GEOLOGY OF ANTARCTICA

1. Global context of Antarctica

Compared with other continents, the geological evolution of Antarctica is relatively little known, since less than 2% of the land emerges from beneath the thick cover of glacier ice. Yet where rocks are exposed, their pristine nature and lack of vegetation has enabled geologists to unravel many key components of the region's history. In addition, the use of geophysical and remote sensing techniques, together with drilling on the Continental Shelf, has helped resolve many of the geological questions posed by the limited outcrop.

Antarctica is the remotest of the world's continents, with its nearest neighbour being South America, some 100 km (560 miles) distant. Yet, relatively early on in the geological exploration of Antarctica it was recognized that Antarctica shared a common history with other southern hemisphere continents, such as South America, Africa, Arabia, India and Australasia. However, these early ideas of movement of continents by joining together, followed by splitting apart, were ridiculed by many geologists and geophysicists, until the revolution in geological thinking in the late 1960s that led to the 'theory of plate tectonics'.

This collection of photographs is assembled to capture the spirit of Antarctica's geological evolution, grouped according to the key events that have shaped the continent. A limited knowledge of geological processes and terms is required to fully appreciate this set.

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Contributors

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2. Antarctica's global connections

The Antarctic continent today forms part of the much larger Antarctic Plate, comprising both continental crust of the land mass and its continental shelf, and ocean floor forming the surrounding deep Southern Ocean. The Antarctic Plate is bounded mainly by the mid-ocean spreading ridges in the Pacific, India and southern South Atlantic oceans. In the South America-Antarctica Peninsula region the plate boundary is less clearly defined and the intervening Scotia Sea consists of at least two microplates.

The Antarctic continent itself consists of two contrasting tectonic provinces, East Antarctic and West Antarctica, separated by the Transantarctic Mountains. East

Antarctica is an ancient Precambrian region of metamorphic continental crust, known as a ‘craton’, on top of which lies horizontally bedded sedimentary rocks of Palaeozoic to Early Cenozoic Age. West Antarctica, in contrast, comprises a series of orogenic belts representing the last 500 million years or so.

Antarctica has long been part of larger supercontinents. The earliest named, Rodinia, is the least well known, but its successors Gondwana and Pangaea are well-constrained by geophysical and geological data. Especially noticeable is that by recombining Africa and South America, along with Antarctica, Australia and India, we find a particularly good fit of the component plates of Gondwana.

3. The foundations of Antarctica

The complexity of metamorphic rocks in East Antarctica, together with limited exposure has precluded the formulation of a coherent history for Precambrian time. Nevertheless, geologists have demonstrated that its history matches well with those of Western Australia and southern Africa, supporting their connectivity within Gondwana. The rocks represented by this period are predominantly schist and gneiss. These were originally sedimentary and igneous rocks, but have been subject to such high temperature and pressure that their original features cannot be distinguished. This period of evolution spans the greater proportion of geological time, from at least 3100 to 480 million years. Towards the end of Precambrian time and into Early Palaeozoic time around 550 million years ago, a mixture of marine sediments and volcanic rocks record active plate margin activity, culminating in several mountain-building events called orogenies. The end products were suites of rocks that were deformed and metamorphosed.

4. The Heart of Gondwana

By Devonian time (around 400 m.y. ago) the continental block of East Antarctica had stabilized above sea level, within the heart of Gondwana. The old mountain chains of earlier orogenies were worn down to their roots, forming a flat surface or erosion known as peneplain. It was on this peneplain that from Devonian to Jurassic time (380 m.y. ago), a flat-flying sequence of sedimentary rocks was deposited. It reaches a thickness of 4 km in the Beardmore Glacier area. First described by geologists on the expeditions of Scott and Shackleton, and named the Beacon Sandstone after the predominant rock type, it excited attention because of the finding of the *Glossopteris* flora, a species of tree, that was also known from other southern hemisphere continents. The Beacon Supergroup, as this sequence of sedimentary rocks is now formally known, also consist of Permian and Triassic coal measures, which form spectacular seams several metres thick in the Transantarctic and Prince Charles Mountains, although in the latter area the local name Amery Group is used. All the evidence points to a sedimentary regime dominated by rivers.

The Beacon Supergroup also contains evidence of early Permian glacial deposits (290 m.y. old). These deposits are indicative of a Gondwana-wide glacial phase that started in the early Carboniferous Period and finished in late Permian time when supercontinent moved across the South Polar region.

5. The break-up of Gondwana

By early Jurassic time, around 180 million years ago the supercontinent began to break up. The first manifestations of this were the intrusion and extrusion of basic magmas into and capping the Beacon Supergroup in the Transantarctic Mountains. The name applied to these rocks is the Ferrar Group. In the Pensacola Mountains, Coats Land, a major intrusion, also of basic magma took place in the Dufek Massif. There are magnificant exposures of intrusive rocks in the Dry Valleys of Victoria Land, where precipitous cliffs of buff-coloured Beacon sandstone are cut vertically, diagonally and horizontally by dark grey sills (horizontal) and dykes (vertical), some of them more than 100 metres thick.

Within the first 20 million years of the onset of break-up, ocean floor had been generated in the region now occupied by the Weddell Sea, and a complex rift system extended across West Antarctica to the region of the present-day Ross Sea. Simultaneously, Gondwana began to split asunder, with the peripheral regions of Gondwana drifting northwards away from Antarctica, which remained in a polar position Spanning about 115 million years, the continents separated from Antarctica in the following order: Southern Africa (145 m.y.), India, Australia, South America (29 m.y. ago).

6. Mesozoic plate margin activity, Antarctic Peninsula

The Antarctic Peninsula saw the deposition of marine mudstones and sandstones, as well as some extensive volcanic rocks, during the Mesozoic Era. These rocks were intruded by granite which forms the backbone of the Peninsula, and were metamorphosed during the Andean Orogeny, so named because of the similar record in the Andes of South America. To the east of the Peninsula, the islands and offshore sedimentary basins saw deposition of highly fossiliferous Cretaceous mudstones and sandstones of both marine and terrestrial origin.

7. Late Cenozoic volcanic activity

Late Cenozoic volcanic activity is associated with the West Antarctic Rift system and plate collision in the Antarctic Peninsula region. The most active areas today are the South Sandwich and South Shetland Islands in the Scotia Arc, a string of islands that connects Antarctica through South Georgia to South America. Several explosive eruptions have occurred in this region in historical time. Further southwest is a large basaltic province centred on James Ross Island, whose eruptive record extends back some 8 m.y. Many of these eruptions were subglacial. Similar rocks to those on James Ross Island occur further south in the Peninsula, on Alexander Island.

The West Antarctic Rift System has remained active sporadically through the last 50 million years. Uplift along the western flanks of the rift produced the Transantarctic Mountains, and immense alpine-scale range, much of it buried under the East Antarctic Ice Sheet. In the McMurdo Sound region and further north in Victoria Land well-known basaltic volcanoes are Mount Melbourne, Mount Discovery, Mount Erebus and Mount Terror. Of these Erebus has the distinction not only of being the highest volcano in Antarctica (3794 m) but also the world’s southernmost active one. Erebus has not produced any violent eruption in recorded history, but it has a long-lived lava lake and regularly emits plumes of steam. At the opposite end of the rift system, in Marie Byrd Land, the volcanoes are largely buried under ice, and no historical activity has been noted.

8. Into the freezer: Cenozoic glaciation

From a climatic perspective, the last of the great geological Eras, the Cenozoic (which started 65 m.y. ago), was a time of global cooling. The cooling was not steady, but was interrupted by warm pulses. By the last 2 million years, the earth had cooled to temperatures not seen for over 250 million years, when the earth was last influenced by ice sheets. The known geological record in Antarctica is too scanty to draw up a detailed record in the first 30 m.y. of the Cenozoic record. We do, however, know from erratics derived from the Ross continental shelf that the climate was warm and supported abundant vegetation. The onset of large-scale glaciation about 35 m.y. ago is documented from deep cores drilled into the continental shelves of the Ross Sea and Prydz Bay. Here, details of a changing glacial regime have been recorded from hundreds of metres of core from sea-ice-based drill rigs and drilling ships including the ongoing international ANDRILL programme of SCAR. The earliest glaciers were accompanied by well-established cool temperate forests of southern beech (*Nothofagus*), podocarps and other flora, such as are found in the Southern Alps of New Zealand and Patagonia today.

As the climate deteriorated well-established forests were replaced by tundra vegetation by about 30 m.y. ago, dominated by a ground hugging species of *Nothofagus*, similar in character to the present-day Arctic willow. This species grew alongside the precursor to the modern Beardmore Glacier in a latitude of nearly 85°S. Major fluctuations of the Antarctic Ice Sheet occurred throughout this period, but according to many scientists it became associated with a cold, arid climate similar to today's about 15 m.y. ago. The ice sheet may even have reached its maximum size at this time, overriding all the mountains and reaching the edge of the continental shelf. Since that time, these scientists argue, that the East Antarctic Ice Sheet at least has remained stable. They are supported in this by the antiquity of the landscape in the Dry Valleys of Victoria Land, where land surfaces have been dated to be many millions of years old, and thus not overridden by ice since then. However, in contrast, a small group of researchers has argued that large-scale removal of the ice sheet took place as recently as 3-4 m.y. ago. Their arguments are based on studies of extensive glacial deposits (called the Sirius Group) scattered throughout the Transantarctic Mountains, from which microfossils indicate this relatively young age. Irrespective of the age of these deposits, they have excited much attention because of the exceptional preservation of *Nothofagus* stems, roots and leaves, together with fresh-looking moss, beetles and flies in close proximity to glaciers. Together, they tell us of a much warmer (but still tundra-like) climate within a few hundred kilometres of the South Pole. The debate continues with vigour, but whenever the final cooling and stabilization of the ice sheet took place, the issue is important because it offers a window on what Antarctica could look like in the future as global warming has increasing impact on the continent.

9. Into the future

The geological record tells us about global temperatures over millions of years. The Earth has experienced phases of global warming and global cooling in the past, so to the geologist climate change is nothing new. However, what is unprecedented is the rate of warming of the planet, and the rapid rise in the atmosphere of the proportion of the greenhouse gas, carbon dioxide. The Intergovernmental Panel on Climate Change in its

2007 report argued that temperature rises will dramatically exceed natural trends as a result of human activity. The accompanying graph, illustrates average global temperature trends over the past 80 million years of so and the onset of southern and northern hemisphere glaciations. Even with the best likely outcome of 1.8°C temperature rise by 2100, the last time the Earth experienced this condition was in the Pliocene Epoch, 3 million years ago (hence the importance of resolving the 'Sirius debate' outlined in section 8), prior to the formation of the major Northern Hemisphere ice sheets. If the likely warming reaches the 4.8°C level as shown in the graph, we have to go right back to the onset of glaciation on the Antarctic continent or anywhere for that matter. Even this 4.8°C level may be too optimistic, given current trends in greenhouse emissions. Furthermore, the Polar Regions are experiencing enhanced global warming overall, but at least as far as Antarctica is concerned this is only evident in the Peninsula. In the heart of Antarctica there may even have been recent cooling. The emerging picture is complex, but we should be concerned about the stability of the ice sheet, and its potential to add to sea-level rise, based on the geological evidence.

10. Mineral wealth of Antarctica

The question of mineral wealth of Antarctic is a highly controversial topic, as the continent remains the only substantial tract on Earth where minerals remain unexploited. Although an attempt was made in 1988 to establish a framework for the exploration of mineral wealth through the Convention on the Regulation of Antarctic Minerals Resources under strictly regulated environmental conditions, the protocol was not ratified and failed to come into force. Instead, with the growing recognition of the scenic, wildlife and scientific value of Antarctica, the environmental lobby gained the upper hand and in 1991 the Protocol on Environmental Protection was initiated and has subsequently come into force. This protocol protects Antarctica for a period of 50 years from exploitation, which for those who have experienced the grandeur of this icy continent is the most desirable outcome.

Of the mineral wealth likely, oil is likely to be the most attractive. The geology of the Antarctic continental shelves is similar in many respects to that of other continents where major oil reserves have been found. However, these are huge obstacles to be overcome, not least the immense size of icebergs, if drilling for oil were to be undertaken on Antarctica continental shelves. Inland, the vast thickness of the ice sheet precludes drilling for hydrocarbons.

Coal is a major feature of the Beacon Supergroup, referred to above. Horizontal seams of Permian and Triassic age occur in the Transantarctic Mountains, the rich black colour contrasting dramatically with the buff sandstones in cliff sections. Similar strata in the Prince Charles Mountains also reveal coal. Despite the quality of the coal, it has never been seriously considered for exploitation.

The last group of potentially economic rocks comprises metallic ores. Best known is the Dufek intrusion in the Pensacola Mountains. This complex of mineral-rich rock is 9 km thick and covers at least 50,000 km^2. It has been likened to the Bushveld Complex in South Africa, and is rich in iron ore, whilst higher value minerals are to be expected in the lower parts of the intrusion, such as cobalt, chromium, nickel, uranium, copper and platinum.

The international community currently regards the value of Antarctica to be greater for aesthetic and environmental reasons, rather than as a potential source of minerals, so let us hope that the current 50 year moratorium on mineral exploitation holds for future generations.