

## **A Broecker Brief**

### **Origin of the 'Glacial Ramp'**

Although there is no doubt that cycles in the Earth's orbital parameters pace glaciation, their physical link to the 100-kyr climate cycle remains unresolved. In this brief, I contrast the two candidates put forth to explain what I will refer to as the 'glacial ramp'. Over the last half-million years, the records for atmospheric CO<sub>2</sub> content, Antarctic air temperature, benthic <sup>18</sup>O and sea level are dominated by this ramp (see Figure 1). I would like to believe that the ramp is driven primarily by a drawdown of atmospheric CO<sub>2</sub>. My reason is that this provides an explanation for the near synchronicity in timing and the near constancy in the amplitude of LGM snowline lowering across the planet. Were the Northern Hemisphere LGM glacial maximum driven by a 20 kyr precession cycle, then the maxima in the Southern Hemisphere should be offset by about 10 kyrs. Instead, glaciers from both hemispheres (and in the tropics) stood at their maximum from about 23 kyrs until 18 kyrs. So it appears that CO<sub>2</sub> is the primary driver of the summer cooling that lowers snowlines. If so, the question becomes what caused the CO<sub>2</sub> drawdown?

Two scenarios are currently on the table. The traditional one is that CO<sub>2</sub> was drawn out of the atmosphere into the deep ocean. I refer to it as the ocean-uptake scenario. The other was recently proposed by Huybers and Langmuir. It postulates that the influx of CO<sub>2</sub> from the Earth's interior is reduced during times of glaciation. I refer to it as the input-starvation scenario. Starting in 1982 when it first became clear that atmospheric CO<sub>2</sub> was reduced during the LGM, and continuing to when the H+L hypothesis was published, I focused my efforts on finding evidence in support of the ocean-uptake scenario. In recent years I have shifted my focus to the input-starvation scenario. One reason for this shift is a frustration related to the failure to find any compelling evidence that the deep ocean uptake was responsible for the ramp. The other is the growing evidence that the flux of CO<sub>2</sub> from continental volcanoes and likely also from sea floor vents was reduced during times of glaciation and enhanced during times of deglaciation.

One puzzling difference among these records shown in Figure 2 stands out. Although the ramps for benthic  $^{18}\text{O}$  and sea level are clearly modulated by the 20-kyr precession cycle, this is less clear for  $\text{CO}_2$ . For example, the  $\text{CO}_2$  record lacks the precession peak at 103 kyr. Further, Heinrich's events appear to modulate the stage 3  $\text{CO}_2$  record but not the benthic  $^{18}\text{O}$  record. This raises an important point. Jimin Yu's records for  $\delta^{13}\text{C}$  and  $\text{CO}_3^{=}$  in the upper and lower NADW for the last 160 kyr (see Figure 3) reveal three prominent episodes of nutrient stratification in the deep Atlantic centered at 22, 65 and 140 kyr. Each corresponds to a minimum in the  $\text{CO}_2$  record. Yu has proposed that during these episodes extra  $\text{CO}_2$  was stored in the deep Atlantic. However, as these stratification episodes lasted only 20 kyr, this mode of  $\text{CO}_2$  storage must have been temporary. It did not contribute to the ramp. Rather, it created bumps on the ramp. Note that Yu's stratification record has no ramp.

Of course ocean stratification is not the only way in which extra  $\text{CO}_2$  could have been stored in the deep ocean. Rather it could have been the result of iron fertilization of the Southern Ocean. Were this the case, then the amount of excess  $\text{CO}_2$  stored in the ocean would reflect the time history of the dust rain onto the Southern Ocean. As is the case for stratification episodes, the dust maxima are centered at 22, 65 and 140 kyr. But again, once the dust flux went back down, the stored  $\text{CO}_2$  would be released. As for stratification, iron fertilization can create 20 kyr-duration bumps but not a ramp.

If ocean storage is responsible for the ramp, there must be an isolated reservoir capable of long-term storage of respiration products. Despite considerable offset, no direct evidence for the existence of such a reservoir has been found. As will be discussed below, it is tempting to couple the release of  $\text{CO}_2$  at the end of the last glacial cycle with the precipitous decrease in the atmospheric  $^{14}\text{C}$  to  $\text{C}$  ratio (see Figure 4). If indeed this is the case, then in my estimation the benthic-planktic age difference for LGM age samples from the equatorial Pacific (see Table 1) eliminate the possibility that it was  $^{14}\text{C}$ -depleted  $\text{CO}_2$  from an isolated reservoir.

This absence of evidence for long-term storage of CO<sub>2</sub> in the deep sea makes it tempting for CO<sub>2</sub> starvation. There are several ways in which this might have occurred: 1) the reduction of emissions from terrestrial volcanoes, 2) the reduction of emissions from oceanic ridges, 3) the release of CO<sub>2</sub> from clathrate or liquid CO<sub>2</sub> temporarily stored in continental margin sediments.

The evidence that ice loads on the continents squelch volcanic activity is convincing. The eruption record in the Rhine Valley has a large peak between 15 kyrs and 5 kyrs (see Figure 5). The well-studied and well-dated eruption record for the Andean volcano Llaima shows that the quiescence during glacial time gave way to a burst of activity extending from 13.5 to 7.5 kyrs (see Figure 6). Finally, the SO<sub>4</sub> record in Greenland ice peaks during this same time period (see Figure 7).

A complication in all this is that the glacial loading of the continents is matched by lowering of sea level. The Huybers and Langmuir group have shown that sea floor elevation changes follow Milankovitch frequencies. The largest of these is associated with the 100 kyr cycle (see Figure 8). So, there is no doubt that ridge crest volcanism is being perturbed by changes in sea level. But how are changes in the release of CO<sub>2</sub> associated with these fluctuations phased with those from the continents? Using the logic applied to the continents one would conclude that they were antiphased. As the amounts of CO<sub>2</sub> released beneath the ocean is comparable to that released from the continents, this would be bad news for the Huybers and Langmuir hypothesis.

However, modeling of the mantle wedge by Oxford's Richard Katz shows that rather being proportional to the sea level change itself, the ridge crest CO<sub>2</sub> release should be proportional to the derivative of sea level change. If so, the largest release of CO<sub>2</sub> should occur during the rapid deglacial sea level rise. David Lund has shown that the release of iron and manganese from the East Pacific Rise peaked during the last deglaciation and during the penultimate deglaciation (see Figures 9 and 10).

In addition to CO<sub>2</sub> releases from the mid ocean ridges, CO<sub>2</sub> appears to be coming out of the continental margins. The evidence for this is the very old apparent <sup>14</sup>C ages for benthic

foraminifera found so far at several places. In each case, the anomalous ages are restricted to the deglacial time interval. Finally, USC's Lowell Stott has pioneered the idea that the glacial to interglacial change in thermocline temperature allows storage of CO<sub>2</sub> as clathrates during cold glacial time followed by release during the period of deglacial warming.

Although the magnitude of the oceanic CO<sub>2</sub> release during the deglacial time interval is ill-defined, it is encouraging that regardless of its source it is centered during the time the CO<sub>2</sub> content of the atmosphere was increasing.

Based on the information in hand, I deem it reasonable to conclude that planetary input of CO<sub>2</sub> was reduced during times of glaciation and enhanced during times of deglaciation. If so, it must contribute to the downward ramp in atmospheric CO<sub>2</sub> concentration. However, far, far more will have to be learned before any firm conclusion can be drawn regarding the magnitude of this downward slope. So far it can only be said that starvation in the planetary emission of CO<sub>2</sub> during times of glaciation must have contributed to the ramp.

Perhaps the strongest piece of evidence favoring deep ocean storage is the timing of the rise of CO<sub>2</sub> at the end of the last glacial period. It matches the timing of the two deglacial peaks in upwelling in the Southern Ocean, i.e., that at 18 to 15 kyrs and that at 13 to 10 kyrs. Bob Anderson, who documented the peaks in upwelling, views this evidence as convincing. His argument is strengthened by the observation that the peak CO<sub>2</sub> release by continental volcanoes was centered during the second phase of the CO<sub>2</sub> rise (i.e., that from 13 to 9 kyrs). So, Anderson would ask, as sea level rose about 50 meters during the interval 17.8 kyrs to 14.6 kyrs, why didn't this shift in loading lead to a rejuvenation of planetary volcanism?

One possible out is to propose that release of CO<sub>2</sub> from ridge crests was more important than that from continents. In Lund's East Pacific Rise record, the Mn and Fe peaks appear to span the entire deglacial interval. However, as the record is certainly smoothed by bioturbation, the timing of both their onset and end remains uncertain as does the presence or absence of a shutdown during the 14.6 to 12.9 kyrs interval when Southern Ocean upwelling weakened (and CO<sub>2</sub> plateaued).

Another possibility is that the warming of the surface ocean took place mainly during the first half of the deglacial was larger than that during the second half. As Severinghaus has shown, Kr and Xe to N<sub>2</sub> ratios in air trapped in polar ice demonstrate that the ocean warmed by 2°C during the first half of the deglaciation. Denton, Schaefer and Putnam have shown that glaciers in New Zealand underwent very rapid retreat during this same time interval. This retreat corresponded to a 4°C rise in New Zealand's summer air temperature. Records obtained as part of the WAIS ice core project suggest that West Antarctica warmed by 10°C during this time interval.

Still another possibility is that much of the extra CO<sub>2</sub> stored in the deep Atlantic during the LGM bump released during this time interval.

There is a way in which the drawdown by ocean uptake might be distinguished from input starvation. It involves the shape of the deep sea CO<sub>3</sub><sup>=</sup> change during deglaciation. Were the CO<sub>2</sub> increase during deglaciation the result of release from the deep ocean, then it would have produced an increase in carbonate ion concentration and hence a calcite preservation event. On the other hand, if this CO<sub>2</sub> came from the Earth's interior, it would have reduced the carbonate ion content and created a calcite dissolution event (see Figure 11).

One complication associated with this strategy is that regrowth of forests during the deglaciation and the early Holocene would have drawn CO<sub>2</sub> out of the ocean producing a CaCO<sub>3</sub> preservation event. As much of this regrowth occurred between 14 and 8 kyrs ago, it would have overlapped and partly obscured the dissolution event created by the CO<sub>2</sub> released from the Earth's interior during the 13.5 kyr to 7.5 kyr time interval. On the other hand, if the increase in atmospheric CO<sub>2</sub> content during this time interval was the result of release from the deep sea, then forest regrowth would have enhanced the calcite preservation event.

As can be seen from Yu's carbonate ion concentration record (Figure 12), there is no indication of either a preservation event or a dissolution event in the deep Atlantic. But the lack of detail, scatter and smoothing by bioturbation prevent any conclusion to be drawn. What is needed is a more detailed record from a high accumulation rate deep sea sediment. A tall order.

Table 1. Summary of benthic-planktic radiocarbon-age differences for samples of LGM age from the deep equatorial Pacific Ocean. The mean of 1525 years is within the uncertainty of today's deep to surface  $^{14}\text{C}$  age difference.

Latitude	Longitude	Depth km	Calendar Age kyrs	$\Delta\text{B-P}$ yrs
<i>Equatorial Pacific</i>				
1°S	146°E	1.9		
	Broecker et al., 2004		21.5	1950 $\pm$ 220
			21.9	1640 $\pm$ 250
6°N	126°E	2.1		
	Broecker et al., 2004		19.1	1325 $\pm$ 200
			18.7	1170 $\pm$ 220
			19.6	1325 $\pm$ 200
1°N	130°E	2.8		
	Broecker et al., 2008		17.9	1790 $\pm$ 170
			18.6	1510 $\pm$ 120
			19.2	1700 $\pm$ 130
2°S	140°W	4.4		
	Broecker and Clark, 2010		17.2	1550 $\pm$ 300
			22.0	1500 $\pm$ 300
			24.2	1700 $\pm$ 300
Average of the 11 LGM results				<b>1575 <math>\pm</math> 150</b>

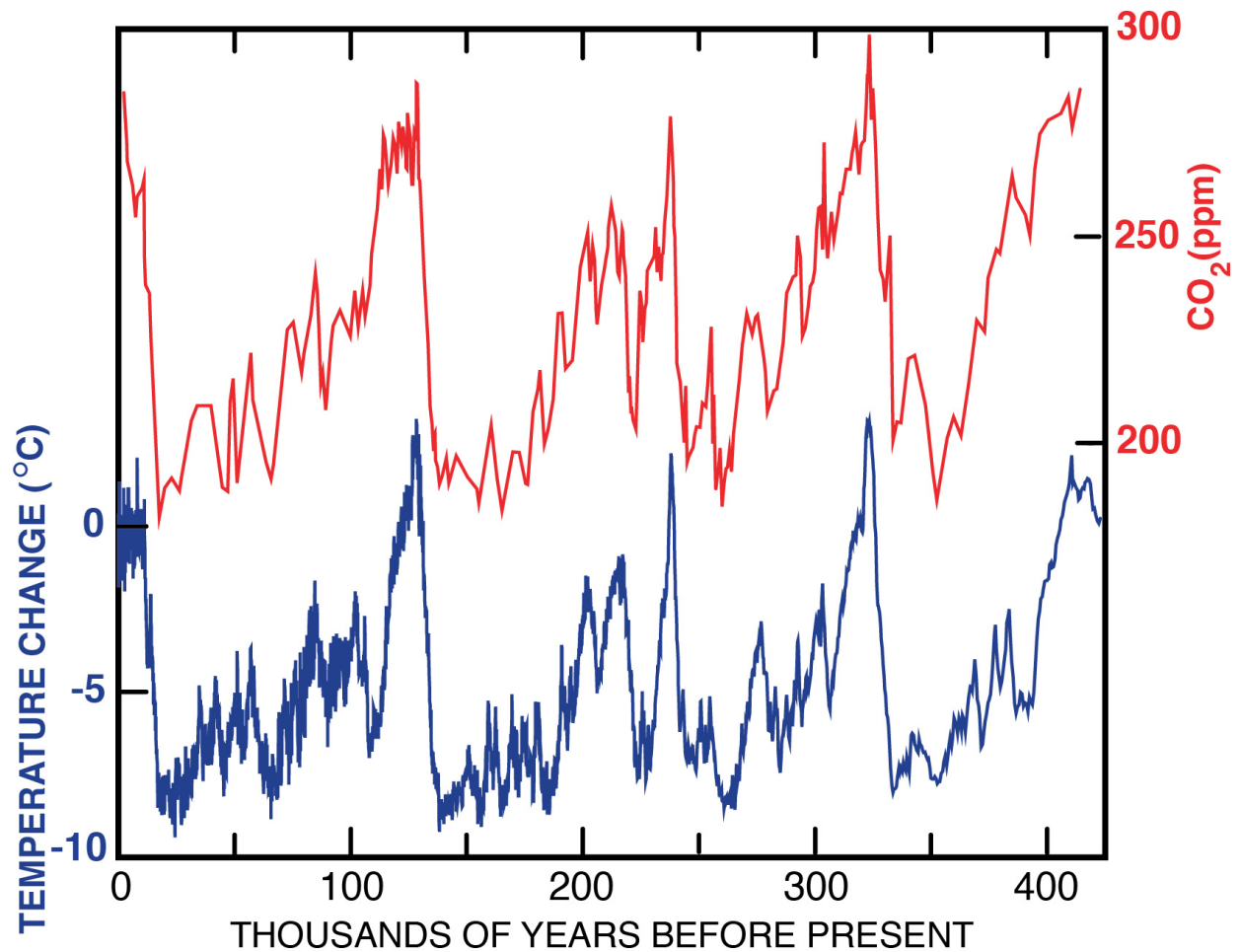


Figure 1. Records of CO<sub>2</sub> and stable isotope –based temperature in Antarctic ice. As can be seen, each 100 kyr-duration cycle is characterized by a long decline (the ramp) followed by a rapid recovery (the Termination).

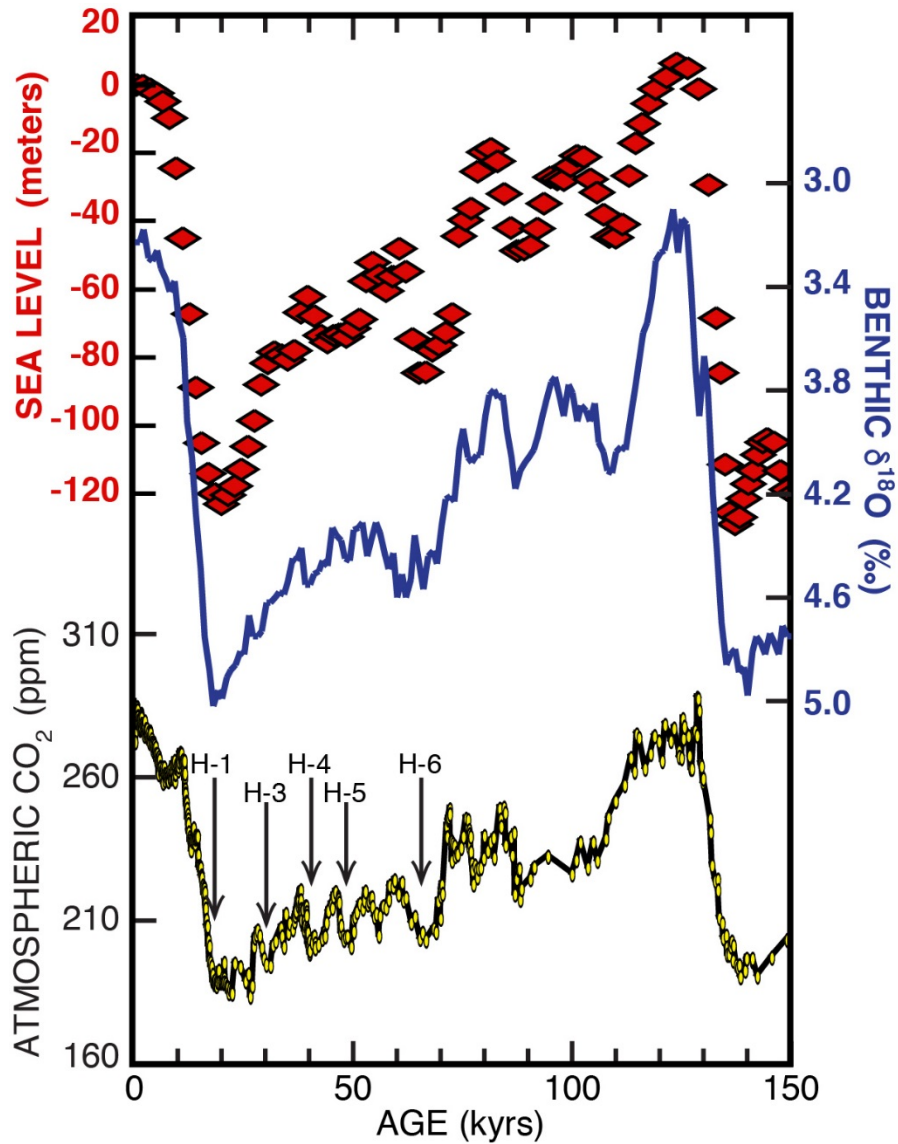


Figure 2. Records of sea level, of  $\delta^{18}\text{O}$  of benthic foraminifera and of atmospheric  $\text{CO}_2$  content for the last 160 kyrs. Note that although the downward ‘ramps’ in the upper two are clearly modulated by the 20 kyr precession cycle, the  $\text{CO}_2$  record is not (for example, the peak at 100 kyrs is absent). Rather, it has two prominent downward bumps, one centered at 67 kyrs (MIS 4) and the other at 22 kyrs (MIS 2), and also ups and downs at the times of H events.

Note also that the initial decline of  $\text{CO}_2$  (centered at 110 kyrs) postdates the decline in the  $\delta^{18}\text{O}$  for benthic forams (centered at 117 kyrs). The latter records some combination of sea level fall and deep sea cooling. It was not driven by  $\text{CO}_2$ .



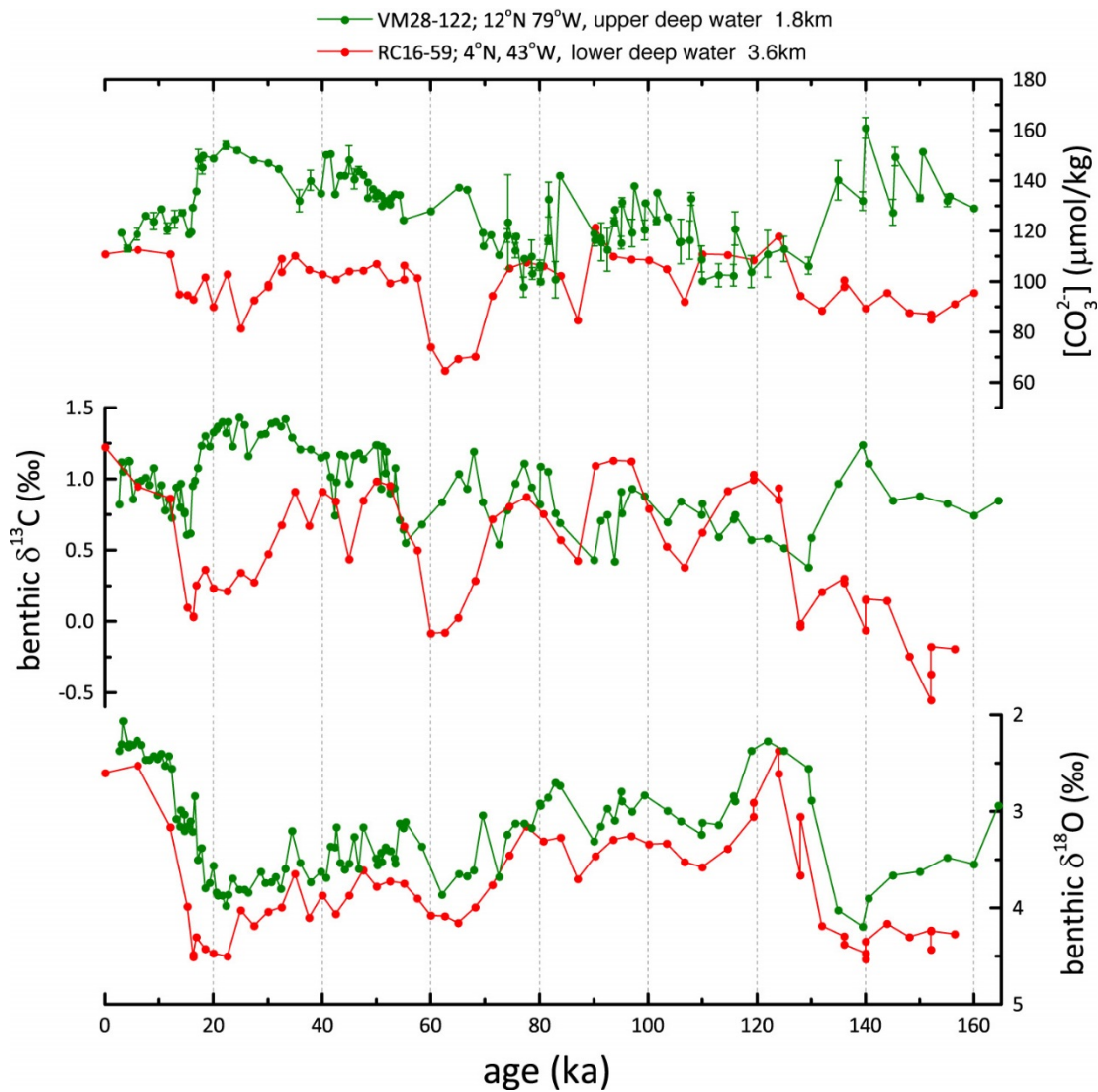


Figure 3. Records for  $\delta^{13}\text{C}$  and  $\text{CO}_3^{2-}$  in two tropical Atlantic sediment cores. The core from the Caribbean records the composition of water spilling over the 1.8 km deep sill which isolates the deep Caribbean from the Atlantic. The core from the Ceara Rise records the composition of Atlantic water at 3.6 km depth. As can be seen, there are two times during the last 120 kyrs when the compositions at these two water depths departs from one another: one is centered at about 65 kyrs and the other at about 20 kyrs. These two times of deep Atlantic stratification match the two downward bumps in atmospheric  $\text{CO}_2$  content. To the extent that stratification fosters  $\text{CO}_2$  storage, this record suggests that storage was confined to two 20 kyr-duration episodes. If so, stratification-induced storage does not contribute to the ramp. Rather, it introduces two bumps which modulate the ramp. The same logic would apply to iron fertilization of the Southern Ocean.

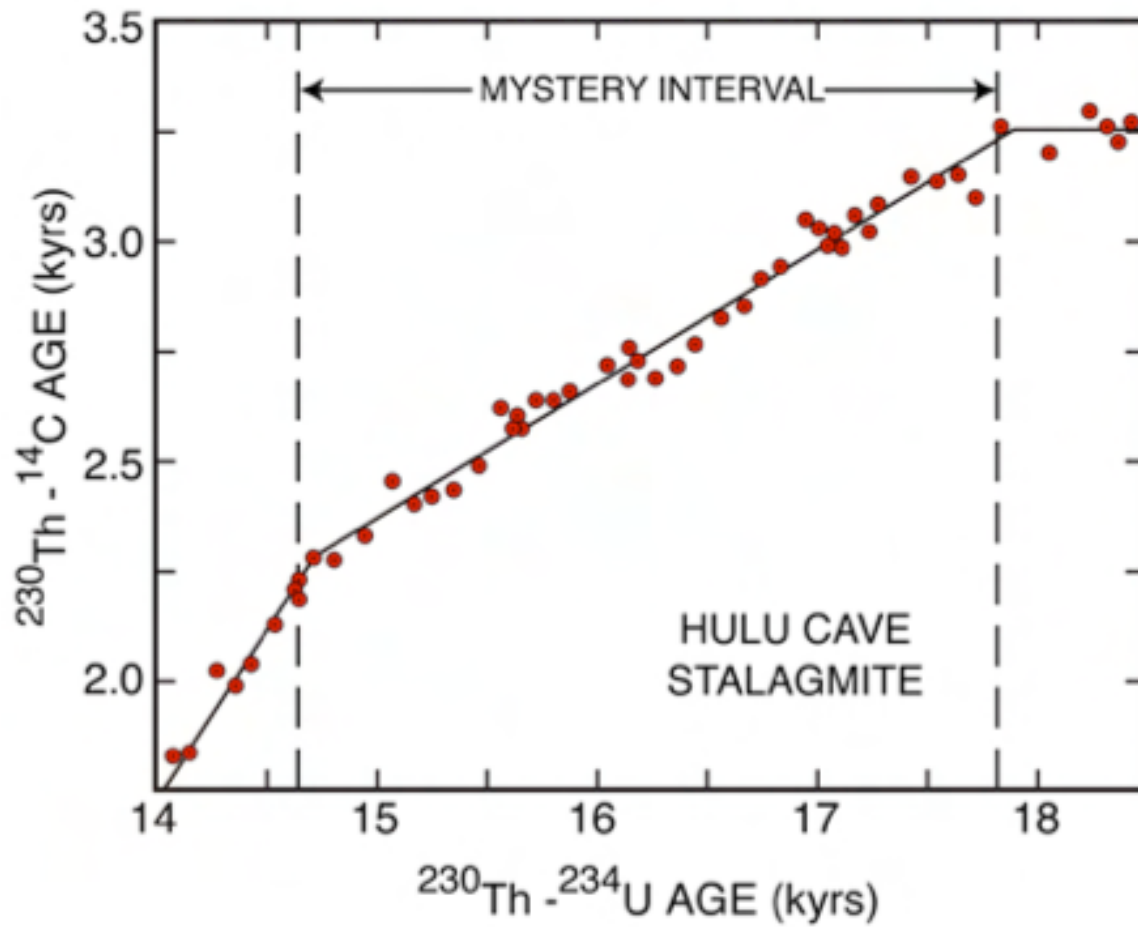


Figure 4. Between 18 and 14 kyrs the offset between  $^{14}\text{C}$  and  $^{230}\text{Th}$  ages drops from 3.25 to 1.80 kyrs. This requires that the inventory of radiocarbon in the ocean-atmosphere reservoir decreased by about 18 percent.

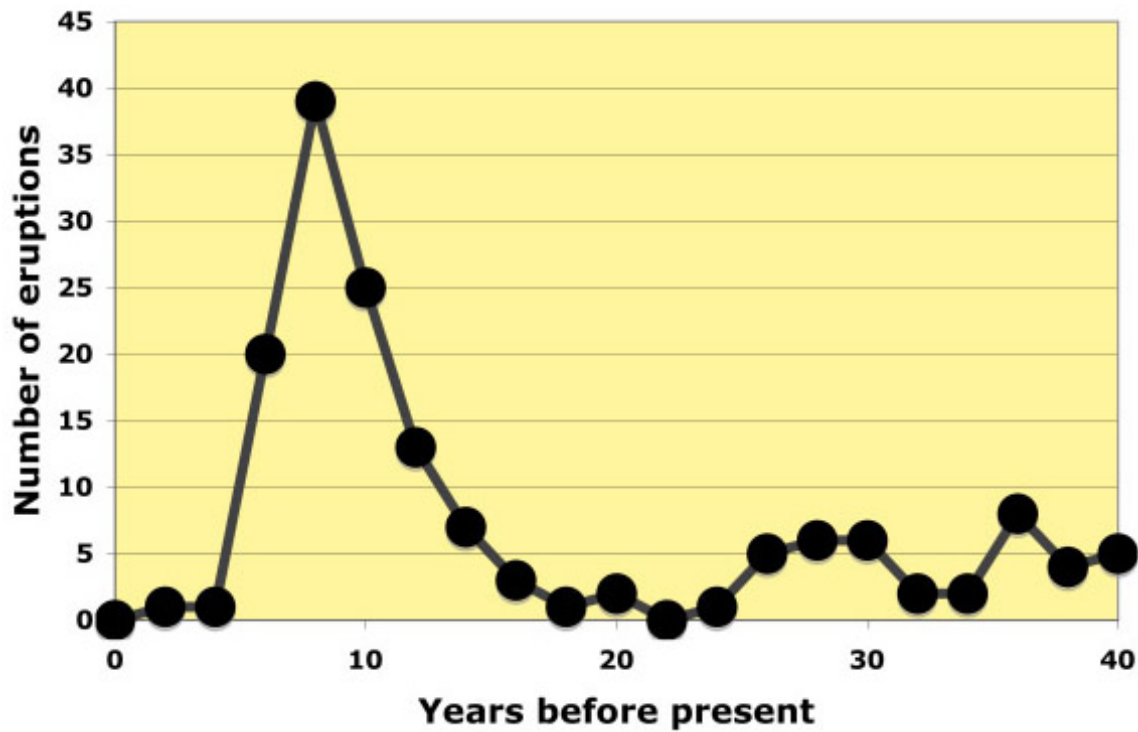


Figure 5. The record of the number of volcanic eruptions each 2 kyrs in the Rhine Graben over the last 40 kyrs. Note there were almost none between 23 and 18 kyrs. This period of quiescence was followed by a peak centered at 8.5 kyrs (Data from Novell et al., 2006).

It should be noted that none of these volcanoes were directly overlain by glacial ice. This suggests that the footprint created by ice loading was considerably larger than that of the ice mass itself.

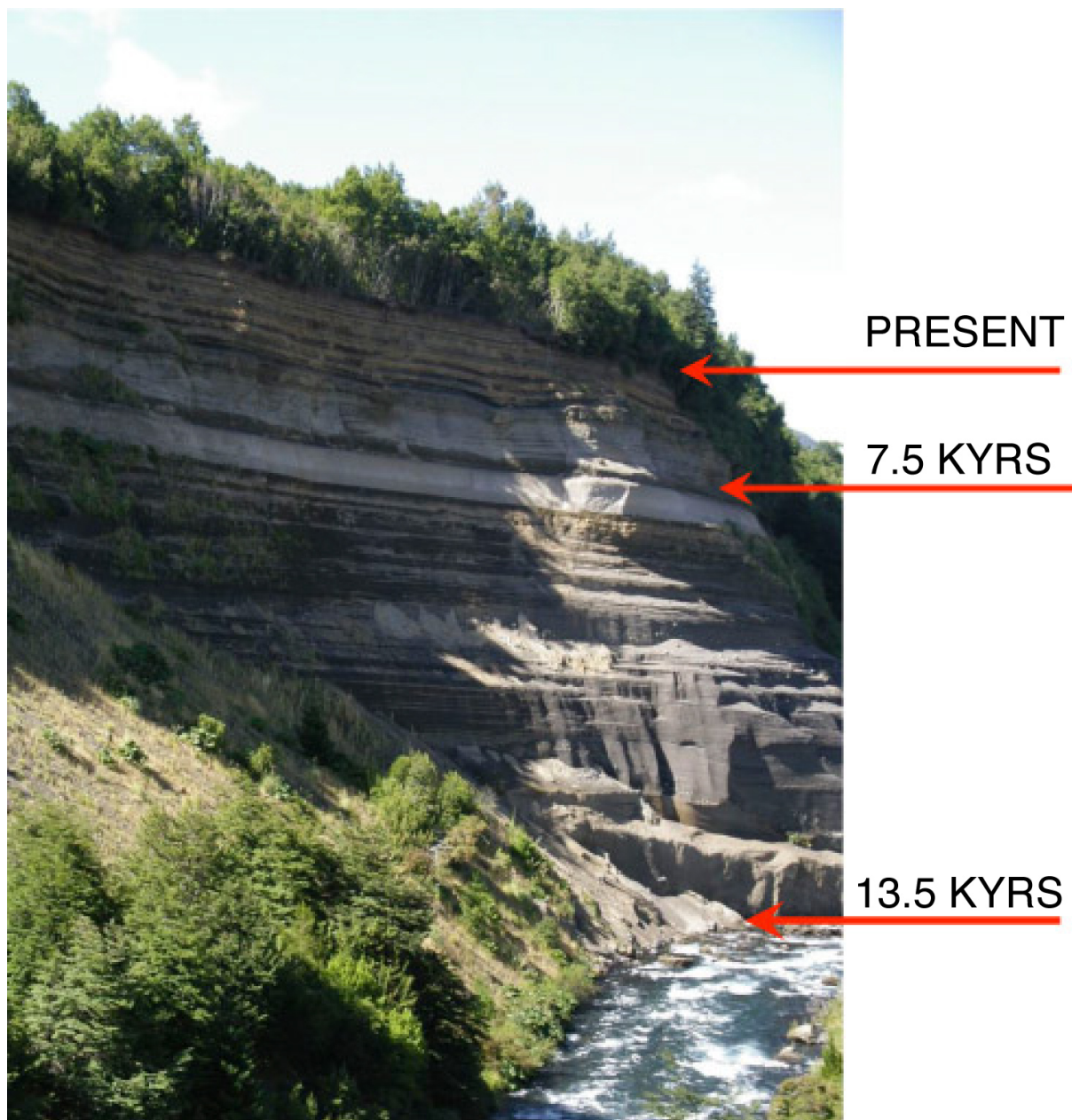


Figure 6. Volcano Llaima has the best dated Andean eruption chronology. The record shows a dearth of eruptions during the LGM followed by a burst of activity between 13.5 and 7.5 kyrs.

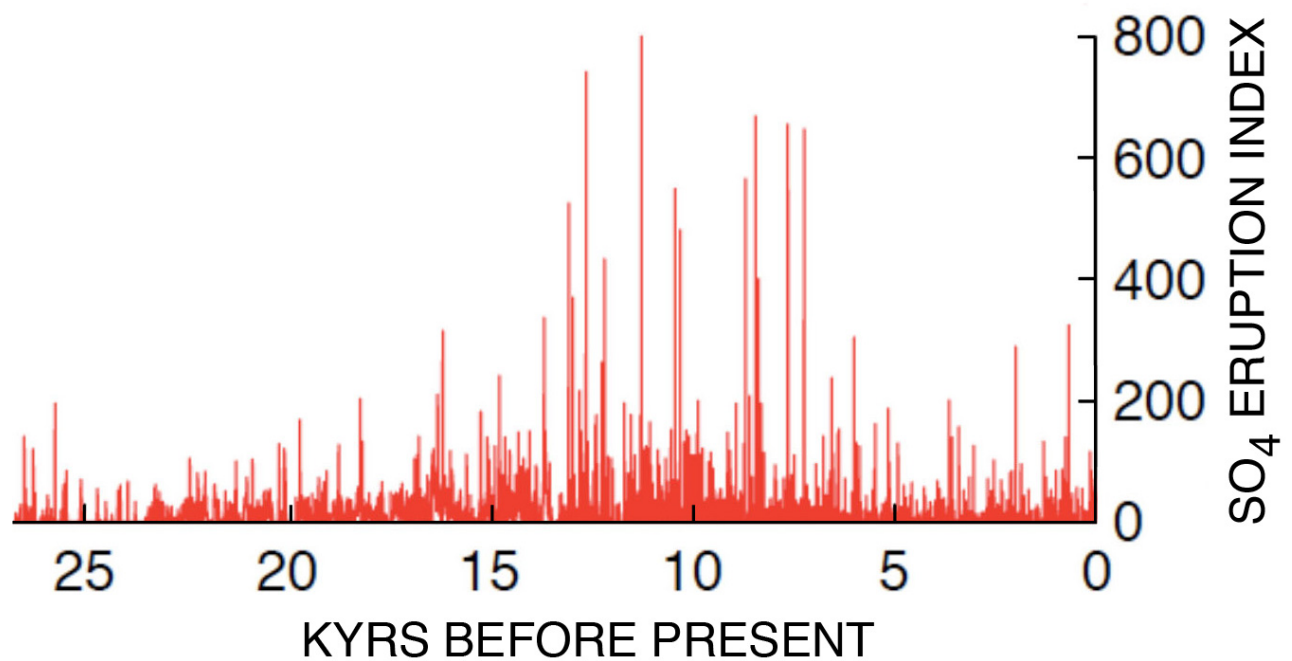


Figure 7. Sulfate peaks in Greenland ice record volcanic eruptions. The reason is that the  $\text{SO}_2$  gas emitted travels some distance before it is oxidized to  $\text{SO}_4^-$  ions. These ions are then carried to the Earth's surface by precipitation. Infrequent during the LGM (23 to 18 krys), these events reappear as a broad maximum during the deglacial period (Zielinski, 2000).



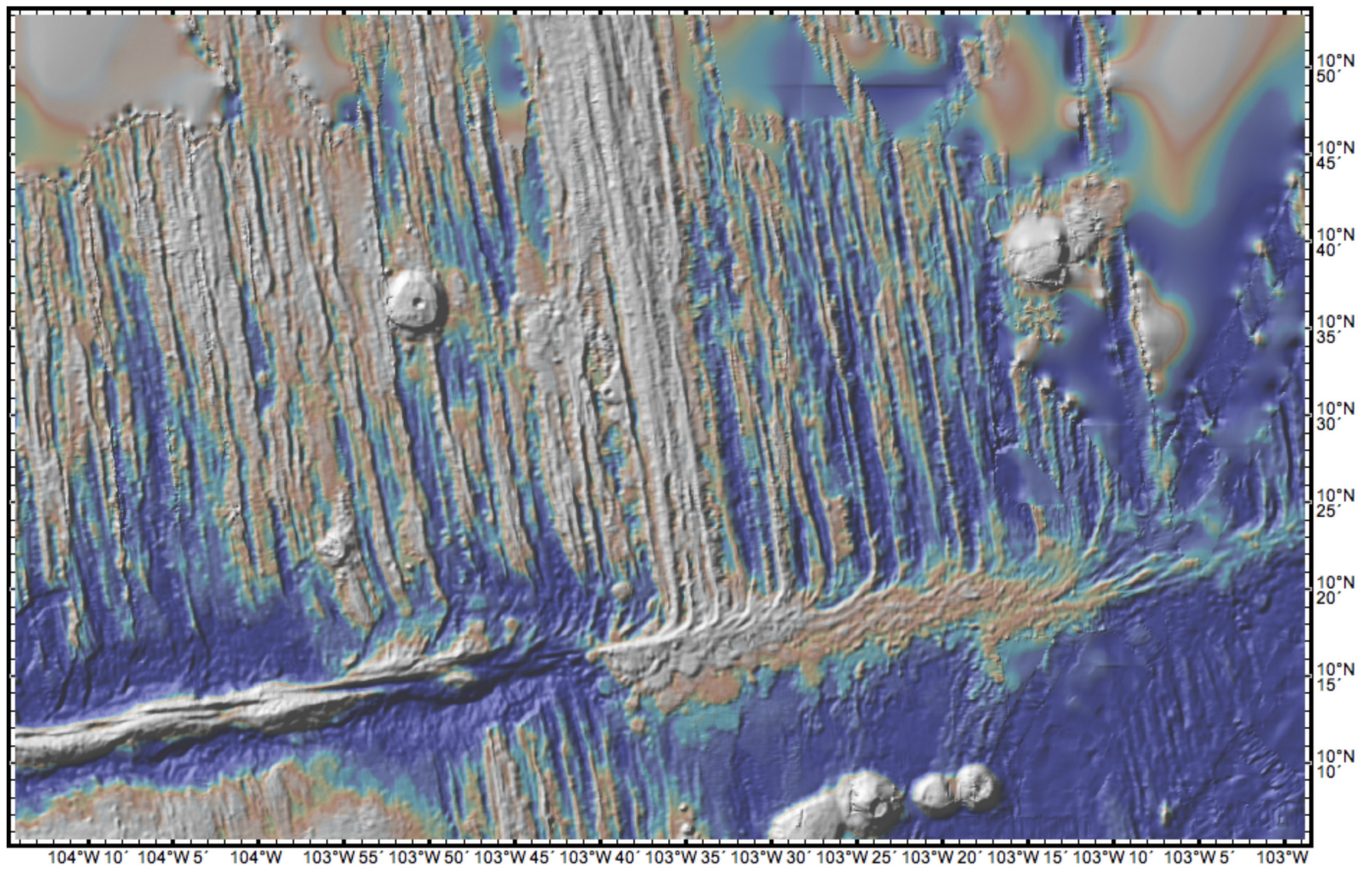


Figure 8. The topography of the sea floor is dominated by linear highs and lows (referred to as Abyssal Hills). Taking advantage of magnetic reversals, their spacing can be converted to age differences. The largest of these depth anomalies are spaced at 100 kyr intervals. Smaller ones have been shown to be spaced at about 20 and about 40 kyrs. Hence a strong case can be made that the strength of sea floor volcanism is related to sea level.

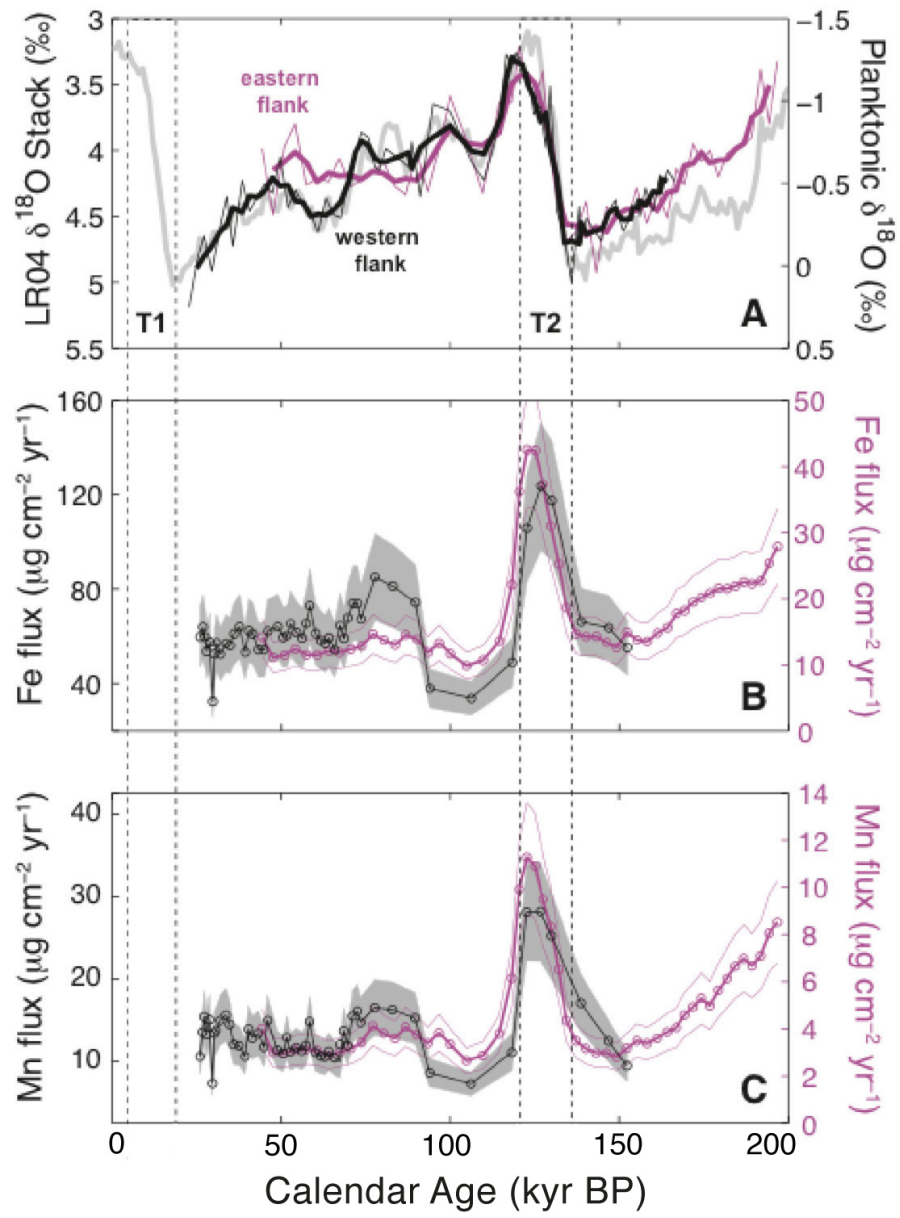


Figure 9. The Lund record for the penultimate glaciation.

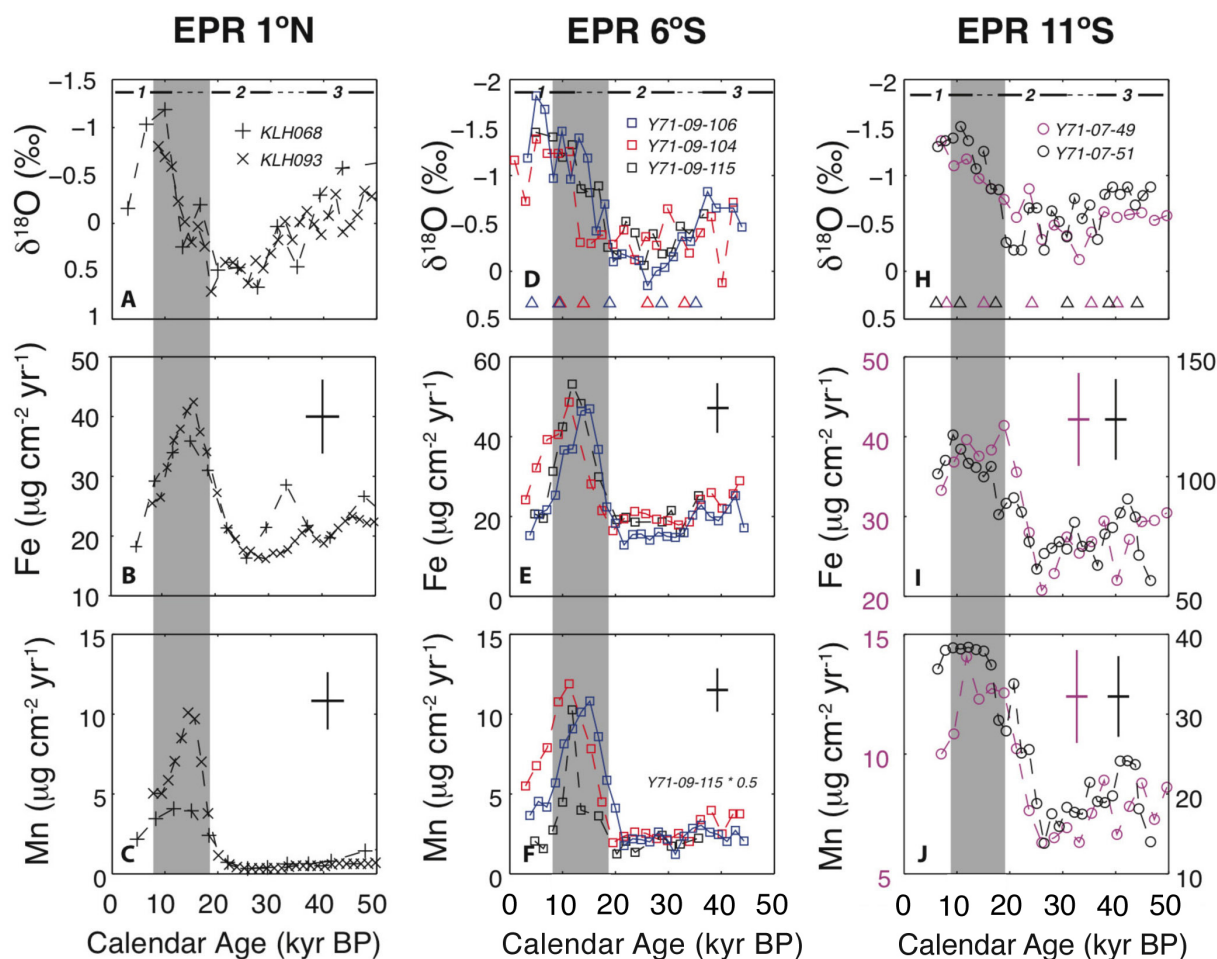


Figure 10. David Lund reports peaks in the abundance of Mn and Fe during times of deglaciation in sediments at three latitudes along the East Pacific Rise. For the most recent deglaciation, the timing of these peaks is established using measurements of both  $^{18}\text{O}$  to  $^{16}\text{O}$  and  $^{14}\text{C}$  to  $\text{C}$  on foraminifera shells. Although there is no proof that the release of  $\text{CO}_2$  is tied to that of Mn and Fe, the timing of these peaks is consistent with predictions by Oxford's Richard Katz.



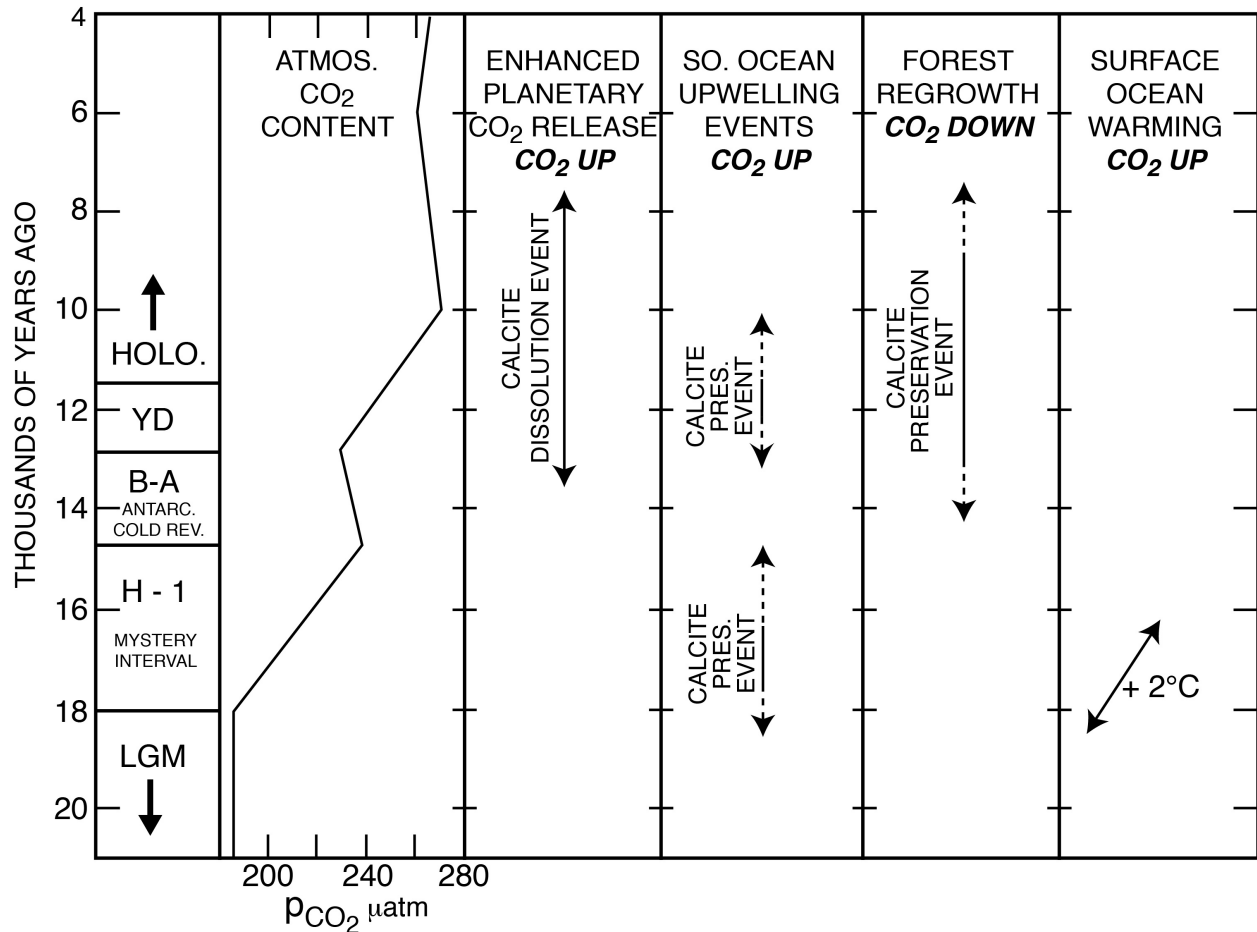


Figure 11. The addition of volcanic CO<sub>2</sub> would have created a deep sea calcite dissolution event. The release of CO<sub>2</sub> stored in the deep sea would have created a preservation event. The preservation event accompanying forest regrowth would enhance the latter and obscure the former. Although the timing of surface-ocean warming is poorly constrained, as shown by the increase in Xe/N<sub>2</sub> and Kr/N<sub>2</sub> ratios in the air trapped in polar ice, a 2°C whole ocean warming occurred between 18 and 16 kyrs.

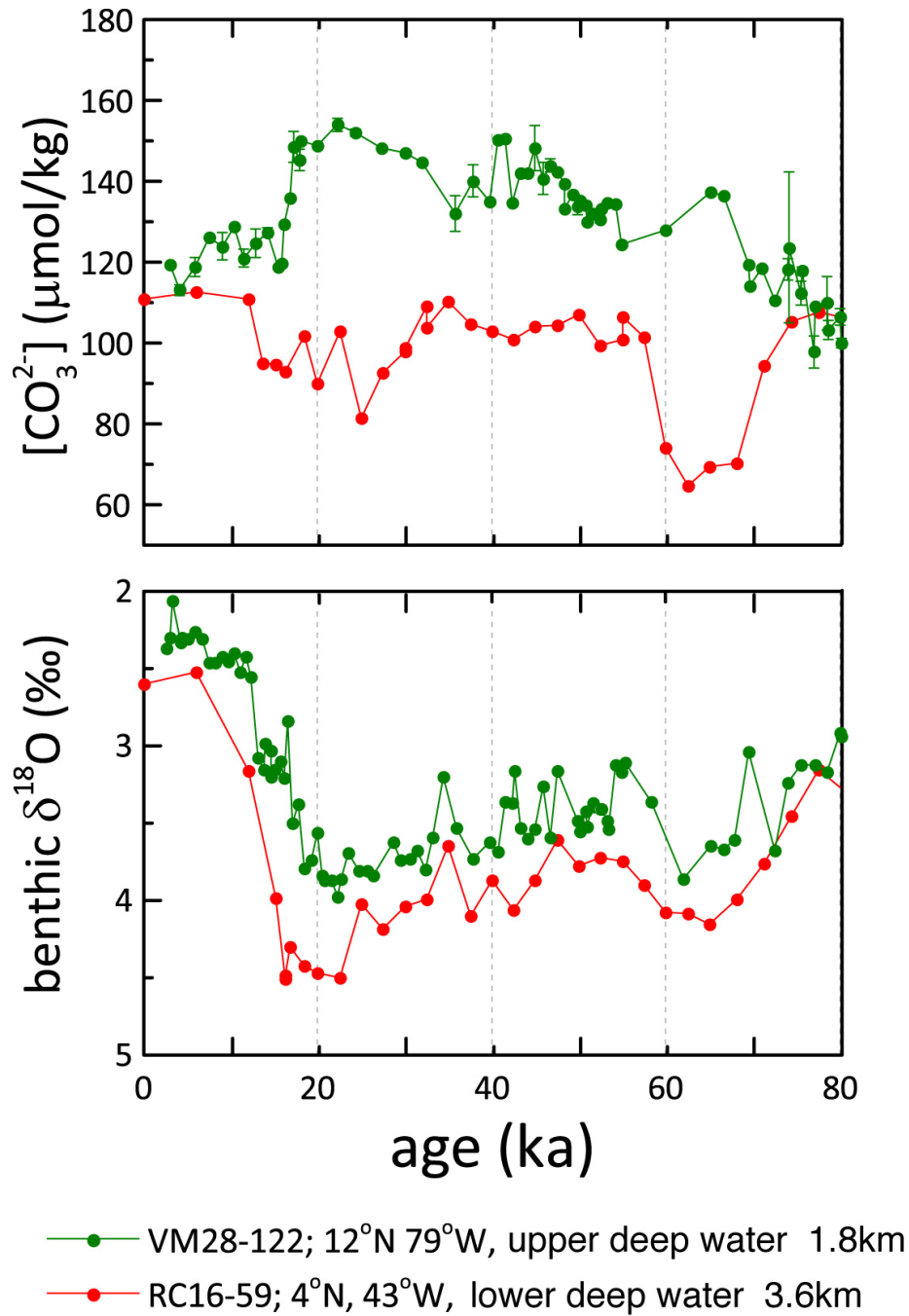


Figure 12. Repeated here is Jimin Yu's  $\text{CO}_3^{2-}$  record for the last 80 kyrs. Note that there is no convincing evidence for either a preservation or a dissolution event. During the last deglaciation, if such an event is to be identified, it will require more detailed measurements on a core with a higher sedimentation rate.