7.2.6 The feedback relationship between climate and Cretaceous volcanism

The crucial message from studies of the long-term carbon cycle is that it is feedbacks that drive and change the climate system over long time-scales. We can estimate the volumes of volcanism in the mid-Cretaceous but the increased CO_2 output is not directly proportional to the CO_2 level in the atmosphere at the time. Remember from Chapter 6 that increased levels of CO_2 in the atmosphere also increase weathering rates which in turn remove CO_2, so the atmospheric levels which determine the climate are not a simple function of the volcanic output. So how can we establish the true importance of volcanism to the Cretaceous climate? The best way is to test how susceptible the climate is to changes in CO_2 using a simple model.

Consider a very simplified version of the GEOCARB model without all the feedbacks looked at in Chapter 6. In this version of the model, we take no consideration of land area, mountains, or the effect of land plants or burial of organic carbon. On land, atmospheric CO_2 is drawn down by silicate weathering, and in the oceans CO_2 is sequestered by carbonate precipitation. CO_2 supply to the atmosphere by degassing is in balance with the weathering and carbonate precipitation processes in our model. Let us start with two atmospheric CO_2 concentrations: modern pre-industrial values of around 280 ppm and values ten times greater, 2800 ppm, which we might expect for a greenhouse world like the Cretaceous (Figure 7.24). This model has volcanoes giving off CO_2 but it is in balance with the other processes.

First, let's try reducing volcanic emissions by 25%: not simply switching off all the CO_2 degassing from volcanoes and other sources, but just reducing their emissions by a quarter. Weathering continues at the same rate, because there is no feedback with the atmospheric CO_2 level. Nothing will happen for a little while, but then slowly at first, silicate weathering will start to have a significant effect upon the atmospheric CO_2 level (Figure 7.24). In a modern pre-industrialized world, CO_2 levels will fall significantly after 20 000–30 000 years and Ice Age conditions ensue not long after. In the greenhouse world, atmospheric CO_2 levels are reduced to the pre-industrial levels after around 1.2 Ma and it too falls into an Ice Age after less than 2 Ma. This effect occurs when the CO_2 emission is reduced by only 25%, in other words the feedbacks in the real world must act to stabilize variations very rapidly. This reduced CO_2 effect is as devastating as huge volcanic eruptions and would be certain to cause mass extinction on time-scales of far less than a million years. It is a devastating extinction mechanism created simply by artificially altering the balance of feedbacks in the carbon cycle.

What if, instead of reducing volcanic CO_2 emissions, we increase them by 25%? This is what would have happened as the ocean ridge spreading rates increased as the superplume event was initiated in the mid-Cretaceous. In fact it may have been more extreme than this, but for the purposes of the model, the outcomes are the same. Remember that weathering rates will not increase because there are no feedbacks in this system. In the pre-industrial system, atmospheric CO_2 levels rise linearly (although represented as a curve on Figure 7.24 because the vertical scale is logarithmic) and reach Cretaceous greenhouse levels after just over 1 Ma. Atmospheric CO_2 levels in the greenhouse world also increase, although the effect is smaller as there is already a great deal of CO_2 in the atmosphere. Maintained for 40 Ma, this situation would extinguish most life and leave the Earth with an atmosphere of almost 10% CO_2. Clearly this did not happen in the Cretaceous but it illustrates the importance of the feedbacks.

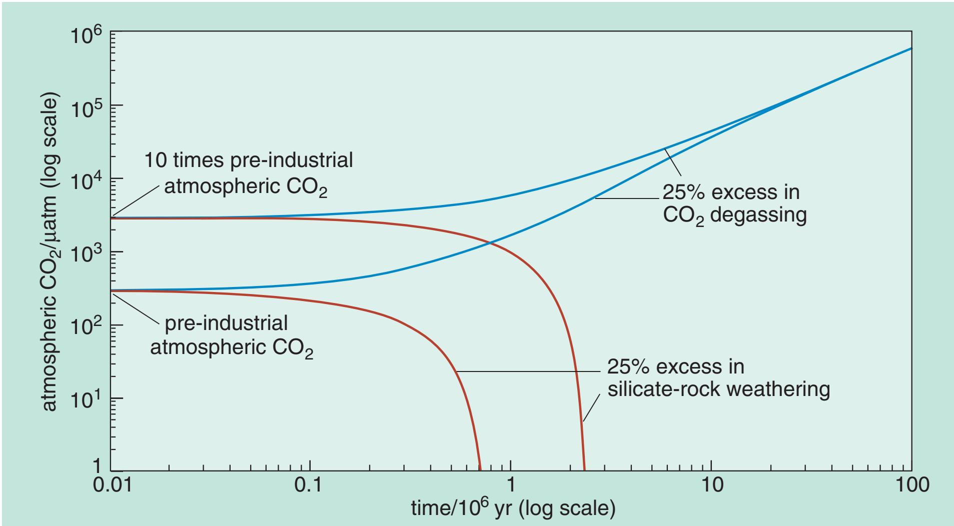

Figure 7.24 The effects on atmospheric CO_2 of a 25% imbalance in degassing and silicate-rock weathering in the absence of feedback mechanisms. Two trends are shown: one starts from 280 µatm (ppm by volume; modern pre-industrial levels) and the other starts from 2800 µatm (approximate Cretaceous levels). The model also assumes present-day uptake of CO_2 by weathering reactions (about 8×10^{18} mol C per Ma); equilibrium removal CO_2 from the ocean into carbonates; no feedback mechanism to remove the extra CO_2 and a balanced organic carbon sub-cycle. *(Berner and Caldeira, 1997.)*

Prolonged volcanic CO_2 input during the mid-Cretaceous virtually doubled the volcanic input into the carbon cycle. However that did not lead to the runaway greenhouse effect we saw in the simple non-feedback model above. In fact if the GEOCARB model is correct, levels of atmospheric CO_2 during the Cretaceous were lower than those earlier in the Phanerozoic, a hypothesis backed up by measurements of atmospheric CO_2 levels (Figure 6.11). If we assume that the atmospheric CO_2 levels were around 2800 ppm (the equivalent of around eight times present-day levels) for the period of the mid-Cretaceous from 120 Ma to 80 Ma, only around 0.14% of the CO_2 release from volcanoes would be required to raise atmospheric CO_2 to that level, based on a doubling of the present-day volcanic CO_2 outgassing. What the additional volcanic CO_2 did was to accelerate feedback reactions which effectively increased weathering rates, added nutrients (along with dissolved CO_2) to the drowned continental shelves and also fertilized biomass production on land. If we want to look for the lost volcanic CO_2 of the mid-Cretaceous, it can be found in abundant Cretaceous coal and oil deposits (Chapter 4) and in huge Cretaceous carbonate deposits (Chapter 5).

7.3 The Deccan Flood Basalt and climate change at the end of the Cretaceous

Like other Cretaceous LIPs, the Deccan Traps (Traps is an old name for layered basalt deposits) covered huge areas with thick successions of basalt flows. In the case of the Deccan, there seems to have been a progression of the volcanic centre from NW to SE during the eruptions which fits the direction in which the Réunion mantle plume would have been moving at the time. Careful work on ancient drainage patterns has shown that the area was uplifted by the plume and that volcanism produced a series of very broad shield-like volcanic edifices.

Early work on the age of the Deccan Traps placed them roughly at the boundary between the Cretaceous and Tertiary but the age range suggested prolonged volcanism lasting from around 80 Ma to 30 Ma, i.e. around 50 Ma. Vincent Courtillot and a team of French and Indian colleagues had analysed rocks from Tibet to study their palaeomagnetism, and determine the rate at which India and Asia had been travelling to their collision at around 50 Ma which led to the formation of the Himalaya. In 1984, Courtillot and colleagues started to analyse the Deccan Traps with the intention of using the variations in palaeomagnetic pole direction they found in basalt layers of different ages to monitor the movement of India prior to and during the collision.

However, rather than the many palaeomagnetic reversals they expected to find in the Deccan lavas, Courtillot and colleagues found that most of the specimens they had collected had the same polarity, in this case the opposite direction to the present day (reversed polarity). By reanalysing all previous data on Deccan, they determined that the whole lava pile exhibited only two reversals, and over much of its area only one reversal. Although palaeomagnetism can be used to measure time by the thicknesses of magnetic reversals and compare these with the magnetic reversals on the ocean floor, it is not an absolute dating technique so some of the samples were dated using K–Ar dating. However, the samples had been altered by many millions of years of exposure to tropical weathering and it was suggested that this alteration might be the reason why the ages were apparently scattered. The samples were re-dated using the Ar–Ar technique which can date very small samples only a few milligrams in weight (the size of a few grains of sand). This analysis showed that the Deccan Traps erupted between 67 Ma and 63 Ma, a duration of only 5 Ma rather than the 50 Ma derived from earlier attempts. More recent work has broadly confirmed the short time-scale of eruptions and more importantly has shown that the basalts initiated around 68 Ma, reached their peak eruption rate within 500 000 years of the end of the Cretaceous and died out around 63 Ma. The total volume of the Deccan Traps is difficult to estimate precisely because a great deal may have been eroded, but estimates range from $5 \times 10^5\,km^3$ to $2.6 \times 10^6\,km^3$, similar to those for other Cretaceous LIPs. We will assume an erupted volume of $1 \times 10^6\,km^3$ for the following discussion but the exact amounts do not affect the final conclusions.

As we saw in the earlier part of this Chapter, the strongest volcanic effects upon climate are felt as a result of the releases of the gases including HCl, HF, SO_2 and CO_2 (Figure 7.6). SO_2 causes short-term cooling as it hydrates to form H_2SO_4 aerosol droplets in the stratosphere. CO_2 gas can contribute to weakly acid rain but the amounts released during individual eruptions are too small to cause significant atmospheric effects. The effects of volcanoes which we consider important today, such as dust and cooling which lasts a few years, are not significant on geological time-scales. Even large flood basalt flows such as the Roza flow in the Columbia River flood basalt did not release sufficient dust and debris to cause significant climatic effects. In the longer term, continued elevated levels of flood basalt volcanism might contribute significant amounts of CO_2, causing a warming effect.

7.3.1 The effects of SO_2 released by Deccan volcanism

We can probably assume that SO_2 released from oceanic eruptions during the mid-Cretaceous pulse in ocean spreading rates would have had little long-term effect upon climate. The eruptions were dominated by submarine eruptions and recycling of sulfur within the spreading ridge system would have prevented much reaching the atmosphere. However, as we saw in Section 7.1.4, larger effusive eruptions on the continents, like the 1783–4 eruption of Laki in Iceland, can have global effects. The difficulty comes in scaling this up to something the size of the Deccan Traps. If we make the simplifying assumption that the main part of the Deccan, around $1 \times 10^6\,km^3$, was erupted within half a million years, that corresponds to an eruption rate of $2\,km^3$ per annum. This is far slower than the eruption rate of the Laki eruption of 1783–4, which erupted around 14 km^3 in less than one year (and of the order of 12.5×10^{10} kg SO_2). Remember however that the Deccan did not erupt continuously but possibly erupted as enormous pahoehoe sheet flows, each lasting a decade or more. The eruptions would have been separated by long periods of inactivity in much the same way as eruptions on Iceland. There are very roughly 500 flows in the main part of the Deccan which indicates only around one major flow every millennium. The volumes of such flows can be calculated by dividing the total volume by the number of flows and the average flow may have been 2000 km^3, larger than the Roza flow of the Columbia River flood basalts which reached around 1300 km^3.

If a 2000 km^3 pahoehoe-style sheet flow took a decade to erupt, it would have an annual eruption rate of 20 $km^3\,yr^{-1}$, an order of magnitude greater than Laki. If it had similar sulfur contents to the lava erupted by Laki, it may have pumped some 1.8×10^{12} kg SO_2 into the atmosphere per annum, over 100 times the present-day volcanic release rate (Box 7.1). This would have been devastating to the local environment but would it have had global effects? The climatic effects would have depended upon two crucial factors:

1. The height of the tropopause and height of the volcanic plume during the eruption. Had this been a present-day eruption and Deccan had been situated close to the tropics, as indeed it was 65 million years ago, the tropopause would be around 18 km high. The thermal plume above the Laki eruption probably reached 10–14 km, and although this penetrated the stratosphere close to the pole, it would be well below the tropopause and would not have caused global climate effects. Although the Deccan eruptions may have seen higher fire fountains and plumes, the hotter later Cretaceous world would also be expected to see a higher tropopause. We simply cannot determine whether the Deccan volcanism would have reached the stratosphere.
2. Had the SO_2 reached the stratosphere, the effects might still have been limited by water exhaustion. As we saw in Section 7.1.3, when large eruptions pump more SO_2 into the stratosphere it becomes hydrated to H_2SO_4 which causes global cooling by absorbing solar radiation. However, this process can only completely hydrate the volcanic SO_2 if there is sufficient H_2O in the stratosphere. Water exhaustion would limit the initial effects of the volcanic eruption but might prolong the overall duration of any global climatic effects to decades.

Although it looks as if SO_2 emissions may have had the potential to disrupt climate during the major Deccan eruptions, this would only have happened if the SO_2 in the plume reached the stratosphere. Moreover, in the following years, long periods of inactivity (almost 1000 years) mean there was ample time for the global climate system to recover between eruptions. In order to quantify the effects of SO_2 release from Deccan upon the climate, we will have to determine whether the volcanic plumes reached the stratosphere and how much SO_2 was released. The hypothesis that Deccan eruptions might lead to rapid cooling, global catastrophe and mass extinction is not disproven. However, in the absence of evidence for the quantity of SO_2 released into the stratosphere, the height of the tropopause in ancient times, and the effects of water exhaustion upon the lifetime of H_2SO_4 aerosols in the stratosphere, the hypothesis remains unproven.

7.3.2 The effects of CO_2 released by Deccan volcanism

SO_2 emissions have the potential to disrupt climate because the amounts released are large in relation to the amounts normally in the atmosphere, but CO_2 emission is very different. The amounts of CO_2 released during effusive eruptions are of the same order as other sources, even for large Deccan eruptions. The Laki eruption in 1783–4 released around 3×10^{10} kg CO_2, but that was probably only one-tenth of the normal annual release from other volcanic sources such as mid-ocean ridges and subaerial volcanoes (see Box 7.1). Deccan flows were releasing perhaps an order of magnitude more per annum (around 3×10^{11} kg CO_2) but that is still only around 1.5% of the current annual output from the industrialized world (about 2×10^{13} kg yr^{-1} CO_2). Remember that each of the Deccan flows may only have continued for a decade, so industrial and agricultural CO_2 release is currently outdoing the Deccan by almost two orders of magnitude and we have been doing it for longer than a decade.

The total CO_2 released by Deccan may have been in the range 2.6×10^{15} kg to 9×10^{15} kg and models including feedbacks for the carbon cycle indicate that Deccan may have increased the CO_2 level of the atmosphere by as much as 75 ppm leading to global warming of the order of 1–2 °C, too little to have caused global climate change and a major extinction at the Cretaceous/Tertiary boundary.

❍ Having dismissed the effects of CO_2 emission from the Deccan, does this affect the conclusions we drew that CO_2 emissions from volcanism during the superplume event in the mid-Cretaceous contributed to global climate change?

● Certainly not. All the calculations above were premised upon sudden but short-lived increases in CO_2 emission. Remember that during the mid-Cretaceous, global spreading rates increased from around 18–20 km^3 yr^{-1} to 35 km^3 yr^{-1}, an increase which was sustained for around 40 million years.

Although the short-term effects of CO_2 released by Deccan volcanism seem unlikely to have been a major cause of climate disruption at the end of the Cretaceous, we should mention an alternative hypothesis for the apparent correlation between flood basalt volcanism and mass extinction events. In Chapter 6, we noted that methane clathrates (methane gas trapped in ice) are a major reservoir for carbon in the oceans. The sudden release of methane from clathrates in ocean floor sediments could occur if the oceans warmed significantly or ocean circulation patterns were disrupted so that bottom waters warmed. This hypothesis has been advanced on the basis of carbon-isotope changes in carbonates and organic sediments for the large Karoo–Ferrar Province which erupted during the Toarcian Age (Early Jurassic) 183 million years ago, and the North Atlantic flood basalts which erupted 60–55 million years ago in the early Palaeogene. However, although the climate was cooling, the seas were still warm at the end of the Cretaceous and there may not therefore have been a large reservoir of methane in ocean floor clathrates.