Volcanic rocks, gold mines and resilient plants: Getting inside of the Rodalquilar Caldera (Almería, Spain)*

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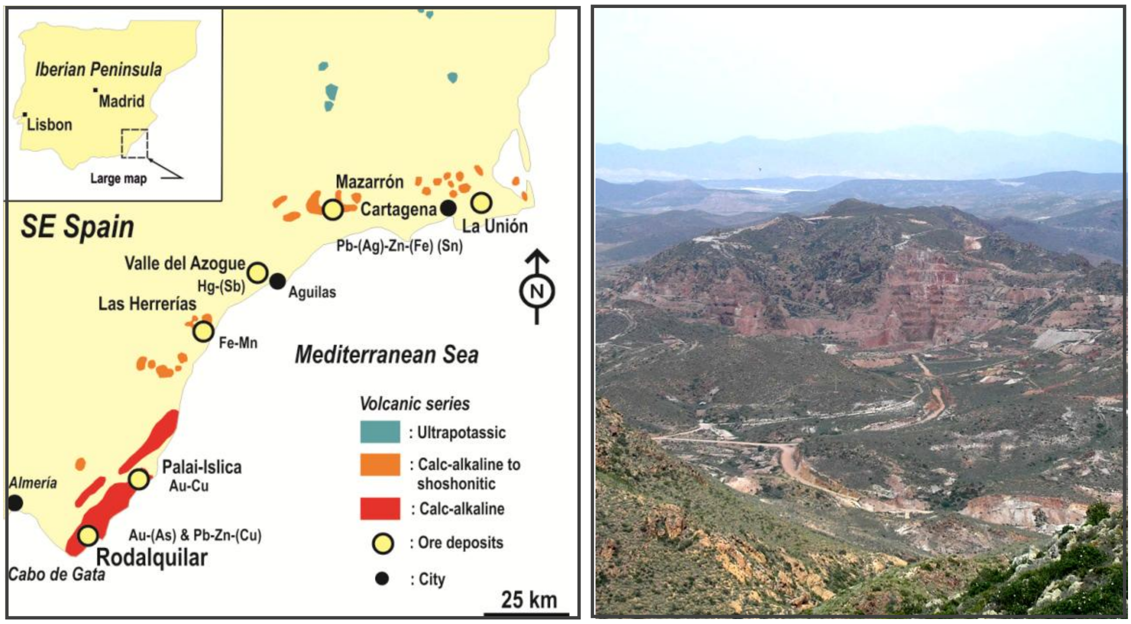
Aula2puntonet - 2021

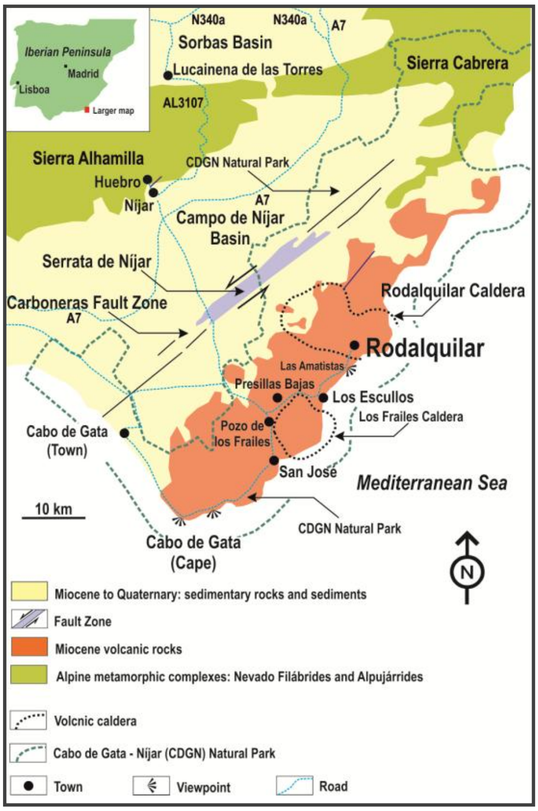
The eastern end of the Rodalquilar volcanic caldera, in the foreground the Rodalquilar Valley; in the background the Playazo and the Mediterranean Sea.

About 14 million years (*Ma*) ago, after the collapse of the Betic-Rif mountain chain that was formed by the African - Iberian collision (*Alpine Orogeny*), a volcanism that would encompass the southeast of Spain, the Alboran Sea (*the western end of the Mediterranean Sea*), and northern Morocco began to develop (*e.g. Doblas & Oyarzun 1989, Oyarzun et al. 1995*). As far as Spain is concerned, this volcanism spread towards the northeast (*up to Cartagena*). Mineral deposits were formed in relation to this volcanism, and many of them were economically exploited. In the case of Rodalquilar, the most important volcanism developed around 11 Ma and gave rise to gold deposits of the epithermal type (*e.g. Oyarzun et al. 2018*).



Left, volcanic rocks and ore deposits in southeastern Spain (adapted from Oyarzun et al. 2018). Right, the Rodalquilar gold mines (Cerro Cinto sector).

**** The Rodalquilar Caldera is located within the Cabo de Gata - Níjar Natural Park and the Geopark of the same name (Junta de Andalucía 2021a,b).***



PARQUE NATURAL
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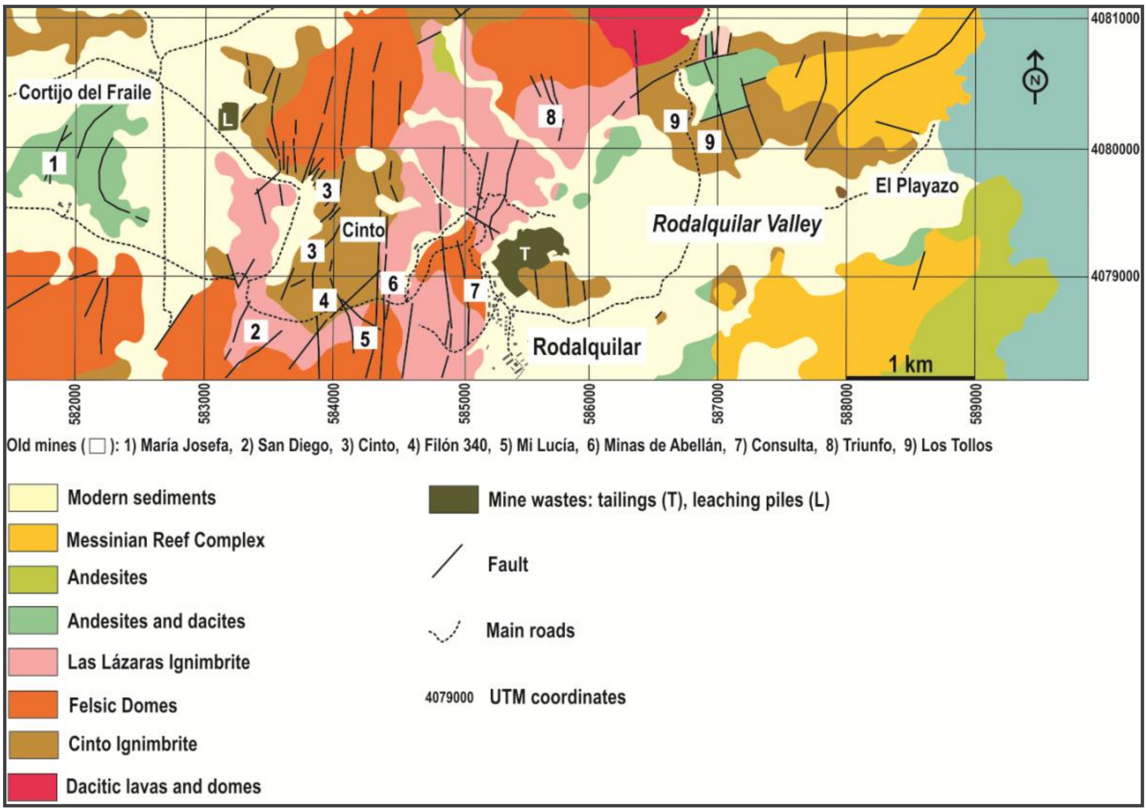
Left, geology of the Cabo de Gata region indicating the limits of the Cabo de Gata - Níjar Natural Park (adapted from Oyarzun et al. 2009). Right above, logo of the Park (Junta de Andalucía 2021a). Bottom right, the Indalo, a rock carving from the Copper Age that represents a human figure with outstretched arms and holding a bow, and which is considered a symbol of Almería (Blog Arhoteles.com 2017).



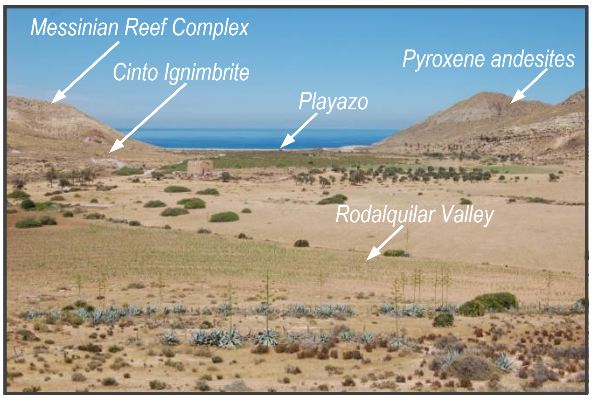
Geologic map of the caldera sector and location of mines in the Rodalquilar mining district. Adapted and slightly modified after Arribas (1993) and Arribas et al. (1995).

Geological units and suggested routes to visit the caldera

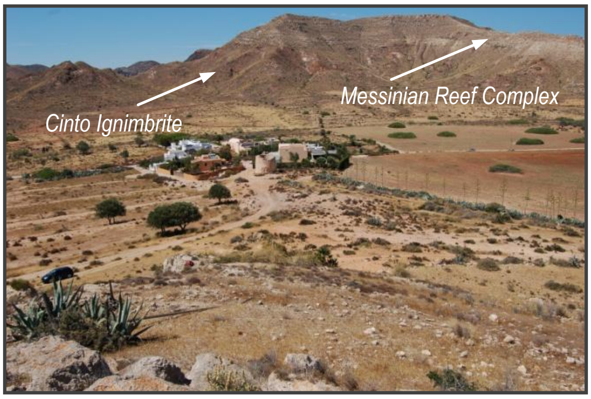
The Caldera de Rodalquilar has an oval shape approximately 8 km long (*east-west*), being an integral part of the Cabo de Gata volcanic block (*see previous figures*).

To visit the caldera we suggest here five routes (*see route map*): 1) from Rodalquilar to Playazo; 2) from Rodalquilar to the Barranco de las Cuchillas; 3) from Rodalquilar to Cortijo del Fraile (*watch out for this name, there are many places with the name "Frailes" between Cabo de Gata and Rodalquilar*); 4) leaving route 2 to the Abellán Mines; and 5) leaving route 2 to the Cinto Mines.

Route 1 takes us along a paved road that is not always in the best conditions. The Rodalquilar valley and the Playazo offer excellent sites to observe the contact relationships between the Cinto Ignimbrite and the limestones of the Messinian Reef Complex. The south of the beach also offers an excellent view of the pyroxene andesites. These andesites are black in color and are younger (*8 Ma*) than the felsic units of the caldera (*Cinto and Las Lázaras ignimbrites*).



Rodalquilar Valley (looking east), Playazo beach in the background.

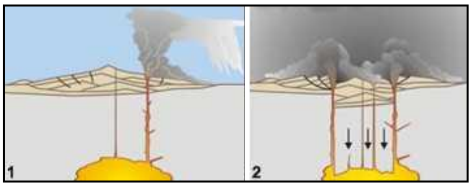


Rodalquilar Valley (looking north); houses: Cortijada de la Ermita.

Route 2 leaves the town at its highest part towards the south first, turning and then entering a valley called the Barranco de las Cuchillas. It is a route that can be done on foot or by car (*for just some 250 m*). It is recommended to leave the car where a road to the lower part

What is a volcanic caldera?

They are large volcanic craters that are formed by two different processes: 1) an explosive volcanic eruption; or 2) collapse of the surface rock into an empty magma chamber.

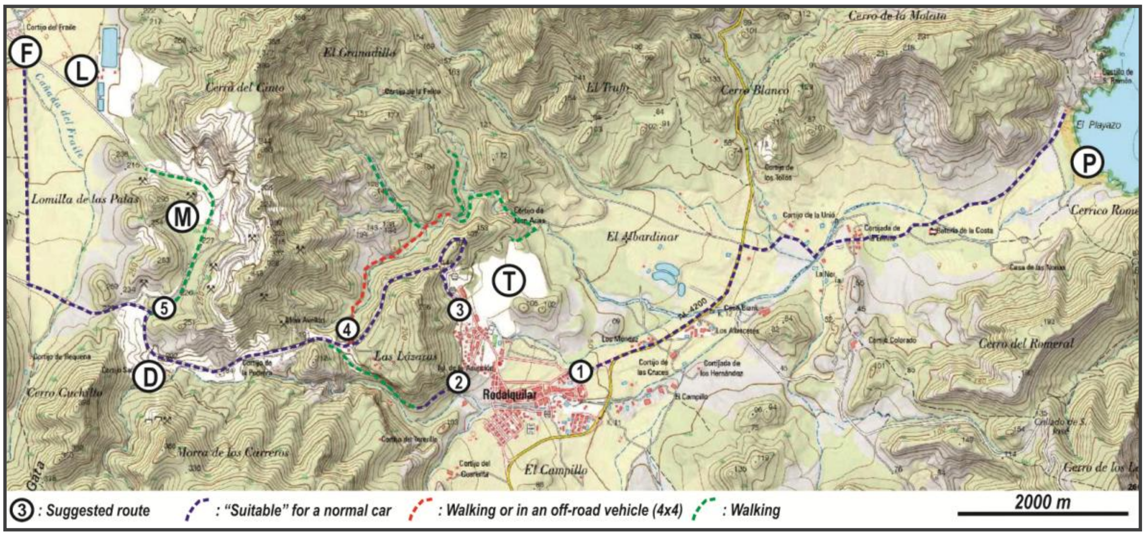


Caldera formation, from the eruption (1) to the collapse of the volcanic edifice (2) Adapted from King (2021).

What is an ignimbrite?

It is a chaotic and hot (typically > 800 °C) mixture of rock fragments, gas and ash that travels rapidly (tens of meters per second) (also known as a "nuée ardent" or pyroclastic flows). These rocks are often associated with the formation of calderas as the volcano collapses, although this is not always the case. Ignimbrite deposits can be huge (tens of meters high) with distinct sectors along the column.

Nuée ardente (pyroclastic flow) emerging from the crater of a volcano, which after it stops advancing, and all the fragments fall and consolidate, will form an ignimbrite (image: Internet Geography 2021) of the ravine begins. This route allows you to have an exceptional view of the Lázaras Ignimbrite, because the dirt track cuts through the unit. It is an exceptional sight since it also allows observing an unusual phenomenon: an ignimbrite with columnar jointing. As a bonus there is a preview of the Cinto Ignimbrite at the beginning of the route.



The routes here suggested (1-5) plotted on the Iberpix 4 topographic base (Instituto Geográfico Nacional 2021). T: tailings; L: Heap leaching zone (1989-1990); D: Cortijo San Diego (mines of); F: Cortijo de los Frailes; M: Minas del Cinto; P: El Playazo.

Images of Route 2. Above, beginning of the route, the Cinto Ignimbrite with goethite veins and an old mining exploration work. Bottom left, the Lázaras Ignimbrite with columnar jointing (looking southeast). On the right, a fallen piece of column along the way.

Route 3. To the north and west of the town of Rodalquilar, the geology is dominated by three main units (*see geological map of the caldera*), the Cinto Ignimbrite, the Felsic Domes, and the Lázaras Ignimbrite. Do not get overly optimistic, at the beginning the ascent is made by a cobbled road in very good conditions, although you quickly enter a dirt track in better or worse conditions (*depending on the year*) but which is nevertheless suitable for normal vehicles.

Left, the initially cobbled road that goes from Rodalquilar to Los Albaricoques (the car is in the opposite direction); in the background: the Denver Plant. Right, the Denver gold ore hydrometallurgical plant; in the foreground the cyanidation tanks (vats); above the ore milling plant (Wikinauta 2008).

Here we can see the first evidences of past mining activity, as the buildings of the old Denver Plant stand out on the hill. Reaching the highest point, the columns of the Lázaras Ignimbrite can be observed once more, although the contact with a felsic dome is found a few meters further along the road (*see the caldera geological map*). Let us highlight the Liesegang rings that can be observed in a small outcrop of ignimbrites in this sector.

Liesegang rings in ignimbrite. These are formed by oscillatory precipitation of iron oxides-hydroxides from the leaching-oxidation of a small grain or grains of pyrite.

The road will take us through an abandoned mining landscape mixed with beautiful outcrops of ignimbrites and felsic domes. These rocks are highly altered, having underwent alteration phenomena both due to hydrothermal processes (*which also led to the formation of the ore deposits*) and supergene (*due to the oxidation of pyrite*) (*see Oyarzun et al. 2018*). Both generated large amounts of sulfuric acid that hydrolyzed the feldspars and bleached the rock (*kaolin formation*), then turning it into ocher tones due to formation of iron oxides-hydroxides. The entrance to *Route 4* that takes us into a valley (*which is on our right*) and the Abellán mines is easily visible as we go.

Left, a small gallery (tunnel) that connects the road with the Cortijo San Diego old mining facilities; the geological unit is the Cinto Ignimbrite, here with a network of goethite and jarosite veins. Right, on the other side of the road, right in front of the previous image, we can see the same unit affected by a small fault zone (FZ).

Continuing along the route, we will find a small tunnel on the left that communicates with the Cortijo de San Diego mining facilities, and about 340 m further west, we arrive to the beginning of *Route 5*. Advancing for about 800 m from there, turn right, and on that straight road you will be able to see the Cinto mines from a distance, finally reaching the old buildings of the Cortijo del Fraile.

Left, the Cinto mines and in the foreground the gold cyanidation pool and pile abandoned in 1990. Cyanide has a short duration in the environment (in the range of days to weeks: epa.govt.nz 2021) so that it does not pose any danger at present. Right, the buildings of the Cortijo del Fraile.

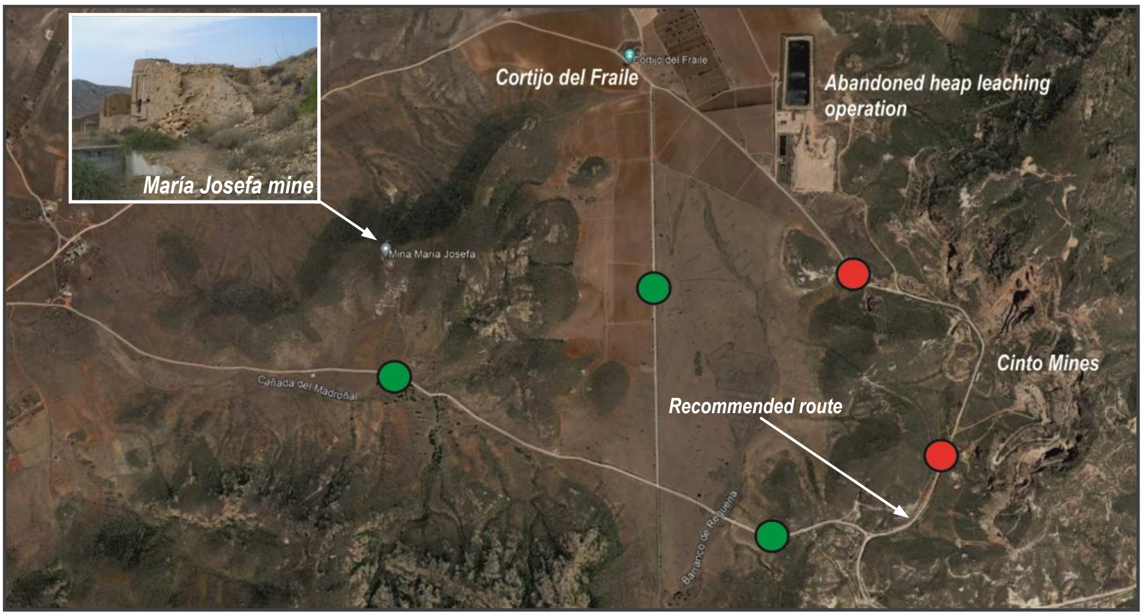
According to Wikipedia (2021), the Cortijo del Fraile is a building that was declared a Site of Cultural Interest with the category of Historical Site, although due to its state of technical ruin, it is now on the red list of heritage in danger (*although no institution is taking responsibility for its state of conservation*). An event known as “the Crime of Nijar” took place in its vicinity on July 22, 1928, which inspired the verse drama entitled “Bodas de Sangre” (*Blood Wedding*) by the famous Spanish poet Federico García Lorca (*Wikipedia 2021*).

Route 4. This route begins by separating from the previous one to the right (*see route map*), and continues in a northeast direction that if followed completely, turns to the southeast and then to the southwest, thus enabling you to return to Rodalquilar on foot. Not in an off-road vehicle (*4x4*), since only one sector is passable with this type of vehicle (*see route map*). The tour takes you directly to the so-called Abellán Mines, another of Rodalquilar’s gold mining-metallurgical failures (*1929-1930*). The dominant rock along the route is the Cinto Ignimbrite, easily recognizable by its white color. The yellow-green color shades are derived from a mineralogy characterized by the presence of alunite-jarosite.


Left, old mining works in the Abellán Mines sector; the Cinto ignimbrites are cut by a small fault zone (arrow). Right, ruins of a building in the Abellán Mines, in the background: the Cinto Hill.

Route 5. We finally have this last tour that in some aspects may be the most interesting of all as it takes us to the most famous gold mines in the district: the Cinto Mines. It is accessed by a road that is cut for vehicles (*for unknown reasons*) by turning to the right about 340 m meters westward of the Cortijo San Diego (*remember the tunnel on the left side of the road*).


The Cinto Mines. Above, a view from the South entering through the cut road. Below, a view from the West. The road seen in both images (arrows) appears in Iberpix4, Google Maps and Google Earth, but it cannot be accessed except by walking.

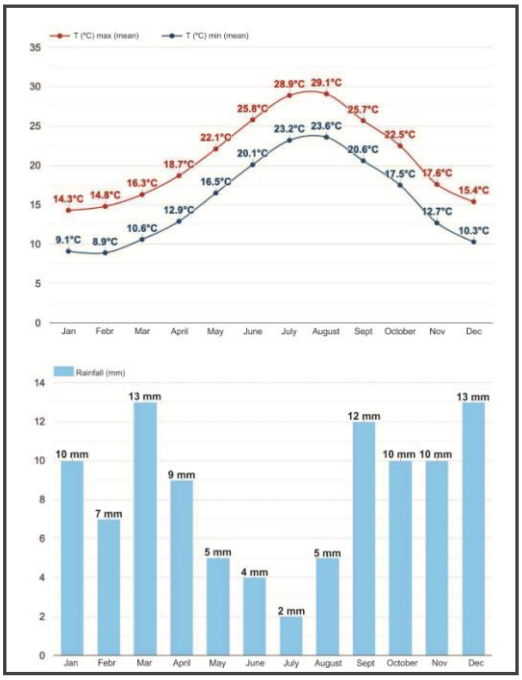


Here you can see the routes that "can" (green circles) be and "cannot" (red circles) be done by car in Routes 3 and 5. The access to the mines from the South is recommended to avoid troubles. Although it is outside the proposed routes, an image of the ruined facilities of the María Josefa mine has been included here (mind the ticks if you visit the place). Google Earth image.

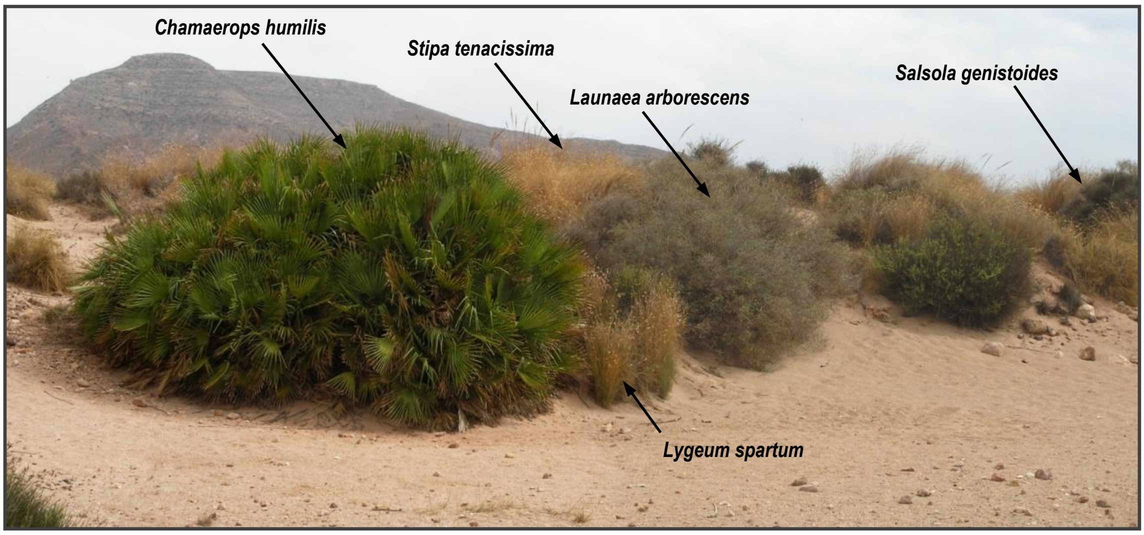
We will find here the three geological units that have been mentioned before, the Cinto and Lázaras ignimbrites as well as the felsic domes. These rocks are highly altered (*advanced argillic alteration*), including their partial silicification and the important presence of alunite. In addition, these rocks are characterized by deep ocher colors as a result of the massive precipitation of iron oxides-hydroxides. Do not look for gold, apart from the fact that the grades were very low (*a few grams per ton*) the gold was so finely dispersed that (*apart from exceptional cases*) it is not recognizable to the naked eye.

The resilient plants of Rodalquilar (a tough vegetation)

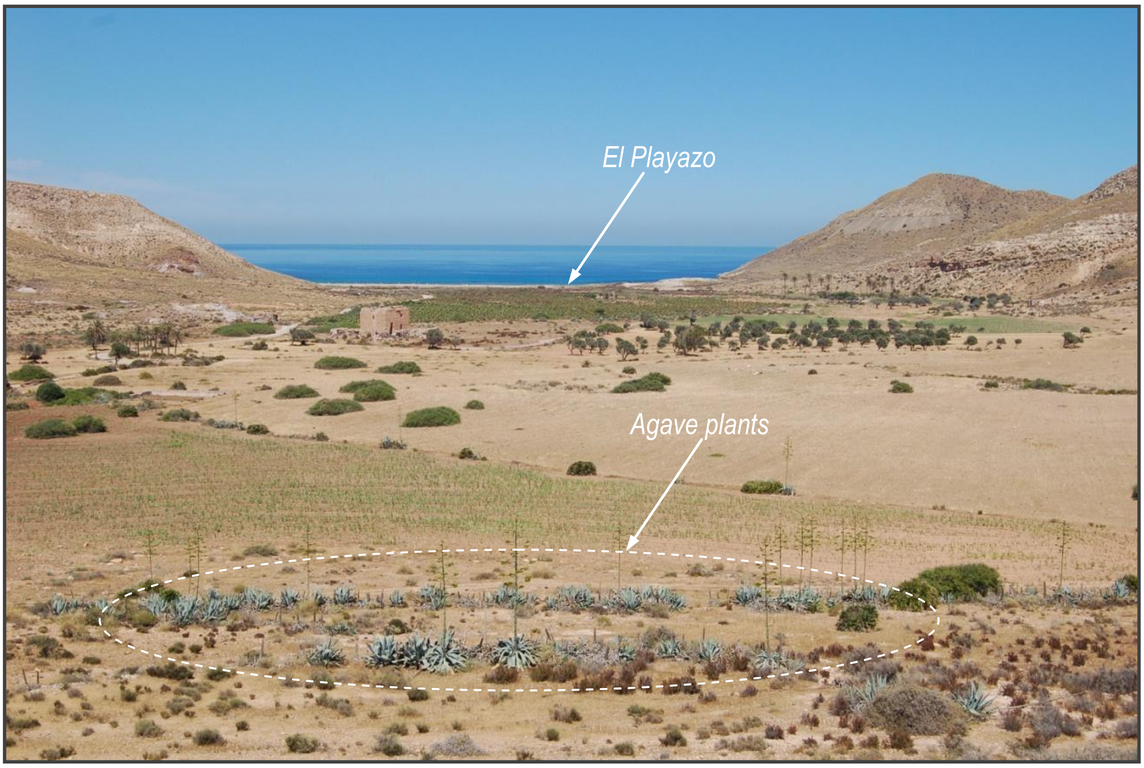
The vegetation of Rodalquilar has been (*and is*) subjected to strong pressure from human, agricultural and mining activities, as well as from harsh climatic conditions, with high temperatures and low precipitation (*see temperature and precipitation figure*), although compensated partly near the coast due to marine influence. Despite this, it preserves the remains of an interesting vegetation, with numerous plants well adapted to these conditions. Many of them have a restricted distribution, being endemic to southern Spain and North Africa, or the Mediterranean region.



Left, average monthly temperatures and rainfall in the Caserío El Campillo, 500 m ENE from Rodalquilar. The month with the lowest average precipitation is July (2 mm), and the maximum average maximum temperature corresponds to August (29.1 ºC). Weather Atlas (2021)

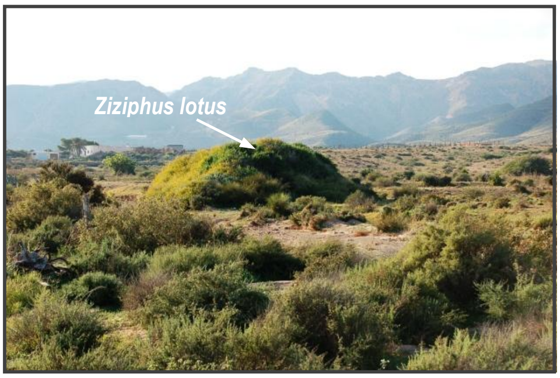


Even on the tailings dumps, the vegetation has gradually reestablished itself. In the image, taken in the lower tailings of Rodalquilar (see route map), there are shrubs such as the Mediterranean dwarf palm (Chamaerops humilis), albardín (Lygeum spartum), esparto (Stipa tenacissima), cardavieja (Launaea arborescens) and mato negro (Salsola genistoides).



View towards El Playazo, in the foreground Agave plants. Various species such as A. fourcroydes and A. sisalana were cultivated to obtain textile fibers, and although their exploitation was abandoned, they remain at present as naturalized specimens.

Many shrubs take hemispherical shapes, have thorny branches, have small leaves or drop them during unfavorable times, thus avoiding excessive water loss. Plants with bulbs, rhizomes or other underground organs also abound, which remain buried during the most unfavorable periods. Some examples are shown below. The scientific names follow the *Flora iberica* nomenclature (*Castroviejo 1986-2021*).



In the center of the left image, the azufaifo (Ziziphus lotus), a thorny deciduous shrub up to two or three meters high, close to the true jujube. Right, detail of the characteristic zigzag branches and small deciduous leaves.

Several legumes of the genisteae group grow in the area. On the left, Genista spartioides, which quickly loses the small leaves. On the right, Ulex parviflorus (a gorse) with branches transformed into thorns.

A cornical (Periploca angustifolia), a shrub with small flowers that give rise to fruits (difollicles) formed by two divergent pieces like horns.


On the left, a Mediterranean dwarf palm (Chamaerops humilis) growing on materials from the lower tailing. It is the only species of palm native to the Iberian Peninsula and the Balearic Islands. On the right, detail of its fruits (arrow).


On the left, flowers of the oroval (Withania frutescens), an Ibero-African Solanaceae that can be found in the Balearic Islands and the south and east of Spain, in Morocco and in Algeria. On the right, detail of the berry fruit enclosed in the persistent calyx.


Rodalquilar Valley. Oleander (Nerium oleander), a shrub native to the Mediterranean region and the Middle East, which grows in 'ramblas' (mostly dry riverbeds although they can be subjected to sudden flash floods), stony ravines and water courses.

In spring and summer, especially if there were some relatively important rains during the winter, the area is covered by numerous plants that bloom and beautify the landscape.

On the left, Fagonia cretica, a herbaceous plant that covers the ground. On the right, Arisarum vulgare, a herbaceous plant that is pollinated by small mosquitoes that are attracted by the smell and moisture of the apex of the spadix, and by the color of the spathe.

Rodalquilar Valley. Asphodels (Asphodelus sp.) grow from rhizomes buried in the ground, forming beautiful plants with white flowers and capsule fruits.

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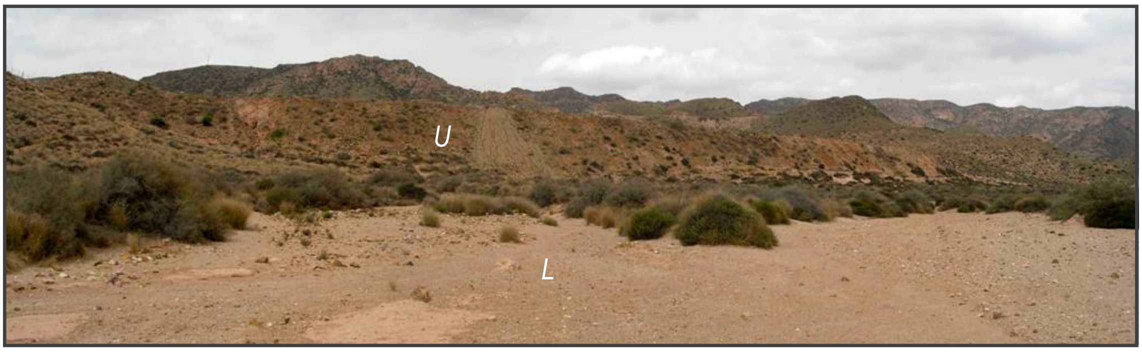
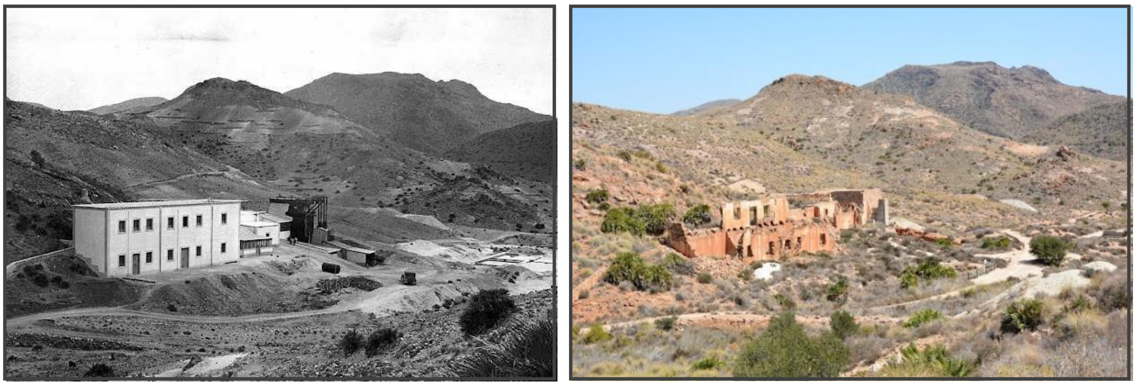


The Rodalquilar main tailings deposits (upper: U; lower: L), derived as residues from the Denver plant. The plants not only have colonized these anthropic and originally barren soils, they have managed to thrive in these technosols.

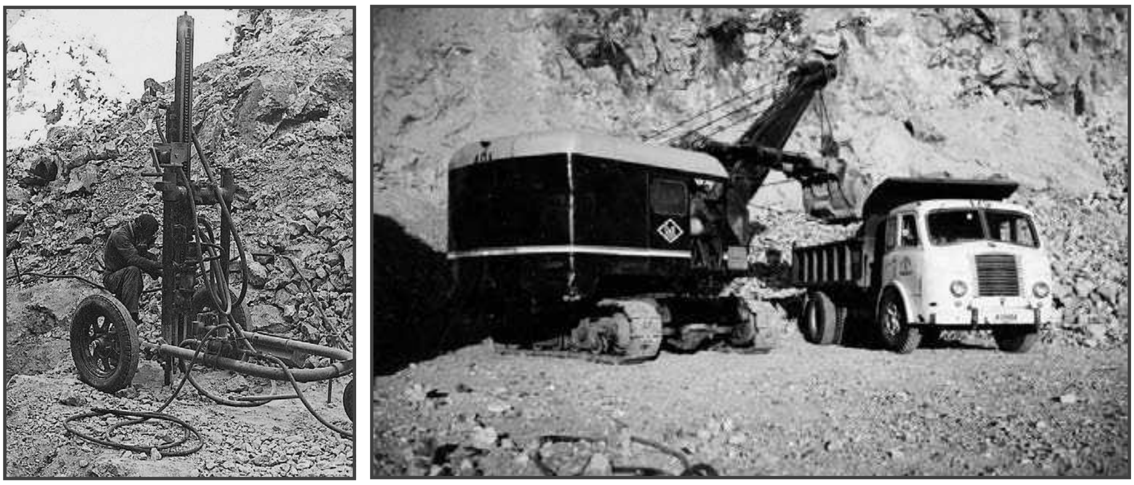
Broken dreams

Rodalquilar has been in many aspects a site of “broken dreams”. Mining initiated around 1825 for Pb, Zn, and Cu, and it was not until 1864 that the miners realized that the ore contained some gold as well. Mining operations belonging to this period are those of Consulta, María Josefa, San Diego and Triunfo. These were small-scale operations and the ore was sent to Murcia for the melting and production of Au-rich Pb, a product ultimately sent overseas to Antwerp (*Belgium*) to separate the gold. By the beginning of the First World War (*1914-1918*) most of mines had closed. In 1925 a mining operation for gold amalgamation with mercury at the María Josefa site was set up, however, a year later technical problems led to the closure of the operation. Another failed incursion into industrial gold amalgamation was carried out between 1929 and1930 at the so called Minas de Abellán.

Modern mining in Rodalquilar (*Hernández Ortíz 2005*) initiates in 1930 by an English company called Minas de Rodalquilar S.A., with the set up of the first cyanide leaching metallurgical operation (*the so called Dorr plant*) near the town of Rodalquilar. In 1934 they managed to mine some 29,000 tonnes at 12 g t^{-1} Au, recovering 240 kg of gold. An ore reserve estimation in 1952 yielded a figure of some 3,348,297 tons at 4.7 g t^{-1} Au involving seven subvertical mineralized bodies (*Hernández Ortíz 2005*).



Time does not forgive. The Abellán Mines main building in 1932 (image: Arnold Heim) and in 2019 (Blog de Paco 2019).



Drilling operation (left) and excavator and dump truck (right) in Rodalquilar (ADARO period) (images: Hernández Ortíz 2016).

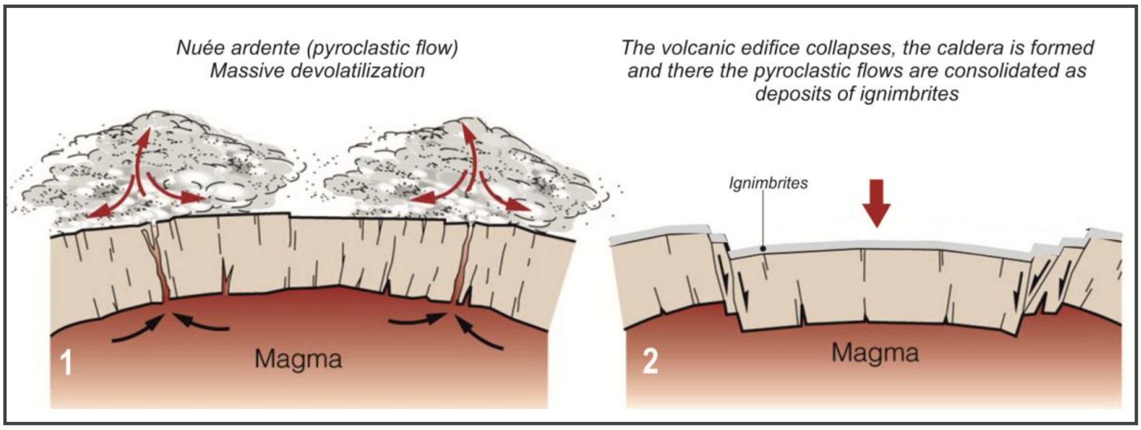
In 1956 the mining company ADARO (*a Spanish state owned company*) inaugurated a new cyanide operation, the so-called Denver plant, which at the time was the largest gold leaching plant in Europe. This operation lasted until 1966 and treated ore from the open pit mines of El Cinto. Between 1943 and 1966 ADARO extracted some 1.6 millions of metric tons of ore grading 3.5 g t^{-1} Au. Most if not all of the tailings around the town of Rodalquilar can be related to this mining period. Based on production data for the period 1943-1966, the volume of tailings may be in the range of 900,000 to 1,250,000 m^3.

Mining methods consisted in underground works to deal with the subvertical/steep dipping ore bodies during the English period and by open pit mining during the ADARO years.

A new mining and metallurgical operation in the Cinto sector began in 1989. This time the company was the Cluff Resources – Antofagasta Holdings JV and the chosen metallurgical procedure was heap leaching followed by CIP (*carbon in pulp*). The intention was to mine about 750,000 metric tons of ore at 2.3 g t^{-1} Au, although by 1990 the operation had been abandoned. As the result of this failed operation, some 120,000 m^3 of tailings still remain there (*the old leaching pile*), near the Cortijo del Fraile.

All in all, this is long history of fails, but why? Well, perhaps because more gold has been mined from the thoughts of men than has been taken from the earth. Apart from some degree of delusional thinking, there might be a reasonable geologic explanation for this disastrous history of failed projects.

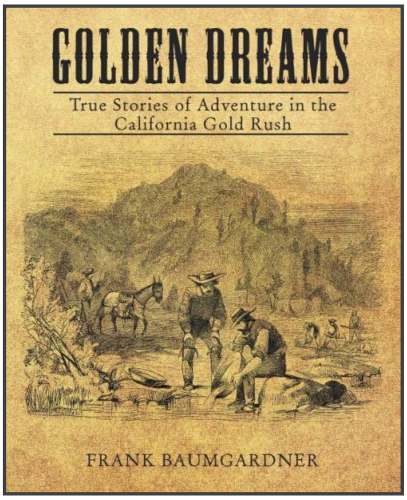
Magmas have volatiles, and these volatiles are required to complex and transport metals, eventually to form ore deposits. However, what happens if a magma loses its volatiles? That is important to take into account, particularly within a geologic setting such as that of Rodalquilar. What is a caldera related volcanic eruption? It is a large display of 'fireworks', with most of the volatiles being lost in a giant blast. In other words, the explosive nature of supereruptions massively disperses the metal-rich volatiles into the atmosphere, thus preventing the formation of large ore deposits in depth (*e.g. Pasteris 1996; John 2008*).



Formation of a large volcanic caldera (several kilometers in diameter) from the eruption (1) to the collapse and infilling with ignimbrites (2). In the first phase, an immense amount of volatiles and metals are lost to the atmosphere (e.g. Oyarzun et al. 2005), which prevents formation of large ore deposits in depth (e.g. Pasteris 1996; John 2008). Adapted from Iriartea (2010).

Massive loss of volatiles. Left, Pinatubo Volcano (Philippines) erupting on June 12, 1991 (Image: Harlow 1991). Right, the eruption of the La Soufrière volcano (Island of Montserrat) on February 11, 2010; the height of the pyroclastic plume reached 15 km (Image: Daily Mail Reporter 2010).

It is estimated that a volume of ~ 5 to 6 km^3 of pyroclastic materials may have been emitted from the Rodalquilar Caldera, and this is only taking into account the processes that led to the formation of the Cinto ignimbrite (*Oyarzun et al. 2021*). Massive devolatilization by large eruptions is a process that has been studied by Pasteris (*1996*) and John (*2008*). Following their ideas, Rodalquilar became what the rules of geology, chemistry and physics allowed it to be, no more, no less: an epithermal gold deposit with small tonnage and grades; a bad combination from an economic point of view.



But dreams of wealth, no matter how absurd they may be, are too powerful to just let them go … Never let facts get in the way of a good story …

Cover: www.amazon.com/Golden-Dreams-Stories-Adventure-California/dp/1480886769

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