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# Literature & Geosciences: Jules Verne's geological novels, from the 19th to the 21st century

## *Littérature & Géosciences : Les romans géologiques de Jules Verne, du XIX$^{e}$ au XXI$^{e}$ siècle*

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**Abstract.** A friend of both François Arago, who founded the *Comptes Rendus de l'Académie des Sciences*, and his brother Jacques, a renowned traveler, Jules Verne (1828–1905) wrote many novels in which his heroes made use of the most recent scientific knowledge of the time. While the novelist only really had a legal background, he did keep himself apprised of all the latest scientific developments. This study, based on a selection of novels wherein geology is very present as well as on contemporary or current scientific publications, shows that today's understanding of the geosciences does indeed agree with Jules Verne's extrapolations. Among the subjects developed are: coal extraction and the hazards of firedamp, so-called "mud volcanoes" and the special case of gold trickling from volcanoes, diamond geo-genesis, the creation of an inland sea in the Sahara, and a foretelling of the Anthropocene Epoch.

**Résumé.** Ami de François Arago, le fondateur des *Comptes Rendus de l'Académie des Sciences*, et de son frère Jacques, un grand voyageur, Jules Verne (1828–1905) a écrit de nombreux romans dans lesquels ses héros utilisent les connaissances scientifiques les plus récentes de l'époque. En effet le romancier, s'il n'avait qu'une formation juridique, se tenait informé des développements de la science. Dans cette étude, basée d'une part sur un choix de romans où la géologie est très présente, et d'autre part sur des publications scientifiques contemporaines ou actuelles, on montre que les géosciences d'aujourd'hui sont en accord avec les extrapolations de Jules Verne. Parmi les sujets développés, citons : l'extraction du charbon et les risques de grisou, les volcans dits « de boue » et le cas particulier de l'or qui s'écoule de certains volcans, la géo-genèse des diamants, la création d'une mer intérieure dans le Sahara, et une prédiction de l'époque Anthropocène.

**Keywords.** History of geology, Diamond formation, Gold formation, Coal formation, Volcanism, Anthropocene.

**Mots-clés.** Histoire de la géologie, Formation des diamants, Formation de l'or, Formation du charbon, Volcanisme, Anthropocène.

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## 1. Introduction

As recalled on the website of the *Comptes Rendus Géoscience* (https://comptes-rendus.academie-sciences.fr/geoscience/page/politique-revue_fr/#historique, accessed March 28, 2022), this scientific journal is one of the current byproducts of the famous *Comptes-Rendus hebdomadaires des séances de l'Académie des Sciences* (hereafter abbreviated as *CRAS*), created in 1835 by François Arago, and whose first volume reported the session of Monday August 3, 1835.

François Arago, physicist, astronomer and statesman, was the eldest child of a family of eight from Estagel in the Pyrénées-Orientales Department (France). He and his brother Jacques, an explorer and writer, were tremendous sources of inspiration for Jules Verne (1828–1905), whose series of novels published under the name of *Voyages extraordinaires* (*Extraordinary Voyages*) often showcased the science of his time, as well as its potential extensions. Let's not overlook, however, that Jules Verne had no formal scientific training (he had studied law and was initially oriented towards a career as a stage writer), yet he had amassed a considerable library, rich in scientific books and travelogues [Burgaud, 1994, Dehs, 2011]. Moreover, throughout his life, Jules Verne regularly read numerous geographical and popular science magazines, from which he recorded notes for future books [Robin, 2005]. He also joined the "Société de Géographie de Paris" in 1865 (just as *Cinq semaines en ballon*, his first novel, was published) and remained a member until 1898, when the trip from Amiens to Paris had become too tiring [Dupuy, 2011].

This article will review and highlight a number of geological sources of Jules Verne's novels—especially from the *CRAS*—and then examine the present developments of some of the topics of scientific knowledge he had selected.

Unless otherwise indicated, the citations offered herein have been extracted from Jules Verne's texts in their version published by Hetzel (Paris) at the date indicated, as an *in*-8° volume, now freely available on the B.N.F.'s *Gallica* site (https://gallica.bnf.fr); references will be made to the parts and chapters (given in Roman numerals) of the novels, as denoted by their abbreviation. All quotes and excerpts have been translated by the author.

## 2. The Arago brothers and Jules Verne

Raised in a well-to-do peasant family with eight children, including two girls, each of the family's six sons had an extraordinary destiny [Sarda, 2002, Jacques, 2017, 2018].

Jean (1788–1836) took part in the Mexican War of Independence (1810–1821), where he was joined by his brother Joseph (1796–1860); they inspired one of the first manuscripts by the young writer Jules Verne, *Un drame au Mexique* (1863 and 1876), initially published in a magazine under the title *Les premiers navires de la marine mexicaine* (1851). Victor (1792–1867), a graduate of the prestigious Polytechnic School, had a rather discreet military career. Étienne (1802–1892), a literary scholar and politician, would as Minister of the Post Office enact the use of postage stamp; he went on to become Paris' first mayor in 1870. A friend of Alexandre Dumas the father, he directed the Théâtre du Vaudeville from 1829 to 1839.

François Arago (1786–1853) was an astronomer at the Paris Observatory, an academician, and a member of Parliament from 1831 to 1852. During his scientific and political life, he was interested in numerous projects, which not only did he support but also overlapped with the future writings of Jules Verne. Let's cite here, in no specific order, and without attempting to be exhaustive: popular astronomy (popularization teachings from 1813 to 1846); lighting of maritime lighthouses (Cordouan, Gironde estuary); modifications to the Seine River course; water quality improvements necessary to the health and hygiene of Parisians. As an "ecologist" before his time, he was concerned by deforestation and wondered about the Earth's "thermometric state" [Sarda, 2002]. As for implementation of the railroad, he emphasized its dangers while appreciating its advantages in expanding travel possibilities. In 1806, he participated in the expedition in charge of measuring the Earth's meridian in Spain and the Balearic Islands [Cartwright, 2001], which inspired Jules Verne to write the *Aventures de trois Russes et de trois Anglais* (1872) and was also referenced in *Hector Servadac* (1877, a.k.a. *Off on a Comet*; hereafter abridged as *HS*), whereby Professor Palmyrin Rosette "resolved to verify again [these] measurements" since he "claimed that the first geodesic operations were marred by inaccuracies" (*HS*: II, IV). François Arago supported Daguerre's work, which predated photography, and campaigned to impose the reliance on French manufacturing, especially for scientific equipment. Appointed in 1848 as Minister of the Navy and the Colonies of the Second Republic, François Arago would, along with Victor Schoelcher, spearhead the abolition of slavery. In May–June 1848, he was appointed Head of State presiding over events that ended in bloody repression, thereby tarnishing his reputation forever.

Jacques Arago (1790–1854), draftsman and writer, is most famous for his travels: in hot-air balloons, on steamships, on the first railway lines. He explored the Mediterranean, the Orient, Africa, in addition to a world tour from 1817 to 1820 on the corvette *L'Uranie*. He would describe it in an 1839 book, *Souvenirs d'un aveugle—Voyage autour du monde* ("Memories of a blind man—Journey around the world"); indeed, his early blindness (from 1837, at the age of 47) did not prevent him from continuing his travels, and he actually died in Brazil.

At home, the Arago brothers encountered many notable figures from Paris' political and cultural scene, as well as from the scientific and literary world. It was at their home in 1850 that the young Jules Verne (only 22 years old at the time), then a stockbroker teased by the muse of writing, met explorers and scientists who would, directly or indirectly, be the source of some of his subjects and novel characters. Jules Verne's scientific library, as reconstructed by specialists, contained the complete works of François Arago (17 volumes, highly technical), yet Jacques' travel accounts do not seem to have been included [Dehs, 2011]. Some excerpts of the contents of his library have indeed been reported in his novels [Burgaud, 1994], and the explicit citations of Arago's name (16 times, between 1865 and 1896) have been listed [Dupuy, 2011].

## 3. *Voyage au Centre de la Terre*: pure and applied geology, and the beginnings of life on Earth

While uncommon for writers, Jules Verne shares with Goethe the eminent honor of having his name attached to a mineral species: goethite and verneite, respectively.

In the case of J. W. Goethe (1749–1832), German writer, jurist and politician, but also scientist and more specifically geologist, the *goethite* species is an iron(III) (oxy)hydroxide of the formula $\alpha$-Fe(O)OH [Mitchell, 1981]; it is one of the components of natural ochres and widely used as a pigment (natural or synthetic). Goethite has a strong affinity for the adsorption of many chemical compounds in solution, such as arsenic, metal cations and (oxy)anions, or various organic compounds (including natural organic matter) [Liu et al., 2014]. Moreover, let's recall that in his novel *Die Wahlverwandtschaften*, Goethe applied the then fashionable theory of chemical interactions, i.e. of "elective affinities", to feelings of love [Goethe, 1809].

As for *verneite*, which is a calcium sodium alumino-fluoride $Na_2Ca_3Al_2F_{14}$, its name seemed obvious to Danish and Italian geologists [Balić-Žunić et al., 2018], who characterized it in fumarole deposits from the volcanoes Hekla (Iceland) and Vesuvius (Italy). As they themselves recalled, this dual location could only evoke Jules Verne's heroes in *Voyage au centre de la Terre* (1864, *Journey to the Center of the Earth*; hereafter abridged as *VCT*), who started out from Snæffels, an extinct volcano in Iceland, and wound up at Stromboli, an active volcano in Italy! This mineral of varied origins has the same crystal structure as a synthetic sample [Courbion and Ferey, 1988].

Snæffels continues to be of interest to scholars of ancient volcanoes in glacier-covered areas. While clearly referencing the novel, researchers thus conducted and analyzed a map of this site to discuss its surficial geology as well as glacial geomorphology [Evans et al., 2016]. The geology of Snaefellsjökull is quite complex and characterized by a sequence of medium alkaline basalts and peralkaline rhyolites. The existence of the ice cover, with a present surface area of 12.5 km$^2$, is thought to be related to the climatic conditions of the "Little Ice Age" and thus stabilized since the Holocene epoch; it includes an outer zone of ice-penetrated moraines, in front of which lies a set of pumice deposits, all likely constituting a record of the poly-thermal conditions of the period. Other specialists had already drawn attention to this site, whose study has made it possible to trace a link between the episodes of volcanism and deglaciation in Iceland [Hardarson and Fitton, 1991]. The decrease in pressure in the magmatic mantle, caused by the disappearance of part of the ice, would be sufficient to modify the composition of magma around Snaefellsjökull. A comparison of the compositions of basaltic rocks from different ice ages has shown that those from the late glacial period, ejected during rapid climatic changes, differ significantly from those of the older post-glacial periods, as a result of melting of the magmatic mantle under the continent.

However, the field of human sciences is also interested in the volcanoes so dear to Jules Verne [Picot, 1994]. More specifically, the *geocritical method*, introduced in 1999 by Westphal, needed to be applied to Verne's novels, since this method of literary analysis studies geographical space and its representations in texts [Westphal, 2011]. This application was recently performed, yielding in particular the contrast between the two volcanic sites constituting the entrance and exit of the heroes' underground journey. Though two volcanoes, each located on an island, are indeed involved, one lies in a cold, uninhabited and barren area (*VCT*: xv-xvi), while the other lies in an agricultural region with a mild and sunny climate (*VCT*: xliv). Moreover, the study's author insists on the dual and symmetrical nature of each of them [Simon, 2020].

It is accurate to say that *VCT* is an iconic "geological novel" in the body of work of Jules Verne [Harkness, 2012] and one whose relationship to the science of his time has been discussed in great detail by Breyer and Butcher [2003]. These authors pointed to numerous borrowings from several classical geological texts of the time, including those of Figuier [1864], but also to some original insights.

More recently, this novel of underground explorations has been reconciled with current research strategies employed in the field of geothermal energy [Gross, 2015]. Yet through a combination of experiments, analyses and modeling, geochemical cycles involving the dehydrogenation of goethite Fe(O)OH to $FeO_2$ (an oxide with the same structure as pyrite $FeS_2$, very stable at high temperature and pressure) have been shown to control the redox equilibria of the Earth's deep mantle in the vicinity of its liquid iron core [Graziano, 2017, Hu et al., 2016, 2017].

Other researchers had already insisted on Jules Verne's marked and constant interest in both islands [Compère, 1977] and volcanoes [Picot, 1994]; therefore, *L'Île Mystérieuse* (1874–1875, *The Mysterious Island*; hereafter abridged as *ÎM*) is of special interest. In this novel, a violent storm sweeps a balloon carrying the heroes to a relatively small island: "the shoreline of the island [would have] a perimeter of more than one hundred miles" and here Jules Verne specified in a note: "About 45 leagues of 4 kilometers per league". As for its surface area: "That is difficult to estimate [...] because it is so capriciously indented" (*ÎM*: I, xi). But moreover, it is something like a geological "chimera": to an implausible extent, the island concentrates on its territory granite and lava, tuffs, sea sands, lakes, and rivers, ... and even a volcano (*ÎM*: I, x and xi), whose awakening would cause the end of the adventure (*ÎM*: II, xv–xix).

What is also of interest for our stated purpose is the mineralogical wealth of the soil and subsoil:

> Cyrus Smith took some small samples of different minerals from his pocket and contentedly said:
>
> "My friends, here is iron ore, here is pyrite, here is clay, here is lime, and here is coal. This is what nature gives us as its contributions to our efforts. Tomorrow we will do our share". (*ÎM*: I, xii).

Thus, the castaways were able to reconstitute, little by little, all the basic industrial products: candles, soap, pottery, window glass, iron, and steel...:

> This metal was not in the state of pure iron, especially that state of steel giving the best service. Now, steel is a combination of iron and carbon derived either from cast iron by removing the excess carbon or from iron by adding the carbon it lacks. [...] the second, produced by the carburation of iron, yields case-hardened steel.
>
> It was this latter method that Cyrus Smith preferred since he possessed iron in its pure state. He succeeded in heating the metal with carbon powder in a crucible made of refractory clay. (*ÎM*: I, xv)

but also, the explosive nitroglycerine (*ÎM*: I, xvii) and even electricity (*ÎM*: II, xviii)!

Though the novel *Voyage au Centre de la Terre* was mainly based on Humphry Davy's geological theory of volcanism [Davy, 1828], as Professor Lidenbrock explained to his nephew Axel (*VCT*: VI and XVII), it was already known at that time that its content was erroneous. However, Jules Verne had always shown a keen interest in the presence of volcanoes as an "actor" in the adventures he wrote [Picot, 1994].

A paleo-anthropological issue arises when his heroes are confronted with not only antediluvian monsters (*VCT*: XXXIII), but also humanoid fossils (*VCT*: XXXVIII). Several scholars [Debus, 2006, Ruddick, 2007, Puech, 2017] have commented on this passage, which is typical of Jules Verne's lack of a clear-cut view of Darwin's ideas on the origin of man, whereas his views seem closer to those of Cuvier and Lamarck.

The origin of life on Earth, which is linked to the presence of water and organic matter, is obviously the subject of many current studies and speculations.

The origin of the Earth's water remains unknown, whether in the oceans and atmosphere or in the rocks and minerals present through the depths of the mantle. Specialists have concluded that meteorites of the enstatite chondrite type contain enough hydrogen to have contributed at least three times the mass of water to the Earth's oceans. These meteorites, which comprise condensed solar nebula gases, have an isotopic composition like that of terrestrial rocks and may therefore be representative of the materials that formed the Earth's mantle [Piani et al., 2020, Peslier, 2020].

The presence of organic matter is also essential for the emergence of life on Earth, which took place about 3.8 Ga ago. These prebiotic organic molecules could have been synthesized abiotically on Earth, for example in iron-bearing sedimentary rocks of hydrothermal systems on the seafloor [Dodd et al., 2017]. Plumes from deep-sea "black smokers" are emissions of sulfide mineral-rich geothermal fluids at temperatures above 360 °C that contain chemolithotrophic microbes; these participate in interactions with surrounding rocks and may help our understanding of the mechanisms of prebiotic organic synthesis [Shock and Schulte, 1998, Sherwood Lollar, 2004]. However, it seems that an extraterrestrial origin is to be privileged: prebiotic organic molecules could also have been synthesized extraterrestrially and then brought to Earth. Electron Paramagnetic Resonance analysis of sediments dating back 3.33 Ga (i.e. from the time of significant volcanic and hydrothermal activity) leads to assuming the precipitation of carbonaceous micrometeorites, deposited in a very calm sea near an island between two volcanic eruptions [Gourier et al., 2019, Gourier and Westall, 2020].

The evolution of life on Earth, coupled with the evolution of organic matter, was able to occur due to a wide variety of freely available energy sources, including geochemical energy, sunlight, oxygen and fire (ignited by thunderstorms or volcanoes, for example). The diversity and complexity of living organisms has led to a concomitant increase in the diversity and complexity of terrestrial organic matter, including organic matter of microbial, plant, pyrotechnic and human origin, which in turn has significantly influenced the Earth's carbon cycle, global climate and overall ecosystems [Sun et al., 2021].

## 4. *Les Indes Noires*: the origin of coal, its exploitation and firedamp

Although coal consumption was still limited at the end of the 17th century (except in England), the need substantially increased with industrial development (blast furnaces for iron and steel—1735; gas for lighting—London, 1807; chemical dyes—1850) and, above all, with the development of transportation driven by the steam engine (locomotive—Stephenson, 1817; paddle-boats, a.k.a. "steam-boats" and propeller-powered ships—1837). In 1926, underground coal reserves in Great Britain were estimated at more than 44 billion tons, while a crisis was looming: underconsumption in some countries (−7% in England), production increases elsewhere, plus competition from other energy sources (oil, fuel oil, electricity) [Levainville, 1926].

The 19th century can be considered as the century of coal, whose production (coke as well as coal gas) allowed for industrial development by providing a vital source of energy. This period ushered in the beginning of the intensification of extractive industries, as recently designated by the word *extractivism*, i.e. "intensification of the massive exploitation of nature, in all its forms". This definition also applies to the case of mining operations, which were abandoned due to unprofitability and then brought back into operation [Bednik, 2016]. Such was indeed the case of the Dochart mine described in the novel *Les Indes Noires* (1877, *The Underground City* or *The Black*

*Indies*; hereafter abridged as *IN*), closed after 150 years of operation (*IN*: I). Thus, the 1851 World's Fair (or "Universal Exhibition") in London did consecrate the "triumph of the mechanical age: on all sides, the primacy of metal and coal is affirmed. [...] The island has indeed become, according to Michelet's expression, a 'block of coal and iron"' [Bédarida, 1991]. The contrast is indeed great between, on the one hand, the site of the factory described at the beginning of the novel (*IN*: IV) and of the underground mine (*passim*) and, on the other, the surrounding countryside that Harry introduces to Nell (*IN*: XVII–XVIII).

Coal is a complex and variable mixture, depending on the place and circumstances of its formation, within which the lignocellulosic compounds of the original plants were degraded, transformed into peat and then progressively into lignite, bitumen and anthracite: "The plant was transformed into mineral" (*IN*: III). This series of maturations (or "coalification") depends on both the nature of the plants and the thermal and microbial conditions in succession over geological time. It also leads to the presence of varying amounts of water, oil and gas in what will be, if mined, the coal seam [Hatcher and Clifford, 1997, Clayton, 1998, Orem and Finkelman, 2003].

The explorers of the underground galleries in *Voyage au centre de la Terre* will see "the whole history of the coal period [that] was written on these dark walls" when they find themselves "in the middle of the coal field". Here again, Jules Verne explained (but more succinctly this time) the formation of "these immense layers of coal" by "the action of natural chemistry" (*VCT*: XX). In *Vingt mille lieues sous les mers* (1869–1870, *Twenty Thousand Leagues Under the Seas*; hereafter abridged as *20ML*), Professor Aronnax and his companions are surprised to find themselves in "underwater coal mines", which constitute for Captain Nemo "an inexhaustible mine": indeed, he "burns this fuel for the manufacture of sodium", subsequently used to assemble his electric batteries (*20ML*: II, X).

The area where the novel is set (Stirling County, Scotland) belonged to the continent Laurasia, which collided with the continent Gondwana around 360 Ma (Lower Carboniferous); the resulting mountain chain is the Variscan (or Hercynian). From 360 Ma, Europe was already part of the Pangea continent, and the tropical climate favored the development of giant fern forests that were later fossilized to form the coalfields, whose age lies between 320 and 300 Ma (Upper Carboniferous) [Faure, 2005]. This sequence resulted in the extensive coal zone (marine-type coal) that starts from the Ruhr Basin in Germany and passes through the French Nord/Pas-de-Calais Basin, which is now closed. The Scottish town of Aberfoyle does exist [Vierne, 1972], even though coal is not being mined there, unlike other places in southern Scotland; however, while no coal is found there, as indicated in an official geological report, slate quarries do still exist [Henderson et al., 1983].

The deleterious health effects of mining often take a long time to develop; these are mainly respiratory diseases, such as silicosis due to inflammation of the lungs by coal dust. In the USA in 2004, 1 in 20 coal miners were still suffering from this condition [Black, 2004]. But it is of course methane that has caused the greatest number of coal mine deaths due to firedamp explosions (*IN*: VII). Methane, $CH_4$, is a colorless and odorless gas; when present in air in proportions ranging from 5% to 15%, an explosive mixture is formed [Karacan et al., 2011], with temperatures capable of exceeding 1000 °C. The triggering spark is often due to electrostatic effects of dust (from coal and/or silicate rocks) [Black, 2004]. James Starr has even specified the following: "firedamp is almost odorless, it is colorless! It only really betrays its presence by the explosion! ... " (*IN*: VII).

Methane is the primary end product, associated with carbon dioxide, of the decomposition of organic matter in lake sediments; moreover, it is derived from a series of hydrolysis reactions of cellulose, proteins, lipids and natural organic matter, with each of the intermediate phases being carried out by specialized groups of bacterial microorganisms [Meslé et al., 2013]. Methane can also be derived from the reduction reaction of otherwise geo-generated $CO_2$ [Thauer, 1998]; however, in the case of coal mines, the most significant source of methane is the thermal decomposition of coal bed kerogen (known as thermogenic), which begins at temperatures around 110 °C in bituminous-grade coals and continues throughout the carbonization process [Clayton, 1998].

Firedamp thus primarily contains methane (80–95%), but also varying proportions of other flammable gases such as ethane (0–8%), propane and higher alkanes (0–4%), as well as nitrogen (2–8%) and carbon dioxide (2.2–6%) [Creedy, 1991]. Coal itself can adsorb methane, ranging from trace to 25 $m^3/t$, with the highest values corresponding to anthracite [Creedy, 1991]. Simon Ford's statements can therefore be better understood: "For me, firedamp was the coal seam"; "No coal, no firedamp! There are no effects without a cause…"; "According to Simon Ford, hydrogen ["protocarbonated hydrogen", i.e. methane] was constantly being released, and one could conclude that some important seam existed" (*IN*: vii). For this reason, he pursued a decisive test: to ignite the gas being released, following which "a light detonation was heard, and a small red flame, a little bluish at its contour, fluttered on the wall" (*IN*: vii). A new vein was thus discovered, which justified the invitation sent at the beginning of the novel to the engineer Starr, so that he would return to the abandoned site (*IN*: i).

To ensure their own lighting, the miners therefore had to use safety lamps, such as the one invented in 1815 by the British chemist Davy [Jensen, 2011], this "good genius" of miners (*IN*: vii). The flame of the oil lamp was enveloped by a metallic cloth which, by decreasing the heating temperature thanks to its conductive power, avoided reaching the ignition temperature of the firedamp (*IN*: iv and vii). To avoid the explosive ignition of "hydrogen protocarbide", Professor Lidenbrock and his companions were equipped for their own lighting with "the ingenious devices of Ruhmkorff" (*VCT*: xi and xx).

The slag heaps resulting from coal mining operations contain on average about 50% coal and 50% mineral material or "waste rock" (i.e. poor in coal, but not "inert"!); their quantity lies on the order of 7% to 10% of the ultimate coal production. Such mining tailings are classified as *technosols*, i.e. soils that are primarily of an engineering origin and contain materials resulting from human activity [Park et al., 2017]. These tailings can be reintroduced into the mine after (full or partial) coal extraction, which will reduce the environmental risks associated with a slag heap dam failure. However, the Dochart pit, once mining was complete, should have been progressively filled with water, or better yet voluntarily flooded in order to limit access and the risk of explosions.

However, the presence of water in contact with fractured rocks, often rich in sulfide ores such as pyrite $FeS_2$, provokes an oxidation reaction (which also involves microorganisms) forming sulfuric acid [Banks and Banks, 2001]:

$$2FeS_{2(s)} + 7O_{2(g)} + 2H_2O_{(l)} \rightarrow 2Fe^{2+} + 4SO_4^{2-} + 4H^+.$$

This phenomenon, well known to mining operators, is called acid mine drainage (AMD); it can lead to very high acid concentrations, with pH values of between 0 and 1 (or even negative values!), and thus to very corrosive solutions [Nordstrom et al., 2000]. Furthermore, AMDs are saline aqueous solutions, rich in dissolved toxic elements (arsenic and metallic elements such as lead, cadmium and mercury). Their discharge from the mine site can then cause significant pollution of the surrounding soils and watercourses, in particular deposits of ochres, which are iron(III) (oxy)hydroxides $Fe(O)OH_{(s)}$ formed by oxidation in the open air [Banks and Banks, 2001]. Flooding does not completely eliminate the circulation of methane, which subsequently assumes a dissolved rather than gaseous form; nor does it eliminate the associated risks.

When groundwater from an abandoned coal mine needs to be pumped out, its high salinity can become an environmental problem because of its toxicity to freshwater aquatic species. A study was conducted at the Ibbenbüren anthracite mine site (Germany), which has been in operation since 1564 and from which a total of about 240 million tons of anthracite have been extracted. The purpose of this study was to examine the individual water–rock interaction processes that cause the overall chemical composition of the AMD solutions. This step is indeed essential to accurately predict the future long-term evolution of water quality [Rinder et al., 2020]. The collected samples were analyzed for their major element and trace element compositions, as well as the isotopic ratios of S and O in sulfates, and O and H in waters. According to this study, the various types of water are the result of water–rock interactions, migration and mixing of various fluids. Pyrite oxidation is the dominant source of sulfate in shallow mine drainage, and in groundwater with low ionic strength ($I < 0.035$). In all cases, modern meteoric waters are the primary source of water for brines, groundwater and mine drainage [Rinder et al., 2020].

To determine whether metal and/or metalloid-rich primary solid phases (such as pyrite) continue to persist in the excavated minerals of old abandoned coal mines, solid-phase analyses of soil samples were collected from the vicinity of a former mine site in Ohio (USA), where underground coal mining began in the 1830s. Thereafter, the factors potentially limiting oxidative dissolution could be identified [Singer et al., 2020]. Regardless of the sampling depth, all soils contained metal (or metalloid) sulfide particles with secondary minerals on their surface, often as heterogeneous aggregates composed of clay minerals and secondary Fe(III) (oxy)hydroxides. Within these aggregates, sulfur was present as very small phases, identified as sulfides of Fe and other trace metals/metalloids (Cu, Se and Zn); furthermore, As(III), As(V) and S(VI) were associated with secondary Fe(III) (oxy)hydroxides. These results indicate that pyrite and other metal sulfides are still present in these soils, which developed on the remains of this historic coal mine, even several decades after deposition of the waste [Singer et al., 2020], hence the importance of taking these results into account for the long-term management of such a site.

The Yulin site (Shaanxi Province, China) is undoubtedly one of the largest coal mines in the world: an area of 7053 km$^2$, 54% of which contains coal mined in hundreds of open-pit mines of various sizes, corresponding to an estimated reserve of $6.94 \times 10^{12}$ tons, or about one-fifth of the national reserve. Yet mine water production affects the region's water regime in various ways: disruption of the natural water resource cycle, lowering of the water table, and pollution of both surface and groundwater [Wang et al., 2018]. In order to assess the environmental risks (water quality and human health impacts), comprehensive analyses of potentially toxic ions and metals were conducted on 19 surface water samples: three lake waters and 16 river waters, plus five samples collected from residents' taps [Zhou et al., 2020]. Using Piper diagrams, among other tools, it was shown that the composition of surface waters is influenced by rock weathering; moreover, the presence of metal elements (while remaining below carcinogenic risk thresholds) is directly correlated with both mining and coal combustion.

## 5. *Kéraban-le-têtu*: the "mud volcanoes", a curiosity

When Lord *Kéraban-le-têtu* (1883, *The Headstrong Turk*, a.k.a. *Keraban the Inflexible*; hereafter abridged as *KT*), out of stubbornness, led his friends on a hazardous journey around the Black Sea, Jules Verne offered many descriptions of cities, landscapes and considerable information about physical and political geography (which is not the subject of the present study). But let's check in with the travelers positioned in front of a surprising phenomenon, namely small eruption cones, from which:

> gaseous and bituminous sources escape, effectively designated as "mud volcanoes", although volcanic action does not intervene in any way in the production of the phenomenon. It is only a mixture of mud, gypsum, limestone, pyrite, and even oil, which, under the pressure of carbonaceous hydrogen gas [i.e. methane $CH_4$], sometimes phosphorous hydrogen [i.e. phosphine $PH_3$, whose pyrogenic properties lead to the appearance of will-o'-the-wisps: see Roels and Verstraete, 2001], escapes with a certain violence. This tumescence, which rises little by little, becomes discouraged to let the eruptive matter escape, and then collapse, at which time these tertiary grounds of the peninsula emptied themselves within a more or less long space of time.
>
> The hydrogen gas, which is produced under these conditions, is due to the slow but permanent decomposition of oil, mixed with these various substances. The rock walls, in which it is contained, end up breaking under the action of water, rainwater or spring water, whose infiltrations are continuous. Then, the effusion is made, as it has been very well said, in the manner of a bottle filled with a foamy liquid, which the elasticity of the gas empties completely. (*KT*: I, xv).

It should be noted that this information, given by the novelist, is not completely contradicted by recent studies of these mud volcanoes [Dimitrov, 2002, Mazzini and Etiope, 2017].

These details, very precise and scientific, are certainly not solely from the pen of Jules Verne! He probably extracted them from various documents he had read, in magazines or works in his library. In particular, the "muddy eruptions or mud volcanoes" of the Taman peninsula, described by Édouard de Verneuil after his trip in the summer of 1836 [Verneuil, 1836, 1837], must have caught his attention. The latter cited an observation made by a third party, according to which "gases with an odor of bitumen and sulfur were constantly given off, and at intervals one could even see jets of flame", and then he added his own observations:

> the mud was soft and unctuous to the touch and had no flavor; but the already hardened cracks were covered with whitish efflorescence, which had a saline flavor, and there was a strong odor of bitumen.
>
> The fragments of rock rejected by the volcanoes attracted our attention [...]; they are ferruginous rocks, argilloid, compact and as if burned, sometimes with the appearance of petrosilex; marly and clayey shales of a brownish gray with impressions of indeterminable plants, carbonated iron hardpans, sandstones usually very hard, harsh to the touch, species of quartzite, and finally soft sandstones with calcareous cement [Verneuil, 1837].

As Jules Verne also specified, this was in fact a very common phenomenon in the region: "These cones of dejections open in great numbers on the surface of the Taman peninsula, and they are also found on the similar terrain of the Kertsch peninsula" (*KT*: I, xv), which was also on the border between the Black Sea and the Sea of Azov. Mount Karabatov is especially famous there, and thus still studied today, as regards the tectonic causes of these phenomena [Sobissevitch et al., 2008, Ovsyuchenko et al., 2017]. A multiscale analysis of remote sensing and morphometric data from different origins, years, scales and resolutions has enabled studying landscapes in the vicinity of mud volcanoes in the central–northern stretch of the Taman Peninsula [Skrypitsyna et al., 2020].

According to a statistical analysis based on 533 earthquakes that have occurred since 1832 in the South Caspian Sea region (Azerbaijan) and 220 mud volcanoes in the same region, a correlation can be established (weakly probable, however) between the activity of mud volcanoes and earthquakes: mud volcanoes would appear between zero and five years before the earthquake [Bagirov et al., 1996].

Mud volcanoes mainly occur in sedimentary basins rich in hydrocarbons (natural gas, oil) and can be used to predict their presence (for purposes of exploitation), yet they are also a source of danger for populations living in their vicinity. In general, mud volcanoes are the source of strong releases of gases included in their sediments, especially methane (along with various hydrocarbons). The following values have been cited for the average composition of gases emitted by the mud volcanoes of the Kerch and Taman peninsulas: 56–84% $CH_4$, 13–42% $CO_2$, 1.5–3.5% $N_2$, 0.5–3.5% other hydrocarbons, plus traces of $H_2S$ [Dimitrov, 2002]. Let's note therefore an inversion with respect to the gases emitted by the magmatic *ignivomous* volcanoes, i.e. richer in $CO_2$ and less rich in $CH_4$. On the whole, mud volcanoes would contribute 25–30% of the total amount of geologically derived atmospheric $CH_4$ [as cited in Mazzini and Etiope, 2017].

The gases emitted, often violently, can ignite spontaneously; however, most mud volcanoes evolve quietly, with only the production of semi-liquid materials, referred to as muds or breccias. Their height can range from a few meters to 400 m, and the area occupied by the solidified emitted muds can extend 100 $km^2$, in assuming various shapes.

The geochemistry of these structures has recently been discussed, along with that of other structures by Mazzini and Etiope [2017]. The breccia is composed of a matrix of clay or shale mud (up to 99% of the total volume), which includes a variable amount of rock fragments, angular to rounded, with a diameter ranging from a few millimeters to a few meters. Originating from rocks traversed by the mud on its way to the surface, these fragments may be of different lithological types and stem from various stratigraphic horizons. As for the composition of the water discharged, it in fact corresponds to a mixture of waters from the various sedimentary zones crossed; these waters may have reacted with one another or with the rocks in contact. Moreover, strong seasonal variations can be observed (e.g. dilution by rainfall).

## 6. *Le Volcan d'or*: a volcano that spits out gold, novelist's invention or reality?

In a posthumous novel, entitled *Le Volcan d'or* (1906, *The Golden Volcano*; hereafter abridged as *VO*), Jules Verne evokes the existence of "a volcano which contains an immense quantity of gold… Yes! a gold volcano… the Golden Mount… […] in the north of the Klondike… a volcano whose next eruption will throw gold nuggets… whose slag is gold dust…" (*VO*: II, II). In fact, the version published in 1906 had been extensively modified by Michel Verne (1861–1925), the novelist's son, who added characters and events; however, Jules Verne's original manuscript was eventually found and published for the first time in 1989; it is from this original version [Verne, 1999] therefore that the following citations have been drawn.

After having exploited, with mixed success, their gold claim by means of classical methods (*VO*: I, XIV), the heroes of the novel learn of the existence of this Golden Mount, where they are headed: "It was in this crater that he [the prospector who informed them] had noted the presence of gold-bearing quartz, nuggets and gold powder which formed like soot from this chimney" and the author added: "As for the gold powder, it was found on the outskirts of the crater, mixed with the layer of lavic ashes" (*VO*: II, VII). As the eruption that should have produced nuggets and gold powder was delayed, the impatient heroes decided to provoke it, by allowing the water of the Rubber Creek, a nearby river, penetrate "the bowels of the volcano" (*VO*: II, VIII); this feat would not prove to be as easy as expected. When the explosion finally occurred: "Accumulated rocks, lava, ash [fell] into the Arctic Ocean" (*VO*: II, XIII), and thus all the hoped-for gold had disappeared!

Even if the content of this novel may seem totally implausible, the presence of gold in volcanic lava has been documented in various places. For example, Jules Verne may have heard about the Galeras Volcano (located in the volcanic chain of the Andes, in southern Colombia), which notably experienced a sizable eruption in 1866. This volcano has had at least 50 eruptive periods in the last 500 years, each one lasting a few years, with an average recurrence of roughly 60 years and with episodes ranging from the emission of fumaroles to violent explosions. Since the end of the 1980s, Galeras Volcano has experienced a resurgence of activity, hence the motivation of specialists to install measuring instruments [Seidl et al., 2003] in order to both better monitor its evolution and output a real-time evaluation of the potential dangers for the nearby population (80,000, across several neighboring localities).

Through a series of analyses of the solids produced by Galeras Volcano, it has been shown that the solidified andesite and magmatic volatiles contained gold at levels of approx. 0.015 mg/kg and 0.04 mg/kg, respectively. The hydrothermal environment of the rocks surrounding the magmatic conduit is of the "high-sulfidation" type with acid sulfates or alunite–kaolinite mixtures, and where magmatic water is the primary fluid. The conditions would thus be favorable for the deposition of metals such as Au and Cu. Therefore, it is quite possible, according to the authors, that a deposit of gold-bearing enargite had been formed during the evolution of this volcanic system [Goff et al., 1994]. Moreover, these authors calculated, on the basis of the gaseous $SO_2$ releases and $SO_4$ contents of the acid sources in the vicinity, that Galeras Volcano releases 0.5 kg of gold into the atmosphere each day, while depositing more than 0.06 kg in the volcanic edifice (i.e. here >20 kg/year)!

However, other types of volcanoes emit gold particles as well. Hence, the presence of crystalline gold particles has been characterized in the plume near the crater of Mount Erebus (Ross Island, Antarctica), as well as in ambient air at distances of up to 1000 km [Meeker et al., 1991]. The gold would circulate here in the form of a gaseous chloride species. Nonetheless, crystals of native Au, from 3 to 40 μm in size and of various shapes, have been found in a fumarolic vent at 800 °C in the Colima Volcano (Mexico), with a concentration of 0.1 to 0.5 μg/kg in the gas condensate [Taran et al., 2000]. Thermodynamic calculations have made it possible, on the basis of reasonable assumptions, to model the volcanic gas system and thus show that the vapor transports gold in the form of $AuH_{(g)}$ and $AuS_{(g)}$ species which, as a result of their mixing with air, oxidize to $Au_{(g)}$ for subsequent deposit.

Such thermodynamic modeling to characterize the mobility of gold in magmatic fluids has also been developed in the special case of porphyry copper deposits, which are known to be rich in gold. The authors have also established the distribution of Au in brines and vapors, which can carry the chemical forms of gold. Their calculations [Gammons and Williams-Jones, 1997] demonstrate that the transport of gold in magmatic fluids can take place in the form of either a chloride complex $AuCl_2^-$ or a sulfide complex $Au(HS)_2^-$, depending on temperature, pressure and especially the chemical composition of the solution. It should be pointed out however that gold can also co-precipitate with copper.

In Papua New Guinea, on the island of Lihir, one of the largest gold deposits in the world can be found, with nearly 1300 tons! This is the Ladolam hydrothermal system, whose deep chloro-sulfate geothermal brine of magmatic origin (neutral to slightly alkaline pH; 5 to 10 wt% NaCl equivalent) contains 13 to 16 parts per billion (p.p.b.) of gold [Simmons and Brown, 2006, Heinrich, 2006]. Given the current gold flow rate of 24 kg/year, this deposit could have formed over 55,000 years.

In another posthumous novel, also heavily modified by Michel Verne and whose original manuscript was recently found and published, two competing astronomers set out on *La Chasse au météore* (1908, *The Meteor Hunt*; hereafter abridged as *CM*). "This bolide is made of gold, pure gold" (*CM*: IX) [Verne, 2004], which is totally improbable and moreover it should have crashed on Earth! However, in another novel, published earlier and clearly presented as an unrealistic fantasy resulting from the collision between Earth and a comet, the heroes were carried into space on an asteroid that they would learn is made of "a gold telluride, a compound which is frequently found on Earth, and in this one, if there is seventy percent tellurium, I estimate that there is thirty percent gold!" (*HS*: II, VIII). Characterized as "calaverite" [Genth, 1868, Hillebrand, 1895], this gold telluride $AuTe_2$ is an ore found in different parts of the world, including Australia, USA, China and Russia [Carnot, 1901, Lenher, 1902, Zhang and Mao, 1995, Vikent'eva et al., 2020]. Naturally, it is mostly used as a resource for gold, e.g. after hydrothermal treatment [Zhao et al., 2010, Zhao and Pring, 2019].

## 7. *L'Étoile du Sud*: natural and synthetic diamonds

In the 1810s, Humphry Davy sought to better understand the nature of diamonds; he went on to highlight, after others (including Tennant and Lavoisier), the analogy between diamonds and coal, but in different crystalline forms. In particular, he compared the combustion products of these two forms of carbon, in the aim of producing synthetic diamonds [Siegfried, 1966].

Several very comprehensive developments [Shirey et al., 2013, Howell et al., 2020] have revealed that diamonds are something like "time capsules" [the term used by Menzies, 1988] that have recorded, in their inclusions and carbon isotopic signatures, the state of the fluids deep in the Earth's mantle at the time of their formation.

In a little-known novel, *L'Étoile du Sud* (1884, *The Southern Star*; hereafter abridged as *ES*), Jules Verne described the pursuit of a stolen diamond, after its synthesis by Cyprien Méré, a French geologist working in the South African mines. The geology of the South African diamond fields had already been sufficiently characterized to be the subject, as early as 1871, of a review, which however was mainly a compilation without discussion [Jones, 1871]. It was completed by certain information on the hypotheses forwarded at the time as to the origin of these diamonds.

Thermodynamic modeling and speciation calculations of geochemical systems (based on the combination of reaction equilibrium constants) are well known in the case of environmental systems: lakes, rivers, but also soils and wastes [Dick, 2019, Araujo et al., 2020]. For example, in the present case, it can be shown [Huizenga et al., 2012] that the reaction:

$$CH_4 + O_2 \rightarrow C_{diam} + 2H_2O$$

derived by the hero of the novel, between "swamp gas" (methane) and oxygen, in a tube ("an out-of-service cannon segment") closed at both ends and subjected to "intense heat" (*ES*: VIII) would, under conditions of high temperature and pressure, allow for diamonds to precipitate as may happen during oxidation of the lithospheric mantle (which is usually in a reduced state).

Cyprien Méré described his "beautiful theory of adamantine formations" (*ES*; XX) using these words: "The only explanation which satisfies [him], if not completely, at least to some extent, is that of the transport by the waters of the elements of the gem, and the subsequent formation of the crystal in situ" (*ES*: III). Furthermore, "diamond could well be formed [...] in the same way as sulfur in solfataras" and thus "diamond deposits [could be considered as] true carbonatars" (*ES*: VIII). Note that this passage of the text has in fact been extracted, nearly word for word, in a summary written by Figuier [1866] from a submission made by de Chancourtois in the *CRAS* dated July 1866 [de Chancourtois, 1866]. As such, it was therefore not really written by Jules Verne! But this theory prefigures what Wilhelm Ostwald would name a little later [Ostwald, 1900, Hulett, 1901] a "ripening", now known under the name of "Ostwald ripening" of crystallization seeds, applicable to crystals and precipitates: in a supersaturated solution, the largest crystals grow to the detriment of the smallest, which dissolve simultaneously [Steefel and van Cappellen, 1990].

After many adventures, Cyprien Méré arrived in "the marvelous cave", where he discovered a universe of shimmering gems: "He found himself transported to one of these mysterious reservoirs, the existence of which he had suspected for so long, at the bottom of which stingy nature was able to hoard and crystallize these precious gems in blocks [...]. It was [...] diamond, ruby, sapphire that this immense crypt contained" (*ES*: XIX). While such hypotheses may seem unrealistic, recent discoveries substantiate Jules Verne and his hero, hence de Chancourtois as well.

Indeed, such scenarios of diamond formation are now recognized [Nestola and Smyth, 2016]. More specifically, from its detailed analysis, the mineral included in a Brazilian diamond has been identified [Pearson et al., 2014] as ringwoodite $(Mg,Fe)_2SiO_4$; subsequently, by relying in particular on thermodynamic stability considerations, the authors assumed that the presence of large amounts of water (in the range of 1.4–2.5% in this mineral formed at great depths: between 410 and 660 km) had to play a key role in diamond genesis. A commentary, associated with this study, evokes the existence of a significant amount of water (in the form of OH groups in minerals) deep in the primitive Earth, whose volume (estimated at $1.4 \times 10^{21}$ kg of water) would then be equivalent to the sum of current oceanic masses [Keppler, 2014]! According to this same author, such a water volume could have constituted an interior ocean like the one described in *VCT*.

Moreover, other thermodynamic calculations indicate the possible role of the chemistry of aqueous fluids present in contact with solids at depth, here eclogite at 900 °C and 5.0 GPa [Sverjensky and Huang, 2015]; diamonds could also form under the influence of a pH drop associated with interactions between water and silicate rocks. Precipitation could have thus ensued (but also dissolution, under the same chemical conditions for fluids in contact with rocks, within the depths of the Earth), even without modification of the redox conditions of the environment. Organic species (formate, propionate) would be involved, and not just $CO_2$ or $CH_4$. Let's note that these predictions, as modeled for the evolution of fluid chemistry during diamond formation by pH drop, at constant oxygen fugacity are in good agreement with the analysis of fluid inclusions in various diamonds from different parts of the world [Sverjensky and Huang, 2015]. However, it should be kept in mind that under this type of calculation, the reaction kinetics have not been considered, which may prove to be important in the case of reactions involving solid mineral phases.

## 8. *L'Invasion de la mer*: a permanent sea or ephemeral lakes in southern Tunisia?

The myth of the existence of an inland sea in southern Tunisia had been evoked since Antiquity, most notably in texts by Herodotus or Ptolemy. Yet it would take until the mid-19th century for the project to revive this myth to be undertaken by the French: based on studies that were sometimes misinterpreted, a military man, Elie Roudaire, supported by Ferdinand de Lesseps (already famous for digging the Suez Canal in 1869) sought to persuade politicians and financiers [Roudaire, 1874, Rouire, 1884, Charles-Roux and Goby, 1957, Létolle and Bendjoudi, 1997, Bendjoudi and Létolle, 1999]. Such a project was bound to seduce Jules Verne, an admirer of F. de Lesseps; consequently, he made it the plot of a novel, set in 1934: *L'Invasion de la mer* (1905, *Invasion of the Sea*; hereafter abridged as *IMer*). This work was the last to be published during his lifetime [Picot, 2004].

This project targeted the region of Chott el Djerid, as explained in detail in the novel by the engineer M. de Schaller, in a chapter appropriately entitled "The inland sea". This "grandiose enterprise, as happy as patriotic", is therefore "the project of a Saharan sea that would be fed by the waters of the Gulf of Gabes". Jules Verne echoes (through the words of the engineer) the positive arguments forwarded by Roudaire:

> In the first place, the climate of Algeria and Tunisia would be improved

> in a notable way. Under the action of the southern winds, the clouds formed by the vapors of the new sea would be resolved in beneficial rains on the whole region for the benefit of its agricultural yield. Moreover, these depressions of the Tunisian sebkha of Djerid and Fedjedj, of the Algerian chotts of Rharsa and Melrir, currently marshy, would be cleaned up under the deep layer of permanent water. After these physical improvements, what commercial gains would not be made in this region transformed by the hand of man? Roudaire rightly put forward these last reasons: it is that the region at the south of the Aurès and the Atlas would be provided with new roads, where the security of caravans would find more serious conditions, it is that trade, thanks to a merchant fleet, would develop in all this region whose depressions prohibited access until now, it is that the troops, put in a position to disembark south of Biskra, would ensure tranquility by increasing French influence in this part of Africa. (*IMer*: IV).

But he also pointed out the criticism that "the depressions could never be filled. [...] the salty water of the Saharan Sea would seep through the soil of the neighboring oases and rising to the surface by a natural effect of capillarity, would destroy the vast plantations of date palms which are the wealth of the country. [...] the waters of the sea would never reach the depressions, and [...] they would evaporate daily through the canal." (*IMer*: IV). Not to mention the opposition of the Tuaregs, the indigenous populations who would then see "the annihilation of several oases" as well as "the ruin in short order for the [Tuareg] tribes living from piracy and plunder." [*IMer*: V—see also Pandolfi, 2019].

This project and the corresponding scientific polemic, in particular between E. Roudaire and A. Pomel or E. Cosson, have been published in the *CRAS* [see the references cited by Ben Ouezdou, 1989, Létolle and Bendjoudi, 1997, Bendjoudi and Létolle, 1999]. Though Jules Verne's novel ends with an unexpected twist, the "hypothesis of the Quaternary Saharan Sea" continues to interest specialists, who now agree on the more realistic existence of ephemeral lakes [Ben Ouezdou, 1989].

During their exploration trip, M. de Schaller and his escort observed that:

> the chott presented well the aspect of these saline lakes, which dry up in summer under the action of the tropical heats. But a part of the liquid layer, dragged under the sands, rejects the gases which charge it, and the ground bristles with blisters which make it resemble a field sown with molehills; as for the bottom of this chott, [...] it consisted of red quartz sand mixed with lime sulfate and carbonate. This layer was covered with efflorescences of sodium sulfate and sodium chloride, a real salt crust. Moreover, the pliocene ground where the chotts and the sebkha meet provides by itself the gypsum and the salt in abundance. (*IMer*: VIII).

Let's point out that the presence of gypsum, rather than salt, shows these deposits not to be of marine origin, which should have been noticed during the original discussions! The highly significant evaporation, during the dry season (May to August), of rainwater from the wet season indeed gives rise to major areas of evaporite formation, which can be characterized (composition, spatial and temporal evolution) thanks to modern Landsat-type satellite techniques [Abbas et al., 2018]. The precipitation sequences of the various species depend not only on the initial composition of the solution, but also on its interactions with soils and aquifers, specifically through ion exchange and precipitation/dissolution mechanisms. Chemical analyses of groundwater in the "Plio-Quaternary" aquifer of this region of Chott el Djerid have revealed, based on saturation indices and geochemical modeling, that its composition is mainly due to the dissolution of evaporites ($MgSO_4$, $Na_2SO_4$, NaCl and $MgCl_2$) and the precipitation of carbonates (calcite $CaCO_3$ and dolomite $CaMg(CO_3)_2$) [Kamel et al., 2008, Kamel, 2013, Salhi et al., 2019].

As for the rains of exceptional intensity, they are in fact not so rare: the case of the meteorological event of January 1990 has been extensively documented [Ben Ouezdou et al., 1990, Bryant et al., 1994]. After two consecutive years of drought, the amount of rainfall, low but continuous for three days, had an intensity up to 50 times the monthly average, or four times the annual average, thus resulting in significant runoff, more than two-thirds of which occurred in closed depressions. Consequently, a short-lived saline lake was created on the Chott el Djerid. However, after 10 months in this arid climate, the lake completely evaporated. According to thermodynamic and geochemical predictions, gypsum ($CaSO_4 \cdot 2H_2O$) and halite (NaCl) were the main minerals formed by precipitation, while the remaining brines were saturated in sylvite (KCl).

While the Saharan inland sea was thus merely a mirage, the Chotts region even to this day generates lots of interest; in 2008, the Tunisian government sought to have the Chott el Djerid added to the "UNESCO World Heritage List" (https://whc.unesco.org/fr/listesindicatives/5385/, accessed on March 28, 2022) but unsuccessfully, so it seems. However, inspired by the historical projects of the 19th century (yet without citing the novel by Jules Verne), researchers have modeled the possible influence of the artificial creation of a permanent lake on the Chott el Djerid [Fathalli et al., 2020]. While recalling the absence of any official project on this topic, they evoked the pumping of sea water from the Gulf of Gabes! For this purpose, they compared the climatic changes between current conditions and those resulting from the presence, on-site in its actual configuration, of a shallow lake with an area of about 1600 $km^2$. According to their conclusions, the influence of the creation of such a lake would basically be limited to an increase in winter nighttime temperature above the surface and a decrease in summer daytime temperature; in addition, they predicted a 280% increase in average rainfall above the lake during winter.

The recent succession since the 1970s of exceptionally dry periods (sometimes over several consecutive years) and exceptionally wet periods has caused significant variations in local agricultural production (olives, cereals, citrus fruits, etc.) and, therefore, difficulties for their operators [Ben Abdelmalek and Nouiri, 2020]. For this reason, greater interest has been focused on the possibilities of geo-engineering to (re)green the Sahara [Pausata et al., 2020]. In the meantime, the exploitation of new mineral resources could be considered, such as the extraction of uranium present in the groundwater of the Chotts region [Dhaoui et al., 2016] and lithium precipitating in the brines of the evaporites of eastern Algeria [Zatout et al., 2020].

## 9. Did Jules Verne foresee the beginning of the Anthropocene Epoch?

In addition to providing a key update on damage to the marine environment [Duarte et al., 2020], with proposals for improving the state of the fauna, flora and waters, Duarte and Krause-Jensen [2020] published a "Commentary" based directly on Jules Verne's vision laid out in his novel *Vingt mille lieues sous les mers* published 150 years prior. While scholars of Verne will not be surprised by the contents of this article, nor by the numerous excerpts quoted, the authors correctly remind us that the novelist (here through the voice of Captain Nemo) was already worried about the overexploitation of the oceans—and more generally of the planet's natural resources. Let's not overlook that the time when Jules Verne wrote his novels corresponds to the onset of the "Industrial Revolution" and to humanity's entry into what will be defined as a new geological era called "Anthropocene", a period in the history of planet Earth when human actions become a destabilizing geological force [Crutzen, 2002a,b, Zetzsch, 2021, Barnosky et al., 2014, Bonneuil and Fressoz, 2017].

Consequently, coal stocks were long considered inexhaustible: for example, in 1839, it was estimated that Britain's current needs could be supplied for another 1340 years (!), whereas, as early as the 1820s, due to the depletion and closure of some mines, the country had to make more reasonable assessments of exploitable reserves [Bonneuil and Fressoz, 2017]. This is exactly what Jules Verne wrote at the beginning of his novel, where he explained the situation in England as well as the origin of the denomination "*Indes Noires*" (i.e. "Black Indies"): "consumption had increased so much during these last years, that certain layers had been exhausted down to their thinnest seams. [...] This was precisely the case of the Aberfoyle coalfields" (*IN*: I). This excessive consumption (*IN*: III) and its certain exhaustion over the more or less long term would make Harry regret "that the whole globe was not composed only of coal!" (*IN*: IV). In the *Voyage au centre de la Terre* as well, Verne had already noted "an excessive consumption [which risks] exhausting [the reserves] in less than three centuries" (*VCT*: XX). Then, in *L'Île Mystérieuse*, he returned to the fact that "this coal, which can rightly be called the most precious of minerals" is now termed a "non-renewable energy resource", and he predicted that there would still be enough for only "at least two hundred and fifty or three hundred years". He then envisaged its replacement as a source of energy from the oxygen and hydrogen produced by the decomposition of water, "because finally without coal, no more machines, and without machines, no more railways, no more steamships, no more factories, no more anything that the progress of modern life requires!" (*ÎM*: II, XI).

But Jules Verne also envisaged, on several occasions, carrying out drastic modifications of the planet, by implementing what one now refers to as *geo-engineering*. However, these proposals were accompanied by warnings, even frank criticisms.

For example, during a dialogue with the engineer M. de Schaller, Captain Hardigan evoked certain aspects of the "progress" expected by the creation of the Saharan Sea:

> "[...] as far as I am concerned, I am not angry to [...] visit one last time [this part of the Djerid] before it has been transformed! Will it gain with the change? ...
>
> - [...] soon you will find the animation of the commercial life there where still meet only the solitudes of the desert...
> - What had its charm, my dear companion...
> - Yes... if however, the abandonment and the emptiness can charm...
> - "A spirit like yours, no doubt," replied Captain Hardigan, "but who knows if the old and faithful admirers of nature will not regret these transformations that the human race imposes upon her!"...
> - Well, my dear Hardigan, don't complain too much, because if the whole Sahara had been still of a lower level than the Mediterranean, be sure that we would have transformed it into an ocean from the Gulf of Gabes to the Atlantic Coast! as it must have existed in certain geological periods.
> - Decidedly, declared the smiling officer, modern engineers do not respect anything anymore! If we let them, they would fill the seas with mountains and our globe would be a smooth and polished ball like an ostrich's egg, suitably arranged for the establishment of railroads!"
>
> And we can take it for granted that, during the few weeks of their journey through the Djerid, the engineer and the officer would not see things in the same light; but they would be no fewer good friends. (*IMer*: VI).

In *Hector Servadac*, a previously published novel, Verne claimed that this creation was already a done deal: "At that time and although for a long time this enterprise had been renounced—the new Saharan sea had been created thanks to French influence." (*HS*: I, XI). In a footnote, he added: "Amazed by the success of the Saharan Sea, created by Captain Roudaire, and not wanting to be outdone by France, England founded an Australian Sea in the center of Australia." (*HS*: I, XIII).

As for the protagonists of *Sans dessus dessous* (1889, *Topsy-Turvy* or *The Purchase of the North Pole*; hereafter abridged as *SDD*), they simply proposed to modify the Earth's climate by moving its axis of rotation! This was to counteract the possible depletion of available coal resources, and thus of derived industrial products (*SDD*: VII). The retired Gun-Club artillerymen, who had previously sent a manned cannonball to the Moon in the twin novels *De la Terre à la Lune* (1865, *From the Earth to the Moon*) and *Autour de la Lune* (1870, *Around the Moon*), first created a company to obtain the concession of the Arctic domain, as duly and officially acquired. In the adjudication clauses, it was explicitly foreseen: "modifications of any nature whatsoever [which] would occur in the geographical and meteorological state of the globe" (*SDD*: I). Hence, should they propose to exploit the coal mines of the North Pole (whose existence is presumed here), this continent would be "obstructed by eternal ice, covered with icebergs and icefields, and in conditions where the exploitation would be difficult" (*SDD*: VII). Consequently, the project to displace the earth's axis of rotation by use of a gigantic cannon specially built at Kilimanjaro: "This displacement of twenty-three degrees twenty-eight minutes will be sufficient to [produce] a quantity of heat sufficient to melt the ice accumulated for thousands of centuries!" (*SDD*: VII). However, the consequences would obviously be dramatic for many other regions: the climatic modifications would, depending on the case, be desertification or floods, cooling or heat waves (*SDD*: XV and XVI). As previously stated for the repurchase of Arctic lands, nobody worried "about the Eskimos, the Chukchi, the Samoyeds! They were not even consulted. [§] Thus goes the world!" (*SDD*: I). The operation was also supposed to make "the Earth more hygienically habitable, and also more productive, since one will be able to sow as soon as one has harvested, and that, the grain germinating without delay, there will be no more time lost in winter. [...] the climatic conditions of our globe will have been transformed to its advantage" (*SDD*: VIII). Fortunately, this project failed, although it seemed to make a resurgence in 2008 [Gagneux, 2010]!

## 10. Conclusion

Shortly after the initial successes of Jules Verne's novels, Pierre-Jules Hetzel, his publisher, wrote what was both a program and a manifesto of the future content of the *Voyages extraordinaires*, in which we should note the explicit reference to both the *CRAS* and François Arago:

> What is promised so often and what is delivered so rarely, instruction that is entertaining and entertainment that instructs, M. Verne gives both unsparingly in each one of his exciting narratives.
>
> The novels of M. Jules Verne have moreover arrived at the perfect time. When one sees the general public hastening to scientific lectures given all over France and that, in the newspapers, art and theatre columns are making way for articles on the proceedings of the Academy of Science, one must conclude that Art for Art's Sake is no longer enough for our era. The time has come for Science to take its place in the realm of Literature.
>
> The merit of M. Jules Verne is to have, boldly and masterfully, taken the first steps into this uncharted land and to have had the unique honor of a well-known scientist say of his works: "These novels will not only entertain you like the best of Alexandre Dumas but will also educate you like the books of François Arago."
>
> [...] [M. Verne] chose as [...] sub-title [to his works]: "*Voyages in Known and Unknown Worlds*." The goal of the series is, in fact, to outline all the *geographical*, *geological*, *physical* and *astronomical* knowledge amassed by modern science and to recount, in an entertaining and picturesque format that is his own, the history of the universe [Hetzel, 1866; the four fields of knowledge were underscored by himself. Translated by Evans, 1988].

We can then witness that this initial program has been perfectly fulfilled, and Jules Verne has also proposed a modern and realistic vision of the environment, an essential component of geosciences.

## Conflicts of interest

The author has no competing interest to declare.

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