Assessing Potential Marine Iron Fertilization from Pacific Ocean Volcanic Systems

Isabel LaRue

Abstract

This project researched which volcanic arcs along the Pacific Ocean have the potential to induce marine primary productivity through iron (Fe) fertilization. To do so, published datasets of volcanic geochemical composition, ash deposition rates, and ocean Fe-limited zones were compiled and analyzed to assess the potential for iron fertilization. Arcs along the coast of Alaska and Asia were determined to have the highest overall Fe-fertilization potential. The Fe-limited zones in the NW pacific ocean are predicted as the most likely places to experience Fe-Fertilization. This area, and the coast of south america, are the only places likely to experience the biological and economic benefits of volcanic iron fertilization.

Introduction and Background

- This project investigates the potential for iron emitted from subduction zone volcano eruptions along the Ring of Fire to spur marine productivity (phytoplankton blooms)
- Phytoplankton blooms are the basis of marine ecosystems and require iron. Worldwide, blooms have been observed after volcanic eruptions (Olgun et al., 2011; Duggen et al., 2010), but this project focuses on the Pacific Ocean Ring of Fire (figure 1)
- Iron is often the most important micronutrient released into marine ecosystems, as it is a limiting factor in high-nutrient-low-chlorophyll (HNLC) zones, which cover about 40% of the world's oceans (figure 1) (Duggen et al., 2010; Olgun et al., 2011)
- Research has been done on single eruption events, but little synthesis has occurred to look at potential over longer timescales/eruption cycles. This is significant, as a bloom leads to marine productivity, which impacts the livelihood of millions of workers, and it can lead to a reduction in atmospheric CO_2. It is thought that oceanic volcanic ash deposition may have had significant impacts on Earth's climate history (Duggen et al., 2010;Lindenthal et al., 2013)
- The Kasatochi volcano in Alaska erupted in 2008 and provides a case study to model volcanic iron fertilization (Langmann et al., 2010; Lindenthal et al., 2013; Kearney et al., 2015)
- Certain volcanoes have a higher potential to effectively deliver iron to marine ecosystems, and this project looked at geochemical composition, typical offshore deposited volcanic ash, downwind distance to HNLC zones, and seasonal variation

Methods

- This project synthesizes published research on volcanic iron fertilization from Langmann et al., 2010; Lindenthal et al., 2013; Kearney et al., 2015; Langmann, 2014; Duggen et al., 2010; Olgan et al., 2011
- Arcs were grouped together, based on location, geochemistry and ash output, as various databases had slightly different arc boundaries.
- Parameters investigated to assess the potential for eruption-induced iron fertilization:
  - Geochemistry: Iron content of volcanic rocks and erupted ash (PetDB)
  - Deposition: Offshore ash deposition rate per millennial (Olgun et al., 2011)
  - Distance: Downwind direction to HNLC zone (Langmann et al, 2010)
  - Seasonality: Seasonal temperature changes (Giovannoni et al, 2012)
- Each parameter categorized on scale of LOW, MODERATE, or HIGH for iron fertilization potential (see Table 1)
- Total fertilization potential calculated by assigning each high score 3 points, medium score 2 points, and low score 1 point
- Calculations required for each parameter
  - Geochemistry: Rock type and iron content for all igneous rock samples averaged
  - Deposition: Average of millennial offshore deposited volcanic ash into Pacific Ocean divided by arc length
  - Distance: Averaged distance from ends and middle of arc to HNLC zone
  - Seasonality: Looked at range of arc latitude

Table 1: Scoring System

Parameter	Geochemistry	Deposition	Distance	Seasonality
Units	Weight Percent	10^15 g /ka/km	Kilometers	Latitude
Low (1 Point)	Below 2.5	Below 0.003	Would not reach	Above 35
Medium (2 Points)	2.5 - 7.0	0.003 - 0.006	Over 500	In both
High (3 Points)	7.0 and above	0.006 and above	Under 500	0 - 35

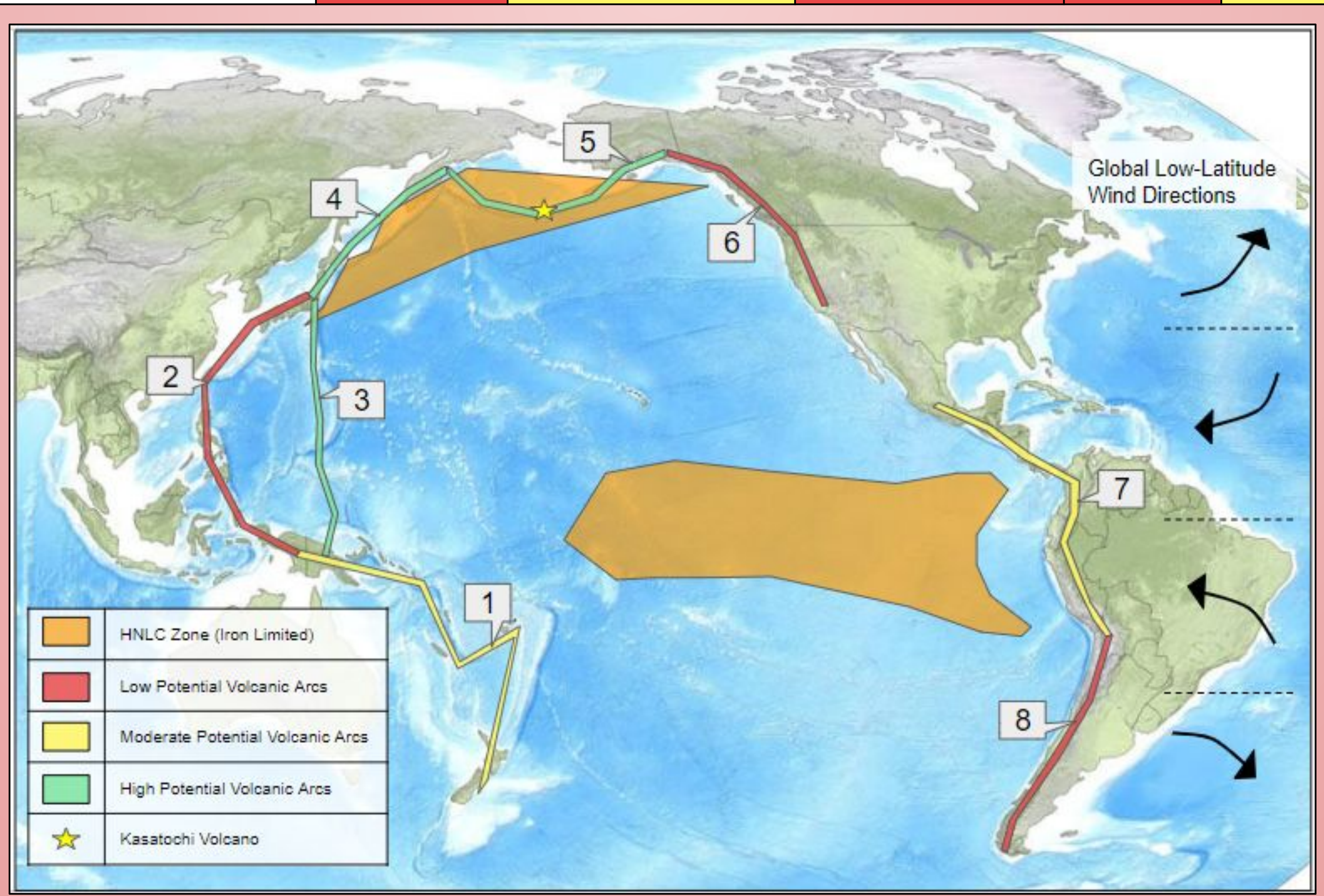
Datasets

Table 2: Example of Geochemical Dataset

Arc	Rock Type and Percent	Fe_2O_3	Fe_2O_3Total	FeO	FeOTotal
Aleutians	Mixed	2.78	5.97	6.54	7.13
	10% Felsic	0.74	2.25	2.9	none
	62% Intermediate	2.8	6.4	6.7	7.3
	22% Mafic	2.8	6.1	8.1	8.1
	6% Clastic	4.86	none	4.87	7.7
Cascades	Felsic	0.52	none	1.12	none

Table 3: Data Table Showing Volcanic Arcs Iron Fertilization Scores

Location	Iron Content of Magma	Offshore Deposited Volcanic Ash (10^{15} g/ka)^C per Millennial per km	Distance via Prevalent Wind Patterns to HNLC Zone	Overall Potential	Seasonal Variation
1. Papua New Guinea to New Zealand	Mafic	0.0079	Far	7	Some
2. Indonesia	Felsic	0.0038	Far	4	No
3. Philippines	Mafic	0.0071	Intermediate	8	No
4. Japan	Mafic	0.0079	Close	9	Yes
5. Aleutians	Intermediate	0.0079	Close	8	Yes
Kasatochi *	Mafic	0.0079	Close	9	Yes
6. Alaska and Cascades	Felsic	0.0026	Far	3	Yes
7. Central / South America	Felsic	0.0063	Intermediate	6	No
8. South America (South)	Felsic	0.0048	Far	4	Some



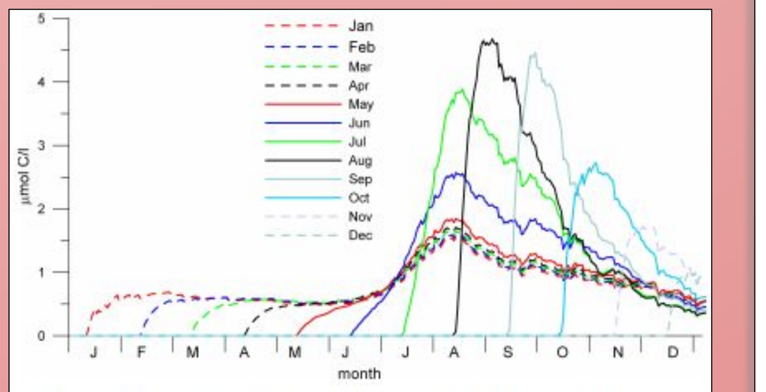


Figure 1: (Above) The study locations, with the volcanic arcs colored based on their potential to cause iron-induced phytoplankton blooms. The Kasatochi volcano is marked with a star, and the general global low-latitude wind directions are marked on the right. The orange sections show the iron-limited regions (HNLC Zone) (Olgan et al., 2010; Free World Maps, 2020)

Figure 2: (Right) Modeled increase in phytoplankton blooms based on the timing of the Kasatochi volcano eruption, from Lindenthal et. al, 2013.

Results

- Table 3 includes overall potential, which shows what volcanic arcs are most likely to produce a Fe-induced phytoplankton bloom, based on the categories before it in the Table
- Seasonal variation is not included in the overall potential and is shown in the last column of Table 3. It is not included because it is not fair to disregard an arc that might have an incredibly high potential in the summer, just because it is at a high latitude (such as Japan, the highest potential arc with a score of 9).
- Figure 1 provides a visual display on the overall potentials shown in Table 3, which are represented by the color of the arcs. This allows for a visual representation of which areas along the Pacific Rim are more likely to produce an Fe-induced phytoplankton bloom.
- The HNLC zones are also noted on figure 1, which are important as these were determined to be the only regions of the ocean were iron fertilization is possible.
- The highest potential volcanic arcs are seen along the coast of Asia (the Philippines and Japan with scores of 8 and 9 respectively) and Alaska (score of 8) due to their proximity to an HNLC zone, geochemical composition and general deposition rate matching the expected criteria
- Kasatochi itself is in the highest potential category for everything, except seasonal variation

Discussion and Conclusion

- The Kasatochi volcano is a high potential volcano, thus it is no surprise that when it erupted in summer it caused large phytoplankton blooms (Langmann et al., 2010; Kearney et al., 2015)
- Results categories are broad (mafic, felsic…), thus there is a large chance that any single eruption might be extremely different than what this data predicts. For example, if an Aleutian volcano erupted, there is a 22% chance that it would be mafic, such as Kasatochi. It is most likely to be intermediate, but there is a 10% chance it could be felsic and contain even less iron than anticipated. The whole chain has been marked intermediate since that is the most likely outcome for a random eruption (PetDB, 2020)
- All volcanoes, even felsic, will deliver iron, so the low geochemical potential spots might have a bloom upon eruption, just smaller (PetDB, 2020)
- This dataset is looking at chains instead of individual volcanoes, so the margin of error is high for any singular eruption, but should be low for a whole series of eruptions from a chain and is thus a good predictor of which chains have an overall high potential. The point of this data is not to predict the likelihood of specific volcanic eruptions causing phytoplankton blooms but to get a sense of which regions of the world have the greatest potential for these blooms
- The highest potential regions are the coast of Asia and Alaska - these areas are most likely to see changes in marine ecosystems and experience economic benefits that result from an increase in marine biomass (fish). These regions are also at high risk of volcanic hazards, but other lower potential regions experience the same volcanic hazards if they have similar typical millennial output
- Of the highest potential arcs, the Aleutians and Japan experience high seasonal variation, meaning the chances of a bloom occuring are lower from a winter eruption
- The lowest potential regions are Alaska and the Cascades, South South America, and Indonesia. These three locations all had no high potential categories, meaning they are low in iron, less likely to erupt, and far from an HNLC zone via wind patterns
- Wind patterns are finicky, and the distances to HNLC zones are based on general low latitude wind directions. An eruption could occur and have the ash carried in a different direction than expected, which could either raise or lower the chances of a bloom depending on the arc (Langmann et al, 2010)
- An eruption in the winter could cause phytoplankton bloom once the weather warms up, this is known as remineralization. A summer phytoplankton bloom caused by a winter eruption will simply be smaller, as shown in Figure 2 (Lindenthal et al., 2013)
- The only ocean regions able to experience iron-induced phytoplankton blooms are the HNLC zones, so the other volcanic factors do not matter if the wind does not carry the ash into one of these zones

Conclusions

- Position of HNLC zones controls where Fe-fertilization potential is highest
- While all volcanic arcs have the potential to cause iron induced phytoplankton blooms, arcs along the coast of Asia and Alaska show the highest potential due to their high iron content, frequent eruptions, and proximity to a HNLC zone
- Due to the impacts of these blooms on the atmosphere, ecosystems and economies, it is important to keep studying volcanic Fe-induced phytoplankton blooms

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