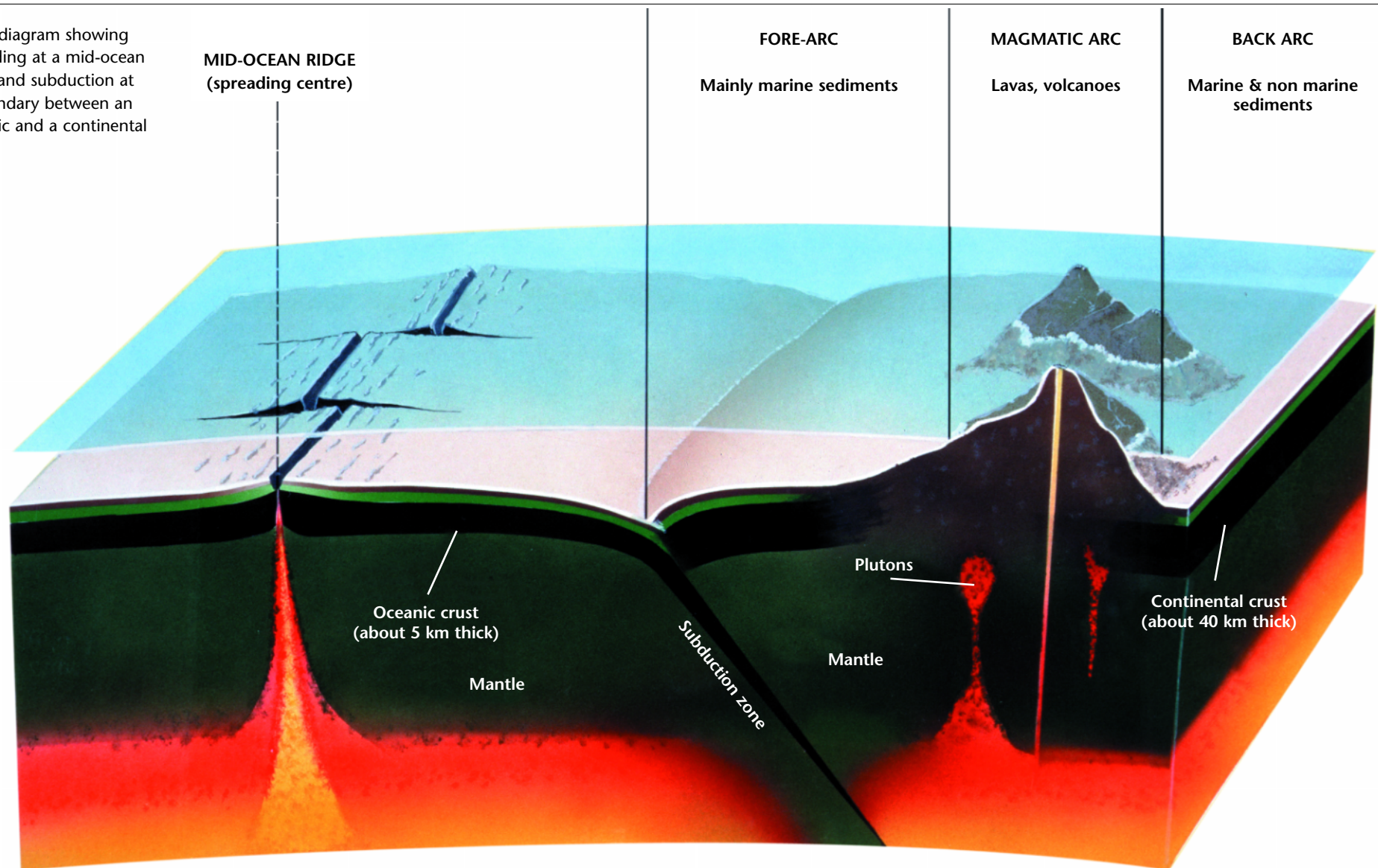




# Continental plate margins

Resource G1

Block diagram showing spreading at a mid-ocean ridge and subduction at a boundary between an oceanic and a continental plate

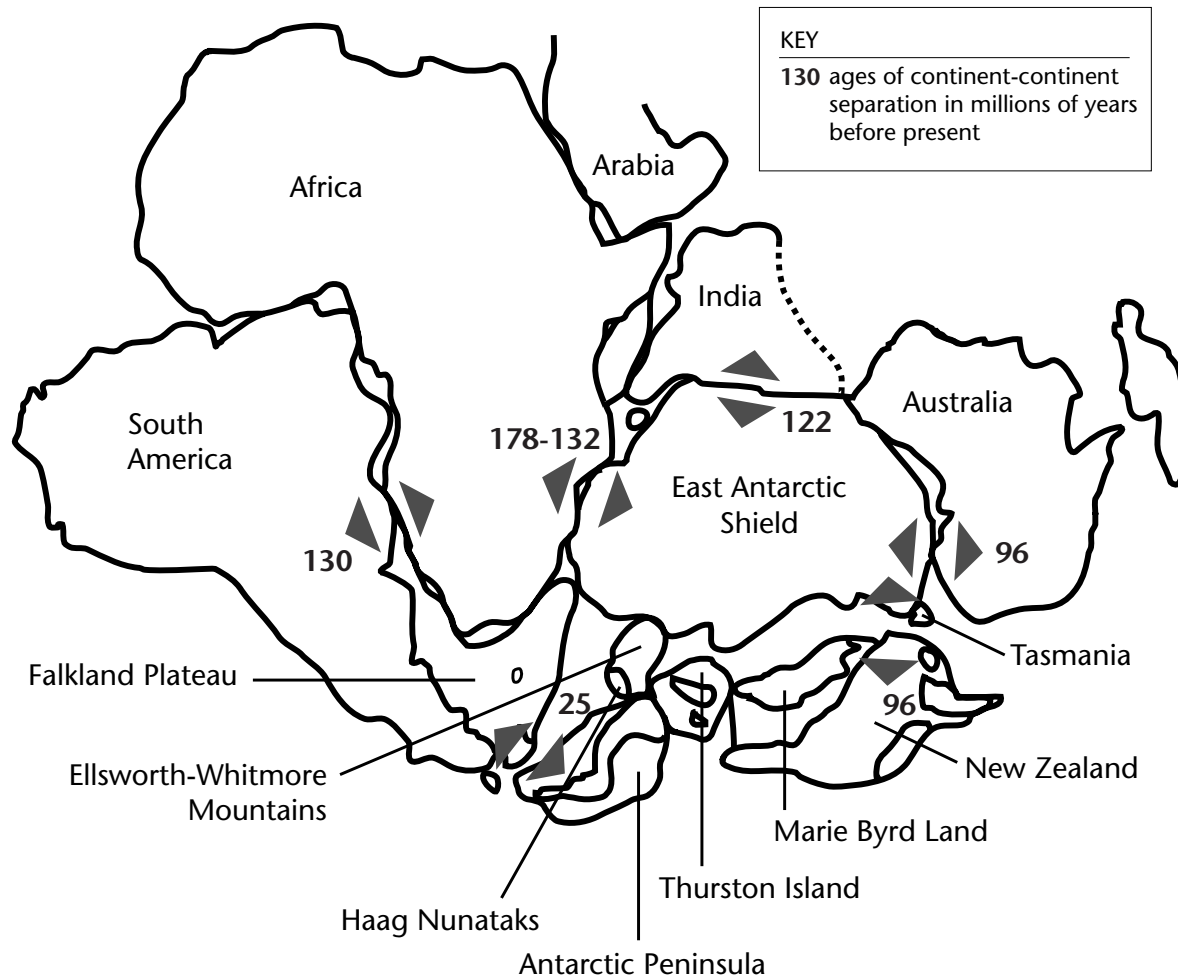




# The break-up of Gondwana

## Resource G2

Map of Gondwana showing break-up dates

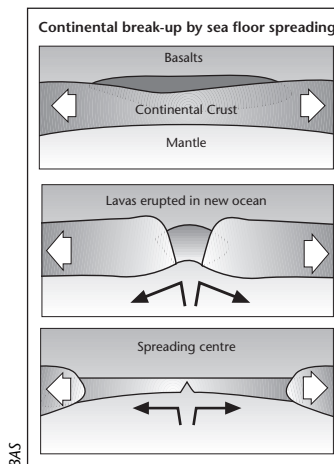


At about 180 million years ago the Gondwana supercontinent began to rift apart. As the continental fragments parted, ocean crust was generated in the intervening rifts, and the new southern oceans were born.

Ocean crust is formed of basalt lava erupted at mid-ocean spreading centres. By successive eruptions the ocean floors spread at the rate of a few centimetres per year. This was fast enough to create the present day southern oceans over a period of 150 million years or so. Africa and South America split to form the South Atlantic, and India moved north as the Indian Ocean opened, eventually colliding with Asia. The result of this collision was massive buckling of the crust which produced the Himalayas.

Different parts of Gondwana separated at different times. The first rift was between Africa and Antarctica, where the continental rifting lasted many tens of millions of years. The earliest signs of the developing rift were the eruption of voluminous lavas in southern Africa and Antarctica at about 180 million years ago. These two parts of the supercontinent did not finally part company until

about 150 million years ago. The rifts between South America and Africa, and between Antarctica, India and Australia took place over much shorter periods of time, but they too were accompanied by huge eruptions of lavas. The last part of the continental break-up, the splitting of Australia and New Zealand from Antarctica, took place 96 million years ago, during the Cretaceous Period.





# Mantle plumes and sea floor spreading

Resource G3

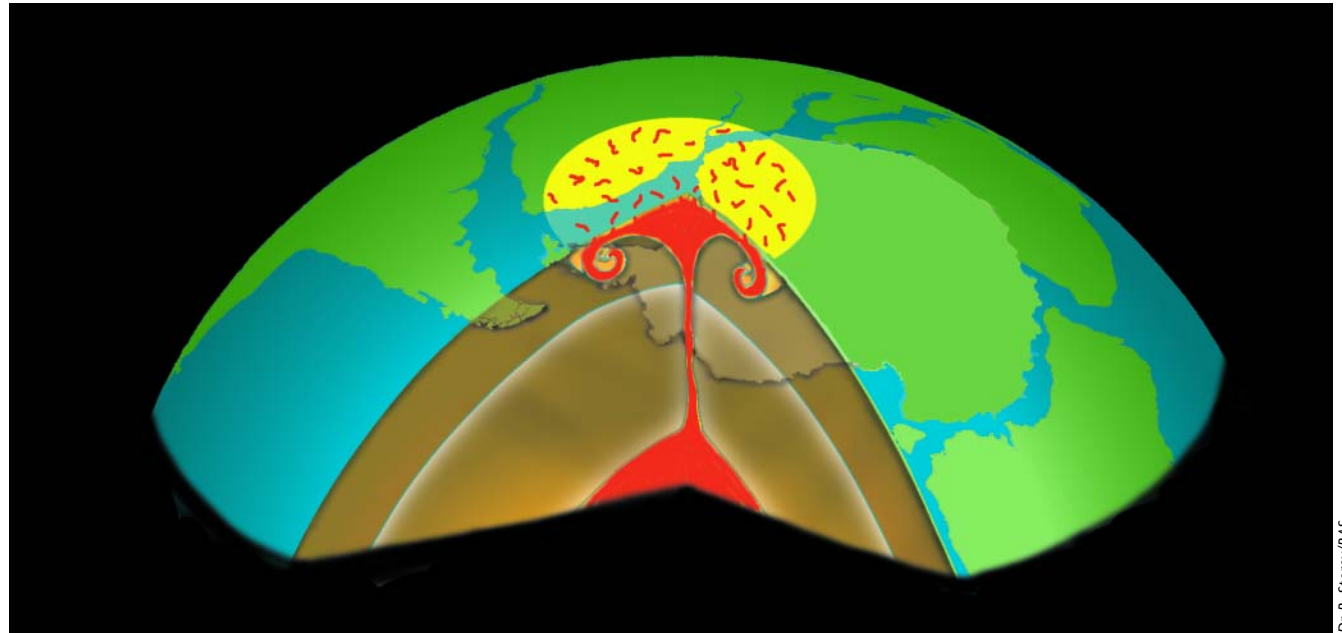
Throughout geological time, continents have drifted over the Earth's surface as rigid plates. Periodically, they have collided and aggregated to form large supercontinents. In turn, large supercontinents have disintegrated to form smaller plates. Before 180 million years ago, today's southern continents, with India, were grouped together and formed a super-continent called Gondwana.

The break up and dispersal of a supercontinent like Gondwana represents a radical change in the plate-tectonic regime, and the reasons for this dramatic change are hotly debated. Current ideas involve either the plate and boundary forces that drive plate motions or some active internal mantle process.

Most workers assume that when the continents are dispersed, as they are today, one of two mechanisms is at work. Firstly the plates may drive themselves – passive subsidence of cooling oceanic plates causes them to move away from mid-ocean spreading ridges and to be consumed (subducted) eventually at destructive plate boundaries. Secondly, the plates may be carried by frictional drag forces exerted by the internal mantle convection system. However, many workers doubt whether these forces are sufficient to cause a supercontinent to break up. Consequently, they invoke the idea of an active-mantle mechanism involving an abnormally hot upwelling in the mantle known as a mantle plume or hotspot.

Plumes are generally envisaged as having a narrow central conduit arising from a thermal disturbance at the core-mantle boundary with, at least initially, a large bulbous mushroom head up to 2000 km in diameter. They are considered to be an important mode of mantle convection that is independent of plate-scale mantle flow.

One geologist, Larson, has speculated that there may have been major periods in the Earth's history when larger mantle plumes, termed superplumes, drastically affected



Three-dimensional diagram of Gondwana, 180 million years ago, showing a mantle plume rising from the core-mantle boundary

both the pattern of mantle convection and plate motions. This is thought to have happened in the South West Pacific Ocean 120 million years ago.

A common factor of mantle-plume models is that plumes have the capacity to generate large quantities of basaltic magma, often before continental break-up. This leads to the eruption of continental flood basalts such as those found in the Indian Deccan Plateau. They can also produce chains of volcanic islands as oceanic plates move over fixed hotspots (as can be seen today in the mid-Pacific island chains that include Hawaii).

Mantle plumes may have a more important role, however, in initiating continental break-up. Ideas vary about how this happens. Some ideas assume the original active mantle hypothesis but envisage the plumes as driving the

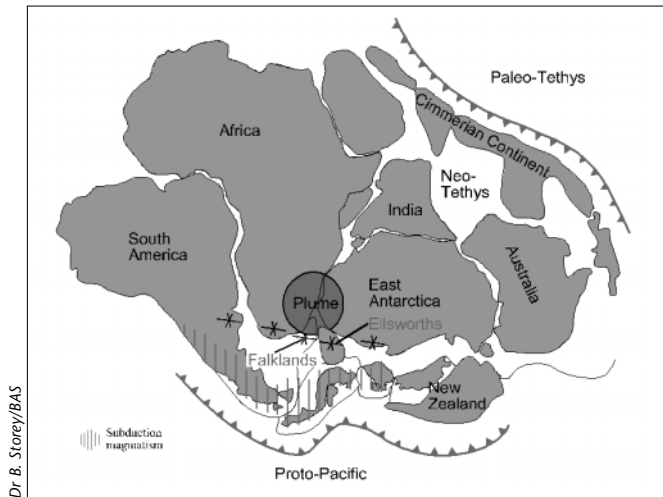
plates and initiating continental break-up by doming and cracking the continents, and thus pushing them apart. Other ideas invoke the passive models, whereby the plume plays no part in the break-up itself but the chance unroofing of a pre-existing or incubating plume results in a rapid outpouring of flood basalt provinces.

Some hybrid models combine aspects of both active and passive models. Here the forces that drive plate motions place the continents under tension when subduction is taking place on both sides of a continent. The arrival of a new plume weakens them and causes them to split and form a new ocean.

Although plumes are generally considered as representing thermal disturbances at the core-mantle boundary it is also possible that hot regions could develop at shallow

Dr B. Storey/BAS





Gondwana's break up in association with a mantle plume

levels in the mantle owing to the insulating effect of supercontinents. The build-up of heat beneath a supercontinent could lead initially to thermal expansion and horizontal temperature gradients in the mantle. This could be followed by doming and fragmentation of the continent and ultimately to the dispersal of continental fragments from hot to cold mantle regions.

The present upsurge of interest in mantle dynamics, the development of new mantle-plume hypotheses and ensuing controversies have led to a re-evaluation of their role in the disintegration of large supercontinents. The testing of these geological models can come only from research in the field, and the fragmentation of Gondwana into smaller continents provides an excellent case history against which to test various models. From a study of Gondwana it seems that plumes were not the ultimate driving force for continental break-up. It proceeded without a plume, and can generally be linked to changes in plate-boundary forces and the overall plate-

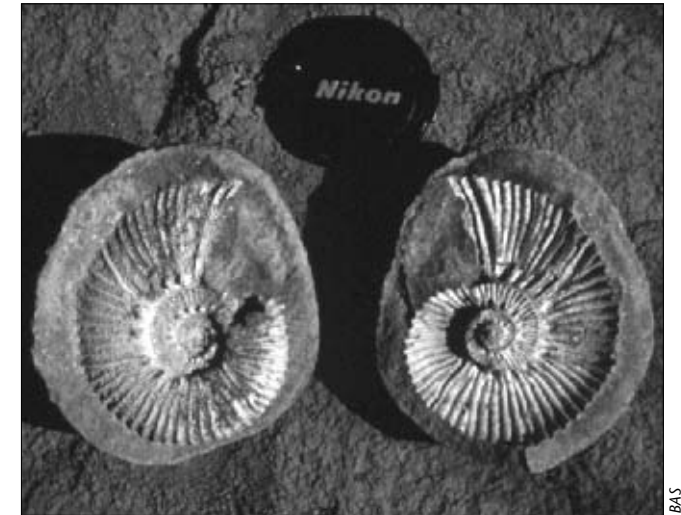
tectonic regime. When mantle plumes were involved, they may have assisted break-up and controlled its location. By contrast, mantle plumes may be the dominant cause of the splitting of smaller continental blocks.

### Stages in the break-up of Gondwana

There were four main stages in the disintegration of the Gondwana continent. The initial rifting stage started in Early Jurassic times (180 million years ago), and led to a seaway forming between West (South America and Africa) and East Gondwana (Antarctica, Australia, India and New Zealand), and to sea-floor spreading in the Somali, Mozambique and possibly Weddell Sea basins. The second stage occurred in Early Cretaceous times (130 million years ago) when this two-plate system was replaced by three, with South America separating from an African-Indian plate, and the African-Indian plate from Antarctica. The third stage occurred in the late Cretaceous times (90–100 million years ago) when Australia and New Zealand separated from the Antarctic core and other small continental



Basalt sills in the Theron Mountains, up to 2000 metres thick. The sills were emplaced into sedimentary rocks just prior to the disintegration of Gondwana, 180 million years ago



Gunnarites – late Cretaceous ammonites from James Ross Island

blocks, Madagascar and the Seychelles, separated from India as it migrated northwards away from Africa and Antarctica. Finally, in mid-Tertiary times the break up of Gondwana was completed when the northern tip of the Antarctic Peninsula separated from southern South America by sea-floor spreading in the Scotia Sea, 25 million years ago. This resulted in the isolation of Antarctica and the development of the circumpolar current in the Southern Ocean.

Continental separation was in most cases closely associated in time with extrusion of flood-basalt provinces that are generally linked to mantle plumes and in some cases connected by chains of volcanic islands to known present-day hotspots. However, in the Indian Ocean, there is some debate on the correlation of specific hotspots and basalt provinces before 120 million years ago because of uncertainties in Gondwana plate motions relative to the fixed hotspot reference frame and the closeness of some hotspots.



# Mineral occurrences in Antarctica

Resource G4

**Ever since the earliest days of geological exploration in Antarctica there has been speculation on the economical mineral wealth of the continent.**

However, detailed knowledge of mineral-deposit potential is lacking and all 'economic' assessments of such supposed wealth therefore remain estimations. Comparison with the adjacent continental fragments of Gondwana have led to suggestions that Antarctica may contain as many mineral deposits as southern Africa and South America, but this does not help to locate possible sites for mineralisation. During 50 years of reconnaissance mapping and detailed scientific research, no large areas of mineralised rocks have been found in the Antarctic. Ironstones have been found in East Antarctica and coal deposits in the Transantarctic Mountains, but these are no larger than deposits of marginal economic viability on other continents. Small areas of hydrothermally mineralised rocks have been found, for example on the Antarctic Peninsula, but none of these has been investigated in detail. Finally, few economic studies have been carried out to establish exploration and mining costs in Antarctica. Although large mineral deposits may lie beneath the ice, the Environmental Protocol to the Antarctic Treaty, which came into force in 1998, bans commercial mining activities in Antarctica. The Protocol provides mechanisms for the review of the ban after 50 years, or before if all the Treaty nations agree. The ban will continue unless or until there are rules in place under which a decision can be taken as to whether mining is environmentally acceptable. The combination of the lack of knowledge, the Environmental Protocol and the harsh environment means that mining on any scale in Antarctica is unlikely for many decades to come.



Dr B. Storey/BAS

A sedimentary succession from Pecora Escarpment in the Transantarctic Mountains. The thick black layer in the centre of the succession is a 3 metre thick Permian coal horizon (260 million years old). During the Permian period, Antarctica was part of Gondwana, it was not glaciated but had a warm temperate climate with lush vegetation. The brown layer at the top of the succession is a Middle Jurassic basalt sill (183 million years old) that was emplaced into the sedimentary rocks at the time of Gondwana break-up.



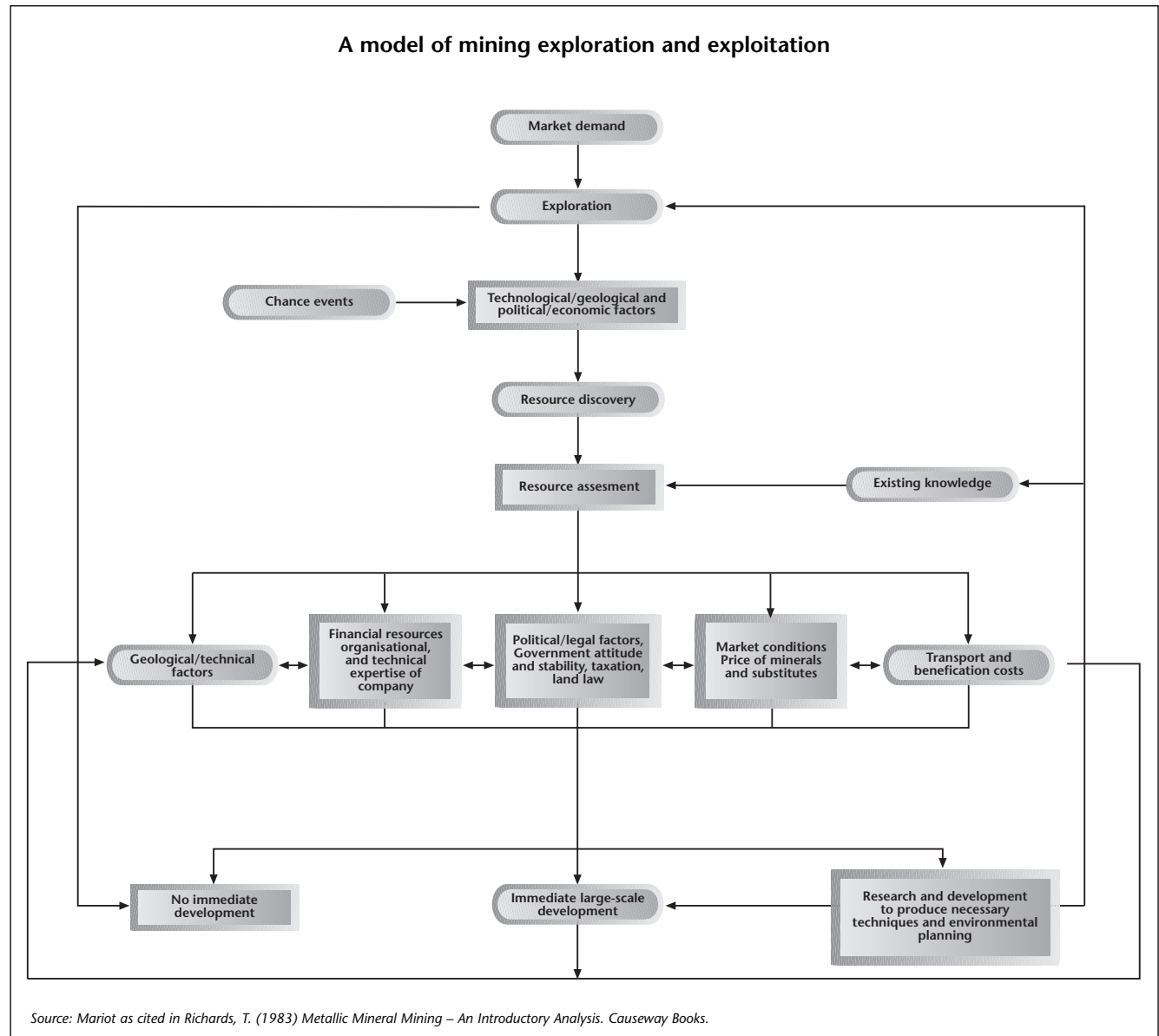


### Factors influencing appraisal

- Aspects of natural environments become resources, when they are appraised as having value for human needs. These needs can be related to basic human requirements (e.g. food, comfort and shelter), or to the desire for cultural satisfaction (that is, they relate to values, aspirations or spiritual wants).
- A resource may be appraised as such by any individual or by a group.
- In the creation of resources the environment offers opportunities yet imposes restrictions and limits.
- While humans can employ their abilities to create resources from the environment, these abilities are not unlimited. Technology is constrained at any point in time not only by the state of human knowledge but also by the cost of its application. Moreover, the environmental cost which may derive from resource exploitation, usually in the form of pollution or habitat damage, may be impossible to overcome.
- Once a resource is perceived, controls on its utilisation might depend not only on the state of its supply or demand but also on sets of desired aims or goals. These may be in the form of group social pressures, they may be political or they may be articulated within a legal framework such as planning and environmental controls.

### A model of mining exploration and production

- The process of appraising mineral resources can be shown as a flow diagram. This is shown on this resource.





As developments in geology have unfolded during the 20th century and the theory of plate tectonics has emerged, knowledge of the geology of Antarctica has become critical to the wider understanding of continental drift and the mechanisms that drive it. Antarctica occupied a position at the core of the ancient supercontinent of Gondwana. Antarctic rocks and fossils have provided important clues in piecing together this supercontinent. Like the atmosphere, ice sheets and ocean currents of Antarctica, its geology has come to be seen as a vital part of the global Earth system. This worksheet explores a number of aspects of Antarctica's geology, some of them new and controversial. It examines first continental drift, then looks at the concept of mantle plumes and associated volcanicity. The worksheet then briefly discusses meteorites and concludes by examining the evidence for mineral resources.

### Gondwana and continental drift

The Earth's continents are part of a series of tectonic plates which are able to move over the planet's surface. The causes of these movements are uncertain. These plates originate in the mid-ocean ridges, known as constructive margins, such as the mid-Atlantic ridge. Here material is created through volcanic action and new plate material moves aside from the ridge in a process known as sea floor spreading. Eventually plates collide with each other and one (always an oceanic one) sinks under the other in what is known as a subduction zone or destructive margin. Material here is carried back to the mantle giving rise to further volcanic activity and the possible development of island arcs.

Where continental plates collide, material on the ocean floor may be crumpled up to form fold mountains such as the Himalayas. Where plates move past each other there is no creation or destruction of material but friction, and



Dr J. Smellie/BAS

Mount Erebus on Ross Island, the largest active volcano in Antarctica, contains a molten lava lake in the summit crater

the discontinuous nature of the movements leads to earthquakes. Such zones, or conservative margins, can be found in California, associated with the San Andreas and other faults. These processes are shown in Resource G1.

Continental drift has resulted in the amalgamation and break up of landmasses over geological time. The best documented example is the break-up of Gondwana of which Antarctica was a central part. This process and some of its consequences are described in Resource G2. This also shows a composite map of Gondwana and the dates on which various parts split apart.

**Task 1** With reference to the Resources G1 and G2 produce a time-line diagram that charts the break-up of Gondwana from 180 million years ago to the present. In no more than two paragraphs summarise the impact of the break-up on the climate, flora and fauna of Antarctica.

### The potential role of mantle plumes in driving continental drift

Since the development of plate tectonics, there has always been debate about the mechanisms that drive the plates. It was considered possible that the plates are carried by frictional drag forces, created by internal convection cells within the mantle. It is now more generally accepted that the plates drive themselves – the basalt emerges hot at mid-ocean ridges and as it cools the oceanic plates gradually subside to eventually sink at the destructive plate boundaries. Many geologists have, however, come to doubt whether these forces are sufficient to cause a super-continent such as Gondwana to break up. This has led some to suggest an active mantle mechanism involving abnormally hot upwellings known as mantle plumes. These are visualised as having narrow central conduits originating in thermal disturbances at the core-mantle boundary. The conduits are capped, at least in the early

stages, by bulbous mushroom heads up to 2000 km in diameter. These plumes are considered capable of acting independently of the passive mantle flows described above. More significantly, very large plumes or 'superplumes' have emerged sporadically. These have initiated and influenced mantle convection and thus the break-up of the super-continent.

**Task 2** Resource G3 describes the role of mantle plumes in detail and explains how they may have contributed to the break-up of Gondwana. Using this resource draw an annotated diagram that explains how superplumes may have led to the separation of continents. What doubts still surround the theory?

### The role of superplumes in palaeoclimates

It is possible that superplumes may help to explain Antarctica's past climates. Of particular interest is the climate 100 million years ago when Antarctica was already located over the South Pole, but enjoyed sub-tropical temperatures. It has been discovered that CO<sub>2</sub> levels at that time were twice what they are today and this may have caused the warm climate. But why were CO<sub>2</sub> levels so high?



BAS geologist collecting samples of accreted ocean floor rocks on Alexander Island

Certainly there was no human activity to explain the rise as there is now. Natural factors such as fires or positive feedback systems in vegetation cycles could have been responsible, though it is doubtful if they could account for all the increases. An alternative possibility is that the CO<sub>2</sub> was emitted by superplumes. This release would have been on a scale that would dwarf human activities today. The prolific biological activity that led to coal, oil and limestone formation in Cretaceous and PermoTriassic times can be seen as a negative feedback system which would have reduced CO<sub>2</sub> levels and reduced temperatures. This possible explanation needs to be linked to the astronomical mechanisms underpinning climatic change, and the effects of the separation of Antarctica from other continents (see Worksheet 8 on Antarctic Climate).

**Task 3** Given that superplumes could have produced huge emissions of CO<sub>2</sub>, draw a system diagram showing past climatic change in Antarctica.

### Volcanicity in Antarctica

Antarctica has about 70 volcanoes that were active in the geological past, but recent activity has been observed at only two. First, Deception Island, situated in the small rift at the northern tip of the Antarctic Peninsula, erupted explosively in 1967, 1969 and 1970, generating large volumes of basaltic ash. The second, Mount Erebus, situated on Ross Island in the Ross Sea, has a permanent molten lava lake, composed of alkali-rich magma held in a crater on the 3794 m high summit. In between, many other dormant or extinct volcanoes are scattered around the Ross Sea, along the Transantarctic Mountains, in Marie Byrd Land and on islands of the northern Antarctic Peninsula. Many of these have hot springs, or fumaroles, indicating potential for volcanic activity. In the area underlain by the East Antarctica shield there are few recent volcanoes, but one, called Gaussberg, is situated at the extreme eastern edge of the continent. This tiny volcano, only 1 km across, erupted below ice some 55,000

years ago. It is well known among geologists because of the very unusual, highly alkaline (especially potassium-rich) composition of its lava and its isolated position.

### Meteorites in Antarctica

Antarctica is very rich in meteorites particularly in the east. It appears that the flowing ice sheet concentrates the meteorites as they are carried towards the Transantarctic Mountains. Collection is very easy from the surface blue ice in this area. It is possible for geophysical reasons, perhaps to do with the Earth's magnetic field, that more meteorites fall in Antarctica than elsewhere, but this is not known for certain.

### Minerals in Antarctica

There are no known economic mineral resources in Antarctica. However, there are a number of mineral occurrences on the continent and assessment of their potential is controversial. Resource G4 is a brief account of the issue prepared by scientists at BAS.

Resource G5 discusses some definitions of resources and shows a model for the process of appraising mineral resources.

**Task 4** Read Resources G4 and G5. Why does the presence of a mineral in Antarctica not necessarily indicate that it is an economically viable resource? What further knowledge about the occurrences is needed before their viability as resources can be assessed? With reference to the Resource on the Environmental Protocol (Resource AT55), explain why this extra knowledge is unlikely to be acquired in the next 50 years. Describe some of the technical problems in exploiting minerals in Antarctica. Why are these even greater than in the deep North Sea or Alaska? The Resources on Nature of Antarctica and Antarctic Climate will assist you with this. Suggest reasons why the possible discovery of large oil reserves in the South Atlantic (e.g. around the Falklands Islands) could lead to pressures on the Environmental Protocol.