The geological singularities of a world-wide patrimony: The giant mercury deposits of Almaden (Spain)

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Abstract

The recent declaration of the Almaden Mine as Patrimony of the Humanity has been a recognition to an exceptional ore deposit. In the Almaden town surroundings special geological events occurred that gave rise to some deposits of a scarce metal that are surely unique at crustal levels. The Hg deposit of Almaden is located in a Hercynian WNW-ESE bearing syncline where a very complete Palaeozoic sedimentary sequence is outcropping, from Lower Ordovician to Upper Devonian ages. These rocks were formed in a marine shelf basin, with some episodes when an important basic and ultrabasic volcanic activity took place, including the formation of diatremic explosive bodies. The Hercynian tectonic has given rise to a synclinal configuration by means of a generalized folding event and another one of shearing with irregular spatial distribution that specially affected the Southern flank. The deposits of Hg are distributed in the Eastern half of the syncline and mainly throughout the Southern flank, in relation to the shear-bands. Two ore-deposit types are recognized, stratiform seams and irregular stockwork bodies. The stratiform deposits are clearly pre-tectonic with respect to the Hercynian events, whereas the second ones show a certain sintectonic character in relation to the deformation by shearing. The biggest deposit was the Almaden Mine, belonging to the stratiform type, whose huge Hg mineral resources have allowed remaining in industrial operation during over 450 years. This has been possible thanks to an exceptional geology that originated an extraordinary deposit whose long mining history has left a marked stamp in the region and its people.

Resumen

La reciente declaración de la Mina de Almadén como Patrimonio de la Humanidad ha sido un reconocimiento a un yacimiento mineral excepcional. En el entorno de la localidad de Almadén se han dado unos acontecimientos geológicos peculiares que han dado lugar ciertos depósitos de un metal escaso que seguramente son irrepetibles a nivel cortical. El yacimiento de Hg de Almadén se halla en un sinclinal hercínico orientado WNW-ESE en donde aflora una secuencia de rocas paleozoicas muy completa que va desde el Ordovícico Inferior hasta el Devónico Superior. Estas rocas se formaron en medios marinos de plataforma, que en ciertos momentos tuvo una importante actividad volcánica de composición básica y ultrabásica principalmente, con la formación de cuerpos explosivos diatrémicos. La tectónica hercínica ha sido la que ha configurado el sinclinal mediante una fase de plegamiento generalizada y otra de cizallamiento de distribución heterogénea en bandas que son especialmente importantes en el flanco meridional. Los yacimientos de Hg se distribuyen en la mitad oriental del sinclinal y especialmente a lo largo del flanco meridional, en buena parte relacionados con las bandas de deformación por cizallamiento. Se reconocen dos tipologías distintas de depósitos, que son estratiformes y cuerpos irregulares a modo de stockworks. Los primeros son claramente precinemáticos respecto a las deformaciones hercínicas, mientras que los segundos muestran un cierto carácter sincinemático en relación con las deformaciones por cizallamiento. El mayor de todos ellos ha sido la mina de Almadén, de tipo estratiforme, cuyos enormes recursos de mineral de Hg han permitido que haya estado en explotación industrial durante unos 450 años. Esto ha sido posible gracias a una geología excepcional, que ha dado lugar a un yacimiento extraordinario, cuya larga historia minera ha dejado una marcada impronta en la región y en sus habitantes.

Key-words: *: mercury, quicksilver, Almadén, giant ore deposits, geology heritage, mining heritage, world-wide patrimony.*

1. Introduction

The declaration of Almaden mining heritage as Patrimony of the Humanity took place the last 30th of June. This has clearly been a very remarkable fact in the history of this spanish town and it supposes an event of great relevance inasmuch as that is the first time that a mining centre received this type of consideration.

The recognition has been granted to a joint candidacy of the two main production centres of liquid metal in the world, the mines of Almaden in Spain and Idrija in Slovenia, and has been named as "the Patrimony of Mercury". The candidacy has tried to reflect the world-wide importance that this metal has had in modern economy and to the technological innovations derived from the mining techniques used for its extraction. It is also outstanding the stamp that mercury has historically left in the architecture, customs, idiosyncrasy and traditions, many of which are unique and exclusive of the people who have sustained their lives on their extraction and its commercialization.

The marked stamp that the mining has left in these places is due to a very long history settled in that extractive activity, that in the case of Almaden has extended during 2000 years without almost no uninterrupted. In its beginnings and for a long time, the operation was made on small scale and was focused to obtain the "red vermilion" that ennobled paintings. The discovery in the XVIth Century of the amalgamation as an extraction method of noble metals, caused the extraction be centred in mercury metal and the production rate has been on great scale ever since. These rates have been high or very high during the 450 years in which the mine has remained active on an industrial scale. Almaden has always been at the world-wide top in production of this stranger and scarce metal.

If Almaden has been able to maintain so high levels of production during such a long period of time, it has been due to the nature of this exceptional deposit. It is a clear example of what in metallogeny is described as a Giant Ore Deposit. Moreover, it is not disrespectful to say that Almaden is a unique case in the terrestrial crust. The mining district of Almaden has, by far, the greater accumulation of mercury resources in the world, having produced over 270,000 metric tons of the liquid metal. In other words, more than 7.7 million mercury flasks have been extracted from the district, of which 7 million have come from the Almaden Mine itself.

The exceptional nature of this mining district on a world-wide scale, and particularly of the Almaden giant deposit, lies on the geological concentration process that has been able to accumulate in such a specific place this huge amount of mercury, an element with a rather low average content at cortical level (about 67 ppb). So much so that Almaden means more than 35% of the recognized Hg resources in the world, with higher grades than any other great deposit in the world (Idrija, Monte Amiatta, McDermitt, Huancavelica, etc.). Besides the spanish deposits appear in a geological context and show metallogenic characters very different to the rest of mercury deposits, which leads to speak of the Almaden type deposits.

This paper tries to show the geological peculiarities of this mining district and particularly of the Almaden Mine. The Patrimony of the Humanity recognition has hardly considered the geological facts, but it has been due to an exceptional chain of geological events that the ore deposit was created. Because of singular geological processes have had a great deposit with very long time in production that gave rise to a rich and specific historic mining industry, which has been now awarded with this declaration.

2. Location and geological setting in the Iberian context

The Almaden town is located about 300 km

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SSW from Madrid, and about 260 km to the NE from Seville. It belongs to Ciudad Real Province in Castilla-La Mancha Region. From a morphological point of view Almaden is in Sierra Morena range spurs in the southern limit of the Southern Castilian plateau.

Fig. 1. The Almadén Syncline in the Hercynian Iberian Domain

From a geologic point of view, Almaden is located in the South flank of an important syncline structure that it is known with the name of the mining town. The outcropping rocks from this syncline are formed by a detritical sedimentary sequence that includes volcanic intercalations. The whole sequence is Palaeozoic age, from Lower Ordovician to Upper Devonian.

In the regional geological context, the Almaden Syncline is located near to the southern edge of Central-Iberian Zone *(fig. 1),* according to the subdivision of the Hercynian Iberian Massif made by *Julivert et. al. (1972)*.

The regional geology around Almaden is characterized by a succession of large Hercynian folds with sub-vertical WNW-ESE bearing axial planes *(fig. 2)*. The general macrostructure of these folds is defined by a litho-stratigraphic unit formed by orthoquartzites that has an important thickness and good extensive regional continuity. This unit is named “Armonicana Quartzite” and it has Arenig age.

The rocks that are outcropping in the region are mainly siliciclastic, were formed in diverse marine environments and they have hardly undergone metamorphic processes that significantly altered their original textures. The Oldest rocks that appear in the anticlines include the “Schist-Greywacky Complex” (CEG) that outcrop in large areas in the centre and the West part of the Iberian Peninsula *(Lozte, 1970; Bouyx, 1970)*. These rocks constitute a monotonous multilayered sequence of shales and greywackes formed in a turbidity environment. A sequence make up by siltstones, black-shales, conglomerates and carbonate lens that is in unconformity over the turbidity multilayer also appears in some sectors *(Bouyx 1970; Ortega and Lodeiro; 1986; San José et. al., 1990; Palero, 1993)*. The age of these rocks is Vendian *(San José et. al., 1990)*, although some authors indicate that the age would also reach Lower Cambrian *(Lorenzo and Solé, 1988; Vidal et. al., 1994)*.

A thick Palaeozoic sedimentary sequence unconformably overlies the Precambrian materials. These rocks would have been deposited in a marine shelf basin throughout 140 million years. Finally, at South of Almaden there is a wide and monotonous sequence formed by black shales, siltstones, greywackes and conglomerates of Lower Carboniferous age. This series receives the name of “Los Pedroches Culm” and was deposited in an unstable marine platform basin *(Pérez Lorente, 1979; Mira et al., 1987)*.

Fig. 2. Geological map around Almadén Syncline. (From Mapa Xeolóxico do Macizo Hespérico of Parga et al., 1982). Pink: Precambrian rocks; green and brown: Lower and Middle Paleozoic; grey: Lower Carboniferous; yellow: Tertiary and Quaternary; red: granitoids

At the end of the Namurian or beginnings of the

Westphalian, the Hercynian Orogeny started in the region. It has been the main tectonic event that is still recognizable nowadays. The Hercynian Orogeny started quite late in this region compared to other zones of the Iberian Massif. The southern part of the Central-Iberian Zone corresponds to an external zone of the Hercynian orogeny, and in consequence suffered the deformation effects of the collision between ancient continents later than inner zones. The Hercynian deformation around Almaden occurred in two stages, of which the first was the main one *(Roiz, 1979; Ortega, 1988)*. In this first stage (F1) the more important macrostructures and folds were formed, as well as an axial plane slaty-cleavage (S1). This stage took place by a nearly N-S shortening and their effects are found widespread. The second tectonic stage (F2) probably took place during Stephanian times, and it consisted in a heterogeneous deformation produced by an E-W shortening. It gave rise to crossed-axes tectonics that originated interference fold figures such as domes and basins. However, fragile shear bands were the main structures formed, of which those with NW-SE direction and anticlockwise displacement, predominate over conjugated clockwise NE-SW ones. Occasionally, an incipient slaty-cleavage was generated (S2) that is transected plain to F1 folds.

After the Hercynian deformations some later structures are recognized, mainly new faults and reactivations of pre-existent ancient faults. This activity must have extended until recent times as evidenced by the Pliocene-Quaternary basaltic volcanic activity at “Campo de Calatrava” *(Gallardo et al., 1998)*, with outcrops located a few kilometres to the East and NE of Almaden.

The magmatic activity in this part of the Central-Iberian Zone is represented by Palaeozoic sin-sedimentary volcanism and Hercynian acid magmatism. The first one appears distributed in several position in the Ordovician to Devonian sequence, but without a doubt, it is among the Silurian and Devonian sediments where there are more abundant, especially in the Almaden Syncline.

The Hercynian magmatism has its exposures in the Fontanosas and Garlitos granite stocks, and in the great Los Pedroches Batholith. The first ones are respectively to the East and the NW of Almaden, whereas the great batholith occupies a large band at the South maintaining the WNW-ESE Hercynian orientation. In the north border of this batholith there are two satellite stocks known as Santa Eufemia and El Guijo. These intrusive bodies are allochthonous and they give rise to a hectometric aureole of thermal metamorphism. This magmatism has two granitic facies: granodiorites and monzogranites. The granodiorites are the oldest ones and they comprise the totality of the Fontanosas stock, most of Garlitos stock and part of the Los Pedroches Batholith. Its emplacement took place between the two Hercynian deformation stages *(Coupez et al., 1988, Escuder & Lorenzo, 2002)*. The monzogranites intrude into the granodiorites *(Donaire and Pascual, 1992)*. They appear in the Los Pedroches Batholith and forming the totality of the satellite stocks. Its emplacement is clearly subsequent to F2 Hercynian stage. Several absolute datings of these granitoids have been published, as the 302±10 million years old for the Fontanosas granodiorites *(Leutwein et. al., 1970)*; the 291±15 Ma of the Los Pedroches monzogranites *(Penha and Arribas, 1974)*; the 300±3 Ma (Fernández et al., 1990) and the 294±22 Ma *(García de Madinabeitia, 2002)* to El Guijo Stock; and the 293±6 Ma to Santa Eufemia Stock *(García de Madinabeitia, 2002)*.

3. The Geology of the Almadén Syncline

The Almaden Synclinal can be defined as a macrostructure that occupies a 30km long stretch with a maximum width of 15km. It has the shape of an asymmetric WNW-ESE basin, with a wider Eastern part than Western one. The fold's south flank is verticalized, whereas the north one is gently dipping. This is a peculiar fact of this great fold, because it is opposed to the regional vergency of the Hercynian structures, which is towards the South.

The rocks that form the syncline show one of the most complete Ordovician to Devonian sequences that can be found in Central-Iberian Zone *(Almela et al., 1962; Saupe, 1973; García Sansegundo et al., 1987)*. The sequence shows different types of sedimentary detritical contributions mainly driven by variations of

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the sea level. Several litho-stratigraphic units can be outlined based on the predominance of one of following three lithologies: orthoquartzites, siltstones and black shales. Four units formed by orthoquartzites with a good regional continuity can be defined and they serve as a geological mapping reference to draw the general structure of the syncline. These units are, from base to top *(Almela et al., 1962; Pardo, 1983; Vilas et al., 1999)*

- "Armonicana Quartzite" of Lower Ordovician (Arenig) age.
- "Canteras Quartzite" of Upper Ordovician (Caradocian) age.
- "Criadero Quartzite", of Ordovician-Silurian transition (Hirnantian-Llandovery) age.
- "Basal Quartzite", of Lower Devonian (Gedinian-Siegenian) age.

Multilayers of siltstone and shale beds along with abundant volcanic and sub-volcanic rocks are placed among these orthoquartzite units, especially in the sequence over the "Criadero Quartzite". These igneous materials are mainly of basic composition (alkaline basalts), but ultrabasic and intermediate compositions are also present.

The igneous rocks appear as sub-intrusive bodies; as dikes and sills; as diatremic bodies (mainly explosive breccia-tuffs); or as volcano-sedimentary layers. In general is possible to say that in the Silurian levels there is a predominance of sub-intrusive volcanic materials, whereas in the Devonian levels the volcano-sedimentary materials are more abundant. At present, the explosive breccia bodies appear limited by faults and tectonized bands, thus it is not possible to determine the original timing with the host rocks. However, it is worth mentioning the fact that the known explosive breccia bodies appear among rocks of ages ranging from Upper Ordovician to Devonian. These rocks are very characteristic of the Almaden syncline and they are named "Frailesca Rock".

The "Frailesca Rock" *(fig. 3)* is mostly formed by volcanic material, either as fragments or as matrix, although also quartzite and black shale fragments can be found. The volcanic material is mainly basaltic with minor ultramaphic rock fragments. The rock displays a distinctive strong carbonatization and sericitization, as seen by optical microscope on thin sections were widespread ankerite carbonate and sericite are the only phases that can be observed. Traces of its original mineralogy are conserved only in certain volcanic fragments. The common aspect of the "Frailesca Rock" is a massive breccia-tuff, but sometimes a certain bedding arrangement can be observed, which doesn't mean a true stratification. The interpretation of this peculiar rock has been changing since it was described for the first time, and nowadays it is understood as diatremic bodies after the studies made during the fall of the XX Century by the Geology Service of the mining company. They constitute, without a doubt, a very peculiar case in the European Hercynian Dominion.

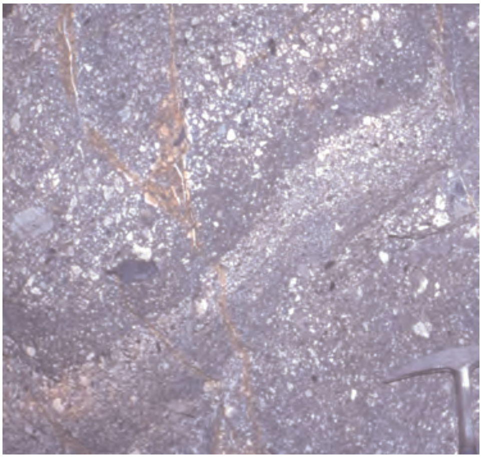

Fig. 3. The "Frailesca Rock" on a tunnel wall of 5th Level in Almadén Mine. The outcropping shows false bedding

The volcanic activity seems to take place in at least 2 pulses. The first one would be an explosive volcanic episode of basaltic composition that originated the "Frailesca Rock". A network of dikes and sills with ultramaphic xenoliths is related to the volcanic breccia-tuffs. Fragments of the same ultramaphic material, characterized by the presence of fuchsite, also appear incorporated on the "Frailesca Rock". The dikes and sills often show peperitic structures, especially when hosted in black shales, evidencing that their emplacement took place when the sediments still had important amounts of water.

The second volcanic pulse is represented by basic rocks, mainly quartz-diabases. These rocks mostly appear as sub-intrusive bodies with an extended form that follows the general structure of the syncline. They display clear relations of intrusion with the "Frailesca Rock", which indicates a later formation than the volcanic breccia-tuffs.

The volcano-sedimentary materials are difficult to relate to a specific volcanic episode. The common heterolithical composition of tuffs and breccias along with clear evidences of reworked material hinder the establishment of its origin.

Intermediate volcanic rocks (mainly trachytes) appear sporadically in the core of the Almaden Syncline. These materials reflect a clear evolution of the volcanism towards more acid composition and they could either represent a third independent volcanic pulse or an acid evolution of the second one.

The geological structure of the Almaden syncline is interpreted as the superposition of the different Hercynian and post-Hercynian deformations. The first Hercynian stage (F1) gave rise to folds of cylindrical geometry, sub-horizontal WNW-ESE axes and sub-vertical axial planes. Folds were formed on all scales and they were generated by perfect buckling. This type of deformation does not bring an important volume reduction and only very incipient development of slaty-cleavage on incompetent rocks (black shales) occurs. The metamorphism is practically absent and only certain basic volcanic rocks, with very susceptible components, gave rise to neo-formed minerals in the zeolite facies *(Saupe, 1973; Higueras et al., 1995)*.

The second Hercynian stage (F2) is mainly represented by fragile shear-bands. They are affecting with different intensity various parts of the syncline. Conical geometry folds can be found too, which are the result of the interference between the E-W shortening with F1 folds. The shear bands can be recognized by strong dipping faults that are longitudinal to the general structure of the syncline, with WNW-ESE to NW-SE direction and anticlockwise displacement. Often these structures are not evident on medium scale mapping, even though more detailed studies showed a very complex structure that is produced by shearing on zones

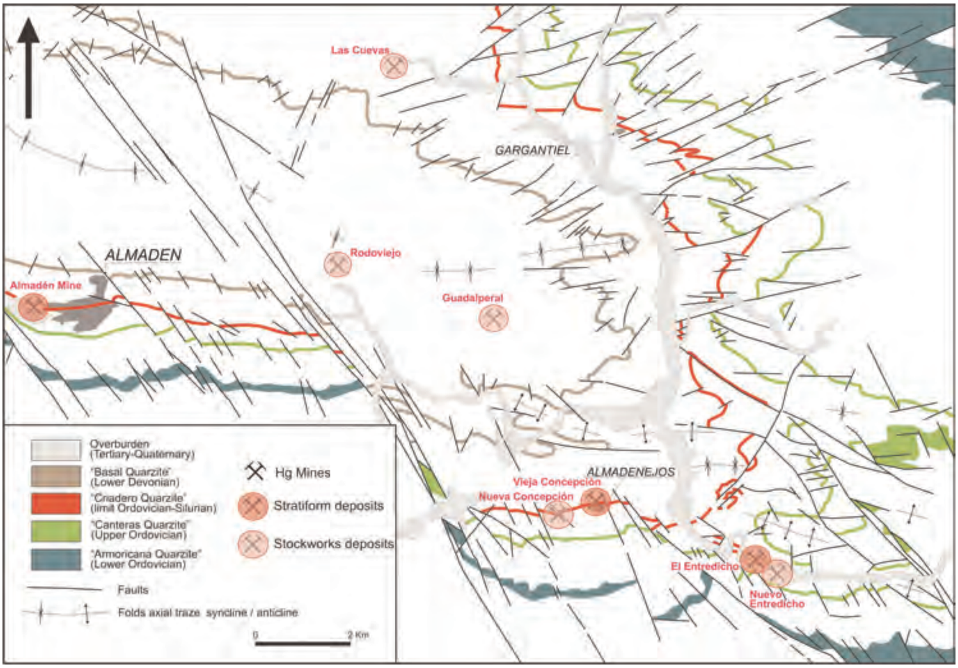

Fig. 4. Geological sketch of Eastern part of Almadén Syncline, delighted traces of orthoquartzite Palaeozoic units and putting the main mercury deposits.

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with apparent slight deformation. This fact is especially important when faults interfere in longitudinal direction with the verticalized multilayers. This happens, for example, throughout the Southern flank of the synclinal, where the geological maps do not succeed reflecting this really complicated structure.

Finally, it is also important to point up the existence of faults cross cutting litho-stratigraphic units. They are easily recognized in the competent units (like quartzite levels). These faults make up two conjugated systems, one of them NW-SE with clockwise displacement, and the other one NE-SW with anticlockwise movement. These faults are the result of a new N-S bearing shortening that has been considered as late-Hercynian tectonic movements. Most of these faults are likely to be inherited, produced during Hercynian times deformation and reactivated under later stress fields.

4. The mercury ore deposits

The name of Almaden is worldwide known for its extraordinary mercury deposits. Almaden is a crustal geochemical anomaly unrivalled by any other place. The huge concentration of this scarce metal encountered in Almaden area is equivalent to all mercury contained in $4{,}03*10^{12}$ metric tons of crustal material. This enormous amount of metal has come mostly from only 6 mines: Almaden, El Entredicho, Las Cuevas, Nueva Concepción, Vieja Concepción and Guadalperal. In addition to these mines there are a dozen of small occurrences and mining registries, as well as a new deposit, found during the 80s, named Nuevo Entredicho that remains unexploited. Altogether these mines and occurrences form a mining district whose geologic context is limited to the Almaden Syncline *(fig. 4)*.

The mercury deposits respond to two different typologies that can be grouped under the terms of stratiform deposits *(fig. 5)* and stockwork deposits *(fig. 6)*. The stratiforms are the biggest ones and they are the Almaden Mine, El Entredicho and Vieja Concepción deposits. The stockworks are smaller but they have higher ore grades, being outstanding examples the mines of Nueva Concepción, Las Cuevas and the unexploited deposit of Nuevo Entredicho.

Fig. 5. Stratiform type ore of San Francisco Seam.14th Level, Almadén Mine.

The stratiform deposits are hosted exclusively in the "Criadero Quartzite" unit. The ore appears impregnating and/or fisural infilling some specific layers, located at the footwall and the hanging-wall of the orthoquartzites unit. The impregnation occurred by filling with cinnabar of the primary rock porosity, essentially the intergranular spaces. The fisural infillings (joins) surely represented the sealing of the porosity originated by cracking during late-diagenetic compaction processes of the quartzite rock. The paragenesis in these deposits is very simple, with cinnabar as the main mineral, followed by small amounts of pyrite and native mercury. Practically at trace levels there are crystalline quartz, dolomite-ankerite, baryte, siderite, and small crystals of cinnabar and pyrite. These trace minerals are occupying fractures that cut through the mineralized quartzite beds and they formed later than the main mineralization.

Fig. 6. Stockwork type ore in a replacement body hosted in volcanic breccias. Western Massif, 2nd Level, Las Cuevas Mine.

The stockwork type deposits are hosted in different lithologies but they show affinity to volcanic materials, even though some minor amount of mineralization can be found in detritical rocks. In these cases ores are always related to nearby volcanic rocks. The paragenesis is more complex than in the stratiform type, with cinnabar and pyrite as the major minerals, accompanied by native mercury, pyrophylite, kaolinite, sericite, ankerite and quartz. A later mineralization with baryte, siderite, dolomite-ankerite, chalcopyrite, pyrite and recrystallized cinnabar is also present. This later paragenesis has scanty volumetrically importance. The main mineralization appears infilling small veins and replacing volcanic rocks, with both kinds being intimately related. Clear examples can be observed where the replacement degree decreases with the distance from the massive cinnabar vein. In detritical materials the mineralization only occurs as infilling veins. The vein and replacement textures allow to establish a sequence of crystallization to the main mineralization process, so that pyrite is the first one to crystallize, followed by pyrophylite and kaolinite, quartz afterwards, and finally the cinnabar.

The timing between both types of deposits can be established on the basis of the relations between mineralizations and Hercynian deformations. Thus, the stratiform bodies are clearly affected by the Hercynian deformations as they are folded, sheared and cut by the structures formed during those tectonic events. On the contrary, the cinnabar veins in stockwork mineralizations, are cutting the Hercynian foliations (slaty and milonitic). In these deposits, ore textures and relations between the mineralization and the host rocks, suggest that their emplacement has taken place in slightly sin-tectonic or late-tectonic conditions with respect to the E-W Hercynian F2 shortening. These relations evidence that stratiform ores are older than stockwork ores, which could be considered to be epigenetical from the stratiform ones.

For a long time the spatial coincidence of Hg ores with the “Frailesca Rock” has been observed, settling down a cause-effect relation between sin-sedimentary volcanism and mineralization process (*Almela at al., 1962; Saupe, 1973 and 1990; Hernández, 1984; Ortega and Hernández, 1992*). The exploration criteria in Almaden mining district has long been based upon this idea. The places where the volcanic breccia-tuffs are in contact with “Criadero Quartzite” were the most solid candidates for the exploration targets. This spatial relation is clear, but it has been verified that stratiform deposits are previous to the emplacement of the “Frailesca Rock”. Indeed, in the El Entredicho Mine, a sill that includes ultramaphic xenoliths related to the “Frailesca Rock”, could be observed in contact with the mineralized quartzite level. The sill produced a narrow “thermal metamorphism” band on the mineralization seam by effect of the igneous rock heat. This heating triggered the removal of cinnabar and produced the recrystallization of the quartzite too. This proves that “Frailesca Rock” volcanism is younger than the stratiform mineralizations, but they have probably been produced by the same geological process and that they are not a consequence from one another. The stockwork mineralizations are post-volcanism, since they host in the volcanic breccia-tuffs and they

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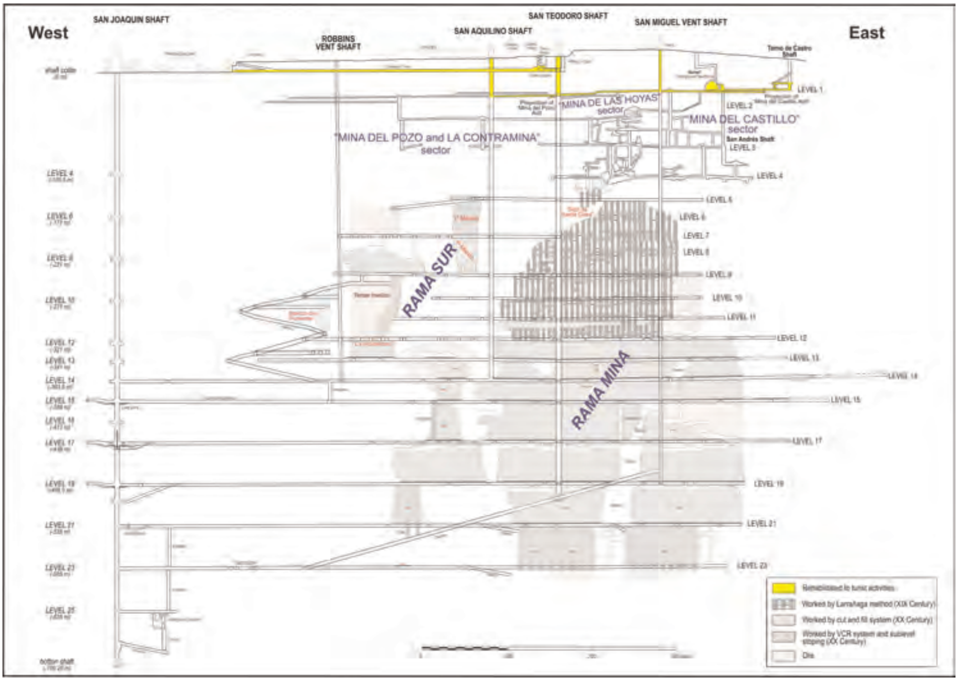

Fig. 4. Geological sketch of Eastern part of Almadén Syncline, delighted traces of orthoquartzite Palaeozoic units and putting the main mercury deposits.

produce alterations that affect them as already consolidated rocks *(Higueras, 1994)*.

The origin and metallogenic process responsible of having generated such great concentration of a scarce element still remains a geological mystery. Two main hypotheses have been suggested. The first one considers a significant geochemical Hg increase in the Palaeozoic marine sedimentary environment, with the metal being fixed by the abundant black shales. A geological event (like volcanism) would have been able to mobilize Hg from this pre-concentration, and store it in levels with adequate porosity and chemical conditions *(Saupe, 1973 and 1990).* The second hypothesis supposes a great geochemical mantellic anomaly with an ascent, canalized by great crustal accidents, of Hg and related ultramaphic volcanism *(Ortega, 1988; Ortega and Hernández, 1992; Higueras et al., 2000)*.

5. The Almadén Mine

The Almaden Mine exploited the Western most Hg deposit of a fringe of occurrences located throughout the southern flank of the syncline *(to see fig. 4)*. It has been the greatest stratiform deposit in the mining district and, thus the biggest mercury deposit ever found. It is remarkable as much for the great volume of metal accumulation as for the high grades of its ores. In order to give an idea of the deposit magnitude, in the last years of production the cut-off was 1% of Hg and the average grade ore was 3.5%. Most Hg deposits in the world exploit ore grades lower than 1% while ores above 3.5% are truly exceptional.

When the mine closed, its tunnels not only offered a catalogue mining methods used during the last 300 years, but also showed a spectacular geology, with unique elements and exceptional examples for diverse subjects like stratigraphy, tectonic, volcanism and metallogeny. The part that has been adapted for tourism use represents one reduced expression of the truly potential that the mine could offer.

5.1. Mine description

The basic mine infrastructure at its closure, consisted of two main shafts: The San Teodoro (522 m deep) and the San Joaquin (700 m deep), along with three auxiliary and vent shafts (San Miguel, San Aquilino and Robbins). These shafts once run the services to a 27 level system, with a separation of about 25 metres between consecutive levels. The 1st to 15th levels were the completely developed ones along with the 17th, 19th, 21st and 23rd levels from the deep part of the mine *(fig. 7)*. For a long time the main shaft was San Teodoro, which got to reach the 19th Level with auxiliary San Miguel and San Aquilino shafts. At the beginning of the 60s San Joaquin shaft was sunk at the western part of the deposit, and turned out to be the main one. It reached all the way down to 27th Level, although the exploitation never developed under the 23th Level. At the beginning of the 80s the Robbins shaft was excavated by rise boring method to facilitate the ventilation of the western zone operations.

The first mining works in Almaden would have been in outcrops located in the Western part of the deposit, where later would become the "Mina del Pozo" and what at deep levels is known as the "Rama Sur". This zone displays a complex geology and the mineralized bodies appear in irregular form with short lateral continuity.

The Eastern part of the deposit was discovered in 1697. Since then the main mining works focused into this area, which has been called the "Rama Mina". This area has easier geology and a good continuity of the mineralized bodies. From the geologic point of view there is another zone named "Los Masivos" which was integrated to the "Rama Mina" in mining planning purposes

5.2. Ore deposit lithology

The ore bodies in the deposit had a sharp stratiform character, with cinnabar located in some very specific levels of the "Criadero Quartzite". These ore bodies received the names of San Pedro and San Diego Seam (SP), San Francisco Seam (SF) and San Nicolas Seam (SN).

The "Criadero Quartzite" in the Almaden mine was subdivided in 3 sections. From footwall to hanging-wall are *(fig. 8)*:

- "Lower Quartzite", with 8 to 15 m thick white orthoquartzite beds. This section includes the San Pedro and San Diego Seam, with 3 to 8 m wide.

- "Middle black shales", with 10 to 15 m of rich carbonaceous matter mudstones and frequent sandy pillow structures that were always barren.

- "Upper Quartzites", composed by 30 to 50 m of multilayered thin grey quartzite and fine micaceous siltstones beds. The beds become increasingly thicker and darker towards the top. "San Francisco" and "San Nicolas" seams are found in this upper part. These seams are from 2,5 to 5m thick and separated by up to 8 m of thin siltstone and carbonaceous mudstones beds. Tectonic lamination is responsible for variation, or even absence, of this barren interbedded.

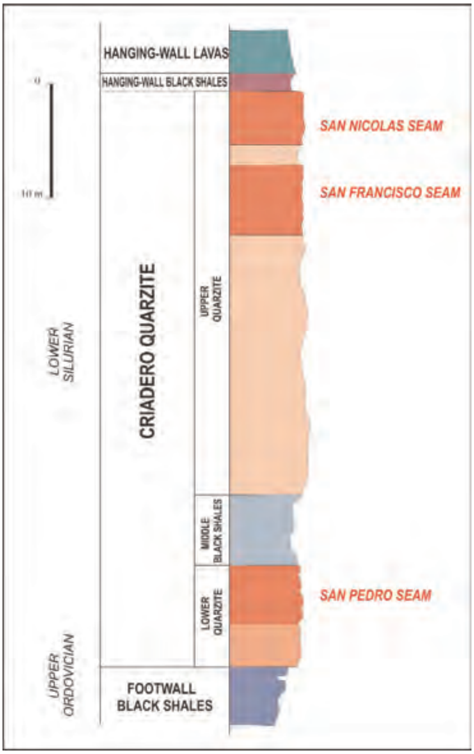

Fig. 8. Stratigraphic column sketch of the "Criadero Quartzite" in Almadén deposit.

A black shale unit with marked sedimentary lamination and fine layers of siltstones and mudstones is found underneath the "Criadero

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Quartzite". This unit is known as "Footwall Black Shales". Another black shale unit called "Hanging-wall Black Shales", formed by foliated graphitic black shales is found overlying the quartzites. Fossils are very common in this shales, mainly graptolites. In fact, the Almaden Mine is a renowned classic world-wide locality for this kind of fossils.

The graphitic shales are partially or totally replaced by intrusive sub-volcanic rock bodies (quartz-diabases) that were called as "Hanging wall Lavas". Besides these rocks, cutting or conformity among sedimentary rocks, there are dikes and sills of volcanic materials, some of them compositionally similar to the "Hanging Wall Lavas" while there are others with aphanitic texture that hinders the allocation to one or another volcanic pulse *(fig. 9)*. Spectacular cases of "thermal metamorphism" of these dikes could be observed on the mineralized quartzites.

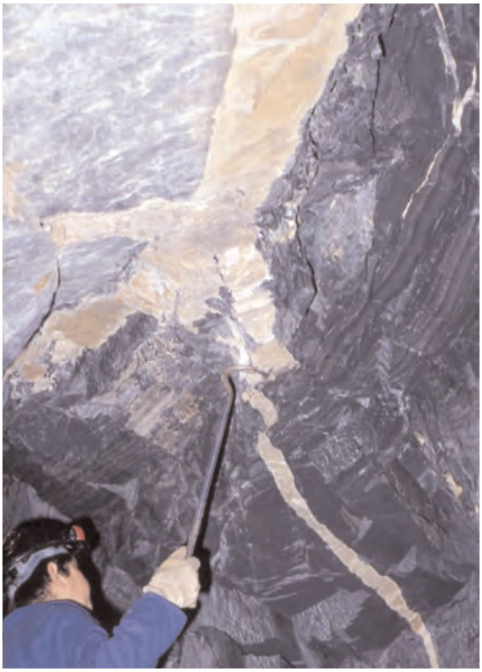

Fig. 9. Aphanitic dykes and sill hosted in "Footwall Black shales" and "Lower Quartzite". This sill in the footwall of quartzite has good continuity and it is a guide in the Almaden Mine geology. 19th Level, Almaden Mine.

A heterolithic breccias formed by fragments of siltstones, orthoquartzites and volcanic rocks showing peperitic structures *(fig. 10)* are found limited by faults in a doubtful stratigraphic position. The peperitic structures are spectacular and they represent another peculiarity of the rich and complex geology of the Almaden Mine.

The volcanic "Frailesca Rock" is a massive lenticular body that hosts in unconformity contact with the rest of the lithological units and is limited by very important WNW-ESE and NW-SE faults. The breccia-tuff material is composed by fragments of variable size and composition, including some quartzites and black shales.

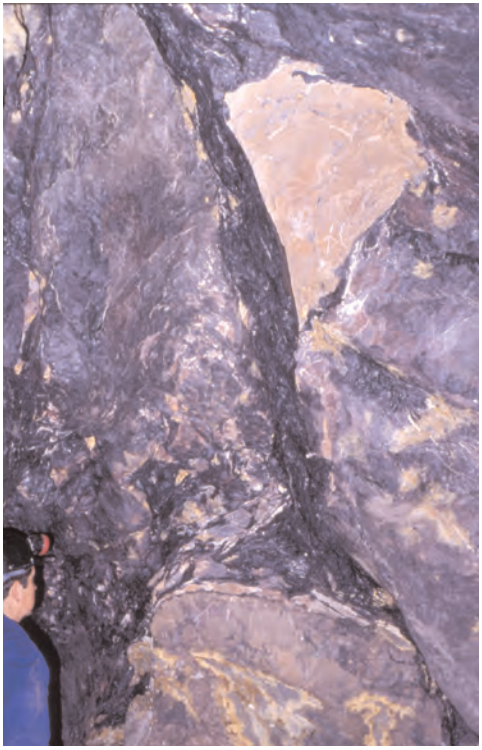

Fig. 10. Heterolithic breccia including volcanic blocks with peperitic structures. 14th Level, Almadén Mine.

5.3. The mineralization

The mineralization of Almaden Mine is characteristic of the stratiform deposits and is constituted by cinnabar impregnating and fissure infilling the orthoquartzite beds. Although in general terms the aspect of the ore is similar in all three seams, there are certain textural differences between San Pedro Seam and the other two seams on top of the "Criadero Quartzite". Thus, while in the first of them the impregnating ores are prevailing *(fig. 11)* in the San Francisco and San Nicolas seams the infilling joins ores are the most common *(fig. 12)*. This is not a general rule, as examples of the different mineralization types are found in all seams. The mineral paragenesis of the deposit is the common of the stratiform type with cinnabar, pyrite and native mercury along with traces of quartz, dolomite, ankerite, baryte and siderite.

Stockwork ores were occasionally found hosted in the "Frailesca Rock" in specific places of the Almaden Mine. This mineralization has an irregular shape and is bounded by WNW-ESE and NW-SE faults. It is uncommon in relation to stratiform ores, but it is the only one that can be seen "in situ" at present in the zone fit out for tourism.

Fig. 11. Cinnabar impregnating quartzite beds in San Pedro Seam, 19th Level, Almaden Mine.

The economic mineralization of Almaden Mine was worked in a maximum length of about 500m and to a depth of 600m. Ores in the San Pedro and San Francisco seams got down beneath the 23rd Level (more than 600 m deep), whereas the San Nicolas seam only reaches the 17th Level (about 425 m). The richest ores of the San Pedro Seam were arranged following a theorical axis with strong plunge to the East that would be going from the San Teodoro Shaft at superficial levels, to the San Miguel Shaft in deep levels. In the case of San Francisco and San Nicolas seams, the richest ores were following another theoretical vertical axis located to the west of San Aquilino Shaft.

Today it is impossible to surely know the tonnages and grades obtained during the exploitation of the deposit, but it is not speculative to venture a production of about 7 million tons with an average grade of 3.5% Hg (approximately 1 flask per metric ton). There has been a variability of grades, ranging from 1% to 40% of Hg. The greater one of the three mineralized seams was the San Pedro and San Diego, followed by the San Francisco and finally by the San Nicolas Seam. An estimation of the amount of metal produced by each one of them would be of 50% extracted from San Pedro-San Diego Seam, 30% from San Francisco and 20% from San Nicolas.

Fig. 12. . Cinnabar infilling joins in dark quartzite beds of San Nicolas Seam. "Tercer Macizo", 7th Level, Almaden Mine.

5.4. Ore-deposit structure

The Almaden deposit is hosted in a verticalized quartzite multilayer that has approximately E-W direction and is affected by fragile WNW-ESE shear bands. The shear bands produce displacements following the main anisotropy of the multilayer which is the stratification planes. The presence of a competent body of "Frailesca Rock" caused the refraction of the shear bands towards the NW-SE direction and in consequence a transpresive zone was created. The multilayer sequence behaves like a rocky massif with marked anisotropy, while the diatremic volcanic body tectonically acts as a compact, isotropic and rigid rocky body.

There are two important fracturing episodes that affected the deposit: *longitudinal shear bands* produced by the E-W F2 Hercynian shortening; and *transversal fractures* originated by tardi-Hercynian movements produced by N-S shortening.

Longitudinal shear bands structures are in pseudo-conformity with stratification planes. They cause a strong deformation in the deposit area and represent an important network of sub-vertical anticlockwise strike-slip faults with fragile and fragile-ductile character. They give rise to significant displacements (up to several hundred meters) and have frequent refractions

Fig. 13. Tectonic wedge producing duplication of a quartzite bed. 14th Level, Almaden Mine

and ramifications in the quartzite multilayer, with different adaptation and assimilation displacement structures. The mining tunnels offered a complete catalogue of tectonic structures produced by this type of deformation, with spectacular examples of drag-folds with subvertical plunge axes, tectonic wedges *(fig. 13)*, milonitic bands, etc., etc. Together with the main anticlockwise WNW-ESE faults, there were other conjugate clockwise NNE-SSW systems, *(fig. 14)*, and also anticlockwise ENE-WSW.

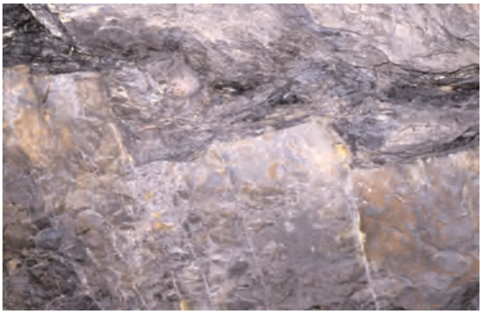

Fig. 14. Domino structure produced by a dextral NNE-SSW shear band cutting to "Lower Quartzite". 14th to 9th Sublevel ramp, Almaden Mine.

Transversal strike-slip faults with NW-SE bearing and usually high dips are cutting at wide angle the "Criadero Quartzite". They produced clockwise movements and they have a more fragile character than the longitudinal ones. These faults lead to translations with irregular importance, whose magnitudes range from a few decimeters to several tens of metres.

The intersection of longitudinal and transversal faults with the "Criadero Quartzite" on sub-vertical position caused the configuration and structuration of the deposit. The general structure can be defined as a dismembered large sub-vertical axe fold of "Criadero Quartzite", produced by anticlockwise translation of a wide longitudinal WNW-ESE shear corridor, which encounters the rigid diatremic body of "Frailesca Rock". This corridor is overlapped by a clockwise transversal NW-SE fracturing that separates the ore deposit in two parts by the displacement of the Eastern block Southwards in relation to the Western block *(fig. 15).* These parts would basically correspond with the "Rama Mina" to the East and the "Rama Sur" to the West.

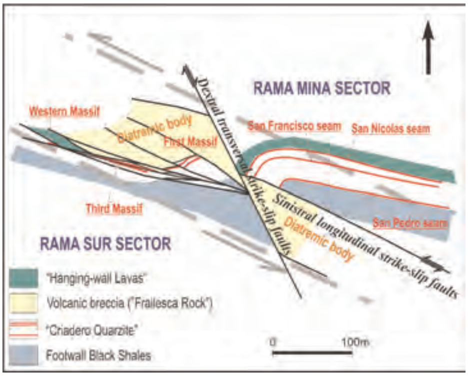

Fig. 15. Structural sketch at superficial levels of Almadén deposit.

Three sectors can be outlined based on disposition of the faults, the "Criadero Quartzite", the volcanic rocks and the orebodies. They are called from East to West as: "Rama Mina", "Los Masivos" and "Rama Sur". These sectors were separated by two important transversal NW-SE faults, named "C Fault" and "A Fault" *(fig. 16)*. The main distinctive features of these sectors would be:

The "Rama Mina" Sector was the classical exploitation sector in the Almaden Mine. The "Criadero Quartzite" appeared a little disarranged by few transversal NW-SE faults that produced small strike-slip jumps. Only one of these faults is worth mentioning the so-called San Miguel Fault. Mineralizations appeared in the classic three seams, but the best grades and the larger volume of ore came from the "San Pedro and San Diego Seam". The "Frailesca Rock" appeared South of the ore-deposit, and separated from the "Criadero Quartzite" by a broad band of "Footwall Black Shales", that became wider towards the East and in depth *(fig. 17)*. The contact between volcanic breccia-tuffs and black shales is an important fault named Southern ("M Fault"), that has a strong dip towards SSW.

The "Los Masivos" Sector was a structurally very complex sector because it was affected by longitudinal faults that formed two anticlockwise systems, the main WNW-ESE, and the other one ENE-WSW (which was called San Aquilino Fault). These faults produced important translocations in the "Criadero Quartzite", including duplication of mineralized seams, which led to the existence of places with high grade ores up to 15 meter wide. Besides the longitudinal deformation an important network of transversal faults was cutting the "Criadero Quartzite". These faults were delimitated by two great faults bearing NW-SE, the "A Fault" at the East and the "C Fault" at the West. Both faults have opposite dips and they converge at about the 8th Level, being the "C Fault" the only one reaching the surface. This fact entailed the absence of "Los Masivos" sector at the top of the deposit. The classic three seams appeared mineralized, but the "San Pedro and San Diego Seam" was getting progressively barren towards the west and depth. So, beneath the 15th Level this Seam was sterile in this sector. On the other hand, "San Francisco" and "San Nicolas" seams had

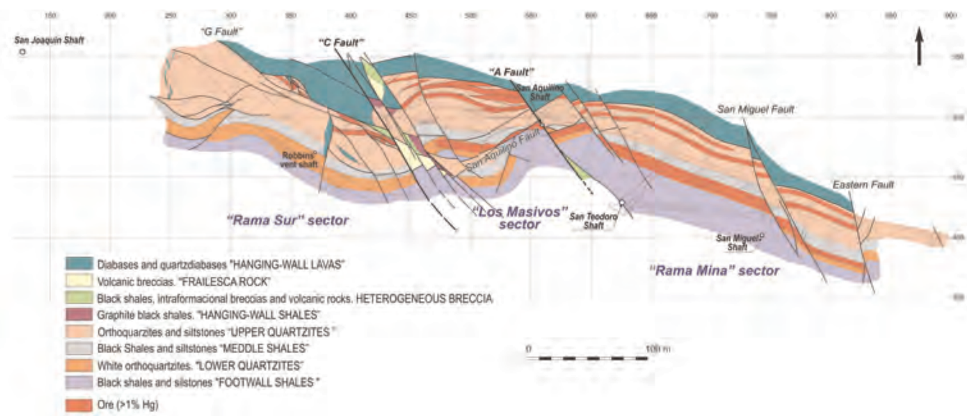

Fig. 16. Geological map of the 13th Level of Almaden Mine.

extraordinary grades, hence the name of the sector, especially at levels between 10th and 14th. Below 14th Level grades started to fall as much horizontally as vertically, even so San Francisco got down to the 21st Level. The "Frailesca Rock" in this sector is located North of the quartzites *(fig. 17)*. In deeper levels volcanic breccia-tuffs practically disappear, as they become replaced by the diabases of "Hanging-wall Lavas". In the Southern part, there are small disjointed blocks of the volcanic breccias limited by faults.

The "Rama Sur" Sector comprised the sector located at the West of the "C Fault". It was a structurally complex area affected by longitudinal fault tectonics. A distinctive structural feature was the existence of several sub-vertical axe folds, which settled much of the translation of the strike-slip faults. In that area there weren't many transverse faults, and they all produced minor displacements. Mineralization was broken off in discontinuous irregular bodies due to strong tectonization, but the ores belonged to the San Francisco and San Nicolas seams. The mineralization finished above the 14th Level. The "Frailesca Rock" was limited to the East by the "C Fault" and to the South by a great longitudinal accident called "G Fault". This fault acts as the Northern limit of the "Criadero Quartzite" and put it in contact with volcanic rocks *(figs. 16 & 17)*. From the 7th floor downwards, the volcanic breccia-tuffs were intruded and replaced by the diabases of the "Hanging-wall Lavas", with the last outcrops of the "Frailesca Rock" at the 14th Level. There are no more volcanic rocks in this sector, except some small dikes and sills hosted in "Criadero quartzite" and "Footwall Black Shales". They are compositionally equivalent to the "Hanging-wall Lavas".

6. Conclusions

The declaration of Almaden, together with Idrija, as Patrimony of the Humanity has implied a consideration of its geological singularity. The conjunction of a series of peculiar geological events during the Paleozoic and the effects of the Hercynian Orogeny in the area, gave rise to a group of mercury deposits without counterpart in the world. Among them, the Almaden Mine is highlighted as a true example of giant ore-deposit.

The Hg mineralizations of the Almaden mining

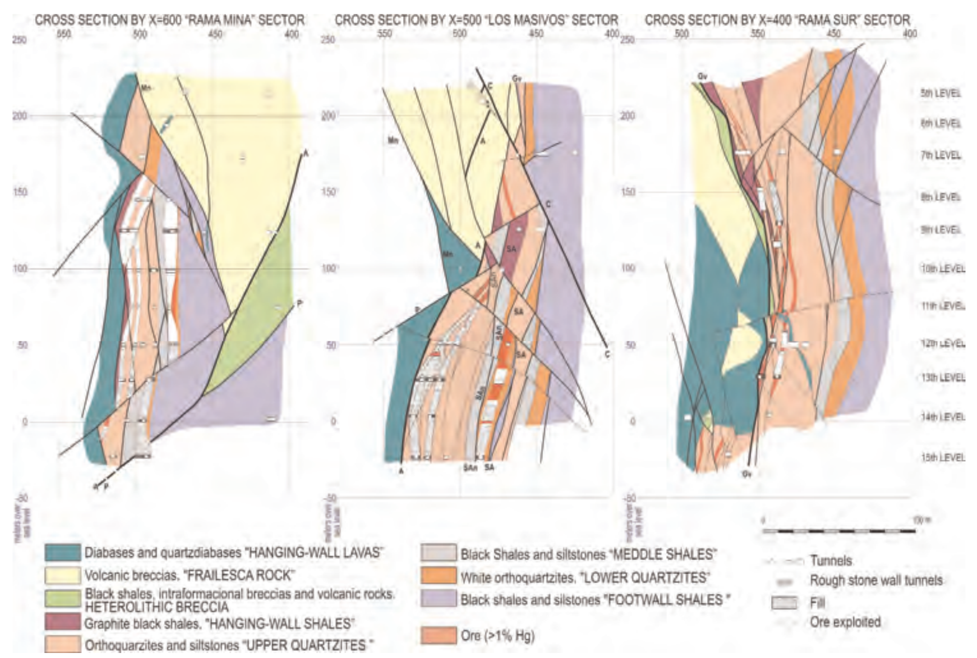

Fig. 17. . Representative geological cross sections of the Almaden deposits between5th and 15th levels..

district are restricted to a syncline where a complete Paleozoic sequence outcrops. This sequence includes volcanic materials of basic and ultrabasic composition, with explosive structures filled with very characteristic volcanic breccia-tuffs locally known as "Frailesca Rock". These materials contrast with the sedimentary deposition environment that mostly was a shallow and stable marine platform.

The Almaden Syncline is a Hercynian macrofold with WNW-ESE direction that shows an asymmetric shape with the Southern flank verticalized and a gently dipping Northern one. This fact contrasts the general vergency of the Hercynian structures in the region, which is southward. It is in this anomalous Southern flank where most part of the Hg deposits are located. This flank is also intensely affected by longitudinal anticlockwise shear bands of general NW-SE direction, formed during an E-W Hercynian shortening.

Two types of mercury deposits can be defined in Almaden district, the stratiforms and the stockworks. The stratiform type mineralizations are clearly pre-tectonic in relation to the Hercynian deformations, while the second ones show a sin-tectonic character respect to the longitudinal shearing. Thus, these deposits are epigenetic and probably come from the stratiform type.

The Almaden Mine has been the greatest exponent of the stratiform type deposits. It had three mineralized seams interbedded in the lithological unit named "Criadero Quartzite". This unit has a vertical disposition and appears interrupted by the "Frailesca Rock" body. The mineralized seams are arranged in an area strongly affected by longitudinal faults, which are cut with other transversal NW-SE strike-slip faults with clockwise displacement. All this leads to a partitioning of the deposit in three sectors which are known from East to the West as "Rama Mina", "Los Masivos" and "Rama Sur". The “Rama Mina” has been the more extended one and also exploited the most continuous ore bodies.

The Almaden Mine, throughout its tunnels, offered a compendium of excellent exhibitions of several geological subjects. A minimal expression of all this is possible to be observed at present at the area adapted for tourist use. It is thanks to this amazing and extraordinary geology that Almaden has become to be considered and awarded as Patrimony of the Humanity.

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