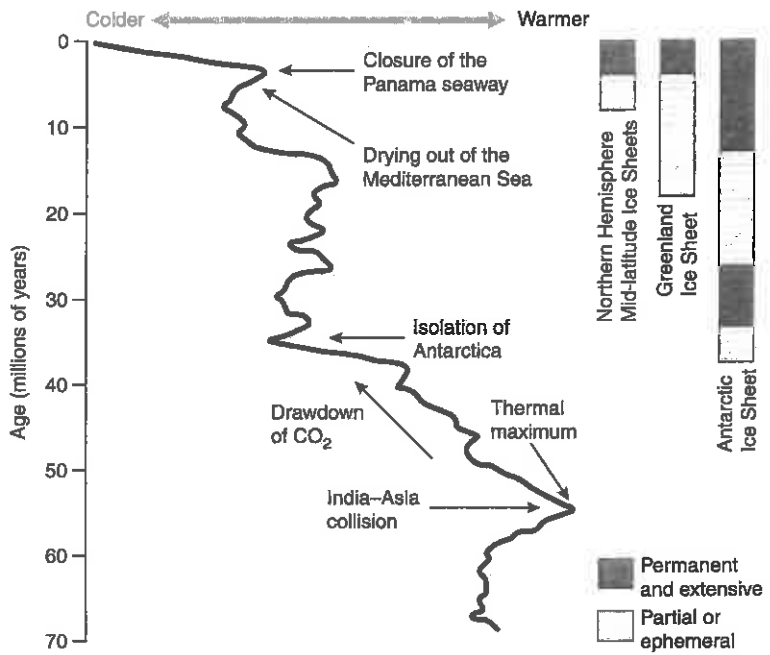
The Cenozoic glacial epoch: the last great cooling

Marine sediments also provide an extended record of global change that has allowed us to gain a deeper understanding of Earth's steady shift from greenhouse to icehouse over the past 55 million years. At the end of the Cretaceous, around 65 million years ago (Ma), lush forests thrived in the Polar Regions and ocean temperatures were much warmer than today. This warm phase continued for the next 10 million years, peaking during the Eocene thermal maximum (Figure 27). From that time onwards, however, Earth's climate began a steady cooling that saw the initiation of widespread glacial conditions, first in Antarctica between 40 and 30 Ma, in Greenland between 20 and 15 Ma, and then in the middle latitudes of the northern hemisphere around 2.5 Ma. Several key events have been implicated in this last great



27. Global temperature change and ice sheet development over the last 70 million years

cooling in Earth history (Figure 27) and these are briefly reviewed next.

The uplift of the Himalayas was underway by 50 Ma after the initial collision between India and Asia. The high rainfall and steep relief in this region created a global hot spot for both physical and chemical weathering. The big rivers that drain the Himalayas transport very high loads of fine sediment and material dissolved in solution. As the rocks of the Himalayas are broken down and transported to the sea, the CO_2 from rainwater combines with the weathering products to form new compounds such as the calcium carbonate ($CaCO_3$) shells of marine creatures. As uplift continued, more and more carbon from the atmosphere became sequestered in the fossils of creatures deposited on the ocean floor. It took a very long period of weathering (about 20 million years) to sufficiently weaken the Earth's greenhouse effect to bring down mean global temperature so that large-scale glaciation could commence in the high latitudes.

As CO_2 levels continued to fall, shifting continents in the southern hemisphere resulted in the isolation of Antarctica. This was a crucial step in the initiation of large-scale glaciation in the Polar South. The opening of marine gateways between Antarctica and South America and between Antarctica and Australia produced the powerful Antarctic Circumpolar Current. This prevented warm ocean currents from reaching the waters around Antarctica and allowed the first permanent ice to accumulate about 35 Ma (Figure 27). The history of Antarctica's ice sheets is chronicled in the IRD record of the Southern Ocean. Recent work on the IRD record in marine sediments around Greenland by German geologist Jörn Thiede and his team has indicated that large-scale glaciation on that landmass was initiated much earlier than previously thought (Figure 27).

At the end of the Miocene, between 5.5 and 5 Ma, the Mediterranean Sea dried out and refilled many times as its

connection with the Atlantic was disrupted by tectonic movements at the Straits of Gibraltar. The Mediterranean became an enormous salt pan as the basin's waters evaporated during times of isolation. These salt deposits can exceed 2 km in thickness. The end result was a *c.*6 per cent fall in the salt load of the global ocean so that sea water became easier to freeze. It has been argued that the extent and thickness of sea ice increased in high latitudes after this period. The enhanced albedo effect that this created would have augmented the long-term trend of Late Cenozoic global cooling.

Finally, in the Late Pliocene, sometime after 4 Ma, the formation of the Isthmus of Panama joined the continents of North and South America and closed the connection between the Atlantic and Pacific Oceans. This strengthened the Gulf Stream and increased the supply of moisture to the land masses around the North Atlantic. The final closure preceded the earliest evidence for large-scale glaciation in the northern hemisphere south of 60°N. The proximity of these events makes this an attractive hypothesis (Figure 27) for the initiation of ice sheet growth in the high middle latitudes of North America and Europe although some computer models suggest that the warming influence of the Gulf Stream may have had the opposite effect.

Over the past 55 million years, a succession of processes driven by tectonics combined to cool our planet. It is difficult to isolate their individual contributions or to be sure about the details of cause and effect over this long period, especially when there are uncertainties in dating and when one considers the complexity of the climate system with its web of internal feedbacks. The tipping point for the initiation of ice sheet formation in the high middle latitudes of the northern hemisphere may have been albedo effects and an orbital nudge that intensified the long-term cooling trend driven by tectonic processes. Once set in glacial mode, the length of glacials and interglacials was paced by the Milankovitch Cycles.