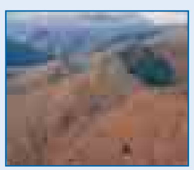
THE STORY OF
EARTH & LIFE

3
THE FIRST CONTINENT



The rocks of the Barberton Mountain Land record the formation of the Earth's first continent.

Carl Anhaeusser

ROUTE MAP TO CHAPTER 3

Age (years before present)	Event
13 700 million	• Big Bang: time began. Energy was transformed into hydrogen and helium as the Universe expanded. • Clumping of gas started galaxy formation. • Clumping of gas within early galaxies started star formation, in which the synthesis of heavy elements commenced. • Stellar explosions (supernovae) mixed heavy elements into the galaxies. Later generations of stars further modified composition of the galaxies.
4 600 million	• Gas and dust in the outer region of the Milky Way galaxy collapsed to form the Sun and planets: the Earth grew by gravitational accumulation of smaller bodies. • The Earth melted, heated by bombardment of smaller bodies, and segregated into layers of different density (core, mantle). A major collision knocked off a portion of the mantle, forming the Moon. • The Earth's surface cooled and an early crust formed. Bombardment declined, but destroyed the crust. The mantle also solidified: carbon dioxide, water vapour and nitrogen degassed from the Earth's interior, forming the atmosphere. • As the Earth cooled, water vapour started to condense to form the oceans.
4 100 million?	• Plate tectonics started; the oldest known rock (a granite in Labrador, Canada) formed.
3 900 million	• The oldest known sedimentary rocks formed (Amitsoq terrane, Greenland).
3 500 million	• The oldest known oceanic crust, consisting of komatiite, formed (the lower Onverwacht Group, Barberton).
3 400 million	• Subduction of oceanic crust created the oldest known island arc (upper Onverwacht Group, Barberton), with associated batholiths.
3 300 million	• Island arcs were eroded, shedding sediment into ocean trenches (the Fig Tree Group, Barberton).
3 200 million	• Island arcs started to amalgamate to form the first micro-continent. Erosion of continental rocks produced conglomerates, sandstones and mudstones (the Moodies Group, Barberton). • Granites formed by melting of thickened crust. • Micro-continents continued to accrete to form the Earth's oldest known continent, the Kaapvaal Craton.
3 100 million	• The continent finally stabilised.

WHAT IS SO SPECIAL ABOUT THE EARTH?

Earth is the third planet from the Sun, at a distance of about 150 million kilometres – an incomprehensible distance, at least in terms of human experience. Light from the Sun takes about eight and a half minutes to travel the distance to Earth.

Earth is, of course, unique in the Solar System in that it supports advanced forms of life and is mantled by a gaseous atmosphere that presently contains a significant amount of oxygen. One of the main reasons why Earth supports life is that it is positioned at the right distance from the Sun (the so-called habitable zone) to support the long-term existence of surface water in liquid form, mainly in the oceans. Any closer and the Sun's radiation would be so intense that water would boil and exist largely, or entirely, in the vapour state. The amount of heat energy reaching planets further from the Sun diminishes to the extent that water is entirely in the solid state (ice). The fortunate coincidence that places the Earth at just the right distance for much of its surface water to be liquid is a critical factor in the existence of life.

The prevailing view is that life not only originated in the oceans, but has existed entirely in water throughout much of Earth's history. The first amphibians emerged from the oceans only 350 million years ago, following plants that colonised land possibly 500 million years ago, and insects, about 430 million years ago. For the preceding several billion years life evolved entirely in the oceans. Earth is also just big enough to retain most of its gases in the atmosphere, whereas smaller bodies with less gravitational attraction (like Mars or the Moon) have long since lost their volatile envelopes.

In addition, Earth has a fairly strong magnetic field. This creates an encircling shield that deflects highly energetic particles ejected from the Sun, thus protecting the atmosphere, oceans and life. The oldest trace of life on Earth is found in cherts (a chemical sediment deposited on the ocean floor – *see* 'The formation of sedimentary rocks' on page 64) such as those at Barberton (**figure 3.1**), where microfossils believed to be cyanobacteria have been preserved. The story of the origin of life is dealt with in more detail in Chapter 6.

But how did Earth form, and when?

Carl Anhaeusser

Figure 3.1 *Chert layers from Barberton contain traces of early life.*

THE DAWN OF TIME

The late Stephen Jay Gould, well-known geologist-palaeontologist from Harvard University, made the point that the most profound contribution geology has made to human thought is the concept of Deep Time. This term, originally coined and popularised by American author John McPhee, refers to the immensity of geological time and the problem that man has in conceptualising the several-billion-year time span over which geological processes on the Earth have been operating.

Geological time – difficult though it may be to conceptualise – provides a sense of security in that there was a beginning, and that time's passage has been regular and marked by familiar cycles such as day-night, the lunar month and the seasonal year (*see* 'Measuring the age of a rock' on page 68 and 'The geological time scale' on page 71). Physicists who grapple with the origin of the universe have a much greater conceptual problem: their equations dictate that time is not a constant but varies as one approaches the speed of light. Stephen Hawking's book *A Brief History of Time* introduces this concept for the general public and explains that the Universe is finite in volume but expanding. Therefore, time and matter must have been formed at a fixed point in the past, which physicists call a singularity.

The concepts of relativity and quantum theory are complex. To keep things simple we will assume that time is constant and can be measured by the regular passage of events encapsulated in standard units which humankind has defined, such as the second and the year. Let us, however, accept the notion that time and the Universe (and therefore geological processes) commenced at a singularity

Figure 3.2 ***The Solar System is embedded in the large Milky Way galaxy, which contains billions of stars and huge clouds of dust and gas. It probably resembles the M74 (or NGC 628) galaxy in the constellation Pisces, shown here. Galaxies began to form by mutual gravitational attraction of hydrogen and helium gas shortly after the Universe was born in the Big Bang about 13 700 million years ago. Local concentrations of gas within these early nebulae collapsed under gravity to give rise to the first stars, which converted hydrogen and helium into heavier elements. Many of these stars exploded as supernovae, distributing heavy elements into the galaxy, and subsequent generations of stars were made from a more complex mixture of elements.***

and that the Universe had a beginning and will, in all likelihood, have an end. The event that marks the beginning of time, as well as matter in the universe, is popularly referred to as the **Big Bang**.

THE BIG BANG

In 1929 American astronomer Edwin Hubble discovered that the universe is expanding. The evidence for this is provided by a shift towards the red (i.e. lower frequency) end of the light spectrum in virtually all galaxies for which these data have been obtained. A red shift in the spectrum of a galaxy is a consequence of the Doppler effect, which relates how the frequency of light (i.e. its colour) emitted from one galaxy is lowered relative to the observer galaxy as the two move apart. The same phenomenon causes the change in pitch of the sound made by a motor vehicle as it passes. If virtually all galaxies are moving apart relative to one another, then the Universe must be expanding away from a single point. The implication of this discovery is that all matter, as well as time, was created by the explosion of a point source of almost infinite density during an event that is believed to have occurred about 13 700 million years ago.

Protons and electrons were formed from other subatomic particles in the first few instants after the Big Bang. They combined to create neutrons that then amalgamated with other protons and electrons to form atoms of hydrogen and helium. The newly formed matter was ejected away from the singularity to create an expanding Universe. As this expanding cloud of gas began to form clumps under the influence of gravity, the Universe started to evolve towards its present form, with regions of concentrated matter, known as **nebulae**, separated by near total emptiness in between.

After the initial flash of the Big Bang, the Universe darkened and remained dark for millions of years. Light was only emitted once matter had locally concentrated to sufficiently high densities under gravity within the nebulae to heat up and trigger nuclear fusion reactions in the first generation of stars about 200 million years after the Big Bang. These reactions not only emitted light and other forms of radiation, but also synthesised heavier chemical elements by the nuclear fusion of lighter elements. These early stars evolved and died, many in spectacular explosions known as **supernovae**, in the process spreading their newly formed mixture of heavier elements into the nebulae.

New stars were born from this debris, modifying it further and eventually ejecting it into the nebulae. Over thousands of millions of years, these nebulae, the galaxies of today, evolved from simple clouds of only hydrogen and helium to gigantic discs containing billions of stars and huge clouds of gas and dust laced with heavy elements, such as are required to form a rocky planet like the Earth. Current theories on the formation of heavy elements in stars suggest that the atoms that make up our world, and us for that matter, have passed through at least two supernovae events, so we have a somewhat intimate association with these celestial extravaganzas.

The Solar System is embedded within one of these galaxies – which we see edge-on in the night sky as the Milky Way – and is a huge amalgamation of stars, dust and gas arranged in a flattened disc with spiral arms, very similar to the M74 galaxy shown in **figure 3.2**. It is about 100 000 light-years across and about 20 000 light-years thick at its centre. (A light-year is the distance light will travel in one year – 9 460 000 million kilometres). The galaxy is rotating, and completes a full revolution every 186 million years. It is believed to have grown to its present size by the amalgamation of smaller galaxies, and today forms part of a cluster of more than 50 galaxies. Two nearer neighbouring galaxies are the Magellanic Clouds, which are visible to the naked eye and appear as two detached portions of the Milky Way.

BIRTH OF THE SOLAR SYSTEM

One rather ordinary star in the outer portion of the Milky Way galaxy, which we call the **Sun**, began to nucleate from the gas and dust of the galactic nebula about 4 600 million years ago, most probably as a result of the gas being compressed by the shockwave of a nearby supernova explosion. Once compressed, the hydrogen and helium, together with other gases and dust, began to collapse under gravity, forming an ever-shrinking disc – the Solar Nebula. As collapse progressed, temperatures in the disc rose, eventually reaching several million degrees at its centre and creating a fireball that ignited nuclear fusion of hydrogen to form our Sun. The Sun is in essence a continuously exploding hydrogen bomb protected from disintegration by the force of gravity.

The young Sun remained embedded in the disc of gas and dust. In the hot, inner region of the disc, only materials with very high melting and boiling points – mainly silicate compounds and nickel-iron alloys – formed solid particles (other materials being in the vapour state). These provided the raw materials for the formation of the inner planets. In the outer, cooler regions of the disc, carbon compounds and frozen water and ammonia formed the bulk of the solid particles. The grains began to clump together to form larger bodies or **planetesimals**, kilometres in diameter. Continued collision and accretion of planetesimals gave rise to Moon-sized bodies that amalgamated under the force of gravity to form complete planets.

The planets closer to the Sun are denser (average 5 g/cm^3), because of the higher temperatures prevailing in the region where they formed. In contrast, more distant planets contain a high proportion of gases and have low densities (average 1.2 g/cm^3), reflecting the cooler conditions that prevailed in the outer regions of the disc during planetary formation. The results of a computer simulation of the process are illustrated in **figure 3.3.** With the passage of time, radiation from the young Sun (the **Solar Wind**) swept away gas and dust that had not collapsed to form planets, producing the dust- and gas-free Solar System we observe today.

Nine planets formed from the gas and dust cloud orbiting the Sun. The four closest to the Sun – Mercury, Venus, Earth and Mars (the so-called inner or terrestrial planets) – are relatively small and are

THE FORMATION OF SEDIMENTARY ROCKS

Rock exposed at the Earth's surface is subject to chemical attack by the atmosphere, a process called **weathering**, which leads to disintegration of the rock. Rocks may also be exposed to mechanical agencies that cause disintegration. Whereas mechanical processes produce only rock fragments, weathering produces a range of products, including: components of the original rock that are not susceptible to weathering; new minerals, particularly clay minerals; and soluble substances.

The products of weathering or mechanical disintegration are transported away from the site of generation by flowing water, wind or ice, in a process known as **erosion**. They will ultimately accumulate elsewhere as sediment. Sediments that are accumulations of fragmental material (clay minerals, sand grains, rock fragments) are known as **clastic sediments**, whereas those that originate by precipitation of material from solution are known as **chemical sediments**. Sediment accumulations may ultimately become converted into sedimentary rocks in a process called **lithification**, which basically involves cementation of the particles.

CLASTIC SEDIMENTS

Flowing water separates material according to size: large particles such as pebbles only move in rapidly flowing water, sand in slower flowing water and silt in even slower flowing water, whereas mud (mainly made of clay minerals) requires hardly any flow to keep it dispersed in water. Sediments deposited by flowing water are therefore differentiated by size into gravel, sand, silt and mud.

Lithification converts gravel into a sedimentary rock called **conglomerate**, sand into a rock called **sandstone**, silt into **siltstone** and mud into **mudstone** (*see* **A–D**, right). Sand usually consists of the mineral quartz (silicon dioxide) because it is hard, chemically resistant and fairly common (quartz is a major constituent of the igneous rock granite, which forms most of the continental crust). Quartz sand may become lithified to the point where it forms an extremely hard, resistant rock type called **quartzite**. Sand sometimes consists mainly of shell fragments, in which case the term **limestone** is used to describe the resulting rock type, although not all limestones are shell accumulations. Some form as a result of photosynthetic bacterial activity.

In contrast to flowing water, flowing ice (i.e. glaciers) does not sort material according to size. As ice melts at the end of a glacier or from an iceberg, the rock material contained in the ice is dumped in an unsorted manner. This results in sediment consisting of a random mixture of material ranging in size from boulders to mud. When lithified, this is referred to as **tillite**. Material consisting of such a random mixture of different-sized particles can also be produced by a mud-flow, such as an avalanche resulting from heavy rain. Distinguishing between deposits formed by mud-flows and tillite is often difficult, and can only be done by examining the context in which the material occurs. Because it is often difficult to tell whether an unsorted rock resulted from glacial activity or from mud-flows, the general term **diamictite** has been coined to describe such a rock, whatever its origin.

Wind is also an important agent of sediment transport. Generally, material deposited by wind consists of fine sand (usually made of quartz). These sand deposits are often very thick. Sandstone resulting from wind deposition can be distinguished from sandstone resulting from flowing water by the associated internal structures (*see* 'Sedimentary structures' on page 86).

CHEMICAL SEDIMENTS

These sediments result from precipitation of substances dissolved in water, usually as a result of evaporation of the water. Depending on the substance precipitating, the resulting rock has different names; often the name of the mineral that precipitated is used to describe the rock. The general term for such a rock is an **evaporite**. One of the most common evaporites is sodium chloride (table salt, termed **halite**), formed during the evaporation of sea water and can occur as layers hundreds of metres thick.

Occasionally, precipitation occurs as a result of a chemical reaction. An example is the precipitation of iron oxide from sea water, which occurred frequently during the early evolution of the Earth (*see* Chapter 4). The high iron content results in a red- to black-coloured rock that consists mainly of iron oxide, known as **iron formation**. Sometimes the precipitation of iron was accompanied by silica precipitation. Silica is white, so the resulting rock consists of white, red and black layers and is known as **banded iron formation** (*see* **E** below).

A

Conglomerate

D

Mudstone

B

Sandstone

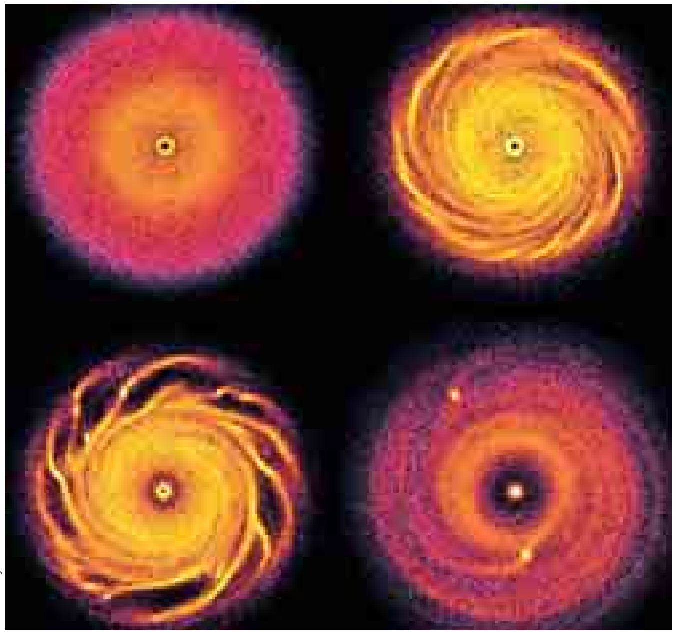
Terence McCarthy

C

Siltstone

E

Banded iron formation



Lucio Mayer

Figure 3.3 ***About 4 600 million years ago, a cloud of gas and dust in the outer reaches of the Milky Way galaxy began to collapse under the influence of gravity. As it shrank it began to rotate ever faster, flattening into a disc shape. Its interior also became hotter until the centre reached several million degrees. Nuclear fusion of hydrogen atoms commenced, producing the Sun. Computer simulation suggests how planets may have formed: material in the disc (top left) began to clump to produce smaller bodies (planetesimals, top right) that grew with time (bottom left) and finally coalesced to form planets (bottom right). The inner planets – Mercury, Venus, Earth and Mars – formed in the hotter, inner region of the disc and are made mainly of rocky material, while the outer planets formed in the cooler, outer disc and consist mainly of gases.***

made up of dense silicate, or rocky, material. The next two planets out from the Sun – Jupiter and Saturn – are gas giants that have rock-ice cores enveloped by hydrogen, helium and other gases. Further out are the two smaller gas giants, Uranus and Neptune, which are so far from the Sun that very little of its radiation reaches them and they are in a permanent state of deep freeze. The outermost planet is Pluto with its giant moon, Charon, whose orbit is off the plane (or ecliptic) of the other planets.

Pluto lies at the inner edge of a vast region of the Solar System that extends to a distance of about 50 Earth-Sun radii from the Sun, known as the Kuiper Belt. In this region, Pluto-like objects seem to abound and at least 700 have so far been identified. Large amounts of unaccreted material from the solar nebula, dominated by ice laced with silicate and carbonaceous dust, lie dispersed in the Oort Cloud, far beyond the Kuiper Belt. Occasionally, lumps of material from these distant regions enter the Solar System as comets.

It is indeed fortunate that the Earth has large planetary neighbours in more distant orbits, and especially Jupiter, for their strong gravitational fields shield the inner planets from impacts by comets. The majority of comets approaching the inner portion of the Solar System are captured by the gravitational field of Jupiter and flung back into deep space. Some cosmologists believe that advanced life would never have been able to evolve on Earth without the protection provided by Jupiter.

THE MOON

The process of planetary growth was probably fairly rapid in geological terms, lasting perhaps less than 60 million years. About 10 million years after the start of planetary formation the Earth had grown to some 65% of its current size and had largely segregated into mantle and core. At this time (about 4.53 billion years ago) it was struck a glancing blow by a Mars-sized object that vaporised part of the mantle. The vapour collected in orbit around the growing Earth, where it condensed and accumulated under gravity to form the Moon. The Earth and Moon continued to grow after this collision to reach their final sizes. The Moon-forming event was so severe that it tilted the Earth's axis of rotation and caused it to precess, like a spinning top knocked off balance, so that the axis of rotation sweeps through a conical path, completing a full revolution once every 26 000 years (the precession of the equinoxes).

The collision left Earth with a sizeable Moon, which is the cause of ocean tides. Even more important was the tilt in the axis of rotation that the collision caused, for it is this tilt that is responsible for the seasons.

But the consequences of the Moon's presence run far deeper. All planets are subject to gravitational forces exerted by the Sun, and more irregularly by neighbouring planets, each in their own orbit. J Laskar and P Robutel of the Bureau des Longitudes in Paris investigated the gravitational effects that planets (and moons) exert on one another, making some startling findings.

Their calculations revealed that gravitational forces have a profound effect not only on rotational frequency (for example, we always see the same face of the Moon), but more importantly on the inclination of the axis of rotation relative to the plane of the orbit. The tilt in the axis of rotation of Mars, for example, varies from 0° to as much as 60° over a period of tens of millions of years, and in a completely chaotic manner. Gravitational perturbations in the inclination of the axis of rotation of Venus were evidently so severe that the planet actually turned upside down and now rotates in the opposite direction to the other inner planets. Uranus lies on its side, with an inclination of 97°, possibly for the same reason.

The Moon saved the Earth from these chaotic oscillations. It is sufficiently massive to have anchored the orientation of the Earth's axis of rotation (**figure 3.4**), so that it deviates by only 1.3° from the average of 23.3°. In the absence of the Moon, Lasker and Robutel calculated that the Earth's axis of rotation would vary from 0° to about 85°, and in a chaotic way. Such variations would have had a profound effect on the Earth's climate, its seasons and the length of its days, and it is unlikely that advanced forms of life could have evolved on the planet.

The formation of the Moon and the large outer planets, especially Jupiter, were propitious events in the early history of the Solar System, for they created conditions favourable for the subsequent appearance and evolution of life, and advanced life in particular. The Earth would probably be a very different place without the Moon or Jupiter.

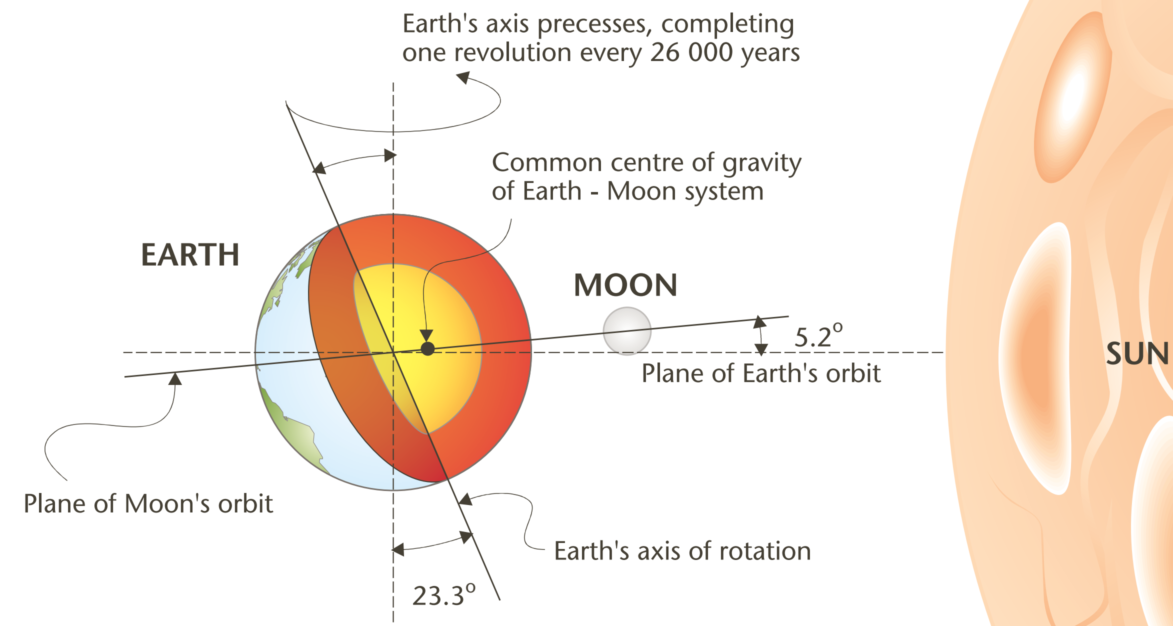


Figure 3.4 ***The Earth and Moon rotate around a common centre of gravity that lies within the Earth but displaced from its centre. This motion has stabilised the inclination of the Earth's axis and protected it from gravitational perturbations induced by other planets.***

MEASURING THE AGE OF A ROCK

Many different, naturally occurring, radioactive chemical elements are employed to measure the ages of rocks. The most common method used to date old rocks employs the radioactive element uranium. There are two kinds of uranium atoms, which are chemically the same, but one is slightly heavier than the other: these are known as isotopes of uranium. Both are radioactive, which means that the atoms are unstable and change or decay into atoms of another chemical element, called the daughter element, over time.

The isotopes of uranium decay to produce different isotopes of lead. The rate of decay is constant, and is called the **half-life**; this is the time it takes for half the atoms in a sample of the material to decay to the daughter element. The half-lives of the uranium isotopes are particularly well known, largely because these isotopes are used for power generation in nuclear reactors and for nuclear weapons manufacture.

Certain minerals incorporate uranium in their structure when they form, but exclude lead. This occurs because of the different chemical properties of uranium and lead. One such mineral is zircon, which is a zirconium silicate. As time passes, uranium atoms in the zircon will decay to lead atoms. These lead atoms are trapped in the crystal structure, even though chemically unsuited to their environment, because the surrounding atoms hold them in place. The longer the time elapsed, the more lead there will be and the less uranium. The time that has elapsed since the zircon formed can thus be calculated from the measured concentrations of the two isotopes of uranium and their respective daughter isotopes present. This gives the age of formation of the zircon.

This method of dating can only be used to date rocks in which the zircon formed at the same time as the rock itself, and is therefore restricted mainly to igneous rocks. Sedimentary rocks cannot be dated in this way, because the zircons they contain come from older rocks.

Uranium dating is unsuitable for very young rocks, because the half-lives of uranium isotopes are very long (thousands of millions of years) and uranium is a rare element, so very little of the daughter isotopes will be present in young zircons. For such rocks, a commonly used method is based on a radioactive isotope of the more common element potassium, which decays to argon. Argon is a chemically unreactive gas, and when a rock forms it contains no argon. Argon accumulates in the rock from the decay of potassium as time passes. The age of formation of the rock is obtained from measurements of the amount of argon and the radioactive isotope of potassium present in the rock.

University of the Witwatersrand

The late Prof Hugh Allsopp was a South African pioneer whose discoveries revolutionised the science of rock dating.

Another well-known method of dating, the Carbon 14 method, is not used in rock dating. The reason for this is that the half-life of the radioactive isotope of carbon is very short, and it is not possible to measure the age of materials older than about 40 000 years.

The methods used to date rocks are simple in principle; in practice they involve complex and expensive equipment and usually special, ultra-clean laboratories for preparation of the samples. There are also many potential sources of error, and great care has to be exercised in selecting samples for dating and in the interpretation of the results. Modern equipment makes it possible to obtain extremely precise ages, with errors of measurement typically better than one part in a thousand.

BROKEN PLANETS AND METEORITES

The region between Mars and Jupiter is characterised by a huge number of orbiting rock fragments, the **asteroids**, representing a planet that failed to form, together with the debris of several planetesimals that were broken up in mutual collisions. The largest of the asteroids is Ceres, 1 000 km in diameter.

Although Jupiter's strong gravitational field in the main protects the inner planets from cometary collisions, it also has a malevolent aspect. Asteroids are sometimes forced off course by the gravitational influence of Jupiter and fly through space, occasionally intersecting the orbit of Earth. When they hit the Earth, the repercussions can be devastating. Some of the consequences of past collisions are discussed later in this book (*see* Chapters 4, 9 and 11).

While hits by large extraterrestrial bodies are fortunately rare, there is nevertheless a constant rain of smaller bodies into the Earth's atmosphere from the Asteroid Belt, as well as cometary debris, which amounts to about 30 000 tonnes per year. Most of these are very small particles that burn up in the atmosphere (forming meteors or shooting stars), but some fragments from the Asteroid Belt are large enough to penetrate the atmosphere and reach the surface. They are known as **meteorites**. Other rare meteorites are derived from material ejected from the surfaces of Mars and the Moon, which themselves have been hit by meteorites and comets large enough to throw material into space.

Thousands of meteorites have been found on Earth and studied in detail, and their age has been measured to be 4 600 million years. A proportion of them are fragments from the cores of broken planets, made of iron and nickel. One example is the famous Hoba meteorite in northern Namibia, which is the largest meteorite known (**figure 3.5**). The majority, however, are fragments of small asteroids consisting

Figure 3.5 *Tens of thousands of bodies, varying in diameter up to 1 000 km, orbit the Sun between Mars and Jupiter. They are known as asteroids. Occasionally small asteroids intersect the Earth's orbit and crash through the atmosphere. We refer to these as meteorites. The asteroids represent a planet that failed to form, as well as the debris of planetesimals that were broken up in mutual collisions. Some of these smashed planetesimals contained nickel-iron cores. The nickel-iron Hoba meteorite near Grootfontein in northern Namibia, shown here, is a fragment of the core of such a body and is the largest known meteorite. The parent bodies of most meteorites formed 4 600 million years ago. Meteorites therefore provide information about conditions prevailing during the formation of the Solar System.*

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mainly of magnesium and iron silicates similar in composition to Earth's mantle, but containing tiny flecks of iron-nickel metal. Unlike the rocks of Earth, meteorites have remained essentially unchanged since they formed about 4 600 million years ago, and have given us a glimpse of the processes that took place in the Solar System as the planets were forming, as well as the nature of the raw material from which our own planet was built.

COOLING AND DIFFERENTIATION OF THE EARTH

In its earliest state the Earth was probably entirely molten, heated by the incessant bombardment of planetesimals as it grew by amalgamating asteroid-like debris from the solar disc under the force of gravity. During its first few tens of millions of years the molten Earth cooled and differentiated into a number of concentric layers – a core, mantle and crust, stratified according to density, with dense iron-nickel metal forming the core. The next few hundred million years of Earth's history saw continued sinking of dense material and the solidification of a thin (less than 30 km thick), lower-density, outer crust.

Throughout this time, though, the Earth (together with the other planets of the Solar System) continued to be bombarded by an intense flux of asteroids and comets, as the Earth's gravitational field swept up solid material in the disc within its orbital region. This ongoing bombardment was responsible for the almost complete destruction of the earliest vestiges of the crust. Those parts of the early crust that were not destroyed by impact events were probably later recycled into the mantle by plate tectonic processes, in particular subduction.

Consequently, there is very little remaining of the rocks that formed in the first few hundred million years of Earth history. This chaotic period of time is referred to as the Hadean Era, derived from *Hades*, the underworld of Greek mythology (i.e. Hell). The oldest terrestrial material that has been dated so far are tiny zircon (zirconium silicate) crystals found in a sedimentary rock from Western Australia, one of which is 4 400 million years old. Although the sediments within which the tiny zircon crystals are found are themselves younger, the existence and age of these grains clearly attests to the presence of Hadean rocks that have subsequently been eroded and obliterated.

In contrast to the Earth, the Moon still preserves much of its very early crust. Rocks brought back by the Apollo and Luna missions to the Moon that have been dated are up to 4 500 million years old. Heavily pock-marked by meteorite impact scars (**figure 3.6**), the Moon is geologically inactive and its early crust remains relatively intact. The Earth would have suffered even more cosmic blows than the Moon as it has a stronger gravitational field, but no trace of this period remains. Only the Moon can provide us with insight into the turbulent events that characterised the very early period of Earth's history (*see* 'Geology of the Moon' on page 74).

The Hadean Earth would not have possessed oceans as it was too hot. As the bombardment waned and the Earth cooled and solidified, water vapour, carbon dioxide and other gases began to form the early atmosphere. These were degassed from the molten interior and possibly augmented by cometary collisions with the Earth. With further cooling, it began to rain as water vapour condensed out of the atmosphere, and the oceans formed. When this happened is not clear. Surface water was definitely present by 3 900 million years ago but may have appeared 300 to 400 million years earlier.

NASA

Figure 3.6 ***The surface of the Moon is very old and still carries the scars of the impacts that characterised the period during which the planets formed.***

THE GEOLOGICAL TIME SCALE

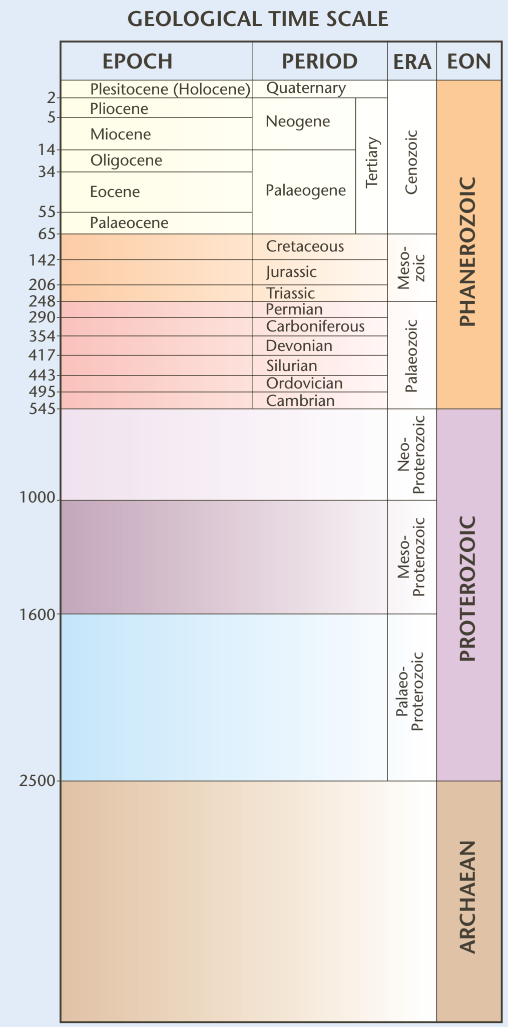
Starting in the 18th century, early geologists in Europe began to produce geological maps. They realised that rocks, particularly sedimentary rocks, could be arranged in order of deposition, i.e. in a relative age sequence. This ordering was based on the stacking of layers, younger on top of older, and on the types of fossils contained in the rocks. They noted that the types of fossils present, which were mainly marine organisms, periodically underwent sudden changes in the varieties of species present. They assigned names to the broad intervals that had similar fossil types, often choosing names from places where rocks of that type were well developed. These names, such as Jurassic and Cretaceous, are still in use today.

The significance of the changes in fossil types was not fully appreciated until Charles Darwin and Alfred Wallace published their theory of evolution. It then soon became generally accepted that the changes in fossils were the result of evolutionary processes. It was realised that long periods of time must have been required to produce these changes, but until the discovery of radioactivity and the development of absolute dating techniques, no one knew how much time was involved.

Dating of rocks using radioactive isotopes has now placed the periods identified by means of fossil types into an absolute time framework. Moreover, dating has also allowed rocks that do not contain fossils to be placed in their correct time slot. Information on both fossil types and age determination has been compiled into a **standard geological column**, or standard geological time scale (*see* diagram, right). The column is divided hierarchically into varying time intervals: **Eons** represent very long periods, **Eras** somewhat shorter periods, and **Periods** and **Epochs** are still shorter.

There are three eons: the **Archaean, Proterozoic** and **Phanerozoic**. Organisms with hard body parts that gave rise to fossils occur only in the Phanerozoic, whereas older rocks contain no fossils, or at best traces of very primitive single-celled organisms. The Archaean and Proterozoic are collectively known as the **Precambrian**. The Phanerozoic is divided into three Eras, the **Palaeozoic** (ancient life), **Mesozoic** (middle life) and **Cenozoic** (recent life), based on fossil types. The subdivision of the Precambrian into Eras is arbitrary. The Phanerozoic Eras are further subdivided into Periods, also based on fossil types.

Sudden changes in fossil types that mark the Era boundaries are now known to be mainly due to sudden mass extinction events, of which the most severe occurred at the end of the Permian, when about 96% of species became extinct. In the more famous end-Cretaceous extinction, which marked the end of the dinosaurs, about 70% of species became extinct.



STRATIGRAPHY

The Earth's crust responds to forces generated in the mantle below, continents moving both laterally and vertically as a result of the action of these forces. At times, continents may be submerged below sea level, and at other times raised and exposed to agents of weathering and erosion. During periods of submersion, sediments will accumulate, resulting in sedimentary rock. Different types of sedimentary rock accumulate, depending, for example, on the rate of subsidence and the rate of sediment supply. There may also be occasional volcanic activity associated with subsidence of the crust. The net result is that periods of subsidence are generally associated with layered accumulations of various types of sedimentary and igneous rocks. Depending on the extent of the area affected by subsidence, these accumulations may be large, extending over millions of square kilometres, or they may be small, covering only tens of square kilometres.

During periods of uplift, weathering and erosion occur, and a previously accumulated pile of sedimentary and volcanic rocks may be partially or completely removed. An uplift event may be followed by later subsidence, during which a new period of sediment accumulation will occur, often depositing sediment on a floor of older, partly eroded sedimentary rock.

By careful mapping of the distribution of sedimentary and associated volcanic rocks, it is possible to identify those formed within the same period of subsidence, and to separate them from accumulations formed during other periods of subsidence. All those rocks deposited during the same period of subsidence belong to a single event, and for convenience are grouped together and referred to as a **Supergroup**.

Supergroups are given names, usually taken from regions where they are particularly well exposed – for example, the Karoo Supergroup, which underlies the Karoo region, and the Witwatersrand Supergroup, whose rocks form the Witwatersrand ridges.

Supergroups thus consist of layers of many different rock types formed during one period of accumulation, each layer representing different conditions of accumulation. The oldest will lie at the bottom of the pile and the youngest at the top in a vertical profile through the pile. During a single period of accumulation, there may be pronounced changes in the prevailing conditions – for example, from persistent deep-water conditions to a prolonged period of shallow-water conditions, followed perhaps by a period of volcanic activity.

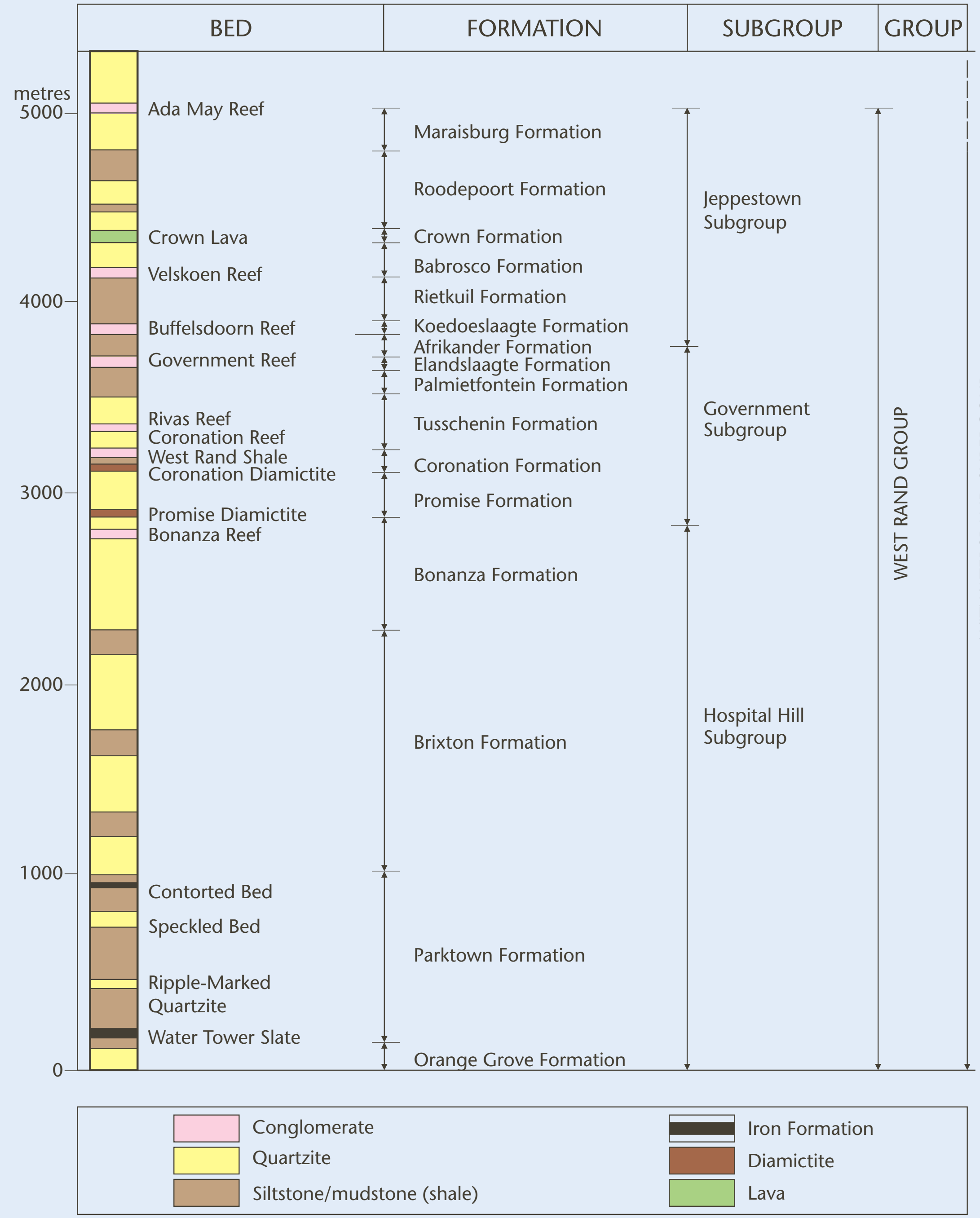
Such changes result in the accumulation of very different types of rocks. It is therefore possible to subdivide the layers making up a Supergroup into smaller entities, based on the types of rocks present. These subdivisions are, in hierarchical order, termed **Groups**, **Subgroups**, **Formations**, **Members** and **Beds**, the last-mentioned representing individual layers. Each of these smaller subdivisions is also given a name, usually the name of the locality where those rocks are best represented. The study of such groups of rocks and their interrelationships is referred to as **stratigraphy**.

The variety of rocks forming a supergroup is conveniently portrayed in diagrammatic form as a vertical column, with the various rock types indicated using different symbols. The oldest layer is placed at the bottom. Vertical heights of symbols on the column are proportional to the thicknesses of the various layers they represent, while the subdivisions are indicated adjacent to the column (*see* diagram, right). Such a diagrammatic representation is known as a **stratigraphic column**.

John Hancox

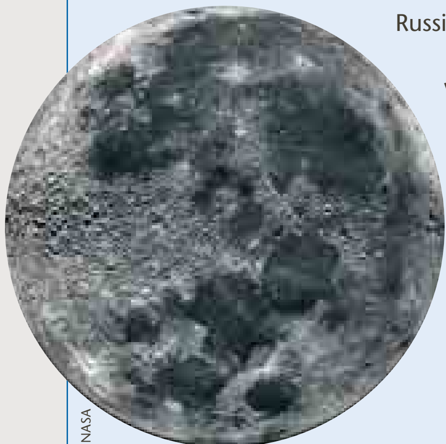
Layered sedimentary rocks of the Karoo Supergroup.

STRATIGRAPHIC COLUMN FOR PORTION OF THE WITWATERSRAND SUPERGROUP.



GEOLOGY OF THE MOON

The geological evolution of the Moon has been pieced together from the study of photographs of its surface, various geophysical studies carried out both from orbiting satellites and on its surface, and from the study of samples brought back by the Apollo astronauts and the Russian Luna missions.



NASA

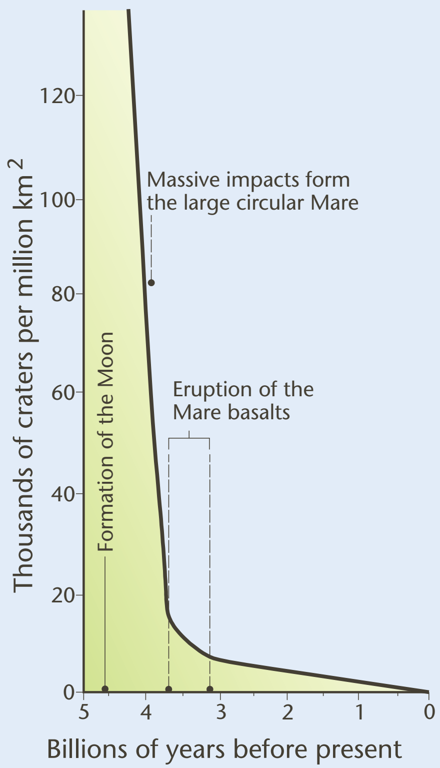
The ancient Lunar Highlands are heavily cratered, while the younger Mare have relatively few craters.

The average density of the Moon is 3.34 g/cm^3 (Earth's is 5.5 g/cm^3), whereas the density of its crust is about 3.0 g/cm^3. The Moon therefore does not have much of an iron core like the Earth, and is thought to consist only of a 1 000-km-thick lithosphere, underlain by asthenosphere about 700 km thick. The Moon is believed to have formed as a result of a collision between the growing Earth and a Mars-sized object, during which a portion of the Earth's embryonic mantle was vaporised and condensed in orbit around the Earth.

The most ancient rocks on the Moon form the very rugged Lunar Highlands and are made of an igneous rock containing abundant calcium feldspar (called anorthosite). These rocks form the paler areas visible on the lunar surface. The Highlands are extremely pock-marked by craters. Highland rocks are up to 4 500 million years old and are believed to represent the early crust that formed during solidification of a once completely molten Moon. The very large number of craters on the Highlands indicates that at this stage of planet formation the rain of space debris was an important geological process.

Around 3 900 million years ago, a number of very large bodies hit the lunar surface, forming gigantic circular basins. Between 3 900 million and 3 100 million years ago, large volumes of basalt erupted and filled these circular depressions, which are visible as the dark areas on the lunar surface. These are known as the Lunar Mare, meaning seas, because early astronomers thought they were seas. Since 3 100 million years ago, relatively fewer impacts have disturbed the Moon's surface. The rate of in-fall of space debris was therefore huge during the first few hundred million years of lunar history, but tailed off quite markedly after about 3 800 million years ago (*see* diagram, right).

It is likely that the Earth experienced a similar history of early crust formation that was accompanied by intense bombardment. The period predating crust formation was probably characterised by a process of aggregation and in-fall of cosmic fragments, the intensity of which was so severe that it resulted in a completely molten Earth. The Moon became geologically inactive soon after its formation and so its ancient initial crust is preserved.



Estimated rate of meteorite fall on the surface of the moon over time.

Carl Anhaeusser

Figure 3.7 *The granodiorite (grey) in this outcrop is the oldest rock in southern Africa, and formed 3 644 million years ago. It is cut by younger granites (pink).*

AGES OF ROCKS

The Earth formed about 4 600 million years ago, and that is the age of the Earth as a whole. The rocks we find on the surface of the Earth are much younger. This may appear paradoxical – a paradox best explained by way of an analogy. We measure our age from the day we were born, but the atoms making up our bodies are much older. Virtually all were present on the Earth when it formed. Many of these atoms were synthesised in stars that existed long before the Earth formed, and most – the hydrogen atoms – date back to the Big Bang itself. So the materials of which we are made are very old. Rocks are just the same. When we measure the age of a rock, we record the time of its formation, although the material from which it is made is much older (*see* 'Measuring the age of a rock' on page 68).

THE ANCIENT CRUST

The oldest known rock on Earth, a granodiorite (a plutonic igneous rock intermediate between a granite and a diorite: *see* 'Classification of igneous rocks' on page 34) from Canada, is 4 100 million years old. The oldest reasonably well preserved crust that clearly represents an identifiable primitive continental landmass is the 3 900- to 3 800-million-year-old Amitsoq terrane of southwest Greenland, which also includes sedimentary rocks. However, this ancient terrane (a region with similar geology and geological history) is highly fragmented and metamorphosed, and does not provide a clear record of events in the early stages of Earth history. Far better preserved are the rocks of southern Africa and Western Australia, where the geological record is remarkably complete.

Barberton Mountain Land

The region in the Mpumalanga Lowveld known as the Barberton Mountain Land has emerged as one of the classic terranes for the study of the Earth's ancient crust, including some of the earliest forms of life. In the mid-1960s the late Al Engel of the University of California at La Jolla wrote:

> *The Barberton Mountain Land offers the geologist a unique opportunity to study the early stages in the evolution of the Earth. There, remnants of the oldest upper mantle, oceanic crust, and an overlying island arc-like rock complex are fossilized in a sea of granite and granitic gneiss ... Studies of these rocks offer deep insight into many aspects of terrestrial differentiation, especially the early evolution of oceanic and continental crusts, the seas, and the atmosphere.*

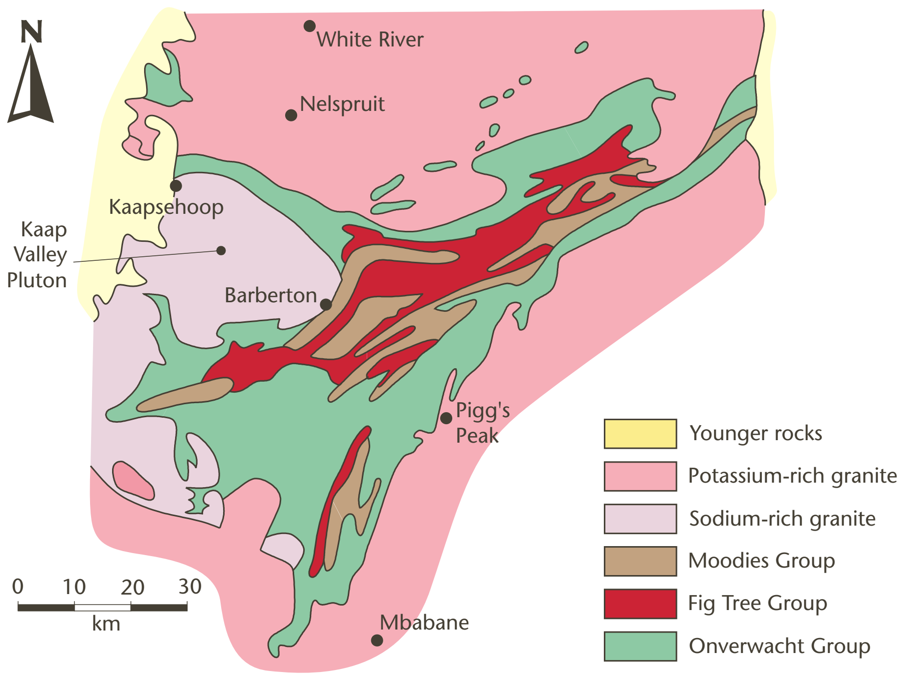


Figure 3.8 ***The rocks of the Barberton region represent the best-preserved example of the Earth's ancient oceanic and continental crust. This crust formed between 3 600 and 3 000 million years ago. Shown here is a geological map of the region. Rocks forming the early oceanic crust have a distinctive green colour. The linear fragments of these rocks, as typified by the Barberton region, are known as greenstone belts. Although originally horizontal, the layers have been folded on themselves, and the oldest now form the outer parts of the belt, while the younger rocks lie in the core. These rocks have been intruded by large bodies of granodiorite (e.g. the Kaap Valley pluton) and granite (the Nelspruit granite batholith).***

These prophetic words are even more appropriate today as numerous studies continue to unravel the secrets of the oldest crustal remnants on Earth. What has emerged is an amazing story, not only of the rocks themselves, but also of the geological environments that prevailed over 3 000 million years ago. This early period of Earth history extending from 4 600 to 2 500 million years ago is known as the Archaean Eon (*see* 'The geological time scale' on page 71).

The rocks of the Barberton Mountain Land consist of two main components: a layered pile of volcanic and sedimentary rocks perhaps 20 km thick, known as the **Barberton Supergroup** (*see* 'Stratigraphy' on page 72). This is enveloped in a sea of granodiorite (**figure 3.7**) and granite batholiths, as illustrated in **figure 3.8** (*see* also 'Geological maps', right). The originally horizontal volcanic and sedimentary rock pile has been folded on itself in the form of a trough and the layers now stand on edge. A stroll across the upturned layers is equivalent to a walk through time as the oldest layers were originally at the bottom of the pile and the youngest at the top. The volcanic and many of the sedimentary rocks are dark green and are therefore commonly referred to as **greenstones** and the entity as a whole as a **greenstone belt** because of its linear form (**figure 3.8**). The granites that surround these rocks are grey to pink in colour and contrast spectacularly with the greenstones.

GEOLOGICAL MAPS

(Note: It is recommended that you read 'Stratigraphy' on page 72 before reading this box.)

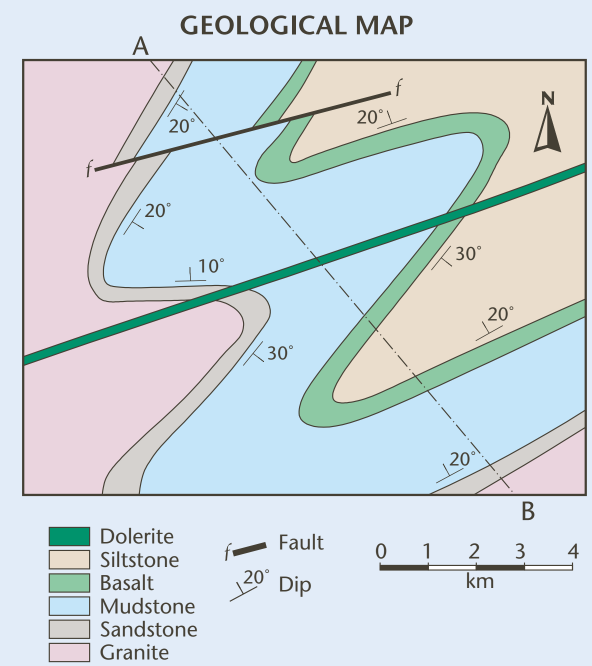
Maps are widely used to convey information about the distribution of some feature over a particular region. The scale of a map is usually stated in relative distances: for example, a scale of 1:50 000 means that a distance of 50 000 cm (i.e. 500 m) on the ground is represented by 1cm on the map. The scale of a map is also often indicated by a scale bar.

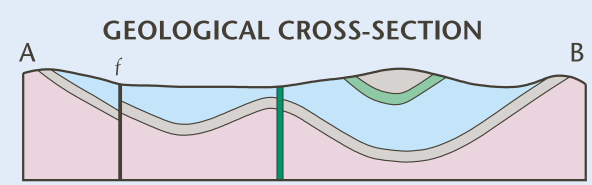
Geological maps are used to portray the distribution of rocks beneath the soil. Detailed maps show the distribution of individual rock types, denoted on the map by different symbols or colours. This cannot be done if the map is to cover a large area, such as an entire country, for example. For such maps, we need to group rock types together. This grouping is done using the principles of stratigraphy (*see* page 72). Detailed maps show each individual bed (i.e. rock type), whereas less detailed maps show only Groups or perhaps only Supergroups. Geological maps also have a **legend** that provides information as to the meanings of colours or symbols used on the map. The rock types on the legend are usually arranged vertically in order of age, the youngest at the top. The stratigraphic affiliation of the various rocks, if known, is normally also given in the legend.

Rocks often are deposited in horizontal layers (e.g. sedimentary rocks) or have some kind of layering associated with them. Earth movements may result in disturbance of the layers, which may vary in intensity from simple tilting to intricate folding. Where tilting of layers has occurred, information about the attitude of the layers is also usually included on geological maps. This takes the form of an arrow denoting the direction in which the layers **dip**, together with the angle, measured from the horizontal, at which they dip, and a line perpendicular to the direction of dip, known as the **strike**.

Knowledge of dip and strike allows one to interpret what happens to layers below the Earth's surface. For example, knowledge of the dip and strike of a gold-bearing rock layer will allow an estimate to be made as to how deep below surface the layer will occur some distance from the place where it crops out on surface. Thus, a geological map together with dip and strike information, enables the construction of geological cross-sections (*see* diagrams, right).

Rock layers may also be disturbed by **faults**. As a result, rock layers become displaced so that they are no longer continuous on a map. Displacements can be very large, often exceeding many kilometres. Faults are therefore also included on geological maps.





An example of a geological map and an interpretive geological cross-section.

The oldest rocks in the Barberton Supergroup consist of a stack of volcanic rocks approximately 7 km thick. This forms the lower part of the **Onverwacht Group**, one of the three major divisions of the Barberton Supergroup, the other two being the largely sedimentary **Fig Tree** and **Moodies Groups** (**figure 3.9**)

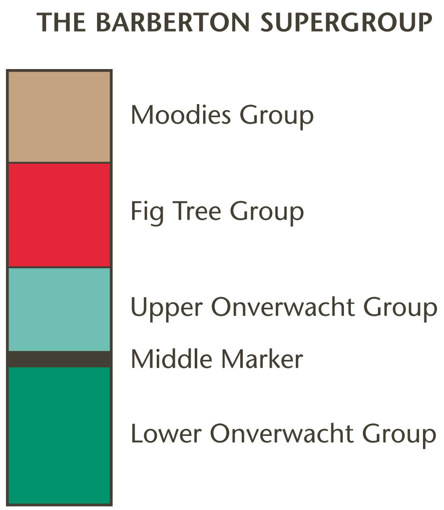


Figure 3.9 ***The layered rocks forming the Barberton greenstone belt have been subdivided into discrete packages. The oldest (lowermost) package is known as the Onverwacht Group, and consists of two parts. The lower part is made up of a volcanic rock known as komatiite and represents former oceanic crust. It is separated from the overlying volcanic rocks by a layer of sedimentary rock consisting of iron oxide and silica, the Middle Marker, which formed on the ocean floor. The upper part of the Onverwacht Group consists of basalt and dacite. It formed at a subduction zone when rising magma erupted on the sea floor, burying the sediment layer. Sediment also accumulated in deep-water trenches associated with the subduction zone to produce the distinctive layered turbidites of the Fig Tree Group. Finally, as the early continent began to grow, and rose significantly above sea level, eroded material was deposited in rivers and shallow water around the early continent, forming the Moodies Group of rocks. These consist of conglomerates (gravels), sandstones and mudstones.***

The volcanic rocks found in the lower Onverwacht Group are related to basalt but have a distinctive chemical composition. They were recognised as a new class of rock in 1969 by twins Morris and Richard Viljoen, then students at the University of the Witwatersrand. These rocks, which were first discovered in the Komati River valley east of Badplaas in the southern part of the Barberton greenstone belt, have appropriately been named **komatiites** (**figure 3.10**) and are now recognised around the world in most localities where ancient greenstone sequences are preserved.

The komatiites poured out as lavas in Archaean oceans some 3 600 to 3 200 million years ago, forming primitive oceanic crust. They commonly show pillow structures (**figure 3.10**) like those on modern ocean floors. Moreover, the komatiitic flows were locally buried from time to time by ocean floor sediments consisting of iron- and silica-rich mud. The komatiites have a unique chemical composition rarely found in younger volcanic regions. What makes them unique is their high content of magnesium. Melting experiments have shown that rocks of this type must have formed at temperatures ranging from about 1 300°C to 1 650°C. In today's world, the highest temperature attained by basaltic lavas erupting on ocean floors seldom exceeds about 1 200°C. This temperature difference suggests that the Archaean volcanic rocks developed from a mantle decidedly hotter than that existing today, and that the Earth has cooled significantly over the past 3 000 million years.

The Middle Marker

The sea-floor sediments that accumulated after the komatiite eruptions had ceased consolidated to form a distinctive, widespread layer of sedimentary rock referred to as the **Middle Marker**. This rock consists of iron oxide and carbon- and silica-rich chert layers (*see* 'The formation of sedimentary rocks' on page 64) together with layers of calcium carbonate. These ancient rocks tell us that in spite of its hotter interior, the Earth already possessed oceans 3 500 million years ago, and like the oceans of today they contained abundant calcium carbonate. It is not possible to determine the precise environment in which the komatiite lavas erupted; all we can deduce is that they formed by volcanic eruptions under the sea. This activity persisted for some time, building up a thick pile of pillow lavas. Then it ceased and a layer of sediment buried the lavas.

It is tempting to interpret these events from what we know about modern-day plate tectonic processes (*see* Chapter 2). Komatiites resemble modern ocean-floor basalts and were possibly erupted at a mid-ocean ridge where new oceanic crust was being formed. At that time, komatiite rather than basalt would have been the main rock type of the oceanic crust because the Earth was hotter. As newly formed crust moved away from the ridge on the ocean floor conveyor, volcanic activity ceased and sediment began to accumulate on the sea floor, burying the komatiite pillow lava. This sediment became the Middle Marker. The package of rocks was carried laterally, conveyor belt-style, until it encountered a subduction zone.

This interpretation of the sequence of events that produced the rocks of the lower Onverwacht Group is plausible, but by no means proven, and there are other interpretations. Research continues on this interesting period of Earth's history and no doubt our understanding of the story these rocks have to tell will improve with time.

The rock pile overlying the Middle Marker, also approximately 7 km thick, forms the upper part of the Onverwacht Group. It consists of a variety of volcanic rocks, including basalt and dacite, somewhat similar to those found in modern-day island arcs. It seems that the early oceanic crust was subducted into the upper mantle, driven by rapidly convecting, small-scale convection cells in the hot upper mantle. Subduction of the oceanic crust led to partial melting and the production of basalt and granodiorite magmas. Some of this erupted onto the ocean floor, burying and preserving it (**figure 3.11**), while most of the granodiorite crystallised in the crust to form batholiths and plutons (*see* 'Igneous intrusions' on page 46). These volcanic and plutonic rocks constituted the Earth's early island arcs. There is rather more basalt in the upper Onverwacht Group than in modern-day island arcs, possibly also a consequence of the hotter mantle in the past.

Associated with these ancient island arcs of the Archaean oceans were trenches that formed as

Carl Anhaeusser

Figure 3.10 ***Although the Earth's surface temperature 3 500 million years ago was much the same as today, its interior was hotter when the rocks of the Barberton region were forming. A very distinctive rock type related to basalt, known as komatiite, erupted to form the early oceanic crust. Eruption processes produced bulbous forms known as pillow lava, shown here, just as undersea eruptions do today.***

oceanic crust cascaded downwards into the mantle. As the volcanic islands began to emerge from the seas adjacent to the trenches, they underwent rapid erosion. The eroded sediment was dumped into the trenches (**figure 3.11**), where it accumulated as very distinctive, fine-grained and layered sedimentary deposits known as **turbidites** (*see* 'Sedimentation in ocean trenches' on page 82).

In the Barberton greenstone belt these sedimentary rocks began forming more than 3 400 million years ago, leading to the development of a 2.5-km-thick, predominantly sedimentary pile known as the **Fig Tree Group**. Most of the Fig Tree sedimentary rocks consist of sandstones, siltstones and mudstones, the mudstones very often black in colour due to the presence of abundant carbon (in the form of graphite). These carbonaceous sediments formed in an environment where virtually no free oxygen was present. Nevertheless, there are indications that

BARBERTON REGION: FORMATION OF EARLY OCEANIC AND CONTINENTAL CRUST

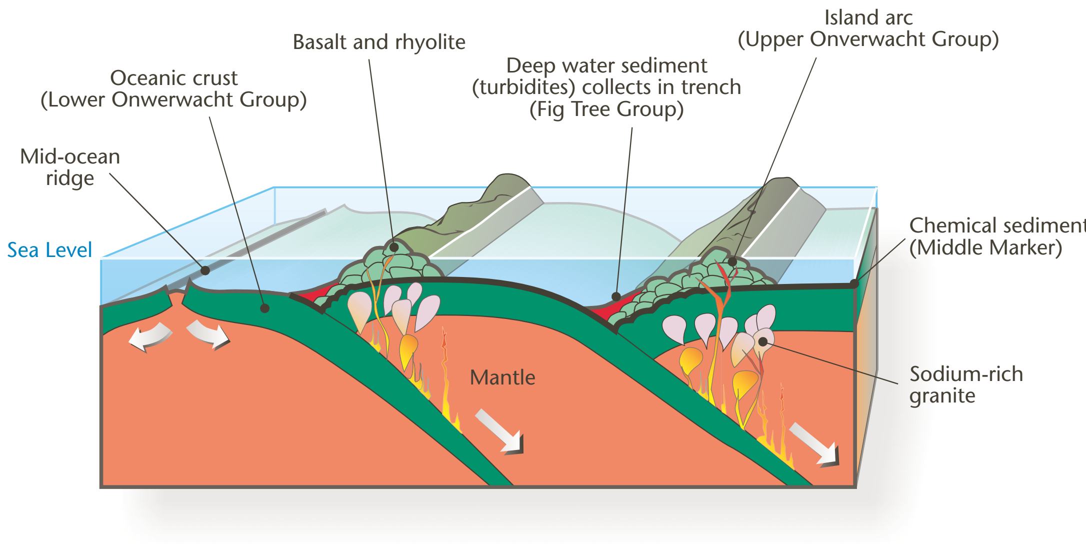


Figure 3.11A *Komatiite magma intruded into the axis of a mid-ocean ridge (left side of figure), forming pillow lavas and new oceanic crust (Lower Onverwacht Group). As this crust moved away from the ridge, the pillow lavas became buried by a layer of chemically precipitated iron oxide and silica (Middle Marker). Oceanic crust was simultaneously being subducted, and water released caused local melting, producing basalt and granodiorite magmas, some of which erupted on the ocean floor, burying the Middle Marker (Upper Onverwacht Group). Granodiorite magma also crystallised in the crust, forming plutons (e.g. Kaap Valley pluton). The volcanoes emerged from the sea, forming ancient island arcs. Sediment eroded from these islands was deposited in adjacent ocean trenches to form the Fig Tree Group.*

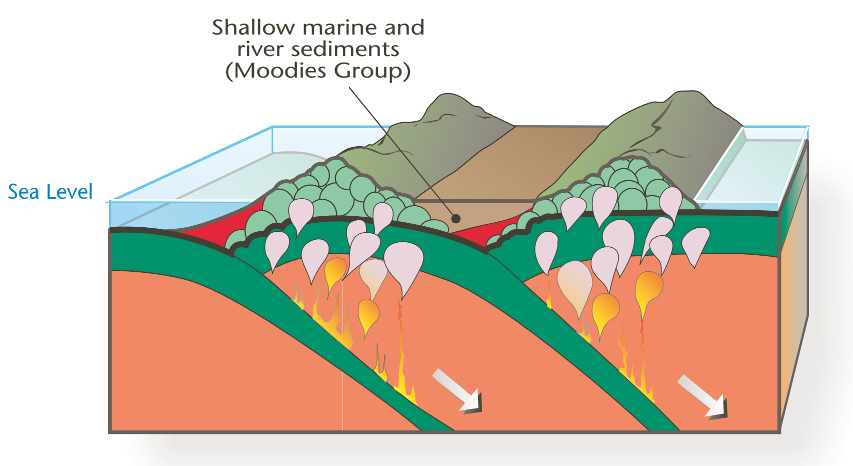


Figure 3.11B *The granodiorite plutons rendered the island arcs buoyant, and they could not be subducted. Collision of arcs resulted in amalgamation and crustal thickening, forming the first micro-continents. Sediment shed by the amalgamated and now deeply eroded island arcs included pebbles of granodiorite and abundant sand that was deposited in rivers and shallow seas on and around these growing micro-continents. These sediments are represented by the Moodies Group.*

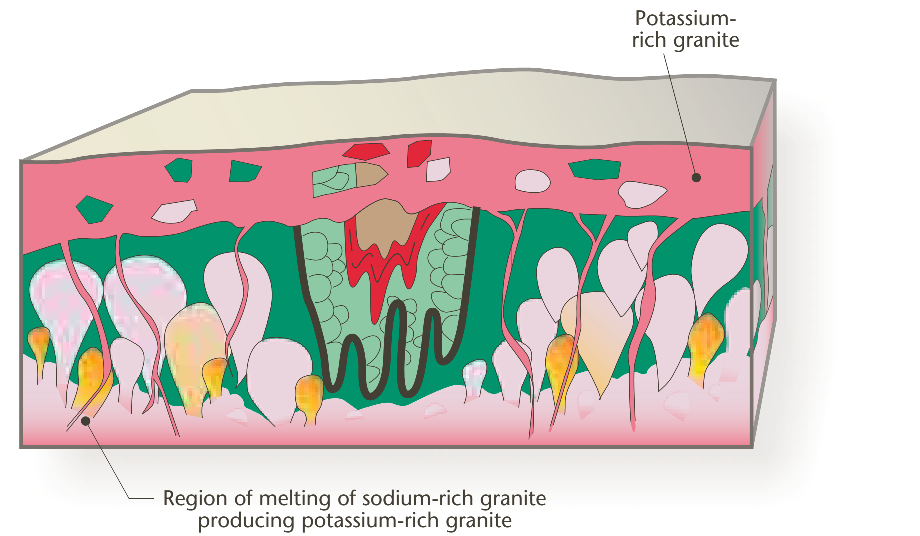


Figure 3.11C *Thickening of the crust caused melting of the more deeply seated granodiorites, producing granite magmas. These intruded upwards and collected as extensive, sheet-like batholiths.*

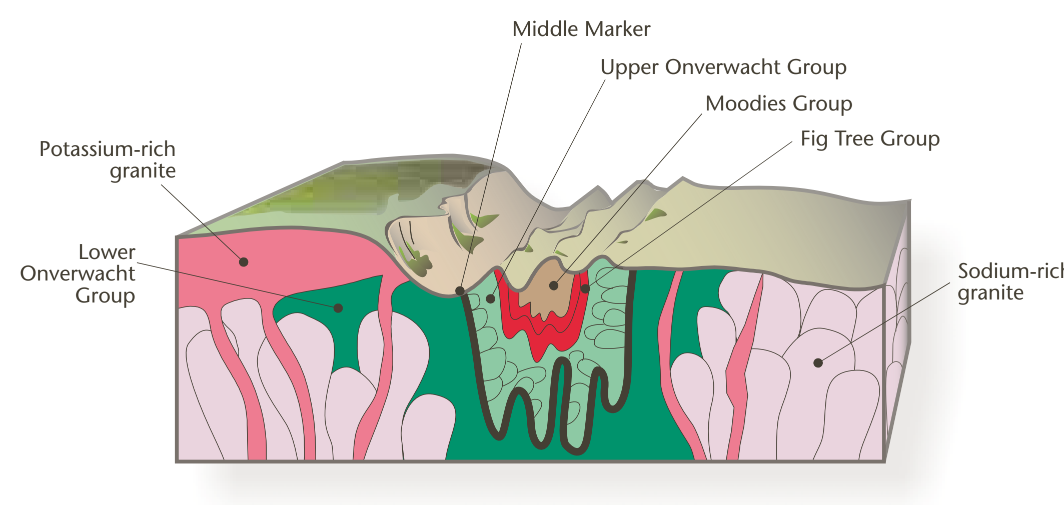


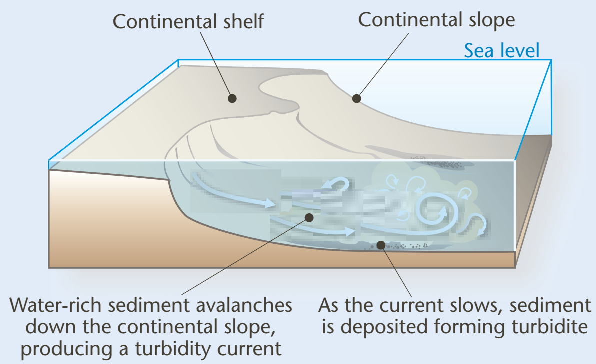
Figure 3.11D *Recent erosion of portions of the granite batholiths has exposed the underlying greenstone belt and its associated granodiorite plutons.*

SEDIMENTATION IN OCEAN TRENCHES

Sediment is delivered to the oceans by rivers, and it generally accumulates on the continental shelf (*see* 'Sedimentation on continental shelves' on page 100). Sand collects in the near-shore environment, silt and mud further out to sea. Sediment can accumulate to great thicknesses and may become unstable; it can collapse in an undersea avalanche down the continental slope. Instability is often triggered by earthquakes.

Undersea avalanches are termed **turbidity currents** and consist of a mixture of sediment and water. Initially, they accelerate down the slope, but slow down at the base of the slope, where they deposit the contained sediment. Coarser sediment deposits first, followed by increasingly finer sediment. The result is a layer of sediment at the bottom of and beyond the slope that is relatively coarse at its base (usually fine sand) and fine (mud) at its top. The thickness depends on the volume of material in the turbidity current, but is seldom more than a metre, usually tens of centimetres.

Each turbidity current produces a separate layer. Sedimentary deposits formed at the base of the continental slope therefore consist of a stack of these size-graded layers, called **turbidites**. The frequency with which turbidity currents occur depends on many factors, such as the width of the continental shelf, the rate of sediment supply to the shelf, and earthquake activity. Trenches that form at subduction zones experience frequent turbidity currents. Landward of the trench is a mountain belt or island arc, where erosion is rapid, so large quantities of sediment are supplied to the shelf. The shelf is typically narrow, so there is not much space to accommodate the sediment and these areas experience frequent earthquakes. The net result is frequent turbidity currents, which produce a very distinctive pile of size-graded layers of sediment in the trench.



John Hancox

Sediments deposited by turbidity currents formed these well-layered rocks in the southern Karoo.

Carl Anhaeusser

Uwe Reimold

Figure 3.12 *Several layers consisting of small spherules, such as illustrated above, have been found in the Fig Tree Group. The spherules originally consisted of glass and were produced by melting of the crust during very severe meteorite impacts. Five such layers have so far been found, indicating that major meteorite impacts were still relatively common 3 300 million years ago.*

life was already flourishing at that time. Primitive organisms, possibly including photosynthesising cyanobacteria, were growing in the shallow water around the volcanic islands. Their growth produced domical structures known as **stromatolites** (*see* 'The formation of sedimentary rocks' on page 64) and they left scattered replicas of their cells in the form of microfossils. This is discussed further in Chapter 6.

By Fig Tree times, the rate of meteorite in-fall had declined markedly (*see* 'The geology of the Moon' on page 74), but there is evidence to suggest that impacts were still common. South African mineralogist Sybrand de Waal has identified strange nickel-rich, iron minerals in the Barberton area that may be oxidised fragments of a nickel-iron meteorite. In addition, geologists from Stanford University, led by Don Lowe, have found several (at least five) sedimentary layers in the Onverwacht and Fig Tree Groups made up entirely of small spheres (**figure 3.12**). The spheres appear very similar to the droplets of molten rock produced by large meteorite impacts, an observation confirmed by chemical evidence.

In all cases, the meteorites impacted on komatiitic or basaltic crust. Lowe is of the opinion that all of the layers located thus far reflect impacts more severe than the one that wiped out the dinosaurs 65 million years ago and could have been made by objects ranging in diameter from 20 to 50 km. A spherule layer of identical age to one in the Onverwacht Group has recently been found in similar rocks in the Pilbara region of Western Australia, and Lowe believes the layers were formed by the same impact, which occurred 3 465 million years ago. There is no evidence of craters, however, but the rocks have been so folded and buckled that we would be unlikely to recognise a crater even if it was present.

THE BEGINNINGS OF A SOUTHERN AFRICAN CONTINENT

As is the case with modern plate tectonic activity, granodiorite magma was produced at sites of Archaean subduction and island-arc formation. Some erupted as lavas on the ocean floor, while the remainder crystallised in the crust to form batholiths (**figure 3.11**). Once this type of primitive crust formed it was not easily destroyed, as the rocks are of lower density and thus more buoyant than the volcanic rocks of oceanic floor and mantle. This prevents their subduction.

Instead, plate tectonic processes began to cause amalgamation of island arcs. Fusion of island arcs created micro-continents made predominantly of granodiorite, which rose above sea level. Weathering and erosion of exposed rock produced sediment that was transported by rivers to accumulate in shallow water around the edges of the micro-continents (**figure 3.11**). Here it formed conglomerates (gravels) and sandstones (sand), while mudstones (mud) and banded iron formations (a chemical precipitate of iron oxide and silica) accumulated in deeper water (*see* 'The formation of sedimentary rocks', page 64).

These types of sedimentary rocks form the uppermost portion of the Barberton Supergroup in another 2.5 km-thick pile of rocks known as the **Moodies Group**. Still preserved in these 3 200-million-year-old rocks are sedimentary structures such as cross-bedding and ripple marks identical to those that are seen forming today, as illustrated in **figure 3.13** (*see* 'Sedimentary structures' on page 86). Some of these structures indicate that the sediments were deposited in basins influenced by tidal activity. This affirms that the Moon, from time immemorial, has exerted a significant gravitational influence on our planet and that the water bodies of the Archaean were not lakes but true oceans. Studies of tide-generated layering in sedimentary rocks of the Moodies Group by Ken Eriksson from Virginia and his students have revealed that the spring tide-neap tide interval was only nine days long, indicating an 18-day lunar month. This implies that the Earth was rotating more rapidly, so day length was shorter than today and there were more days per year.

At that time there were no terrestrial plants. The atmosphere was very different from today: there was little or no free oxygen, and water vapour, carbon dioxide and nitrogen made up the bulk of the atmosphere. Atmospheric pressure was considerably higher (*see* Chapter 6). Carbon monoxide, ammonia and even hydrogen cyanide and hydrogen sulphide may also have been present.

This atmosphere was probably far more chemically aggressive than today, rapidly decomposing rocks with which it came into contact. Without the stabilising effect of vegetation, no soils could have formed and decomposing rock would have been quickly eroded by rain, streams and rivers. Rocky outcrops would undoubtedly have dominated the continental landscape.

CONSOLIDATION OF THE EARLY CONTINENT

As the earliest micro-continents amalgamated they were subjected to continuing magma addition, with more granodiorite being added. The earliest granodiorites, like those found in the Barberton-Swaziland region (**figure 3.7**), range in age from about 3 600

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Figure 3.13 ***Ripple marks preserved in 3 200-million-year-old sedimentary rocks of the Moodies Group. The layers were originally horizontal but are now vertical due to folding.***

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Figure 3.14 ***Mixed rocks called migmatites formed during the intrusion of granodiorite magma into older volcanic rocks.***

to 3 200 million years, and they are chemically distinctive, having a high sodium content. By contrast, the later granitic rocks in this region are potassium-enriched and range from about 3 100 to 2 700 million years in age. These rocks were added incrementally to the growing continent.

The granodiorites generally appear on geological maps as circular or oval-shaped plutons, which invaded the greenstone belts from below like rising hot-air balloons, probably while partly solid. This upward emplacement style (or **diapirism** – analogous to the rising globular blobs in novelty lava lamps) caused considerable structural disturbance to all the rocks in the region immediately surrounding them.

The greenstones became folded on themselves as they sank into the cusps between the rising plutons. Rocks along the margins of the plutons became intensely folded, forming **gneisses**. Pieces of the surrounding rocks torn off by the intrusions were heated and plastically transformed into complex, mixed rocks known as **migmatites** (**figure 3.14**). The largest intrusion of this type, the Kaap Valley pluton, is responsible for the circular, approximately 30-km-diameter De Kaap valley near the historical gold mining town of Barberton (**figure 3.8**).

The later granitic rocks occur in the form of massive, sheet-like batholiths. Some of these bodies – such as the Nelspruit batholith north of Barberton, the Mpuluzi batholith southeast of Badplaas and the Pigg's Peak batholith in Swaziland – exceed 60 km in diameter. The magmas appear to have formed by remelting of the earlier granodiorite as the crust thickened. They intruded through the older rocks and spread out as extensive, horizontal sheets (**figure 3.11**). These various additions of granite, which began to develop approximately 3 200 million years ago, progressively stabilised the continental crust. The stabilisation was aided by the formation of a thick keel in the mantle beneath the early continental crust.

At a still later stage, between about 3 000 and 2 700 million years ago, the Archaean crust was again intruded by a few smaller granite plutons that represented the final stages of continent development

SEDIMENTARY STRUCTURES

Most sedimentary rocks are formed by deposition of sediment from flowing or standing water. At the time of deposition, certain features may form in the sediment that are preserved in the resulting rock. These are known as sedimentary structures, and often provide useful information about the conditions under which deposition occurred.

STRATIFICATION

Sedimentary rocks are often stratified or layered, known as **bedding**. Each layer or bed usually represents an increment of deposition. For example, in glacial lakes that freeze over in winter, the bottom sediment shows pronounced layering: during the summer thaw, melt-water streams deposit silt in the lake, while during winter very fine sediment slowly settles from the water column. These seasonal changes produce alternating mud and silt layers, known as **varves**.

Pronounced layering also develops in the sedimentary deposits on the beds of lakes fed by rivers which experience periodic flooding. Under normal conditions, fine sediment rich in organic matter accumulates, but during a flood, a layer of coarser silt will be deposited on the lake bed. As the flood wanes, finer and finer material is deposited, so the layers formed by a flood become finer upwards through the layer, called **graded bedding**. Graded bedding also forms in sediment layers deposited by turbidity currents (*see* **A**, right, and 'Sedimentation in ocean trenches' on page 82).

Sand is usually transported along the bed of a stream or across a beach by water or wind, and often moves as a series of parallel ripple structures. Particles are eroded from behind each ripple, are carried up its back, and then avalanche over the crest to form a relatively steep face to the ripple. Gradually the ripple advances while others follow behind (**B**). The surfaces that were eroded (that is, behind the ripple) form flat layers or **beds**.

Within each of these beds the lower part of the sloping avalanche face is usually preserved. These sloping surfaces form **cross bedding** (**C**), which is useful because it gives information on the direction of current flow during sediment deposition. In sand deposited under the influence of tides, the cross beds will slope in opposite directions in alternate beds. The thickness of a cross-bedded layer can range from a few centimetres for small ripples, to a metre or more for dunes that form in large rivers, to tens of metres for wind-blown sand dunes such as those in the Namib Desert (**D**).

SURFACE FEATURES

Ripple-covered bedding surfaces are often preserved in sedimentary deposits. When the rock is exposed, it may break apart along such surfaces, exposing the fossil **ripple marks** (**E**). Muddy sediment deposited on a riverbank usually dries in the sun and cracks due to shrinkage. A flash flood may deposit sand over the mud-cracked surface, filling the cracks with sand and depositing a layer of sand over the mud. This too can be exposed during subsequent erosion, producing fossil **mud cracks** (**F**).

Coastal mudflats form in areas protected from wave action where there is a supply of fine sediment. At low tide, the muddy surface is exposed, but this is submerged as the tide comes in. In hot, arid climates, sea water in the mud evaporates and salt crystals form little cubes at the sediment surface. The crystal shape is occasionally preserved in the sedimentary rock, forming **salt casts** (**G**).

Another feature occasionally observed on bedding surfaces are tracks and burrows left by animals of various kinds (including humans). These are known as **trace fossils** (**H**). Isolated raindrops falling on soft mud usually form small indentations, known as **raindrop impressions**. These too can become buried and preserved (**I**).

By mapping out the types of sedimentary rocks present in a particular area and examining the sedimentary structures they contain, it is possible to reconstruct the geographical environment that existed at the time the sediment layers were laid down.

Graded bed, with conglomerate at the base grading up to mudstone at the top

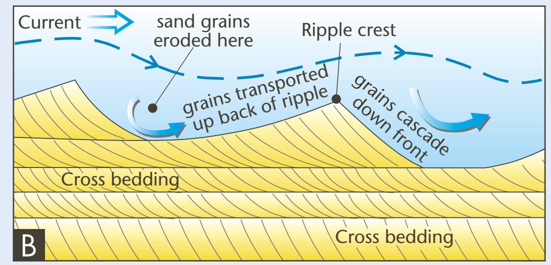

Diagram showing how cross bedding forms

Cross bedded sandstone

©Terence McCarthy

Very large cross bedding in wind-blown sand in the Namib Desert

Fossilised ripples in a sandstone

Fossilised mud cracks

Salt casts

Fossilised animal tracks

Fossilised raindrop impressions (right) and modern-day equivalents (left)

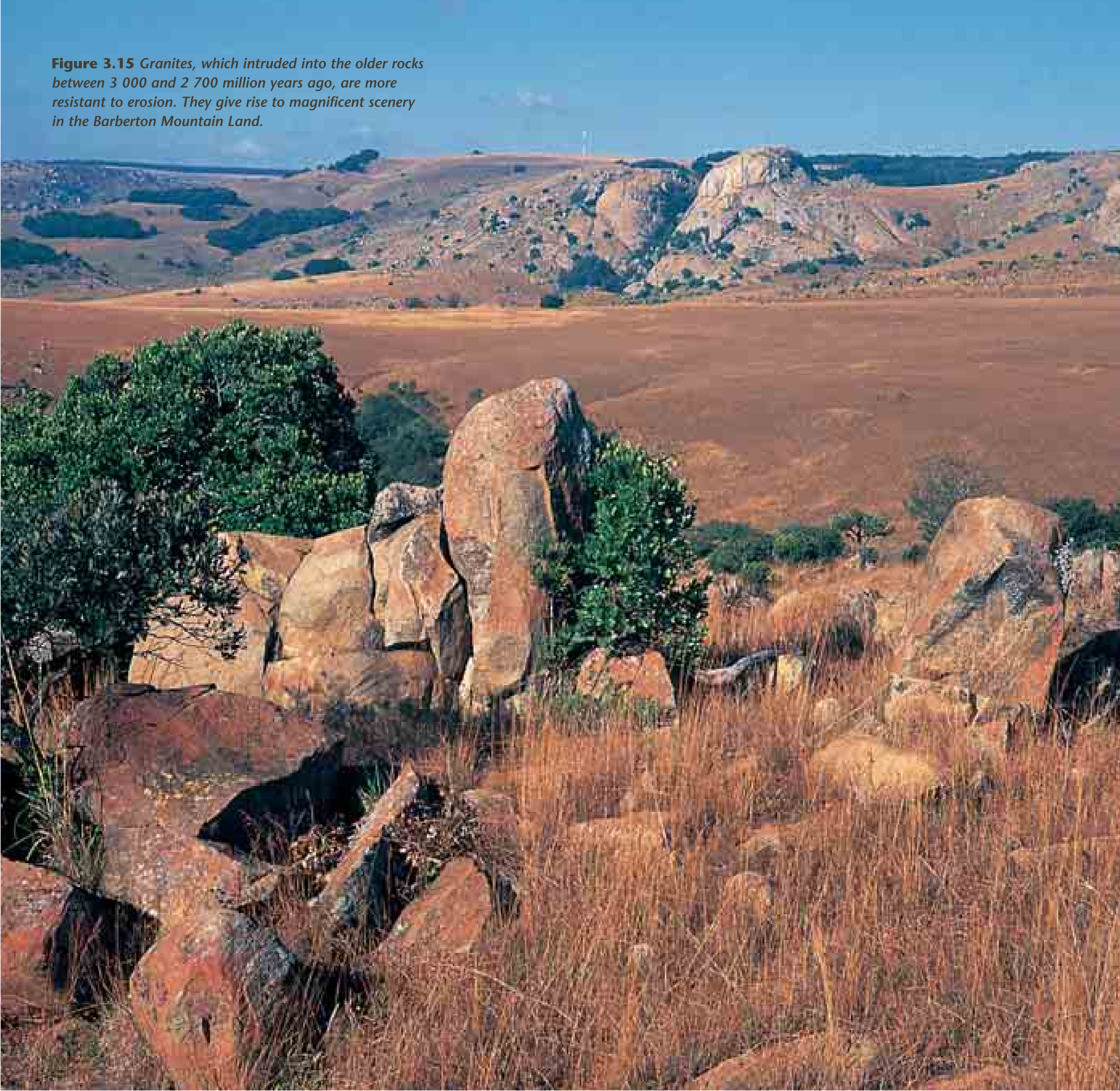

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Figure 3.15 *Granites, which intruded into the older rocks between 3 000 and 2 700 million years ago, are more resistant to erosion. They give rise to magnificent scenery in the Barberton Mountain Land.*

in the region. These plutons – such as the Mpangeni pluton in the Crocodile River gorge east of Nelspruit and the Mbabane pluton in Swaziland – today give rise to some spectacular scenery (**figure 3.15**).

In the Barberton Mountain Land we see fragments of the oldest known oceanic and continental crust. As the micro-continent grew, more island arc material was added on the northern side, along with other fragments of ancient ocean floor. Today these later additions can be seen as northeasterly trending linear greenstone belts, such as the Murchison Range, Pietersburg and Sutherland-Giyani belts in the Limpopo Province (**figure 3.16**). Crustal material was also added on the western side of the continent, producing linear belts such as those at Amalia and Kraaipan in the North West Province. Remnants of ancient oceanic crust in a sea of granodiorites, granites and gneisses can also be seen between the Witwatersrand and Pretoria, especially in the Muldersdrif area. These linear greenstone belts possibly mark the boundaries or sutures between amalgamated micro-continental fragments (**figure 3.17**).

A remarkable aspect of this early continent is that once formed, its rocks have remained essentially unchanged for 3 000 million years. Such blocks of ancient crust, with their distinctive greenstone-granodiorite-granite association, have been termed **cratons** to distinguish them from later-formed continental crust. Although most of this ancient craton, which is known as the **Kaapvaal Craton**, is buried beneath younger rocks, it forms the core of southern Africa (**figure 3.17**). This ancient continent was originally probably much larger – we have no idea how large – but has lost pieces by later rifting. The Pilbara region of Western Australia, as well as portions of Madagascar and India, probably once formed part of the Kaapvaal Craton (see Chapter 5). Cratons similar to Kaapvaal formed at about the same time or slightly later elsewhere on the globe, and terranes like those of the Barberton and Pilbara regions occur in other parts of Africa, Greenland, Antarctica, Canada, Finland, Brazil and Siberia.

THE SIGNIFICANCE OF THE BARBERTON MOUNTAIN LAND

The rocks of the Barberton area preserve a record of the formation of the Earth's first sizeable continent. However, there is a long gap in Earth's early geological record from the formation of the Earth 4 600 million years ago to the creation of the early crust in the

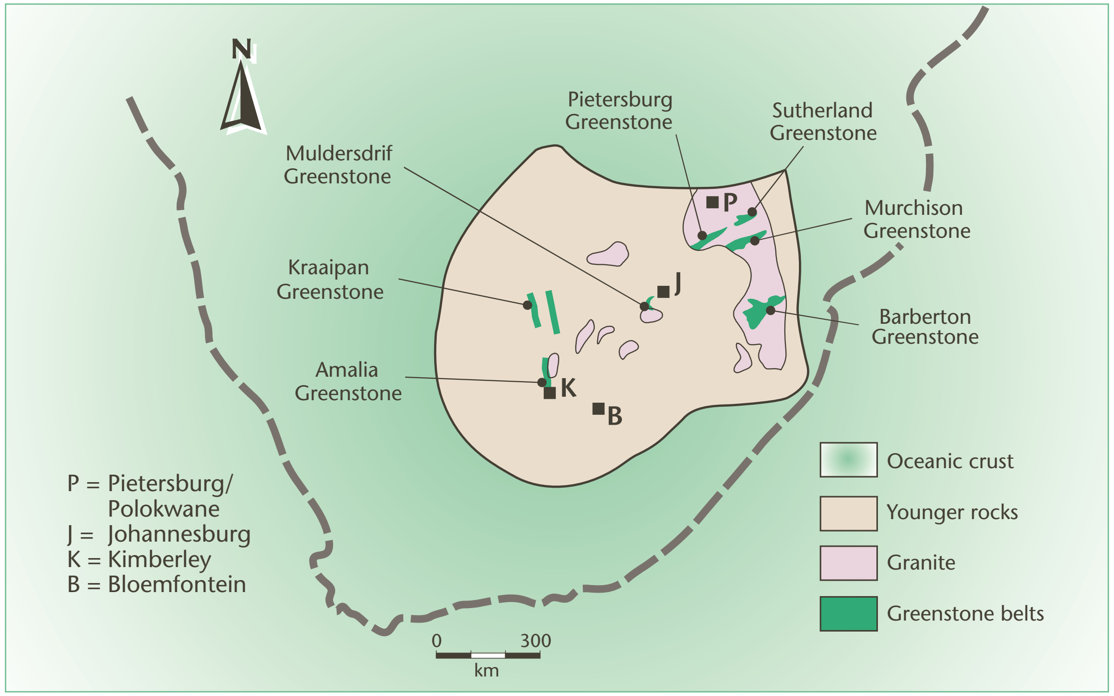

Figure 3.16 *The micro-continent represented by the rocks of the Barberton area continued to grow by the accretion of similar terranes on the northern and western flanks. They are marked by rocks similar to those in the Barberton area. Accretion produced a small continent – the Earth's oldest – known as the Kaapvaal Craton. Much of it is today buried under younger rocks, as illustrated. It was originally much larger, but the eastern section has been separated by later rifting. (The coastline of South Africa and the locations of cities are shown for reference.)*

Barberton region. Events in the earlier portion of this time gap have been pieced together from the study of the Moon and indicate an extremely violent and hot beginning to Earth history. Initially, bombardment from space was the dominant process, but decreased in intensity over the first 500 million years. No clear evidence of this violent period remains on Earth, but as on the Moon, which still carries the scars of bombardment, it is likely that a crust formed during this period.

Recycling of the remnants of this ancient crust, probably by plate tectonic processes, seems to have started more than 4 000 million years ago. Evidence for this is provided by 4 100-million-year-old granitic rocks, commonly produced at subduction zones, that have been found in Canada, as well as the 4 000- to 4400-million-year-old zircons found in Western Australia. These have chemical characteristics indicating that they were derived from continental crust.

Rocks of the 3 900-million-year-old Amitsoq region of west Greenland contain banded iron formation, indicating that surface water, possibly even oceans, existed on Earth by that time. But because of their superb preservation, the rocks of the Barberton region provide the first glimpse of the large-scale geological processes involved. When these rocks were forming, the Earth differed in important ways from today. Its interior was hotter, while its surface temperature was much the same as today, sustaining oceans. The temperature gradient in the Earth would therefore have been greater, perhaps leading to a more vigorous form of plate tectonics, with far smaller plates.

Island arcs may have been more abundant, and rapidly amalgamated, forming the first micro-continents. The variety of granite types is greater in these ancient terranes compared to today, and the early period of granodiorite, followed by later granite, is

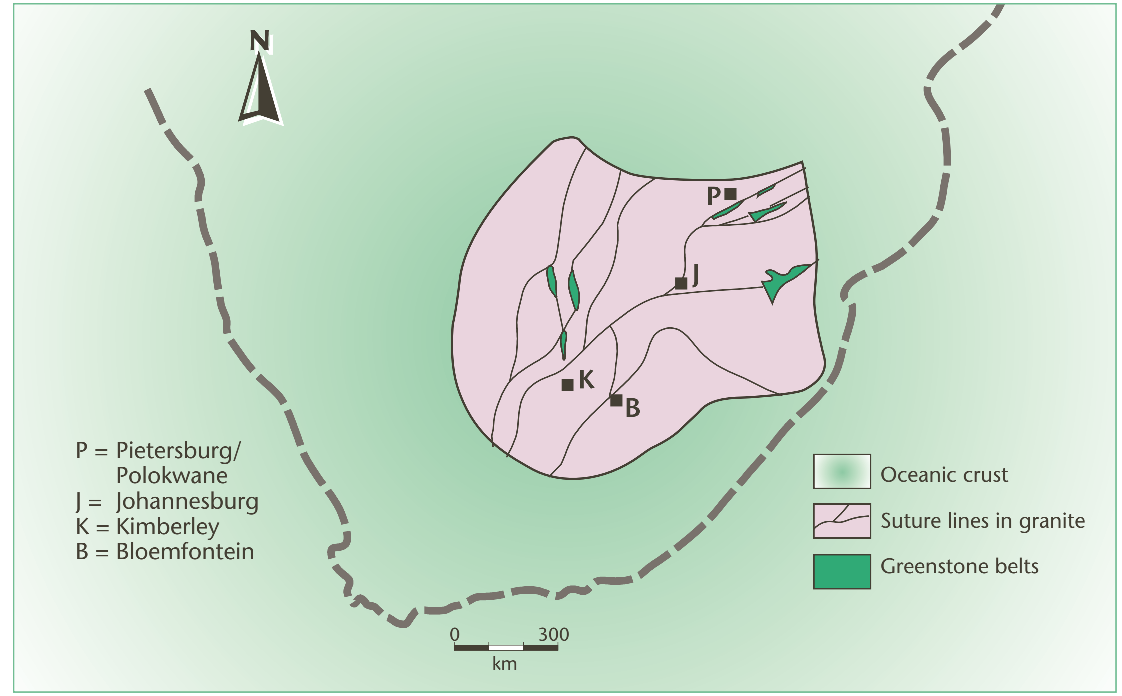

Figure 3.17 *The Kaapvaal Craton is believed to have assembled by the amalgamation of many micro-continents and the greenstone belts are believed to mark the suture lines between the fragments. This map (compiled by Maarten de Wit of the University of Cape Town and his colleagues) shows the possible locations of individual micro-continents. (The coastline of South Africa and the locations of cities are shown for reference.)*

unique to this period. Also different in these ancient terranes is the absence of significant metamorphic belts along zones of island arc collision, possibly also a consequence of a hotter Earth with smaller plates and a more rapidly recycling crust.

In other respects the Earth was similar to today. Oceans were present and subject to tidal influences. Oceanic crust was being created by underwater volcanic eruptions and recycled at subduction zones. Continents had formed and drainage networks had developed on these early continents. In addition, eroded material was being deposited in adjacent oceans to form early particulate (clastic) sedimentary rocks. Life was flourishing in the oceans and photosynthesising organisms had probably already appeared.

These primitive forms of life were extracting carbon dioxide from the water, causing the mineral calcite to precipitate in distinctive stromatolite structures. Moreover, sizeable continents, which included the Kaapvaal Craton, had formed. This particular continent provided a basement on which a remarkable variety of sedimentary and other formations were deposited over the subsequent 3 000 million years, producing southern Africa's rich geological legacy.

SUGGESTED FURTHER READING

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