

## Salt production in Italy: from ancient salt springs to modern mining

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**Abstract.** In Italy, salt production methods evolved over the centuries, from coastal salt pans to artificial evaporation of brines, to modern underground and solution mining. Rock salt production in inland areas dates back to Etruscan times, in modern Tuscany. In the Middle Ages, the salt springs of Volterra were systematically and continuously exploited, and since the early 1900s production was carried out with engineered solution mining, that allowed Solvay to build a large soda factory in Rosignano in 1913. In the last decades of the 20th century, solution mining started also in Calabria. Here, in the Timpa del Salto mine, some sinkholes appeared in 1984, triggering a landslide and an overflow of brine, an event that gradually led to the interruption of mining activities. Calabria is also known for the longest-lived Italian underground rock salt mine (Altomonte-Lungro mine), exploited almost continuously since antiquity and active until 1978. Finally, in Sicily, numerous underground salt mines were intensively exploited since the second half of the 20th century, and three are still active (Realmonte, Racalmuto, Petralia). We outline the historical development of these Italian salt production sites and the evolution of mining technologies as used in different geological contexts.

**Key words:** Rock salt, Mining history, Messinian, solution mining.

### INTRODUCTION

#### GEOLOGY OF SALT DEPOSITS IN ITALY

During the Messinian Age (7.2–5.3 Ma) “the Mediterranean area underwent a series of rapid and dramatic paleogeographic changes involving complex feedbacks among tectonics, eustasy and climate” (Roveri et al., 2001). In particular, the end of this age is characterized by the well-known and debated Messinian salinity crisis, when the Mediterranean basin separated from the Atlantic and underwent several cycles of evaporation and, in some cases, desiccation (Krijgsman et al., 1999; Roveri and Manzi, 2006; Vai, 2016). This event led to the deposition of a distinctive evaporitic and post-evaporitic geological succession, especially in the most isolated basins.

In the Italian geological literature, the terms *serie gessoso-solfifera* or *formazione gessoso-solfifera* (gypsum-sulphur formation) have been used at least since the work of Giuseppe Scarabelli (1820–1905) to indicate Upper Miocene strata including large masses of gypsum, anhydrite, sulphur-bearing limestones, rock salt and other salts interbedded with terrigenous deposits distributed along the Apennine arc, from Piedmont to Sicily (Fig. 1). The gessoso-solfifera was of great economic interest due to the presence of large deposits of sulphur, rock salt and potassium-magnesium salts. The stratigraphy of the formations involved was assessed by the Italian geologist Selli (1954, 1960) to indicate a pile of deposits corresponding to the Messinian Stage and representative of the set of palaeoceanographic events known as the Messinian salinity crisis.

The mineral deposits included in the *gessoso-solfifera* show a repeated sequence of minerals, from the least to the most soluble: first calcite, aragonite, and dolomite, that form carbonate rocks, then gypsum and anhydrite (calcium sulphate), to halite (rock salt), and lastly potassium and magnesium salts (sylvite, carnallite, kainite). All the rock salt deposits of continental Italy and the rock salt and potassium-magnesium salts deposits of Sicily are part of this biogenic-chemical geological succession enclosed between Miocene and Pliocene terrigenous deposits. The Messinian Age ended with the Zanclean flood, when the Strait of Gibraltar opened, and the Pliocene began.

Many sulphur deposits of the *gessoso-solfifera* have been exploited in Emilia-Romagna, Marche, Campania, Calabria, and especially in Sicily (Castaldo and Stampanoni, 1975) giving birth to the important Italian mining industry of the 19th and 20th centuries. Rock salt resources of the *gessoso-solfifera* have long been exploited not only by underground mining, but also by collecting brines from natural salt springs, later extracted from dedicated wells, as in Salsomaggiore (Northern Apennines). Here, numerous salt springs have been known and exploited since ancient times (Bacci, 1571), and from the 19th century they were used for medical purposes (cold hypersaline salsobromiodic water), for food-grade salt production, and for the chemical and pharmaceutical industry (elemental iodine and bromine production). From 1923 to 1938, almost 90 wells were drilled in this area, to depths ranging from 400 to 1300 m, for the combined production of brines, natural gas and crude oil.

#### CASE STUDIES: TUSCANY, CALABRIA AND SICILY

In Tuscany the salt deposits of the area south-west of Volterra consist of halite layers included within the Messinian *gessoso-solfifera*, locally made up of irregularly interbedded sand, marl and clay with minor gypsum and anhydrite. Overall,

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# Messinian deposits of the Apennine-Maghrebian foredeep and surrounding areas

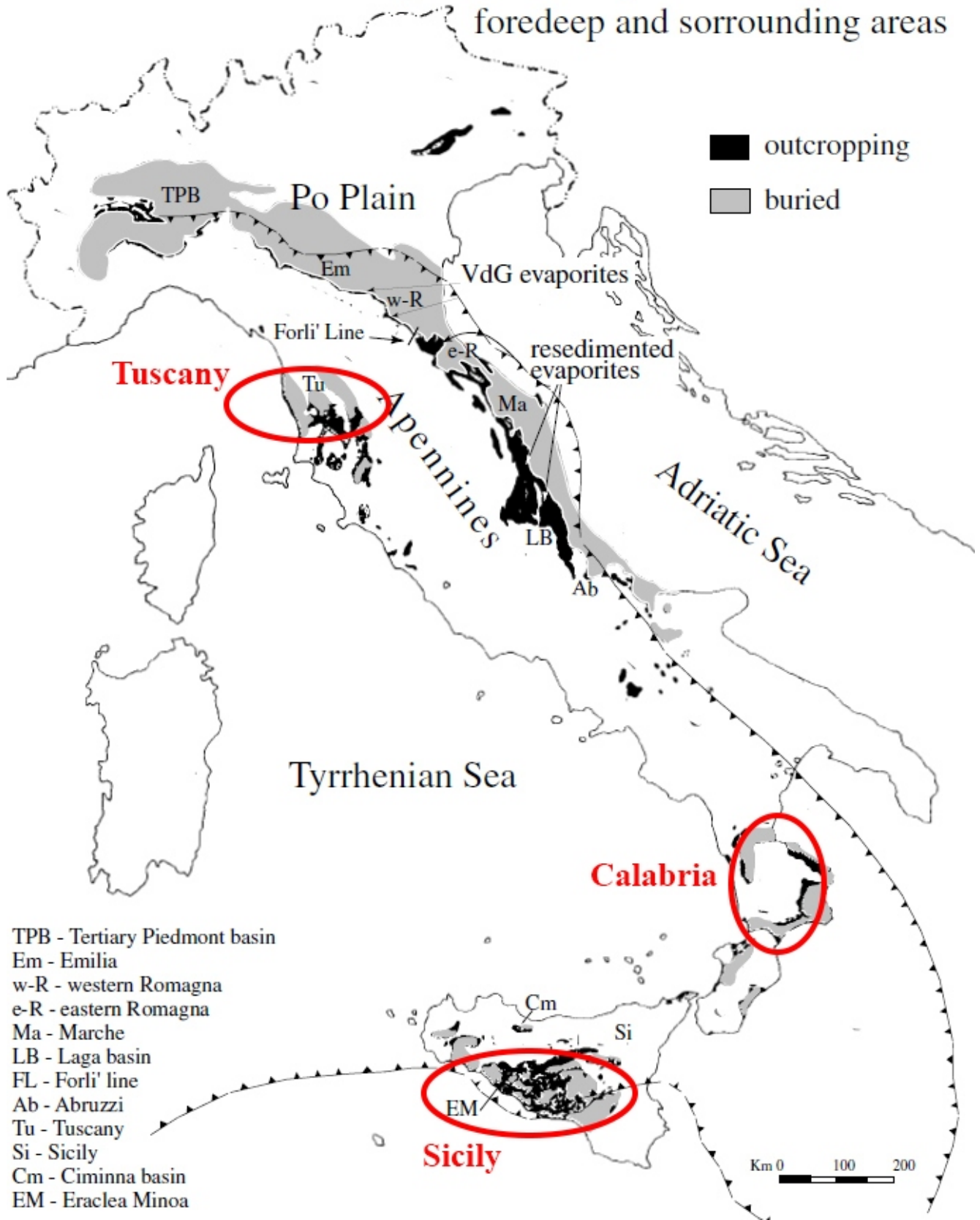


Fig. 1. Distribution of Messinian deposits in Italy

The red circles indicate the main salt production sites analyzed in the paper (redrawn from Roveri et al., 2001)

the thickness of the evaporitic unit varies between 200 and 500 m, and normally shows 2 to 3 principal salt layers of lenticular shape. The dimensions of the lenses or masses of halite can reach 1 km in length, hundreds of metres in width and a thickness ranging from 15 to 30 m. The thickness of the clayey deposits that separates the various salt masses is extremely variable, normally ranging from 20 to 40 m; interfingering of salt with clays, and vice versa, is also commonly present. The depth of the salt layers, today exploited by solution mining, varies between 100 to 200 m (Mazzanti et al., 1963).

In Calabria the salt masses exploited in Altomonte-Lungro and Timpa del Salto mines (two sites over 80 km apart), are again contained in the *gessoso-solfifera*. The deposit of Lungro is a large mass of finely stratified halite interbedded in a clay and sandstone succession. It spans for ~1 km parallel to the contact of the transgression between the Late Miocene and the Ligurian shales. The salt mass is over 500 m thick and lies in sub-vertical position (Ogniben, 1969). At Lungro, underground mining was active until 1978. The deposit of Timpa del Salto, again of Messinian age, is located in a detrital-saline unit formed of clay and anhydrite often cemented by salt beds. The deposit has a fairly regular morphology, with 4 layers of varying thickness, up to 300 m or more at the hinge of the anticline. The top of the salt layers is located between 300 and 650 m deep (Gisotti, 1992). Here, salt was produced by solution mining from 1969 to 2009.

In Sicily the *gessoso-solfifera* outcrops in the central basin. The salt deposits are grouped in a large NE–SW-oriented strip of central Sicily, from Sciacca to Petralia, and includes the active mines of Petralia, Realmonte and Racalmuto (Castaldo and Stampanoni, 1975). The salt masses have been affected by intense compressional tectonics that determined a system of folds increasing the thickness of the salt layers up to 400–600 m, as in the mine of Realmonte. In Sicily there are also important deposits of potassium-magnesium salts, consisting of kainite masses (with minor carnallite and silvite) interbedded with halite layers, as in the mines of Realmonte, Bosco and Pasquasia (Adamo and Ramberti, 1979). The Pasquasia mine was actively exploited for potash with state-of-the-art mining equipment and infrastructures until 1992.

## PROTO-INDUSTRIAL SALT PRODUCTION

### ANTIQUITY TO THE LATE MIDDLE AGES

Since ancient times, and still nowadays, humankind has produced or extracted edible salt from three main sources: by natural evaporation of sea water, by forced evaporation (boiling) of sea water or brines produced from salt springs or dedicated wells, or by extracting it in its natural solid form, in rock salt mines. Salt has always been an indispensable commodity for daily life, not only for seasoning food, but also for preserving fish, meat and olives, as well as for the preparation of cheese and dairy products. The traditional and most widespread technology used in the Mediterranean area, characterized by hot and dry summers, was the production of salt from sea water by evaporation, easily carried out in the low and sunny coastal lagoons, transformed and engineered as saltworks or “salt pans”. This method has been used since the Neolithic (Weller, 2015), and many salt pans such as that of Trapani (Sicily) and Cagliari (Sardinia) were built by the Phoenicians, and today, besides salt production, they stand as geosites for cultural heritage conservation and as tourist destinations.

Before the foundation of Rome, the salt pans of the present Northern Lazio coast were under the control of the Etruscan city of Veii, as was the road system for the distribution of salt towards the inland areas, which only in the centuries to come would take the name of *Via Ostiense* (from the Tyrrhenian coast to Rome) and *Via Salaria* (from Rome to the East). In the 4th century BCE, the control of these salt pans was the cause of the conflict between Rome and the city of Veii, which was then defeated and destroyed. Even later, the salt produced in the coastal salt pans was widely used by the Romans (Alessandri and Attema, 2022). In 150 BCE, Cato the Elder in his *De Agricultura* recommended storing a *modius* of salt per year (~8.5 litres, or 10 kg) for each member of the family, and slightly less for each slave, both for direct consumption and for preserving food.

Marcus Manilius’ description of fish processing and conservation (30–40 CE) in his *Astronomica* suggests that many Roman-era saltworks were associated with fish-salting facilities (Lowe, 2018). In the 1st century CE, Lucius Columella (*De Re Rustica*, book 12) also described how to prepare salted pork. Pliny the Elder (*Naturalis Historia*, book 31) distinguished native from artificial salt. He listed many natural salts coming from different locations, such as accumulations near salt springs, salt crusts around salt lakes and natural salt dug from the ground, including the Egyptian “ammonium” salt. The ammonium salt of Greek and Roman writers was a pure salt produced in the oases of the Libyan desert, particularly in that of Ammonium (today Siwah); it was of such excellent quality that later it was cited as medicine by Galen and Dioscorides (Ruska, 1928). Among the artificial salts, Pliny cited, as the best and most abundant, the common salt produced by evaporation of sea water in coastal salt pans; he also mentioned the salt of Babylon, which forms a bituminous surface foam when the brine is boiled. In his opinion, the salt produced by evaporation or boiling of brines yielded a salt of lower quality.

The late Latin author Rutilius Namatianus in *De Reditu Suo* wrote of his voyage home to Gaul, carried out between 415 and 417 CE, during which he visited some salt pans in the territory of Volterra, built near his host’s mansion. Here, seawater entered the salt marshes through channels, running down through little trenches and flooding a system of many divided ponds. A system of locks conveniently controlled the water flow, so that in the summer the entrapped sea water evaporated, being no longer in contact with the open sea.

The second method of salt production, by forced evaporation of brines in coarse pottery placed on a wood fire (*briquetage*) was mainly (but not exclusively) practiced in inland areas far from the sea (Harding, 2014). In the Sichuan region (China) there is evidence of this technique since 3000 BCE, first using brines collected from salt springs and then, after the 3rd century BCE, with brines produced from drilled wells. In Europe, the containers used for briquetage were made of thick-walled ceramic materials, but in China they were large boilers made of iron (Kurlansky, 2003). In late antiquity, ceramic was abandoned in favour of larger metallic boilers, first using lead and then iron.

The third method of salt production, mining, was widely practiced by the Proto-Celtic speaking populations of Central Europe, who exploited the salt deposits of Halle in Saxony and those of Hallstatt and Hallein, both in the Salzburg area (Reschreiter and Kowarik, 2019). The wealth coming from the salt trade stimulated the development of the Hallstatt culture in the Iron Age (700–450 BCE). In Italy, the Altomonte-Lungro salt mine (Calabria) was probably already used in prehistoric times and then also by the Greeks and Romans.

After the collapse of the Roman Empire, the Mediterranean saltworks did not cease their production, but were simply managed by the new rulers, the Byzantine people and the Arabs. In particular, in the Adriatic area, the emerging power of Venice in the 9th century stimulated technical progress from the single evaporation pond of the primitive salt pans into a more efficient system of multiple ponds where increasingly concentrated solutions were accurately stored and managed (Kurlansky, 2003). In the 10th century, in addition to the Venetian salt pans of Chioggia and of those facing the Dalmatian coast, the archbishop of Ravenna promoted the creation of new saltworks in Cervia (in operation since 965), along the coast of Romagna, and directly controlled by the Pope. Later, intense competition pushed the Venetians to control the Mediterranean salt markets, importing salt from Egypt, Crimea, Crete, Cyprus, Puglia, Sardinia, Ibiza and Algeria, trying to dominate the supply and to control production. From the 13th century the *Camera Salis* (Chamber of Salt) of Venice issued rigid trade licenses that established not only the price and the quantity of salt that could be exported, but also the geographic areas. This system favoured Venice in the conflict with the republic of Genoa (1379–1381), its rival in the Mediterranean trades, initially of a commercial nature and then transformed into a real war.

#### EARLY MINING TREATISES: AGRICOLA AND BIRINGUCCIO

The Renaissance marks the modern development of mining technology, mineral prospecting and metallurgical practices. These were clearly recognized and documented in German-speaking areas as early as the first half of the 15th century. Many practices had to be readapted or reinvented, and new metal smelting and refining processes were introduced, as was systematization of alchemical practices based on the use of fire. The new metallurgical methods of that period are best described in Vannoccio Biringuccio's *De la Pirotechnia* (1540), while Georgius Agricola's *De Re Metallica* (1556) and *De Natura Fossilium* (1546) are the milestones of both mining-metallurgical technologies and geological-mineralogical studies, respectively, and so also of salt production.

Book 2 of *De la Pirotechnia* (Biringuccio, 1540) contains a chapter focused on salt production, either by mining or by water concentration, *i.e.*, natural evaporation of sea water or forced evaporation of brines. Biringuccio described the salt pans of the Mediterranean, the saltworks of Halla (Tyrol), and the iron boilers utilized there. As in "Halla in the Duchy of Austria (modern Hall in Tyrol), even in Volterra salt is produced from salt water extracted from some wells". "The salt water is boiled and evaporated in lead boilers. The final product is a snow-white salt, produced in such a large quantity that it satisfies not only the local needs, but also those of Florence and its nearby territory". The lead boilers used in Volterra were similar to those used for vitriol production. Unfortunately, Biringuccio did not describe salt rock mining.

Book 12 of *De Re Metallica* (Agricola, 1556) reports that "salt water is converted into salt either in salt pans with the power of the sun (Fig. 2), or in boilers and pots with the power of fire" (Fig. 3). Concerning the salt pans, Agricola recommended that to boost rapid and uniform evaporation, the ponds must be shallow, flat, horizontal, and effectively encrusted to avoid water losses. In hot and dry countries, salt pans can evaporate either seawater or brines produced from salt springs or wells. He described the geometry of the ponds, divided into basins and canals, the flow of the water and the final harvesting of salt with shovels and rakes. As for forced evaporation, Agricola recalled

the best practices for the construction of buildings that house boilers, so that the walls and furnaces are functional and safe from fires or rain. Boilers must be made of iron or lead. In the workshops of *Halae Hermundurorum* (Halle in Saxony) both the foremen and the laborers worked half naked, dressed only in short pants, to better withstand the heat of the furnaces.

## SALT PRODUCTION IN TUSCANY

#### MOJE DI VOLTERRA: FROM SALT SPRINGS TO SOLUTION MINING

Numerous salt springs were known and exploited in the territory of Volterra, probably since Etruscan times, in the present localities of Buriano, Montegemoli, Saline and Querceto. The first historical evidence of salt production dates back to 962, when Emperor Otto I established the sharing of jurisdiction and financial incomes over the local saltworks into equal parts between the Bishop and the Commune of Volterra. The salt trade was in fact one of the main sources of wealth in medieval Volterra. A legal document of the Bishop, dated 974, indicated the saltworks as *moja regis* (*moja*, from the late Latin *muria*, brine, and *regis*, of the sovereign). In the same years, a manuscript of the municipal archive of Volterra reported the description of two trips made by salt workers from Volterra to Halle (Saxony), invited in 981 by the Emperor Otto II to instruct German workers in both the art of salting and brine boiler construction (Borelli, 2000).

Political, economic and military struggles for the control of the saltworks among the Bishop and the Commune of Volterra took place between the 12th and the 14th century, which ended up with an affirmation of the town government, that began to take away the jurisdiction of the *moje* from the Bishop, purchasing wells or lands nearby saline springs. Thus, the Commune set up a sort of monopoly on salt production and trade. Between 1240 and 1250, saltworks privileges were also disputed by the emperor Frederick II, who claimed and confiscated the old rights over the *moje* in favour of the Holy Roman Empire. Inevitably, the economic importance of salt awakened the interest of Siena and Florence, that were almost continuously fighting for the domination of Tuscany. Volterra lost its autonomy in 1472 after military conquest by Florence, then under the lordship of Lorenzo de' Medici *il Magnifico* (1449–1492). The saltworks became property of Florence, which however soon reassigned the concession to the town of Volterra, under a yearly fee, because only the long-established local experience was able to manage salt production profitably.

Here, salt production was carried out by evaporation of hypersaline brine (close to saturation) extracted from hand-dug wells, according to a system that remained almost unchanged from the time of the first written testimonies until the end of the 17th century, and with few modifications even until the beginning of the 20th century. A well was excavated, lined with bricks and mortar and completed with an oak timber casing; the salt water was drawn with buckets lifted by a manual winch (*burbera*), and then poured into lead boilers, measuring ~2–3 m, placed on wood-fired furnaces. The working conditions were very demanding, also due to the need to keep the furnaces ceaselessly active (Martelli, 1843). In Volterra salt production almost never stopped, and production was certainly continuous from the time of the Medici until the Grand Duchy of Tuscany (Targioni Tozzetti, 1770), and is still active today. The 17th century manuscripts by Rocco Romegialli and Raffaello Maffei describe the production methods of the Volterra saltworks and the organization of the



Fig. 2. Evaporation of sea water by the action of the sun and wind (Agricola, 1556: 441)

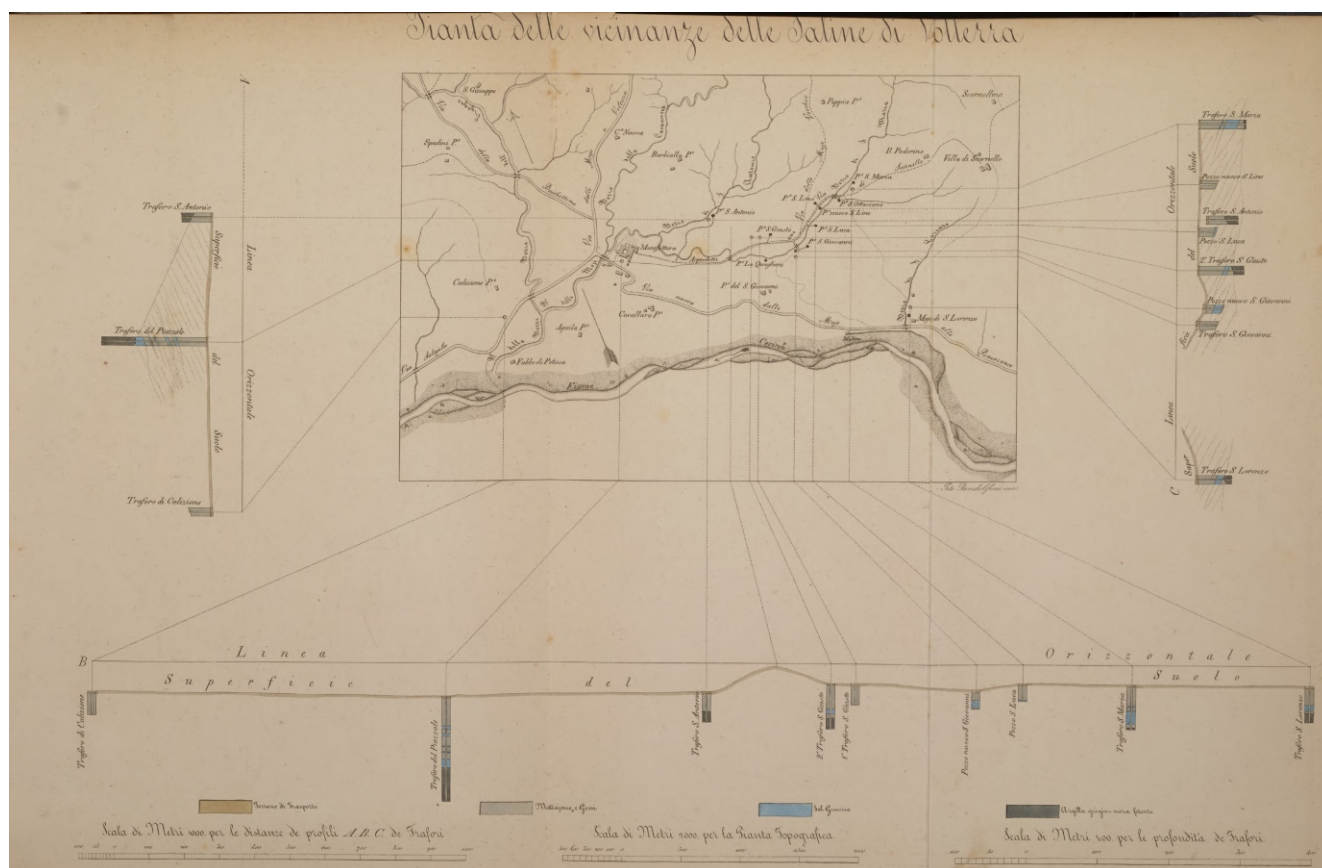


Fig. 3. Forced evaporation of natural brines by means of artificial heat (Agricola, 1556: 449)

*Dogana del Sale* (salt custom), an institution of medieval origin which presided over the storage and distribution of the saltworks production (Romegialli, 1636; Maffei, 1650).

In the 17th century Florence carried out a technical and administrative modernization of the salt production facilities (Targioni Tozzetti, 1770). The grand duke Peter Leopold I (later archduke of Austria, King of Hungary and Bohemia, and Holy Roman Emperor Leopold II) visited the saltworks in 1773 and stimulated the transition of salt production from an artisanal to an industrial stage. New industrial facilities were built under the auspices and public money of Pietro Leopoldo between 1787 to 1790; these are known as the *Moje nuove* or *Fabbriche leo-*

*poldine* (New *moje*, or Leopoldine plants). Parts of these buildings still exist today and, together with a church and some annexed buildings, shaped the community of Saline, today part of the municipality of Volterra. In the following decades, initiatives and projects multiplied to develop productivity, reduce costs and improve working conditions (Martelli, 1843). The leopoldine plants were in operation until WW1, with much modernization implemented during the 19th century, such as automatic pumping systems to withdraw water from wells, the use of mechanical drilling rigs, and the development of a new road network, including the construction of a railway line linking Volterra to Cecina (1860–1863).



**Fig. 4. Stratigraphic profiles and location of the boreholes designed and studied by Paolo Savi in Saline di Volterra during his geognostic campaign of 1852–1857 (Savi, 1862)**

In the second half of the 19th century, Paolo Savi, professor of geology at the University of Pisa, carried out a detailed study of the rock salt of Volterra. More specifically, in 1832 an artesian well drilled at a depth of 148 m near the saltworks revealed five layers of rock salt, two of which were ~10 m thick. Savi planned a geognostic campaign (1852–1857) to study the extension and characteristics of the salt deposit, which included the drilling and sampling of 7 boreholes (Fig. 4), up to 60 m deep. Due to the low production of brine in the dry season, and the growing number of infill wells drilled in the area that increased capital expenses, Savi proposed to centralize brine production by a system of horizontal tunnels that would connect the existing wells into a single production well, used to feed the whole industrial complex. The project was never realized for economic reasons. Shortly afterwards, the mining engineer Augusto Schneider was commissioned to draw up a project for a possible salt mine, but the venture was not followed up due to the high financial risks, which made the traditional method economically preferable (Savi, 1862).

After the unification of Italy (1861) the saltworks of Volterra became the property of the newborn Italian state. In the early 20th century, Solvay introduced solution mining methods (single or multiple injection and production wells), more efficient for large scale salt production, although demanding as regards fresh water supply (Moncada, 1940). In August 1944 the saltworks were totally destroyed by the German army. After the war, diesel fuel replaced wood as fuel for furnaces. Since the end of Italian state monopoly (1974), the Volterra plants have been progressively privatized.

#### SOLVAY AND THE CHEMICAL PLANT OF ROSIGNANO MARITTIMO

In modern times, salt production was, and still is, associated with the 19th century development of the chemical industry for the production of sodium carbonate (or soda,  $\text{Na}_2\text{CO}_3$ ). In the early years, soda was produced using the Leblanc process and later by the Solvay process. In 1913 Ernest Solvay chose Rosignano, a small coastal town of central Tuscany, as the most suitable location to build a soda plant. The reason for this choice was at least threefold: the rock salt deposits of Volterra (35 km); the limestone quarries of Acquabona (4.5 km); and the railroad heading to the port of Leghorn (25 km). The coastal railway line Livorno (Leghorn)-Vada-Cecina was inaugurated in 1910, which directly connected Rome to Leghorn and Pisa.

In 1911 Solvay obtained a license from the State Monopoly, Ministry of Finances to carry out geological and mining surveys near Volterra and Rosignano, and in 1912 he commissioned technical assessments of the above limestone quarries (Ministero dell'Agricoltura, 1915). Both activities gave satisfactory results, and the Rosignano plant construction began in 1913. A year later, a 4400 m long cableway was installed to connect the plant with the limestone quarry. In 1913 the drilling of wells for solution mining began near Ponte Ginori, a decade later extended to the Volterra saltworks. In 1918 the first brine was pumped to Rosignano through a 30 km cast iron pipeline, which was then extended by another 10 km a few years later (Cheli and Luzzati, 2010).



**Fig. 5. Satellite view showing the environmental footprint of part of the saline di Volterra active concession for solution mining. Here is visible the dense network of access roads to well clusters, roughly aligned and spaced ~30 to 50 m from each other. Controlled ground deformation is present around the wells, although several small sinkholes are visible (dark circular spots; <https://maps.app.goo.gl/Q4qXBS4SoXqGYTBA8>)**

Solvay decided to produce the brine from drilled wells by applying the recently developed solution mining methods, that is pumping fresh water under pressure into salt layers through injection and production wells drilled at depths ranging from 100 to 200 m. Solvay used multiple well technology, implemented by drilling wells in staggered lines spaced 30 to 50 m apart, a method still used today. In 2018, salt production in this area was ~1.5 million tons, which also required the availability of over 6 million m<sup>3</sup> of fresh water. It has long been known that known that solution mining induces deformation of the ground surface. Here, sinkholes are the clearest evidence of this mining activity (Fig. 5). This stimulated the drawing up of specific guidelines for the design, monitoring and environmental control of the mining operations, aimed at land management, territorial and industrial safety, and landscape protection policies.

In the Rosignano plant the brine, once purified, is used to prepare many chemical products, obtained both by the Solvay process (soda, calcium chloride, etc.) and the chloralkali process (chlorine, sodium hydroxide, etc.). The solid wastes resulting from soda production (fine-grained limestone mixed with gypsum, sand and clay) have long been released into the sea along the nearby coastal area. Over the years, this has caused the formation of almost 5 km of “white beaches”, clearly visible also from satellite images, and sometimes questioned as regards environmental impacts on the local tourist area.

## SALT PRODUCTION IN CALABRIA

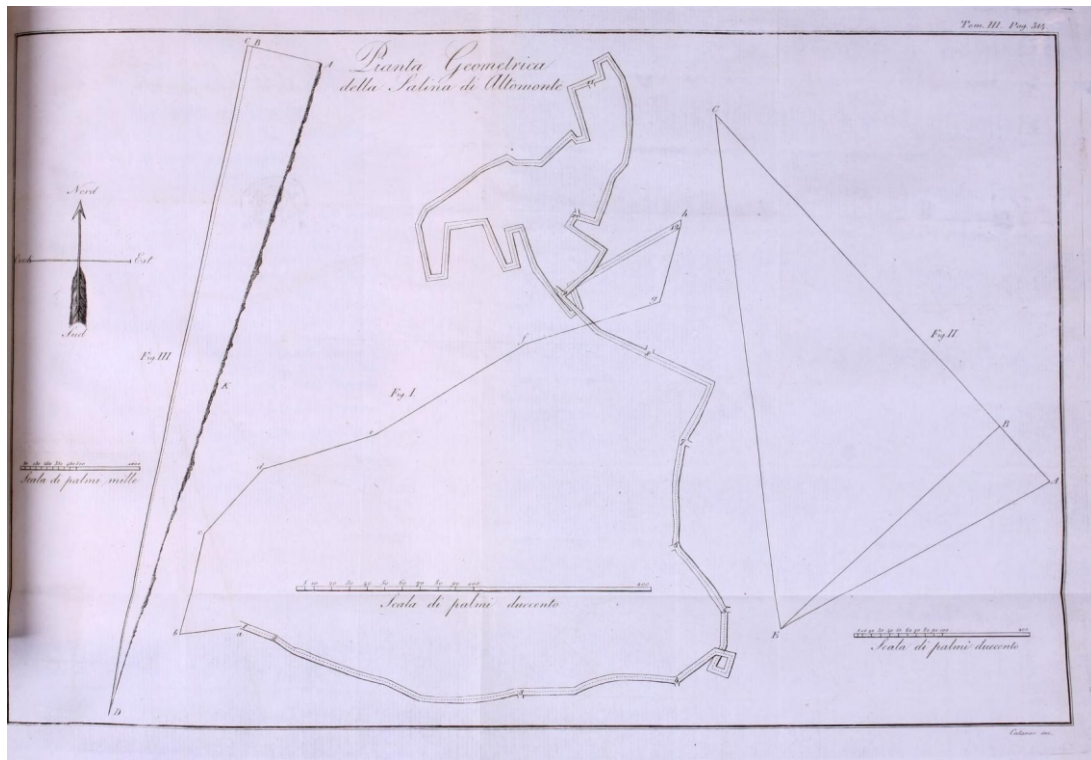
ALTOMONTE-LUNGRO, THE LONGEST-LIVED UNDERGROUND SALT MINE IN ITALY

The Altomonte-Lungro mine has been documented since the Middle Ages, with almost continuous operations up to 1978. It is quite likely that salt production from open pit or near-surface excavation dates back to the Greek and Roman civilization of

the area, or even to prehistory. During the Middle Ages, mining methods were aimed at obtaining maximum profit. This mine, rather than being rationally developed by horizontal levels, was deepened vertically, following the winding path of the salt layers of higher quality. Inevitably, this soon caused problems of rock instability, scarce ventilation and water infiltration, that characterized this mine up to its abandonment (1978).

After the Napoleonic invasion of the Kingdom of Naples (1806–1815), the modernizing spirit of the new rulers (Joseph Bonaparte and later Joachim Murat) was aimed at reorganizing the rigid administration of the ancient feudal kingdom, trying to eradicate feudalism, and suppressing most of the rights and privileges of the old nobility. Mines were nationalized, and the mineral resources of Calabria aroused the interest of the French government, due to potential advantages for military needs and for the state economy. Experts from academia, military and technical Corps were soon engaged in technical assessments and site inspections, and most of the mineral samples collected in Calabria were analyzed at the *Real Istituto di incoraggiamento alle scienze naturali* (Royal Institute of Natural Sciences, Naples), which expressed very positive opinions and highlighted that mineral resources were generally underexploited and poorly valued, in part due to a complete lack of geological knowledge of the area (Marcelli, 2006).

Concerning rock salt production, the naturalist and geologist Giuseppe Melograni (1750–1827) published a detailed report of his field trip of 1811, rich in geological and geographical observations, technical descriptions, surveys and practical recommendations for modern and rational mining activity (Melograni, 1822). Again in 1811, Marquis Giuseppe de Turris, an administrator very close to Murat, commissioned Pietro Pulli, Inspector General of the ammunition, gun powder and saltpeter production of the Kingdom of Naples, to provide information on the economic and social conditions of the Altomonte-Lungro salt mine (Pulli, 1813, 1817).



**Fig. 6. Geometrical survey (horizontal plane) of the underground works of the salt mine of Altomonte-Lungro, made in 1811–1814 (Melograni, 1822; <https://www.biodiversitylibrary.org/item/35424#page/390/mode/1up>)**

In the early 1800's, the salt mass of Altomonte-Lungro was mined by large chambers and irregular tunnels, forming 3 to 4 superimposed levels. Rock and salt excavation were performed by hand with pickaxes, as well as salt transportation to the surface, by means of bags carried on the backs of the miners, up to 40 kg per bag. Access to the underground was granted via a single inclined tunnel, by more than 1000 steps cut in the salt mass. Melograni also visited the Altomonte-Lungro mine in 1814, and proposed carrying out wall and roof reinforcements in various sections of the tunnels, widening the critical underground passages, as well as rationalizing rock cutting to correspond with the salt mass under exploitation and improve safety for the workers. He also proposed the excavation of a vertical shaft, connected to a horizontal passageway to facilitate ventilation and water drainage (Melograni, 1822). He drew a modern topographical sketch of the mine, although limited to the access tunnel and without indicating the survey methods. From a historical and cartographic standpoint, this document is among the first rational planimetric representations of an Italian mining site, apparently based on instrumental measurements of angles and distances (Fig. 6).

The technical improvements proposed by Melograni were not approved. A few years later, Thomas Hallam, an English entrepreneur owner of numerous steam spinning mills for silk production in Villa San Giovanni (province of Reggio di Calabria), was called to inspect the mine. He modified Melograni's project, downsizing it, especially in the vertical shaft and drainage tunnel configuration, but this project was also not approved. Only in 1823 did Inspector Gabriele Lamannis receive approval, and so the Royal Corps of engineers was entrusted to perform detailed external topographical surveys to design and plan the excavation of the vertical shaft.

Gregorio Galli, official of the Royal Corps of Engineers (*Real Corpo del Genio*) and native to Calabria, was sent to Lungro in January 1825. He wrote a detailed report of the internal and external geometry of the mine (Galli, 1828). His report includes accurate leveling, numbering and measurement of the main key points, referenced on a new map (Fig. 7). He also carried out a survey of the mine on the vertical plane, and drew a detailed cross-section (Fig. 8). The leveling was necessary to plan and design the shaft to cross an existing tunnel, midway to the deepest point of the mine, in order to improve ventilation. However, water drainage problems would not have been fully resolved, since the deeper horizontal passageway construction was not approved.

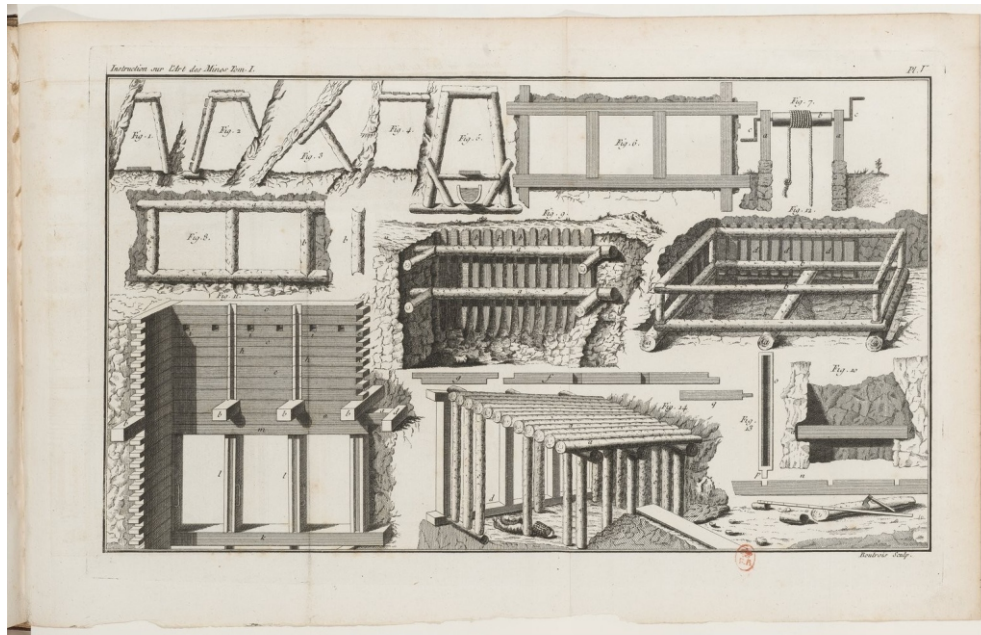
After one month of topographic measurements and surveys, on 5 March 1825 the excavation of the shaft began. Galli also supported the mine director during its construction: he knew the *boisage perdu* technique described by Delius (1778), and probably the shaft much resembled this configuration (Fig. 9). The shaft had a square section 2 m wide; ventilation was achieved with an external double-box bellows. The shaft reached precisely the programmed point, the roof of the *Sopracielo* chamber, on 13 September 1827, at a depth of 300 Neapolitan palms (80 m). The excavation work lasted 2 years and 6 months, less than 10 cm per day of excavation rate. During the construction, a stairway with wood ladders and an external manual winch was installed to lift the debris with canvas bags. This shaft was then known as "Galli's shaft". Unfortunately, in the next 50 years it was used only for ventilation: in fact, the winch and the stairway, useful as an alternative safety passage to the underground works, were removed soon after its construction (Sole, 1981).



Fig. 7. Geometry (horizontal plane) of the underground works of the Altomonte-Lungro salt mine; survey performed in 1824; the colours indicate the different levels of the mine (Galli, 1828)



Fig. 8. Geometry (vertical cross-section) of the underground works of the of the Altomonte-Lungro salt mine; survey performed in 1824 (Galli, 1828)



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**Fig. 9. Scheme of shaft excavation and wall reinforcement by Delius' *boisage perdu* technique, quoted by Galli (1828): the first modern shaft excavated from 1825 to 1827 in the Altomonte-Lungro mine probably greatly resembled this configuration (Delius, 1778)**

In the mid-19th century, the mine, with its four production levels, a ventilation shaft and a large but messy tunneling network, was the most important industrial enterprise and the greatest concentration of workers in Calabria, with over 400 miners plus technical and administrative staff, and related industries, a number comparable only to the steam spinning mills of Villa San Giovanni. The revolutionary movements of 1848 also reached Calabria, and led to more or less violent occupations of croplands and to local riots against taxes. In May 1848 the extreme poverty pushed the laborers to also occupy the Lungro mine, to exploit it independently. Only military force put an end to the occupation (Basile, 1960).

In 1879 Torquato Taramelli (1845–1922), professor of mineralogy and geology at the University of Pavia, was on a field trip to Calabria. He visited Lungro almost by chance and very quickly, reporting stratigraphic and palaeontological observations of the surrounding formations, both still largely unknown at the time. However, his report contains also first-hand descriptions of the working conditions he saw inside the mine. The miners, “tireless and patient like ants, go up and down in double row about 1500 steps, naked, out of breath, panting, and go back up carrying at least 40 kg of salt on their backs... On the top of the main shaft I saw a hoist, but it did not work. Backpacking is cheaper, and those people do not earn more than a lira a day” (Taramelli, 1880).

After 1880, the mine director Giovanni Bellavite further improved the conditions of the mine, which was about to be closed due to poor ventilation. In 1883 he completed a new shaft 3 m in diameter and 120 m deep (out of the originally planned 250 m), which connected most of the internal levels of the mine, solving ventilation problems. The shaft was also equipped with a steam hoist, with a nominal installed power of 10 HP. He also promoted the use of compressed air underground. Only a decade earlier, in 1871, the use of black powder for tunneling had been introduced, which on one hand reduced excavation times and significantly increased production, while on the other aggravated underground ventilation problems once again (Bellavite, 1884).

At the beginning of 1900, the final decline of the mine began. The government assessed that sea salt produced in Sicily was cheaper than rock salt; at the time, the Italian government owned not less than 10 saltworks for the production of sea salt. Here, the “slow death” technique was used, *i.e.* ever-decreasing mine exploitation until all the workers retired, without layoffs but without hiring. Miners’ access to the underground was never solved: even in the 1970s, two out of eight working hours of the daily shift were lost in going up and down, as there were over 2000 steps to walk. Overall, in the Altomonte-Lungro mine, only basic mining methods and poor design and planning were adopted until the end of the 20th century, until its final abandonment in 1978.

#### SOLUTION MINING AND ENVIRONMENTAL ISSUES AT TIMPA DEL SALTO MINE

In the last decades of the 20th century, solution mining started also in the territory of Belvedere di Spinello (Timpa del Salto mine), ~100 km south of Lungro. In this area, many salt mines survived until the first half of the 19th century, when the Bourbon administration decided for their abandonment because they were considered fiscally uncontrollable and no longer necessary for the needs of the Kingdom. The salt mines of this area had been known and exploited since the Middle Ages (“Salinella di Neto mine” near Altilia, “Basilico mine” near Cerenzia and the nearby “Zinga mine”, etc.), still existing and visited by Melograni (Melograni, 1822).

Mining operations resumed only in 1967 when the “Timpa del Salto” concession was assigned to the then largest Italian mining and chemical company (Montecatini Edison). The Timpa del Salto mine started production in 1969, adopting the solution mining technique, with doublets of wells, *i.e.*, one well for the injection of fresh water and one well for the production of brine. Each pair of wells were connected by hydraulic fracturing at the bottom of the salt layer. On average, the depth of the wells was ~400 to 600 m, drilled through a salt mass over 200 m thick (Gisotti, 1992). The brine was transported with a 40 km



**Fig. 10. Timpa del Salto mine: sinkhole no. 1, collapsed in April 1984 (Gisotti, 1992)**

pipeline to the Cirò Marina purification plant. High-purity salt production (99.96% NaCl) was about one million tons per year, and it was primarily used for feeding the chloralkali process at Marghera Plant, near Venice, owned by the same company. Indeed, the Cirò Marina plant included an offshore loading facility (a massive pipeline laid on a dedicated jetty, both recently dismantled) for shipping salt on commercial ships.

Salt production in the northern area of the Timpa del Salto mine continued until 1984, creating a number of underground voids filled with brine. With this method, when the dissolution reaches the top of the salt layer, the overlying rocks normally collapse, developing a sinkhole, whose severity and time evolution depends on the mechanical characteristics of the deposits, the size of the underground voids and the rock thickness above. Such method was revealed as unsafe and inadequate for this site. A first sinkhole reached the surface in 1983, with very minor damage due to the small volume of brine involved. One year later a very large sinkhole (50–120 m) and a triggered landslide collapsed on 25 April 1984, causing a large flood of brine to the surface, estimated at about 100,000 m<sup>3</sup> (Fig. 10). The brine invaded the surrounding irrigation canals and polluted 150 hectares of olive and citrus groves. A month before the event, macroscopic cracks and fissures had appeared on the ground, which were not related to the underground voids induced in the mine. A total of five sinkholes reached the topographic surface (Roda and Martelli, 2006).

Three years after the mining accident, notwithstanding environmental issues and the fierce opposition of the local stakeholders, the Italian administration authorized the continuation of the mining operations, imposing the abandonment of the northern area, the adoption of single wells with a double pipe technique (an outer pipe for fresh water injection and an inner pipe

for brine production), but only in the southern area of the mine, and the adoption of a monitoring network for the control of ground deformation. However, further assessments of the delicate environmental issues led to the gradual interruption of the activities of both the Timpa del Salto mine and the refining plant in Cirò Marina, that ended production in 2009.

## SALT MINING IN SICILY

### SALT (AND SULPHUR) IN THE 19TH CENTURY

Salt and sulphur in Sicily have been mined since immemorial times. Concerning sulphur mining, not discussed in this paper, extremely complex social, political, technological and economic issues characterized mining in the 18th and 19th century in southern Italy (kingdom of Naples, that included Sicily, which in 1816 merged into the kingdom of the Two Sicilies). The 1919 report of the Corps of mines states: "The number of mines existing in Sicily amount to over 1300, of which 1274 are sulphur mines. Since most of them are of very limited importance, or in such conditions that they cannot be mined profitably, it was deemed appropriate to indicate in this list only those which are presumed susceptible to long and useful exploitation" (Ministero dell'Agricoltura, 1921).

The proliferation of sulphur mines in Sicily was largely due to the juridical principle of land ownership confirmed by Ferdinand of Bourbon (Law no. 46 on the exploration and excavation of the kingdom's mines, Naples, 17 October 1826) which essentially left a free hand to the landowners of large estates, through the extension of ownership to the subsoil. Moreover, very close links existed between the sulphur industry and the

agricultural sector, in which cereals and sulphur were the expression of the same economic system, nourished by common networks of commercial exchanges and social relations, by the same models of production and work organization and by similar contractual procedures. The political system that underpinned the organization of croplands and mines materialized in the identification of the “Prince of wheat” as the owner of the sulphur mines.

However, the Sicilian sulphur industry of the late 19th and early 20th century managed to play an important economic role, not only locally, but also on a global scale. The first Italian technical institute for mining was founded in Caltanissetta in 1862 by Sebastiano Mottura (1831–1897); here superintendents and specialists were trained to increase the technical level of local mines. In the first decade of 1900 Sicily held the sulphur monopoly, with a production of over 90% of the world’s sulphur market, mainly used by the chemical industry for the production of sulphuric acid ( $H_2SO_4$ ). From a production of a few thousand tons at the beginning of the 19th century, with around 500 mines, it rose to over half a million tons at the end of 1800, with around 1000 active mines and 40,000 employees (Squarzina, 1963; Barone, 2002). In 1894, the German-born American chemist Herman Frasch successfully tested a new method to produce sulphur in Louisiana, by drilling wells for injecting superheated water into underground deposits to melt the sulphur, and lifting the mixture of liquid sulphur and water to the surface by means of compressed air. This process eliminated all the dangerous and expensive underground mining operations and inefficient and polluting surface refining processes. Moreover, from the early 20th century, pyrite production (mainly from Tuscany) gradually replaced sulphur as a raw material for the production of sulphuric acid. After WW2, traditional sulphur mining lost its predominant role in the supply chain of this commodity, and all Italian sulphur mines ceased their activity between 1960 and 1980.

As far as rock salt is concerned, alongside its geological history in common with that of sulphur, there is a fundamental aspect that distinguishes the mining of this commodity. In Sicily, the excavation of rock salt was allowed for everyone for their own use, upon authorization of the land owner, and no tax was imposed on this salt. This principle also applied to the coastal salt pans: “Contrary to the rest of the kingdom of Italy, in Sicily there is no legal restriction regarding the production and trade of salt” (Jervis, 1881). It is worth recalling that salt tax is one of the oldest tax levies. Since ancient times, State monopolies developed with the aim of controlling prices, regulating the revenues of intermediaries and subjecting them to taxation. In ancient Rome, salt was such a precious commodity that soldiers were paid with it, hence the term “salary”, still used today. After Italian unification (1861), the law 1862/710 on the monopoly of salt (and tobacco) established a new tariff on the price of salt and tobacco, conceived as an indirect tax on consumption. A few years later, the law 1865/2397 established that the production, storage and trade of salt was an exclusive right of the State monopoly, whose administration also managed salt extraction sites and supervised the related industrial and trading facilities. This was valid only in the territory subject to the monopoly, i.e., all of Italy with the exception of Sicily and Sardinia (Moncada, 1940).

Therefore, after 1861 the salt mines of Sicily were again not subjected to a State monopoly, similarly to the previous Bourbon administration. In this period, rock salt was mined and produced only for local uses, and at many sites. William Paget Jervis (1832–1906), a British mining engineer and naturalized Italian listed and described more than ten official mines, most of them underground, although at shallow depths (Jervis, 1881). He cited three mines in the territory of Racalmuto (Pantanelli, Giona and Sacchitello), in which black powder was necessary

for tunnelling through very hard massive rock salt, and the Petralia Soprana mine, likely the first large underground rock salt mine in Sicily, with its dedicated inclined mining tunnel to access the underground. A few decades later, many of the deposits indicated above would prove to be very important, but still underexploited; in early 1900 most of the rock salt production came from the mines of Racalmuto and Cammarata. From 1870 to 2019 the official records of the Italian Corps of mines and of the Regional offices reported 55 underground mining concessions for the production of rock salt and potash in Sicily. Here, the system of public ownership of the subsoil came into full force only after Royal Decree no. 1443 of 1927. Before this date (Ministero dell’Agricoltura, 1921), about 15 salt mines had been operated by right of ownership, and were subject to concession only after 1927.

#### MODERN UNDERGROUND SALT MINING

In 1960 in Sicily there were 36 active concessions for salt mining. In the following decades this number decreased due to a complete reorganization of the sector. Today, three large underground mines are active (Realmonte, Racalmuto and Petralia) and operated by Italkali with state-of-the art technology. Common features of these mines are: a) access to the underground by large-section truck-accessible ramps; b) adoption of room-and-pillar mining technology; c) completely mechanized salt production; d) food-grade rock salt produced by continuous miners, i.e., special mining machines driven by electric motors to avoid salt contamination; e) use of dumpers with stainless steel dump boxes; f) rock salt crushing, optical sorting (if necessary), grinding and screening performed in underground facilities.

The Realmonte mine produces over 1.5 million tons of salt per year; so far, it features more than 70 km of truck-accessible tunnels. Inside, a salt cathedral accessible by bus down to a depth of ~100 m was excavated in the 1980s, which can accommodate up to 800 people and contains several works of art carved in salt (Fig. 11). The Realmonte deposit contains significant reserves of kainite and carnallite exploited in recent decades, but now (2024) on hold.

The Racalmuto mine produces ~0.2 million tons per year; so far, it features more than 60 km of truck-accessible tunnels, down to a depth of ~100 m. It produces both food-grade and industrial-grade salt (Fig. 12).

The Petralia mine produces over 0.7 million tons per year; so far, it features more than 50 km of truck-accessible tunnels and 9 underground levels down to 400 m below the surface. Here, the entire chain of food-grade salt production is carried out underground, without any manipulation or chemical treatment. The salt is transported to the surface already packaged and ready for the final market (Fig. 13).

Numerous geological exploration campaigns were carried out in Sicily in the second half of the 20th century, obtaining increasing detail on mineral resources (rock salt, sulphur, oil and gas, etc.) thanks in part to the new tools of geophysics and deep drilling. This exploration also highlighted the presence of potash deposits, associated and interbedded with the rock salt, some of which are characterized by a sufficient volume to justify economic exploitation. Before 1970, at least seven potash deposits were identified (Castaldo and Stampanoni, 1975). The most important one was exploited by the Pasquasia mine, first licensed for sulphur (1919 to 1931) and then for potash (1959 to 1992). Initially, the mine exploited a layer of sylvite ( $KCl\cdot NaCl$ ) and carnallite ( $KCl\cdot MgCl_2\cdot 6H_2O$ ) and later the deeper layers of kainite ( $MgSO_4\cdot KCl\cdot 3H_2O$ ). The production of kainite peaked ~1.35 million tons per year in 1988, and the mine was equipped with the necessary mineral processing facilities (kainite selective flotation, potassium sulphate production, etc.).



Fig. 11. Realmonte mine: the underground rock-salt cathedral (photo credits: Paolo Macini)



Fig. 12. Racalmuto mine: typical truck-accessible tunnel (<https://italkali.com/photo-gallery/>)



Fig. 13. Petralia mine: continuous miner machine for food-grade salt production (<https://italkali.com/photo-gallery/>)

Pasquasia was one of the most modern Italian mines of the time, and used state-of-the-art mining technology: continuous miners, drilling machines, front loaders, dumpers, automatic conveyor belts, etc. The mine adopted a rational room-and-pillar mining system; a helicoidal ramp 1800 m long connected the underground levels to the surface. Four ventilation and extraction large diameter shafts (6 m) were also constructed, the deepest of which reached a depth of ~1000 m.

## CONCLUSIONS

The modern Italian mining activity, before and after the Industrial Revolution, encompassed the exploitation of a large number of small mineral deposits. However, in some cases, especially in the rock salt production sector, mining was significant not only for the temporal continuity of mining operations, sometimes dating back to Etruscan or even prehistoric times, but also for the social relationships of the nearby population and the development of particular taxation regimes and specific administrative, production and trading systems. A coexistence of extremely complex social, political, technological, and economic issues characterized salt mining, such as workforce organization (employment vs. migration), long-debated child labour issues, salt monopoly, salary conditions, feudal privileges, safety of underground working conditions, trade union struggles, etc.

In Italy, at the end of the 15th century, most of the Italian metalliferous mines were abandoned, and the country remained substantially poorly exploited until the first half of the 19th century, when intensive mining activity resumed in Tuscany, Sicily, Sardinia and Romagna, especially after the unification of Italy, and as a consequence too of the need for new materials, metals and energy for the newborn state.

Our paper outlines the historical development of the most important Italian rock salt production sites and the evolution of geological knowledge and mining technologies used in different geographical contexts. Exploited since antiquity as an indispensable commodity for daily life, salt production in Italy greatly increased in the late 19th and early 20th century, due to the growing demand for salt (NaCl, sodium chloride) for the chemical industry, primarily as a raw material for producing soda ( $\text{Na}_2\text{CO}_3$ , sodium carbonate), chlorine and other chemicals. At present, the production of salt in Italy (from food-grade to industrial-grade), include a few coastal salt pans, one solution mining site in Tuscany (Saline di Volterra) and three underground mines in Sicily (Realmonte, Racalmuto and Petralia).

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