxide and silicates in siliceous replacement zones in fractured tuffaceous and volcanic rocks, and found mainly in Zacatecas, San Luis Potosi and the southern part of the state of Mexico; 3) limestone replacement deposits that comprise manganese silicates and oxides close to granitoid stocks, found in eastern Durango, eastern Coahuila, and northern Guerrero; 4) tuff replacement deposits, that display manganese oxides in bedded tuffs, found only in one deposit, near Santa Rosalia, Baja California Sur. This deposit, because it is of early Pliocene age will be described in the youngest mineralizing epoch below. Most manganese ore is found in a few large deposits of the Lucifer (type 4), and stratabound deposits at San Francisco, Jalisco, and Molango, Hidalgo (previously described). A variant of (type 1) which occurs at Gavilan, Baja California Sur, reveals stringers in fractured basalt, and is situated in peninsular California. Presently the Molango deposit, Hidalgo (Pérez-Tello, 2009), is the largest deposit being mined in Mexico, and for that matter in
the whole of North America. The Talamantes (type 1) deposit in Chihuahua and others have been idle for several years.

Figure 11 is derived from Plate 39 slightly modified, contained in Trask and Rodriguez-Cabo (1948). Inasmuch that only the more important deposits, and, or those whose age is reasonably well known, are mentioned in this report, the reader is referred to U.S.G.S. Bulletin 954-F for additional descriptions and other pertinent data. However, we note that up to the mid-1940s, Trask and Rodriguez-Cabo concluded that manganese had been reported at 335 deposits in 20 states in Mexico. The important deposits are designated in Figure 11.

Fissure fillings (type 1) are the most common type in Mexico and several are found in Chihuahua, of which the Talamantes deposit (Wilson and Rocha, 1956), is the largest. The Chihuahua deposits as a whole have been described by Ayub (1959). Other deposits in Chihuahua that have been described individually are Terrenates (Wilson and Rocha, 1956; Jimenez-V., 1956; and McNulty 1969); and Borregos (Wilson, 1956). The age of these deposits is not known with certainty, except for the Talamantes ores that was dated at post-42.5 Ma (late Eocene) by Clark et al. (1979). The Gavilan deposit on Punta Concepción, Baja California Sur is included here, but the basalt host rock may be of late Miocene age (Hausback, 1984).

Silicified replacement deposits (type 2) are common and in which rhyolites and trachytic tuffs and agglomerates are replaced by manganese and silica, in zones along faults and fractures. The resistant silicified host rock forms a topographic high relative to the country rock (Trask and Rodriguez-Cabo, 1948). In some deposits, ore bodies form chimneys, and in others mineralization has spread laterally from fissures, subparallel to the bedding. Iron is often introduced with the manganese. Some 20 deposits of this type are known in north-central Zacatecas and northwestern San Luis Potosi. Important deposits are the Abundancia mine (Wilson and Rocha, 1956c) in Zacatecas; Montana de Manganeso (Wilson and Rocha, 1956b) in San Luis Potosi; Picacho de La Candela, Durango; and a deposit near Arcelia, Guerrero, in southwestern Mexico state. The La Guadalupana deposit, 15 km north of Arcelia is the same (?) as the Tlalchapa deposit (Trask and Rodriguez-Cabo, 1948) on Figure 11. Deposits in Sonora, Durango, and Zacatecas have been described in more detail by Ayub (1960). The age of these deposits is difficult to verify, but at Montaña de Manganeso and Abundancia, the epigenetic deposits are hosted in Late Cretaceous sediments.

Limestone-replacement deposits (type 3) occur near intrusive granitoid bodies. Examples are Dinamita, Durango; Buenavista, Guerrero; Guadalcazar, San Luis Potosi, and Candela, Coahuila. The ore is found in recrystallized and also in unmetamorphosed limestone, and in other places in breccia zones (Trask and Rodriguez-Cabo, 1948). Other deposits that are larger than average include Sarnosa and Luz, Durango in the Dinamita group, and Milagro, Coahuila, part of the Candela deposits. Mineralization found in brecciated zones in limestone include those near Muzzquiz and Hipolito, Coahuila; and San Pedro Ocampo, Zacatecas. The age of the deposits at Guadalcazar are Tertiary, being found at the contact of a granitoid intrusive of that age within Cretaceous limestone. At Sarnosa, Early Cretaceous limestone is intruded by a quartz monzonite stock of likely Tertiary age with manganese being found at the periphery of the intrusion.

Tuff replacement deposits (type 4) include one of the largest in Mexico located at Lucifer, Baja California Sur. The ore is characterized by siliceous and maganiferrous replacements of tuff and has been described by Wilson and Veytia (1949). Because it is Pliocene in age it is considered in the youngest mineralizing epoch later in this paper.

Other, miscellaneous deposits are discussed by Trask and Rodriguez-Cabo (1948), but because they collectively amount to less than five percent of the ore produced during 1942-45 they are not considered here.

Two of the largest manganese deposits mined in recent years are San Francisco, Jalisco (Fig. 11); and Molango, Hidalgo (Fig. 5). There are 44 prospects in the Autlan-El Grullo district in Jalisco, some of which have been classified as hydrothermal in origin (Rodriguez-Medina et al., 1992b). However, the San Francisco deposit occurs in tuffs and contains oxides of manganese and iron that have been deposited in a lacustrine basin (Zantop, 1981) in a continental environment of early Tertiary age. However, this age assignment has been challenged by Zarate-Del Valle (1997) who contends that the host rock can be correlated with the volcanosedimentary facies (Hautervian-Aptian) of the Guerrero-Colima orogen complex. Emplacement of the metals is envisaged by chemical precipitation from volcanically derived solutions that entered the depositional basin. The deposit was classified as exhalative-sedimentary by Zantop (1978). Other smaller manganese deposits in Jalisco have been described by Echegoyen and Almanza (1963).

Tungsten deposits

The states that have produced tungsten are located in northwestern Mexico; Baja California, Sonora, and western Chihuahua are the principal producers. The lower California deposits have been described by Fries and Schmitter (1945), those in Sonora by Weise and Cardenas (1945), and the Guadalupana deposit in Chihuahua by Schulze (1953). In general terms, tungsten in these deposits is related to batholithic rocks in the form of contact replacement, pegmatite, and vein mineralization.

Scheelite deposits are located in the northern part of the Sierra de Juárez in Baja California in an area that covers 600 km². These pyrometasomatic-replacement deposits are found in tactites developed in metamorphosed late Paleozoic sediments that have been intruded by Mesozoic diorites and pegmatites of the batholith (Fries and Schmitter, 1945). Metamorphosed rocks are found in northwest-trending zones and less regular groups of roof pendants. Of the numerous mineralized localities, El Fenomeno mine sustained commercial production during World War I, and also from 1937-43 (Fries and Schmitter, 1945). The age of mineralization can be loosely tied to K-Ar determinations of the batholithic rocks in the area by Gastil et al. (1975), who concluded that granitoid rock emplacement was probably complete by 90 Ma, which suggests that the tungsten deposits were formed about this time. More recent ⁴¹Ar/³⁹Ar dates in the Laguna de Juarez and El Topo plutons (Ortega-Rivera, 2003), within the mineralized region, span 100-79 Ma and 100-83 Ma respectively, and suggest a larger age span. Figure 12 shows the location of the El Fenomeno mine and smaller deposits in the adjacent Corte de Madera and Cerro El Topo localities. Included here are Los Cinco Hermanos and Olivia deposits which have produced little ore.

An early description of producing localities in Sonora was given by Wiese and Cardenas (1945) who recognized three mineralization types; 1) contact-metamorphic deposits in
Figure 11. Manganese deposits of the Late Cretaceous-early Miocene interval are cited by name for those deposits where ages are available. Modified from Trask and Rodriguez-Cabo (1948). From Clark and Fitch (2009).
Figure 12. Tungsten deposits of the Late Cretaceous-early Miocene interval. Modified from Weise and Cárdenas (1945) and Clark and Fitch (2009).
limestone; 2) pegmatite dikes in granite; and 3) quartz veins in granite. The first recorded production was in 1916, and in 1952-53, 80% of the national production came from the Baviacora district, being surpassed in 1960-1962 when 100% of Mexico’s tungsten production came from the same district (Cendejas-Cruz et al., 1992).

Some of the most important contact-metamorphic deposits are located near Hermosillo. The host limestones are Permian age and have been intruded by granitoid plutons forming scheelite-bearing tectites. Among the deposits immediately south of Hermosillo are the San Juan de Dios, Cinco de Mayo, and El Carmen mines. The Palo Verde deposit was exploited during World War II. In all, several mines produced ore in the Hermosillo district, and are collectively designated (Ho) on Figure 12.

Elsewhere, following discovery and production in the early 1950’s, mining was suspended but then renewed in the 1970’s in the Baviacora district, where deposits are related to the El Jaralito batholith (Damon et al., 1983b, Roldan-Quintana, 1991). The El Jaralito batholith, an I-type, has been dated at 70-52 Ma. Important mines and, or mineralized zones, include the San Antonio, Santa Elena, Bonanza, Los Moros, El Contrabando, and Cerro de Batamote localities (Cendejas-Cruz et al., 1992).

At the San Antonio mine, Dunn and Burt (1979) note the close spatial relationship between high-grade scheelite mineralization and small pegmatite dikes with mineralization in the carbonate wall rocks. Deposits in the Baviacora district are indicated by (Bv) on Figure 12. Other deposits of this type, but with more intermittent production are in the Bacanora area, specifically La Northeña mine. Other replacement deposits include the Virgen de Guadalupe mine near Guaymas and deposits near Sahuaripa plus El Saturno and Picacho. Further east, near Rio Yaqui other deposits include Tecalote, Extension de Uranio, Cadena de Cobre, and Coker. In some of these localities the age of the intrusion is given as Laramide (Pérez-Segura, 1985). El Nacimiento was described by Rocha-Moreno (1953). Near Alamos, in the San Alberto prospect, scheelite is located in an endoskarn below a quartzite of Mesozoic age (Pérez-Segura, 1985).

Pegmatite related tungsten mineralization of importance is related to the El Jaralito batholith (Damon et al., 1983b). Roldan-Quintana, 1991). The El Jaralito batholith, an I-type, has been dated at 70-52 Ma. Important mines and, or mineralized zones, include the San Antonio, Santa Elena, Bonanza, Los Moros, El Contrabando, and Cerro de Batamote localities (Cendejas-Cruz et al., 1992).

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Pegmatite related tungsten mineralization of importance is located east of the Yaqui river at Santa Rosa, San Nicolas, and Santa Ana, all represented by SA on Figure 12, and also at El Encinal, La Dura (El Tungsteno claim), El Trueno, and Llano Norteña (Weise and Cardenas, 1945).

Vein-bearing tungsten localities that are hosted in granitoids include La Paz and El Cobre; the latter was also worked for molybdenum (Weise and Cardenas, 1945).

Another locality that has produced tungsten in Sonora as by-product is the Washington mine where breccia pipe, polymetallic mineralization includes scheelite. Sericite, in the alteration assemblage, was dated at 46 Ma (Clark et al., 1979a).

In adjacent southwestern Chihuahua, the Guadalupana mine (Schulze, 1953), tungsten mineralization occurs in quartz veins and pegmatites that contain scheelite hosted by granodiorite. There are also minor amounts of copper and molybdenum. The age of sericite in the alteration envelope is 51 Ma (Clark et al., 1979a).

In the San José del Desierto, Durango, porphyry copper deposit, dated at 63.3 Ma (Clark et al., 1979a), tungsten is also present (Carrasco-Centero and, Cardenas-Vargas 1975).

In the Rosario district of southern Sinaloa, tungsten and molybdenum are found in the Guayabo mine where a quartz vein contains wolframite and molybdenite, all hosted in granodiorite (Bustamante-Yafiez et al., 1992).

In central Mexico, scheelite was obtained as a by product of gold and silver ore in fissure veins and replacements at the El Maguey mine, located in the Comanja granite in the Sierra de Guanajuato. Bismuth minerals have also been reported at this locality (Yañez-Mondragon et al., 1992). The Comanja granite has been dated at 53-51 Ma by Zimmermann et al. (1990).

In the last years of production at the Inguaran porphyry copper deposit in Michoacán (Fig. 6), tungsten concentrations were obtained by hydraulic mining and gravimetric concentration from the 0.02 and 0.04 % W contained in the tailings (Osoria et al., 1991).

Gold and silver deposits

There has been considerable interest in gold and silver over a time span of nearly 500 years. Correspondingly, the relative geological literature is extensive, but only the more modern reports are mentioned here. In 1966, Edward Wisser pronounced the Mexican volcanic province from the United States border southward toward Mexico City, the Sierra Madre Occidental (SMO), as the greatest epithermal silver province in the world. Gross production to that time was estimated at $1.5 billion in silver and gold. His classic study explored the relationship between mineralized structures of SMO, width of vein deposit, and gold to silver ratios relative to base metals, and height above the basement (pre-Tertiary volcanic sequence). Wisser’s work concentrated on the important Au-Ag deposits on the western flank of SMO. Extrapolation of the geological sequences to the eastern flank of SMO along the Altas Llanuras physiographic subprovince was made by Clark et al. (1979b), who emphasized the presence of the prominent Pb-Zn-Ag-Au-(Cu) assemblage, later acknowledged by Albinson et al. (2001). Many, but not all fissure-vein deposits have proven to be epithermal.

In 1991, Clark and Melendez divided all Au-Ag deposits into 11 subclasses including one non-geological type; namely dumps and tailings that could be reworked by modern methods of precious metals recovery. The reader is referred to this report for details that, for space reasons, are not given in the present analysis. The presently considered sub-classes of Au-Ag deposits are 1) veins (epithermal, high and low sulfidation); 2) mesothermal deposits; 3) mantoos and chimneys; 4) replacement (skarn and tectite); 5) by-product in porphyry copper deposits; 6) by-product in massive sulfides; 7) placer; 8) disseminations in sedimentary rocks; 9) disseminations in volcanic rocks; 10) disseminations in intrusive rocks; 11) structurally controlled disseminated deposits; and 12) hot spring deposits.

Gold and silver in epithermal vein deposits

These are a prodigious number of vein deposits in Mexico, especially in western Mexico, as previously noted, and associated with the Occidental arc of Clark et al. (1982), of which only a small number (48) are shown in Figure 13 whose age has been established beyond doubt. In a series of papers Ferrari et al. (1999, 2002, 2007) recognized space-time patterns of Cenozoic arc volcanism in Sierra made Occidental and the Trans-Mexican Volcanic Belt (TMVB). Of particular interest
in the Late Cretaceous-early Miocene interval under consideration are the igneous complexes recognized in the Late Cretaceous-Paleocene plutonic and volcanic rocks; Eocene andesites and lesser rhyolites of the Lower Volcanic Complex, and silicic ignimbrites emplaced during two pulses in the Oligocene (32-28 Ma) and early Miocene (24-20 Ma) and referred to as the Upper Volcanic Supergroup Ferran et al. (2001). These events provide more details than the ignimbrite flare-up from 40 to ~20 Ma (Coney, 1976) and the continuity of magmatism and mineralization from ~140 to 16 Ma (Clark et al., 1979a, 1982) that covered a wider region in northern Mexico.

Precious metal mineralization in the Late Cretaceous-early Miocene interval (Clark et al. 1979a, 1982) was likewise more precisely defined by Campbruí et al. (2003) who recognized three epochs, namely 1) between ~48 and ~40 Ma (Eocene), 2) between ~36 and ~27 Ma (Late Eocene-Oligocene), and 3) between ~23 and ~18 Ma (early Miocene) which overlap three of the main volcanic pulses.

Epithermal deposits are reported from 12 states that span 48-45 (?) Ma at Batopilas to 18 Ma at Ixtacaxamitlín, Puebla (Trílía, et al., 2004). Additionally, mineralization is considered to have occurred within less than 2 Ma after the associated siliceous volcanic or related intrusive rocks were emplaced. New ages of early Miocene mineralization in SMO were presented for 7 deposits: Lluvia de Oro, Durango; El Indio, El Zapote, Santa María de Oro, and La Yesca, in Nayarit; Cinco Minas, Jalisco; and Mezquital del Oro Zacatecas. These ages, from southern SMO contrast with late-Eocene-Oligocene ages noted by Clark et al. (1979a) for vein deposits located further north in SMO. The new determinations support similar ages found at other localities at similar latitudes, and north of the TMVB, at El Oro, 27 Ma (Albinson et al., 2001), state of Mexico, Bolaños, 22 Ma (Lyons, 1988), San Martín de Bolanos, 23-21 Ma (Scheubel et al., 1998), Jalisco; and at Pachuca-Real del Monte, 20 Ma (Mckee et al., 1992), Hidalgo. The latter deposit is located well east of SMO (Geyne et al., 1963; Dreier, 1976), and an early Miocene age of mineralization was first reported by P. E. Damon (personal communication, 1991).

Evidence of Oligocene or older epithermal mineralization south of TMVB was also presented by Campbruí et al. (2003), at the La Guitarra deposit, Mexico state, which probably occurred after the emplacement of a rhyolite neck dated at 35 Ma. This determination supports Oligocene age mineralization in the southern part of the Occidental arc (south of TMVB) recognized at Taxco, 38-36 (?) Ma (Alain-Alvarez et al., 2002) and at Real de Guadalupe, 40-37 Ma (Albinson and Parrilla 1988), both in Guerrero. The reader is referred to Campbruí et al. (2003, table 1) for a complete list of deposits and their ages that are shown on Figure 13. Subsequently, the age of El Barquenño deposits has been determined by Campbruí et al. (2006) at ~58 Ma and as such documents an earlier interval of Paleocene Au-Ag epithermal-vein mineralization than had been previously recognized.

Another aspect evident in Campbruí et al. (2003, fig. 3) is that in southern SMO there is a younging of volcanism from east to west, together with ages of epithermal deposits, as predicted by Clark et al. (1979a, figs. 3, 4), during the regressive sweep of magmatism during late Oligocene-early Miocene time. Of further interest in fissure-vein deposits is the possibility of encountering stockworks in the wall rocks, as at Las Torres mine, Guanajuato district and at Real de Angeles, Zacatecas (Pearson et al., 1988) and flooding of permeable wall rocks with mineralizing fluids as seen at Dolores (see Overbay et al., 2001, and Melendez-Castro, 2009).

In summary, the unweighted average of 27 major vein localities for which ages and grades were reported by Albinson et al. (2001), and shown among others in Figure 13, is 8.29 g/t Au, and 331 g/t Ag (Clark and Melendez, 1991). The unique, native-silver deposit at Batopilas, said to carry >2,000 g/t Ag in some pockets, was not included in the average.

Gold and Silver in Mesothermal deposits

The recognition of mesothermal vein deposits located along the trace of the Mojave-Sonora megashear in northwestern Sonora was made by Albinson (1989). Subsequently, Iriondo and Atkinson (2000) proposed that these deposits were generated during the Laramide orogeny. Included in this group from northwest to southeast are Sierra Pinta, Quitovac, La Herradura. Tajitos, Campó Juarez, San Felix, El Chanate, and San Francisco (Pérez-Segura, 2008), see also Figure 13. The age of these deposits falls within the interval 60-40 Ma (late Paleocene-Eocene). They are further characterized by low Ag:Au ratios (<10:1), variable age host rocks, and temperatures of homogenization of fluid inclusions in two populations: a first stage of 300 ± 50°C and a second stage of 200 ± 50°C among other features (Pérez-Segura, 1993, 2008).

Of further interest in this belt of gold deposits is the recognition of thrust faults in the Quitovac area that varies gradually from N63°W to N23°E and has been interpreted by Iriondo et al. (2005) to represent a clockwise rotation in the direction of Laramide thrusting through time. The onset of thrusting occurred between 75 and 61 Ma and terminated ~39 Ma. The emplacement of mesothermal (orogenic) gold mineralization is spatially associated with thrusting.

Gold and silver in mantos and chimney deposits

Some of the best examples are in Chihuahua at Santa Eulalia and Naica. Silver and to a lesser extent gold are part of the polymetallic assemblage. For example at Santa Eulalia, silver and gold values are 320 g/t Ag and trace gold in the mantos (Megaw et al., 1988), but there is significantly less silver (250 g/t Ag) and trace Au in the chimney deposits. At Naica, the chimney values are 200 g/t Ag and 0.5 g/t Au, and at Mapami (Ojuela), Durango, mantos carry 200 g/t Ag and trace Au, whereas chimneys average 50 g/t Ag and 3.0 g/t Au. For other mantos and chimney values the reader is referred to Megaw et al. (1988, table 1), and Megaw et al., (1996, table 1). The distribution of mantos and chimneys is shown in Figure 7.

Overall, for 8 deposits, using the data of Clark and Melendez (1991), and the silver values at Santa Eulalia of Megaw et al. (1988), and the values at Ojuela cited above, but excluding the very high grades at San Pedro Corralitos, Chihuahua, the unweighted average is 0.67 g/t Au and 305 g/t Ag.

Gold and silver in skarn deposits

Examples taken from Megaw et al. (1988, table 1), show skarn at Santa Eulalia carrying less silver than mantos and chimneys, namely 125g/t Ag and trace Au, and there are similar silver but higher gold values at Naica; 150 g/t Au and 0.3 g/t Au. At La Encantada, Coahuila, skarns, carry 200 g/t Ag and there is no report of Au. Silver values in this deposit are 250 g/t and 400 g/t in chimneys and mantos respectively. The distribution of Au-Ag-bearing skarns is also shown on Figure 7 and coincides with...
Figure 13. Distribution of gold and silver in epithermal fissure-vein deposits, and gold with minor silver values in mesothermal deposits, Late Cretaceous-early Miocene (modified after Wisser, 1966; Clark et al., 1979a, b; Albinson et al., 2001; Camprubi et al., 2003; Camprubi and Albinson, 2006, 2007; Pérez-Segura, 2008. From Clark and Fitch 2009).
the manto and chimney deposits. Gilmer (1987, fig. 95) noted the strong correlation of these deposits at basin-uplift margins. The unweighted average grade of 6 skarn deposits cited by Clark and Melendez (1991), for which chimneys and mantos are largely absent, is 0.4 g/t Au and 196 g/t Ag.

Los Filos, Guerrero is a complex of three major deposits: Nakay, Bermejal, and the Los Filos-Aguita open pits. Los Filos mineralization is associated with a diorite sill and granodiorite stocks emplaced in calcareous rocks of Late Cretaceous age with the formation of skarn deposits. Bermejal and Nakay have similar geologic frameworks. At Los Filos 75% of the gold is within the diorite sill, whereas Bermejal exhibits a Cu-Pb-Zn-Au assemblage, and at Nakay gold is accompanied by Ag, Bi, Te, Cu, and Zn in exoskarn. Total proven and probable reserves contain 6,555 M oz Au (see Rivera-Abundis et al., 2009a), and gold recovery is by heap leach methods.

Gold and silver in porphyry copper deposits
Porphyry deposits with average gold content ≥ 0.4 g/mt may be defined, albeit arbitrarily, as gold rich (Sillitoe, 1979). In Mexico, Cananea is cited as carrying 0.1 tAu (Barton et al., 1995), and three other deposits that carry small quantities of gold and, or silver are Washington, O.17 g/t Au, 16 g/t Ag; La Verde 0.08 g/t Au, 2 g/t Ag (Clark and Melendez, 1991) and El Arco, O.3 g/t Au (Barton et al., 1995). Porphyry deposit locations are shown in Figure 6.

Thus, for four deposits, the unweighted average grades are 0.16 g/t Au and 4.5 g/t Ag. However, with the huge reserves at Cananea of 1.8 Gt, it could be considered as a major gold deposit of 18,000 kg (5.8 M oz) Au.

Gold and silver in massive sulfide deposits
Using 37 deposits in Miranda (1995), the unweighted average content is 0.93 g/t Au and 189 g/t Ag. However all of these deposits are older than the late Cretaceous-early Miocene mineralizing epoch. Their distribution is shown in Figure 5.

Gold and Silver in Placer Deposits
Because of the Recent age of these deposits, discussion of their gold content is withheld for the latest section of this report.

Gold and silver disseminated in sedimentary deposits
Gold is disseminated in 4 sediment-hosted deposits in Sonora (Fig. 14): Amelia, Santa Gertrudis, Lluvia de Oro, and El Chanate (Crespo, 1998; Newell et al., 2004; 2005 and 2009). Using the low end of the range values cited by Clark and Melendez (1991), and a revised figure for Santa Gertrudis (Alba-Pascoc, 1998), the unweighted average content is 1.72 g/t Au and 2 g/t Ag, with a typically low Au: Ag ratio for these deposits. Silver values are only recorded at Lluvia de Oro (Rothemund et al., 2001).

The Real de Angeles, bulk minable deposit carries 75g/t Ag, 1.0 Pb, 0.92 % Zn with recoverable Cd values. Mineralization is located in Cretaceous age siltstones, in the form of veins and veinlets, which form a stockwork in the shallow parts of the ore body, with iron sulfides disseminated along bedding planes (Pearson et al., 1988). In the San Martin, Queretaro, sediment-hosted deposit, gold and silver are found in breccias, 2-5 g/t Au and 40-80 g/t Ag; in mantos, 3-5 g/t Au and 40-60 g/t Ag; and in stockworks, 1-2 g/t Au and 50 g/t Ag (Ortiz-Hernandez et al., 1989a). For individual ore body values see Rivera-Abundis et al. (2009c).

Gold and silver disseminated in volcanic rocks
Two large tonnage examples illustrate this subclass (Fig. 14): Mulatos, Sonora (Slaude 2001; Pérez-Segura y Ochoa-Landin, 2009) and El Sauzal, Chihuahua (Charest, et al., 2004; Weiss et al., 2009). The values used for Mulatos are for the San Francisco-Cerro Estrella deposit (40Mt, average 1.79 g/t Au) and for El Sauzal is 2.0 MT at 3.4 g/t Au. The unweighted average metal content for these two deposits is 2.2 g/t Au.

Gold and silver disseminated in intrusive rocks
Four deposits are included in this subclass, all in Sonora (Fig. 14). Cerro Colorado and Magallanes are associated with rhyolite domes; and Banco de Oro, in the same range as the Tajitos fissure-vein mineralization, is partially hosted by rhyolite porphyries and granite Silberman et al. (1988). La Choya is hosted by granite (Summers et al., 1993, 1998) and is also considered under structurally-controlled deposits. Silver values are recorded only at Magallanes (21 g/t Ag), and at Banco de Oro (1 g/t). The unweighted average gold value for these four deposits is 0.95 g/t Au.

Gold and silver in structurally controlled deposits
These deposits have been defined by Graubard (1984) for gold mineralization associated with low-angle shears and faults related to thrusting or detachments. Two examples are cited that exemplify this subclass that occur in northwestern Sonora (Clark, 1998; Pérez-Segura et al., 1998). The La Herradura deposit (Fig. 14) is structurally controlled and is located in metamorphic rocks of Precambrian age that includes biotite- and quartzo-feldspathic gneisses and chlorite schists. These rocks have been broken by a series of faults due to Tertiary reactivation of the Jurassic-age Mojave-Sonora megashear faults (De la Garza et al., 1998). The geology of the oxidized deposit is dominated by strongly sheared gneisses that are present in northwest-trending lithotectonic slices, 20-50m wide, bounded by high-angle faults. La Herradura is further classified as a mesothermal, low sulfidation deposit. The metamorphosed and igneous rocks at La Herradura generally resemble those at both Cargo Muchacho and Mesquite in southern California, and the structural grain resembles Mesquite, although the La Herradura gold-bearing quartz veins appear more like Cargo Muchacho (De la Garza et al., 1998). The deposit contains approximately 93,330 kg (3 M oz) Au at an average grade of 1.0 g/t Au (de la Torres-Carlos, 2009); and is exploited by open-pit methods. Estimated geological resources (measured and indicated) have a cut-off grade of 0.35 g/t Au, and there are three mineralized zones: Centauro, Yaqui, and Duñas.

Further southeast in the Sonoran disseminated gold belt (Jacques Ayala and Clark, 1998), a smaller structurally controlled deposit occurs at Lluvia de Oro where gold is disseminated in zones of Cretaceous sedimentary rocks associated with a northeast-trending shear. Reserves before initiation of open-pit mining were 4 Mt at a grade of 1.0 g/t Au and 2.95 g/t Ag (Teran-Cruz, 1998). Mineralization is considered to be Oligocene age (Rothemund, 2000). Regionally, the deposit is located on the west side of the Magdalena core complex, resulting in displacement of previously emplaced rocks to the southwest along the Magdalena detachment fault in late
Figure 14. Late Cretaceous–early Miocene gold and silver deposits disseminated in sedimentary, volcanic, and intrusive rocks, plus those that are structurally controlled by shears and detachments. La Choya and Lluvia del Oro appear in two subclasses and all four subclasses are underlain by Proterozoic terranes in Sonora. From Clark and Fitch (2009).
Rare Earth Elements will be discussed in a later section, see also Figure 16.

Development Associates, 2007), and there are similarities with the footwall. Sericite in the cataclasite was dated at 91-79 Ma. The deformed diorite complex was intruded by granodiorite (91 Ma, Echo Bay, 1997) and a diorite complex (129 Ma). The deformed diorite complex was intruded by granodiorite and a low-angle fault forms the contact between these units with the diorite in the hanging wall and granodiorite in the footwall. Sericite in the cataclasite was dated at 91-79 Ma. The average grade of the deposit is 1.0 g/t Au (Mine Development Associates, 2007), all in Baja California Sur. At Quitovac (Fig. 14) gold-bearing quartz veins are hosted in dynamically metamorphosed green schist facies rocks (Irondo and Atkinson, 2000). In Sonora, new H and O isotope data indicate that water in the mineralizing fluid is of metamorphic origin. This type of vein formation needs an accompanying orogeny to dehydrate basement rocks to form the mineralizing fluids. Consequently, Irondo and Atkinson (2000) conclude that the Laramide orogeny (~80-40 Ma) is a preferable mechanism than the Mojave-Sonora megashear to explain gold mineralization in northwest Sonora. Additionally, they propose that the roots of Laramide thrusts and associated structures acted as the deep conduits for the ascent of metamorphic fluids.

At Paradones Amarillos (Mine Development Associates, 2007), Baja California Sur (Fig. 14), the mineralization occupies a cataclastic zone of more than 10 km lateral extent between granodiorite (91 Ma, Echo Bay, 1997) and a diorite complex (129 Ma). The deformed diorite complex was intruded by granodiorite and a low-angle fault forms the contact between these units with the diorite in the hanging wall and granodiorite in the footwall. Sericite in the cataclasite was dated at 91-79 Ma. The average grade of the deposit is 1.0 g/t Au (Mine Development Associates, 2007), and there are similarities with the cataclastic shear zone at Los Uvares (Bustamante-Garcia, 1999).

Accordingly, for 8 deposits where credible values have been reported, and using the lower assay values at Quitovac, El Triunfo-San Antonio, and San Francisco, the average unweighted value is 1.33 g/t Au, but the large tonnage at La Herradura skews the average towards 1.0 g/t Au. Silver is recorded only at Lluvia de Oro (2.95 g/t Ag).

Gold and silver in hot spring deposits

Because of their late Tertiary-Quaternary age these deposits will be discussed in a later section, see also Figure 16.

Rare Earth Elements

Apart from small concentrations of Rare Earth Elements (lanthanides) in igneous rocks that relate to their petrogenesis, and in meteorites, there are, to date, no known concentrations of these metals sufficiently high to warrant extraction in Mexico. Nevertheless, there are several sub-economic deposits that merit brief discussion.

In 1990, Gomez-Caballero surveyed the Rare Earth Elements (REE) localities and divided deposits into primary and secondary environments. The secondary environment includes placer deposits that will be described in the latest mineralizing epoch. In the primary environment, REE are located in Mexico in carbonatite and alkaline rocks. Alkaline rocks were identified as the eastern magmatic province, Tamaulipas and Veracruz states; the southern prolongation of the Rio Grande rift zone in Chihuahua and Coahuila; and also in the Proterozoic Oaxaca Complex. Other possibilities include association with magmatic segregation iron deposits in Chihuahua, Coahuila, and Durango; and phosphate deposits in Baja California Sur.

At the Picacho igneous complex in the northwestern part of the Sierra de Tamaulipas (Fig. 15), REE have been reported by Elias-Herrera et al. (1990, 1991). The age of this complex is probably between early Oligocene to mid-Miocene. Nepheline-bearing rocks from a stock at the center of the complex host radioactive veins rich in apatite with REE mineralization from 1.3 to 3.0 percent. The petrogenesis of these rocks have been further studied by Ramirez-Fernandez (1996) who also recognized a minor carbonatite phase. The tectonic implications were noted by Ramirez-Fernandez and Keller (1997, 1998) who recognized in northeastern Mexico a transition from a subduction regime to intraplate extension. Subsequently, Ramirez-Fernandez et al. (2006, 2009) reported three REE-bearing minerals: baenrasite, britholite, and cheralite from the carbonatite phase.

Carbonatites were first recognized in north-central Chihuahua during 1992-93 and briefly reported on by Comaduran et al. (1996). Three localities near Villa Ahumada were further discussed by Nandigam et al. (1997, 1999, 2009). These localities include from north to south, Mariana, a carbonatite breccia that intrudes granite porphyry and which was tested by nine reverse circulation holes. A small carbonatite plug and dike that cut a Tertiary-age tuff comprise the El Indio locality. Yuca is a stock-like intrusion, 900 m in diameter displaying roof pendants at its crest, around which are located smaller bodies of breccia, dikes, and sills. Radiometric \(^{40}Ar/^{39}Ar\) determinations show that the age of intrusion is 36 Ma (Nandigam, 2000, Nandigam et al., 2009). Compositional types recognized, from least to most highly differentiated, are magnesio-, calcio-, and ferrocarbonatites, and the concentration of Th, U, Nb, Y and REE increases with differentiation. The Yuca carbonatite is associated with up to 2,000 times enrichment of La and Ce with respect to chondrite.

Potential sources of lanthanide concentrations in Mexico, within the time frame being considered, are iron deposits containing apatite (and hence Ce), tin-bearing granite with concentrations of xenotime (Y), syenites and pegmatites that bear monazite (Ce), and phosphorites that may contain Ln and Y. For more details on these localities the reader is referred to Gomez-Caballero (1990, fig. 2).

Mississippi Valley type deposits

Sierra Mojada, on the margin of the Sabinas basin, has already been included in limestone replacement deposits of Figure 7, based on temperatures of formation greater than 200°C (Megaw et al, 1988). Nevertheless, evidence of Pb and Zn oxide mineralization south of the Sierra Mojada fault suggests low temperature, MVT mineralization (Trillita et al., 2006, 2007, 2009).

In the Sierra de La Purisima and Sierra San Marcos in the Mineral de Reforma district, Coahuila (Fig. 15) stratabound mineralization is controlled by a reef facies of the Early Cretaceous Cupido Formation, and consists of sphalerite, barite, and siderite with traces of pyrite and chalcopyrite, all of which have been affected by supergene alteration. Scarcse fluid inclusion data from the hypogene minerals fall between 100-150°C with salinities between 7.5 and 20 wt% eq. NaCl (Gonzalez-Ramos, 1984).

In northeastern Chihuahua, at the Tres Marias mine, Sain-Eidukat et al. (2008) have identified botryoidal sphalerite with...
Figure 15. Rare earth element, Mississippi Valley type, and mafic-ultramafic rock deposits of the Late-Cretaceous-early Miocene interval. From Clark and Fitch, 2009).
inclusions of bitumen. The authors conclude that the initial mineralization of Ge-rich sphalerite and galena plus abundant bitumen could have formed by MVT processes that was later affected by a higher temperature siliceous alteration that includes the formation of willemite and hemimorphite.

These three deposits are thought to have formed from marine water trapped in sediment (connate water) and expelled during Laramide orogenesis. As such, their age of formation is imperfectly known.

**Mafic-ultramafic- rock deposits**

Two localities have been identified by Ortiz-Hernández et al. (2003). In the Yuma terrane (Fig. 15), Ojos Negros, Baja California Sur comprises metagabbro, and dikes of dolerite and granophyre. Apart from talc and serpentinite and stockworks of magnesite, there are low contents of Ni (298 ppm) and Cr (140 ppm).

The San Javier, Sinaloa locality is situated at the junction of Cortez and Guerrero terranes (Fig. 15) and is associated with several diatremes, 20-600 m width, of micaceous peridotite of possible kimberlite affinity. These rocks, emplaced in black slates that exhibit intercalations of limestone and polymeric conglomerate of late Mesozoic age, have been converted by metamorphism to greenschist facies (Servais et al, 1982, 1985). Trace amounts of Au, Pt, Pd, Rh, Ir, Ni, and Co were recorded in the quartzites of the sedimentary sequence at Real de San Javier. Details of the San Javier locality are given in Ortiz-Hernández et al. (2006).

**MID-MIOCENE TO RECENT**

This section examines the last epoch, approximately 16-0 Ma, in which metallic minerals formed and is based on Clark and Fitch (2005). Metallic mineral deposits that have been isotopically dated, or those for which there is good geological reasoning to ascertain their age, are shown on Figure 16.

**Lithologic and tectonic framework**

Subduction by plate convergence, so prevalent in northern Mexico during the preceding interval, was replaced by the Pacific-Cocos-North America triple junction migrating south along the western edge of the continent. By 16 Ma it was west of northern Baja California, and by 12 Ma west of southern Baja California (Lonsdale, 1989, 1991), and from 12 to approximately 5 Ma, the triple junction was south of Cabo San Lucas. Late Miocene (8 to 5.5 Ma) extension produced an embayment in the continental margin and this was followed by opening of the Gulf of California. Subsequent rifting and spreading in the gulf produced faults connected northward with the San Andreas fault (Sedlock et al., 1993), see Figure 16.

Accompanying these tectonic events were the development of several volcanic provinces around the Gulf of California (Gastil et al., 1979). Extrusions varying in composition from rhyolite to basalt were deposited on both sides of the northern part of the Gulf, and basaltic rocks are prevalent in the southern part of the peninsula. Alkaline volcanism occurred in the Baja California peninsula from 13 Ma onwards and has been dominant since about 10 Ma (Sawlan, 1991) during rifting and development of the Gulf of California. Marine strata of late Miocene age are located in the eastern gulf and nearby coastal areas, in contrast to marine Pliocene sediments that are found in the western gulf and coastal Baja California.

The development of the dominantly calc-alkalic Trans-Mexican Volcanic Belt (Gómez-Tuena et al., 2007), from late Miocene onwards resulted from subduction of the Cocos and Rivera plates (Nixon et al., 1987). Near its eastern extremity is the San Andreu Tuxtla center and further south is the Modern Chiapanecan arc (Damon and Montesinos, 1978). With the exception of placer and beach deposits, the remaining deposits discussed in the final 16 Ma interval are related directly or indirectly to tectonic and magmatic events in the continental and oceanic environments.

**Mineral Deposits (< 16 Ma)**

Following the wealth and diversity of mineralization in the late Cretaceous - early Miocene epoch, the mid-Miocene to Recent interval reveals still other classes of mineralization due to changes in tectonic regimes, accompanying magmatism and sedimentation. These regimes, offer prime exploration possibilities inasmuch as they appear to have been underexplored to date. Among the mineralization that occurs in this interval are porphyry copper and contact replacement, stratabound copper and manganese, placer gold and tin, black-sand beach, hot-spring gold, geothermal, and black and white smoker and shallow water hydrothermal vent deposits.

**Porphyry copper and contact replacement deposits**

The Chiapanecan volcanic arc hosts a porphyry copper deposit; which is located above the Mayan terrane in Chiapas (Fig. 16). Among a number of significant mineral deposits recognized in the Miocene arc, Damon and Montesinos (1978) refer to Toliman, that occurs in the southeastern corner of the state, as having all the aspects of a classic disseminated porphyry copper deposit, whose age is 5.8 Ma.

Across the state line in adjacent Oaxaca, the La Carmen prospect is a contact metamorphic deposit of granodiorite intruding limestone. Magnetite is predominant with lesser amounts of sphalerite (Damon and Montesinos, 1978). Two K-Ar dates on the granitoid phases fall between 13 and 12 Ma. In regard to exploration potential, the Chiapas Massif is regarded by Damon and Montesinos as most probably being an excellent target for Miocene mineralization associated with the roots of stratovolcanoes as outlined by Sillitoe (1973).

There is one mineralized locality within the modern Chiapanecan arc, and this occurs at Santa Fe (Pantoja-Alor, 1991), where gold mining took place before and after the Revolution, with latest production at La Victoria mine in 1972. Sulfide minerals are abundant within a stock that intrudes Oligocene-age limestones. The Santa Fe mine has been designated as a porphyry copper deposit on Figure 16 but it also has characteristics of a contact metamorphic deposit, and vein mineralization has also been exploited. Several K-Ar dates on intrusive phases in the Santa Fe area consistently fall between 3 and 2 Ma (Damon and Montesinos, 1978).

**Gold and silver deposits**

In northern Baja California at San Felipe (Fig. 16), a significant deposit was exploited by Empresas Frisco S. A. Mineralization occurs in a low-angle, quartz-filled structure that contains epithermal veining, breccia, and stockwork. The footwall rocks are a metamorphic complex of Paleozoic age, an overlying hanging wall of andesites of Cretaceous age, explosion breccias and rhyolites dikes of late Tertiary age (Ibarra-Serrano, 1996; see also Ibarra-Serrano, 2009). Resources/reserves amounted to 260,000 oz Au and 1,680,000 oz Ag, with average
Figure 16. Placer, beach, geothermal, stratabound, porphyry copper, hot spring, other Au-Ag, Fe, black smoker, and shallow water hydrothermal vent deposits of the late Miocene-Present interval (modified from Clark and Fitch, 2005, 2009).
grades of 4.6 g/t Au and 309 g/t Ag. The age of the deposit is 9 Ma or slightly younger, and conforms to Miocene-Pliocene volcanic rocks in this area (Gastil et al., 1975).

The Ixhuatan deposit is located 5 km south of Santa Fe in Chiapas. Mineralization contains significant Au-Ag values and occurs in diatremes areally associated with alkaline basalts and andesites (2.8 Ma), that have been intruded by diorites and granodiorites of the same age (see Miranda-Gasca et al., 2009).

**Stratabound copper-cobalt-zinc and manganese ores**

The Boleo district, at Santa Rosalía, on the east coast of Baja California Sur (Fig. 16), has been a producer of copper for over 120 years. Estimates are that about 19 million tons of ore at approximately 4% copper have been produced during this time (Escandon-Valle, 1996). Of this, just over 13 million tons averaging 4.8 percent copper were produced by a French company between 1886 and 1947. Some of the earliest reports on the deposit were published by Fuchs (1886) and Saladin (1892). The district extends along the coast and around Santa Rosalía for over 60 km². Recent measured and indicated resources are as follows using 3D block models and based on a copper equivalent (Cu eq) cut-off grade of 0.5% (Cu eq = Cu + 15 Co/1.5 + 1.2 Zn/1.5); 277.2 Mt, 1.77% Cu eq; 0.77% Cu, 0.06% Co, 0.62% Zn, and 3.00% Mn (Albinson and Hodson, 2007).

The principal lithologies at Boleo consist of pre-Tertiary quartz monzonite, overlain by the Miocene Comondú Formation andesite tuffs and agglomerates, (24 to 11 Ma), followed by the late Miocene-early Pliocene Boleo Formation conglomerates, sands and tuffs of intermediate composition, all overlain by the Gloria Formation of middle Pliocene age consisting of a sequence of sands and agglomerates, followed upwards by the Infemfo and Santa Rosalía Formations and finally by the Tres Virgenes (Pleistocene-Recent) volcanic rocks and terrace and alluvial deposits (Wilson and Rocha, 1955). The close of subduction and the change to extensional tectonics, includes pre-rift (12.5-10 Ma) high K-basaltic lavas, and synrift (9-1 Ma) alkalic basaltic andesites (Sawlan and Smith, 1984).

The Boleo deposits occur in the Santa Rosalía basin which formed as a consequence of late Miocene rifting. In the five mantos, numbered from 0-4 from the surface downward, the mineralized beds are flat lying, 1-15 m in thickness and laterally continuous, being disrupted by faults from a few tens to as much as 250 m vertical displacement. The ore minerals include chalcocite, chalcopyrite, digenite, carrollite, pyrolusite, sphalerite, and pyrite. Some 40 percent of the copper, cobalt and zinc are found within the molecular structure of montmorillonite.

The origin of the Boleo deposits has been addressed by Touwaide (1920), who favored a copper source formed by leaching tuff by conneate and ground water, and by Echavarrí-Pérez and Pérez-Segura (1975), who noted the presence of frambooidal pyrite, and the absence of replacement textures. They concluded the deposit was formed by syngenetic processes, at an early diageneric stage in a reducing medium caused by bacterial action. A recent assessment of the Boleo ore is by Bailes et al. (2001), who note that many of the pyrite frambooids are rimmed to varying degrees by chalcocite, and cobalt is associated with several sulfide minerals, including enrichment rims on chalocite and chalcopyrite, possibly in the form of carrollite (CuCoNi)₂S₂. Secondary ore minerals in mantos are products of chemical breakdown of primary sulfides above the water table. Bailes et al. (2001) conclude that mineralized fractures, related to extensional faulting as the Gulf of California developed, were points of entry of hydrothermal fluids, leading to early diagenetic or syngenetic deposition of metals that invaded the underlying conglomerates, and overlying slumps breccias and mud and fine ash at the base of mantos. A deep source of hydrothermal brines is consistent with present day geothermal fields in the region and the high geothermal gradient of 1°C per 15 m depth in the Boleo district, (see also Ochoa-Landin et al., 2009).

The Lucifer manganese deposit, situated 17 km northwest of Santa Rosalía, was developed in 1941, and became a leading producer in Mexico (Wilson and Veytia, 1949). Ores of manganese and copper occur in latticelike anidesitic tuff of the Boleo Formation, which is underlain by the Comondú andesitic and basaltic flows, tuffs, and agglomerates, and overlain by the Gloria Formation and younger formations referred to above. The ore at the Lucifer mine forms a gently dipping tabular deposit enclosed in tuffs, with thickness varying from 1 to 6 meters. A flat fault lies above the ore zone, and normal faults offset the ore body by as much as 8 meters. Ore minerals include fine-grained cryptomelane and pyrolusite, and contain 45 to 50 percent manganese. Wilson and Veytia (1949) favored a hydrothermal origin in which solutions rose along faults in the underlying Comondú volcanics, and then spread laterally in the tuff beds, with partial replacement. Overall, the origin of the Lucifer manganese ores was considered to be closely related to the Boleo copper deposits in which manganese is a common constituent.

A later study by Freiberg (1983) recognizes textural and depositional characteristics of the ore deposit and host sedimentary rocks that imply formation in a shallow marine basin and whose ore solutions originated from hot springs. Upon venting, the mineralizing solutions mixed with and impregnated the matrices of pyroclastic materials of the Boleo Formation. The contemporaneous deposition of tuffs with manganese suggests a relation to a magmatic source. Manganese was envisioned as being scavenged by hot aqueous solutions from the Comondú volcanics. The hydrothermal solutions were probably derived from seawater which interacted with the Comondú volcanic rocks in a convection system similar to Recent mineralization in spreading environments at mid-ocean ridges (Freiberg, 1983).

**Placer deposits**

The preponderance of fissure-vein gold deposits in the western part of Sierra Madre Occidental dictates the abundance of gold placers in the western part of Mexico. In Sonora, West (1993) has plotted the placer fields that were discovered in the southwestern part of the state (Fig. 16). From south to north these are Cieneguila (La Cienega, 1770); Santa Rosa de Buenavista (1775); San Francisco de Asís (El Boludo, 1803); Las Palomas (1935); La Basura (1835); El Tren (1844); El Zoni (1844); Quitovac (1835); and Sonoita (no date). These deposits are collectively situated on the flanks of ranges in the subprovince of Buried Ranges (King, 1939) and they are inclined towards adjacent basins. Individually published reports include a description of the placers of Sonora (Tyler, 1891), dry placers in northern Sonora (Merril, 1908), La Ciénega (Hill, 1902), Rio Yauqui (Anonymous, 1994), and El Boludo (Orozco-Fararoni, 1997; Wilson et al., 2009). For other localities in Sonora refer to Cendejas-Cruz et al. (1992).

The El Boludo deposit was described in detail by Wilson (2001), and Wilson et al. (2003, 2009). This is the only locality in Sonora, and the whole of Mexico, where modern mining is
taking place by way of a unique air-separation technology (Piggott, 1999, 2000). At El Boludo, gold-bearing veins, found in the foothills of the adjacent Sierra La Salada are hosted by Proteroozoic quartz-feldspar gneiss. Gold eroded from these veins has formed an extensive placer in three distinct sedimentary horizons comprising pediment and alluvial fan deposits rather than a lacustrine origin, as envisaged by Radelli and Pérez-Segura (1992). Au/Ag ratios determined by electron microprobe analyses were used to match placer gold particles with their primary vein source. The total resource of gold-bearing sediments contained in the El Boludo placer field, amenable to air separation technology, has been estimated at 25 Mm³, grading 0.26 g/m³ Au (Wilson et al., 2003).

In Sinaloa, the Bacubirito placer has been described by Abel (1922), Hurst (1922), and Espinoza (1932); the Yecorato placer by Canon (1971), and Slipp and Stuckenrath (1973); and the placers of Rio Sinaloa by Cárdenas-Vargas and Camacho-A. (1973). Other placer deposits in Sinaloa occur at El Orito, in terraces of the El Fuerte river, El Tambor, and in the Rosario river (Bustamante-Yanez et al., 1992).

At Santo Domingo, Chihuahua, on the Conchas River, the gold-bearing placer has been investigated by Barry (1923), and Clark (1987a, b). Potential for gold extraction from placers is also cited at Placer de Guadalupe (Durán-Miramontes et al., 1994).

In Jalisco, a placer tin deposit at Rio de Lagos was described by Pérez-Sodi and Larios (1949). In addition, there are three other localities: Teocaltiche-Villa Hidalgo, Encarnación de Díaz, and Las Latas where placers are associated with primary tin mineralization (Rodríguez-Medina et al., 1992b).

In north-central Durango, tin placers have been described at La Laguna de Santiagoillo and San Bartolo, to the north of the valley of Canatlán (Rocha-Moreno, 1968). Tin placers also occur at America-Saporí, where cassiterite is concentrated in paleo-channels and terraces that drain the primary deposits. Gold placers are found in the western part of the state in the San Lorenzo and Piaxtla rivers below vein deposits of Tayoltita and other mines in the San Dinis district, and also in the Rio San Diego, in the Pueblo Nuevo area (Carrasco-Centeno et al., 1993).

In east-central San Luis Potosí, there are metallic deposits in two alluvial fans in the Guadalazcar district, near the villages of Guadalazcar and El Realejo. The sand and gravels have been derived from the large Tertiary granite intrusion in this area. The metallic content of gravels in the Las Papas area of the district resulted in assays of 0.04% Sn, 0.0015% Hg, 9.44 g/t Ag, and 0.06 g/t Au (Fries and Schmitter, 1948).

The Pinzan Morado-Placeres del Oro area in Guerrero and adjacent Rio del Oro and tributaries has been described by Were-Keenan and Sanchez-Bautista (1975).

The placer deposits of peninsula California have been referred to by Oviedo (1895), and in particular, at Caltamalii (Bonfont, 1900; Islas-Lopez, 1999), located near El Arco. The Rosario gold placer is located southwest of the El Triunfo-San Antonio district in Baja California Sur (Bustamante-Garcia, 1999), adjacent the nearby Juan Marquez deposit (Rocha-Moreno, 1973), and placer La Muela (Altamirano-Ramírez, 1971).

**Beach deposits**

Beach deposits of heavy minerals have been identified in Guerrero and Oaxaca states (Rocha-Moreno, 1947; Martin-Barajas, 1980). These accumulations have been derived from the metamorphic terranes of the Acatlán and Oaxaca complexes. Fluvial transport was followed by concentration by waves and currents of the Pacific Ocean. Three types of deposit are recognized by Martín-Barajas (1987), namely, 1) river-mouth; 2) beaches and bars; and 3) eolian, depending on local conditions in the littoral environment. The heavy minerals investigated include magnetite, ilmenite, rutile, zircon, monazite, and garnet. Localities include Playa de Cayacal, Bahía de Agua Dulce, Boca del Río Verde, Boca del Río Colotepec, and Playa de Ventanilla (Fig. 16).

In the San Antonio del Mar marine terrace and modern beach deposits in Baja California, magnetite and ilmenite occur with traces of zircon and leucoxene (Islas-López, 1999).

Disseminated gold and silver in hot-spring deposits

A hot spring, epithermal gold province has been recognized between Indio, California and San Felipe, Baja California (Fischer-Watt Gold Co., 1991). Five deposits in this province are located in Mexico (Clark and Melendez, 1991). The province is characterized by crustal thinning, volcanism, and high heat flow, on which was superimposed a northwest trending transcurrent fault system (Sharp, 1982). Highly permeable fracture zones formed conduits for hydrothermal activity that resulted in hot springs and geyser development, and large alteration areas that display silica veining and flooding, with potentially economic concentrations of gold and silver. The prospects in Baja California include Santa Lucia, El Cerrito, Tina, and Patria, (Fig. 16). The age of the deposits is late Tertiary-Quaternary, and is clearly associated with ongoing tectonic dislocation in the Gulf of California and the San Andreas fault system. Because of paucity of data the nearby Montezuma prospect is placed in the “other Au-Ag deposits” category. Ignoring the very high values cited in the Santa Lucía deposit, the average gold content of El Cerrito, Tina, and Patria is 1.6 g/t Au and < 56 g/t Ag. No production has been recorded. These deposits are similar to the gold-bearing Pliocene, hot-spring system at Modoc, located 24 km south-southwest of Indio, California, where Fischer-Watt (1991) reports a substantial deposit.

The polymetallic hot-spring deposits at Comanjilla and Jacintos (Saldaña, 1990), adjacent the active El Bajo range-front fault, Sierra de Guanajuato, appear to be the upper part of the Buchanan (1991) precious metal deposits model, but may not be directly related to the Guanajuato district mineralization because of the large intervening time span (Randall, et al. 1994).

Among the siliceous sinter deposits with a hydrothermal origin discussed by Camprubi and Albinson (2007) and listed in their compilation of epithermal deposits with an age of <18 Ma, is Ixtacamaxtitlán, Puebla (see Fig. 13).

**Terrestrial geothermal areas**

Active high-temperature geothermal volcanic areas are of interest in the search for base-metal and precious-metal deposits, inasmuch as they provide valuable insight to systems that existed in analogous older terranes (Henley, 1985). For example porphyry copper-molybdenum deposits are found at deeper levels within calc-alkaline volcanic systems, and Kuroko-type massive sulfides are interpreted as sea-floor, telescoped equivalents of terrestrial epithermal deposits. Typical models for geothermal systems in andesite-volcanic terranes and silicic-volcanic environments have also been advanced. Thus, the present rate of gold deposition at Waiotapa, New Zealand is...
known (Hedenquist and Henley, 1985), and from this, the time needed to produce a multimillion ounce orebody, under the same conditions, can be projected. In general, active geothermal systems may contain subeconomic metallization, as for example Mo and lesser amounts of Cu, Pb, Zn, and Mn, and anomalous quantities of Au that have been documented in the Valles Caldera, New Mexico (Goff and Gardner, 1994).

In Mexico, the relation between ongoing geothermal activity and the presence of epithermal mineralization in older terranes in the same locality is scant. In the vertically stacked are bodies of the Guanajuato district (Echegoyen et al., 1970; Buchanan, 1981), a volcano-plutonic center (Randall et al., 1994), the main mineralization in the lower zone took place from 31 to 28 Ma (mid-Oligocene). Structurally above, in the intermediate zone, are two geothermal systems, Maren and El Cubilete that are peripheral to the deeply eroded caldera. The age of these two systems is unknown in detail but is considered to be mid-to-late Oligocene. They are 200 m above the lower zone and appear to represent part of the upper parts of Buchanan's (1981), epithermal, fissure-vein model. The upper zone, where geothermal activity is presently active, is on the downthrown side of the range-front fault of this district. At Jacintos and Comanjilla, hot springs show values of several metals including Au, Ag, Pb, Zn, and Cu (Saldaña, 1991). However, although the mineralized zones are in close proximity, they may be unrelated because of the large time span between present-day hot springs and the intermediate and lower zones of mineralization (Randall et al., 1994).

Throughout Mexico 1,283 thermal springs have been identified including hot springs, fumaroles, sulfur springs, mud volcanoes, water wells, or combinations thereof. They are grouped into 515 geothermal zones by assigning them to the same aquifer or by having a common origin (Razo, and Romero, 1991). They are further divided into seven provinces. Thus there are four important zones in the San Andreas and Sonora-Sinaloa province, closely spaced in northern Baja California, in or near the Mexicali Valley and the trace of the San Andreas fault. These include Rítito, Guadalupe Victoria, Tulecheck, and Cerro Prieto. In the latter, where power generation began in 1973, gold was detected in the scale of two production pipes (Julio Alvarez-Rosas, personal communication, 2005: Alonso-Espinosa and Mooser, 1964). Although no gold was reported from the Salton Sea geothermal system, located 80 km to the north, there were several sulfophile metals reported in concentrations up to 2,000 ppm (White, 1968). Coincidently, or not, the hot-spring gold concentrations of Au are known in alteration silica (Efren Pérez-Segura, written communication, February, 2009), and the potential for encountering economic mineralization in the TMVB seems evident. For a description of the major geothermal fields in Mexico, see Hiriart-LaBert, (2009).

Deep Sea hydrothermal vents
Deep Sea hydrothermal vents (Black and White Smokers)
The final episode of metallization in the mid-Miocene to Recent epoch is associated with the occurrence of hydrothermal plumes associated with oceanic spreading centers at latitude 21°N and in the Guaymas Basin. Using a manned diving saucer (Francheteau et al., 1979) describe the hydrothermal emissions that they discovered at latitude 21°N on the East Pacific Rise (EPR) spreading center, some 250 km south of Cabo San Lucas, Baja California Sur (see Fig. 16). The expedition was part of the Rivera-Tamayo (RITA) study of the EPR. Two sites were sampled on the lightly sedimented flanks of structural depressions located approximately 600 to 700 m west of the axis of the extrusion zone in which the youngest lavas occur. Massive sulfides were sampled from various parts of irregular columnar edifices, about 10 m high and 5 m wide. The material consists of friable and porous components that are easily broken. Ore minerals identified include sphalerite, pyrite, marcasite, chalcopyrite, iron oxides, and amorphous silica. Analyses were made by x-ray fluorescence and atomic absorption spectrometry that also revealed the presence of Co, Pb, Ag, Cd and Mn. The sulfide phases are mainly sphalerite and pyrite with minor chalcopyrite and marcasite. The origin of these sulfides is attributed to chemical precipitates when hot, convectively circulating seawater leaches metals from the ocean crust and forms the deposits at the basalt-seawater interface. The resulting massive sulfides of ore grade can be preserved if the bottom waters are anoxic or if the deposits become buried under sediment or lava (Francheteau et al., 1979).

In general, the active chimneys are classified as black smokers if the precipitates are dark colored (high temperature), or white smokers if the precipitates are light colored (lower temperature). Pyrrhotite is the initial precipitate from the undiluted hydrothermal fluid and is the dominant particulate in the dark-colored plume issuing from vents. It may be replaced by pyrite and marcasite (Zierenberg et al., 1984).

Cu-Fe sulfides and anhydrite dominate the highest temperature vents and cubic cubanite has also been identified. Anhydrite is abundant in active vents and often contains fine-grained inclusions of dendritic pyrite and chalcopyrite. Wurtzite predominates in active chimneys and is abundant in basal mounds, whereas sphalerite and pyrite are more abundant in inactive mounds. Minor amounts of marcasite occur with pyrite. Sulfur isotope values of anhydrite and barite indicate disequilibrium with coexisting sulfides and demonstrate that seawater sulfate is their sulfur source. Oxygen isotope geothermometry applied to anhydrite sulfate indicates temperatures of 194 to 222°C (Zierenberg et al. 1984).

Precious metal values, with the exception of silver, are low. Silver content is less than 240 ppm and is associated with zinc sulfide phases rather than discrete silver-bearing minerals. Silica, alkali-metals, and manganese are dispersed into the water by hydrothermal plumes. Gold and platinumoid values are less than 0.2 ppm and 3.0 ppb respectively (Zierenberg et al., 1984).

Another locality, but within the central part of the Gulf of California, where sea floor spreading hydrothermal activity has been documented, is in the Guaymas basin (Lonsdale et al., 1980). The basin consists of two northeast-trending grabens, named the Northern and Southern Troughs (Fig. 16), each approximately 40 to 20 km long, respectively, and 3 to 4 km wide. High heat flow (>1.2 Wm⁻²) measurements were the first
and N\textsubscript{2} (54\%). Crusts contain minor amounts of pyrite and N\textsubscript{2} (88\%) and CH\textsubscript{4} (12\%). The vent water is less saline than sea water vents correspond to continental margin extension with high geothermal gradients, and that there are no obvious links with volcanic activity.

**MINERALIZING EPOCHS**

The recognizable mineralizing epochs are shown graphically in Figure 17. In all, six epochs are distinguished and further illustrate the same mineralizing intervals summarized in Table 2. In the following sections metal assemblages, type of deposit, and the relation to the prevailing tectonic environment are discussed.

**Proterozoic (~1.1-1.0 Ga)**

A limited number of deposits are associated with the Oaxaca terrane (Fig. 3) and these include titanium related to anorthosite of the Oaxaca Complex; REE related to pegmatites; and precious metal in veins in gneiss host rocks (Figs. 3 and 17).

As previously discussed, other limited exposures of Proterozoic lithologies in the Molango, Hidalgo, and Los Filtros, Chihuahua areas are devoid of metal occurrences, whereas gold in veinlets at Novillo, Tamualipas has been assumed to be of post-Grenville age (Eguiluz de Atuniano, et al., 2004). The more widespread Proterozoic rocks of northern Sonora, while host to important deposits, to date, do not reveal metal concentration of Precambrian age.

**Early Paleozoic (470-397 Ma)**

In spite of tectonism in southern Mexico in Devonian (Acadian), Mississippian and Permian time, as previously discussed, plus thermal events in the Acatlan Complex interpreted as part of the Laurentia-Gondwana collision and subsequent formation of Pangea, metallizing processes are scant; for example, the Mazapa de Madero Ti-(Cr-Ni) mineralization pods contained in anorthosites of the Chuacús Group, Cr and Ni have also been identified in mafic-ultramafic rocks at Tehuitzingo and Tecomatlán in Puebla (Figs. 4 and 17) that represent tectonized ophiolite, which formed part of the oceanic crust on which were deposited sediments of the Acatlan Complex.

Elsewhere, particularly at Canon Novillo, Tamualipas, weak Ni-Cr-Cu-Pt mineralization is related to a possible subduction complex.

The majority of Mexico was subject to an axis of sedimentation from Cambro-Ordovician time becoming restricted in the Silurian-Devonian interval, but broadening in late Paleozoic time, as indicated by the paleogeographic maps of López-Ramos (1969). It is in this widespread region that mineralization appears to be largely absent.

**Perm-Triassic (265-228 Ma)**

By Permian time polymetallic Pb-Zn-Ag-(Cu-Au) deposits appear to have formed in the environment of the Chiaapas Massif (Fig. 4), although the mineralization has not specifically been dated.

The Tepéitlán VMS deposit has been interpreted to occur in a Perm-Triassic protolith or possibly a deformational event of this age (Figs. 4 and 17). Mineralization occurs at El Tigre, Baja California Sur, where the Cr content of chrome spinel is 50\% Cr\textsubscript{2}O\textsubscript{3} (Bustamante-Garcia, 1999), in an ophiolite of Late Triassic age. While the ophiolites reflect the convergence of oceanic plates in the west, to date no mineralization has been registered along the Tarahuma-Ouachita orogenic trend in northern Mexico.
Figure 17. Composite diagram showing six metallic epochs: Proterozoic, Early Paleozoic, Permo-Triassic, Jurassic-Early Cretaceous, Late Cretaceous-early Miocene, and late Miocene - Present. Distributions are from SW to NE. Late Cretaceous-early Miocene epoch is modified from Clark et al. (1979, 1982) relative to the subduction zone. Late Miocene to Present deposits are from Clark and Fitch (2005, 2009).
Jurassic-Early Cretaceous (190-110 Ma)

This interval is characterized by the widespread distribution of VMS deposits in parts of western and central Mexico as well as isolated examples in Chihuahua and Baja California (Fig. 5). These deposits are predominantly associated with submarine volcano-sedimentary sequences of the Guerrero terrane, itself divided into three or more subterranes of Late Jurassic-Early Cretaceous age (Campa and Coney, 1983). Of these, the Telolapan-terrane exhibits low grade regional metamorphism, is severely deformed, and is thrust eastward along its eastern margin. The Zihuateanejo and Huéhtamo terranes are deformed but not metamorphosed, but all subterranes have been accreted subsequently onto the southern part of the North American continent.

The age assignments of the VMS deposits shown in Figure 17 are largely based on the isotopic determinations of Mortensen et al. (2008). However, for several deposits for which specific ages have not been determined, it is assumed that their age is similar to those for which age has been measured, particularly if they are in the same geographic cluster and in the same subterrane. Obvious exceptions, based on stratigraphic evidence are Arroyo Seco (AS) and Teziutlan (Tz).

Also contained in this mineralizing epoch are the important stratabound manganese ores of Molango, Hidalgo, perhaps related to depositional and hydrothermal events associated with the opening of the Gulf of Mexico.

Another deposit type is found at San Juan Mazatlán, Oaxaca and at El Arco, Baja California, and these represent the oldest porphyry copper deposits in Mexico, and reflect a subduction regime.

Finally, two red-bed Cu deposits in Chihuahua of Early Cretaceous age and numerous occurrences of mafic-ultramafic rocks, that contain minor contents of Ni, Co, Cr, Au and Pt-group elements were located along the western margin of mainland Mexico, complete the diversity of deposit types and contained metallic elements.

Late Cretaceous-early Miocene (100-16 Ma)

This interval exhibits a great variety of metallic deposits. The overall distribution is similar to that portrayed by Clark et al. (1979a, 1982) in which the deposits fall within an envelope of magmatic activity, subduction related, that swept eastward as the Farallon plate was consumed. However, in the present version of this distribution (Fig. 17) a greater variety of metallic assemblages has been included because more age determinations have been made in the ensuing 30 years.

Porphyry Cu-Mo-(W-Au) deposits

The diachronous, broad sweep of the porphyry deposits is clearly identified as before (Fig. 17), and is attributed to a younging of ages southwards due to oblique subduction along the western margin of the Mexican mainland during this time as noted earlier. The largest concentration of these deposits and those of greatest economic importance are located in the Caborca and Chihuahua terranes (Fig. 6). Lack of space prevents inclusion but a few of these deposits in Figure 17. Nevertheless, Fortuna de Cobre, San José del Desierto, Cananea, La Caridad, Florida Barrigón, Lucía, Tameapa, La Guadalupana, Washington, and Inguruan are representative of porphyry copper deposits.

Polymetallic Pb-Zn-Ag-(Cu) deposits

This distinctive assemblage (Fig. 7), ranging in character from stock-contact skarns to massive-sulfide mantos (Megaw et al., 1988) is largely confined to Cretaceous carbonate host rocks and thus appears relatively late within the Late Cretaceous-Early Tertiary interval as shown by the Dinamita, Naica, Santa Eulalia, and Providencia deposits in Figure 17.

Volcanogenic and other Fe deposits

There are two main clusters of these deposits as noted in Figure 8, namely (1) eastern Chihuahua and western Coahuila, and (2) along the coast of four states in southwestern Mexico. In addition, three other deposits, two of which are currently being mined, are located in Durango, Sonora, and Sinaloa. Figure 17 shows that there is considerable variation in age, as well as geographic distribution, with El Encino being the oldest (Corona et al., 2009a, b, c, d), and El Anteojo representing the youngest.

Volcanogenic and sandstone- U deposits

The well-known Sierra Peña Blanca volcanogenic uranium province in Chihuahua and other deposits in adjacent Sonora, appear to be tied to the Chihuahua cratonic terrane. The Sierra Peña Blanca deposits post-date volcanic units of late Eocene-early Oligocene age, and Los Amoles deposit in Sonora is located in Late Cretaceous volcanic rocks as previously noted. La Coma and adjacent deposits in Nuevo Leon (Fig. 8) are sandstone uranium deposits and whose origin is related to that of similar deposits in adjacent South Texas.

Volcanogenic Sn deposits

Among the probable 1,000 tin localities identified by Foshag and Fries (1942), the majority are associated with Tertiary volcanic rocks, especially rhyolites of the central plateau, a few of the important localities having been shown in Figure 9. The age of these deposits is Oligocene that defines the northern Mexican tin belt (Huspeni et al., 1984; Ruiz, 1988). Cerro de los Remedios in Durango, reflects this age in Figure 17.

Mercury and Antimony deposits

For the limited number of mercury deposits for which reliable data are available (Fig. 10), several deposits in northern Mexico occur near the contact of underlying Mesozoic sedimentary and overlying volcanic rocks. In the Canoas district, Zacatecas ores occur as young as Oligocene (Gallagher, 1952). Other deposits are located in Cretaceous host rocks, as at Nuevo Mercurio, also in Zacatecas; Sierra Gorda, Queretaro; as are those at Huahuaxtla and probably also at Huitzuco, both in Guerrero. The Cretaceous sedimentary rock-hosted mercury deposits in Sierra Gorda, Queretaro, are probably Late Cretaceous-Tertiary in age (Rodolfo Corona-Esquível, written communication, March, 2009). Canoas and El Cuarenta deposits are plotted in Figure 17.

As shown in Figure 10, the geographical distribution of the few antimony deposits for which data are available overlaps that of mercury in the central part of Mexico. However, the stratigraphic position of host rocks is more variable than that of mercury and varies from Triassic at El Antimonio, Sonora, to Late Jurassic units at Sán José (Wadley), San Luis Potosi. However, at El Antimonio mineralization may be related to later igneous intrusions and in the San José district mineralization may be related to intrusions of Tertiary age where the manto deposits are also associated with mercury mineralization, but not in the cavity-filling vein deposits. In the nearby La Maroma district the fissure-vein deposits may have a similar Tertiary age.
As a consequence of the uncertainty of the age of the antimony deposits discussed herein, only El Antimonio appears in Figure 17, and is assigned a possible Late- or post-Cretaceous age according to White and Guiza (1949).

**Manganese deposits**

There is a widespread distribution of deposits in numerous terranes along a central axis from north to south in Mexico and also several deposits along the eastern coast of Baja California Sur (Fig. 11). A total of 335 deposits in 20 states were identified by Trask and Rodriguez-Cabo (1948) and were divided into four types.

Of the fissure-vein deposits, the Talamantes, Chihuahua mineralization has been determined at post-42.5 Ma (Clark et al., 1979a). Among several silicified replacement deposits, at Montaña de Manganeso, San Luis Potosí, the epigenetic mineralization is hosted in Late Cretaceous sediments. The third type, limestone replacements, is found near intrusive granitoids at several localities, and at Guadalcazar, San Luis Potosí, the age of the intrusion that invades Cretaceous limestone is Tertiary.

The important San Francisco deposit, Jalisco characterizes a sedimentary exhalative type (Zantop, 1978) in a continental environment, and has been assigned an Early Tertiary age. San Francisco, Talamantes, and Guadalcazar have been assigned the same Early Tertiary (Eocene) age in Figure 17.

**Tungsten deposits**

As shown in Figure 12, several important deposits are located in the batholithic terranes of Sonora and northern Baja California. Of these, the age of the El Fenomeno deposit is reasonably well known (~90 Ma) in northern Baja California, and at the La Guadalupana property (51 Ma) in southwestern Chihuahua (Clark et al., 1979a). Tungsten is also found in the ore assemblage in the Washington, Sonora, breccia pipe (46 Ma), designated a porphyry copper deposit in Figures 6 and 17.

**Epithermal Ag-Au deposits**

In contrast to the porphyry deposits, the epithermal precious metal deposits, the majority of which are located in Early Tertiary volcanic rocks, and consequently at a high stratigraphic level above basement, are tied primarily to the regressive sweep of volcanism referred to by Clark et al. (1979a). Not all the deposits shown in Figure 13 whose ages have been isotopically determined, could be accommodated in Figure 17. Collectively, epithermal Ag-Au mineralization spans the late Paleocene-early Miocene interval. Seventeen of these deposits are shown in Figure 17, varying in age from Mala Noche (48.9 Ma) to Bascis (27.0 Ma).

**Mesothermal Ag-Au deposits**

Mesothermal precious metal deposits, of which gold is the principal component, are located in veins and other structurally controlled types and occur in northwestern Sonora being located along or near the trace of the Mojave-Sonora megashear. As such, they form a distinct subprovince when compared to the distribution of Ag-Au epithermal deposits that are related to volcanism during this epoch. Mesothermal precious metal deposits were formed in the 60-40 Ma interval during the Laramide-orogeny (Pérez-Segura, 2008). They vary in geographic position from Quitovac (65-48 Ma, Iriondo et al., 2005) in the northwest to San Francisco (~41 Ma Perez-Segura et al., 1996) in the southeast.

**Gold and Silver in Disseminated and Structurally controlled deposits**

Precious Metal disseminations in sedimentary rocks (Fig. 14) are characterized by Lluvia de Oro, (~18 Ma, Rothemund, 2000), and Real de Angeles (~45 Ma, Pearson et al., 1988), of which the latter is shown diagrammatically in Figure 17.

Gold and silver disseminated in volcanic rocks (Fig. 14) is portrayed at Mulatos (33-24 Ma, Pérez-Segura and Ochoa-Landin, 2009), and el Sauzal (31-29 Ma, Sellepack, 1997). Although space limitations in Figure 17 prevent their inclusion, they clearly overlap the ages of epithermal deposits that contain precious metals.

An example of gold and silver disseminated in intrusive rocks (Fig. 14) is exemplified at La Choya where the intrusive has been dated at 52-48 Ma (Pérez-Segura, 2008).

Finally, gold and silver related to structurally controlled deposits (Fig. 14) as previously described and where mineralization age has been determined includes San Francisco (41-28 Ma, Pérez-Segura, et al., 1996). Again, because of the profusion of deposits in this mineralizing epoch, lack of space precludes their inclusion in Figure 17, but clearly they overlap in time those of epithermal characteristics.

**REE, MVT, and Mafic-Ultamafic rock deposits**

Only two locales of primary REE deposits are known where ages have been reasonably well established (Fig.15). In north-central Chihuahua the Yuca carbonatite has been dated at 36 Ma (Nandigam, 2000), whereas at the El Picacho igneous complex in the Sierra de Tamaulipas, the age is probably early Oligocene-mid-Miocene (Elías-Herrera et al., 1990, 1991).

Three localities have been identified by Trílía et al. (2009) where base metal mineralization has been characterized as being of MVT (Mississippi Valley Type), two in Coahuila and one in adjacent Chihuahua. These three deposits are thought to have formed from marine water trapped in sediment (comatate water) and expelled during Laramide orogenesis. As such, their age of formation is imperfectly known and they do not appear in Figure 17.

Of the two mafic-ultamafic rock deposits shown in Figure 15, Ojos Negros in the Vizcaino peninsula of Baja California Sur has been assigned to the Late Cretaceous-Paleocene by Ortiz-Hernandez et al. (2006), and is shown on Figure 17.

**Late-Miocene to Recent (< 16 Ma)**

As metallic deposits of the youngest mineralizing epoch (Fig. 17) have already been discussed by Clark and Fitch (2005), only brief mention of their relative ages is made as follows.

**Porphyry Cu and contact replacement Fe deposits**

One of the youngest of the Mexican porphyry Cu deposits is located at Toliman (5.8 Ma), Chiapas (Damon and Montesinos, 1978). It and the La Carmen contact metasomatic deposit (13-12 Ma) in adjacent Oaxaca (Fig. 16) reflect magmatism associated with the subduction of the Cocos plate along the Acapulco trench. Further inland, the Santa Fe deposit (3-2 Ma) has porphyry copper characteristics, but also exhibits contact metasomatic and fissure-vein mineralization.

**Au-Ag mineralization**

Adjacent the Santa Fe deposit (Fig. 16) is the breccia pipe controlled Ixhuatan Au-Ag mineralization associated with alkaline basalts and andesites (2.8 Ma), (see Miranda-Gasca et al., 2009).
Beach deposits
Juan Marquez are shown in Figure 17. Still ongoing. From northeast to southwest Guadalcazar, Santo transportation from pre-existing deposits, their concentration is comment is made here other than to designate them as having a Mexico (Fig. 16) has been previously discussed and no further deposits are shown in Figure 17.

Stratabound Cu-Co-Zn and Mn ores
The Boleo deposits of the Santa Rosalia basin are located in five mantos within the Boleo Formation of late Miocene-early Pliocene age. Some 17 km further northwest of Santa Rosalia (Fig. 16) are the Lucifer manganese deposits that are also deposited in the Boleo Formation. Both deposits are located to the west of the spreading center (Fig. 16) and appear on Figure 17.

Placer Au, Sn, deposits
The widespread distribution of these deposits in western Mexico (Fig. 16) has been previously discussed and no further comment is made here other than to designate them as having a Pliocene - Quaternary age. In instances of erosion and transportation from pre-existing deposits, their concentration is still ongoing. From northeast to southwest Guadalcazar, Santo Domingo, America-Sapioris, Laguna de Santiago, Calmali, and Juan Marquez are shown in Figure 17.

Beach Deposits
Black sand, Quaternary beach deposits, derived from the Oaxaca and Acatlán complexes, like some placer deposits, are still undergoing additional accumulations. Likewise, the black-sand deposits at San Antonio del Mar are derived from intrusive and metamorphic rocks in the northern part of the Baja California peninsula. The Bahia de Agua Dulce and Boca del Río Colotepec deposits are shown in Figure 17.

Geothermal fields, deep-sea and shallow-water hydrothermal vents
Active geothermal fields have been included because of their likely relation to hydrothermal systems, which in places are related to metal-being systems, past and present, as is the case of the proximity of hot-spring, precious-metal deposits adjacent geothermal fields in the Cerro Prieto area (Fig. 16) and the gold found in scale of two production pipes. Figure 17 shows the location of Cerro Prieto, La Primavera, Los Azufres, Pathe, and Los Humeros geothermal fields.

Offshore, ongoing deep-sea hydrothermal activity, commonly referred to as “Black and White Smokers”, occurs at two locales where plate tectonic activity has resulted in the accumulation of metaliferous deposits. While these deposits are not of economic importance to date, they provide excellent insight to the formation of some submarine massive sulfides. The Northern and Southern Troughs of the Guaymas Basin are shown in Figure 17.

Three shallow-water hydrothermal vents, located at depths of less than 200 m below surface, are thought to occur in faulted submarine areas of high heat flow. The Baja Concepción locality appears in Figure 17.

SUMMARY AND CONCLUSIONS
A brief historical review shows that the widespread distribution of precious and other metallic deposits in Mexico has led to an ongoing, documented quest for their development that exceeds 1,000 years. During this time, and reflecting political pressures and economic realities, six periods in the development of Mexico’s mineral wealth can be recognized: Pre-Colonial; Colonial, Post-Colonial; Post-Revolution; Mexicanization; and Post-Mexicanization.

Six epochs of metallization are found in Mexico: Proterozoic, Paleozoic, Permo-Triassic; Jurassic-Early Cretaceous; Late Cretaceous-early Miocene; and late Miocene-Recent. The Early Paleozoic and Permo-Triassic intervals have few metallic accumulations and consequently are poorly defined.

The relative scarcity of deposits presently known in the Proterozoic, Early Paleozoic, and Permo-Triassic epochs stems from the difficulty of appraising their presence in the older and often concealed rocks, compared to the surface or near surface environment where most metallic deposits discoveries are made.

In this study, it is apparent that the diversity of metals concentrated in a variety of deposit types increases with the passage of time, and reaches its maximum in the Late Cretaceous-early-Miocene epoch as illustrated in Figure 17.

The spatial distribution of metallic deposits in each of the metalizing epochs is portrayed in 13 maps, Figures 3-16. Of these, 10 maps were employed to show the diversity of assemblages in the Late Cretaceous-early Miocene metallizing epoch (Figures 6-15). Each map could be regarded as a sub-province of the Mexican metallic province. It is anticipated that the time and space distribution of individual metals, or metal assemblages portrayed in this synthesis will aid in future exploration for deposits inasmuch that it subscribes to the well-known exploration philosophy that “elephants are most likely to be found in elephant country”.

Other important factors contributing to the geographic distribution of economic metallic ore deposits are rock composition, as for example the titanium deposits of the Oaxaca Complex; specific tectonic events such as the Laramide Orogeny in which deformation and accompanying magmatic events and associated epigenetic processes of concentration were so widespread; and syngenetic processes that fostered the accumulation of red-bed copper deposits, manganese ores, and possibly the Boleo and Lucifer stratabound deposits.

The spatial distribution of deposits in the six mineralizing epochs has been shown on tectonostratigraphic terrain maps and this clearly demonstrates those deposits that are controlled, or not, by a specific terrane. As previously noted, the Oaxaca Complex and terrane controls titanium deposits, and the Guerrero terrane controls the great majority of VMS deposits of Jurassic-Early Cretaceous age. The cratonic character of the Chihuahua terrane appears also to dictate the magnitude of copper and molybdenum concentrated at Cananea and La Caridad in the Late Cretaceous-early Miocene epoch as compared with deposits located in non-cratonic terranes to the south. Major concentrations of uranium appear to be similarly affected as at Sierra Peña Blanca, and adjacent localities in Chihuahua and Sonora.

However, the widespread distribution of numerous deposits of Cu, Pb, Zn, Ag, Au, Sn, Hg, Sb, and Fe, that are found in belts that straddle several terranes, clearly suggests that they owe their origin to a considerable extent to first order tectonic events as is the case of oceanic-plate subduction induced magmatism.
and related structures, particularly along the tectonically active western Mexico Margin. This in turn brings into consideration the three potential magma and metal sources involved: subducted oceanic lithosphere, mantle, and overlying continental crust (Clark et al., 1982), and the effect of accreted terranes (Campa and Coney, 1983).

In the varied and abundant Late Cretaceous-early Miocene epoch the resulting metallic sub-province for porphyry Cu-Mo-(W) deposits forms a well defined belt along the western margin of Mexico, and there is limited spatial overlap with Fe and other elements. But more significant overlap occurs with Sn, Hg and Sb albeit individual localities are restricted to specific host rocks in northern-central Mexico where also there are numerous Pb-Zn-Ag-(Au) concentrations, many of which are contained in Cretaceous limestones. The widespread distribution of Mn in four classes of deposit, of which few have been dated, covers multiple terranes and consequently overlaps several other metallic assemblages and reflects the controlling physical-chemical parameters which dictated their deposition. The bulk of W ores are restricted to granitoid terranes of northwestern Mexico and fissure-vein, precious-metal deposits, many important localities of which have been dated, are predominantly distributed in the occidental, volcanic arcs. In contrast, the mesothermal Au-(Ag) deposits, located along the trend of Mojave-Sonora Megashear trend in Sonora have been related to the Laramide Orogeny. A limited number of other previous metal deposits are disseminated in sedimentary, volcanic and intrusive host rocks or controlling structures. The remaining deposits of this epoch include REE and Th bearing concentrations located in carbonate or an alkaline complex in northern and northeast Mexico respectively and a few examples of Mississippi Valley type deposits are located in this region. Additionally, the areal distribution of each metallic assemblage shown in Figures 6-15 is likely to be modified as the age of more deposits will be determined by future studies.

The youngest metallizing epoch encompasses the last 16 million years and is dominated by tectonic events and surficial processes. These include the youngest porphyry Cu, Fe and Au deposits in Chiapas and Oaxaca, whose origin, again, is related to subduction related processes. Included in this interval is the San Felipe gold deposit, and the hot spring gold deposits in northern Baja California. They and the nearby geothermal fields in the Cerro Prieto area are within the tectonic regime that led to the formation of the Gulf of California. An additional region of high heat flow exists in the volcanic activity of the Trans-Mexican Volcanic Belt, and in locales on the East Pacific Rise and Gulf of California spreading centers that gave rise to Black and White Smoker deposits. Shallow water hydrothermal vent deposits may be independent of magmatic activity.

Another class of deposit is found in the unique tectonic regime of northwestern Mexico, namely the stratabound Cu-Co-Zn deposits at Boleo and the Mn-bearing deposit at Lucifer.

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REFERENCES
Aguijera-Sch., E., 1971, Exploración geofísica de un cuerpo de hierro en Hércules, Coahuila: Asociación de Ingenieros de Minas, Metalurgistas y Geólogos de México, Memoria de la IX Convención Nacional, p. 79-84.


Bonifant, M., 1900, Los Placeres de Calmali, Baja California: Minero Mexicano, v. 39, no. 18.


Cluff, Robert, Kirby, Dan, and Payne, John, 2009, Depósitos de sulfuros masivos volcánogenos con asociación de metales preciosos, Campo Morado, Guerrero, Mexico in Kenneth F. Clark, Guillermo A. Salas-Piza, and R. Cubillas-Estrada (eds.), Geología Económica de Mexico, 2 Ed.: Asociación de Ingenieros de Minas, Metalurgistas y Geólogos de Mexico, Servicio Geológico Mexicano, p. 636-641.


Corona-Esquivel, R., Tapia-Zúñiga, C., Henríquez, F., Tritia, J., Morales-Isnunza, A., Levresse, G., y Pérez-Flores, E., 2009c,


Nieto-Samaniego, A.F., Alaniz-Álvarez, S.A., and Camprubí Cano, A., 2005, La Mesa Central de México: Estratigrafía, estructura y evolución tectónica cenozoica, in A.F. Nieto-
Ortega-Gutiérrez, F., and and 6 others, 1992, Carta Geológica de la Republica Mexicana: Instituto de Geología, Universidad Nacional Autónoma de México, 5a ed., Escala 1 : 2, 000,000, (with explanatory text).
Ortiz-Hernández, L.E., Escamilla-Casas, J.C., Flores-Castro, K., Ramírez-Cordona, M., y Acevedo-Sandoval, O., 2006, Características geológicas y potencial metalogenético de los principales complejos ultramaficos-máficos de México, in J.


Oviedo, D., 1895, Los Nuevos Placeres de la Baja California: Minero Mexicano, v.27, no. 11.


Pérez-Siliceo, R., y Gallagher, D., 1946, Informe sobre la geología de los criaderos de mercurio en la zona minera de Nuevo Mercurio, Distrito de Mazapil, Zacatecas: Boletín de Minas y Petróleo, v. 17, no. 5, p. 3-6.


Ramírez, S., 1885, Estudio en Durango: Minero Mexicano, v. 12, no. 21, p. 254-263.


Rocha-Moreno, V.S., 1973, Comentarios sobre los trabajos de experimentación y exploración realizados en los placeros de oro de Juan Marquez en Baja California Sur: Consejo de Recursos Naturales No Renovables, 4º Seminario Interno sobre Exploración Geológica-Minería, p. 29-32.


Ruvalcaba-Ruiz, Delfino, 1989, Geología y origen de los yacimientos de fierro de Hércules, Coahuila. .


Salas, G.P., 1975b, Carta Metalogenética de la Republica Mexicana: Consejo de Recursos Minerales, Escala 1:2,000,000.


Salas, G.P., 1975a, Mapa Metalogenético de La Republica Mexicana: Consejo de Recursos Minerales, Escala 1:3, 500,000.


Sanchez-Ramirez, D., 2011, Los depósitos de uranio en La Cuenca de Burgos y su correlación con depósitos del sur de Texas: Asociación de Ingenieros de Minas, Metalurgistas, y Geólogos, Memoria de la XXIX Convención Nacional.


Servicio Geológico Mexicano, 2007, Carta Geológica de la Republica Mexicana: Pachuca, Hidalgo, 6ª ed., Scale, 1:2,000,000.


Touwaide, M. E., 1930, Origin of the Boleo Copper deposit, Lower California, Mexico: Economic Geology, v. 30, p. 113-143.


Wisser, E.H., 1954, Geology and ore deposits of Baja California, Mexico: Economic Geology, v. 49, p. 44-76.


