https://www.science-climat-energie.be/2024/02/08/lislande-l-ile-de-tous-les-dangers/

Iceland, the island of danger

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Brigitte Van Vliet-Lanoë, Directeur de recherche CNRS, Emérite, Brest, France
Alain Préat, Prof. Emérite, Université Libre de Bruxelles

Main topic : Iceland attracts tourists as much as it does scientists tasked with forecasting the significant natural hazards inherent in its unique geological context. There's not a week goes by when Iceland doesn't feature prominently in the media, and even more so today with the evacuation of the population on 11 November following the awakening of the volcano at Grindavik, 40km southwest of Reykjavik. The current eruption has been forecast since 21 July 2023, and was activated in December and on 14 January 2024. This is neither the first nor the last time that volcanism has made or will make news. Grindavik is not the only eruption underway: between 40 and 50 of the 1,330 known volcanoes on Earth are erupting at any one time. This eruptive activity is accompanied by 'disastrous' effects such as frequent earthquakes, sulphur and ash aerosols, sub-glacial melting of the ice caps, glacio-isostatic discharges, and uplift... Yes, Iceland is under close survey... because it is located on an active hot spot.

Laki or 'Lakagigar' is a volcanic system in the graben across Iceland. Colossal fissure eruption in 1783-1784 with lava flows up to 60 km long, ash projection and SO_2 emission

1. Basic geology

Iceland is a volcanic island well known for its volcanic eruptions and high geothermal gradient. It is one of the best studied, strategically located at the heart of the North Atlantic Ocean, under the influence of marine currents such as the temperate Irminger flows and the North Atlantic drift, on the one hand, and the cold currents of the East Greenland and its NE Icelandic drift, on the other (Van Vliet-Lanoë et al., 2021). It is therefore a key area for understanding climate change in the North Atlantic.

The island is linked to several determining geological factors that are still at work today. The first is associated with a powerful magmatic upwelling, a *hotspot* (also shown here), and the second is linked to the fault systems of the Gakkel oceanic rift, to the north of the Kara platform (Grachev, 2003 ; Chamov et al., 2019), which is connected to the mid-ocean Atlantic rift that separates America from Eurasia. This hotspot allows the rocks of the Earth's abnormally hot mantle to rise into the asthenosphere with partial melting of the surface part of the mantle. The result is the production of large quantities of magma that has fuelled Icelandic volcanism for probably 55 Ma (Chazot et al., 2017). This magma production is partly related to the energy of the tides (tidal control) that affect our planet (see 2.2 below).

The whole was initially formed by the break-up of the supercontinent Pangea from the south 200 Ma ago ((SCE, 2018) and the opening of the North Atlantic accompanied by volcanic emissions from 65 Ma (effective opening of the Fram Strait at the end of the Eocene). Iceland occupies a special place in this context, as it is located on the ridge (Figures 1 to 4), which opened up and separated the European and American plates, gradually migrating over the hot spot (Figure 4 and here). This situation is at the origin of an abnormally high production of basaltic magma, so that at this point the oceanic ridge is outcropping on land, unlike its average depth of 2,500 m in the Atlantic (Chazot, 2020). This ridge is at the origin of several volcanic zones linked to the south and north by two transform fault zones (West and East volcanic zones, Figure 1) (Bergerat et Angelier, 1999). These zones are still seismically active, with several hundred earthquakes a week.

The widening of the ridge that joins the two plates has allowed magma to be injected from time to time, generating volcanic eruptions in the air, under the sea or in the sub-glacial zone (e.g. the Bardarbunga volcano (sub-glacial), the Eldfell volcano (underwater eruption, etc., with more than 200 craters including around 130 active volcanoes, see the list here). This magmatic activity is expressed by a very high geothermal gradient (>150°C/km instead of 25 to 30°C/km in most parts of the world). This activity is also accompanied by the emission of numerous hot springs located on faults, geysers on land or on the ocean floor, and hydrothermal vents associated with submarine volcanoes. This heat flow extends as far as Greenland due to the almost 300 km height/depth and more than 100 km extension of the hot spot (Figure 4) (Wolfe et al., 1997).

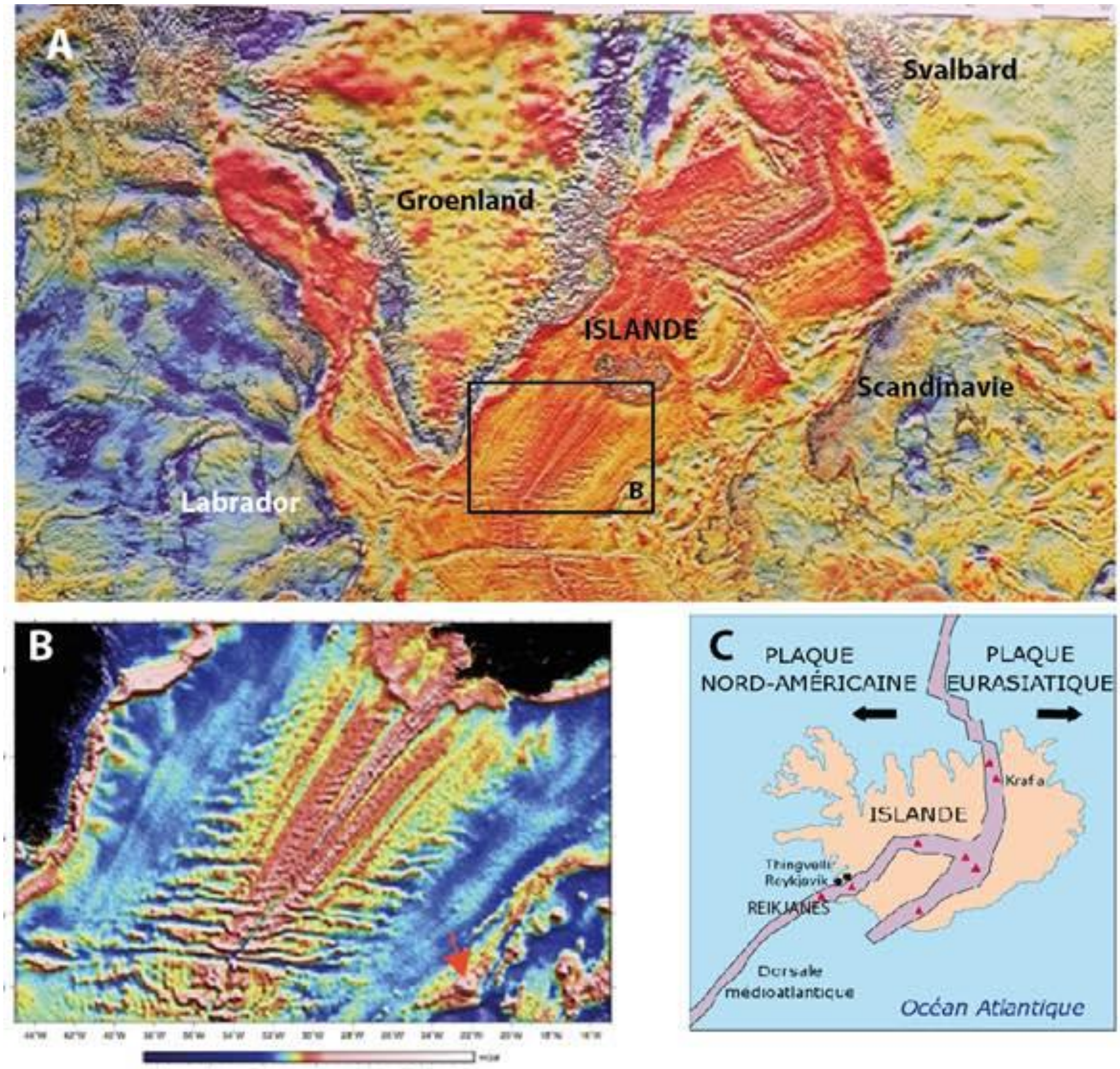

*Figure 1. **A**) Open-air gravity map of the North-East Atlantic region. Document taken from the world gravity map (Bonvalot et al. 2012). This map shows the main structural features of the North-East Atlantic region, such as ridges, both active and extinct, and major transform faults**; B**) Map of free-air gravity anomalies in the Reykjanes Basin (also see Figures 3 and 4**); C)** Simplified position of the Icelandic rifts. Also here.*

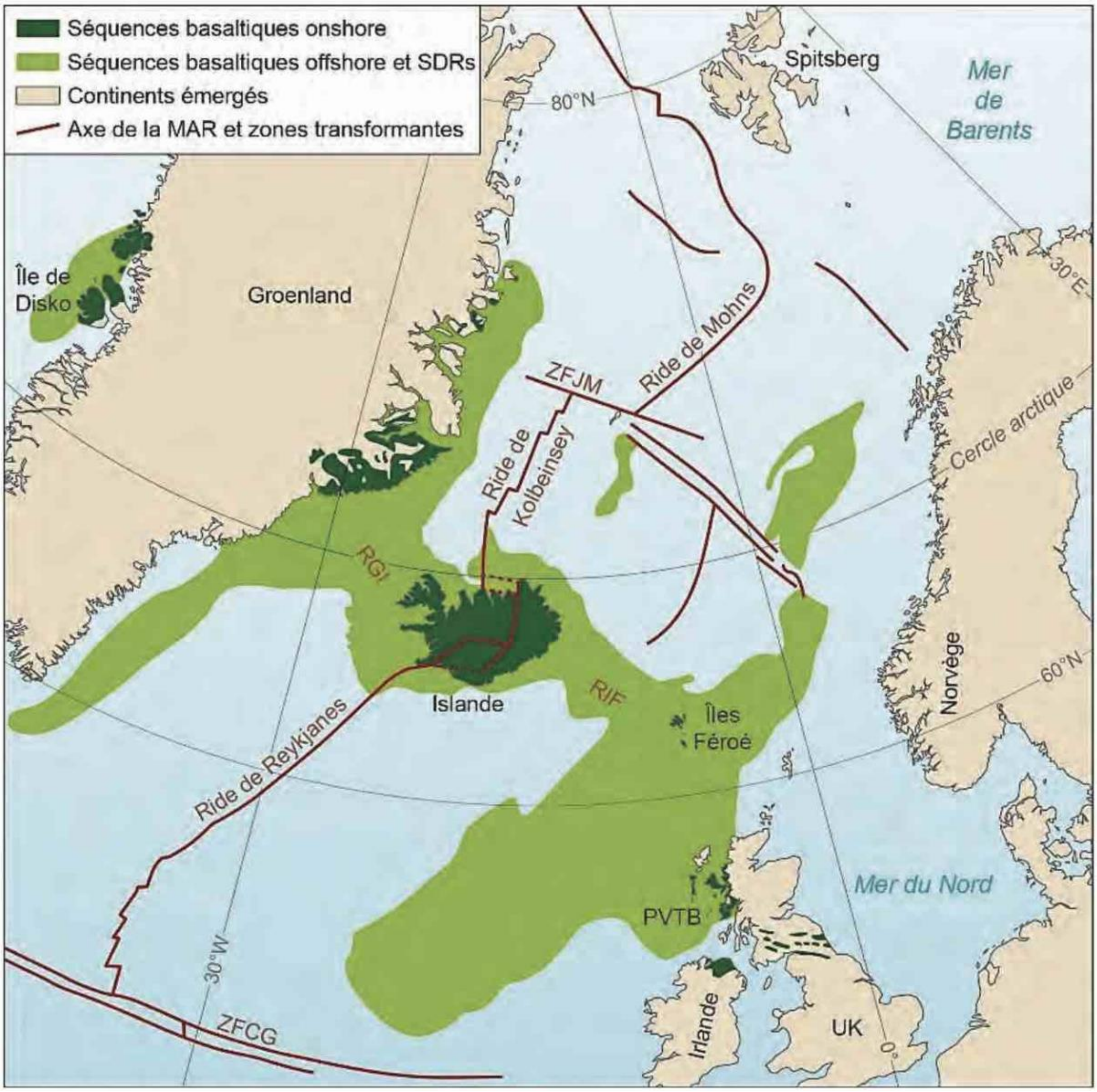

Figure 2. The Thule igneous province (after Storey et al. 2007; Thodarson and Larsen 2007; Chauvet et al. 2019 in Van Vliet-Lanoë et al., 2021). The two main ridges (Reykjanes and Kolbeinsey) are shown in Figure 3. ***The ridges mark the boundary between the American (left) and European (right) tectonic plates. They cross Iceland from SW to NNE, where an active rift can be seen.***

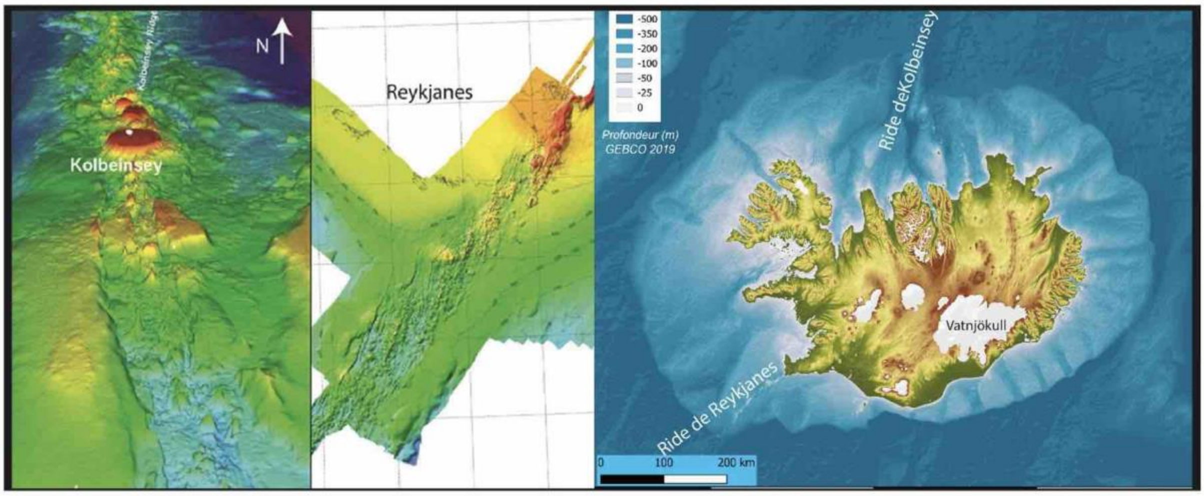

Figure 3. **A**) Kolbeinsey and **B**) Reykjanes submarine ridges (multibeam echosounder images, HAFRO.is). In Van Vliet-Lanoë et al. (2021)) (also Figure 7). The Kolbeinsey ridge reflects an oblique transform fault with the very shallow Tjörnes fracture zone where a submarine eruption was reported in 1372 (on the Kolbeinsey ridge but its exact location is uncertain). Other reports of historical submarine eruptions in northern Iceland have an even more uncertain location (Smithsonial Institution, 1999 ; Yeo et al., 2016). The Reykjanes volcanic system is at least 45 km long, with 30 km between the coast and the Langjökull glacier. The associated volcanic system is defined by a row of shield volcanoes.

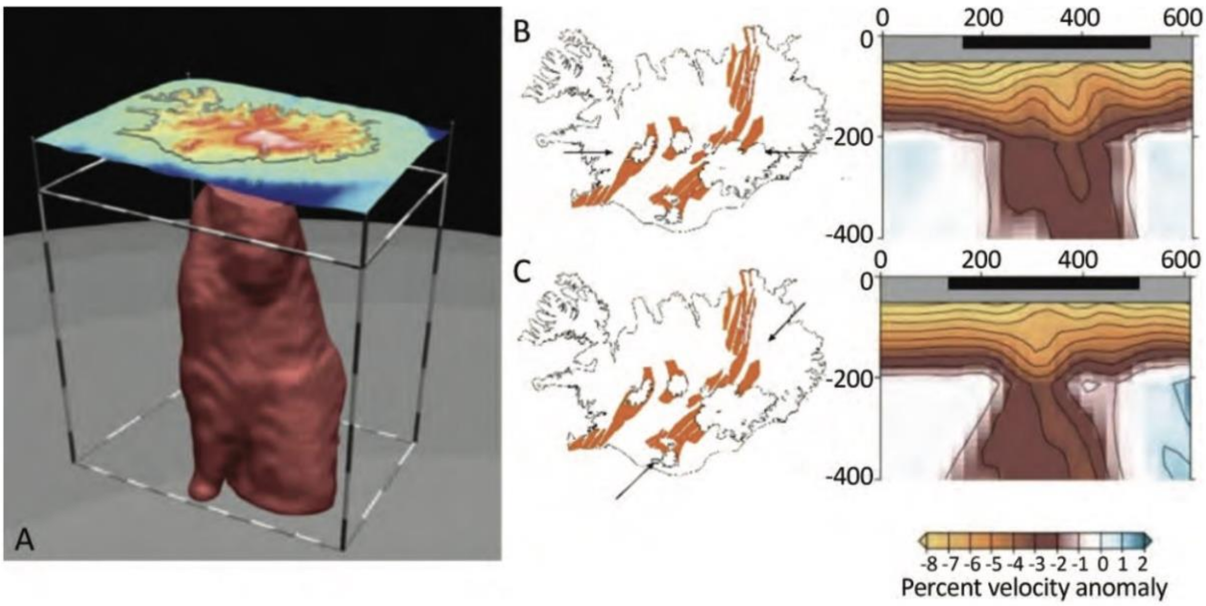

*Figure 4. Imagery illustrating the narrow cylindrical shape of the mantle plume **(A)**, with a radius of about 150 km (low-velocity anomaly to a depth of at least 400 km, according to (Wolfe et al. 1997). Vertical sections in the ICEMAN model by Allen et al. (2002)) in Van Vliet-Lanoë et al. (2021)) perpendicular **(B)** and parallel **(C)** to the rift. These sections illustrate the vertical conduit between 400 and 200 km depth and the horizontal plume above. Vertical axis = depth in km.*

The Icelandic mantle plume (Figure 4) was superimposed late (around 3 Ma) at the contact of the two submarine ridges, and the relief of the island is induced by the magmatic plume at the plate boundary. The mid-ocean ridge connected to Iceland to the north and south has two segments, **the Reykjanes ridge to the south, and the Kolbeinsey ridge to the north** (Figures 2 and 3). These ridges correspond to submarine segments of the Mid-Atlantic Ridge at their junction with Iceland. Within the island, this passage is marked by rift zones or faulted volcanic zones associated with active volcanism, as evidenced by basalts of different chemical compositions (Figure 5), and numerous earthquakes.

The emission of lava that accompanies volcanism occurs in discrete swarms of fissures, 10 to 100 km long, known as volcanic systems (Figures 5, 7 and 9). These systems are characterized by various tectonic features, normal faults, extensionally open fissures, collapsed graben structures, dykes (injections) and alignments of small or large volcanic craters, cinder cones or spatter cones, tuyas (subglacial volcanoes) and shield volcanoes (interglacial volcanoes).

2. Iceland: Quaternary and Recent geology and volcanic activity

2.1. A constantly evolving rift

Iceland as we know it today emerged 15 Ma ago and gradually widened (Figure 6) because of the activity of the Atlantic rift at the contact between the American and Eurasian tectonic plates (Figures 1 to 3). It is still punctuated by the hotspot. The hotspot is currently located under the large Vatnajökull cap, to the east of the eastern rift, just above the still active Grimsvötn (location 20 in Figure 5) and Bárðarbunga stratovolcano complex.

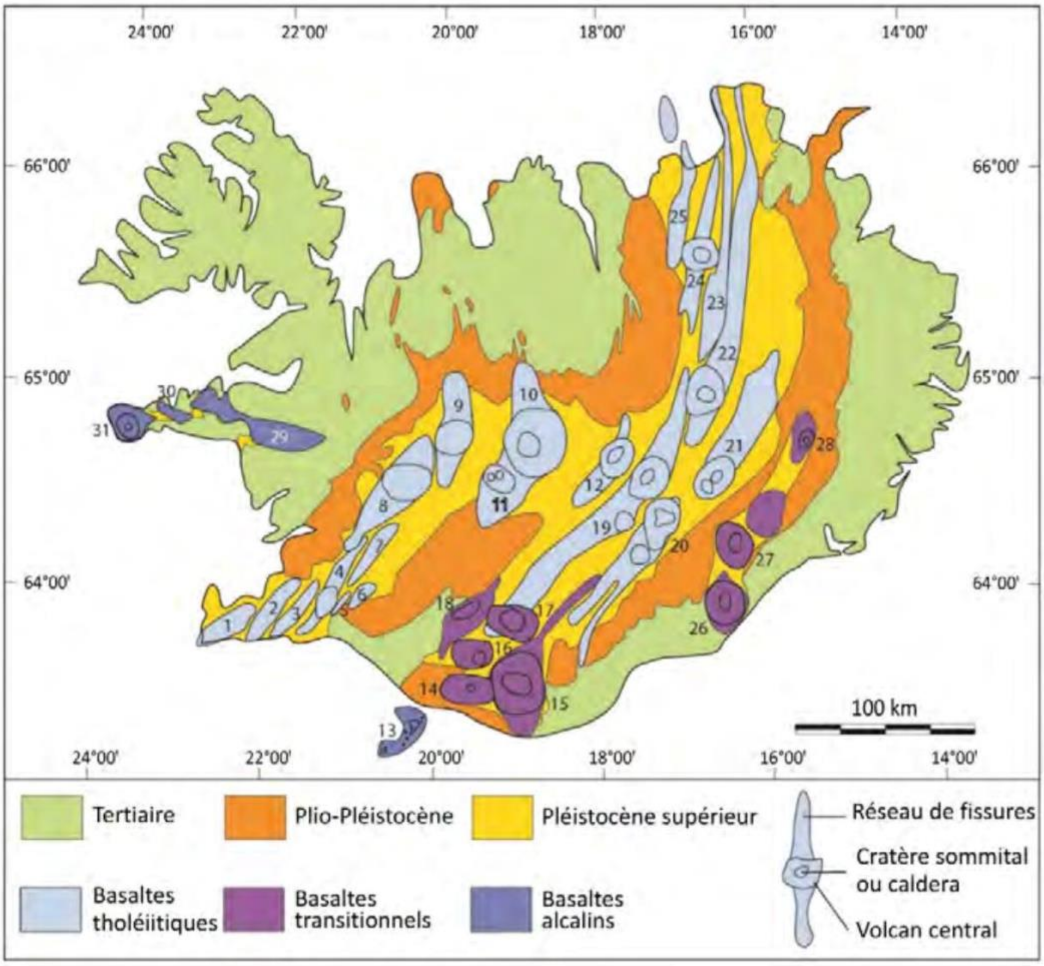

Figure 5: Geological map of Iceland showing basic bedrock geology, currently active rift and volcanic zones, axis of anticlines, axis of synclines, transverse faults and volcanic systems. WRZ Western Rift Zone, NRZ Northern Rift Zone, TFZ Tjörnes Fracture Zone, SISZ South Iceland Seismic Zone (Modified from Einarsson et Sæmundsson 1987, Sigmundsson et al. 2018, Bergerat et Plateaux, 2012). ***Main central volcanoes and active fissure systems****. 1 to 4 Reykjanes 1: includes the Grindavik area; 2: Krýsuvík and Fagradarfjell; 3: Brennisteinfjöll; 4: Hengill; 5: Hrómundartin- dur; 6: Grimsnes; 7: Hrafnabjörg; 8: Prestahnjúkur; 9: Kjölur; 10: Hofsjökull; 11: Kerlingarfjöll; 12: Tungnafellsjökull; 13: Vestmannaeyjar; 14: Eyjafjallajökull; 15: Katla; 16: Tindfjöll; 17: Hekla; 18: Torfajökull; 19: Veiðivötn; 20: Grímsvötn; 21: Kverkfjöll; 22: Askja; 23: Fremrinamur; 24: Krafla; 25: Þeistareykir; 26: Öræfajökull; 27: Esjufjöll; 28: Snæfell; 29: Ljósufjöll; 30: Lysuskarö; 31: Snæfellsjökull. Magmatic affinities (tholeiitic, transitional and alkaline) according to Sigmarsson and Steinthorsson (2007) and Sigmarsson et al. (2008)) in Van Vliet et al. (2021). Aslo here.*

The West Iceland continental rift has not been very active since the rift gap (Figure 6), except during glacial periods. The east rift (the most recent, 3 Ma), on the other hand, is very active, because it is fed by the hotspot. Iceland and its active volcanoes are therefore under close surveillance: **the melting of the glaciers since the last deglaciation, and more recently, seems to favor explosive phreato-magmatic volcanism. The average eruption frequency here is one every 4-5 years, but certain periods can be more active.**

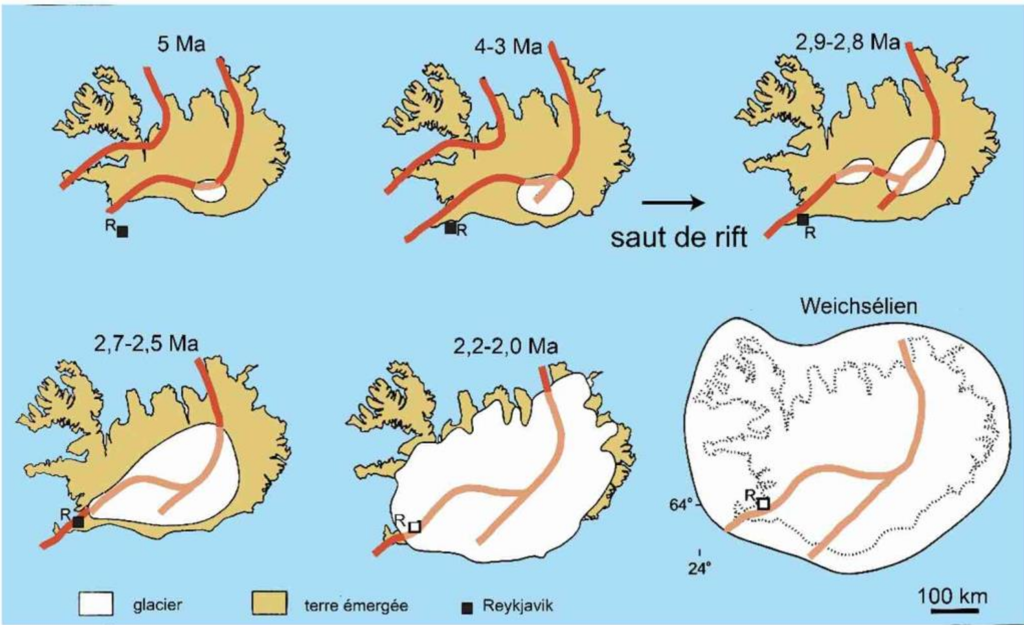

Figure 6. Plio-Pleistocene freeze-up of Iceland. Completed after (Geirsdottir et Eiriksson 1994). However, it is not impossible that around 3 Ma, the ice cap extended further than recommended by these authors, favoring the rift jump (3 Ma) by glacial overload.

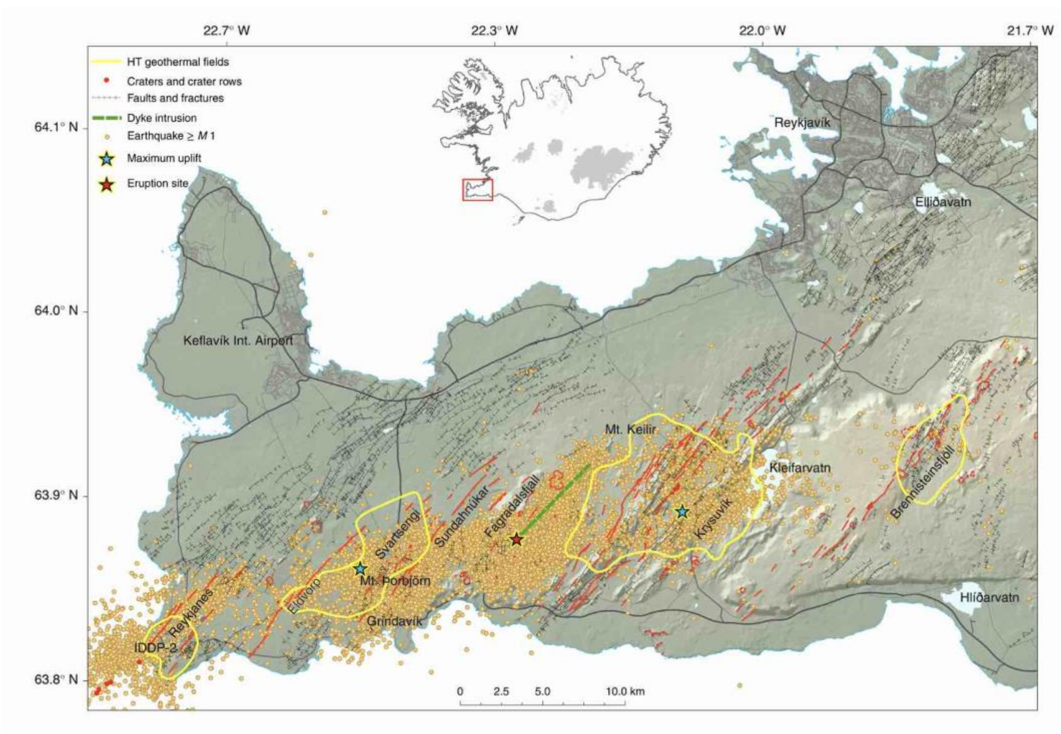

Figure 7. Fault zones on the Reykjanes peninsula with the area of the fissural eruption of Fagradafjell on 19/03/21 (location no. 2, Figure 5). The eruption of 3 /08/22 is NE of the Fragardarfjell fault field, which depends on the Krýsuvík volcanic system (right), itself inactive for 900 years, and the last eruption on the Reykjanes peninsula dates to 1240 AD. The red and black fault lines indicate post-glacial volcanic eruptive fissures and opening fissures respectively. The yellow lines indicate the extent of the geothermal fields (Flóvenz et al., 2021).

2.2. Eruptions

In Iceland, apart from stratovolcanoes, eruptions are mainly fissural (Figures 7, 8 and 9).

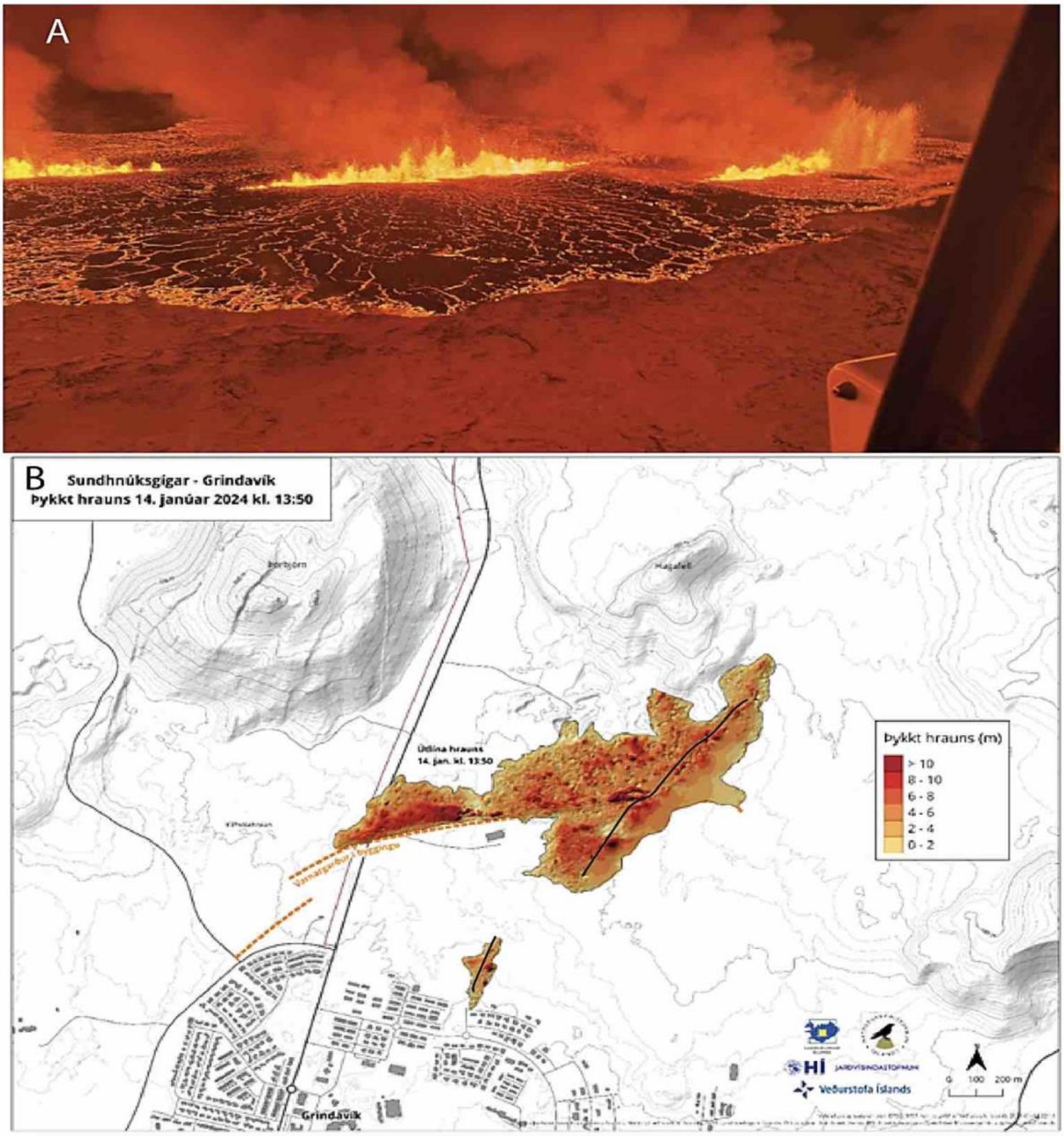

*Figure 8. Fissural eruptions. **A**) aerial view: relay transtensional faults, Svartsengi (eruption of 11/12/2023). **B)** 14 January 2024 at Grindavik, location 1, figure 5 (Vedur.is). The orange dotted lines are dams designed to limit the spread of the lava.*

On the scale of the last glaciation and the end of our interglacial period, subglacial volcanism is a form of phreato-magmatism induced specifically by the melting of the ice cover, via partial confinement of the magma in the magma chamber, followed by its **isostatic discharge during deglaciation (Figure 10).** This discharge will induce an increase in the partial melting rate of the upper mantle when the latter is decompressed, through an adiabatic decrease in the pressure applied by the cap (Maclennan et al., 2002; Eason et al., 2015 *in* Van Vliet et al. (2021). A thick ice cap constrains partial melting of the mantle at depth, and hence volcanic activity, except in the case of very large strato-volcanoes, which generally emerge from the cap (Grimsvötn, location 20 in Figure 5).

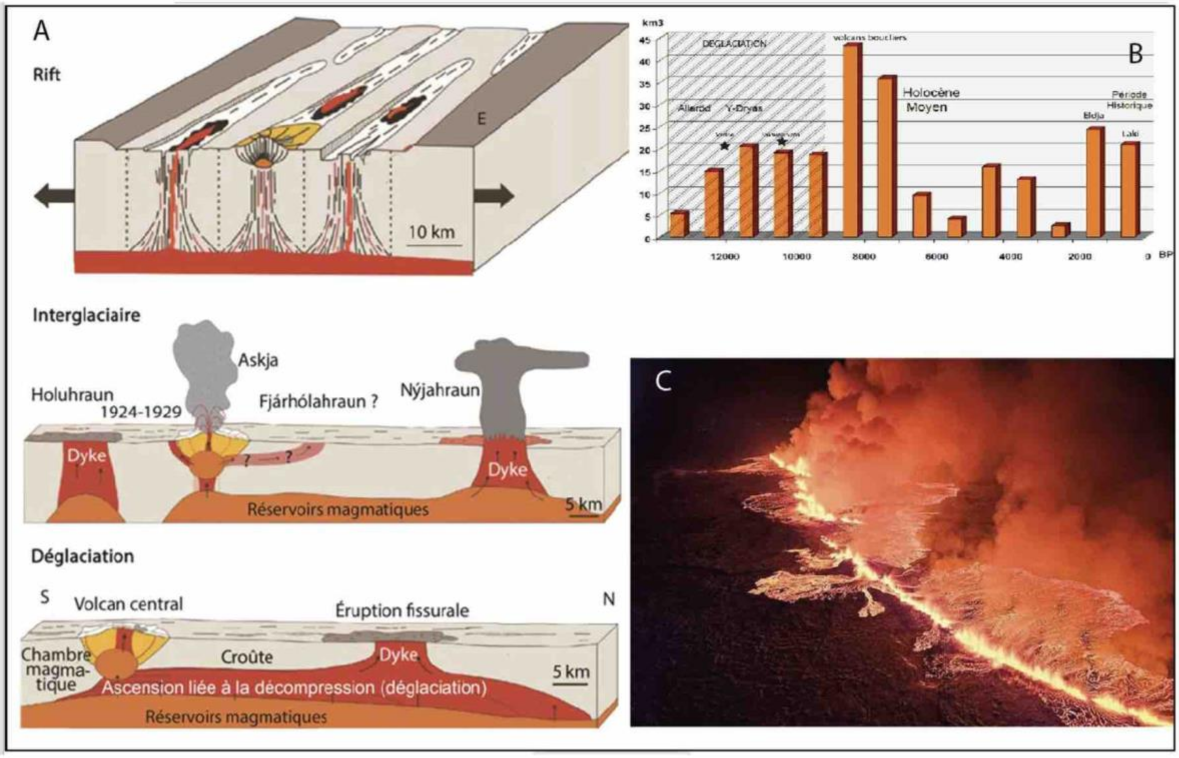

Figure 9. ***A)*** *Formations of fissural rift volcanoes in interglacial (Askja area example, location 22, Figure 5) and deglacial periods, modified from Harley et al., 2013);* ***B)*** *Comparative volumes of volcanic emissions in deglacial and Holocene periods. The effusive volume emitted is maximum immediately after the end of deglaciation of the island, at around 8.3 ka. Modified from Hjartasson (2003) in Van Vliet et al. (2021).*

On a global scale, an assessment of the history of volcanic eruptions shows that subaerial volcanism increased by a factor of two to six over several tens of centuries during the last deglaciation, as did seismic activity. In Iceland, the frequency of eruptions was 30 to 50 times greater in the 1500 years following the start of the last deglaciation (MacLennan et al., 2002). Most of the volume was emitted during the 3,000 years following the deglaciation ((Sinton et al., 2005), which also caused isostatic stress release and reactivation of faults (Mörner, 1981; Turpeinen et al., 2008) within and beyond the limits of the cap (James et Bent, 1994). **Guðmundsson (1986) has suggested that the variation in crustal stress due to glacio-isostatic discharge increases fracturing of magma chambers and thus increases eruption rates.**

On the scale of the historical period, Icelandic fissural activity appears in secular periods. It is also constrained on Reykjanes and on the flat peninsulas to the NE of the island by seawater infiltrating at depth. The last three volcano-tectonic episodes occurred on Reykjanes in the 13th century, around 2000 years ago and around 3200 years ago (Saemundsson et al., 2018). The Stampar crater row, NE of Grindavik dates from 1210-1240 AD.

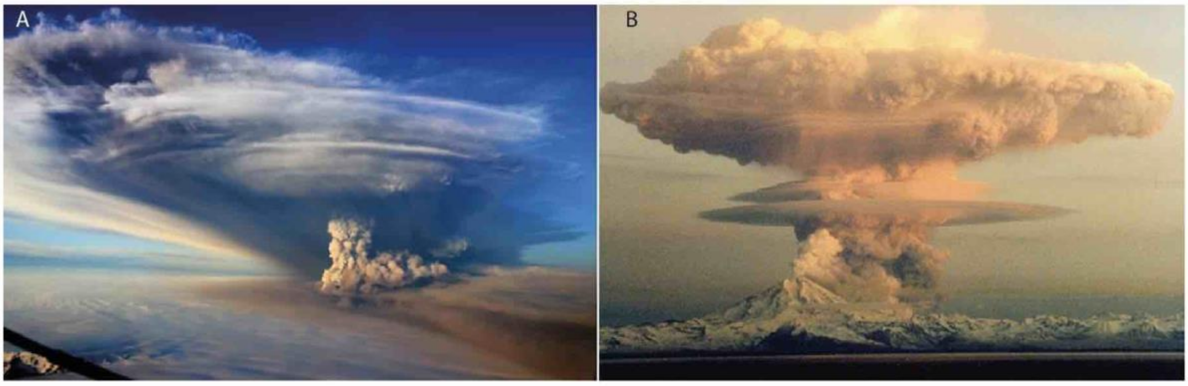

*Figure 10. **A**) Basaltic phreato-magmatic eruption of Grimsvötn volcano (location 20, figure 5), in 2011 (image Egill Adalsteinsson / EPA/ The Conversation.) **B**) Acidic Plinian eruption on a subduction zone, Mount Redoubt in Alaska, on 21 April 1990 with stratospheric plume. Photo USGS.*

Phreato-magmatic volcanism is not unique to Iceland, but is much more common, particularly in the case of submarine (Hunga Tunga, Tonga archipelago), island or coastal volcanism. It also occurs in the Azores and Canary Islands, and in large lakes in calderas such as the Taal volcano in the Philippines (1965) or the Laacher See volcano (Eifel, Germany), 40 ka ago. This type of volcanism is typically associated with ocean ripples (Iceland), a continental rift (Niragongo) or a mobile hot spot beneath the Earth's crust (Hawaii and Eifel).

The Grimsvötn stratovolcano (location 20 in Figure 5) is regularly active, as evidenced by its tephra production. It is characterized by phreato-magmatic eruptive activity induced by infiltration of sub-glacial meltwater, which is functional even during the ice age. However, the volume of ash emitted by plinian-type phreato-magmatic explosions increases enormously at the start of the interglacial, both in the current interglacial and in the previous one. **This explosive volcanic activity is most often exacerbated by the infiltration of water from a lake or subglacial channels formed by basal melting, as in the case of Eyafjallajokull (location 14, Figure 5) in 2010 or Grimvötn in 2011 (Figures 5 and 9).**

The rest of the world's phreato-magmatic eruptions are formed by the reliefs, often snow-covered, of the Pacific Ring of Fire, in association with crustal subduction beneath the continental margins and volcanism that is naturally explosive because of the nature of its lavas (andesitic, silica-rich, viscous, and explosive). It is linked to the "digestion" of sedimentary masses entrained by the folding of the plate into the asthenosphere (Figure 11) and is responsible for plinian eruptions, with dense plumes of ash and gas rising very high into the stratosphere (>35 km) (Figure 10B, Redoubt volcano). This is the case of the

Andes chain (Nevado del Ruiz, 1985), the Alaskan islands (Katmai volcano), the Aleutian Islands (Pavlof volcano) and Kamtachka, and of course the Rockies with 26 volcanoes, including the eruption of Mount Saint Helens in 1980, and a veritable ice cap, as in the case of Mount Rainier (Cascade Range, USA), whose most recent activity was recorded between 1820 and 1894, with major explosive phases (tephra) during the Holocene.

Pavlof volcano is a subduction stratovolcano in the Aleutian chain with deep-seated activity and dehydration of the plunging crust or 'slab' (McNut 1987). It has been one of the most active volcanoes in the United States since 1980, with around twenty eruptions recorded between 1928 and 2021, including 9 magmatic eruptions and 13 phreato-magmatic eruptions in the last 11 years (1973-1983) (McNutt, 1987).

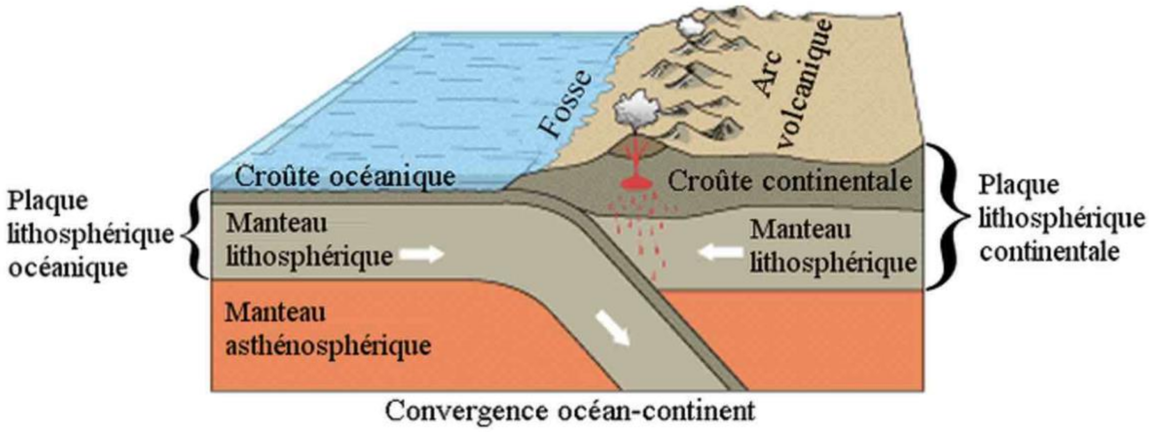

Figure 11. Volcanic arc at the plunge of the subducting plate into the upper mantle.

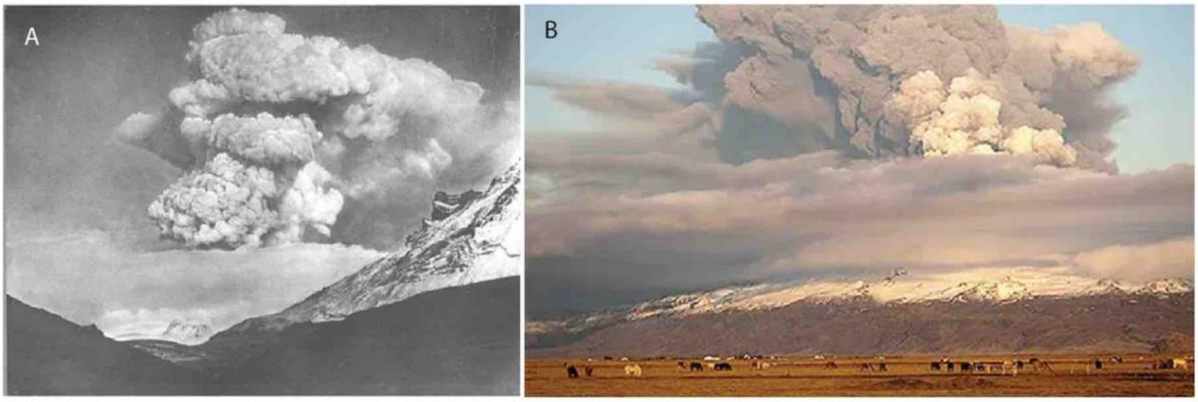

Figure 12. Phreato-magmatic eruptions. ***A)*** *Katla rhyolite volcano in 1918 (Photo: Kjartan Guðmundsson).* ***B)*** *Basaltic volcano Eyjafjallajökull (location 14, figure 5), April 21, 2010. Photo S. Olafs / epa / Corbis.*

Acidic Plinian eruptions are most often associated with a subduction zone and produce much more gas and ashes (Novarupta in the Katmai caldera, 1912, Alaska). In Iceland, a long mineralogical decantation of an initially andesitic magmatic reservoir leads, in shallow reservoirs (3 km), to the evolution in acid magmas emitted at the onset of an eruption, partly in subglacial conditions. This was the case with the Katla eruption in 11,200 BP or 380 AD (Dark Ages; location 15, Figure 5) or the Askja eruption (location 12, Figures 5 and 12).

2.3. Lunar, solar and glacio-isostatic forcing of volcanic eruptions

The Reykjanes peninsula, where the Grindavik eruption took place (location 1 *in* Figure 5), is a direct extension of the Reykjanes oceanic rift (Figures 2, 3 and 7). Volcanism is essentially fissural but airborne and fed directly by the oceanic rift, i.e. by volcanism, and stored in deep reservoirs (5 km), as at Reykjanes. No volcanic eruptions had occurred for 815 years on the peninsula until 19 March 2021, when a fissure appeared to the south of the Tuya of Fragradarlsfjell, location 2, Figure 5 (Figure 12) with three powerful successive effusive eruptions.

The Moon's attraction is strongest during a new or full moon: the Sun, Moon and Earth are aligned and add up their respective forces of attraction on the tide. This generates **terrestrial tides** that can exceed one meter (measured by satellite), i.e. slightly more than twice the height of the solar terrestrial tides (Caudron, 2018), leading to greater uplift and surface extension of the Earth's crust, reopening existing deep faults. The spring equinox is scheduled for 20 March 2024. The distance between the Sun and Earth varies, with perihelion at 147 million kilometers and aphelion at 152 million kilometers. The Earth was at aphelion (the furthest position from the Sun) on 6/07/2023 when volcanic activity (swelling and faulting) began in Grindavik (location 1, figure 5). **The Earth passed through perihelion on Wednesday 3 January 2024, facilitating the eruption on 13 January with a high lunar tidal coefficient. This lunar tide would therefore be more effective at perihelion in generating eruptive events**.

Analysis of the behavior of the Ruapetehu andesite and englacial volcano (Lake Taupo, Northern New Zealand) also justifies this **association between fissural volcanism and tides. Girona et al (2018) showed that the volcano and the Moon were synchronised around three months before the eruption.** However weak the tidal forces, apart from opening fissures, regularly compress the magma reservoir and its gas pocket (water vapour and other gases), inducing a fortnightly rhythm (full moon and new moon) of pressure build-up in the gas pocket and sustained seismic activity when the plug retaining the gas is tight enough, acting on a sealed volcanic edifice. This would be valid for periods of intense eruptions grouped together in the Pahoka-Mangamate event, which would have lasted between 200 and 400 years (Gomez-Vasconcelos et al., 2020).

The Grindavik eruption, which was first triggered after the New Moon (13/12/23) on 18/12/23, at 22:17, was located on one of the first major faults in the Reykjanes transtensional system (Figures 7 and 8), after the opening of superficial faults on 09/07 at 18:30 in Grindavik (Full Moon on 5/07/2023), followed by the first injection at a rate of 5 m3/s of a dyke since the 23rd (New Moon 18/07/23, tidal coefficient : 93; see Figure 13) and a brief explosion at its onset (fumes). This eruption resumed on 14/01/2024 at 8am (Figure 8B) New Moon 11/01, tidal coefficient: 97). It began with an explosion after an episode of surface swelling indicating the injection of magma into the subsurface reservoir (c.1 km) with a major seismic event at 03h (intensity 3 to 4). The outpouring of lava began on 14/01 at 08:00 on two parallel faults, just long enough for the lava to rise from the surface reservoir. Houses in Grindavik were affected.

On this fissural field, the main factor is the lateral infiltration of seawater into the permeable substratum, generating a vapor lock on the Svartsengi geothermal reservoir (Figure 8B) close to the surface (1200m) (Receveur et al., 2019), allowing a topographic swelling monitored by interferometry. This volcanic zone appears to be preparing for another eruption as more magma accumulates below the surface (120 m altitude for Svartsengi) and the bedrock in this sector continues to rise. An analysis (Figure 13) of the eruption dates for this volcanic complex shows a marked relationship with the tidal coefficients, suggesting a resumption of the eruption on 12/02, and in March and April (shown in yellow in Figure 13). **A resumption of the eruption is expected by the Icelandic Meteorological Institute (https://en.vedur.is/) and the University of Iceland, which announced on 1/02/24 that around 6.5 million m^3 of magma had accumulated beneath the Svartsengi region. According to this assessment, the magma will soon reach the same volume as the eruption of 14 January 2024. This eruption could occur at the times indicated (Figure 13) due to particularly high tidal coefficients.**

Date	Maximal tide coef.	GRINDAVIK ERUPTIONS
06/07/23	87	Early swell
13 /12/ 23	93	First fissural eruption (Svartsengi)
22 /12/ 23 Winter solstice	59	
14 /01/24	97	Grindavik fissural eruption
12/02/ 24	110	Renewed eruption?
12 /03/ 24	116	
20 /03/ 24 Equinoxe	67	
08 /04/ 24	109	Renewed eruption?
08 /05/24	101	
06/06/24	86	
20/06/24 Summer solstice	76	
24/06/24	81	
24 /07/ 24	95	

Figure 13. Relationship between tidal coefficients, the position of the Sun and volcanism in the Svartsengi and Grindavik area (also Figures 5 and 8B).

This tidal forcing is not expressed for the neighboring fault field: the Fagradarfjell (2021-2023; Figure 7), located at around 400 m altitude in the drained zone of the Reykjanes peninsula. But it is not impossible that the frequent fissural eruptions of the NE rift, such as Holuhraun, with an emerging superficial aquifer, could react. This latest fissural eruption in 2014-2015, derived from Barđarbunga was the largest in Iceland for over 300 years and lasted almost six months. As in Svartsengi and Grindavik, Holuhraun was characterised by particularly high SO_2 emissions (Carboni et al., 2019).

2.4. Climate forcing

Current global warming is responsible for a significant melting of the ice caps, particularly in the south and west of the island. Since 1890, the area covered by glaciers has shrunk by almost 2,200 km², or 18%. But almost a third of this retreat has taken place since 2000, according to the latest figures from Icelandic glaciologists, geologists, and geophysicists. **The retreat recorded over two decades is 810 km²** (Aðalgeirsdóttir et al., 2020).

Reykjanes was deglaciated 14,500 years ago, in association with a particularly strong solar eruption that caused the sudden deglaciation of the Bölling (Bard et al., 2023). The Reykjanes peninsula was deglaciated around 14,300 years ago, but the cape of this peninsula did not emerge from the sea until around 5,000 years ago (Saemundsonn et al., 2020).

Episodes of secular activity in Icelandic volcanism can be linked to solar activity and its hot cycles, which are responsible for deglaciation and therefore for an isostatic unloading of the whole island, as during the last Dansgaard-Oeschger events of the Tardiglacial period (SCE, 2020), and also the warming of the Bronze Age Optimum (3600-3100 BP or 1600-1100 BC), the Roman Period (-40 BC), the Carolingian Period (≈ 800 AD) and the foundation of Iceland (930 AD : Landmana), the Optimum Middle Ages (1100-1350 AD), which were greatly disturbed by volcanic activity, particularly Reykjanes (Saemundsson et al. , 2018). The reactivation of Reykjanes and Holuraun rift activity at the beginning of the 21st century is probably partly linked to a resumption of activity in the Mid-Atlantic Ridge.

2.5. Iceland : climate and powerful volcanic eruptions

A series of mega-eruptions have marked quaternary and recent geological history, both in Iceland (Katla volcano in 12.1 ka: Vedde ash (Figure 14) and in subduction zones (Tambora, Krakatau). These ancient eruptions are archived in the form of sulphates in the Antarctic EDML (= Epica Dronning Maud Land) and Greenland NGRIP (= North Greenland Ice Core Project) ice cores (Severi et al., 2007). Several well-dated events have been recorded over the last 400 years: Krakatau (1884), Tambora (1815 AD) and Huaynaputyna (1600 AD). **Most mega-eruptions are followed by a climatic cooling associated with the loading of dust or reflective sulphuric aerosols in the stratosphere, or even in the mesosphere, which, when picked up by streamers at the top of the troposphere, reflect solar radiation, reducing the insolation reaching the ground**. Significant cooling occurred around 73 ka BP with the super-eruption and collapse of the Lake Toba caldera on the island of Sumatra. It has an estimated explosivity index of 8, suggesting a plume at least 45 km high. It is thought to have caused a volcanic winter lasting at least six years. However, according to records of sulphate levels in ice cores, the sudden cooling took place around 75 ka BP, i.e. at least 2 ka before the explosion.

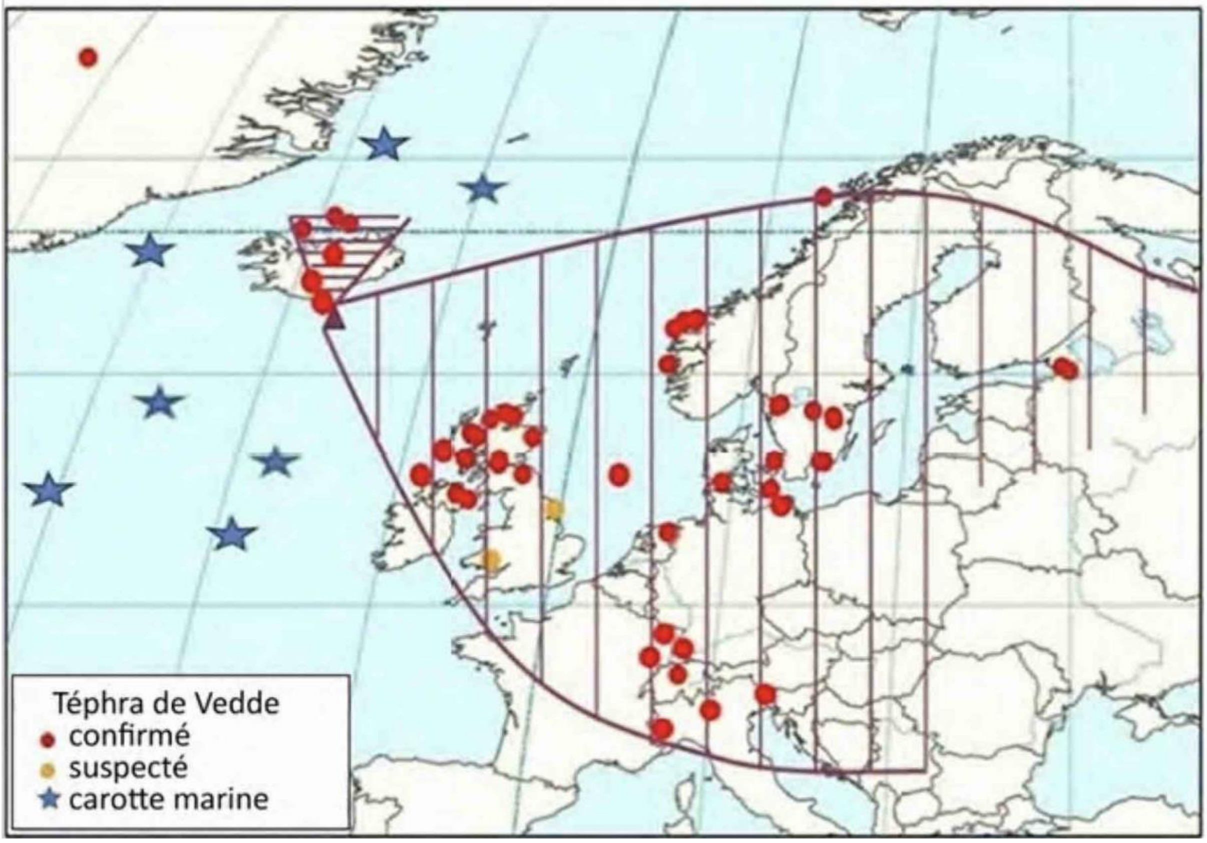

Figure 14. Extension of the Vedde tephra in the North Atlantic (stars) and adjacent continents (modified and extended from Tomlinson et al. 2012).

3. Iceland: volcanoes and gases

As a result of this major magmatic activity, Iceland has 39 geothermal zones, each with its own series of hot springs, geysers and so on. This thermal heat is the basis of energy production for the population. Volcanic activity also produces CO_2 (see 4).

3.1. Water vapor

Subglacial volcanism is probably the largest emitter of water vapor, but is relatively limited throughout the world, apart from Iceland, West Antarctica, and the peri-Antarctic islands. In the case of a "direct" volcanic eruption, in most of the cases we described in part 2, the gaseous emission of an eruption is marked mainly by the expulsion of enormous quantities of steam, the main greenhouse gas, but also especially large quantities of SO_2, as in the case of the eruption of Laki in 1783-84. It should be noted that in the case of subglacial or submarine eruptions (Hunga Tunga, see § 3.2), enormous quantities of water vapor are usually released into the atmosphere, sometimes reaching the upper stratosphere. In comparison, the amount of CO_2 released is minimal. There is no clear evidence of the influence of Hunga Tunga on the Arctic vortex of 2022-2023 or on its composition, but on the noctilucent clouds (Figure 15) linked to ice micro-crystals in the mesosphere (80-90 km altitude), which were first observed in 1883, shortly after the eruption of the Krakatoa volcano.

Figure 15. Noctilucent clouds in Iceland (2023; photo Gunnar Geirsson).

3.2. SO_2

After water vapor, sulphur dioxide is by far the most abundant and the biggest climate disrupter when injected into the upper troposphere and stratosphere. 4,000 tonnes per day were measured in the stratosphere on 8 January 2023. For recent eruptions over the last 25 years, El Chichon (7 Mt, 1M = 1 Mega = 106 = one million) and Mount Pinatubo (20 Mt) have emitted the largest quantities of SO_2into the atmosphere (tropo- and stratosphere). These two volcanoes are located at low latitudes, but they both had high eruption rates. **Whether from small or large eruptions, volcanic sulphuric aerosols are toxic and often fluorinated. They reflect sunlight back into space, cooling the global climate.** The eruption of Mount Tambora in 1815 produced enough ash and aerosols to cancel the summer in Europe and North America in 1816. The fissural eruption of 1783-1784 AD Laki (Iceland) began on 8 June 1783 and released 122 Tg (1T = 10^12 = thousand billion) of sulphur dioxide (SO_2) in eight months into the upper troposphere and lower stratosphere (Schmidt et al., 2010), killing Icelandic cattle in the process and dramatically polluting the European atmosphere. The fissural eruption from Barđarbunga (Holuhraun) in 2011 resulted in a similar SO_2 emission of nearly 12 Mt, which exceeds the total SO_2 emissions in industrialized Europe. The climatic coolings of the Recent Dryas were catalyzed by the exceptionally sulphur-rich eruptions of 12880 BP of the Laacher See volcano (Eifel, Germany) and that of Vedde (Katla; 12.0-11.8 ka BP, Figure 14).

In addition to this important gas, we may add chlorine issued from the volcanic vaporization of seawater, so this activity seems not harmless for the ozone layer. On the other hand, excess seawater vapor injected, as in Iceland for example, brings chlorides into the upper stratosphere for several years and influences the chemistry of the atmosphere (Santee et al., 2023, Evan et al, 2023), which can temporarily exacerbate the weakening of the ozone layer in conjunction with the quality of solar activity (SCE, 2023), as shown by the exceptional increase in the size of the Antarctic Ozone Hole in September 2023.

Various articles have cultivated the myth of global warming, particularly in winter, induced by a large injection of water vapor into the stratosphere, as in the case of the Hunga Tunga volcano. This phenomenon has not been demonstrated, either for Pinatubo (Polvani et al., 2019) or for Hunga Tunga (Millán et al., 2022; Manney et al. 2023).

4. The case of CO_2 : is volcanism a normal or related terrestrial function, or even a contributor to climate change?

Several comments on social networks claim that a volcanic eruption in the Reykjanes peninsula region of Iceland is emitting more carbon dioxide into the atmosphere than human activity. It's a 'conspiracy' theory that comes up almost every time there's a major volcanic eruption across the globe. Humanity's annual carbon emissions from burning fossil fuels and forests, etc. They are 40 to 100 times higher than all volcanic emissions.

CO_2 emissions from volcanoes and other magmatically active regions into the atmosphere and oceans are estimated at 280 to 360 million tonnes (0.28 to 0.36 Gt; 1G = 1 Giga = 10^9 = one billion) per year, including those released into the oceans by oceanic ripples. During the progressive emplacement of volcanic dykes, the role of volcanism in CO_2 degassing is usually related to the *in situ* combustion/metabolization of sedimentary organic matter. This is connected to the initial position of the Icelandic hotspot and the start of Atlantic rifting 65 Ma ago (Ganino and Arndt, 2009). **Although lower than recent estimates, the global volcanic flux implies that a significant proportion of the CO_2 from the Earth's mantle is derived from subducted organic sediments, thermally metamorphosed with CO_2 release.**

There is therefore no warming (under the 'greenhouse hypothesis') to be feared from Icelandic volcanoes, even though several authors believe that CO_2 degassing from subglacial volcanoes is underestimated ((IlyInskaya et al., 2017; Kamis, 2023).

4.1. Inheritance

On the other hand, Cenozoic pre-Quaternary geological data show that very large episodes of effusive volcanism linked to large provinces, such as those that cross the Atlantic at the level of Iceland (Figure 3) (> 105 km^2 and volumes produced > 105 km3 (Bryan et Ferrari, 2013), regularly occurred. Their development may last >50 Ma, but most (>75%) of the total magmatic volume is episodic in the form of discrete short (1 to 5 Ma) paroxysmal phases. These include those associated with continental trapps (Siberia, Deccan, Parana, Ethiopia, etc.), other oceanic shelves (Java, Kerguelen, etc.) and intracontinental rifts (Ethiopian rift and the Asal rift in Djibouti), and the passive margins of the central Atlantic/Arctic (Chazot et al., 2017).). The basaltic trapps of the Deccan are among the best known. They are 2 km thick, were emplaced in 1 Ma at the Cretaceous/Tertiary boundary 66 Ma ago (or 'K/T boundary'). They have a current volume of 0.5 million km^3 and occupy a surface area of 500,000 km^2 (before erosion, their surface area was three times greater). According to Caldeira et Rampino (1990) and Sobolev et al. (2011), they emitted 75 ppm of CO_2 into the atmosphere, inducing a warming of just under 1°C (according to the greenhouse effect hypothesis!), which according to these authors is insufficient to explain the mass extinction of organisms at the K/T boundary. In detail, the events are more complex: it is estimated that 1,000 to 6,000 Gt/C (which is less than the quantity emitted in the Siberian trapps at the Permian/Triassic boundary) were injected during the K/T event, in addition to which SO_2 was added to the atmosphere at this period (Tobin et al., 2017). A warming of 2° to 4° C also occurred just at the end of the Maastrichtian, before the K/T boundary, with no decisive involvement of CO_2 in the decline of organisms. These events were followed 56 Ma ago (Paleocene/Eocene transition) by an emission of more than 10,000 PgC (1P or 1Peta = 1015 or one million billion), i.e. of the same order of magnitude as current fossil carbon reserves (cf. PETM hyperthermal event, *in* SCE, 2019).

4.2 Realistic estimates

The range of carbon estimates is wide because it depends - on the methods used, - the assumptions about the origin of the carbon emitted, and - the models used. Based on gas emissions of SO_2 and CO_2 detected on satellite imagery, Ficher et al. (2019) reached between 2005 and 2015, to a global volcanic production 1) for non-eruptive emissions CO_2 of 51.3 ± 5.7 Tg CO_2/year (11.7 × 1011 mol CO_2/year) and 2) for volcanic eruptions 1.8 ± 0.9 Tg/year. The possible sources of carbon are numerous and well documented in the literature devoted to the PETM event (= Paleocene Eocene Thermal Event in SCE, 2019): biogenic methane (clathrates or 'methane hydrates'), thermogenic methane, carbon buried in permafrost, carbon linked to fires with peat, and coal combustion, carbon spread by a comet, carbon linked to the desiccation and oxidation of agricultural organic matter (ploughing) or from the Earth's mantle, in the form of CO2, notably through volcanic activity. In the latter case, this activity would be linked to the huge emission of magmas during the continental drift or oceanic fragmentation. This the case of the North Atlantic when the North Atlantic Volcanic Province was formed (separation of Greenland and Baffin Island to the west, then England and the Faroe Islands to the east). It should be noted that permafrost is one of the most frequently cited of these sources, which are regularly cited in the literature, although a large part is issued today in Arctic of underlying oil-bearing sedimentary basin. However, it seems from that time, and until at least 48 Ma (peak of the Lower Eocene), permafrost was limited in Antarctica, and very limited to very high latitudes in the Arctic: recorded boreal forests. From 3.6 to 0.8 million years ago (Pliocene and early Pleistocene), climates similar to (and even warmer than) those predicted for future warming were the rule (Kjaer et al., 2022).

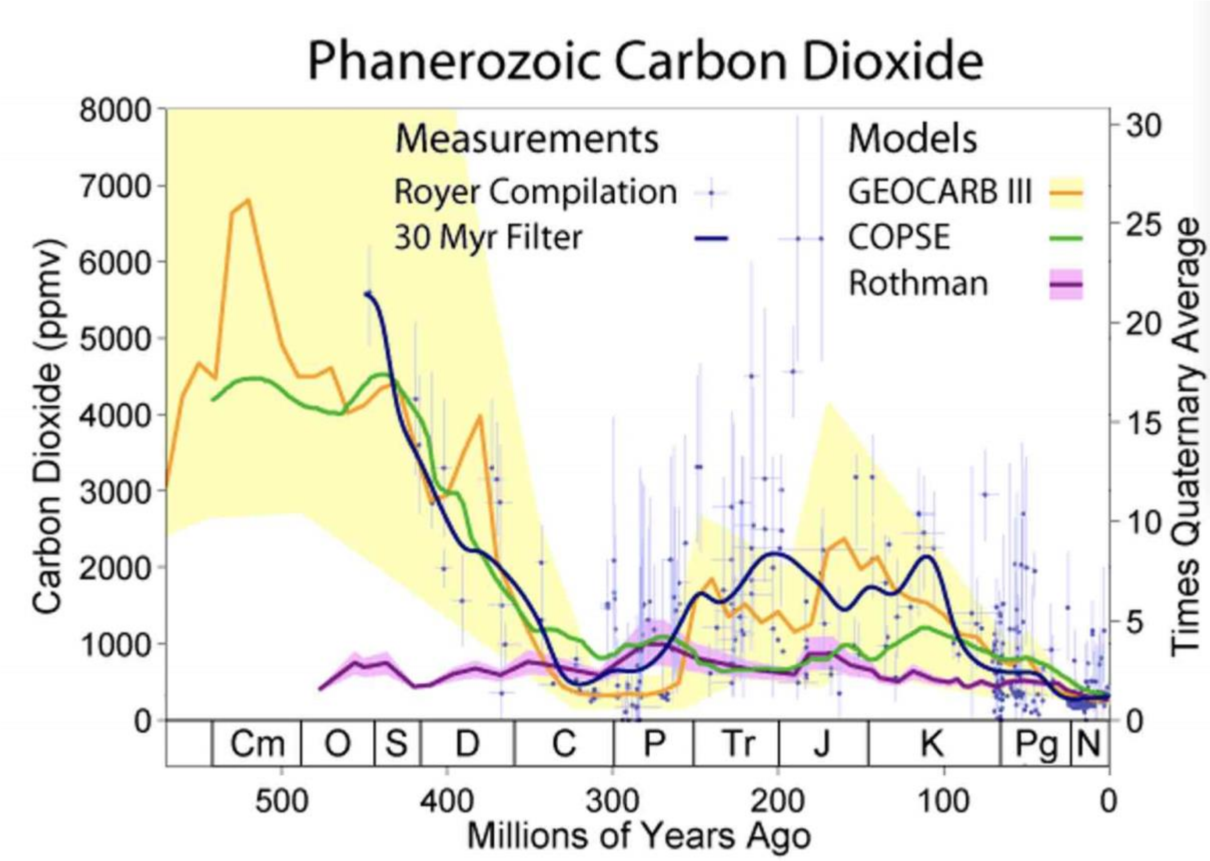

Figure 16. Evolution of estimated carbon dioxide concentrations during the Phanerozoic. Three estimates are based on geochemical modelling: GEOCARB III (Berner and Kothavala, 2001), Carbon-Oxygen-Phosphorus-Sulfur-Evolution COPSE (Bergman et al., 2004) and Rothman (2001). ***Current atmospheric concentrations have never been so low since 300 Ma. It has also been much higher since 600 Ma.*** *The RCO_2 value is a multiple of the current atmospheric concentration of this gas. Stratigraphy: : Ogg et al. (2016). N: Neogene and Quaternary.*

The question of the PETM (most extreme global warming episode) is of great importance, since this interval is considered by most authors to be a potential analogue of the current situation, although the initial conditions were very different. The chemistry of ^{3}He has shown that warming preceded the emission of carbon into the atmosphere, and spectral analysis (astronomical forcing) based on bio- and magnetostratigraphic data shows the importance of eccentricity cycles during the Lower Paleogene and their link with warming periods (discussion and references in SCE, 2019). It should be noted that, on a geological timescale, current atmospheric CO2 levels have never been so low (Figure 16 and SCE, 2018).

Even today, it is difficult to quantify the quantities of CO_2 released. For a stratovolcano that highly emits CO_2 like the Etna, estimates are several thousand tonnes per day during periods of inactivity, and up to several tens of thousands of tonnes per day during eruptions (Chazot et al., 2017). Also, this outgassing of CO_2 is a major danger for people living on the slopes of volcanoes, as CO_2 is a gas heavier than air which accumulates in inhabited topographical depressions (see the Lake Nyos disaster in Cameroon). Degassing and vaporization in the periphery of volcanoes can also lead to the emission of very spectacular and sometimes dangerous mud volcanoes, as in the accidental case of Yogyakarta on an oil well in Indonesia (Mathieu, 2021).

5. Last minute (8/02/2024) ...

The return of volcanic activity on 8/02 at 6 pm is a little ahead of the tidal coefficient which is increasing rapidly (morning: 67; evening 76). This new eruption reactivates an alignment of craters to the SE of Mt. Stóra-Skógfell, in parallel with the first one at Svartsengi. It is therefore still to the east of the major lava injection (Figure 17), which lies directly above the major Reykjanes fracture zone that crosses the peninsula to the sea. This inflow of lava is accompanied by an outgassing of water vapour (Figure 18).

This suggests that we are only in the early stages of a major eruption that will last for several months.

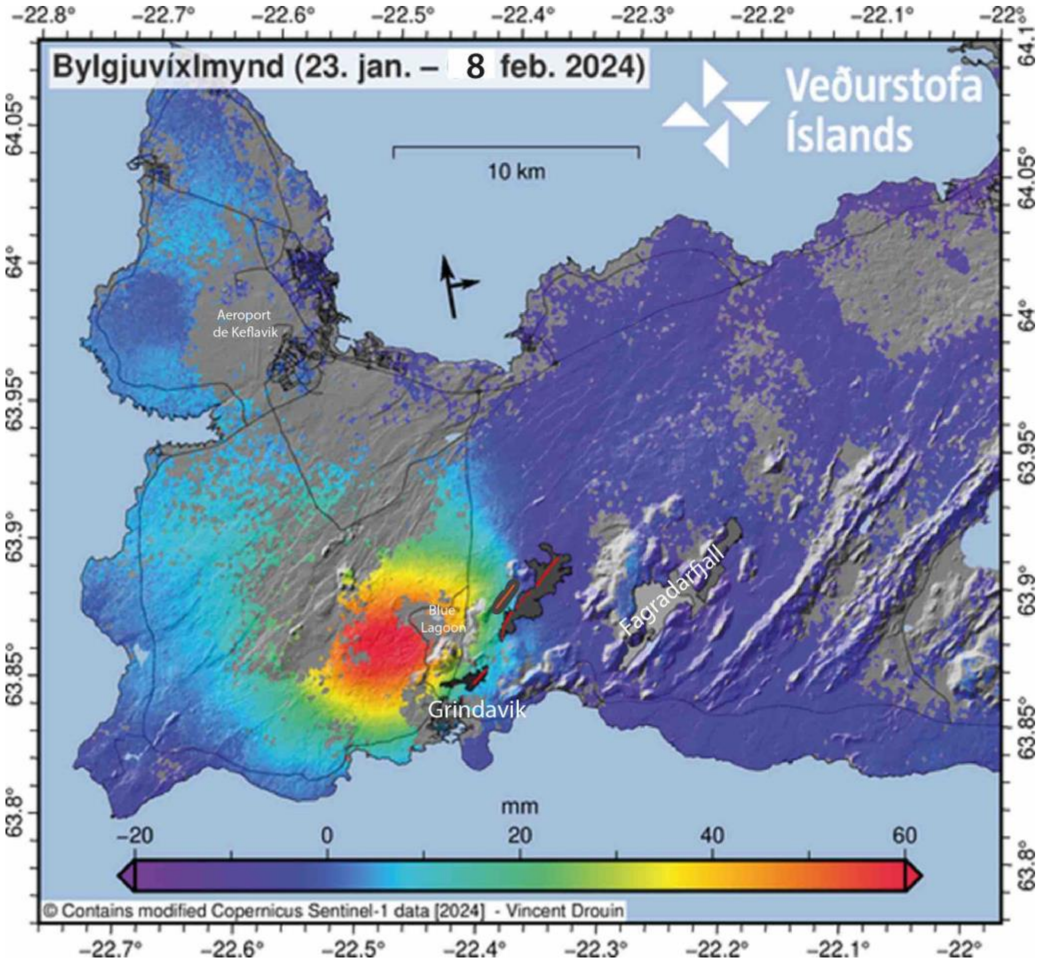

Figure 17. Latest satellite levelling, showing changes in ground surface between 23/01 and 4/02/24. The red shading shows the area of maximum uplift. Modified from Vedur 8/02/2024.

Figure 18. Outgassing of water vapour, Grindavik, 8 February 2024 (Photo: Special Unit of the National Police Commissioner).

6. Conclusion

So, contrary to what the media are saying, volcanic eruptions are not likely to increase global warming, but rather cool it down to a greater or lesser extent depending on their intensity and their powerful production of SO_2, associated with toxicity for human and animal populations. The geological history of our planet provides excellent examples of this.

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