Newsletter #6- 3rd July 2020

Amateur Geological Society of the Hunter Valley Inc.

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Editorial

First things first... another reminder about Annual Fees, which were due before June ended. See p5. I've left the reminder in, for the benefit of the slow payers.

As the COVID-19 restrictions are eased, AGSHV members can get out and about; this includes me. I've been logging the gology along the Yarraman-Kingaroy Link Trail (YKLT) with George Winter on 22nd and 23rd June, as a project of the Geological Society of Australia – Queensland Division. This 55-km foot/bike trail links two we have logged in the past, the Brisbane Valley Rail Trail (BVRT) – 161-km and the Kilkivan-Kingaroy Rail Trail (KKRT) – 88-km. Logging of the YKLT is an ongoing exercise – three more days?

As in previous Newsletters, I have put in quite a few videos (mostly YouTubes) on geological topics. There are also several summary articles condensed from scientific papers. These include contributions by Chris Morton and Richard Bale. I have tracked down the "parent" scientific paper for each article, and have included a link to them, but only for those that are free to download. I've included a few "light-hearted" articles, not so many this time, but members have submitted fewer light items than in the past.

My article on "Dykes" in Newsletter #5 included a few comments on the so-called Laki fissure eruption in 1783-1784. Icelanders call it Lakagígar – the "Craters of Laki" – after the mountain Laki, near the eruption. I found a paper written by Dr Claudia Wieners about the aftermath of this eruption (about 22% of Iceland's population died in the two-year period after the eruption, many in the ensuing famine), so I sent her an email, seeking further information. Her detailed reply gave me the incentive to write a follow-up article. This was quite a job, because the Icelandic language has a couple of letters not used in English, and there can be accents over the vowel sounds (including ý) so I had to chase-up each instance from the Windows Character Map, or an online Icelandic-English dictionary for which Dr Wieners emailed me the link. Personal names and placenames were mostly a copy-and-paste job, often needing to change the style, size, and colour of the font. All this, while trying to avoid typos in long words from a language I do not know.

I have added a few videos and links about Iceland, and geological features of an igneous intrusion in a very scenic part of southern Patagonia (southern Chile).

There are two more parts from Winston Pratt's ongoing series on the plant fossils of southeastern Australia. Watch this space (or the corresponding space in future Newsletters). I finish with reviews of a couple of books I've read recently; one on the Lakagígur eruption, and the other on what you could call atmospheric optics, phenomena "between Heaven and Earth".

As the COVID-19 restrictions are eased, we can get out-and-about once again. We don't need to remain armchair geologists only; we can go visit outcrops. I'm also picking up some of the threads that I put aside months ago, and this might delay future Newsletters. I'll keep producing them, and will welcome any contributions from members, especially reports of any field trips. So let's have some *news* for future *News*letters!

Annual Fees Reminder

Our Annual Fees for AGSHV Membership were due before 1st July 2020, which is our annual renewal date. Due to the Corona Virus, we have put off holding our usual AGM in July till later in the year. Depending on circumstances, this could be sometime in August to October, but we will advise our members when we know more. We still need all our members to pay their annual fees so that our club remains viable. Even though we are not holding regular meetings, we still have our annual insurance and IT expenses and probably others that generally crop up. As you all know, members must be financial to be able to vote in the AGM and also enjoy the benefits of our Society.

Early notification of fees and what the rates are was voted on at our last AGM:

a. Fees to remain at $35 for singles and $60 for couples (at same address). All children under the age of 18 years are covered by the family fee.

b. Fees for non-members on excursions are to remain at $5. This fee is to cover their insurance costs. Non-members can attend 2 x 1-day activities for $5 each time. Thereafter or multiday activities require full membership.

c. University Student Membership Fee is to remain at $20.

Deposit/transfer payment to our Newcastle Perm account: BSB: 650300, Account: 984228007

Name: Amateur Geological Society of the Hunter Valley Inc. (Please quote family name as reference.)

Thanks to those who have already paid.

Regards Richard Bale
AGSHV Secretary

What Else I do in my Spare Time

AGSHV Members who went "on Safari" in 2018 to the Central Queensland Gemfields will remember George Winter, who helped me on the day at Esk. George is a fellow Retired Member of the Geological Society of Australia (GSA), and also an ex-University of NSW graduate like me. We have logged the geology along a couple of trails in SE Queensland - the Brisbane Valley Rail Trail (BVRT) in 2018, and the Kilkivan-Kingaroy Rail Trail (KKRT) in 2019 - and co-led a one-day GSA field trip to the upper Brisbane and Stanley Rivers in 2018. This sort of work has been on our backburners during the COVID-19 sit-in. As the situation eases, and we are allowed out-and-about, George and I began logging the geology of the Yarraman-Kingaroy Link Trail, which links the two Rail Trails. The time we take to do the logging and write it up might delay this and future Newsletters.

Brochures for the two Rail Trails have been put on the GSA website:

https://www.gsa.org.au/Public/Divisions/QLD_subpages/Rocks_and_Landscape_Notes.aspx?WebsiteKey=a8c3ae88-b6eb-48e1-bea8-adfed361add5&hkey=648b9b05-2706-4890-b3ab-3c306c82384d

Geological Videos

Odds and Ends:

Faces of Earth - Building the Planet
or https://www.youtube.com/watch?v=y-cc8fs3xYY

Early signs of life preserved in Paleoarchean hot spring deposits
or https://www.youtube.com/watch?v=dsClgzVND7U

Rift! Geologic Clues to What's Tearing Africa Apart
or https://www.youtube.com/watch?v=3jpbArY2L78

The Lakes Of The Great Rift Valley Travel Guide (East Africa) Vacation Travel Video Guide
or https://www.youtube.com/watch?v=ZA40k4XHfHs

William Sager- The Largest Volcano in the World-Mid Pacific Ocean
or https://www.youtube.com/watch?v=8bhUEYNNr1Y

13--Introduction to Quaternary Geochronology (LIPI Indonesia lectures 2013)
or https://www.youtube.com/watch?v=wiit66aw-qw

Intra-plate Volcanism in North Queensland and eastern New Guinea: A Cryptic Mantle Plume? *or* https://www.youtube.com/watch?v=Xsh9NNq1KsY

May 2020 GSA SA Division Talks with Teagan Romyn and Dillon Brown (University of Adelaide) *or* https://www.youtube.com/watch?v=uAGnUgNrpGA

Volatiles in the Deep Earth
or https://www.youtube.com/watch?v=1JAVYYCOaH4

Geoscience: The Stavely Arc – uncovering the geological evolution of western Victoria
or https://www.youtube.com/watch?v=yPf4UAK4k14

A good series of long videos on the history of Earth, particularly the development of Life - Historical Geology – presented by Christopher White:

https://www.youtube.com/channel/UC8Px_TvQyyMCGrQjDKR90Gw/videos

Geodynamics and the Himalaya:

Past Movements of Continents across the Earth's Surface and the Ultimate Fate of Humankind *or* https://www.youtube.com/watch?v=5l080o_CXS8

Mantle dynamics and the rise and fall of mountain belts
or https://www.youtube.com/watch?v=NR87Tmn_13o

Arc-continent collision, continent-continent collision and continental subduction in the Himalaya *or* https://www.youtube.com/watch?v=6czMBlgmEg8

Geochronology and the pace of Himalayan tectonics
or https://www.youtube.com/watch?v=REWVy7DzHxI

Geological constraints on the tectonic evolution of the Himalaya
or https://www.youtube.com/watch?v=7yra8j6FqVQ

Survival of an island arc in continental collision: Kohistan
or https://www.youtube.com/watch?v=zQDjQsf2D7c

Ore deposit styles:

After an introduction in Spanish, the English language presentation starts at 2:50; skip if you want to.
[SEG] Exploration for Epithermal Gold Deposits: Discovery vs. Dogma by Jeffrey W. Hedenquist *or* https://www.youtube.com/watch?v=uVZgvMqO8qw

ODH002: Arcs, Rifts and Metallogeny – John Thompson
or https://www.youtube.com/watch?v=jU9Whigic1g

ODH019: Magmatic–hydrothermal systems and the formation of epithermal deposits – Jeffrey Hedenquist *or* https://www.youtube.com/watch?v=hkwGgvhR4mo

ODH020: Polydeformed and metamorphosed Zn-Pb-Ag deposits in volcanic–sedimentary basins–Nils Jansson *or* https://www.youtube.com/watch?v=oJqUsdh1As4

ODH017: The formation of IOCG and IOA mineral systems: A case study of El Laco, Chile – Adam Simon *or* https://www.youtube.com/watch?v=zE3pGFyGJ9Q

ODH004: Timescales and length scales in magmatic sulfide mineral systems – Stephen Barnes *or* https://www.youtube.com/watch?v=Cxa0SKNnogw

ODH007: Primary volatiles in layered intrusions and their effect on Ni-Cu-PGE mine...– Katie McFall *or* https://www.youtube.com/watch?v=S1j8p8m-WDI

ODH008: iCRAG, Basins, and Sustainable Metals – Search for the Circular Grail – Murray Hitzman *or* https://www.youtube.com/watch?v=TZO_C83a7fo

Mineral economics and metal supply:

ODH012: Future metal supply – why price rises and cost innovations alone won't save us – Rick Valenta *or* https://www.youtube.com/watch?v=JlbvAtQfsTk

ODH001: Metal production over time; the impact of major events and implications for COVID-19 *or* https://www.youtube.com/watch?v=Xva72eKGq1s

Porphyry-type deposits:

Porphyry-type ore deposits: origins, fertility indicators and exploration targeting
or https://www.youtube.com/watch?v=e00bpUYNdko

Farhad Bouzari: Porphyry Indicator Minerals
or https://www.youtube.com/watch?v=jC_plOvBwlE

Porphyry copper deposit formation in the context of transcrustal magma systems
or https://www.youtube.com/watch?v=ksihbZVu8vM

1- Geophysical Response and Geological Reality for Porphyry Cu (Mo-Au) Deposit- Richard Tosdal, 2018 *or* https://www.youtube.com/watch?v=OoPy_e97rBo

2- Pathfinder Elements in a Porphyry Cu System- Richard Tosdal, 2016
or https://www.youtube.com/watch?v=DYIImBjPK38

Earth's magmatic field, and geomagnetic reversals:

Exploring Extremes of Earth's Magnetic Field - Perspectives on Ocean Science
or https://www.youtube.com/watch?v=pP88J_nzanE

Tracking Variations in the Earth's Magnetic Field - Perspectives on Ocean Science
or https://www.youtube.com/watch?v=2uIyUOAC1kU

Geomagnetic Reversals and excursions: The origin of Earth's magnetic field - Bruce Buffett
or https://www.youtube.com/watch?v=oYHPVGuQAVw

Earth's Magnetic Field: From Satellites to Reversals - Perspectives on Ocean Science
or https://www.youtube.com/watch?v=lJxrs0v-3b0

A long Zoom forum from *The Geological Society (of London)* on the future of Geoscience. It takes everybody over 4 minutes to sort out teething troubles, and then realise they are ready to go. Skip to 4:10 if you want to:

The Future of Geoscience Summit
or https://www.youtube.com/watch?v=r-PbVAOyADc

Mars Exploration:

When Mars Was Like Earth: Five Years of Exploration with the Curiosity Rover
or https://www.youtube.com/watch?v=KP18C1zjuSs

Methane on Mars: potential origin and seepage - Giuseppe Etiope (SETI Talks 2016)
or https://www.youtube.com/watch?v=UwJxDUZ_TEQ

Geological field trip to Gale crater, Mars - Marion Nachon (SETI Talks 2016)
or https://www.youtube.com/watch?v=ItkfKRFXo3A

After a long introduction on the state of Earth's oceans that almost hijacks the John Carlson Lecture, the main topic begins with the Speaker's introduction at 7:35:

Eighth Annual John Carlson Lecture -- Searching for Ancient Life on Mars
or https://www.youtube.com/watch?v=Xv-7qZUlFMg

Roving on Mars: Revving up for Future Exploration of the Red Planet
or https://www.youtube.com/watch?v=PpBVUX_EQdA

Mars Mission Update: June 2020
or https://www.youtube.com/watch?v=bmcr2FaoWoU

LIVESCI=NCE

Newly discovered Yellowstone eruption is one of 'top 5 eruptions of all time'

By Brandon Specktor - Senior Writer

It's one of two newly detected 'supereruptions' that rocked North America (and the world) 9 million years ago.

Fountain Paint Pot, one of the many hydrothermal features fueled by the angry hotspot below Yellowstone National Park. (Image: © National Park Service)

Below the picturesque geysers and rainbow-tinted hot springs of Yellowstone National Park lurks one of the most destructive volcanoes on Earth. The gargantuan Yellowstone hotspot (also known as the Yellowstone supervolcano) has erupted at least 10 times over the past 16 million years, permanently altering the geography of North America, periodically warping Earth's climate and throwing flakes of airborne ash to every corner of the world.

Now, the discovery of two ancient supereruptions — including the single largest in the hotspot's history — reveals an unexpected trend: The Yellowstone hotspot's activity may finally be waning.

Researchers made the new discovery, which was published June 1 in the journal Geology, by analyzing a wide tract of volcanic rock coughed up by the Yellowstone hotspot across vast swaths of the western United States.

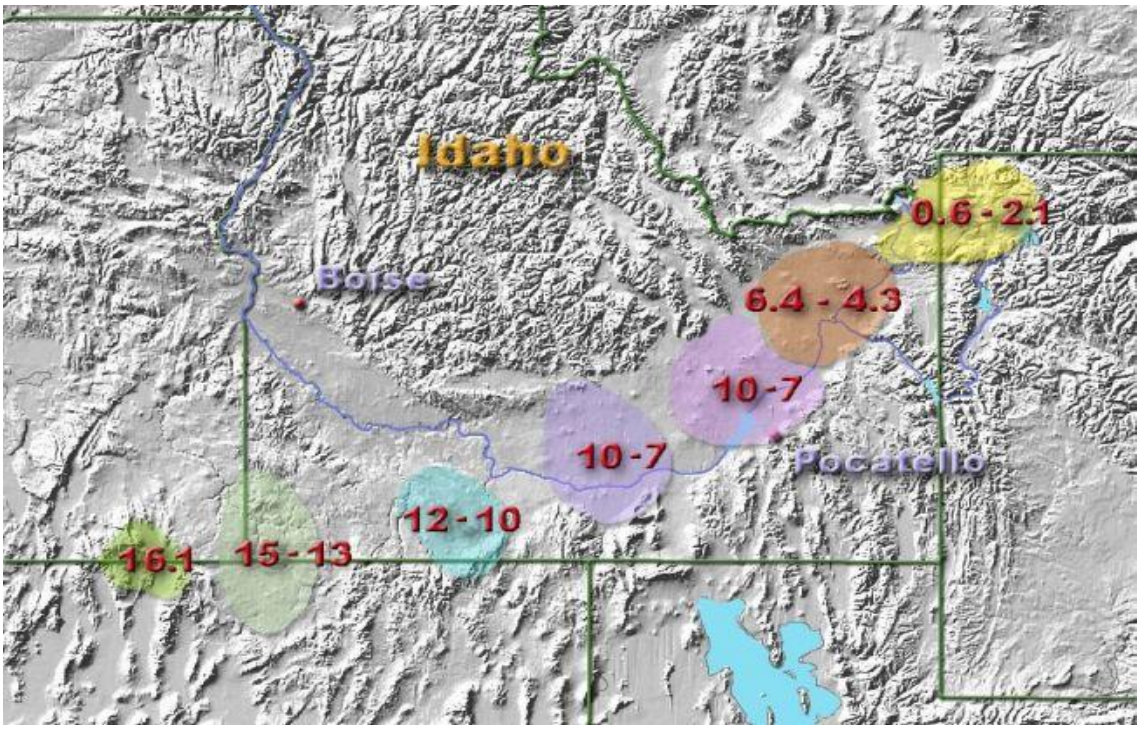
According to the study authors, the new discovery rewrites the hotspot's ancient history."It seems that the Yellowstone hotspot has experienced a three-fold decrease in its capacity to produce supereruption events," lead study author Thomas Knott, a volcanologist at the University of Leicester in England, said in a statement. "This is a very significant decline."

Related: Rainbow basin: Photos of Yellowstone's colorful Grand Prismatic Hot Spring

The sleeping giant

The Yellowstone hotspot is a mysterious blob of hot rock in Earth's mantle, currently sitting under a 1,530 square mile (4,000 square kilometers) stretch of Yellowstone National Park. While the enormous heat source fuels the park's most iconic features (including the Old Faithful geyser), it hasn't always been there. Like a big sauce pot sliding over an oven burner, Earth's ever-moving tectonic plates have shifted various parts of what are now Idaho, Nevada, Montana, Oregon and Wyoming over the hotspot during the past 17 million years, leaving a trail of ancient volcanic wreckage behind it.

The largest, most cataclysmic of these eruptions are called supereruptions. These Earth-shuddering blasts measure 8 or higher on the Volcanic Explosivity Index (VEI), which measures a volcano's relative explosivity by the height of its ash column and the volume of its leftover lava. The 1980 eruption of Mount St. Helens measured 5 on the VEI; because the scale is logarithmic, a level-8 supereruption is about 1,000 times more explosive than that.



This map shows the movement of the Yellowstone hotspot over the last 16 million years, with 7 known supereruptions marked accordingly. (Image credit: Kelvin Case via Wikimedia Commons, CC-BY-3.0)

The most recent Yellowstone supereruption occurred 630,000 years ago and formed much of the modern geography of the park; another occurred below the park 2.1 million years ago. Prior to this, the eruption history gets murkier. Researchers have recorded at least four other supereruptions over the past 12 million years, but one 2016 study estimated that at least a dozen supereruptions have occurred since then. Finding evidence for specific eruptions is tricky, as large volcanic deposits tend to overlap and can look very similar to one another.

In the new study, researchers attempted to solve that problem by performing the most in-depth analysis of North America's ancient volcanic rock tracts ever conducted. Using a multidisciplinary approach, the team correlated widely-separated volcanic deposits in Idaho and Nevada with seven characteristics, including the color of the rock, the rock's age, its chemical composition and the polarity of magnetic minerals inside the rocks.

It turned out that a smattering of volcanic deposits previously attributed to a series of small eruptions actually resulted from two gargantuan ones. The oldest — called the McMullen Creek supereruption — occurred about 9 million years ago over a 4,600-square-mile (12,000 square km) stretch of what is now southern Idaho, the researchers found.

The second, called the Grey's Landing supereruption, occurred 8.72 million years ago and was absolutely "colossal," the team wrote in the study. This eruption covered roughly 8,900 square miles (23,000 square km) of what is now southern Idaho and northern Nevada — making it the single largest eruption of the Yellowstone hotspot ever detected.

"The Grey's Landing supereruption … is one of the top five eruptions of all time," Knott said. "[It] enameled an area the size of New Jersey in searing-hot volcanic glass that instantly sterilized the land surface. Particulates would have choked the stratosphere, raining fine ash over the entire United States and gradually encompassing the globe."

This epic eruption appears to have been about 30% larger than the hotspot's next-biggest eruption, which occurred 2.1 million years ago. There are now six recorded supereruptions that occurred during the Miocene epoch, between 23 million and 5.3 million years ago. These eruptions occurred, on average, every 500,000 years, the researchers wrote. By comparison, the two supereruptions that occurred since then are separated by 1.5 million years.

This reduced rate of giant eruptions doesn't mean we're off the hook. Another supereruption could potentially happen at any time — however, Knott added, it will likely take hundreds of thousands of years to occur. Only by diligently monitoring seismic activity around the park will scientists have a clue as to when it's coming.

(*Thanks Chris Morton*)

The above is a lay-person's summary; the original article is in the journal **Geology**, rather heavy-duty reading:

Discovery of two new super-eruptions from the Yellowstone hotspot track (USA): Is the Yellowstone hotspot waning? *or*

https://pubs.geoscienceworld.org/gsa/geology/article/doi/10.1130/G47384.1/586793/Discovery-of-two-new-super-eruptions-from-the

Open the link, then click on the PDF button, and read the paper on-screen, or download and print it.

If you want more about the track of the Yellowstone hot-spot plume track, try these:

Yellowstone Plume Head: Postulated Tectonic Relations to the Vancouver Slab,Continental Boundaries, and Climate

or

https://www.researchgate.net/publication/215608601_Yellowstone_plume_head_Postulated_tectonic_relations_to_the_Vancouver_slab_continental_boundaries_and_climate

And:

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12 Supereruptions Pockmark Path of Yellowstone Hotspot

By Becky Oskin March 28, 2016

A deep canyon in southern Idaho exposes volcanic deposits left behind by several different eruptions.

(Image: © David Finn, University of California, Santa Cruz)

Up to 12 massive volcanic blasts occurred between 8 million and 12 million years ago in Idaho's Snake River Plain, leading up to today's Yellowstone supervolcano, new research reveals.

A dozen of these ancient supereruptions took place along the Yellowstone hotspot track, researchers reported Feb. 10 in the journal Geological Society of America Bulletin. The trail of eruptions marks where the North American tectonic plate sailed over a superhot blob of mantle rock called a hotspot. (The mantle is the rocky layer between Earth's crust and core.)

Though learning of more supereruptions in the West may seem unsettling, the findings do not suggest that Yellowstone today is any more hazardous than previously suspected. Instead, the researchers said they are now studying whether Yellowstone is actually dwindling in strength compared to the larger and more violent eruptions that occurred 12 million years ago. [See photos of how researchers studied the Snake River Plain's ancient supereruptions]

"While it is well-known that Yellowstone has erupted catastrophically in recent times, perhaps less widely appreciated is that these were just the latest in a protracted history of numerous catastrophic supereruptions that have burned a track along the Snake River eastwards from Oregon to Yellowstone," lead study author Tom Knott, a geochemist at the University of Leicester in the United Kingdom, said in a statement.

The rainbow-colored hot springs and high-flying geysers at Yellowstone National Park in Wyoming are fed by an underground reservoir of molten rock. The park formed in a series of eruptions during the past 2 million years. Powerful explosions 640,000 years ago created a giant crater and spewed ash as far as New York. The most recent eruption occurred about 70,000 years ago.

Until now, geologists did not have a firm count of the number of eruptions in Idaho and surrounding states that predate Yellowstone, nor a good estimate of the size of each outburst. The new study suggests there are fewer volcanic eruptions in the central Snake River Plain than previously believed. However, the 12 recorded giant eruptions were likely "significantly larger" than other studies suggested, the researchers said.

The craters formed by these giant eruptions are now buried under sediment and younger lava flows. To better understand past eruptions, Knott led an international team of volcano experts in analyzing the many layers of lava plating central Idaho. The researchers fingerprinted different eruptions by testing for changes in the chemical makeup of the rocks and the rocks' magnetic orientation. (Every volcanic eruption produces lava with a unique chemical makeup.) The team correlated these volcanic deposits across hundreds of miles (thousands of kilometers).

With the new correlations, the team reduced the number of eruptions thought to have originated from the central Snake River Plain by more than half. The research also revealed that these eruptions were significantly larger than suspected, and may have rivaled those at Yellowstone. [Countdown: History's Most Destructive Volcanoes]

Hotspots seem to stay in one place while the Earth's crust trundles over them. The crustal movement creates a line of volcanoes, like the crumbs left behind by a fairytale Hansel and Gretel. The Hawaiian islands and Emperor Seamounts are textbook examples of hotspot volcanism.

One of the supereruptions from the Yellowstone hotspot track, called the Castleford Crossing eruption, now covers an area more than 5,400 square miles (14,000 square km) in southern Idaho, and is more than 4,200 feet (1.3 km) thick in the caldera of the Castleford Crossing supervolcano. The eruption was likely 10 times as powerful as Mount St. Helens' 1980 blast, the study reported.

"The size and magnitude of this newly defined eruption is as large as, if not larger than better-known eruptions at Yellowstone, and it is just the first in an emerging record of newly discovered supereruptions during a period of intense magmatic activity between 8 [million] and 12 million years ago," Knott said.

Follow us @livescience, Facebook & Google+. Original article on Live Science.

For more information on the Yellowstone (super)volcano see these links (repeated from AGSHV Newsletter #4:

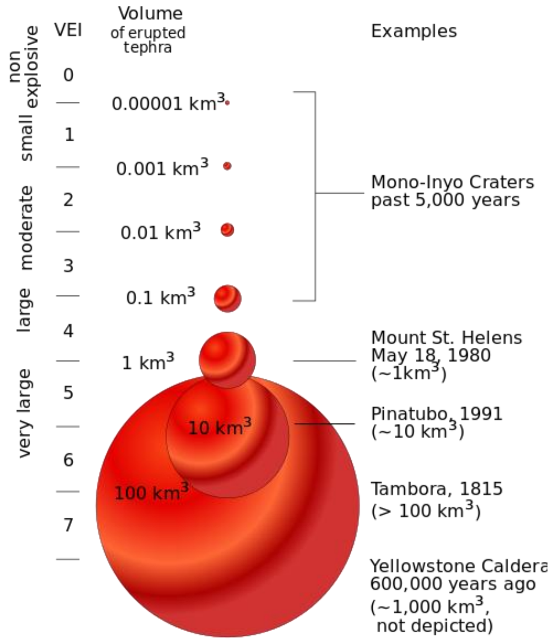
Yes! Yellowstone is a Volcano
or https://www.youtube.com/watch?v=-GRJK0k1sBw

Yellowstone Eruptions
or https://www.youtube.com/watch?v=pbrps7r-hmY

The Yellowstone Volcano: Past, Present and Future
or https://www.youtube.com/watch?v=gNdMZ6CGKm8

You Don’t Need to Worry About Yellowstone (or Any Other Supervolcano)
or https://www.youtube.com/watch?v=v0c7wcpJslg

For completeness here is a summary of the Volcanic Explosivity Index (VEI)



https://en.wikipedia.org/wiki/File:VEIfigure_en.svg

If you want/need something simpler, try Nick Zentner's YouTube videos:

'Nick From Home' Livestream #70 – Yellowstone Geology
or https://www.youtube.com/watch?v=5GOFt2-3Ij8

'Nick From Home' Livestream #20 – Supervolcanoes
or https://www.youtube.com/watch?v=hZC_I1XoYS0&t=1092s

'Nick From Home' Livestream #49 - Hot Spot Volcanism
or https://www.youtube.com/watch?v=46qt4MQxImc&t=4984s

'Nick From Home' Livestream #35 - Volcanoes & Climate
or https://www.youtube.com/watch?v=66bz9bENwZk&t=7s

Australia has also had chains of volcanoes:

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Hidden Superchain of Volcanoes Discovered in Australia

[Note: superchain of volcanoes, NOT chain of supervolcanoes – Bill D'Arcy]

By Tia Ghose September 14, 2015

Scientists recently realized that separate chains of volcanic activity in Australia were actually caused by a single hotsput lurking under the Earth's lithosphere. The new superchain, called the Cosgrove Volcanic Track, spans 1,240 miles (2,000 kilometers)

(Image: © Drew Whitehouse, NCI National Facility VizLab)

Scientists have just found the world's longest chain of volcanoes on a continent, hiding in plain sight.

The newly discovered Australian volcano chain isn't a complete surprise, though: Geologists have long known of small, separate chains of volcanic activity on the island continent. However, new research reveals a hidden hotspot once churned beneath regions with no signs of surface volcanism, connecting these separate strings of volcanoes into one megachain.

That 1,240-mile-long (2,000 kilometers) chain of fire spanned most of eastern Australia, from Hillsborough in the north, where rainforest meets the Great Barrier Reef, to the island of Tasmania in the south.

"The track is nearly three times the length of the famous Yellowstone hotspot track on the North American continent," Rhodri Davies, an earth scientist at Australian National University, said in a statement. [See Amazing Photos of the World's Wild Volcanoes]

String of volcanoes

Scientists had long known that four separate tracks of past volcanic activity fringed the eastern portion of Australia, with each showing distinctive signs of past volcanic activity, from vast lava fields to fields awash in a volcanic mineral called leucitite that's dark gray to black in color. Some of these regions were separated by hundreds of miles, leading geologists to think the areas weren't connected.

But Davies and his colleagues suspected that the Australian volcanism had a common source: a mantle plume that melted the crust as the Australian plate inched northward over millions of years. (Whereas many volcanoes form at the boundaries of tectonic plates, where hot magma seeps up through fissures in the Earth, others form when mantle plumes, or hot jets of magma, at the boundary between the mantle and Earth's core reach the surface.)

To bolster their hypothesis, Davis and his colleagues used the fraction of radioactive argon isotopes (versions of argon with different atomic weights) to estimate when volcanic activity first appeared in each of these regions. They combined this data with past work showing how the Australian plate had moved over the millennia. From this information, they could estimate where and when volcanism affected certain regions.

The team found that the same hotspot, likely from a mantle plume, was responsible for all of the volcanic activity crossing eastern Australia. The new volcanic chain, which the team dubbed the Cosgrove volcanic track, was formed between 9 million and 33 million years ago. (None of the volcanoes on Australia's mainland have been active during the recent past.)

However, there are large gaps in volcanic activity on the surface of this track. To understand why, the team modeled the thickness of the lithosphere, the stiff layer that forms the upper mantle and Earth's crust.

Plate thickness and melt

It turned out that, at certain spots along the Australian tectonic plate, the lithosphere was so thick that the mantle plume couldn't permeate all the way through to create melting the showed up at Earth's surface. However, at other points, the lithosphere was just barely thin enough to show the tiniest hints of magma at the surface. One of these spots is a region of northern New South Wales rich in leucitite, which contains high concentrations of potassium, thorium and uranium. Surface volcanism appeared only when the lithosphere was less than 81 miles (130 km) thick, the researchers reported today (Sept. 14) in the journal Nature.

The new finds could help scientists model how mantle plumes interact with the continental crust to create volcanism.

"Now that we know there is a direct relationship between the volume and chemical composition of magma and the thickness of the continent, we can go back and interpret the geological record better," study co-author Ian Campbell, also an earth scientist at Australian National University, said in the statement.

Follow Tia Ghose on Twitterand Google+. Follow Live Science @livescience, Facebook & Google+. Original article on Live Science.

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Hope diamond formed stunningly close to Earth's core

By Rafi Letzter - Staff Writer an hour ago [hot off the press, a couple of weeks earlier!]

New evidence suggests these blue stones originated surprisingly close to Earth's core.

A photograph shows the Hope diamond, taken from India in the 1600s. New evidence suggests this diamond originated hundreds of miles below Earth's crust.

(Image: © Photo courtesy of the Smithsonian Institution)

Two of the world's most famous diamonds may have originated super deep below Earth's surface, near the planet's core.

All of Earth's natural diamonds first form deep underground from our perspective on the surface. But from the perspective of this planet's great bulk, their usual births occur relatively far from the core. Zest the Earth like a lemon, and you'd uncover diamonds growing at the bottoms of tectonic plates. Those diamonds form about 90 to 125 miles (150 to 200 kilometers) deep, under pressure that exists just where the crust meets the more fluid outer mantle, or middle layer of the planet. No mines reach that far underground, but some of those diamonds do make their way up to where humans can reach them.

The "Hope" diamond, a large and famous stone, as well as the "Cullinan" diamond, the largest rough gemstone ever found, are different. They're "super deep" stones, new research confirms. A 2018 paper showed that these boron-blue gemstones likely originated somewhere in the planet's hot "mantle," a region between the crust and the liquid outer core of the planet, Live Science previously reported This new research shows that, at least sometimes, the stones form deep in this hot zone.

The research presented today (June 24) at the Goldschmidt geochemistry conference, finds remnants of a mineral called bridgmanite in two less famous diamonds of the same types as the famous gemstones. *[Bridgmanite is (Mg,Fe)SiO_3, like one variety of pyroxene, but the extremely high pressure deep in Earth's interior "re-aligns" the crystal structure to a much denser arrangement – Bill D'Arcy.]*

All diamonds are crystals made of carbon and various chemical impurities. The type of any specific diamond is determined by the impurities and other conditions present during its creation. So any two diamonds of the same type likely formed in similar conditions.

Bridgmanite is a very common mineral inside Earth, but it doesn't form in the crust or even the upper mantle. "What we actually see in the diamonds when they reach [the] surface is not bridgmanite, but the minerals left when it breaks down as the pressure decreases," Evan Smith of the Gemological Institute of America said in a statement. "Finding these minerals trapped in a diamond means that the diamond itself must have crystallized at a depth where bridgmanite exists, very deep within the Earth."

This discovery, the researchers said, suggests both large blue stones originated in the lower mantle, a fluid zone extending from 410 miles (660 km) deep all the way to the planet's liquid outer core.

The first, a 20-carat "type IIb blue diamond" from South Africa, showed evidence of bridgmanite under examination with laser light. The Hope diamond, at 45.52 carats, is a larger example of the same diamond type.

Another diamond, a 124-carat stone about the size of a walnut, is called a "CLIPPIR" diamond (which stands for Cullinan-like, Large, Inclusion-Poor, Pure, Irregular, and Resorbed). It's from Lesotho, a country encircled by South Africa. And, as its type suggests, it is like the 3,106.75-carat Cullinan. Researchers already knew that CLIPPIRs came from very deep below the crust, but this study offers the first direct evidence that they come from the lower mantle.

Neither the Hope nor the Cullinan diamonds were studied as part of this research. But the researchers said that what's true of the less-famous stones is likely true of the more-famous stones as well.

The Cullinan diamond no longer exists in its original large state, having long since been chopped up into smaller stones for sale. The largest two of these is now part of Queen Elizabeth II's "crown jewels."

The massive rough diamond turned up in 1905 just 18 feet (5.5 meters) below the surface at the British-owned Premier Mine in South Africa — a long way from its birthplace in the lower mantle. It was quickly shipped out of the region as part of the British imperial project that exploited and abused Black laborers in order to extract the region's mineral wealth, according to Rapaport, an international corporate network that serves the jewelery market.

The Hope diamond's precise origins are much hazier, but according to the Smithsonian Institution (which now has custody of the diamond), workers at the Kollur mines in India likely discovered the stone before it was sold to the French merchant Jean Baptiste Tavernier in 1668.

Karin Hofmeester, a historian at the International Institute of Social History in Amsterdam, wrote in an essay that men, women and children worked by the 10s of thousands in these dangerous mines at the time for slim wages and food. It's not clear who was responsible for the Hope diamond's discovery or where precisely it turned up.

Researchers do know that when it was found it weighed 122.2-carats, according to the Smithsonian. Once cut to its current state, the Hope passed into the hands of the French royal family, wealthy British collectors, and then American businessmen before ending up at the Smithsonian — a world away from both its lower mantle point of origin and the mine in India where it was discovered.

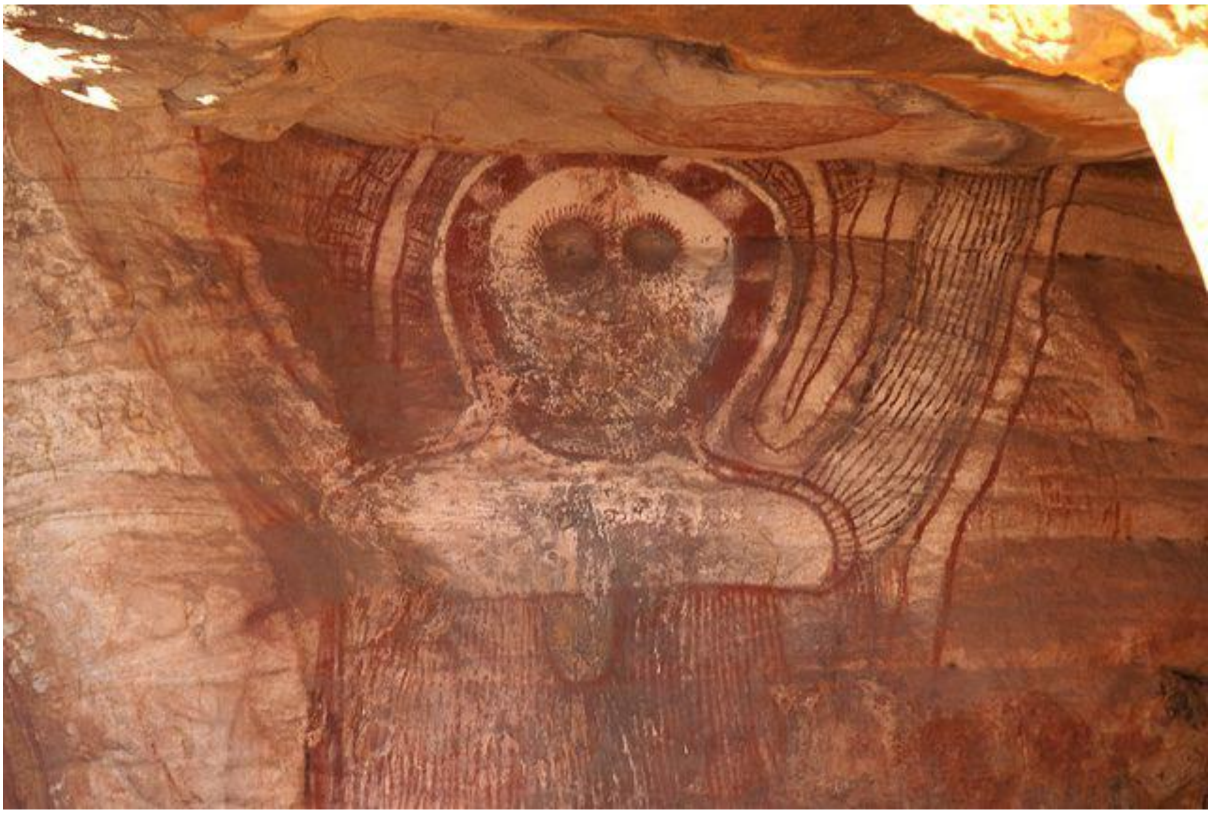
Originally published on Live Science.

[*An interesting social phenomenon in the above... a direct dig at the "British Imperial project that exploited and abused Black laborers", but no such dig at the sultans who owned the Indian mines – Bill D'Arcy.*]

LIVESCI=NCE

Did Mega-Drought Kill Ancient Aboriginal Culture?

By Tia Ghose January 10, 2013



After a 1500-year drought, rock art changed from an earlier style called Gwion and the Wandjina paintings emerged. The Wandjina figures have round faces with big eyes.

(Image: © Jbenwell | Flickr.com)

A 1,500-year drought in Australia may have led to the demise of an ancient aboriginal culture, a new study suggests.

The results, published Nov. 28 in the journal Geophysical Research Letters, show that geological traces of a mega-drought in the northwest Kimberley region of Western Australia coincide with a gap and transition in the region's rock art style.

The finding suggests that the people who lived prior to the drought, called the Gwion, either left the region or dramatically altered their culture as a result of the drought, and a new culture called the Wanjinda eventually took its place.

"There is this significant gap in rock art. A possible reason for that is that the climate at that time changed so markedly that the artists who produced the Gwion Gwion art moved on from the Kimberley region," said study co-author Hamish McGowan, a climatologist at the University of Queensland in Australia.

But not everyone agrees with that interpretation. While the evidence for a drought is very convincing, archaeological sites show continuous occupation during that time, said Peter Veth, an archaeologist at the University of Western Australia who is an expert in the Kimberley's rock art and was not involved in the study.

"They reconfigure themselves on the land and often do portray things quite differently, but I don't see it as a different people," Veth told LiveScience.

Ancient inhabitants

Aboriginal cultures have inhabited Northwest Australia for the past roughly 45,000 years, McGowan said. But at least 17,000 years ago during the Pleistocene Era, a culture called the Gwion began depicting aspects of their life on the rocks in the region. The Gwion art depicted some extinct animals (such as a marsupial lion that went extinct during the last ice age) but also groups of slim figures in what look like ancient celebrations. [Image Gallery: Europe's Oldest Rock Art] The Gwion culture flourished in Australia at least 17,000 years ago, and often depicted slim figures in large groups.

(Image credit: TimJN1 Wikimedia Commons)

But between 5,000 and 7,000 years ago, traces of the Gwion rock art disappeared, and it wasn't until around 4,000 years ago when a new style of rock-art painting called the Wandjina, which depicts round faces with big eyes, emerged. It is still practiced today.

Pollen record

To understand why the rock art changed, McGowan and his colleagues analyzed sediments drilled from Black Springs, Australia. They found that around 6,300 years ago, the type of pollen started to change, suggesting a transition from a lush environment to one characterized by scrubby forests and open grasslands. The sediments also show an increase in dust, suggesting much drier conditions.

The results painted a picture of an ancient mega-drought that roughly coincided with the disappearance of Gwion art, McGowan said.

"The northwest of Australia can undergo very substantive natural changes in climate, which in the past have severely impacted Aboriginal society," he told LiveScience, adding the climate change and disappearance of Gwion art suggest these people left the region.

But while it's likely that the drought radically altered the local societies, the rock art from the area isn't dated well enough to make conclusions about the complete disappearance of the culture, Veth said. What's more, archaeological evidence suggests the area was continuously occupied, he told LiveScience. For instance, archaeologists find very similar stone tools throughout the drought, Veth said. "They have identified a very interesting climate episode and it does seem to correlate with this switch — and that's the word I would use — a switch in the way people are portraying art," he said.

Follow LiveScience on Twitter @livescience. We're also on Facebook & Google+.

(*Thanks Chris Morton*)

The original article, published in Geophysical Research Letters (Volume39, Issue 22, 28 November 2012) is:

Evidence of ENSO mega-drought triggered collapse of prehistory Aboriginal society in northwest Australia

or https://agupubs.onlinelibrary.wiley.com/doi/10.1029/2012GL053916

Read on-line, or click the PDF button to download an advertisement-free easy-to-read copy.

Ancient Aboriginal underwater archaeological sites discovered, and a new frontier for study

Scientists have discovered Australia's first ever ancient Aboriginal underwater archaeological sites, settled on the sea bed for thousands of years.

Hidden relics, including hundreds of stone tools and grinding stones, have been found at two sites off Western Australia's remote Pilbara region, close to the Burrup Peninsula which is renowned for its ancient rock engravings.

For me, this is the find of a lifetime," said lead archaeologist Associate Professor Jonathan Benjamin from Flinders University.

"I'm absolutely thrilled that we went out looking for something that we didn't know if we could find or not.

"But we have actually, really succeeded.

Coastline swallowed by the sea

Australia's landmass used to be much larger, almost a third bigger, before sea levels rose and drowned the landscape between 7,000 and 18,000 years ago after the last ice age.

The sea level has risen 130 metres during that time, shrinking the country's land mass by two million square kilometres and handing it to the sea.

"The scientific information we can gain from these sites has the potential to rewrite Australian history," Dr Benjamin said.

Chelsea Wiseman and Jonathan Benjamin after they discovered Australia's first underwater

Aboriginal archaeological sites. (ABC Pilbara: Tia Calvo)

The Australian Archaeological Association described the research, titled The Deep History of Sea Country, as "highly significant".

"I think it is a significant advance in understanding the huge cultural landscapes around the coast of Australia," association spokesman Professor Peter Veth said. He said the confirmation that the sites exist would likely lead to further research in other locations.

"I would not be surprised if traditional owner corporations and researchers look at some of their sea countries throughout areas like the northern Great Barrier Reef, Shark Bay, and possibly the south-west [of WA] to try and match up some of those oral traditions and histories people have of the sea encroaching," he said.

Australia's oldest underwater archaeology

The discoveries of 269 artefacts at Cape Bruguieres and an 8,500-year-old underwater freshwater spring at Flying Foam Passage off Dampier were published today in the open access scientific journal PLOS One:

https://journals.plos.org/plosone/article?id=10.1371/journal.pone.0233912

It followed a three-year investigation by teams from Flinders University, University of Western Australia, James Cook University, Airborne Research Australia, and University of York in the United Kingdom.

The research was conducted with the Murujuga Aboriginal Corporation, representing five groups who are traditional custodians or Ngurra-ra Ngarli for the Burrup Peninsula.

Scientists hope the discoveries and future finds will help shed more light on Aboriginal ways of life thousands of years ago. PHD student Chelsea Wiseman described it as a new frontier for Australian archaeology.

"[It] has the potential to really change what we understand about Australian history," she said.

Oldest evidence of a moving tectonic plate found in Australia

NATIONAL GEOGRAPHIC

SCIENCE

Plate tectonics sculpted Earth's surface and may have set the stage for the emergence of life. A new study offers clues about how this planetary churning began.

BY MAYA WEI-HAAS

PUBLISHED APRIL 22, 2020

In the desolate landscape of western Australia, a rocky outcrop that formed more than three billion years ago is giving geologists an unprecedented look at the early churnings of our planet. These rocks—among the most ancient in the world—contain what may be the oldest direct evidence of the movement of tectonic plates.

The rocks formed when magma oozed up from beneath Earth's surface into a now-vanished ocean, cooling and hardening into a bulbous mass. As detailed in a new study in *Science Advances*, magnetic signatures preserved in the rock suggest the region was inching across the planet 3.2 billion years ago at similar speeds to tectonic plates today—nearly half a billion years earlier than previous evidence of such movement.

"This is kind of the smoking gun," says geochemist Annie Bauer of the University of Wisconsin-Madison, who was not part of the new study. "This is the most important evidence we can get [of early plate motion]."

Today, Earth's tectonic plates continually shift and migrate—a process that builds mountains, carves basins, and drives volcanic eruptions. These motions sculpted a variety of ecological niches, including hydrothermal vents at the bottom of the sea and boiling pools of water on the surface—the types of environments where life is believed to have formed.

"While piecing together the story of plate tectonics, we're helping to piece together our own origin story," says the study's lead author Alec Brenner, a Ph.D. student at Harvard University.

Hunting for ancient rocks

Our planet coalesced from a swirling cloud of gas and dust some 4.5 billion years ago, and initially it was scorching hot. Oceans of molten rock glowed on the surface, and volcanoes likely spit lava into the air. But Earth soon began to cool, and over tens of millions of years, the surface hardened into a crust.

Scientists believe this early crust was a singular cap enveloping the planet, much like the surface of Mars today. At some point—estimates vary from roughly four billion to a billion years ago—this cap fractured into a global jigsaw of crust, with pieces crashing into each other and driving rock down into the mantle or up into the sky. Plate tectonics was born.

But very little is known about how and when this transition took place. Plate tectonics continually recycles Earth's rock, melting crust and dredging up fresh lava, which erases evidence of the distant past. "Basically, the first half of Earth's history is represented today by only about 5 percent of surface rocks," Brenner says.

Many studies of early plate tectonics infer motion by identifying chemical clues, such as the composition of ancient minerals that point to formation within subduction zones—where one tectonic plate plunges beneath another. But to chart the movement of plates, scientists have to use other measures such as the preserved magnetic signatures of the rocks.

In 2016, Brenner's future advisor at Harvard, paleomagnetist Roger Fu, began poring over maps of Australia in search of ancient rocks where he might use these magnetic fingerprints to directly measure the early drift of Earth's crust. Fu and a colleague eventually homed in on a site: The Honeyeater basalt of western Australia. In the summer of 2017, Brenner and Fu ventured into the Australian outback to hunt down the 3.2-billion-year-old rocks.

They drilled around a hundred cores of rock from various parts of the outcrop, noting the position and orientation for each and combining them with more than a hundred previously collected samples. Back in the lab, they analyzed the magnetic signatures of each sample, encoded in iron-rich minerals that orient themselves like tiny compass needles as they crystallize.

After accounting for changes in the rock's position since it formed—a process known as a fold test—the compass needles all aligned, suggesting they represented the true ancient magnetic signature of the rock. "Maybe we are on to something here," Fu recalls thinking.

Tectonic beginnings

The team compared the calculated position of the Honeyeater basalt to a previously analyzed outcrop of rock nearby, which is slightly older and contains an earlier magnetic signature. The analysis revealed that the crust was shifting about 2.5 centimeters each year at the time these rocks formed.

That rate "would be totally run-of-the-mill ordinary for a plate tectonic setting like what we have on the modern Earth," Brenner says.

The motion may have occurred while Earth was still covered by a single cap of crust, although the speed is faster than what would be expected if that were the case. The find instead hints that just over a billion years after our planet formed, plate tectonics could have already been revving up.

However, the evidence from this one location does not necessarily mean that plates were moving all around the world, Brenner says. Plate tectonics likely began in fits and starts, with crust breaking apart and moving in some areas earlier than others.

"It might be kind of a patchy process," says Bauer, who recently published a study demonstrating the uneven beginnings of early plate movements.

The mechanism driving this early movement is also unclear, says paleomagnetist John Geissman of the University of Texas at Dallas, who was not involved in the new study. One major force behind modern plate motions is the tug of rocky slabs as they plunge into the mantle at subduction zones. But other processes could have been at play billions of years ago, such as rising plumes of magma forcing rocks apart at the surface.

If these early stirrings 3.2 billion years ago were indeed the beginnings of plate tectonics, they point to a remarkably early start for Earth's geologic churn, which was a pivotal point for the evolution of life as we know it. Plate tectonics acts like a planetary thermostat, cycling greenhouse gasses from the deep Earth to the atmosphere. It drives volcanic eruptions, which dredge up fresh nutrients from deep underground. It may even have played a role in piping oxygen into the skies.

By understanding the origins of plate tectonics, "you can try to nail down timing of events that were crucial for the development of life on this planet," says geochemist Val Finlayson from the University of Maryland, who was not part of the study.

To do that, scientists are continuing to scour the earth for more signs of ancient movement. Brenner says: "We are actually, as we speak, running through the data analysis for another [rock] unit."

The original research paper is:

Paleomagnetic evidence for modern-like plate motion velocities at 3.2 Ga
or https://advances.sciencemag.org/content/advances/6/17/eaaz8670.full.pdf

See a sunset on Uranus, other worlds (and a moon, too) in this NASA simulator

If you know enough about Earth's atmosphere you can model the appearance of sunset. The same applies to other planets (and moons).

On the website of

SPACE.com

there is a sunset simulator. Click the following link, and scroll down to the video of simulations:
https://www.space.com/sunset-on-uranus-and-more-nasa-simulator-videos.html

The root of anomalously specular reflections from solid surfaces on Saturn's moon Titan

On Earth we have the hydrological Cycle (or Water Cycle): H_2O as a gas phase (water vapour) evaporates from oceans and lakes, condenses to liquid cloud droplets, which coalesce to form rain, unless the temperature is so low that ice forms (snow), and falls to pile up as ice-caps and glaciers. Saturn's moon Titan is so far from the sun that an identical hydrological system couldn't operate there; all H_2O would be frozen permanently as ice. On Titan, the temperature and atmospheric chemistry is appropriate for an analogous cycle to exist using methane. Earth-based radiotelescopes were used to beam radar at Titan. Specular radar reflections ("shinyness", or mirror-image reflections) from very smooth, flat areas near Titan's equator were interpreted as methane lakes surfaces. The Cassini space probe found lakes on Titan (some bigger than the Great Lakes shared between Canada and USA), but none coinciding with the equatorial specular radar reflections. This situation remained an anomaly for years; however a new interpretation is that they may be "dried" lakes or seas with flat beds.

See:

nature
communications

https://www.nature.com/articles/s41467-020-16663-1

Fun, Fun, Fun

Secretary **Richard Bale** has sent in links to two marvellous websites, where you could spend days browsing. Here is some wonderful Blue Mountains history, as well as more recent stuff; and a wonderful cornucopia of geological items: Field Geology of the Shoalhaven District, and New England items. There is so much here that I could have limited Newsletter #6 to just this paragraph (and the Annual Fees Reminder).

John's Blue Mountains Blog
or https://johnsbluemountainsblog.blogspot.com/
Make sure you dig around in the Blog Archive.

John's New England Minerals and General Geology Blog
or https://johnsnewenglandminerals.blogspot.com/2013/12/list-of-all-blog-entries-to-date.html

(Thanks Richard Bale)

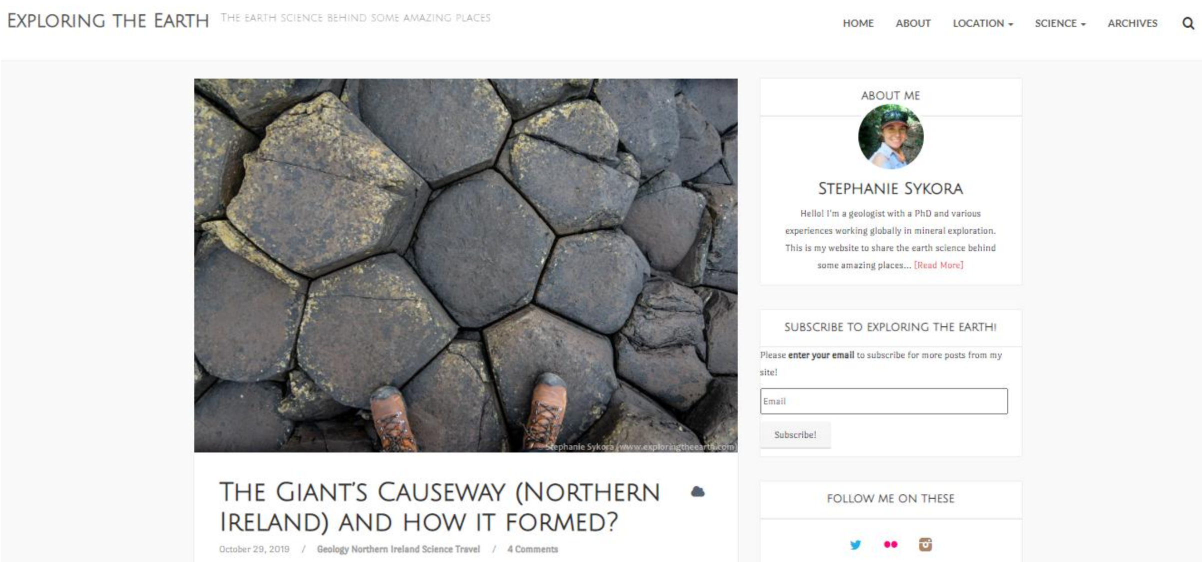
Something humorous from President Chris Morton:

First Elevator1.mp4

(*Thanks Chris Morton*)

Not Necessarily So

You've probably seen "explanations" of columnar joints in basalts that talk of contraction during cooling to produce regular hexagonal prismatic columns. This is an overstatement of the case... so many of the columns aren't regular hexagons, but rather irregular pentagons, as this photo from Stephanie Sykora's website http://exploringtheearth.com/ shows:



There are several pentagonal prisms, and many of the hexagons are far from regular.

Gennady Tkachenko-Papizh, a Prodigy

Elaine Collier sent a fascinating YouTube video to Secretary Richard Bale, who forwarded it to me. I won't embed it into the Newsletter, because of the size of the file, so I'll provide the link below:

Gennady Tkachenko Papizh ~ Incredible Voice original version
or https://www.youtube.com/watch?v=MInTxF2sgqM&feature=youtu.be

Look over to the right in the "Recommended for You" section for more videos from Gennady.

(*Thanks, Elaine and Richard*)

Here is more from Gennady:

Gennady Tkachenko Papizh ~ Incredible Voice original version
or https://www.youtube.com/watch?v=MInTxF2sgqM&feature=youtu.be

STUNNING Pure VOICE Singing The Earth's Song | All Genadi Tkachenko's Auditions | Got Talent Global
or https://www.youtube.com/watch?v=g9VjiTDbVDk

Gennady Tkachenko Papizh - Jungle Dream / Urban Flex feat (Original Mix)
or https://www.youtube.com/watch?v=i63VK7aEJpc

Gennady Tkachenko-Papizh. PILGRIM
or https://www.youtube.com/watch?v=bUrjQZfSqMo

I know amazing singers from other cultures too:

Mongolian Singing

Here is Enkhjargal Dandaarvanchig singing and playing his morin khuur:
Mongolian Overtone Singer , the most spetacular singer you ever see.
or https://www.youtube.com/watch?v=HwANedEkqaY

Su-Ren Baiju is another wonderfully talented Mongolian throat singer (and morin khuur player):
Mongolian Incredible Throat Singing Part 1
or https://www.youtube.com/watch?v=rg_HAPEhIAI

Mongolian Incredible Throat Singing Part 2
or https://www.youtube.com/watch?v=TBYItNSP_KQ

Another singer (whose name I don't know), accompanied by a Mongolian hammered dulcimer:
Mongolian voice: Khoomii
or https://www.youtube.com/watch?v=VKqP2skE6-Y

A video about the folk tradition of Khöömei:
The Mongolian traditional art of Khöömei
or https://www.youtube.com/watch?v=hV8EJOvvPvY

Throat singing, otherwise known as polytonic overtone singing is found in other cultures; Tuva (a small republic – ex-USSR – across from the northwest border of Mongolia); the Inuit (also called Eskimos) of eastern Canada, and even some talented Europeans.

Location of Tuva.

Here is German singer Anna-Maria Hefele, a member of the ensemble Supersonus performing "Ritus":
RITUS – SUPERSONUS
or https://www.youtube.com/watch?v=s4BJ3wng6Mk
with Eva-Maria Rusche on harpsichord, Anna-Liisa Eller on kannel (Estonian plucked dulcimer or zither), Wolf Janscha on Jew's harp, and Marco Ambrosini on Jew's harp and nyckelharpa (Swedish keyed and bowed "harp".

And "Rosary Sonata":
Rosary Sonata 1 – SUPERSONUS
or https://www.youtube.com/watch?v=ysSLfwEk5l4

Anna-Maria explains and teaches overtone singing in several videos, including:
polyphonic overtone singing - Anna-Maria Hefele
or https://www.youtube.com/watch?v=vC9Qh709gas

and:
polyphonic overtone singing - explained visually
or https://www.youtube.com/watch?v=UHTF1-IhuC0

Follow-Up on the Lakagígur Eruption (Iceland, 1783-1784)

After finishing Newsletter #5, I sent an inquiry to **HAGSTOFA ÍSLANDS | STATISTICS ICELAND** (a bureau of the Prime Minister's Office), asking about the nation's fall in population during the 1750s (See Newsletter #5, p94, upper chart.):

[Saturday 6th June 2020 5:55]

Vef Ábending frá Bill D'Arcy,

með Tölvupóstfang: billdarcy_geo@bigpond.com,

hefur borist:

I am an Australian geologist, and the effects of the 1783-1784 Skaftáreldar interest me. Can you tell me why the population fell in the 1750s also?

The reply from **Heiðrún Sigurðardóttir** (*Samskipti og miðlun | Communication and dissemination*) was prompt (~32 hours), but a little general:

Hello,

Iceland 1752-1758: In general the Icelandic historiography describes these years of deteriorating living conditions and population decline as characterized by a combination of several factors: Unfavorable environmental factors such as temporary cold climate, drift ice from Greenland and large-scale volcanic eruption of Katla (1755), reduced fish catches, hunger, malnutrition and other related human diseases like „scorbutus“ (Icelandic: *„skyrbjúgur“*).

With best regards

Heiðrún

I had found a preprint of a research paper about the famine associated with the Lakagígar Eruption:

Haze, Hunger, Hesitation: Disaster Aid after the 1783 Lakagígur Eruption *or* https://www.researchgate.net/publication/338483006_Haze_Hunger_Hesitation_Disaster_Aid_after_the_1783_Lakagigar_Eruption

by **Dr Claudia Wieners**, of the *Institute of Economics, Scuola Superiore Sant'Anna*, Pisa, Italy.

I thought she would be a good source of information on the fall in Iceland's population during the 1750s, so I sent her an email asking about this event:

Dear Dr Wieners,

I have just finished reading the preprint of your paper **Haze, Hunger, Hesitation: Disaster Aid after the 1783 Lakagígar Eruption**, from the viewpoint of a (retired) geologist.

I had long been interested in the population effects of this event, and recently plotted the population graph using the chart-maker on the www.statice.si website, and notice the significant drop in the population during the 1750s:

I sent an enquiry to **statice.is**

I am very grateful for the prompt (~32 hours) reply from Heiðrún

Heiðrún's reply was a little general for my complete understanding. Can you shed further light on this event, or suggest useful references?

Regards,

Bill D'Arcy

She replied as follows:

Dear Dr. D'Arcy,

First, about the paper on the Lakagígar eruption: I have by now heavily revised the paper, including further references and some considerations on famine vulnerability, so if you are interested, I could send you a copy of the new version.

[The new version is: Haze, Hunger, Hesitation: Disaster Aid after the 1783 Lakagígar Eruption or https://www.preprints.org/manuscript/202001.0070/v2 Claudia Wieners - *Bill D'Arcy]*

On the 1750ies: This was indeed "just" a spell of bad weather, especially in the North of Iceland. The Katla eruption in 1755 probably didn't help, but I think that its effects were much more limited than in the case of the Lakagígar eruption. Cold weather generally leads to stunted grass growth, thus lack of fodder and loss of livestock (the main source of food). Greenlandic drift ice may have exacerbated the cold weather, and in addition hampered fishing (the second source of food). Moist summers also caused problems by spoiling the hay harvest. In general, a single bad year could often be lived through, but a series of cold years brought hunger. Below is what bishop Hannes Finnsson wrote in his essay "Um mannfækun af hallærum (On population loss through famine)", 1796. [ ] indicate remarks from me. Sorry, it is not a very good translation, and I'll transcribe a few Icelandic letters which my keybord can't handle. I hope this helps you, let me know if you need anything else.

If I may ask: what is your project about?

Best

Claudia Wieners

In the year 1751 began a dearth, which peaked in 1757. In this time span it spread over the whole country, more and damaging, the weaker the resistance grew. Around Langenes the livestock loss became biggest, and 40 farms were left in 1751 by their farmers, who lacked the strength to operate them; many died of hunger. The Dean Thorstein Ketilsson says in his notes that the inhabitants of the North and East became much impoverished and lost their animals, and in 1750 40 farms were deserted on Langenes in Vopnafjördur and Fljótsdal and 44 persons died from hunger. 1752 was a bad year in many places [with much frost]. Illness reigned in summer and autumn, which in particular killed children and the elderly; [...] In Borgarfjördur the loss of sheep was so bad, that in Myrasysla alone 2000 are said to have died. [...] Still in October in Hunavatnssysla the hay laid on the pastures and could not be brought in due to lasting moist conditions. In 1754 in Skagaströnd there was snowdrift and frost, which continued for 18 weeks; the ground was in certain meadows covered with snow till the beginning of summer. Jón Ólafsson says that this time 50000 sheep and 4000 horses died in the North. Dean Gudlaugur Sveinsson i Vatnsfjord ... writes: From new year 1754 the winter was very harsh, so that animals died in heaps, especially in the North; to this was added bad grass growth next summer, and the harvested hay was spoilt; the next winter until Christmas was as harsh as the previous and fishing failed; ... this time, the surviving horses ate the dead ones. 1755 the times were very bad, both due to the previous hard times and ill conditions on land and sea, which the previous winter had caused. Many farms were given up, and the increased vagabondism and begging caused disorder and thieving. The Katla eruption caused the desertion of 50 farms [in the neighbourhood of the volcano, I believe]. Drift-ice lay around the north till September 3rd, and prevented 2 trade ships from reaching the harbours in summer [no grain from Denmark]. 1756 times grew even worse, especially in the North and around Borgarfjördur, so that people died from hunger and misery. From Fljóta-ombud [I think, a collection of farms rented out] a tax of 227 ríkisdalir was due (to the Hólar bishopric) but ... only 20 were paid, and 20 of the farms were deserted. The winter from New Year till its end was harsh and was followed by a cold spring, but summer was very wet. The autumn and first half of winter brought unsteady weather, but fishing went well. Thieving and the eating of horsemeat increased *[Eating horsemeat was usually discouraged by the Church, and at times banned in various bishoprics – Bill D'Arcy]*. Bad grass growth in this summer was ubiquitous, and in addition, hay could not be dried due to continuous wet conditions, but, having been stored in frozen conditions, it had to be thrown away as being useless as fodder. Much sea ice lay around the North and caused cold and frost in the middle of summer in July and August. On July 27th there fell snow one ell deep, *[Several nations used a length measure of the arm from the elbow to the fingertips, called the ell, about 0.45-m. "Ell" meant "arm" in*

> *several languages, hence "elbow" meant "arm bend" – Bill D'Arcy]* which meant that mowing could not begin before August 25th, and only then did the sea ice leave. 1757 the winter itself was not as harsh, as its consequences would indicate. The Katla eruption contributed to this, as well as the consecutive bad hay harvests and fishing which had depleted the country's welfare. Vice Lawman Eggert Ólafson says "that the spring 1757 was so harsh, that on Skagaströnd in the end of May and beginning of June there was frost at noon time, even with sunshine, and no grass had yet come up". The lack of foodstuff was so large that hunger and associated illnesses killed 2500 in Skálholts bishopric ... According to calculations of births and deaths in the bishopric of Skálholt, 4395 more people died then were born in 1752-59, and 1829 in the bishopric of Hólar [Hólar was in the North and held about 1/4 of the population, Skálholt was in the south, west and east].

Her detailed reply hit the spot, and she is an expert on the economic and social consequences of the Lakagígar[1] eruption; she set me straight on this too. I've used information she sent to flesh-out my understanding of the Lakagígar event, and I've put the following account together:

The Lakagígar Eruption of 1783-4, and the Associated Disaster

The fundamental tectonic setting of Iceland involves a mantle plume superimposed on (or "subimposed" under?) an oceanic spreading ridge. The spreading ridge is between the North American and the Eurasian plates; its spreading opened the North Atlantic Ocean. The pair of lithospheric plates has been drifting northwest over the underlying mantle for tens of millions of years. The deeper mantle hosts a plume that generates eruptions of mainly basalt.

[1] We English speakers are more familiar with the term Laki, which is the name of a low bedrock mountain, an inactive volcano. An array of tensional fissure (related to plate tectonic "sea"-floor spreading) developed, coincidentally running through this mountain, and the eruption proceeded northeastwards along 27 km of this fissure-array, producing - among other landforms - ash cones and spatter cones, which have craters on the top). Icelanders use the term Lakagígar which means "craters of Laki". Note that the first descriptions were made by locals - including a clergyman (Jón Steingrímsson) – who naturally were busy with their own activities, and didn't want to get too close to something as fearsome as a vigorous volcanic eruption. Another name for the event is Skaftáreldar which means "Fires of Skaftár". Much of the lava flowed into the valley of the Skaftár River and through its gorge towards some villages, including Klaustur, where Steingrímsson lived. In the late 1700s, even scientists (or natural philosophers as they were known then) believed that volcanoes had some association with underground fires, so "fires in the Skaftár (gorge)" was a very reasonable description for the event. The fissure zone extends northeastwards under the ice-cap Vatnajökull, and connects with the caldera of Grímsvötn volcano, which was active (but less spectacular than Lakagígar) from May 1783 to May 1785, so the name "Grímsvötn" is often included in the episode.

Major tectonic elements of the North Atlantic Ocean's seafloor:

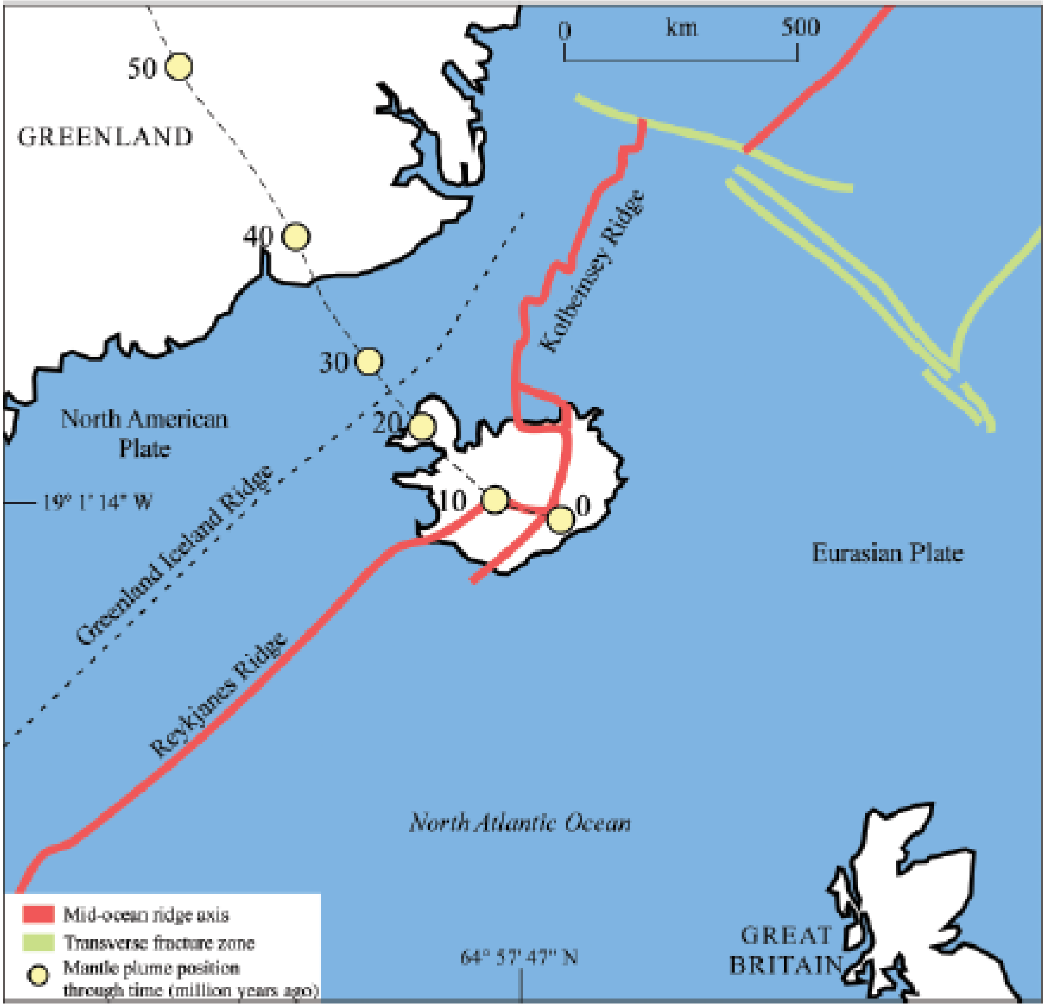


Figure 1.1 Tectonic context of Iceland. At present Iceland is divided by the Kolbeinsey Ridge in the north and the Rekjanes Ridge in the south. The yellow circles show the position of the mantle plume from 50 million years ago to present. [Modified from *Fitton et al.* [1997]; design credit Nathan Mennen.]

From: *Iceland Tectonics, Volcanics, and Glacial Features*, (2020); Tamie J. Jovanelly; Wiley.

The spreading motion moves previously-erupted lava aside from the ridge; so the older the rock, the further it is from the current axis of spreading or plate boundary:

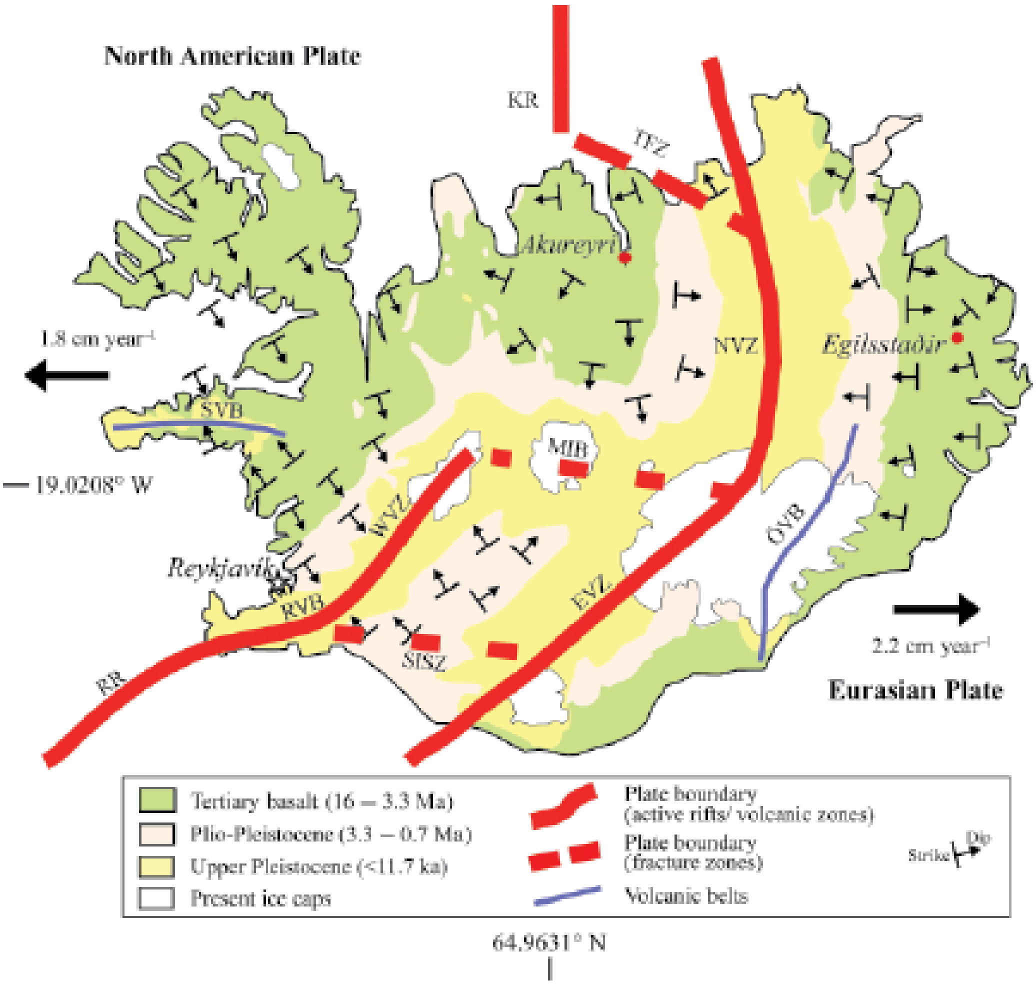
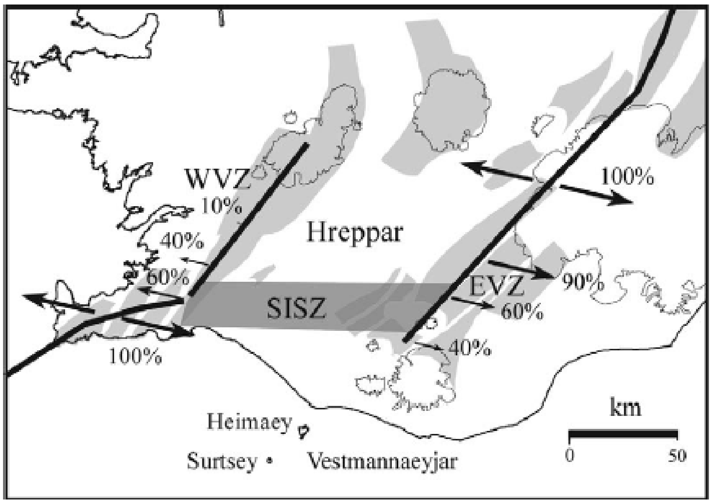


Figure 2.1 Iceland's volcanic zones, associated plate boundaries, and general geologic age of bedrock. KR, Kolbeinsey Ridge; RR, Reykjanes Ridge; EVZ, East Volcanic Zone; WVZ, West Volcanic Zone; NVZ, North Volcanic Zone; SISZ, South Iceland Seismic Zone; MIB, Mid-Iceland Volcanic Belt; TFZ, Tjörnes Fracture Zone; ÖVB, Öræfi Volcanic Flank; RVB, Reykjanes Volcanic Belt; SVB, Snæfellsnes Volcanic Belt. [Adapted from *Sæmundsson* [1979]; design credit Nathan Mennen.]

From: *Iceland Tectonics, Volcanics, and Glacial Features*, (2020); Tamie J. Jovanelly; Wiley.

There is a partitioning of spreading between the East Volcanic Zone (EVZ) and the West Volcanic Zone (WVZ):

Fig. 2.2. Partition of plate spreading between the Western Volcanic Zone (WVZ) and the Eastern Volcanic Zone (EVZ). The spreading rate increases from north to south along the WVZ progressively from zero to 60% of spreading at the Hengill volcano and the opposite pattern is valid for the parallel EVZ. The surface structures associated with a rift in the EVZ terminates just north of the Mýrdalsjökull ice cap. The Hreppar micro-plate is located between the parallel spreading zones. Plate spreading data are taken from LaFemina et al. *(2005).*



Fissure zones indicated in light grey. The fissure zone containing the Lakagígar fissure chain (extending SW from Grímsvötn) is the grey area under the head of the 90% arrow for the EVS. The fissure zone hosting the earlier Eldgjá fissure eruption (934-940 or 939-940) is under the heads of the 40% and 60% arrows for the EVZ. The fissure zone hosting the Bárðarbunga- Holuhraun eruption system (see Newsletter #5) is north of Vatnajökull icecap (the white area under the 100% arrow for the EVZ), and is the grey area immediately west of the heavy line that indicates the spreading axis.

From: *Katla and Eyjafjallajökull Volcanoes*, (2010); Erik Sturkell, Páll Einarsson, Freysteinn Sigmundsson, Andy Hooper, Benedikt G. Ófeigsson, Halldór Geirsson and Halldór Ólafsson. In: *The Mýrdalsjökull Ice Cap, Iceland: Glacial Processes, Sediments and Landforms on an Active Volcano*, (2010); Johannes Krűger, Anders Schomacker and Kurt H. Kjær (Eds); pp 7-21; Elsevier.

The partitioning of spreading is accommodated by transform fault motion on the South Iceland Seismic Zone (SISZ):

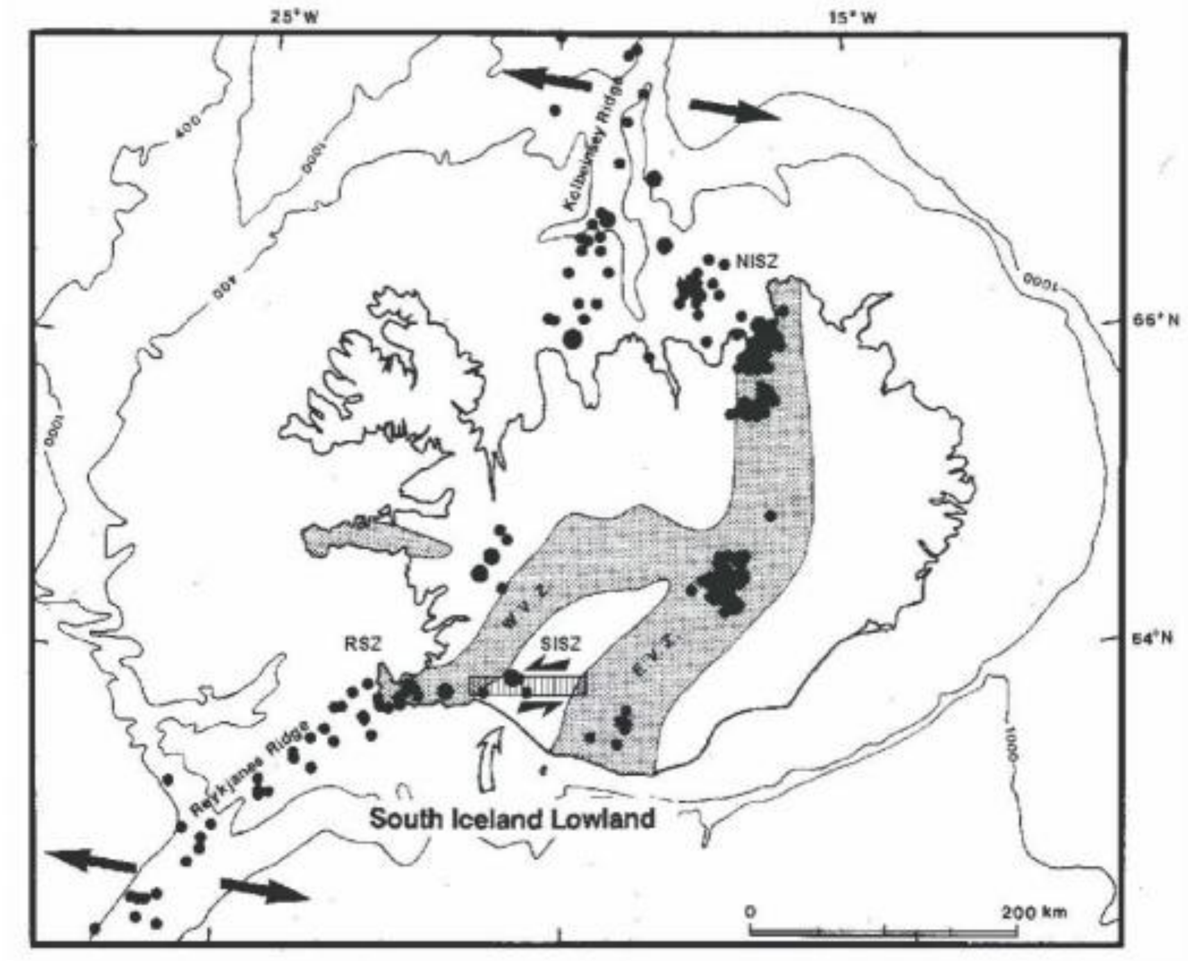


Figure 1: The Interrelationship between the Volcanic and Seismic Zones in Iceland

Sense of fault motion on the South Iceland Seismic Zone (SISZ), as predicted from plate-tectonic theory.

From: *Probabilistic Seismic Hazard Mapping Of Iceland. Proposed seismic zoning and de-aggregation mapping for EUROCODE 8*, Julius Solnes , Ragnar Sigbjörnsson and Jonas Eliasson, (2004). In*: 13th World Conference on Earthquake Engineering*; Vancouver, B.C., Canada, August 1-6; 2004; (Paper No. 2337)

The theoretical sense-of-movement is confirmed by first-motion seismic analysis, which determines the direction of “jolt” when the seismic wave arrives at the seismometer. Measurement of first-motion at several seismic stations builds confidence in the focal mechanism (the orientation of the fault, and the sense of slip on the fault surface):

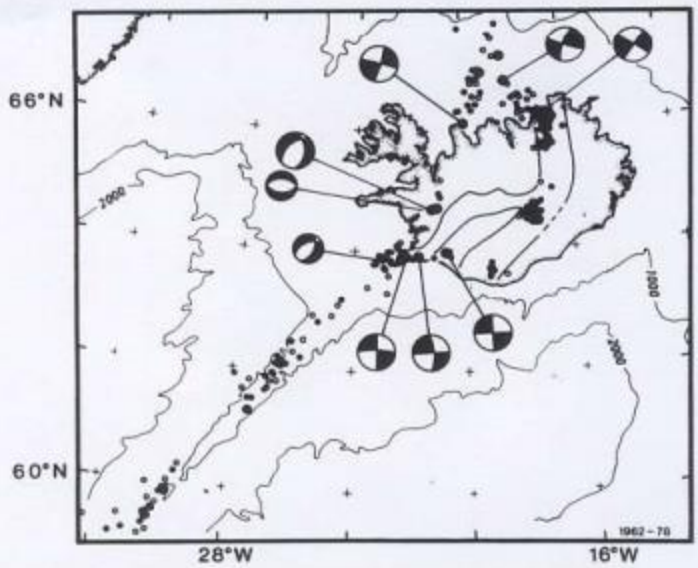


Fig. 1. Epicenters and focal mechanisms of earthquakes in the Iceland region. Epicenters are from the PDE lists of USCGS, later NOAA and USGS, for the time period 1962-1978. Open circles denote epicenters determined with fewer than 10 P-wave readings or epicenters of earthquakes smaller than $m_b=4.5$ Dots are events of $m_b=4.5$ and larger, located with 10 or more readings. Large dots are events of $m_b=5.0$ and larger. The focal mechanisms are shown schematically as lower hemisphere equal-area projections, compressional quadrants black. The volcanic rift zones of Iceland are shown.

The three black and white circles lowest on the diagrams depict focal mechanisms for three earthquakes on the SISZ. The focal mechanism diagrams each offer an ambiguous situation:

Either

a) *There were three near-vertical faults trending N-S, with senses of movement: W-block moved N / E-block moved S*

Or

b) *There was one near-vertical fault trending E-W, with sense of movement: N-block moved W / S-block moved E*

“Ground truth” in the form of fault-traces, and plate tectonic theory agree with b) above.

From: *Seismicity pattern in the South Iceland Seismic Zone*, Páll Einarsson, Sveinbjörn Björnsson, Gillian Foulger, Ragnar Steffánsson and þórunn Skaftadöttir, (1981); reprinted from *Earthquake Prediction - An International Review: Maurice Ewing Series 4*; © 1981 by the American Geophysical Union.

The spreading ridge is a zone of tension that has produced swarms of fissures parallel to the axis of the ridge, running generally NE-SW.

Photo 7 Almannagjá is a dramatic tensional fracture in Þingvellir National Park. [Courtesy of Russell Maddrey.]

From: *Iceland Tectonics, Volcanics, and Glacial Features,* (2020); Tamie J. Jovanelly; Wiley.

Fig. 4.2 Meeting on the vertex of the Mid-Atlantic Ridge © Wolfgang Fraedrich

The "Bridge between North America and Eurasia." The"keystone graben" running into the distance marks the nominal locus-line of the spreading ridge.

From: GeoGuide – *Iceland from the West to the South*, (2019); Wolfgang Fraedrich & Neli Heidari; Springer.

Fig. 6.56 A group of young German researchers—standing on Miðlina, the bridge between two tectonic plates © Wolfgang Fraedrich

From: GeoGuide – *Iceland from the West to the South*, (2019); Wolfgang Fraedrich & Neli Heidari; Springer.

The fissure zones are lines of weakness that are sometimes exploited by volcanic eruptions associated with central volcanic centres. One example runs SW from Grímsvötn, which is under Vatnajökull ice-cap glacier. (Note Bárðarbunga, 20 km north of Grímsvötn – See Newsletter #5.)

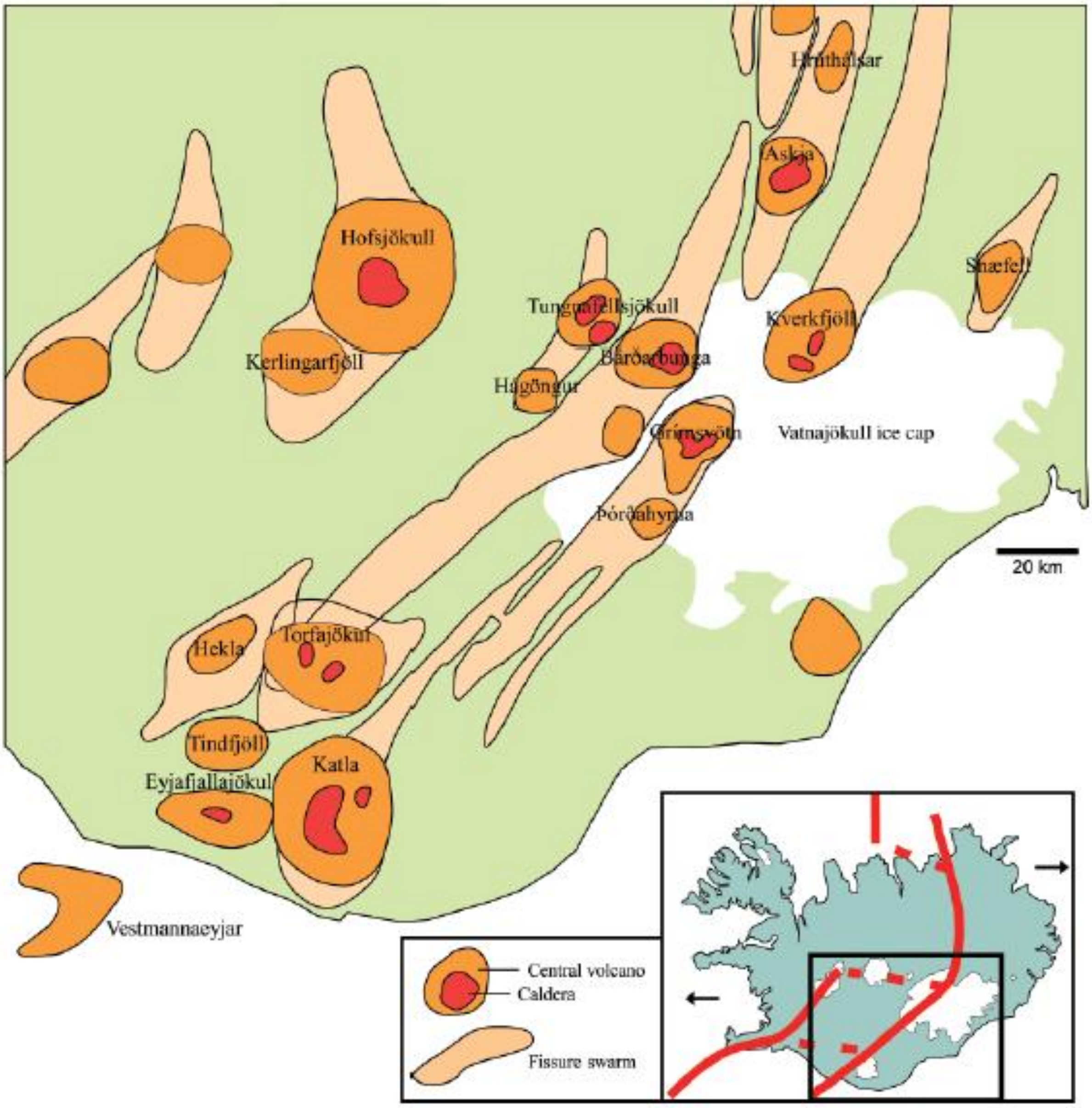


Figure 9.1 Active fissure, volcanic systems, and central volcanoes found in southern and central Iceland.

From: *Iceland Tectonics, Volcanics, and Glacial Features*, (2020); Tamie J. Jovanelly; Wiley

After about six weeks of mild earthquakes (tremors), on Sunday 8th June 1783 an eruption began (as it turned out, on the fissure swarm extending SW from Grímsvötn) with a dense ash-cloud.

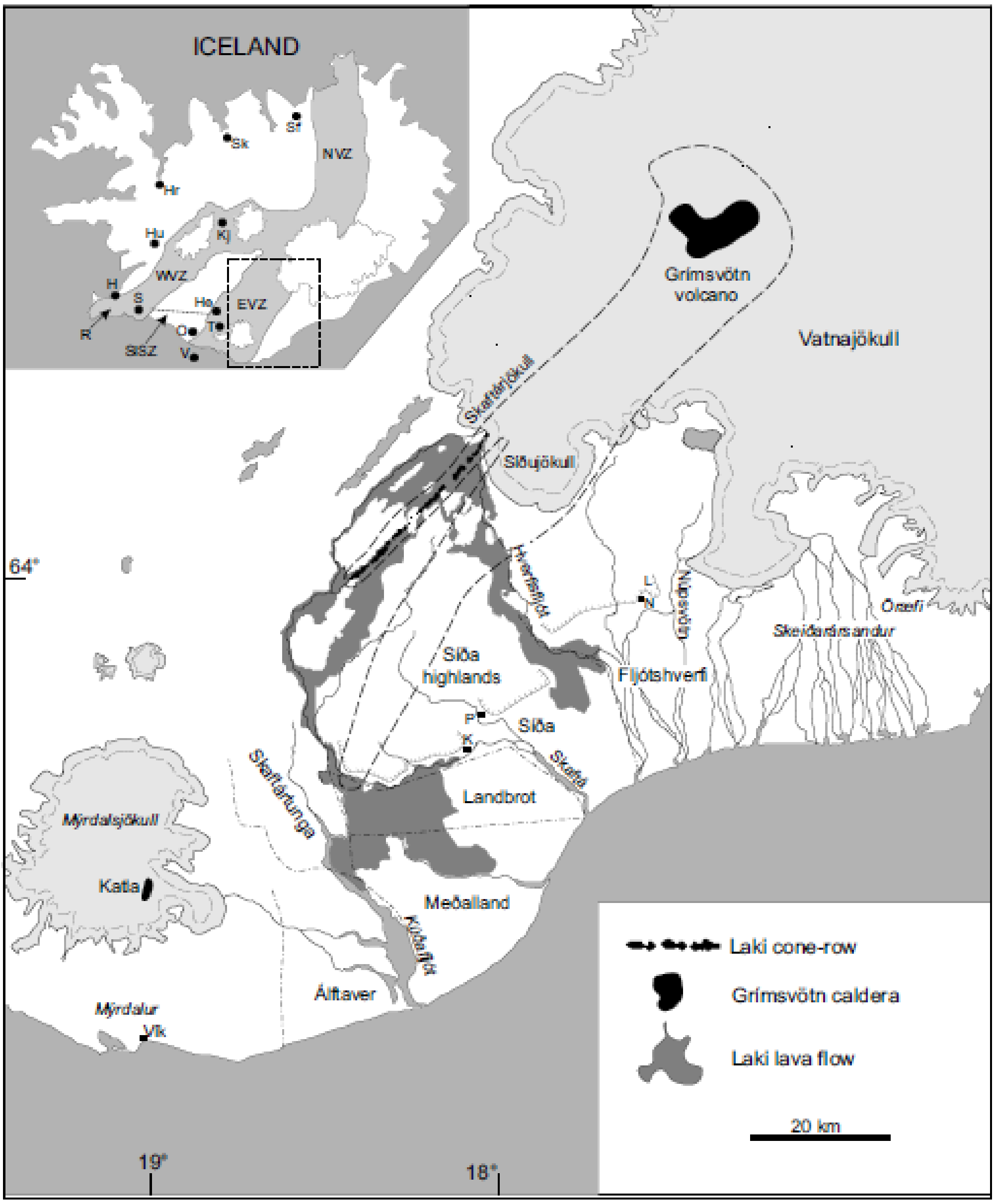


Figure 1. Simplified map of the study area showing the position of the Laki vent system within the Grímsvötn volcanic system (thick broken line) and the location of the Fire districts, the areas most affected by the Laki eruption. District boundaries are shown as broken-dotted lines. Also shown are other districts, the ice caps and outlet glaciers mentioned in the text, along with position of the Grímsvötn and Katla volcanoes. The scarp referred to in the text is shown as hachured lines. The location the farms Kirkjubæjarklaustur (K) and Prestbakki (P) is indicated by filled squares. L and N designate the position of Lómagnúpur Mountain and Núpsstaður farm. Inset shows the location of rift zones in Iceland; box is area of figure and filled circles indicate places elsewhere in Iceland that are mentioned in the text. Abbreviations are as follows: H, Hafnarfjörður; He, Hekla; Hu, Húsafell; Hr, Hrútafjarðará River; Kj, Kjölur; O, Oddi in Rangárvellir; R, Reykjanes; S, Selvogsheiði; Sf, Skjálfandafljót River; Sk, Skagafjörður; T, Tindfjöll and Þórsmörk; V, Vestmannaeyjar; WVZ, Western Volcanic Zone; EVZ, Eastern Volcanic Zone; NVZ, Northern Volcanic Zone; SISZ, South Iceland Seismic Zone. – *Einfaldað yfirlitskort af Vestur Skaftafellssýslu og nágrenni ásamt helstu örnefnum. Innsett kort sýnir staðsetningu rannsóknarsvæðisins.*

From: *The 1783–1785 A.D. Laki-Grímsvötn eruptions II: Appraisal based on contemporary accounts;* Thorvaldur Thordarson, Guðrún Larsen, Sigurður Steinþórsson and Stephen Self; 2003.
or https://www.researchgate.net/publication/280489763_The_1783-1785_AD_Laki-Grimsvotn_eruptions_II_Appraisal_based_on_contemporary_accounts

Subsequent eruptions progressed northeastwards:

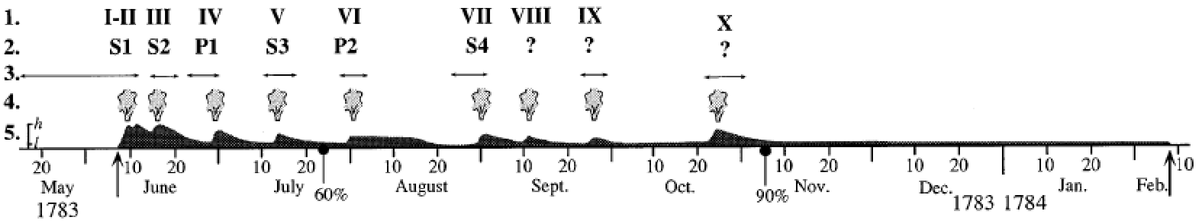


Fig. 2 Illustration of sequence of events during the Laki eruption up to eruption episode X. Eruption episodes are shown in *row 1*, labeled I–X; S, strombolian fall units; P, phreatomagmatic fall units. *Row 2* shows the primary fall units produced by the eruption episodes. *Row 3* designates earthquake swarms; the *horizontal bars* show the duration of each swarm. Timing of explosive activity is shown in *row 4*, where *eruption clouds* denote explosive activity at Laki fissures. Row 5 (*stippled area*) shows qualitatively the fluctuations in lava production during the eruption; *h* and *l* indicate high and low discharge, respectively (not to scale). *Vertical arrows* mark the beginning and end of Laki fissure eruption and the *60%* and *90%* refer to volume fraction erupted up to that time. (Modified from Thordarson and Self 1993)

From: *Sulfur, chlorine, and fluorine degassing and atmospheric loading by the 1783–1784 AD Laki (Skaftár Fires) eruption in Iceland*; Th. Thordarson, S. Self, N. Óskarsson & T. Hulsebosch; (1996)
or
https://www.researchgate.net/publication/226927839_The_Laki_Skaftr_Fires_and_Grmsvtn_eruptions_in_17831785**.**

Geological mapping from the modern era reveals the nature of the volcanic features along the series of fissures:

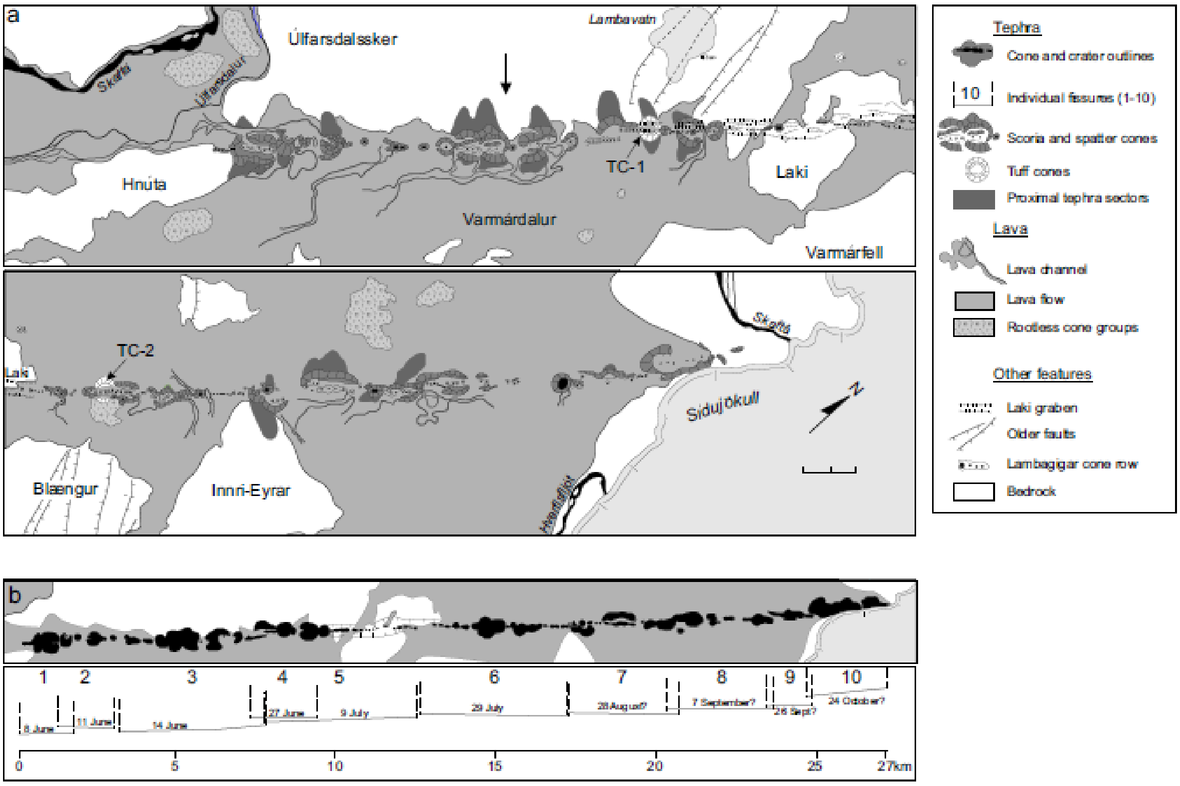


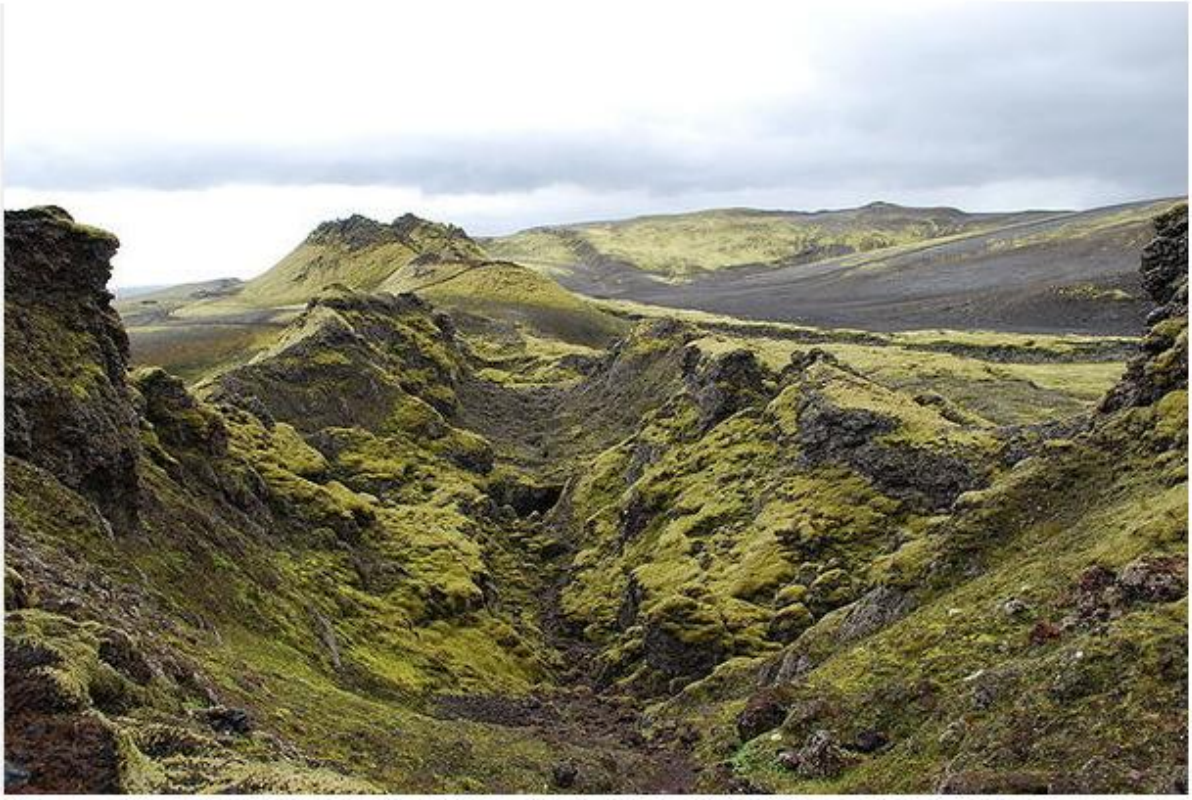
Figure 3. Map of the Laki fissures: demonstrating the main features of the cone-row and surrounding lavas. TC-1 and TC-2 indicate the tuff cones SW and NE of Laki, respectively. Extent of individual fissures, labelled 1 through 10, shown schematically. Cones on fissure 3 (arrow) where first visited and described by Sveinn Pálsson in 1794. – *Lakagígar, gjóskukeilur, gígaraðir og sprungur. Örin bendir á gígana sem Sveinn Pálsson kannaði og lýsti 1794.*

Initial (1784) interpretations were that the lava flows had come from Laki (a bedrock hill marking an extinct volcano). An early belief that volcanoes were powered by underground fires gave the eruption one of its alternative names - Skaftáreldar (Skaftár Fires). The Skaftár river valley (filled by lava, which flowed downstream into a gorge – off the map area)) is in the NW corner of the map above.

From: *The 1783–1785 A.D. Laki-Grímsvötn eruptions II: Appraisal based on contemporary accounts;* Thorvaldur Thordarson, Guðrún Larsen, Sigurður Steinþórsson and Stephen Self; 2003.

or https://www.researchgate.net/publication/280489763_The_1783-1785_AD_Laki-Grimsvotn_eruptions_II_Appraisal_based_on_contemporary_accounts

From Google Earth, corresponding approximately to b) above. The green double triangle is Laki.



The remains of the fissure (over 14 miles long) created by Laki's eruption, Wikimedia Commons

This fissure volcano on Hawaii shows what Laki might have looked like as it erupted, Wikimedia Commons

View from the top of Laki mountain, looking northeast along the Lakagígar crater row towards Vatnajökull ice-cap glacier.

From: *Island on Fire*, Alexandra Witze and Jeff Kanipe, (2014); Profile Books.

The extent of the basaltic lava, which flowed along various river valleys, has been mapped in detail:

Figure 2. Map of the Fire districts and Síða highlands showing the regional topography, relevant landmarks and place names, along with distribution of vents, lava flows, and rootless cone (pseudocrater) groups. Note that location of farms destroyed by the lava is shown as it was prior to 1783. The pen circles and labels 7a–7f show the locations of the photographs in Figure 7. Modified from Thordarson and Self (1993). – *Örnefnakort af Eldsveitunum og Síðumannaafrétti. Hringir eru dregnir um staði sem sýndir eru á 7. mynd.*

The lava flowed down several river valleys, through gorges, and onto the coastal lowland plain.

From: *The 1783–1785 A.D. Laki-Grímsvötn eruptions II: Appraisal based on contemporary accounts;* Thorvaldur Thordarson, Guðrún Larsen, Sigurður Steinþórsson and Stephen Self; 2003.
or https://www.researchgate.net/publication/280489763_The_1783-1785_AD_Laki-Grimsvotn_eruptions_II_Appraisal_based_on_contemporary_accounts

An uncluttered diagram of the lava flows that ran down the river valleys:

Between June 1783 and February 1784, two great arms of lava flooded down from Laki to embrace each side of the town of Klaustur.

Note relationship between Laki mountain and Lakagígar crater row.

From: *Island on Fire*, Alexandra Witze & Jeff Kanipe, (2014); Profile Books.

There were also gaseous emissions. These produced a "dry fog" that reached the European mainland, propelled by the prevailing westerly winds, as was fine ash. On June 10th (two days after the eruption started), ash that withered tree leaves and turned grass yellow began falling in SW Norway; and on the same day, ships entering the harbour at Copenhagen (Denmark) were noted to have their sails and decks darkened by ash. On June 16th there was a haze reported in Prague that dimmed and reddened the sun; a similar haze also covered Berlin on the 17th. The haze, this time reported as humid, dimmed the sun in Laon (France) on the 18th; and was noted in Padua (Italy) on the same day. On the 23rd an English clergyman in Hampshire observed the haze, which turned the grass yellow "as if scorched with frost". By the 26th it was reported in St Petersburg, and in Moscow on the 30th.

Over much of Europe the haze was so dense that all but the brightest stars were invisible at night. It was also high above the ground. People who ascended mountains found the haze was still overhead, and still thick.

Some of these (and other) reports mention a sulphurous smell, strongly hinting at a high content of SO_2 for the haze. Some of the gas phase was blown out of the vents high into the atmosphere to form a regional/global haze, and some degassed more quietly from the flowing and crystallising lava, to form a local haze or fog. Some of the high-level gas reached the stratosphere, which is an efficient store and global transport agency of very fine particles and pollutant gas molecules. Low-level sulphur dioxide is prone to being washed out of the air by rainfall, and needs frequent replenishment by ongoing or repeated eruptions if it is to survive long; but stratospheric SO_2 is long-lived, and will build up with repeated or prolonged injections. Systems-analysis of the eruption suggests a protocol to estimate the amount of volatiles:

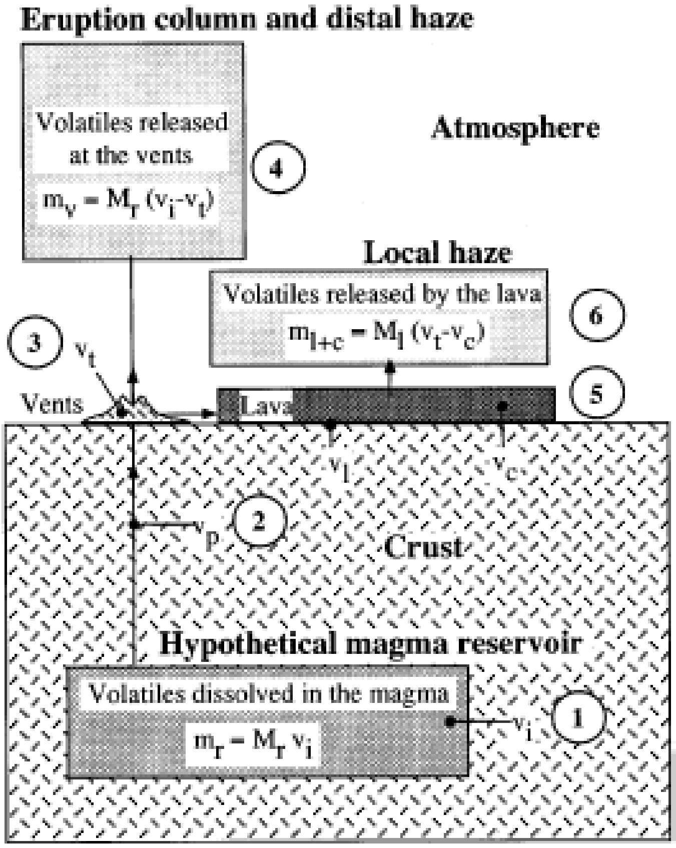


Fig. 13 Illustration outlining a volatile budget model for basaltic fissure eruptions. *1* Hypothetical magma reservoir containing magma of the mass M_r (taken here to be equal to erupted volume of magma) and total amount of dissolved volatiles m_r; the measured concentration of volatiles in glass inclusions, v_i, represents the concentration of volatiles dissolved in the magma. The total mass of volatiles dissolved in the magma prior to eruption is given by the lowermost equation. *2* Quenched magma fraction due to interaction with external water, represented by phreatomagmatic tephra at the surface containing volatile concentrations v_p. *3* Vent accumulations of pyroclastic material containing concentrations of volatiles v_t, which represents volatile fraction of m_r which did not escape the magma as it emerged from the vents. *4* Eruption column (lava fountain plus convecting plume) containing total amount of volatiles released at the vents, m_v, as given by the uppermost equation. *5* Lava flow of mass M_l and volatile concentration v_l in lava selvages and v_c in crystalline lava. *6* Amount of volatiles, m_{l+c}, released by the degassing of lava during and after emplacement is given by the middle equation

From: *Sulfur, chlorine, and fluorine degassing and atmospheric loading by the 1783–1784 AD Laki (Skaftár Fires) eruption in Iceland*; Th. Thordarson, S. Self, N. Óskarsson & T. Hulsebosch; (1996) *or* https://www.researchgate.net/publication/226927839_The_Laki_Skaftr_Fires_and_Grmsvtn_eruptions_in_17831785.

A semi-quantitative distribution of volatiles from a Lakagígar-style fissure eruption:

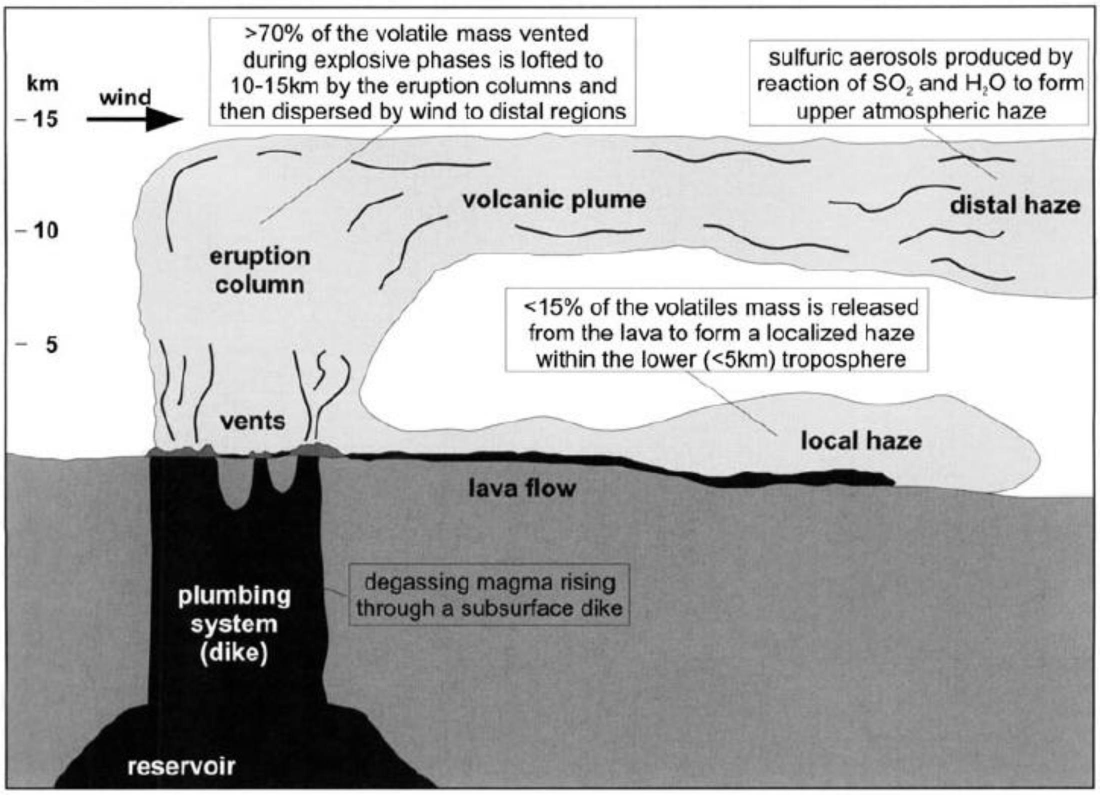


Fig. 3. A schematic illustration showing the key features of the two-stage degassing in flood lava eruptions (modified from Thordarson *et al.* 1996).

From: *Sulphur release from flood lava eruptions in the Veidivotn, Grimsvotn and Katla volcanic systems, Iceland*, (2003); T. Thordarson, S. Self, D. I Miller, G. Larsen & E. G. Vilmundardottir. In: Oppenheimer, C., Pyle, D.M. & Barclay, J. (eds) 2003. *Volcanic Degassing.* Geological Society, London, Special Publications, 213; pp 103-120.

Chemical analysis of the solid products of the eruption allows one to distribute quantitatively the budget of volatile components, especially SO_2:

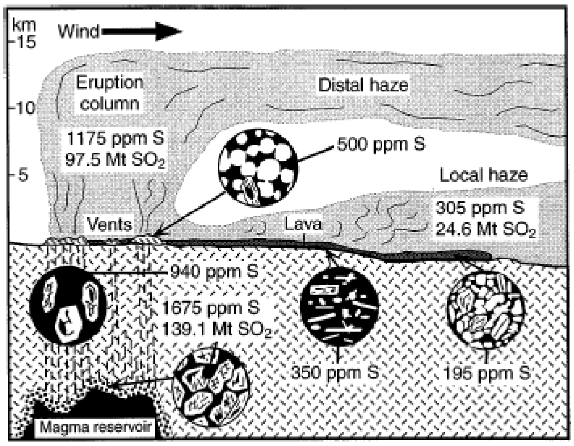


Fig. 14 Illustration of the Laki eruption viewed from the southwest (not to scale) showing the amount of S retained in samples from various eruption stages and their relationship to the degassing of the magma. Also shown is the total amount of SO_2 dissolved in the Laki magma prior to eruption and the estimated SO_2 yield by various eruption stages. The gas columns and plumes generated by the magma degassing are shown as *fine stippled areas*. *Distal haze* denotes the gas liberated at the vents and carried to high altitudes by the eruption columns, and *local haze* denotes that produced by gas rising from the lava flow. Other features are as indicated in Fig. 4

There were lava flows on the west - left - side of the fissure, further west out of the view, not just a single flow to the east, as might be wrongly inferred from this diagram.

From: *Sulfur, chlorine, and fluorine degassing and atmospheric loading by the 1783–1784 AD Laki (Skaftár Fires) eruption in Iceland*; Th. Thordarson, S. Self, N. Óskarsson & T. Hulsebosch; (1996) *or* https://www.researchgate.net/publication/226927839_The_Laki_Skaftr_Fires_and_Grmsvtn_eruptions_in_17831785.

The total yield of SO_2 is calculated at 122 Mt, which had the potential to form ~250 Mt of H_2SO_4 aerosol. Water vapour (~238 Mt), carbon dioxide (~349 Mt), chlorine (~7 Mt) and fluorine (~15 Mt) were also significant components of the vapour. The fluorine is especially toxic, both as a vapour, and in the fine ash that fell on the pasture. Much of the herds and flocks of livestock died, but it is difficult to prove fluorinosis as a definite cause. Starvation of livestock by loss of pasture is an important factor, which in turn contributed to the (human) famine.

	1703	1785 (% of 1703)	1795
Cattle	35860	16592 (46%)	22488
Horses	26909	12786 (48%)	22599
Sheep	278994	64459 (23%)	241171

Table 1: Number of farming animals in Iceland before, 2 years after, and 12 years after the Lakagígar eruption. Based on data from [Rafnsson, 1984a].

From: *Haze, Hunger, Hesitation: Disaster Aid after the 1783 Lakagígar Eruption*, (2020); Claudia E. Wieners

or

https://www.researchgate.net/publication/338483006_Haze_Hunger_Hesitation_Disaster_Aid_after_the_1783_Lakagigar_Eruption

The revised version of her manuscript is:

Haze, Hunger, Hesitation: Disaster Aid after the 1783 Lakagígar Eruption
or https://www.preprints.org/manuscript/202001.0070/v2 *Claudia Wieners*

"*The horses lost all their flesh, the skin began to rot off along the spines. The sheep were affected even more wretchedly. There was hardly a part on them free of swellings, especially their jaws, so large that they protruded through the skin…Both bones and gristle were as soft as if they had been chewed.*"

Rev. Jon Steingrimsson

From: *The Eruption of Laki: an Icelandic Volcano in 1783*; Victoria M. Lord

The resulting famine, compounded with other factors, killed about 22% of Iceland's human population:

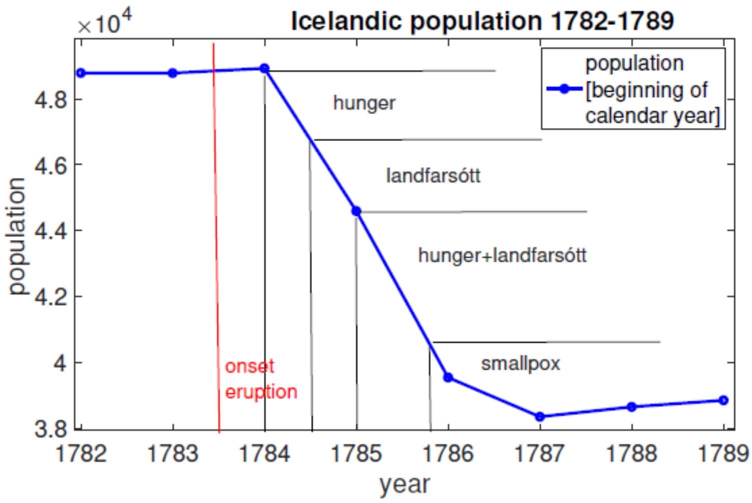


Figure 1: Population of Iceland, 1782-1789, and main causes of death ('landfarsótt' being non-specified contagious diseases). Based on data from [Hálfdanarson, 1894].

From: *Haze, Hunger, Hesitation: Disaster Aid after the 1783 Lakagígar Eruption*, (2020); Claudia E. Wieners
or
https://www.researchgate.net/publication/338483006_Haze_Hunger_Hesitation_Disaster_Aid_after_the_1783_Lakagigar_Eruption

The revised version of Dr Wieners' manuscript is:

Haze, Hunger, Hesitation: Disaster Aid after the 1783 Lakagígar Eruption
or https://www.preprints.org/manuscript/202001.0070/v2 *Claudia Wieners*

The death toll was not caused by volcanic vapour pollution alone. Dr Wieners analysed the likely fluorine dose the people absorbed, and concludes that although people might have been poisoned by fluorine, the dose was probably insufficient to kill many healthy people. Furthermore, the delay between eruption and the fall in population was probably too long to result from fluorinosis, and agrees more closely with gradual depletion of food stocks, followed by malnutrition and starvation. An exhumed skeleton (of the only person buried at an appropriate cemetery in the appropriate time-span) showed no signs of fluorinosis. There is also difficulty of trying to diagnose people from a time-distance of one-quarter of a millenium (except the sole exhumed skeleton), especially when almost all of the people reporting the symptoms had no medical training.

There were many social factors at play that made the situation worse. A large part of the population were subsistence farmers and their families; many of them lost most of their livestock and crops because of the eruption, so they had little left to trade for fish with the coastal fishermen, and their diet suffered. Naturally, mal-nourished people were more prone to diseases, and the consequences of disease were more severe (including death). Much of the economic activity of Iceland involved trade of fish back to Denmark; the priority was to keep the profitable trade going, rather than distribute the fish free-of-charge to destitute Icelanders. Much of the population were assigned to particular farms, so it was difficult for refugees to move elsewhere, where they could seek help. Some local (Iceland-based) administrators hesitated to order support of the impoverished citizens at the expense of the established trade arrangements, without instructions or permission from their Danish overlords. In an unfortunate complementary fashion, the Danish officials were reluctant to provide aid without a comprehensive evaluation of the situation. Communication with the mainland (by sailing vessels) was slow, relying on trade vessels, and largely closed-down during winter. Sea-ice kept some ships away from some ports, so that the extent of the problem was underestimated. When finally, written orders were issued to aid the locals, they were entrusted to only one vessel of a fleet of four carrying emergency grain, and these orders were lost when that vessel was wrecked on Iceland's coast.

There are numerous reports of powerful thunderstorms in Britain and on the Continent during the latter half of 1783; the aerosol droplets would have been hygroscopic (water-attracting) and quite likely acted as condensation nuclei ("cloud seeds"). Other unrelated phenomena were thrown into contemporary reports of the mix of unusual weather events; meteor showers, and (local) earthquakes in southern Europe, and these reports were widely repeated.

The Autumn of 1783, and Winter of 1783-4 were unusually cold, probably due to the incoming solar energy being reflected away more than usual by the high concentration of aerosol droplets. With the colder weather (and its longer duration) came unusually greater snowfall; the Spring thaw resulted in many great floods in Europe, especially on land that was considered higher than plausible flood levels. "Normal" fog in this cold weather was considered by many to be a continuation of the "dry haze" of the previous summer; very likely there was ongoing volcanic haze, and coincident fog events whenever the weather conditions were appropriate.

Cold weather reached all around the Northern Hemisphere. Parts of the young United States of America were gripped by cold; these included the mouth of the Mississippi at the river-port of New Orleans, which was ice-bound, and there were ice-floes in the Gulf of Mexico. Some authors have suggested that the North American cold was due the volcanic haze being carried there, around Earth by the prevailing high-level wind (the jet-stream); however plentiful haze, no matter how it was distributed, would induce cooling, and eventual atmospheric mixing (over several months) would distribute the cool air throughout the hemisphere. Cold weather appears to have been more widespread than the dry haze.

There is little evidence that the Lakagígar eruption affected the Southern Hemisphere, other than through interaction by trade and communications of European colonies in the south with their distressed homelands in the north.

Benjamin Franklin was at this time US Ambassador to France, and living in Passy near Paris during the Lakagígar eruptions. Many people believe he was the first person to make the connection between the haze and the news of a major eruption in Iceland. The earliest publicly-made suggestion of a link was by the naturalist Mourgue de Montredon on 7th August 1783 in a public lecture at the

Royal Academy of Montpelier. M. de Montredon suggested that the sulphurous smell corresponded with a volcanic source, and Iceland was in the news because of a new (temporary) volcanic island named Nyey, reported by sailors off the SW coast.

In May 1784 Franklin wrote about the weather to a physician friend, Thomas Percival in Manchester, with whom he frequently exchanged letters about the weather. In his letter, Franklin speculated that the cold winter and dry haze may have been caused either by meteors, or perhaps by the recent eruptions in Iceland. Franklin had heard of "Hecla" (Hekla), Iceland's then most famous volcano, and the new island Nyey, and he suggested these as the source of the haze. Apparently news about Lakagígar had not reached Franklin by May 1784. Franklin's speculations remained private until Percival read his letter to the Manchester Literary and Philosophical Society in December 1784.

True to his character as a naturalist, Franklin had been experimenting; he had been trying to light brown paper with a burning glass, and found it very difficult, due to the dimming of the sun by the haze, and he included this informationin his letter to Percival.

Other natural philosophers had gone public before December 1784 with speculations about the link between the dry fog and the cold weather; but Franklin took the further step of suggesting a search of historic records for similar summer hazes preceding cold winters, and proposed this association as a general predictor of hard winter to come.

Geology in Iceland

While we have been talking about Iceland, here are a few YouTubes of Iceland through a geologist's eyes.

How to explore Iceland through the eyes of a geologist: Part 1 – A Land of Ice and Fire
or http://exploringtheearth.com/2016/07/05/geological-journey-iceland-land-fire-ice-part-1/

How to explore Iceland through the eyes of a geologist: Part 2 – Volcanic Landscapes of the North
or http://exploringtheearth.com/2016/08/27/iceland-volcanic-landscapes-north/

How to explore Iceland through the eyes of a geologist: Part 3 – Glaciers and volcanoes of the centre and south
or http://exploringtheearth.com/2016/09/26/iceland-glaciers-volcanoes-south/

These are from Stephanie Sykora's website *Exploring the Earth:* http://exploringtheearth.com/ from which I have posted links to YouTube videos previously, probably even these three.

And the field trip to Sweden and Iceland mentioned in Part 1:
CODES/Lakehead Iceland and Sweden Field Trip (2015)
or https://www.youtube.com/watch?v=8V1Y7u47qBo&feature=youtu.be

While we are on ore deposits:

David Cooke - Mineral Chemistry in Exploration
or https://www.youtube.com/watch?v=EEeekSxPWwQ

Et Tu Okmok?

While we are thinking about volcanic eruptions, and their long-term consequences, here is an extract from:

geoz
VIEW THIS NEWSLETTER AS A WEBSITE
Geological Society of Australia's news service
CONTRIBUTE | SUBSCRIBE | CONTACT

A massive eruption of Alaska's Okmok volcano early in 43 BCE is postulated to have caused an extreme cold period across Europe that may have played a role in the decline of the Roman Republic. It is thought that resultant crop failures, famine, and disease, exacerbated social unrest and contributed to political realignments throughout the Mediterranean region following the assassination of Julius Caesar in 44 BCE.

The abstract only of the research paper (full article available only by subscription to PNAS):

Extreme climate after massive eruption of Alaska's Okmok volcano in 43 BCE and effects on the late Roman Republic and Ptolemaic Kingdom
is available at: https://www.pnas.org/content/early/2020/06/25/2002722117

For a summary article, see this:

Eruption of Alaska's Okmok volcano linked to mysterious period of extreme cold in ancient Rome or https://www.dri.edu/eruption-of-alaskas-okmok-volcano-linked-to-mysterious-period-of-extreme-cold-in-ancient-rome/?fbclid=IwAR0mu2R8-EzHp3YKfbEri_QPbpivg-d-faaWxeQYMD-gcC1Ji9VH3LJhXKw

Note: the eruption in 43 BC was *after* the assassination of Julius Caesar in 44 BC.

Torres del Paine Laccolith, South America

And a nice long motorbike ride southwards through Chile:

The scenery around 20:45 onwards for a while shows the Cuernos del Paine ("Horns among the blue")

The horizontal pale unit is a granite sill; the dark rock below is the "floor" of the intrusion, the dark tops of the peaks are erosional remnants of the roof; the cliffs are the erosional walls of valleys carved by glaciers.

More information on the Cuernos and Torres del Paine:

Travels in Geology: Exploring an icon of Patagonia: Chile's Torres del Paine National Park
or https://www.earthmagazine.org/article/travels-geology-exploring-icon-patagonia-chiles-torres-del-paine-national-park

Wandering in the mountains: geology, nature, and adventure teaching lessons in life
or https://wallaceterrycjr.com/category/general-geology/

A virtual field trip to a beautifully exposed pluton
or http://www.gly.uga.edu/railsback/VFT/VFTTDP.html

Torres del Paine - The Patagonian Diamond .
or https://www.geoexpro.com/articles/2015/03/torres-del-paine-the-patagonian-diamond

Los Cuernos: the Horns of Patagonia
or https://www.gadventures.com.au/blog/los-cuernos-the-horns-of-patagonia/

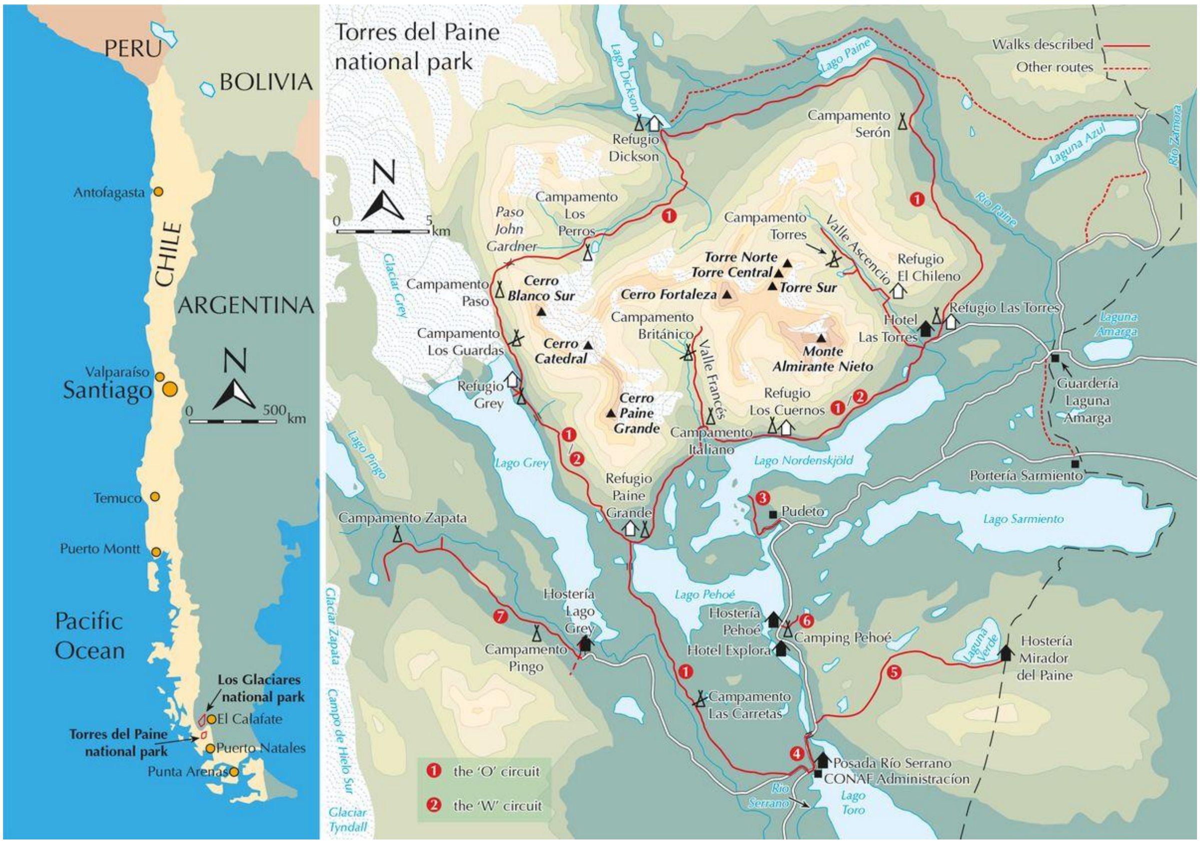
Research papers on the laccolith:

Source and fractionation controls on subduction-related plutons and dike swarms in southern Patagonia (Torres del Paine area) and the low Nb/Ta of upper crustal igneous rocks
or https://link.springer.com/content/pdf/10.1007/s00410-018-1467-0.pdf

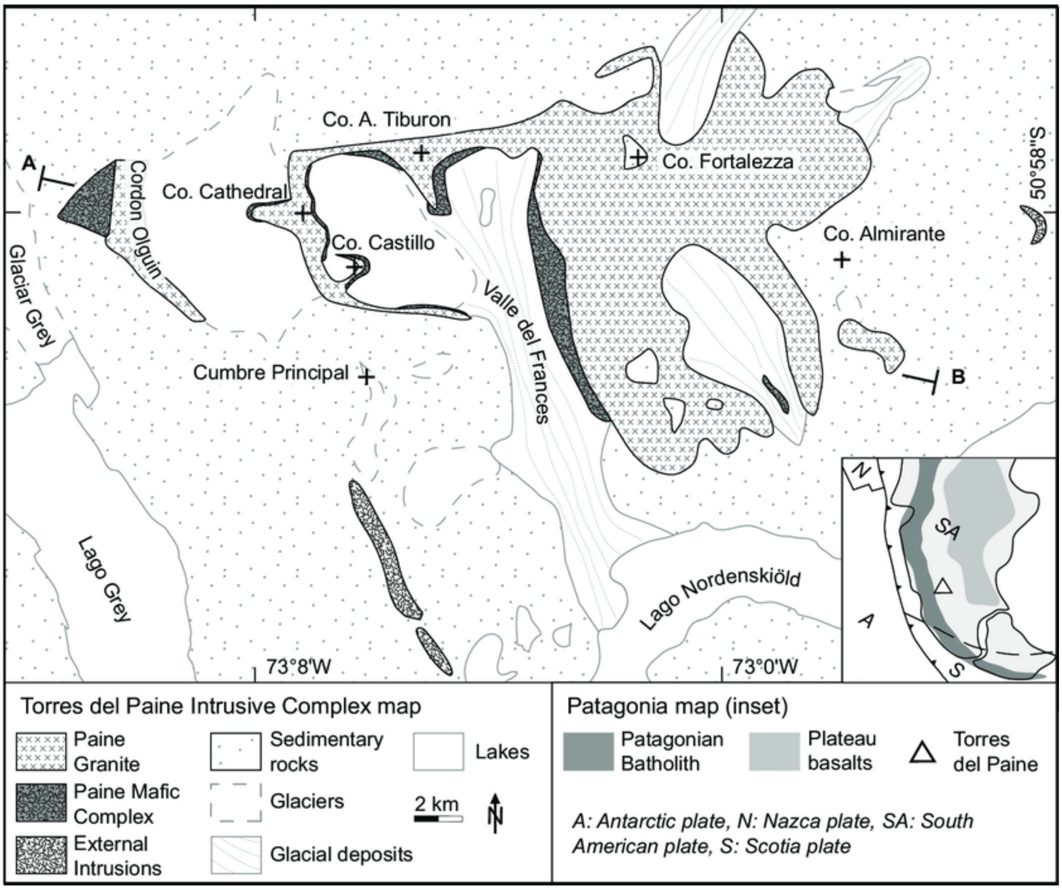
The Torres del Paine intrusion as a model for a shallow magma chamber
or https://meetingorganizer.copernicus.org/EGU2014/EGU2014-15626-1.pdf

A Detailed Geochemical Study of a Shallow Arc-related Laccolith; the Torres del Paine Mafic Complex (Patagonia)
or https://academic.oup.com/petrology/article/54/2/273/1484891

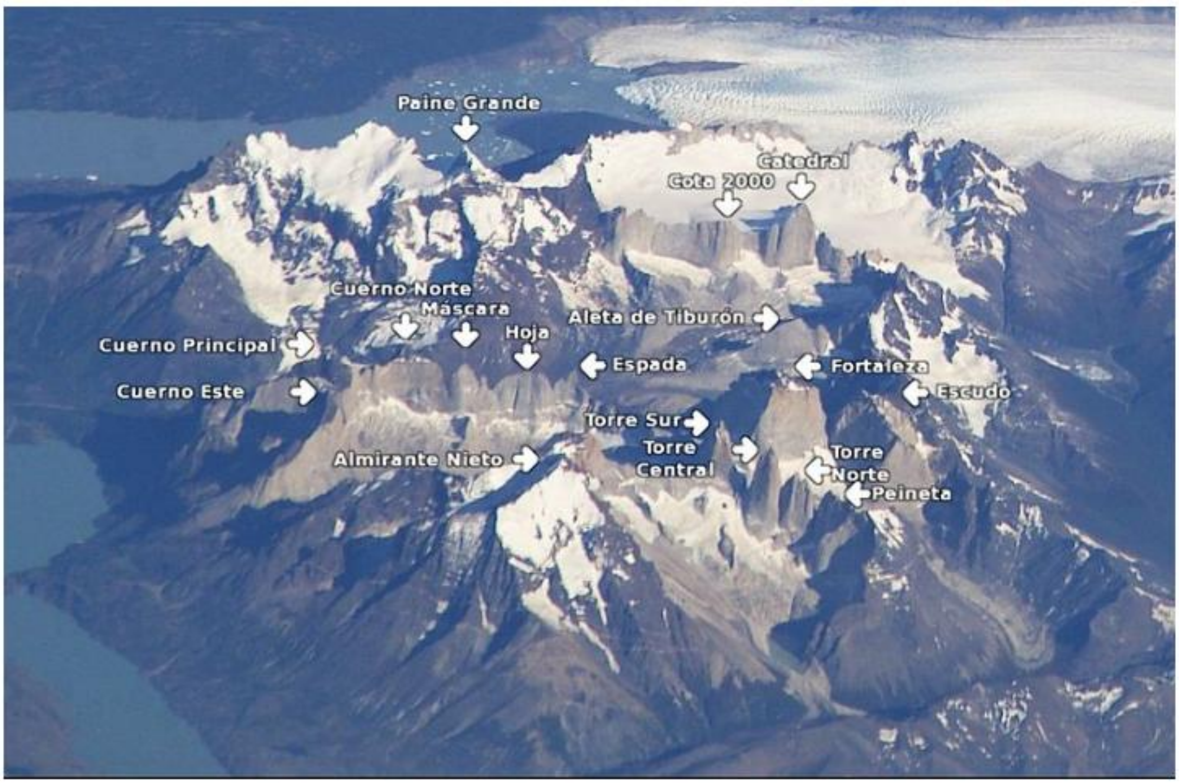
Click on the PDF icon to see a reader-friendly version.



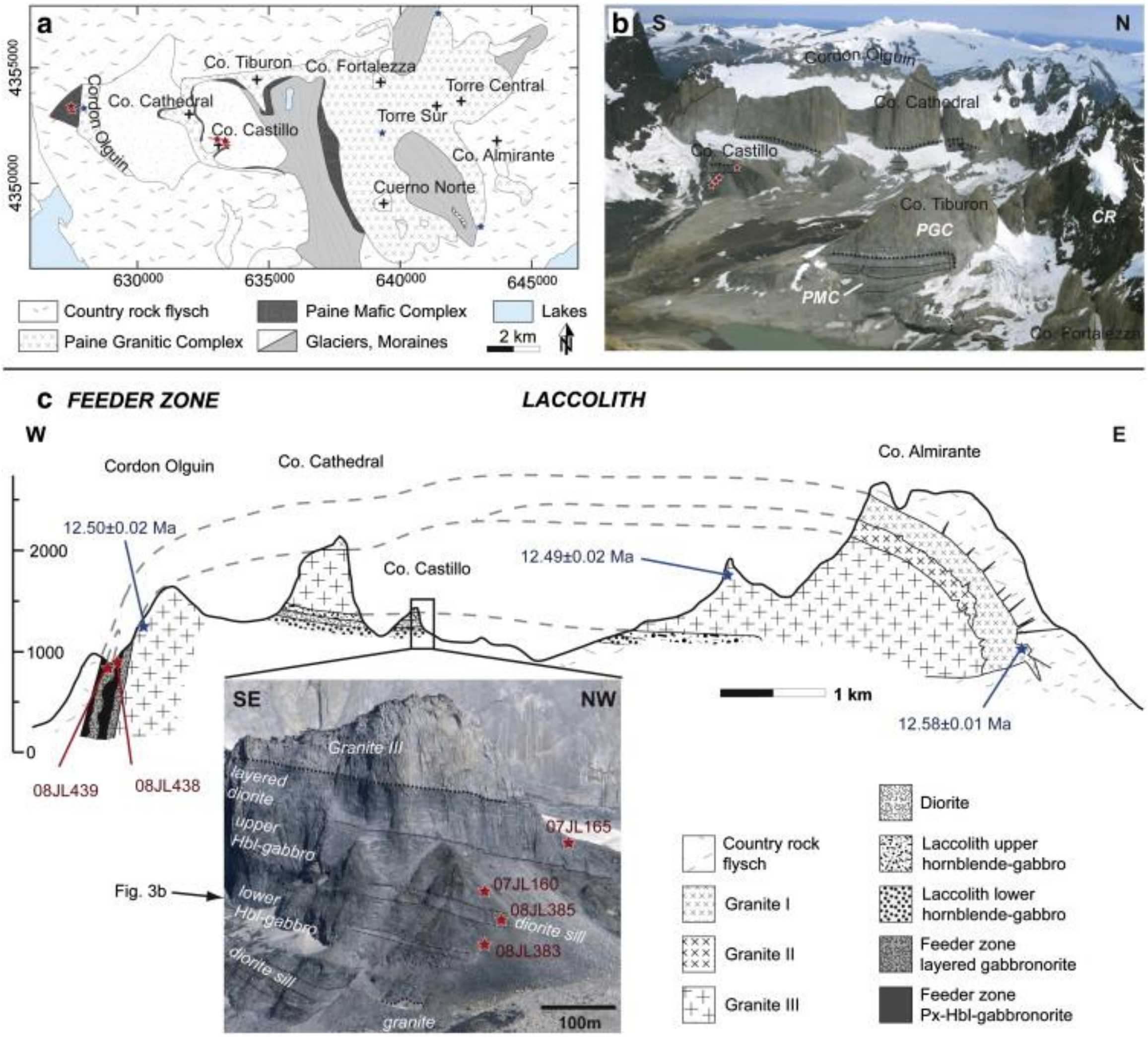
Location and topography of the Torres del Paine and the Cuernos del Paine



Simplified Geological Map of the Cuernos del Paine



Cuernos del Paine and Torres del Paine.



Details of Cuernos del Paine Geology

PERIOD PALAEO PLANTS of

SOUTH-EASTERN AUSTRALIA

10. The GLOSSOPTERIS FLORA (Part 6)

PERMIAN (300 —252 Ma)

WOOD

The generic terms Dadoxylon and Araucarioxylon have been confused due to the classification of Glossopteris being based on leaf morphology. As the Glossopteris wood anatomy is of the Araucarioxylon type (a gymnospermous wood with regular sized water conducting cells) Araucarioxylon is now the generally accepted term.

All photos are of Glossopteris wood from Late Permian Coal Measures in the Sydney — Gunnedah Basin from Scone (Photos 1 to 6), Boggabri (Photos 7 and 8) and Wollongong (Photo 10).

Photos 1 & 2, 3 & 4, & & 6, 7 & 8, each pair is an end and side view of the same specimen while Photo 9 is a close up of 7 & 8 showing tissue grain. Photo 10 is of a silicified pebble, originally of petrified wood which has been eroded from its matrix, buried and silicified in quartz sand, uncovered and rounded by the sand and surf and finally polished in a tumble polisher.

Photo 1

Photo 2

Photo 3

Photo 4

Photo 5

Photo 6

Photo 7

Photo 8

Photo 9

Photo 10

(Winston Pratt)

PERIOD PALAEO PLANTS of

SOUTH-EASTERN AUSTRALIA

11. The GLOSSOPTERIS FLORA (Part 7)

PERMIAN (300 — 252 Ma)

LEAVES

Glossopteris species classification is based on leaf morphology and there are over 100 species. There is a wide variety of the spoon-shaped leaves from long (G. ampla is up to 1m in length) to short, from wide to narrow (Photos 2 & 3) and all combinations in between. Most have a smooth regular edge. There is considerable variation in the angle at which the veins leave he midrib from almost right to acute angles (Photos 4 & 5) and there is considerable variation in the degree and positioning of the veinlet mesh. The Glossopteris trees were deciduous and the leaves shed in the autumn fall form 'autumnal bank' fossils (Photo 8) in which the whole rock is composed of layer upon layer of leaf fossils. It is probable that some of the many species adapted to less waterlogged habitats where fossilisation is less likely to occur. Photo 5 is from Dunedoo, NSW while all of the others are from the Newcastle Coal Measures.

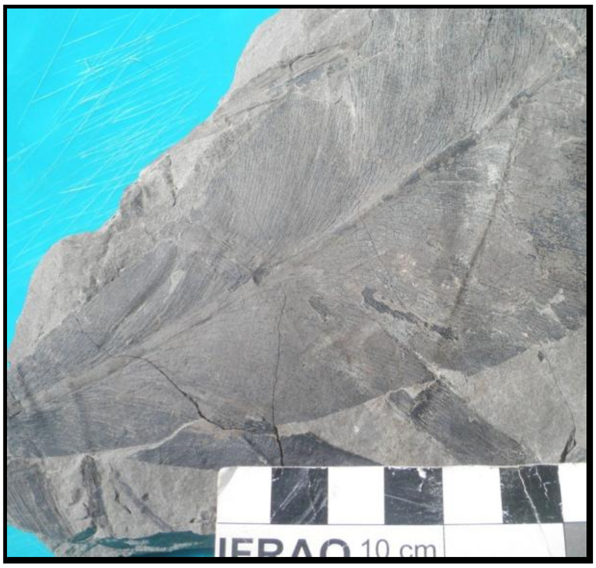


Photo 1

Photo 2

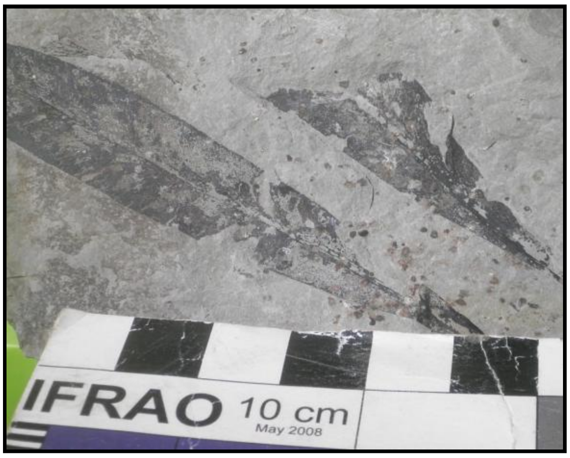


Photo 3

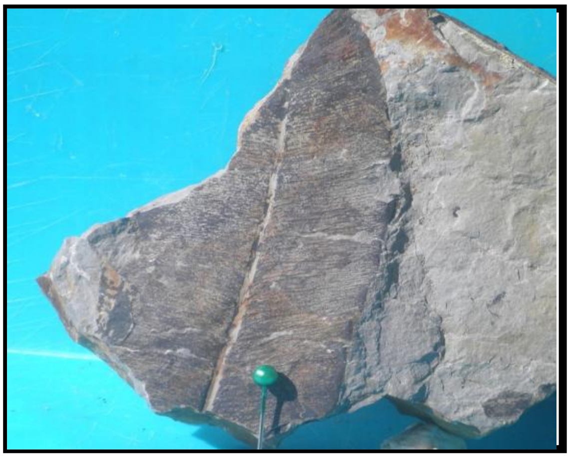


Photo 4

Photo 5

Photo 6

Photo 7

Photo 8

(Winston Pratt)

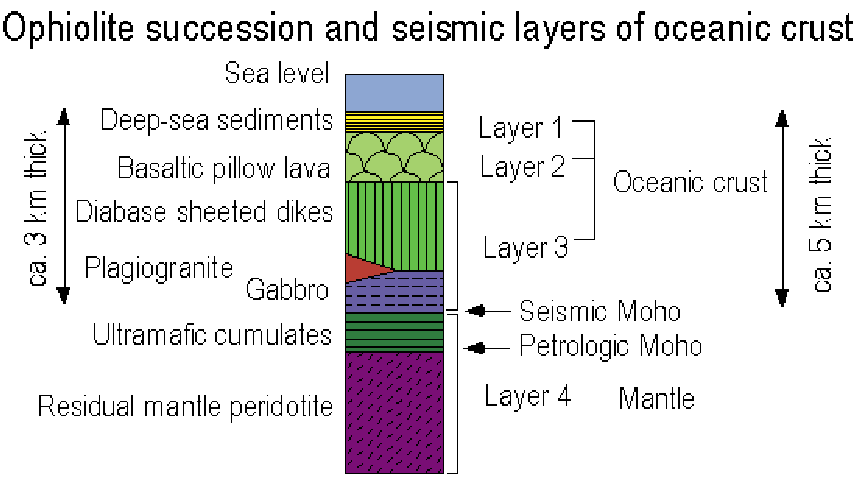
How Sharp is the Moho?

The pioneering Croatian seismologist Andrija Mohorovičić analysed the 8th October 1909 earthquake southeast of Zagreb. His analysis showed that there are two main layers, with a boundary about 54 km below the surface. The seismic (earthquake) waves travelled faster in the lower layer than the upper, indicating that the two layers have different physical properties, especially density. In due course, the upper layer was called the Crust, the lower was called the Mantle, and the boundary was named the Mohorovičić Discontinuity in his honour (generally shortened to Moho by English-speakers).

Subsequent studies showed that the Moho is 25-60 km below surface in continental areas and 5-9 km below the sea floor in areas of deep ocean basins (kilometres deep, and truly oceanic, rather than flooded continental margins). Other studies (from seismic-wave travel velocities) indicated that the density of the lower continental crust is 2.7-3.0 grams per cubic centimetre (g/cm^3), the lower oceanic crust is 3.0-3.3 g/cm^3, and the uppermost mantle is 3.3 g/cm^3 (and increasing downwards). At first there was no real certainty about the composition (mineralogy or rock-type) of these layers.

Marine geophysical studies in the 1950s to 1970s led to the concepts of plate tectonics; and sea-floor sampling helped confirm the nature of the uppermost oceanic crust (thin sediment resting on basalt). On-land geological mapping at a few localities revealed a rare suite of rock units: deep-marine sedimentary rocks overlying basalt lava flows, many with pillow-structures. Under the basalt is dolerite (which Americans call diabase) in the form of 100% sub-vertical dykes – intrusive dykes into intrusive dykes into intrusive dykes into... Many of the dykes have chilled margins, demonstrating chilling of younger dykes against cooled earlier ones. Below the dykes are gabbro units, chemically similar to the overlying dolerite and basalt, but coarser-grained. Below the gabbro is coarse-grained peridotite, an ultramafic rock consisting largely of olivine and pyroxene. Field relations of the gabbro and peridotite units indicate that they are the fill of magma chambers. The peridotite is essentially undeformed, but is sometimes layered, sometimes massive. In many cases there is deformed harzburgite (essentially olivine – two-pyroxene coarse-grained rock, another ultramafic rock-type) beneath the undeformed peridotite. Comparison between these rock suites and the upper-oceanic crustal samples, referenced against the geophysical models of density, convinced people that the field geologists were looking at a sequence through old oceanic crust down into upper mantle, which was rather surprisingly perched on continental land.

The above description is very simplified; the process of getting oceanic crust and mantle away from where it was created and up onto/into continental crust involves enormous force, which deforms and disrupts (along faults) the oceanic rock sequence. In most examples there is a need to sort out the disrupted fragments from the surrounding continental and shallow marine rocks, and then re-assemble the fragments. Often, parts of the sequence (top, interior or base) are not available (eroded away, buried by later rocks, or faulted away into some unrecognised location). The complete sequence is known as an **ophiolite**, which has a reconstructed thickness of 5-10 km down to the base of the gabbro/peridotite magma chamber, nicely matching the modern oceanic crust's thickness.



Comparison between ophiolite and modern oceanic crust.

The process of solidifying the magma in the deep chamber involves progressive crystallisation and growth firstly of olivine and pyroxene crystals, which are denser than the still-liquid magma, and sink to the chamber's floor, making peridotite (layered or massive). The overlying part of the chamber contains a mush of pyroxene crystals in liquid, from which plagioclase feldspar crystallises. The mixture of pyroxene and plagioclase is gabbro. The solidified magma chamber becomes a two-layered igneous intrusion; the upper layer of gabbro has a density of ~3.0 g/cm^3, the lower layer of peridotite has density of ~3.3 g/cm^3. This corresponds to the density contrast determined by the seismologists, so the peridotite/gabbro boundary is called the **geophysical Moho (**or **seismic Moho)**. Below this (typically a few hundred metres lower) is the boundary between the newly-generated igneous oceanic crust (the floor of the magma chamber) and the residual mantle from which the magma was extracted. The residual mantle is the solid stuff that didn't melt when the magmas forming the overlying oceanic crust were generated and rose into position. This boundary is between undeformed ultramafic rock (basal layer of the magma chamber) and deformed ultramafic rock (residual mantle), and there isn't a great mineralogical difference, so essentially no density contrast; the seismic waves aren't strongly refracted or reflected, and the seismologists cannot "see" it. Its petrological and tectonic significance is crucial however, so it is referred to as the **Petrologic Moho** (or **Petrological Moho**).

Both versions of the Moho can be as sharp as any igneous intrusive or internal contact you have ever seen. This is the Seismic Moho:

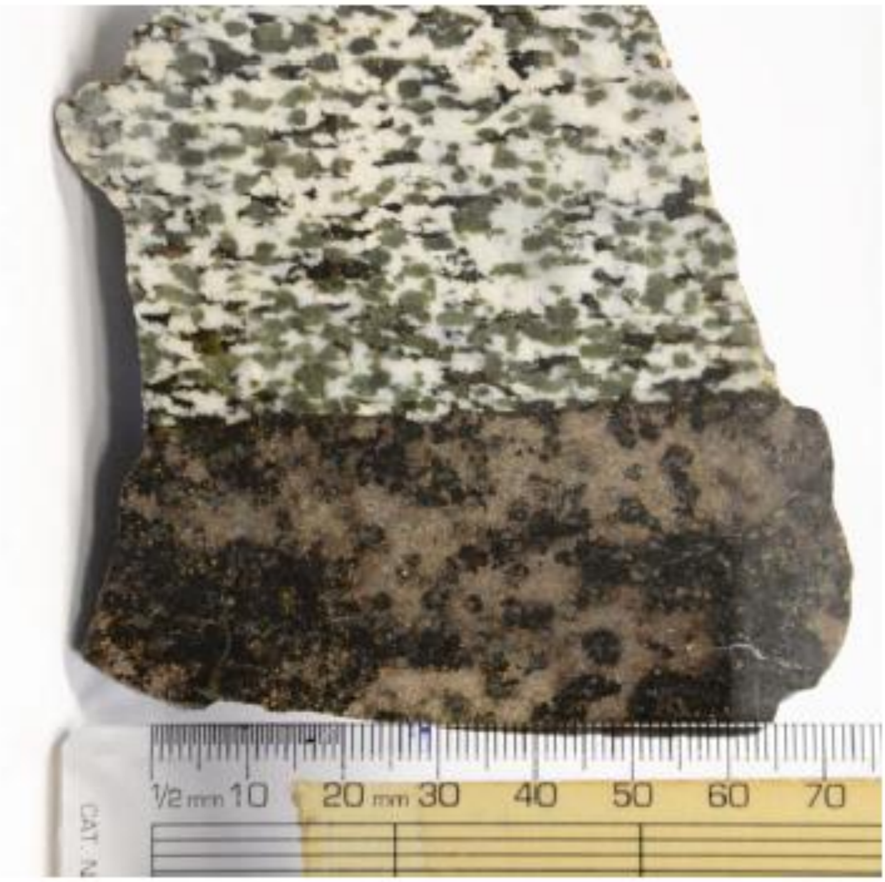


Fig. 4.7 Hand specimen of the Semail Ophiolite Moho, separating dark upper mantle harzburgite below from pale coloured lower crust gabbro above

From: GeoGuide - *Geology of the Oman Mountains, Arabian Peninsula*, (2019); Mike Searle

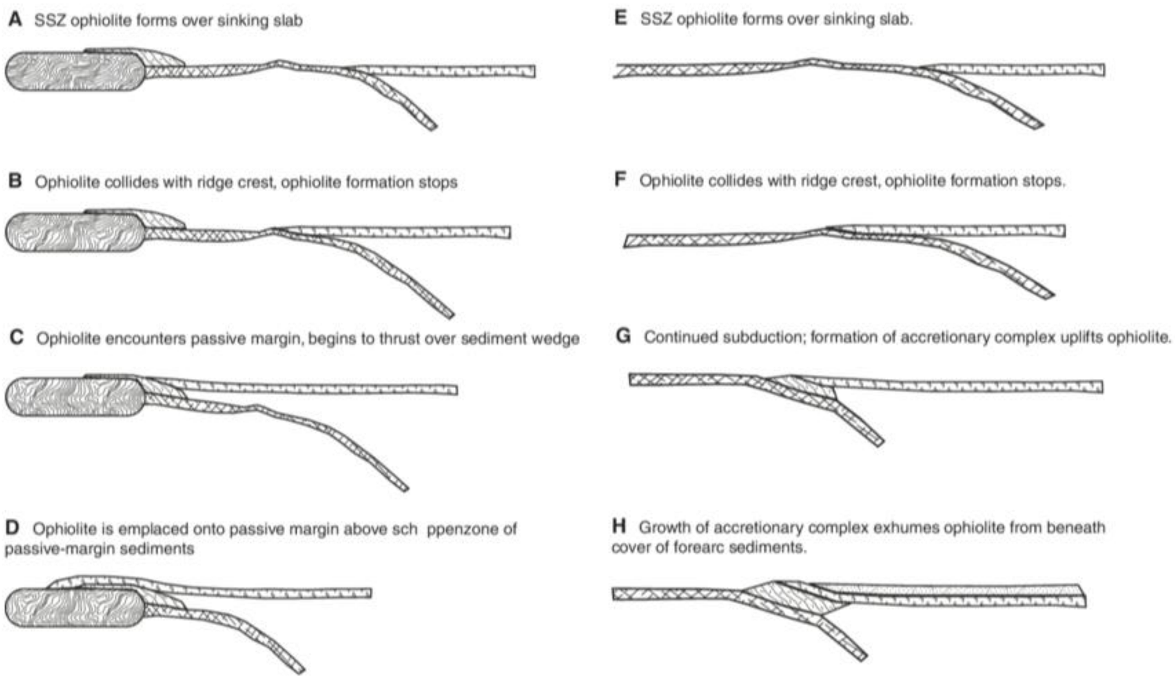
Often, the contact is interleaved:

Fig. 4.8 Sharp Moho contact between peridotites of the mantle sequence (right) and pale coloured layered gabbros of the lower crustal sequence (left), Fanjah–Nakhl road

From: GeoGuide - *Geology of the Oman Mountains, Arabian Peninsula*, (2019); Mike Searle

Ophiolites are quite rare, because unusual circumstances are required if they are to be preserved within continental crust. Oceanic lithosphere (mostly upper mantle plus thin moderate density oceanic crust) is more-dense than continental lithosphere (subequal upper mantle and moderate density continental crust). In any collisional situation, the standard response is for the denser oceanic lithosphere to be displaced under the continental lithosphere. This is standard subduction.

For the oceanic crust (in the form of an ophiolite suite or assemblage) to "get onto, or amongst" the continental crust, it seems necessary for the oceanic lithosphere to de-laminate, with the some or all of the oceanic crust and maybe some uppermost mantle at the base, peeling off the top of the down-going subducting slab of lithosphere, and riding over the edge of the bock of continental crust (or else being emplaced in the wedge of marine sediment shed off the eroding continent). This unusual over-riding situation is called **obduction**, and is the global equivalent of a paper miss-feed by your desktop printer. (The analogy carries forward... your printer and/or the networked computer gives you a "paper jam" message; and you discover a sheet of paper, generally crumpled-up in the innards of the machine, akin to the dismembered units of the ophiolite suite.) Like a paper jam, obduction is a rare anomalous event.



Various hypothetical processes for getting ophiolites up onto/into continental crust.

Australian examples of probable (dismembered) ophiolites are found near Bingara and Coolac NSW, and northwest of Rockhampton Qld.

The effects of the more usual subduction process are displayed at Port Macquarie (AGSHV field trips in past years), with the added complication there that some of the subducted material "bobbed back up" towards the surface, where it is now exposed at the current level of erosion.

The University of Derby has a series of short YouTube videos on the Oman ophiolite, narrated by Hugh Rollinson:

Oman Ophiolite – Introduction
or https://www.youtube.com/watch?v=XP37dDQeoCE

Oman Ophiolite - Lavas 1
or https://www.youtube.com/watch?v=yv7Bif74zx4

Oman Ophiolite - Lavas 2 (Wadi Jizzi)
or https://www.youtube.com/watch?v=4mjXKgUx6Mg

Oman Ophiolite – Dykes
or https://www.youtube.com/watch?v=RzJ_6cH0v0M

Oman Ophiolite – Gabbros
or https://www.youtube.com/watch?v=X4DXihtTCns&t=15s

Oman Ophiolite - Lower oceanic crust and moho
or https://www.youtube.com/watch?v=b5LqC0QzJJg&t=32s

Oman Ophiolite - Mantle 1
or https://www.youtube.com/watch?v=RgtqazNcxYk&t=28s

Oman Ophiolite - Mantle 2 (Muscat)
or https://www.youtube.com/watch?v=F2u9Gf9O_Js

Oman Ophiolite - Late Intrusions (plagiogranites)
or https://www.youtube.com/watch?v=rj4wpJ7I3VQ

Chromite in the shallow mantle, Oman
or https://www.youtube.com/watch?v=QNeEcVH7T-M

Sifa blueschists, Oman
or https://www.youtube.com/watch?v=zbQkiFoirLU&t=12s

Earth's rock-solid connections between Canada and Australia contain clues about the origin of life

June 18, 2020 5.47am AEST Updated June 19, 2020 3.28am AEST

Half Dome in California is constituted from granite, a relatively less dense type of rock. (Shutterstock)

The rocks at the surface of the modern Earth are broadly divided into two types: felsic and mafic. Felsic rocks are generally relatively low density — for a rock — and light in colour because they are made from whitish minerals rich in silicon and aluminium. Half Dome in California is made of granite that is a felsic rock. Mafic rocks, in contrast, are relatively high in density and dark in colour because they contain minerals rich in iron and magnesium; Giants Causeway in Northern Ireland is made of basalt, which is a mafic rock.

The difference in density between felsic and mafic rocks means that felsic rocks are more buoyant, and therefore sit at higher elevations above the Earth's mantle (the layer inside the Earth between the crust and the core). For this reason, felsic rocks make up Earth's continents whereas the lower elevation crust under the oceans is mafic.

The mechanisms that separated the rocks at Earth's surface into these two groups may have also created the environment needed for life to flourish 4.3 billion years ago, very early in the history of Earth.

The Giants Causeway in Northern Ireland is an unusual rock formation comprising mafic rocks. (Shutterstock)

The separation into these two rock types is the result of plate tectonics: where the tectonic plates separate and move apart, the rocks below become depressurized, melt and fill in the gap between them, like the Mid-Atlantic Ridge. The rock that fills the gap between the plates is mafic. When one plate slides below another, fluids released from the lower plate cause melting in the mantle. These melts have to pass through the upper plate to reach the surface. On their way to the surface, they undergo a series of processes called fractional crystalization, which can change mafic melts into felsic melts.

Establishing timelines

When this separation happened is a matter of great debate in the Earth sciences because it may allow us to determine when the Earth became habitable for life. Many Earth scientists believe that the weathering of continental crust may have provided the nutrients for life to thrive; identifying when the first continents formed indicates when this may have occurred.

Earth scientists also debate whether plate tectonic processes in the past were the same as those occurring today, and whether they were even needed to form continental crust in the past. The first continental crust may have been formed through the interaction of oceanic crust and mantle plumes of heat coming from the Earth's core. Another theory suggests that continental crust formed through meteorite bombardment.

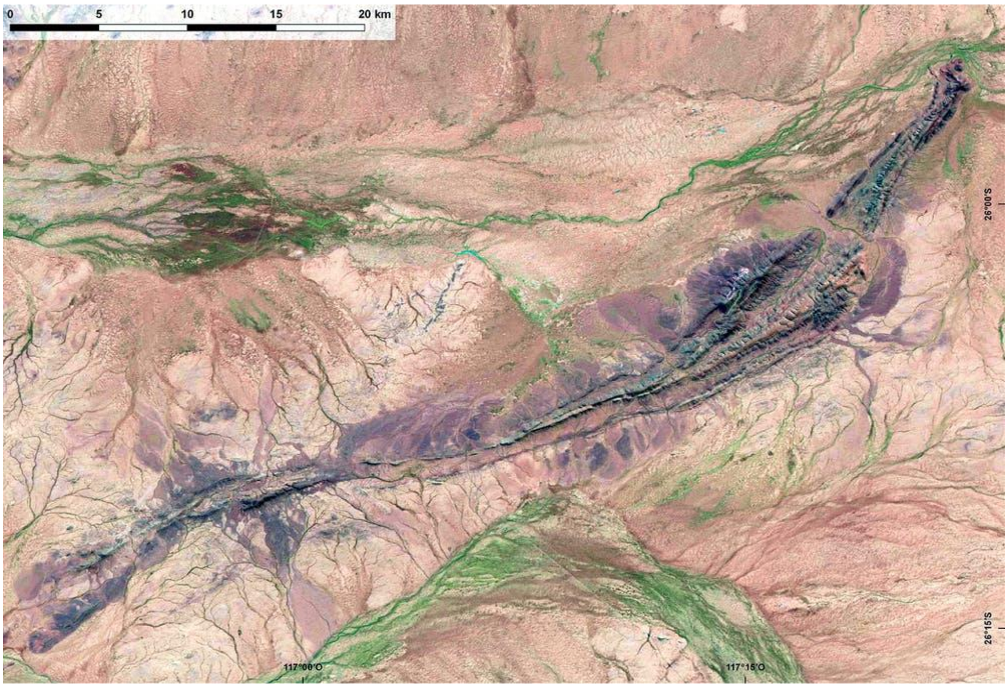
The exact mechanism is important for understanding the history and evolution of Earth, and may help understand the processes that could be occurring on other planets.

Reviewing the records

Our recent study looked at the oldest geological material on Earth. The results suggest that Earth was already separating into these two rock types by 4.3 billion years ago — effectively since the beginning of the Earth's geological record. Our data also gave intriguing insights into the tectonic processes that may have been occurring at that time.

The origin of continental crust is debated in part because the further back in time you go, the fewer rocks there are to study. Samples from the Acasta Gneiss Complex in northern Canada were found to be about four billion years old — the oldest known rocks on Earth. These Acasta Gneiss rocks are felsic and composed of tonalite-trondhjemite-granodiorite.

There are very few older samples from Earth, the most famous of which is the Jack Hills zircons. These are up to 4.3 billion years old, 300 million years older than the Acasta Gneiss. They are tiny grains of mineral zircon that have been eroded out of their parental rock (the rock in which they initially crystallized).



A contrast-enhanced true colour satellite image (Landsat 5) of the Jack Hills in Western Australia. (Gretarsson), CC BY

These zircons are found in much younger sediments in Australia, which means that it's difficult to determine what kind of rocks these minerals originally came from, leaving open the question of whether there was continental crust during the earliest period of Earth's history.

Continental connections

In our recent study, we compared all aspects of the chemistry of the zircon crystals from Acasta rocks to the Jack Hills zircons to see if they could have been formed in a similar environment.

We found that the two sets of zircon grains are chemically identical, suggesting that they formed from the same kinds of rocks and likely in the same kinds of tectonic settings. This means that the Earth may have started to create continental-type crust very soon after it formed.

The chemical composition of both suites of zircon crystals also suggest that they grew in magmas that originated at great depth in the Earth. Deep origins for magmas are a typical sign of subduction on the modern Earth.

We compared the amount of uranium in the crystals to the amount of ytterbium, a rare element. When a magma forms at great depth, the mineral garnet is often present, which gathers ytterbium. This means less ytterbium is taken up by zircon crystals, suggesting that a relative lack of ytterbium indicates that these magmas formed in deep environments.

The Jack Hills zircons are known to have crystallized at relatively low temperatures. We found that the temperatures from Acasta zircons matched exactly with the Jack Hills zircons, further indicating their similarity.

Finding the beginning

Ultimately, our results indicate that the tectonic processes occurring at the beginning of the geological record may not have been so different from the processes occurring afterwards. Evidence that things were not too different to modern Earth brings intriguing insights into the potential for the origin of life and the habitability of the early Earth, possibly confirming that life was present very early in Earth's history.

This is a corrected version of a story originally published on June 17, 2020. The earlier story said 4.3 million years ago instead of 4.3 billion years ago.

Geology Plate tectonics

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View all partners

How the Pilbara was formed more than 3 billion years ago

April 17, 2018 6.52am AEST

In the field studying the rock association in the Doolena Gap greenstone belt, 30 km north of Marble bar in the Pilbara region of Western Australia. David Murphy, Author provided

The remote Pilbara region of northern Western Australia is one of Earth's oldest blocks of continental crust, and we now think we know how it formed, as explained in research published today in Nature Geoscience.

The region is well known for its rich, ancient Aboriginal history extending over at least 40,000 years. It also features an incredibly diverse ecosystem, with many species found nowhere else.

The architecture of this ancient crust leads to a distinctive landscape as viewed from above, with light-coloured oval features that are granite domes surrounded by dark belts of volcanic and sedimentary rocks, known as greenstone belts

This unique geological architecture bears witness to the history of our planet

Billions of years ago

The Pilbara region began to form more than 3.6 billion years ago and our research supports the idea that its rocks were not formed through the plate tectonics processes that we see in operation today.

In plate tectonics, the outermost layer of Earth consists of fragmented, stiff "tectonic plates" that drift across the planetary surface, interacting at their boundaries. New crust is generated and destroyed at plate boundaries and this process is associated with most of Earth's current volcanic and earthquake activity.

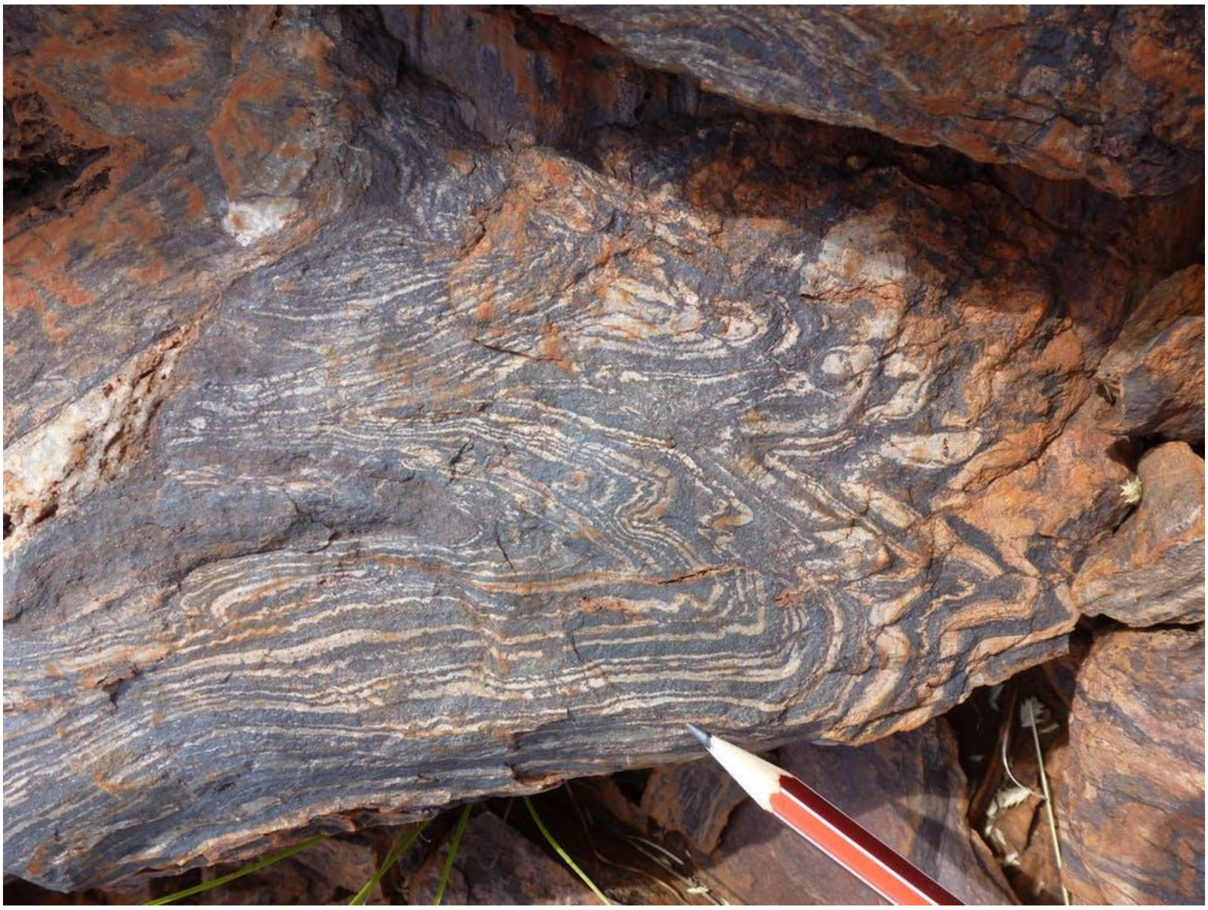
The plate boundaries are generally composed of fairly straight segments, hundreds of kilometres long. Witness the long chain of volcanoes along South America's west coast.

So why do the rocks in the Pilbara exhibit this unusual granite-greenstone geometry? In our research we detail how these rocks formed, describing a series of "gravitational overturn" events that affected the ancient crust in the East Pilbara well before plate-tectonic processes began around 3.2 billion years ago.

Gravitational overturn

What is a gravitational overturn? The young Earth was roasting hot. Its large heat content resulted in widespread volcanism. It was too warm for the rigid plates required for plate tectonics to operate.

Imagine retrieving a long-forgotten chocolate bar from your pocket, which then bends and drips over your fingers as you attempt to enjoy a snack. (Modern plates resemble a cold chocolate bar straight from the fridge: it does not bend and breaks when you want a corner.)



Photograph of at least 3.5-billion-year-old banded-iron formation showing intensive deformation as a result of gravitational overturn until 3.41 billion years ago. Daniel Wiemer, Author provided.

The hot early Earth erupted thick piles of basalt lavas that formed a dense crust barely supported by the underlying mantle. The base of this cooling crust experienced further heating from the hot mantle below until it started to melt, generating relatively buoyant granitic magmas.

This process led to an unstable stratification of the ancient proto-crust: low-density granites were overlain by high-density basalts. Due to the high heat, both layers could bend and flow, leading to instability.

The granitic blobs wanted to rise and the basalts wanted to sink. Scientists call the rising blobs "plumes" and the reorganisation process "gravitational overturn".

In the early Earth, with its high temperatures and soft crust, the granites rose up through the crust where it formed buoyant stable crust, while most of the dense basalt crust sunk into the mantle. This process is preserved in the Pilbara as the oval-shaped granite domes and the preserved remnants of the basalt crust as the greenstone belts.

The landscape today

North of Marble Bar, by looking at rock fabrics, we discovered the remains of the oldest recorded gravitational overturn in the Pilbara. Intensely deformed rocks preserve traces of the ascent of a rising granite plume and the associated down-going of the dense volcanic crust.

A rugged landscape formed above the deformed greenstone belts in the Doolena Gap greenstone belt, 30km north of Marble bar. David Murphy, Author provided

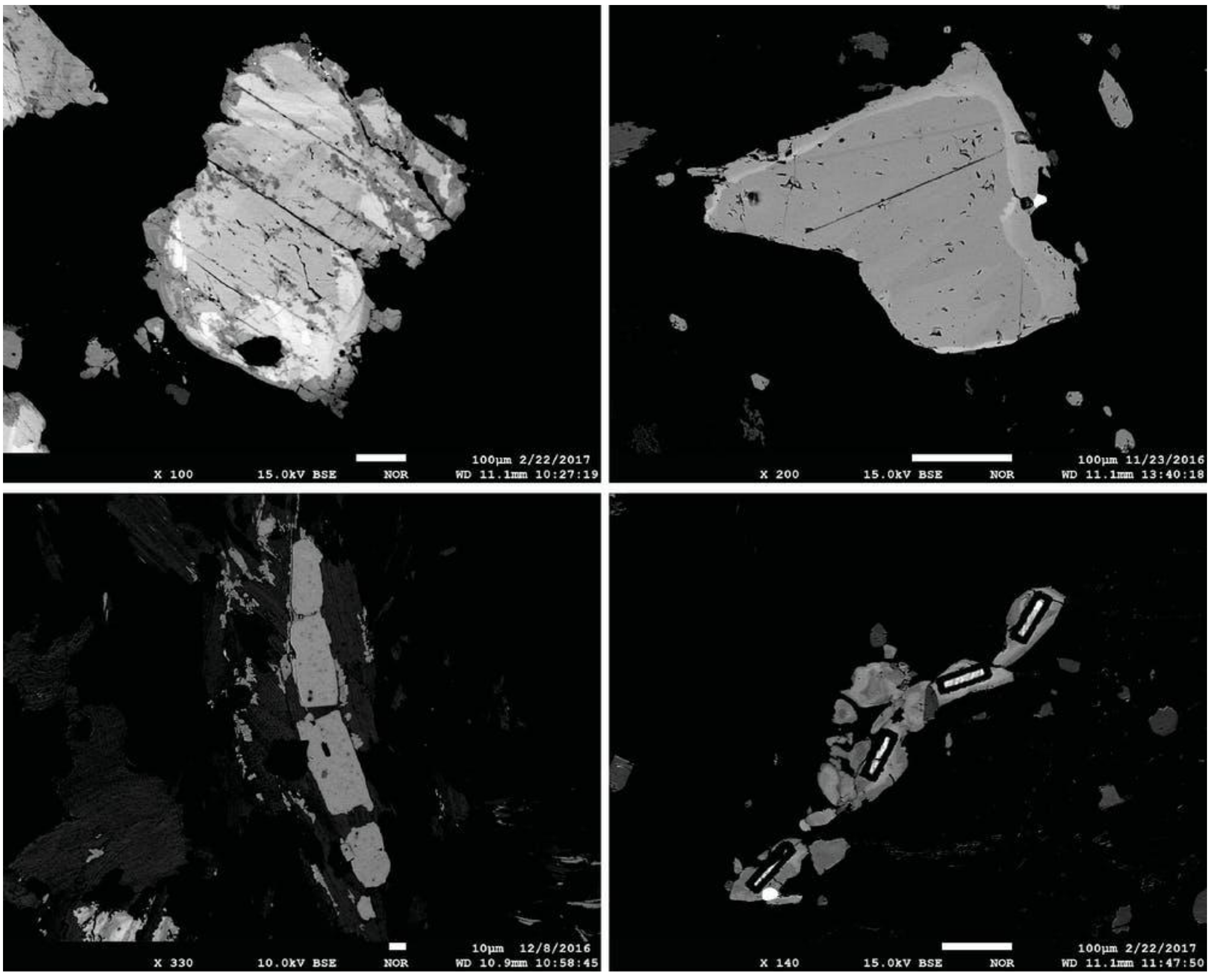
Our field observations, geochemical analyses and thermodynamic models demonstrate that rocks collected from the dome margin represent high silica magma that originally melted at a depth of around 42km before crystallising as granites at 20km.

Uranium-lead dating of zircon in the laboratory revealed that these rocks crystallised from 3.6-billion to 3.5 billion years ago.

The intensely sheared rocks at the boundary of the rising dome and sinking volcanic rocks contain a metamorphic mineral, titanite, that formed during the gravitational overturn.

We dated several of these mineral grains and they average 3.42 billion years old. By dating both pre- and post-gravitational overturn rock associations, we were able to constrain its duration to a 40-million-year period.

Combining our research with the published work of other geologists, it appears that the Pilbara experienced at least three gravitational overturns separated by 100-million-year intervals.



Back scatter electron image of titanite taken at Central Analytical Research Facility, QUT. The upper two images are primary magmatic images that have undergone deformation and alteration during the gravitational overturn. The lower two images are metamorphic titanite that formed during the gravitational overturn. The rectangular shapes in the bottom right image are laser pit from the dating process. Lana Wenham, Author provided.

We speculate that the cyclicity of overturn events in the Pilbara is the ancient equivalent of the 500- to 600-million-year Wilson cycle, one full round of crust from formation until destruction in the plate tectonic style in existence since 3.2 billion years ago.

The Pilbara keeps inspiring scientists worldwide to finding answers to one of humankind's great questions: how did nature provide the platform for the eventual evolution of life?

We plan to test the idea of characteristic ancient overturn cycles elsewhere in the Pilbara and on other continents where ancient crust is preserved

(*Thanks to Chris Morton for both articles above.*)

Australia on the move: how GPS keeps up with a continent in constant motion

February 6, 2017 5.57am AEDT

Nothing on the Earth's solid surface is static because all land is moving very slowly due to continental drift. This very slow movement affects everything around you in the same way so you can't tell it is happening, unless you are able to very accurately measure where on the Earth's surface you are.

The Australian continent, perched on the planet's fastest moving tectonic plate, is drifting at about seven centimetres a year to the northeast. This is taking features marked on our maps out of line with the global navigation satellite systems (GNSS) such as GPS.

These global systems guide our smartphones, cars and other geo-positioning devices used in sectors such as construction, transport, mining, agriculture and surveying.

How can we keep our map coordinates up to date? That is a challenge faced by today's geodesists.

Knowing where things are

Geolocation devices determine their location in relation to known reference points – stable survey marks that have been fixed in the ground and precisely measured.

These reference points and their coordinate system of latitudes, longitudes and heights are called a geodetic datum. Every country has its own datum, and the one Australia has used to date is called the Geocentric Datum of Australia 1994, or GDA94. The coordinates of fixed features on our maps, such as roads, buildings, property boundaries and utilities, as well as the coordinates of moving objects, vehicles, aircraft, and ships are all based on GDA94.

In the early 1990s, GDA94 was defined so that it “moved” with the drift of the Australian continent, like a giant net tied to the landscape. The effect was that fixed features had unchanging three-dimensional coordinates.

In contrast, the GNSS devices we now increasingly rely on use a different datum to determine their coordinates.

Satellite positioning systems – such as GPS, the Russian GLONASS, the European Union’s Galileo and China’s BeiDou – give coordinates based on a datum that is not fixed to any continent, but rather the average of all continents, so the coordinates of fixed features on the Earth’s surface, such as the Australian continent, are always changing, like slow-moving ships at sea.

The global GNSS coordinates and the Australian GDA94 coordinates are getting further out of alignment every year.

Precise positioning on the horizon

Historically, coordinate differences of a metre or so have not accurate enough for users to notice. When GDA94 was first introduced, the GPS locations were only accurate to around 100 metres and sometimes much worse.

But two important things have happened since then. Australia has moved about 1.6 metres northeast, effectively moving the location of mapped features and their associated GDA94 coordinates.

At the same time, positioning technology has evolved considerably. By 2020, Australia will have moved by 1.8 metres and many of us will own devices that could pinpoint locations

with accuracy as small as, well, a smartphone. With real-time access to precise satellite positioning at our fingertips, we’ll notice discrepancies with GDA94-mapped features.

Imagine the confusion if a driverless car can determine its coordinates with (say) decimetre accuracy, in the GNSS datum, but the stored map features were referenced to our old datum

GDA94 and were nearly two metres different. That’s probably not even in the same lane.

The upshot is that Australia’s datum needs updating to ensure Australia’s plate-fixed maps are in sync with devices with accurate positioning capabilities.

A two-stage modernisation

Australia's datum is being modernised in two stages to allow for the complexity of the change.

Stage 1 begins this year and involves defining a new datum which on average shifts all coordinates in Australia by 1.8 metres to the northeast. Called GDA2020, this new continent-fixed datum will bring the coordinates of Australia's mapped features back into line with global systems in the year 2020.

In 2020, Stage 2 of the modernisation will establish a different kind of location reference system, similar to the global one, that will continually measure and model Australia's movement. The modelling will include local ground deformation and subsidence effects which can affect heights, as well as global tectonic motion which is mostly horizontal.

Then the location information we rely upon will always be in alignment with the devices we use to access it. But we will have to get used to the coordinates of "fixed" features in the Australian landscape changing by seven centimetres per year. This will be in sync with the satellites that provide all our modern positioning. It will be future proof!

Who is making the changes?

The Intergovernmental Committee on Surveying and Mapping (ICSM) has formed a group to oversee the process of implementing GDA2020.

The GDA Modernisation Implementation Working Group (GMIWG) is helping users and government agencies to develop coordinate transformation tools and technical resources, and providing information for software developers, equipment providers and users of spatial information.

Geodesists from Geoscience Australia and all the states and territories have been working on the tools required for the transition to GDA2020. While the new datum will be officially gazetted early this year, it will probably take until mid-2018 before it is widely adopted.

How do the changes affect you?

The key thing to remember is that in order to be reliable, location information must be identified by the datum as well as the latitude, longitude and height coordinate values.

People who work with accurate spatial information and rely on positioning technologies will need to keep up to date with the important changes being made to Australia's datum.

For others, the datum shift will be largely invisible, apart from improvements to the location services provided by smartphones

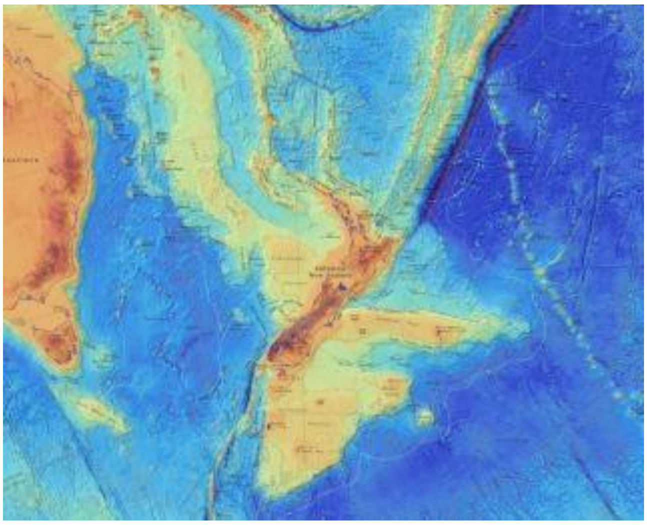
(*Thanks to Chris Morton*)

LIVESCI=NCE

Lost continent of Zealandia mapped in unprecedented detail

By Brandon Specktor - Senior Writer 11 hours ago

Earth's eighth continent is 94% underwater and 100% awesome.



A bathymetric map of the lost continent of Zealandia.

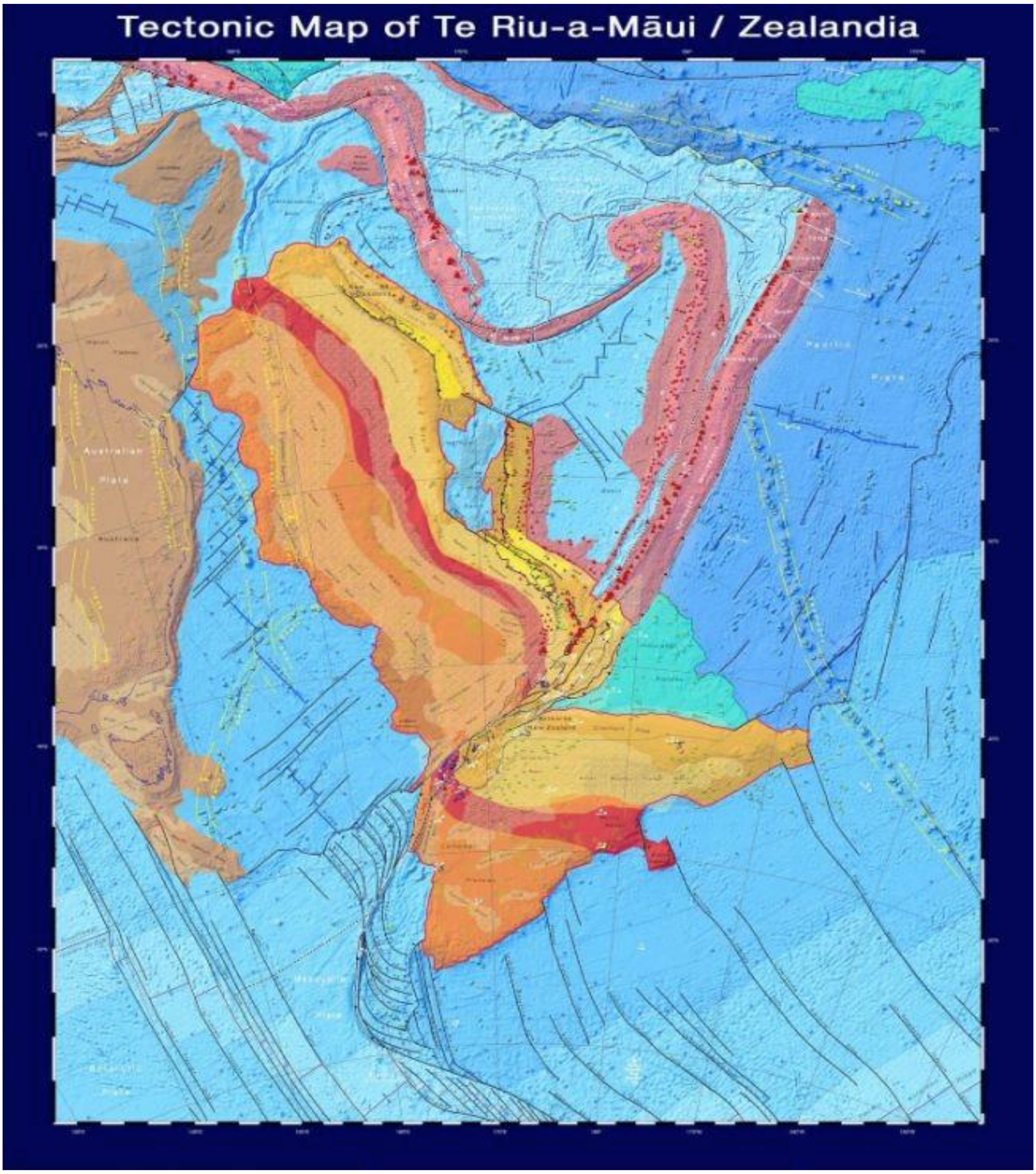
(Image: © GNS Science)

Earth's mysterious eighth continent doesn't appear on most conventional maps; that's because almost 95% of its land mass is submerged thousands of feet beneath the Pacific Ocean.

Zealandia — or Te Riu-a-Māui, as it's referred to in the indigenous Māori language — is a 2 million-square-mile (5 million square kilometers) continent east of Australia, beneath modern-day New Zealand. Scientists discovered the sprawling underwater mass in the 1990s, then gave it formal continent status in 2017. Still, the "lost continent" remains largely unknown and poorly studied due to its Atlantean geography.

Now, GNS Science — a geohazards research and consultancy organization owned by the government of New Zealand — hopes to raise Zealandia (in public awareness, at least) with a suite of new maps and interactive tools that capture the lost continent in unprecedented detail.

"We've made these maps to provide an accurate, complete and up-to-date picture of the geology of the New Zealand and southwest Pacific area — better than we have had before," Nick Mortimer, a geologist and lead author of the maps, said in a statement. "Their value is that they provide a fresh context in which to explain and understand the setting of New Zealand's volcanoes, plate boundary and sedimentary basins."



A tectonic map showing the age and type of rock beneath Zealandia. (Image credit: GNS Science)

The new maps reveal Zealandia's bathymetry (the shape of the ocean floor) as well as its tectonic history, showing how volcanism and tectonic motion have shaped the continent over millions of years. Data for the bathymetric map was provided by the Seabed2030 project — a global effort to map the entire ocean floor by 2030. (The project is about 20% complete.)

The team also released interactive versions of both maps on a new Zealandia webpage. Spend a few minutes clicking around the hyper-detailed images — and, when someone asks what you're doing, simply tell them you're "discovering Earth's lost continent."

(*Thanks to Chris Morton*)

Interactive webpage:
E TŪHURA - EXPLORE ZEALANDIA
or
https://data.gns.cri.nz/tez/index.html?content=/mapservice/Content/Zealandia/Home.html

There is a bit more technical detail about the maps and website on GNS science:
https://www.gns.cri.nz/Home/News-and-Events/Media-Releases/New-maps-and-website-give-fresh-insights-into-NZ-continent-22-06-2020

New maps and website give fresh insights into NZ continent

22/06/2020

Two maps and a website released by GNS Science this week give insights into the amazing forces that shaped Aotearoa New Zealand and the mostly submerged continent that lies beneath our feet.

The maps cover the bathymetry (shape of the ocean floor) and the tectonic origins of Earth's eighth continent – the 5 million square kilometre Te Riu-a-Māui / Zealandia on which New Zealand sits.

They can also be accessed through a new interactive website called E Tūhura - Explore Zealandia (TEZ) – http://data.gns.cri.nz/tez. TEZ is designed for exploring onland and offshore geoscience data in and around Te Riu-a-Māui / Zealandia.

"These maps are a scientific benchmark – but they're also more than that. They're a way of communicating our work to our colleagues, stakeholders, educators and the public," lead author of the maps, geologist Dr Nick Mortimer says.

"We've made these maps to provide an accurate, complete and up-to-date picture of the geology of the New Zealand and southwest Pacific area - better than we have had before.

“Their value is that they provide a fresh context in which to explain and understand the setting of New Zealand’s volcanoes, plate boundary and sedimentary basins.”

The TEZ website presents a wealth of maps, graphics and other information on the continent compiled in GNS Science research programmes.

Programme Leader Vaughan Stagpoole says TEZ provides the perfect way for users to explore geoscience data from the comfort of their homes or offices.

“Users can zoom and pan around different thematic geoscience webmaps of the region. They can readily view and interrogate the maps and turn layers on or off. They can also query features in the layers and generate custom maps of their own,” Dr Stagpoole says.

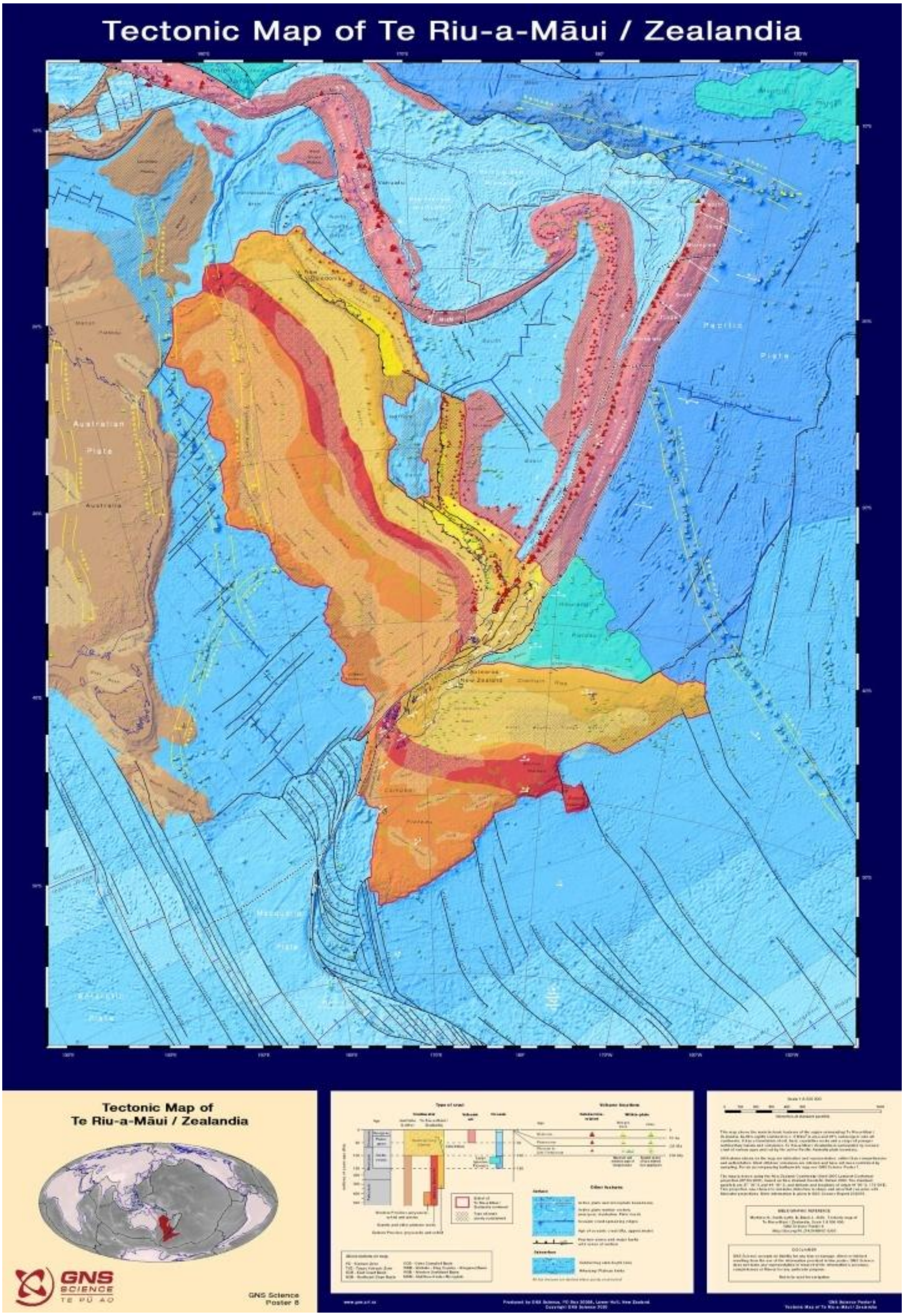
As more research results become available, GNS Science will update the maps and add more information to the interactive website.

Background

The authors of the maps are Nick Mortimer, Belinda Smith Lyttle, and Jenny Black. The project team for the TEZ website is Phil Scadden, Andrew Boyes, Vaughan Stagpoole and Jenny Black.

The tectonic map

This highlights the 5 million sq km Te Riu-a-Māui / Zealanda continent, a small part of which is on land, but most of which is under the sea. The colours show continental crust in red, orange, yellow and brown hues and oceanic crust in blues. Island arc crust is pink and large igneous province crust is green. (A large igneous province is a large accumulation of igneous rocks resulting from magma travelling through the crust towards the surface).


Tectonic Map of Te Riu-a-Māui / Zealandia
Tectonic Map of
Te Riu-a-Māui / Zealandia
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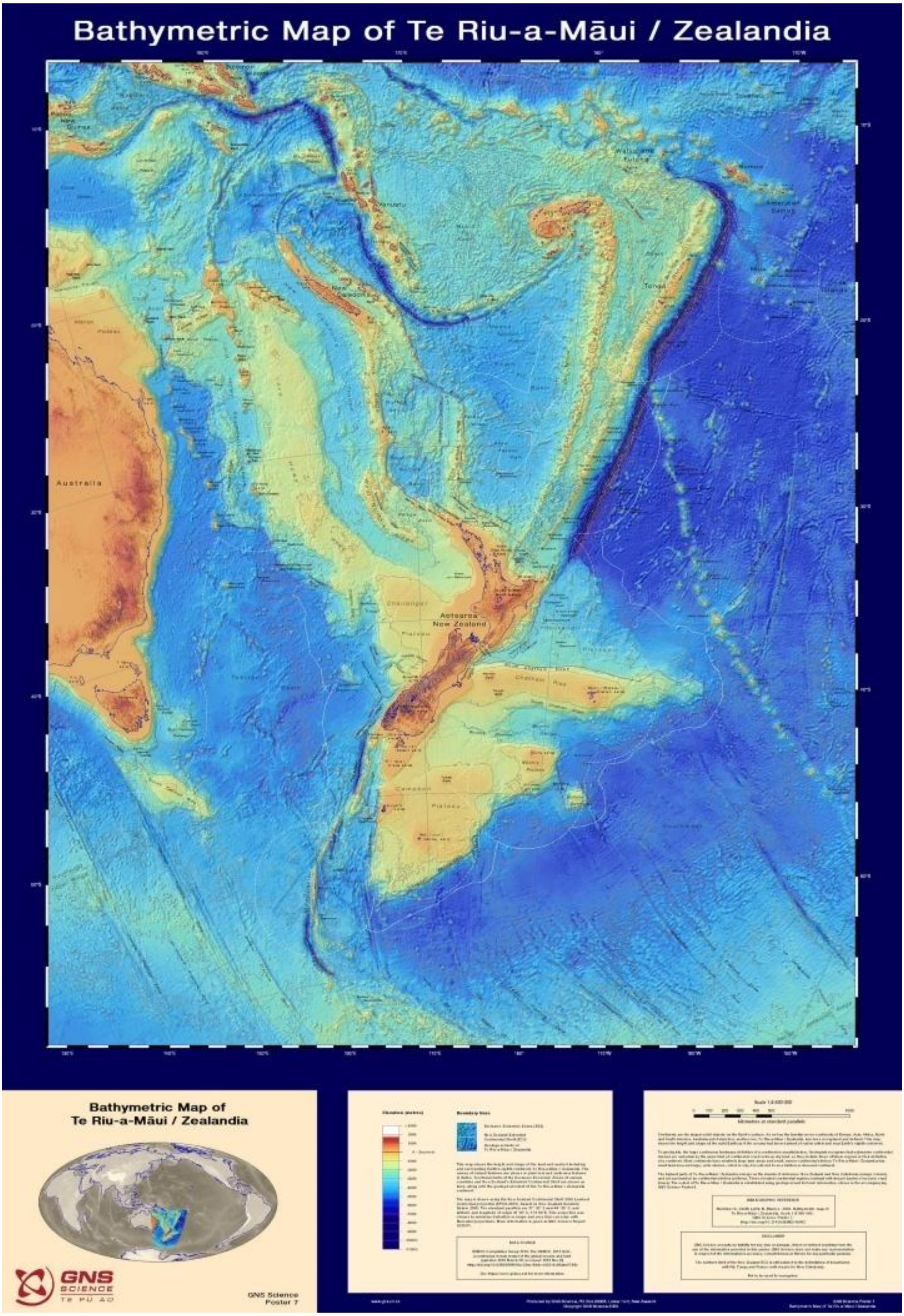
Poster 8

The bathymetric map

This map uses the GEBCO 2019 grid, the first output of the Seabed2030 project which is a global initiative to map the ocean floor of the entire world by 2030. The project is a collaboration between The Nippon Foundation in Japan and the General Bathymetric Chart of the Oceans (GEBCO). NIWA, GNS Science and Land Information New Zealand are jointly leading the South and West Pacific Ocean Regional Data Assembly and Coordination Centre, based in Wellington.


Bathymetric Map of Te Riu-a-Māui / Zealandia
Australia
Challenger
Plateau
Aotearoa
New Zealand
Chatham Rise
Campbell
Plateau
Bathymetric Map of
Te Riu-a-Māui / Zealandia
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Poster 7

Availability of maps

Copies of the printed maps are available either as flat or folded at $15 each ($25 the pair). PDF files can be downloaded at no cost. Both maps and PDFs are available through the GNS Online Store. An accompanying GNS Science Report 2020/01 lists the data sources used to compile the map posters. The GIS layers from the posters are also available through the TEZ interactive website.

E Tūhura - Explore Zealandia interactive website http://data.gns.cri.nz/tez

This consists of three maps with multiple layers. **The Geoscience data webmap** shows a compilation of research data. Geology layers include GNS Science's 1:250 000 onland geology and Petlab database sample locations. Users can add further layers to customise their maps.

The Tectonic webmap displays interpretations of the types and age of crust, major faults, plate and microplate boundaries, plate motion vectors, subducting slab depths, basement geology, and sedimentary basins. It also shows locations of ancient and modern volcanoes.

The Bathymetric web map shows the shape of the solid land and seabed in a seamless colour scheme with a hillshade background. It also depicts coastlines, territorial limits and names of major undersea features.


Te Riu-a-Māui / Zealandia
is Earth's eighth continent.
NEW CALEDONIA
AUSTRALIA
94% underwater
Pacific Ocean
Area 5 million sq km
Tasman Sea
NEW ZEALAND
Te Riu-a-Māui / Zealandia has the features of Earth's seven other continents:
Elevation above surrounding oceanic crust
Diverse geology
Crust thicker than that found in oceans
Area greater than 1 million sq km
Clearly defined limits
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When I was active in my former career in the exploration and mining industry, I was a member of AIG (Australian Institute of Geoscientists), the appropriate professional organization. Their newsletter, AIG News is open access (not hidden behind a Members' log-in):

https://www.aig.org.au/news/

As well as Industry news they sometimes have other articles, such as this half-page snippet from Newsletter 139:

Institute News Snippets

Yarrabubba crater in WA outback world's oldest recognised impact structure

Around 2 billion years ago when Earth was covered in ice, a meteorite slammed into what is now outback Western Australia.

The impact left a 70-kilometre-wide scar on the land known as Yarrabubba impact crater.

"The age we've got for the Yarrabubba impact structure makes it the oldest impact structure on the planet," said Chris Kirkland, a geologist at Curtin University.

Within the red dirt of Barlangi rock is evidence of Earth's violent past. (Supplied: Timmons Erickson)

Source: https://www.abc.net.au - Read the full article at **https://tinyurl.com/aignews139-yarrabubba**

The article referred to is an ABC News – Science online summary page:

Yarrabubba crater in WA outback world's oldest recognised impact structure
or https://www.abc.net.au/news/science/2020-01-22/wa-crater-yarrabubba-meteorite-impact-worlds-oldest/11881786?fbclid=IwAR0RqpqvZFb5cXfMQc3fN0Prp2Iqo2Bk4F5GscQhGgBJ_RuR0CsYbONXJPk

The appropriate scientific paper is:

Precise radiometric age establishes Yarrabubba, Western Australia, as Earth's oldest recognised meteorite impact structure
or https://www.nature.com/articles/s41467-019-13985-7.pdf

Read Any Good Books Lately?

Island on Fire

Information for the article about Lakagígar in this Newsletter came from a number of sources. Many are rather technical, but one that is very readable is *Island on Fire,* (2014); Alexandra Witze & Jeff Kanipe. I began this book (on-screen) more out of a sense of duty to do the research than for pleasure, but I enjoyed the experience.

The book starts with an account of the 1973 eruption of Eldfell volcano on Heimaey, an island off Iceland's SW coast. Threatened by the loss of the island's fishing harbour, a workforce was tasked with pumping seawater onto the lava, freezing portions, and diverting the remaining liquid lava to flow away from the harbour. This operation marks the first real large-scale success in controlling a volcanic event so as to avert a disaster.

The story moves on to the eruption of Lakagígar from the viewpoint of Jón Steingrímsson, a clergyman whose home and church were near the lava flows that emanated from the fissure eruption. There are biographical notes about Jón in his younger days.

The narrative switches to the general tectonic setting of volcanoes, in plate-tectonic terms, then focuses on a short description of Iceland's main volcanoes. The next chapter, about supervolcanoes, begins with a description of Yellowstone (Wyoming, USA), Toba (Sumatra) and Santorini (Eastern Mediterranean); then moves to lesser (but still very powerful) volcanoes: Vesuvius, Tambora (eastern Indonesian island of Sumbawa), and Krakatau (Sunda Strait, between Sumatra and Java).

Next is an account of the aftermath of the Lakagígar eruption, once again mainly through the eyes of Jón Steingrímsson.

The fifth and sixth chapters are about the unusual weather phenomena associated with the eruption that were recorded across Europe, Moving from shorter-term weather events, the narrative moves onto the longer-term severe winters experienced throughout the Northern Hemisphere. There is then a description of research into Lakagígar and other volcanic eruptions; beginning with the accounts of contemporary naturalists like English astronomer William Herschel and Benjamin Franklin (then living in France as US Ambassador); and moving onto recent research conducted on ice-cores extracted from deep bore-holes on Greenland and Antarctica.

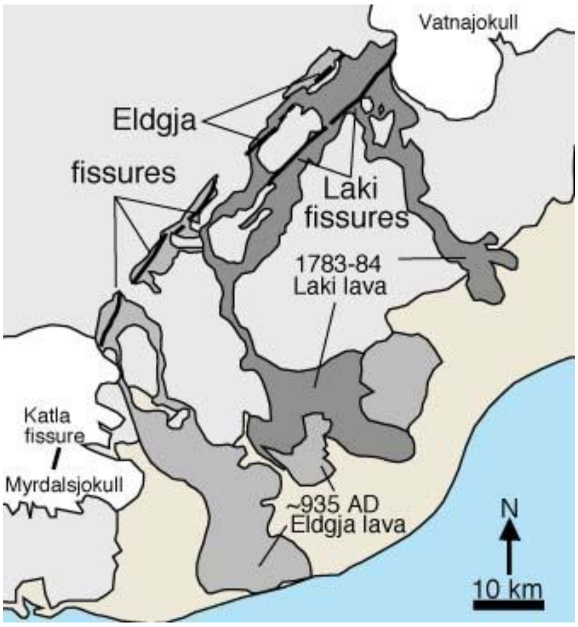
The story switches forward to the 21st Century, beginning with the authors' guided tour of the crater chain of Lakagígar and the lava flows; and then mentions interviews with a descendent of Jón Steingrímsson who still lives in the district, and with the custodian of the replica of Jón's church, which was built on the site of the original. Next is an account of life during the 2011 eruption of Grímsvötn, which dropped ash over the countryside affected by the 1783 Lakagígar eruption. Many of the current inhabitants are of course descendents of people affected by the 1783-1784 disaster.

Following this is a chapter on the many ways volcanoes can kill; direct deaths by either burning in lava flows, or being hit by ejected stones are rare. More common causes are: CO_2 outbursts from lakes associated with quiescent volcanoes (Lake Nyos, Cameroon), jökulhlaup (huge floods caused when eruptions melt overlying ice-caps) as in Iceland, pyroclastic flows (also called *nuées ardentes*) such as at Pompeii and Martinique (in the Caribbean), volcanic fog (vog) such as in Hawaii's Kilauea, fluorine toxicity (fluorinosis) which may have caused some deaths in Iceland and across Europe in 1783-5, to indirect effects of Lakagígar, such as cold, and disease associated with the temporary colder climate. The chapter next examines the deadly Great London Smog event of 1952 (five days of pea-soup fog charged with smoke particles, that caused about 4000 prompt deaths, with about 100,000 sick people, and about 6000 total deaths over the following months). The final section of the chapter is an account of work by a group of researchers who combined the parameters of the Lakagígar eruption with 21st Century demographics and modern climate models to estimate potential deaths across Europe if a Lakagígar-style eruption were to occur now. The result is ~142,000 deaths forecast.

The final chapter (*The Next Big Bang; How Worried Should We Be?*) is a look to the future. It begins with Eyjafjallajökull, which was subject to tremors for two decades; these grew into earthquakes, then an eruption, beginning on 20th March 2010. GPS receivers on its flanks showed the mountain to be “inflating” prior to the eruption, so there had been strong hints of the impending eruption. Two huge jökulhlaup rushed down the north flank of the mountain on the 14th and 15th of April, and the first ash plumes began near dawn on the 14th. Tracking the ash with the only appropriate radar installation (at Reykjavík airport) was difficult because of intervening ridges. Initially the ash plume drifted eastwards towards Norway, then swung southwards towards Britain. The Volcanic Ash Advisory Centre (VAAC) in London took on the plume-tracking role.

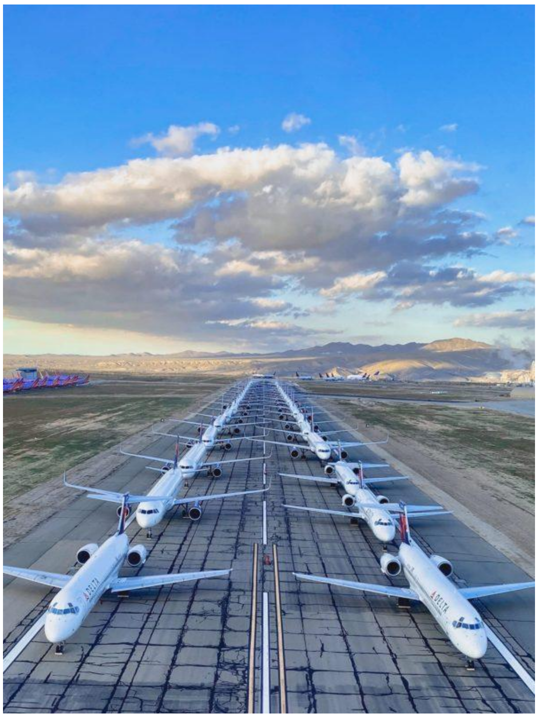
There had been an incident in 1982 when a British Airways jetliner flew through the erupting ash-plume of Indonesia’s Mount Galunggung; all four engines stopped as ash melted in the engines and coated the turbine blades, disrupting the gas flow. Fortunately, the shut-down engines cool off, the melted-on coating solidified, cracked, and fell away, allowing the flight crew to re-start the engines wihout the aircraft plunging into the ocean. After this, the VAAC wasn’t taking any chances, and aircraft were grounded wherever the plume was expected to drift. After a week the bans were eased, but not before the cancellation of ~100,000 flights, stranding about ten million passengers, and costing billions of Euros. The eruption of Eyjafjallajökull was small by any measure, with a VEI of 3.

The narrative moves on to a dramatic hypothetical fissure eruption between Lakagígar and the even larger 934 (or 939) - 940 AD fissure eruption at Eldgja (the two systems are parallel, and about 8 km apart).



From: The Laki and Grimsvotn Eruptions of 1783-1785
or
http://volcano.oregonstate.edu/oldroot/volcanoes/volc_images/europe_west_asia/laki.html

The imaginative scenario is spot-on in one particular; the account suggests that the aircraft industry would be severely stressed by flight closures, and the airline companies would “...move as many planes as they can to Buenos Aires, Cape Town and Sydney, but many declare bankruptcy." The COVID-19 crisis has shut down ~90% of scheduled flights, and huge numbers of aircraft are parked up, awaiting the easing of restrictions.



Delta Air Lines plane storage in Victorville, CA

The average repeat time for Eyjafjallajökull-sized eruptions is ~10-20 years; for Lakagígar events the average repeat time is 250-500 years. Perhaps the biggest danger is from VEI 3-4 size eruptions near large- and mega-cities like Naples and Mexico City, where millions of people are at risk. About half-a-billion people worldwide are in peril from a nearby modest eruption. More-violent eruptions are less-frequent, but the potential death toll rises accordingly.

It is not a simple matter to find all past eruptions to work out a potential frequency distribution. Ice-cores from Greenland and Antarctica show that a huge eruption (VEI 7) took place in about 1257-1258. (For comparison, Mt St Helens in 1980 was VEI 5, Krakatau in 1883 and Pinatubo in 1991 were VEI 6, Tambora in 1815 was VEI 7, and Yellowstone in the Pleistocene was VEI 8.) Ash in cores from both polar zones indicates a tropical source, potentially Indonesia. The ash chemistry strongly implicates Rinjani/Samalas on Lombok (the island east of Bali). This was one of the largest eruptions in Holocene times (the last ~11,000 years), but it has not been identified in any culture's historical record!

In Iceland the risk is probably rising, as first the Pleistocene continental ice-sheet, then the individual ice-caps melt, and the underlying volcanoes are unloaded.

Rainbows, Haloes, and Glories

All of us are interested in Geology, and many (most?, all?) of us are interested in astronomy. This book; *Rainbows, Haloes, and Glories*, (1980); by Robert Greenler is a classic work on the in-between area; things of our atmosphere, or the effects of our atmosphere.

You might think that the first chapter **Rainbows** would have nothing to surprise you, because rainbows are so familiar. So try these for size...

Single rainbows are the most common; and you probably have seen “double rainbows”. The primary bow is caused when a ray of sunlight enters a raindrop with refraction, is reflected once, then leaves the drop with another refraction. The second arc (outer, fainter and wider – with reversed sequence of colours) is the secondary bow, where the ray is reflected twice. There is nothing to prevent a third, fourth, or even more reflections; however at each reflection, some light intensity is lost to the refracted beam that left the drop at the previous reflection. (The light energy that left the raindrops to form the primary bow is not available to form a second reflection, so there is less energy available for the Secondary... and so forth.) The third-order and fourth-order rainbows are very feeble, being of lower intensity and wider dispersion than the primary and secondary; but they have been seen and photographed on *very* rare occasions. How many people know that such things exist, or where to look? To see the primary (and secondary) bow, you need to turn your back to the Sun; but for the third- and fourth-order bows you need to face the Sun, (and you are looking into the glare). That glare is another member of the rainbow family; the zero-order rain“bow”, which consists of light that is refracted on entering the raindrop, and passes through, to leave the “back” of the raindrop, with a second refraction. The geometry is such that there is no concentration of light into a narrow band “bow”; rather the light is spread out into a wide (tens of degrees across) circular zone that fades away towards the edges.

The Sun’s white light can be separated into colours ranging from red to blue, because the different wavelengths of the components are refracted by slightly different angles. You can think of the coloured arc as a red rainbow beside an orange rainbow beside... Infrared light is “beside” the red component of the sun’s spectrum, and invisible to our eyes, but not to infrared-sensitive film. Using infrared-sensitive film and a matching filter that blocks visible light, it is possible to photograph the infrared rainbow, sitting alongside (just above) the position where the red is/would be.

There is a slight difference between the refractive index of seawater and fresh water (*e g* rainwater). This means that if you are on a fast-moving boat (on seawater) the rainbow seen in any spray kicked up has a slightly different position than would be expected for a rain-shower rainbow. If there is a rain-shower rainbow at the same time, the two rainbow arcs do not quite “line-up”, and this misalignment can be seen and photographed.

The second chapter on **Ice-crystal refraction effects: halos, arcs, and spots** deals with phenomena that originate in a part of the atmosphere above where rainbows form. The air is cooler at higher altitudes; any free H_2O may be water, or ice (If the temperature is below 0° C, the water may freeze to ice, or may exist as a supercooled liquid.)

Sometimes rainbows are explained in terms of the raindrops being “like prisms that split the white light into its coloured components”. The analogy is rather forced, because raindrops don’t have planar faces, and the light-path through raindrops is different from that through laboratory prisms (where there is no reflection involved between the two refractions). It is different for ice crystals, which have planar faces, and they can act as prisms. The ice crystals can form cirrus clouds (horsetails), or the widespread high, glary “ground-glass” altostratus cloud of uniform appearance. Altostratus is the best sky in which to see the effects of light refracted through ice crystals. Much depends on the shape of the crystals. Many are like pencils... elongate hexagonal prisms; others are stubby, like six-sided disks. These different shapes have different aerodynamic properties, and depending on turbulence of the air, the crystals can be randomly or preferentially orientated. Refracted light-rays may be diffused or concentrated in various directions, depending on the distribution of orientations, resulting in brighter areas, arcs or spots in the sky, with particular positions in reference to the Sun’s position.

The pattern most often noticed is the 22° arc or halo, a bright circle around the Sun (or the Moon). Further away is the (rare) fainter 46° halo. When you see a drawing of the classical refraction-of-light experiment, everything is drawn symmetrically; the prism is drawn in end-on view, and the light-path is in the plane of the drawing. Suppose you twist the prism out of end-on orientation, then the light still passes through, and is refracted, but the light-path through the skewed prism is changed. In effect the prism is no longer acting as a 60° prism, but as one with a slightly wider angle, and the light-beam isn't refracted "down" quite so much. Also the light is now refracted (and diverged according to wavelength) "sideways" a little, too; out of the plane. The many different orientations of the ice crystals in the sky are like laboratory prisms with different amounts of skewness (as described above). There are other differences between laboratory prisms and ice crystals; glass has a refractive index of ~1.5, for ice the value is ~1.33; also, for the laboratory prism, adjacent faces are 60° apart, but for ice, the adjacent faces are 120° apart. It's "the second face over" that forms a 60° angle. There is no refracted path between adjacent faces 120° apart; because the geometry is "wrong." Light hitting one face is refracted "away" from the adjacent face, and cannot hit it. It can only hit the "second face over" in either direction, the face opposite (parallel to itself), or one of the two end faces.

Some of the arcs and spots in the sky are spread out into bands with spectral colours. The best-known are sun-dogs (also called parhelia); two bright spots, each "level" with the sun, and sitting just "outside" the 22° halo, often coloured redder on the side "nearer" the Sun, grading to bluer "away" from the Sun, over a few degrees of arc. The end faces of a prism are perpendicular to the side faces, making 90° prisms, through which the light-path is different again, especially when "skew" paths (with various extents of "skewness") are considered. This family of rays generates yet another family of arcs.

Chapter 2 is strongly analytical, concentrating on the light-paths through ice crystals, and how they direct light in particular directions, creating bright arcs and spots or patches in the sky's ice-crystal clouds. The author uses spot-simulations (where many individual ray-paths are calculated together, and the apparent position for each is plotted as a dot). The computer-generated images are included in the pages. The many pathways through the several types of ice crystals, with their various distributions of orientation produce a "skyfull" of haloes; depending on the intensity, some or many will be too vague to notice.

The third chapter **Ice-crystal reflection effects: pillars, circles, and crosses** complements the second. Just as ice crystals refract light, so light reflects off their faces. Just as in the case of refraction, the distribution of orientation of the ice crystals will concentrate light into certain directions, or disperse it away. In the absence of refraction, the reflection phenomena are non-coloured, or Sun-coloured (white). We Australians rarely see sun-pillars, because they require ice crystals near the ground in fairly calm air, and this is rare at low latitudes and altitudes like most of Australia. Another common feature is the parhelic circle, which is parallel to the horizon, and so named because it passes through the parhelia (the sundogs), and naturally the Sun also. To see a full 360° parhelic circle requires ice crystals (with an appropriate distribution of orientation) all around you, and this doesn't always happen. Some of these arcs and circles cut across other arcs (including those caused by refraction), and these crossings are often regarded as crosses, sometimes being given a religious or mystical significance. Such features are more often seen at high latitudes, where the air is colder, the freezing level is nearer the ground, and the appropriate weather conditions occur more often. Any of the fainter arcs are usually more visible at these high latitudes too.

This chapter too is fairly analytical, and concentrates on the light-paths that cause the various arcs, illustrating many by computer-generated images using spot-simulations. The clustering of ink-dots simulates the light intensity seen in the sky.

The fourth chapter is about **Complex displays, past and present**. Ice crystals both refract and reflect light, and these simultaneous effects are pulled together in this chapter to talk about real-life arcs and spots and circles in their commonly-seen combinations. Many individual features and combinations are very rare (or rarely observed and documented). Several illustrated examples are described, and analysed in a process the author calls “sky archaeology”. The examples include Johannes Hevelius’ (Hevel’s) Gdansk (Danzig) “Seven Suns” on 20th February 1661; Johann Lowitz’s St Petersburg display on 18th June 1790; William Parry’s display of 8th April 1820 while ice-bound in a ship off Melville Island in the Canadian Arctic; Frank Bavendick’s display of 8th March 1920 at Ellendale North Dakota; J R Blake’s accumulated observations in Antarctica during the 1958-1959 southern Summer; and photographs taken at the US South Pole research station in 1977 by Robert Greenler[2] (the author) and Austin Hogan.

Chapter 5 **Scattering: light in the sky and color in the clouds** deals with the causes of colours of the clouds when the sun is low (near sunrise or sunset), and the colour of the cloudless sky in full daytime, and at or near (before and after) sunset-time.

Sunlight traversing the air in a cloudless sky is partially scattered. Particles much larger than the wavelength of light (such as dust, pollen and water droplets) don’t scatter the light very much (Mie Scattering), so most of the light energy carries onward with little deviation. This leads to a bright area in the sky around the sun’s disk. (When you look at the sky from a shaded location, keeping the sun’s disk barely hidden, the sky adjacent to the sun is dazzlingly bright; you are then seeing Mie Scattering.) For particles of sizes close to the wavelength of sunlight (these particles are the very molecules of air – N_2 and O_2) the degree of scattering is greater, and increases as the wavelength shortens. This is Raleigh scattering. A ray of sunlight passing overhead has the bluer wavelengths “scattered out sideways” preferentially, and this is what reaches you when you look at the sky in directions well away from the sun. If you look nearly towards the sun, this light is somewhat reddened because the bluer wavelengths have been preferentially scattered away. The effect is difficult to see, because the more intense Mie Scattering dazzles you. When the sun is low in the sky, its light is dimmed overall by shining slant-wise through a greater path of air, and Mie Scattering is reduced, allowing you to see the preferential reddening of the light coming from the sky near the sun, which is light with some of the blue wavelengths scattered away, so the remnant reaching you is reddened (to orange or yellow). Illumination of any clouds by this redder light turns them into the beautiful colours of a spectacular sunset. The cloudless sky after sunset is still lit by sunlight, even when the air just above you isn’t lit anymore. As the sun sinks further after sunset, the proportion of sunlit air shrinks, and the pattern of Raleigh scattering changes as the sunlight’s path through the air changes. The reddened light illuminates the upper air, and bluer light scattered out by the lower unlit air mix to give the purples of late twilight.

Clouds take on other colours. The white clouds of daytime consist of water droplets much larger than the wavelength of the sun’s light, so all wavelengths are scattered nearly equally; white light hits them, and scatters off, still white. Some light penetrates into (and through) clouds (that’s why it’s not pitch dark under an overcast sky), so clouds absorb light too. The amount of absorption

[2] Greenler doesn’t mention another famous halo display. The first ascent of the Matterhorn in the Alps (on the Swiss-Italian border) was on 14th July 1865, by a party of seven, including English mountaineer Edward Whymper. During the descent, one of the party slipped and fell, pulling three others off the mountain. The rope connected to the uppermost three (including Whymper) broke, allowing them to survive. A little later, the three survivors saw a halo display develop (which Whymper sketched), containing two huge crosses. Whymper, who was a talented illustrator, included a woodcut of the display as the frontispiece of his 1880 book The Ascent of the Matterhorn. The picture shows the upper three-quarters of an elliptical arch, divided down the middle, and with a large cross nearly filling the upper portion of each half. There have been a few analyses Whymper’s description and illustration, and the various components of the display have been identified with well-known halo arcs and segments. Many people have miss-reported the illustration or Whymper’s description, apparently caught up in mystical story-telling. I have seen references to three crosses (presumably one for each survivor), or four crosses (one for each victim), and comments that “they” (rather than Whymper alone) sketched the display.

depends on the concentration of the droplets and the path-length of the light (the size of the cloud). If the cloud is between you and the sun, absorption will be great, and the cloud will appear grey (dimmed white-balanced light). Water vapour clouds can be dark grey, never black ("Black clouds" is dramatic exaggeration.) Clouds of smoke can be black because of fine particles of black carbon; or grey because they contain water droplets. Many organic flammable materials are composed of compounds rich in both hydrogen and carbon atoms. Un-burned carbon particles are black, the combustion product of hydrogen is steam, which can condense to transparent water droplets, and these scatter white light evenly; the final mixture of black and white is grey.

Other subjects are discussed in Chapter 5. Crepuscular rays are straight bands of brightly-lit sky where distant clouds partially block the sunlight. The perspective of the view makes them appear to radiate from the Sun, whereas the light paths of the various rays are virtually parallel. After sunset at your location, clouds beyond your western horizon can partially obscure the Sun's rays passing high over you. Gaps in and between the upper edges of those clouds allow beams of yellowed sunlight (Raleigh Scattering) to light the sky overhead in yellow bands, with blue bands between, representing the shadows of the clouds, where there is no direct illumination by the Sun, so the blue predominates. Crepuscular rays that cross the whole sky appear to converge opposite the sun, and these are called "anti-crepuscular rays".

As the sun sinks below the western horizon after sunset, a pink band rises in the eastern sky, with a mid-blue region below, down to the horizon (unless clouds hide the effect). The blue is the shadow of the solid Earth on the air to the east (the Earthshadow). The pink band is air illuminated by reddened sunlight, and is called the Belt of Venus. As the sun sinks further, the Earthshadow rises higher above the horizon, and eventually (say 30 minutes after sunset), no direct sunlight reaches the upper air east of you, all is in shadow, and the Belt of Venus has faded away. Naturally all these features can be seen before sunrise, but in reverse sequence, and in the opposite direction.

Two other topics are also treated in this chapter; these are "ice blink" and "water sky", and are restricted to polar latitudes. When the sky is uniformly overcast, ice reflects more light up onto the base of the overcast layer than sea does. Brighter areas due to ice reflecting extra light onto the base of the overcast are called ice-blink, and darker areas of the overcast caused by open leads of water between ice floes are called water sky. To an experienced mariner, ice blink in a certain direction means: "ice (icebergs or an ice-shelf) in that direction. Danger!". In contrast, a knowledgeable explorer plodding over the Arctic sea-ice towards the North Pole, who saw a darker area on the base of the cloud-cover coulg think: "water sky over there, there's an open lead of water in the distance that would block my route". He could adjust his course to steer around the lead without the trouble of walking up to it, then following around the shoreline looking for a way past.

Chapter 6 is about **Diffraction: the corona, the glory, and the spectre of the Brocken**. The corona is a bright circle of light a few degrees across, centred on the Sun[3] or the Moon. The effect around the Sun is dazzlingly bright; around the moon it is often seen to be bluer near the Moon's disk, and with a red ring (or more than one) at the rim. Sometimes the corona around the Sun can be studied in the reflection of a pool of water, which has a reflectance of about 2%. The colours are a result of interference of light. (People who have used a petrological microscope are familiar with interference colours – **Brian England**...). The same colours are seen on the surface of rain puddles that are on an asphalt road where cars have been leaking sump-oil. Also, these are the colours of the Oily-Rainbow stuff found on the surface of pools of water (see p 22 in Newsletter #3 **Gooey! Slimy! Colorful! What can it possibly be?**)

Similar gaudy interference colours can be seen often in, and on the edges of some clouds, within about 20° of the sun's direction. These are iridescent clouds.

[3] This "corona around the Sun" is not the same thing as the **solar corona**, which is the Sun's outer atmosphere, invisible except during a total eclipse of the Sun.

Interference colours are common in Nature: the bright blue-green of ducks' wing-feathers, gem-quality opal, brightly-coloured butterfly wings, and the scum on water puddles caused by the sheaths of the bacterium *Leptothrix discophora* floating on the surface. These effects are caused by regularly-spaced fine structures. Similar structures are common in human technology: CDs and DVDs, films of oxidised engine oil floating on water, and purpose-made diffraction gratings that are used in place of prisms to disperse light into spectra.

Another rare interference effect is Bishop's Ring, a circular bright patch of sky around the Sun, often tinged blue or brown, sometimes with a reddish rim. The Ring was described by Rev Sereno Bishop, a missionary living in Honululu, after the 1883 eruption of Krakatau. Greenler explains it as diffraction formed by extremely fine volcanic ash[4] injected into the upper atmosphere during the eruption.

When Bishop's Ring is visible, the sulphate aerosol particles also alter the scattering of light in the upper air, to produce dimmer skies (as in Lakagígar), or enhanced purple skies late into twilight (after Pinatubo).

The final section of the chapter concentrates on "The Spectre/Specter of the Brocken", and the hieligenschein. I'll describe these in reverse order. When you stand on dewy short grass (such as a football pitch) there is a bright halo around the shadow of your head. This glow is called hieligenschein, and depends on how light interacts with the spherical shape of dew-drops. Light rays that hit transparent spheres centrally, reflect from the rear face and return along the same path; light rays hitting just off-centre reflect back almost along the same path. When you look at your shadow on dewy grass, light passing over your shoulders hits dewdrops alongside the shadow of your head, and the almost-central rays can come back into your eyes, to make a bright area around your head's shadow. Light passing you a few metres away will reflect light back along and near the incoming path, so you don't see a bright glow "over there". Anybody standing "over there" will see his or her own hieligenschein. The famous Italian sculptor Benvenuto Cellini saw the hieligenchein around his head's shadow, but not around anybody else's, and concluded that it was a sign of his own genius, so he wrote in his autobiography! Accordingly, hieligenschein is sometimes called Cellini's Halo.

The same effect can be seen sometimes in fog rather than dew. For this you need special geometry. You need to be on high ground (such as a mountain-top) with the sun behind you, and a sunlit bank of fog stretched out in front of you. The sun's rays streaming past the peak hit droplets in the fog and reflect back towards the peak, where you are standing, forming a sort of hieligenschein around the shadow of the peak. The same effect can be seen from aircraft flying over low clouds, as a bright glow around the plane's shadow. Slightly different is the dry hieligenschein, seen when an aircraft flies over grass or a ploughed field. The light hitting the ground beside the plane's shadow fully illuminates each blade of grass or clod of earth, so there you see sun-lit grass or earth only. If you look away from the aircraft's shadow you see an unresolvable mixture of grass plus the shadow along the sides of each stalk (or dirt clod plus shadow on the sides of the clods). These shadows darken your view of the grass or earth away from the plane's shadow.

The fog droplets that produce hieligenschein can be sufficiently regularly-spaced to yield interference colours, with a redder ring around the edge of the bright patch when poorly-developed, or a Glory, which has a series of gaudily-coloured interference rings, when the optical conditions are just right.

[4] Greenler was mostly right in his 1980 book, but our knowledge-base has grown, especially since the 1991 eruption of Pinatubo. The main cause we now know to be sulphate aerosol particles that evolved from SO_2 molecules (rather than solid ash particles) injected into the stratosphere during large eruptions, including Krakatau and Pinatubo.

Weather conditions and the geometry of the Brocken peak in central Germany are especially favourable (plentiful fog, and a readily-accessible peak) to produce a splendid version of this effect which has become famous as “The Specter of the Brocken”.

The final chapter is **Atmospheric refraction: mirages, twinkling stars, and the green flash**. Our atmosphere increases in physical density downwards, and with this goes an increase in optical density or refractive index (R I). Light refracts in a way that deflects light rays towards the denser medium. Usually there is a sharp physical boundary between two substances where refraction is being studied (such as a glass prism or lens, and air), so the refraction is likewise sharp. For the earth’s atmosphere, there is a gradual transition through the air, and a corresponding gradual change of R I, so the light-path curves gradually. For a non-vertical beam coming down through the atmosphere, it steepens a little on the downward path. If you look back up the beam, you see back along the final part of the beam, not the upper part, so the light source appears to be above its real position. The flatter the beam, the greater the refraction; for a beam tangent to Earth’s surface (90° from vertical) the deviation is 28′ 59″ (for air at 10° C and 101 kPa pressure). The Sun’s disk is 31′ 27″ – 32′ 32″ across (Earth’s orbit is a near-circular ellipse, so its distance from the sun varies ~1%, and its angular diameter also varies by the same amount.) When the Sun’s disk appears to touch the horizon, the spatial geometry means that the top of the sun would disappear in a few seconds if there was no air. The image is raised above its real geometric position. This effect is greater for flatter angles, so the bottom of the Sun’s image is raised more than the top, making the view of the Sun seem less-tall than its width (the flattened Sun). The air column is never uniform, but has layers of various densities (these vary with day-to-day weather), which refract different levels of the Sun’s image different amounts when it is near the horizon. The results can be strangely-distorted views of the Sun: Chinese lanterns, wineglass shapes, or even a Sun cut up into horizontal slices.

The refraction also contributes to mirages. The sun heats the ground, which in turn warms the air in the few decimetres or metres above the ground. This warmer air is less physically and optically dense than the overlying air. The sky just above the horizon is bright silvery blue. Light beams from this part of the sky can approach the ground, where refraction in the less dense air curves the beam upwards into your eyes. So you are looking slightly downwards at the ground, but seeing the part of the sky just above the horizon. The most obvious way to interpret the scene is that you are seeing the low sky reflected off the surface of a distant pool of water. This is the Inferior Mirage, where the image is below the real object being seen (the “pool of water” is below the area of real sky that you see). The inferior mirage is also inverted; the real “downward-facing” sky is imaged as an “upward-facing” pool of water.

In higher latitudes there can be cold air above warmer water. This arrangement bends the light rays downwards, so that rays from a distant object (such as a boat or island kilometres away) will curve downwards into your eyes. The boat or island can appear to “float” in the sky above the distant horizon, because you are looking slightly upwards at the image. In less sophisticated times, centuries ago, this would have seemed like magic. When the density contrast is less extreme, the distant feature doesn’t appear to be detached and floating above the horizon, but rather to be stretched upwards while still connected to the ground in the distance (“looming”). This is the Superior Mirage, which is upright (not inverted), and above the real object. One special case exists when distant peaks loom upwards to resemble towers; this is the Fata Morgana (named after Morgan the Fairy, fabled half-sister to the legendary King Arthur).

Depending on the arrangement and temperature of air layers, certain features in a distant scene may not be visible, because there is no light path from the object to your eye. The relevant light rays either hit the ground in front of your feet or pass over your head. There is a level in the distant scene below which nothing can be seen; Greenler calls it the vanishing line. Other authors write about a "blind zone" or "blind strip" which is a horizontal strip between the vanishing line and its counterpart in the refracted image; you cannot see anything in this blind zone or strip[5].

When there is a temperature inversion (a layer of warm air over colder, with a gradual transition from layer to layer) a number of unusual effects are possible, depending on the height, temperature, and thickness of the warmer layer; the height of the observer and the distant scene, and the distance to that scene. One remarkable possibility is for a raised upright image to be base-to-base with an inverted image below it (resembling, say, a ship and its reflection raised above the horizon), and as well the top half of the ship (lower down) peeping over the horizon.

In rare circumstances, the cooler air below the inversion can act as a duct or guide for light. As light rays are refracted towards denser (cooler) air, a ray entering at a glancing angle into the cooler layer cannot refract out of the layer, and will be confined within the layer. If the inversion is very widespread, the cool layer will curve over the horizon, allowing very distant (hundreds of kilometres away) scenes to be seen by a suitably positioned observer. One version of this phenomenon is called the Novaya Zemlya Effect after that island in the Arctic Ocean (north of Siberia). There have been reports of people seeing the Sun when it is almost 5° below the horizon. The light has been ducted from a point hundreds of kilometres to the west where the Sun is visible (above the horizon).

There are suggestions that this ducting effect has led to discoveries of distant islands, The Celtic inhabitants of the Faroe Islands (in the middle of the triangle between Scotland, Norway and Iceland) reached Iceland to the northwest, over 400 km away. There is no direct line of sight to Iceland (over the horizon), and it is suggested that a ducted image encouraged them to sail that way in quite fragile boats. Similarly, when Erik the Red was exiled from Iceland, he sailed northwest almost 400 km to discover Greenland. The sea currents and winds for such a journey are unfavourable, so it seems unlikely that anyone would chance a long journey in that direction. Had he seen, or heard of, an image of Greenland ducted from over the horizon?

The final few pages of the book deal with distortion of images as light passes through the turbulent atmosphere; and various colour effects as the atmosphere disperses polychromatic light (white or nearly-so) into spectral colours.

Light from stars passing through our turbulent atmosphere encounters moving "packets" of air with different temperatures, and hence different refractive indices. The stars are so distant that they act as infinitesimally small light sources, so the light-path from any star to your eye is a thin pencil, smaller than the moving packets of air. These packets will deflect the light path rapidly by small amounts, so the star will appear to shift rapidly by small amounts. Simultaneously, the packets may disperse and concentrate the light beams in rapid succession, causing rapid fluctuations in brightness as well. The sum effect is seen as twinkling of the stars. Light from stars nearer the horizon passes through a greater thickness of air, so twinkling is strongest for stars close to the horizon. Planets are not point-sources, but tiny disks, and light from planets travels as a broader bundle of rays; some are randomly concentrated while others are simultaneously dispersed; the net effect being a more uniform overall light from planets, which twinkle less than stars. This effect was known as far back as Aristotle's time.

[5] It is plausible that an oncoming car might hide in such a blind zone, invisible to approaching drivers. Light beams starting horizontally from the oncoming car are refracted over your head; so are light beams that start out directly towards your eyes and likewise pass over your head; light beams that start more-steeply downwards from the oncoming car pass into the very hot air just above the tar, are refracted upwards sharply, and also to pass above your head. There is no beam path from the oncoming car to your eyes, you can't see it, and don't know it's there. The driver of the truck you are overtaking can see the oncoming car because his/her eyes are higher up and in the way of one of the light paths from the car. I have never seen anything in print about this possibility, so I don't know if I'm onto something or just making a fool of myself.

The white light from stars is not merely deflected by refraction in the air; it is also dispersed into spectral colours. The twinkling of bright stars a few degrees above the horizon causes them to change colour rapidly too. The general refraction of light in a downward-bending curve is not uniform; blue light refracts more than redder wavelengths, so even as the star or planet “seems” to be above its geometric position, so the greater bending of the blue component is at the top of the image, and the redder wavelengths are shifted towards the lower side of the image. There will be a blue rim at the “top” of the planet, Sun or Moon, and a red rim at the bottom. When the Sun is almost fully set, this blue rim is still there, but the shorter, bluer wavelengths are attenuated by Raleigh Scattering, so the resulting colour is usually green. When the horizon is low and sharp (ideally a water horizon such as an ocean or wide lake), and the air is clear, the very topmost bit of the setting sun is seen for a second or two as a green point. This is the famous Green Flash, which featured in a Jules Verne novel “Le Rayon-Vert” (The Green Ray). The Green Flash can also be seen at sunrise, but you need to be looking in just the right direction at the moment of sunrise. When there is a thick cloudbank low in the western sky, there can be a corresponding red flash as the lower edge of the Sun peeps below the cloud bank.