

Climate affected by extra source of volcanic CO₂ degassing

by Laura Carter

In today's science news, "climate change" and "greenhouse effect" are common words because, human fossil fuel consumption contributes extreme amounts of carbon dioxide—a green house gas, CO₂— to the atmosphere since 1850. This has sparked many scientific investigations into long term (on a million year time scale) climate variation as the result of global CO₂ cycling processes. Recent work suggests that further back in time, e.g. the Cretaceous period (~65 million years ago), normal processes in nature, such as volcanic activity, could have been a more important contributor of CO₂ to the atmosphere than it is today, due to changes in the location of volcanism, magma supply, and number of active volcanoes.

During the Cretaceous period when sea level was higher, carbon was locked in carbonate rocks deposited in shallow marine settings within the continents, such as the Western Interior Seaway that spanned from Canada through Texas. After sea level receded again, most of the coastline of North America (the Sierra Nevada volcanic arc), like other tectonic plate margins around the world, experienced active volcanism as oceanic crust subducted beneath continental crust and melted. As magma rose from the mantle through ≤40 kilometers of crust, it interacted with the surrounding crustal rocks before crystallizing as granitic batholiths that are now exposed within the Sierra Nevada Mountains, or erupting to the surface as lava^{1,2}.

When magma intrudes into rocks containing carbonate, interaction with magma can break the rock down, triggering CO₂ gas release in two different ways: 1) assimilation, in which the carbonate is broken down and consumed by the molten liquid³; and 2) skarnification (see Figure 1), in which elements dissolved in the hot aqueous fluids that leach from the magma body alter the surrounding mineralogy and produce ores like copper⁴. Both processes are expected to release carbon dioxide from the rock (see Reaction 1 and 2 respectively in Figure 1). As a gas, the CO₂ can escape the magma at the volcanic vent either passively or during an eruption.

Skarns exposed by erosion are well-documented by ore geologists, who investigate their physical and geochemical properties by collecting rock samples from outcrops. In contrast, volcanologists and petrologists must use laboratory modeling techniques and measurable observations to understand assimilation processes. For instance, assimilation causes high CO₂ outputs at volcanoes, carbonate ejecta in the lava, and geochemical signatures that show mantle-and-crust mixing, such as at Mt. Etna and Vesuvius in Italy, Popocatepetl in Mexico, and Mt. Merapi in Indonesia³. Since these volcanoes recently erupted proximal to dense population areas, their gas fluxes are closely monitored especially because extra CO₂ has been linked to increased explosivity during eruption--dangerous for nearby communities.

Since magma-crust interaction happens at significant depth, the best way to investigate these processes is via laboratory experiments. One of these, a pressure cooker of sorts, is a piston cylinder apparatus, which uses hydraulic presses to simulate variable depths in the crust (up to 100,000 times atmospheric pressure, ~35 km deep), while electricity heats the system to magmatic temperatures (up to 1200 °C). The magma is given time to interact with carbonate (up to a few days), then they are flash cooled to freeze the melt into a glass for analysis³.

Experiments have determined that the extent of melt availability determines the amount of carbonate that can be dissolved, meaning hotter magma chambers are able to release more carbon and consume as much carbonate as half of the mass of magma³. By weight, half of the consumed carbonate is then converted to CO₂, while the other chemicals remain in the magma (Reaction 1, Figure 1). Additionally, experiments with different types of magma indicate that magmas near the surface have significantly

cooled and crystallized minerals, changes the composition of the residual melt (dacite). Dacite cannot ingest as much carbonate as the younger, hotter magmas (basalt, andesite; see Figure 1)⁵. This means that as the magma ascends to the surface it releases a lot of extra CO₂ early on, but slows over time.

Near the Earth's surface, water cannot dissolve as easily in magmas, meaning that any H₂O transported in the magma from the subducted oceanic plate will leach into the surrounding carbonate rock (see "skarn aureole" in schematic). At this point, reaction 2 occurs, which trades the carbonate mineral for unique skarn minerals and releases CO₂⁴ (Reaction 2, Figure 1). It is unknown how far the water can migrate away from the magma (Centimeters? Kilometers?), making it difficult to quantify how much carbonate is broken down, but it seems probable that skarnification releases more CO₂ than assimilation near the end of the magma's path.

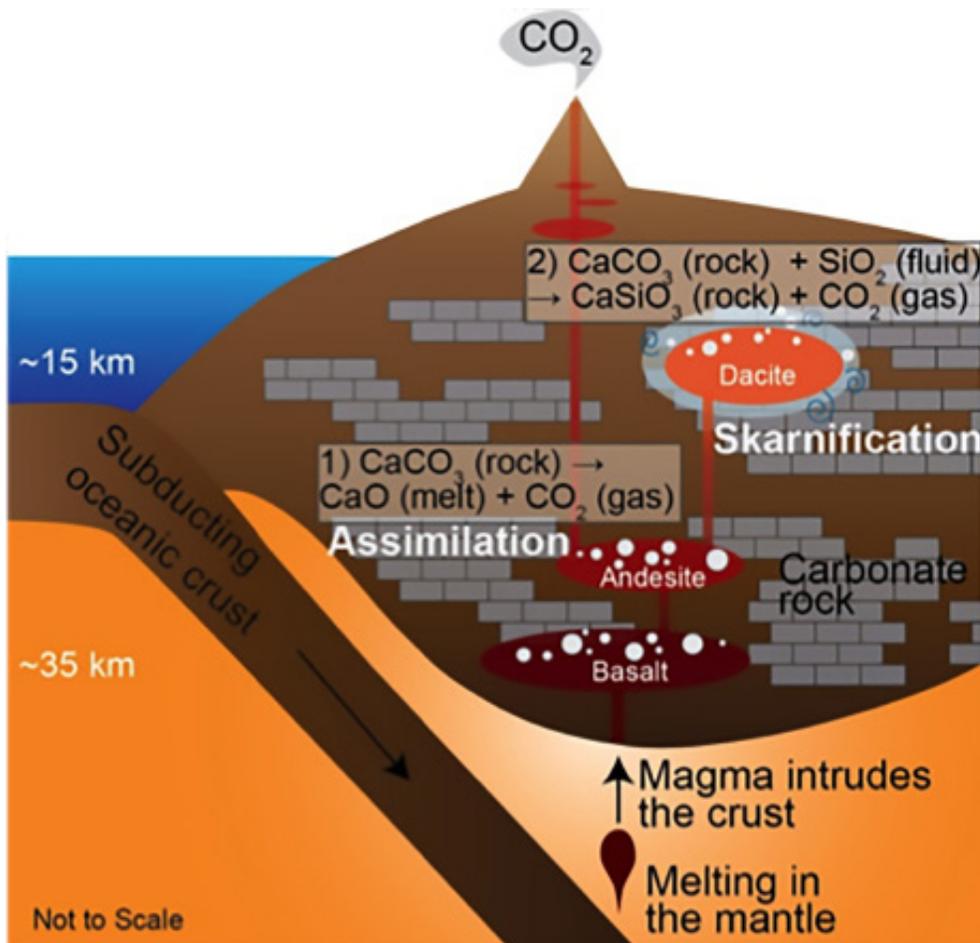


Figure 1. Assimilation and skarnification processes in volcanism at convergent plate margins.

Reaction 1: $\text{CaCO}_3 (\text{rock}) \rightarrow \text{CaO} (\text{melt}) + \text{CO}_2 (\text{gas})$.

Reaction 2: $\text{CaCO}_3 (\text{rock}) + \text{SiO}_2 (\text{fluid}) \rightarrow \text{CaSiO}_3 (\text{rock}) + \text{CO}_2 (\text{gas})$

Due to a higher number of volcanoes (particularly those sitting atop carbonate rocks, in the Cretaceous period), the atmosphere could have received as much as 10-100 times the present-day volcanic CO₂ output^{3,5,7}. Comparing the amount of CO₂ produced in experiments with measured present-day degassing rates at particular volcanoes, however, suggests that only a portion of the magma chamber interacts with surrounding carbonate (<50% at Merapi, Etna, Vesuvius and Popocatepetl)⁵. If this was true in the Cretaceous period, too, then volcanoes could have degassed more than observed in modern times.

Breakdown of carbonate in any of these forms enhances the dangers of the volcanic system⁹. First, the rock underlying the volcano is now weak and unstable, making landslides more likely, like the one that may have kicked off the 1980 eruption at Mt. St. Helens. Second, if any barriers (such as crystals or viscous magma) prevent gas escape, the pressure can build up and either cause earthquakes and/or produce more violent volcanic eruptions (such as when the cap is taken off a shaken soda bottle). This is dangerous and destructive to nearby communities, like those affected by the 2010 Merapi eruption (see Figure 2).

Another important consequence of assimilation and/or skarnification is that by contributing potentially significant amounts of carbon dioxide—a greenhouse gas—to the atmosphere, these processes may play a role in climate change. Today, industrial inputs greatly exceed volcanic emissions, and are often linked to the current short-term changing, warmer climate. In the deep geologic record, experiments suggest that carbonate-magma interaction within the crust throughout Earth's billion year history could have spiked atmospheric CO₂ concentrations and led to warming before human fossil fuel interference, but on much longer timescales.



Figure 2: A house destroyed by the 2010 Merapi eruption. Photo Credit BAYISMOYO/AFP/Getty7 Images.

REFERENCES

1. Lackey, J. S., Valley, J. W. & Saleeby, J. B. Supracrustal input to magmas in the deep crust of Sierra Nevada batholith: Evidence from high-O zircon. *Earth Planet. Sci. Lett.* 235, 315–330 (2005).
2. Lee, C. T. a et al. Continental arc-island arc fluctuations, growth of crustal carbonates, and long-term climate change. *Geosphere* 9, 21–36 (2013).
3. Carter, L. B. & Dasgupta, R. Hydrous basalt-limestone interaction at crustal conditions: Implications for generation of ultracalcic melts and outflux of CO₂ at volcanic arcs. *Earth Planet. Sci. Lett.* 427, 202–214 (2015).
4. Lee, C.-T. a. & Lackey, J. S. Global Continental Arc Flare-ups and Their Relation to Long-Term Greenhouse Conditions. *Elements* 11, 125–130 (2015).
5. Carter, L. B. & Dasgupta, R. Effect of melt composition on crustal carbonate assimilation—Implications for the transition from calcite consumption to skarnification and associated CO₂ degassing. *Geochemistry Geophys. Geosystems* (under review).
6. Burton, M. R., Sawyer, G. M. & Granieri, D. Deep Carbon Emissions from Volcanoes. *Rev. Mineral. Geochemistry* 75, 323–354 (2013).
7. Sano, Y. & Williams, S. N. Fluxes of mantle and subducted carbon along convergent plate boundaries. *Geophys. Res. Lett.* 23, 2749–2752 (1996).
9. Irving, A. & Wyllie, P. J. Subsolidus and melting relationships for calcite, magnesite and the join CaCO₃-MgCO₃ to 36 Kb. *Geochim. Cosmochim. Acta* 39, 35–53 (1975).



Laura Carter is a fourth year PhD candidate in experimental petrology, advised by Dr. Rajdeep Dasgupta