At a time of widespread apprehension over the impact of human activities upon our biosphere and atmosphere, it is helpful to consider the history of past environmental fluctuations and to draw some relevant lessons from careful study of former human interactions with their natural surroundings. At the present time, there is growing concern that the burning of coal and oil over the last 200 years and the more recent but rapidly accelerating clearance of tropical forests may alter the balance between incoming solar radiation and outgoing terrestrial radiation in ways as yet hard to predict in detail, but which are more likely to lead to global warming than otherwise. The desire to predict possible future climatic changes likely to be triggered by the anthropogenic increase in the atmospheric concentration of carbon dioxide, methane, nitrous oxide and other greenhouse-enhancing gases has spawned an enormous literature (see Graedel and Crutzen 1995, and Houghton et al. 1995, 1996, for useful summaries). These attempts to gaze into the future have also re-invigorated studies of the geologically recent past, particularly the Quaternary period, which is the topic of this book.

The Quaternary period spans roughly the last 2 million years of geological time (Fig. 1.1) and is of critical importance in Earth history. It was during this period of remarkably frequent and rapid changes in world climate (Fig. 1.2) (Flint 1971; Butzer 1974; West and Sparks 1977; Bowen 1978; Goudie 1983; Anderson and Borns 1994; Ehlers 1996) that bipedal, toolmaking, fire-using hominids emerged from Africa and gradually moved out to occupy Eurasia, Australia and the Americas, as well as distant oceanic islands throughout the globe. The Quaternary is thus not simply the coda to 4.5 billion years of Earth history, but is also the time during which we became fully human.

One lesson we are slowly learning after the long saga of continuous human interaction with our environment is that we ourselves are an integral part of that same environment, and that we are the custodians rather than the owners of the lands we now inhabit (Suzuki 1990; Ponting 1991; Tolba 1992). We return to this theme in the final chapter of this book when we consider the past, present and possible future impact of our species upon the air we breathe, the water we drink, and the land and the sea which sustain the plant and animal life upon which we depend for our survival (Mungall and McLaren 1991; McMichael 1993; Holland and Petersen 1995; Simmons 1996).

The aims of this book are to examine some of the global environmental fluctuations of the last 2 million years, to analyse some of the more important evidence.
used in reconstructing Quaternary environments (Bowen 1978; Lowe and Walker 1984; Bradley 1985), and to consider some of the ways in which living organisms (including humans) have responded to past environmental changes. We also believe that a knowledge of the past, besides being intrinsically interesting, is also our only real guide to what may befall us in the future.

**PRELUDE TO THE QUATERNARY**

An accurate long-term perspective on global climatic change has now become possible owing to recent advances in our understanding of world tectonic history. The combined evidence from deep-sea drilling, seismic surveys and palaeomagnetic studies has allowed reconstruction of sea-floor spreading history, and of continental apparent polar-wandering curves. The data from land and sea are impressive and persuasive. The timing of late Cainozoic ice build-up in the two hemispheres is now reasonably well known, as are some of the associated changes in oceanic and atmospheric circulation, which are in turn related to the origin and expansion of the deserts and the contraction of the tropical rainforests. A proper understanding of Quaternary climatic changes therefore requires some appreciation of the legacy of the Tertiary.

The Tertiary and Quaternary periods together comprise the Cainozoic era and embrace the past 65 million years (Fig. 1.1). The present geographical distribution of land, sea and ice (Fig. 1.3) and of the corresponding morphoclimatic regions shown in Fig. 1.4 are the end-product of Mesozoic and Cainozoic lithospheric plate movements and sea-floor spreading. A number of major regional episodes, including Himalayan uplift, Antarctic ice accumulation, closure of the Panama isthmus, build-up of the North American ice sheets, intertropical cooling and desiccation, and expansion of savanna at the expense of tropical rainforest, were all closely linked with the global tectonic events of the Tertiary (Ruddiman and Kutzbach 1991; Quade et al. 1995; Derbyshire 1996; Liu et al. 1996; Raunstein et al. 1997) and are the subject of Chapter 2.

**QUATERNARY GLACIATIONS**

Ice began to accumulate on Antarctica well over 20 million years ago. Ice build-up came much later in the northern hemisphere, and it was not until 2.4 million years ago that major ice sheets began to grow rapidly in North America. For reasons which remain obscure, but which appear to be closely related to cyclical changes in the Earth's orbital path around the sun and in the tilt of the Earth's axis (Jiang and
Peltier (1996), the great ice sheets of the northern hemisphere in particular developed a characteristic cycle of slow build-up to full glacial conditions, followed by rapid ice melting and deglaciation. These topics are the focus of Chapters 3 to 5.

**QUATERNARY SEA-LEVEL CHANGES**

The larger of the Quaternary ice caps were up to 4 km thick. As the ice caps slowly built up to attain their maximum thickness, the underlying bedrock was progressively depressed beneath the weight of accumulating ice. When the ice melted, the crust slowly rose again to its preglacial level. These isostatic readjustments to the waxing and waning of the great Quaternary ice sheets caused changes in the relative levels of land and sea. During glacial maxima, roughly 5.5% of the world's water was locked up in the form of ice (the corresponding value today is 1.7%). As the ice sheets grew, so the level of the world's oceans fell by up to 150 m, depending upon total ice volume. With deglaciation and rapid melting of the ice caps, sea-level rose once more to about present levels. These glacio-eustatic sea-level fluctuations are analysed in Chapter 6, together with the influence of isostasy and other tectonic movements upon global and local sea-levels (Warrick et al. 1993).

**EVIDENCE FROM THE OCEANS**

Reconstruction of past sea-level fluctuations can throw useful light on the rate of accumulation and the rate of melting of global ice, but well-dated Quaternary sea-level histories only extend back some 250,000 years, so that the first 90% of the record must be sought elsewhere, most notably from deep-sea cores.

Inferences about changes or fluctuations in ocean circulation patterns used to depend very largely upon sedimentological and microfossil studies. Analysis of the oxygen isotopic composition of the calcareous tests of suitable benthonic and planktonic foraminifera now provides an additional and powerful means of assessing changes in ocean water temperature and salinity at depth and near the surface (see Chapter 7). After allowing for local effects, it is also possible to use this technique to estimate changes in
global ice volume. Deduced changes in regional surface salinity can also indicate changes in runoff from major rivers, changes in evaporation, and changes in the amount of seasonal rainfall (De Deckker 1997). The record from deep-sea cores has the double advantage of good global coverage and of spanning much of the Cainozoic. There are comparatively few such long, continuous terrestrial records, and those that do exist are usually confined to particular types of lake basin. It is still too soon to say whether or not the long ice cores collected from Antarctica and Greenland represent a continuous sequence of ice accumulation, although present evidence seems to indicate an unbroken record spanning the last interglacial in Greenland and over 50,000 years beyond that in Antarctica. The Chinese loess record also appears to provide an unbroken record matching that of the Greenland ice cores in its remarkable detail (Porter and An 1995; An and Porter 1997).

RIVERS, LAKES AND GROUNDWATER

Although the oceanic record can provide unrivalled information about the pattern and tempo of global climatic fluctuations in the Quaternary, it is often more useful to know about the direct changes to the landscape caused by local and regional hydrological fluctuations. Our increased understanding of the global linkages or teleconnections between historic floods, droughts and sea surface temperature anomalies, epitomised by the climatic variations associated with El Niño-Southern Oscillation events (Allan et al. 1996), demonstrates the very practical relevance of such studies. A further and still unresolved issue is the nature of the interactions between climatic variability (including short-term droughts and longer-term climatic desiccation) and desertification processes (Williams and Balling 1996). Such former hydrological changes are evident in the Quaternary depositional legacy of rivers large and small, as well as in the ever-changing response of lakes to local fluctuations in evaporation, precipitation, and groundwater levels. Unfortunately for our purposes, the alluvial history of most rivers can only be pieced together from fragmentary and often poorly dated suites of sediments. However, as Chapter 8 points out, rivers and lakes together can yield highly informative accounts of how certain regions responded to the environmental vicissitudes of the Quaternary, and of how they may well respond in the future (Costa et al. 1995; Gregory et al. 1995).
EVIDENCE FROM THE DESERTS

A growing body of evidence from deep sea cores, lake deposits and ice cores shows that times of lowest world temperature during the Quaternary (glacial maxima) were times of greatest aridity on land, with massive export of desert dust offshore, and even to central Antarctica (Yung et al. 1996). Deserts are excellent geological and geomorphological museums, for the very aridity to which they owe their existence has minimised the destructive impact of fluvial erosion and has helped to conserve an array of river, lake and wind-blown deposits. These deposits sometimes contain remarkably well preserved and occasionally, as in certain semi-arid rift valleys in Africa, or the loess plateau in China, a nearly-continuous fossil vertebrate and invertebrate record spanning most of the late Pliocene and Quaternary. Chapter 9 enlarges on these topics.

EVIDENCE FROM NON-MARINE FLORA AND FAUNA

The emergence of the plants and animals upon which humans have long depended for food and shelter took place against the environmental changes of the late Tertiary and was finally accomplished during the Quaternary. Changes in the non-marine plant and animal record provide an invaluable adjunct to the purely physical evidence furnished by landforms and sediments, and can be used to reconstruct former temperature and rainfall fluctuations with great precision and accuracy. Some organisms are inherently sensitive to local changes in habitat, and may respond rapidly to external disturbance. Perhaps the most versatile and certain of the best tested methods used in Quaternary environmental reconstruction is the technique of pollen analysis, which is considered in some detail in Chapter 10, along with other more circumscribed techniques.

HUMAN ORIGINS, INNOVATIONS AND MIGRATIONS

As the great Quaternary ice caps waxed and waned, and deserts expanded and contracted, a small-brained vegetarian hominin left its footprints clearly visible in a carbonatite ash which was laid down during a volcanic eruption near Laetoli in Tanzania nearly 4 million years ago. This creature, Australopithecus afarensis, was fully bipedal, and may well be the ancestor from which later hominids, including the genus Homo, were to derive. Chapter 11 describes the slow progression from user of tools to toolmaker, discusses the development and refinement of stone knapping techniques, and concludes with a short analysis of the origins of plant and animal domestication. The food-producing economy of the Neolithic saw the virtual demise of most hunter-gatherer societies around the world, and the inception of modern urban civilisation.

ATMOSPHERIC CIRCULATION DURING THE QUATERNARY

The cultural development of our human forebears took place against a background of ever-changing global climate. In the intertropical zone, for instance, cool, dry and windy glacial maxima alternated with warm, wet interglacial. Regions delineated as arid in Figs 1.3 and 1.4 were sometimes studded with deep freshwater lakes; areas now under rainforest were sometimes covered in savanna, or partly mantled with wind-blown sand.

Chapter 12 is an attempt to explore some of the changes in global atmospheric circulation patterns during the Quaternary, particularly the terminal Pleistocene towards 18,000 years ago, and the early Holocene around 9000 years ago. We do this for two very good reasons. First, the last 20,000 years contain the best-dated, best-preserved and most abundant palaeoclimatic evidence with which to test global atmospheric circulation models. Second, the two time-spikes considered coincide, respectively, with the last glacial maximum (18,000 years ago) and the so-called early Holocene ‘climatic optimum’ of 9000 years ago, which we prefer to regard as simply the postglacial antithesis of the full glacial climate. Between them, they encompass a substantial component of climatic range of the most recent glacial–postglacial cycle (Bell and Walker 1992; Wright et al. 1993).

ENVIRONMENTAL CHANGES: PAST, PRESENT, FUTURE

Throughout the Quaternary there has been a prolonged series of interactions between hominids (ancestral humans) and their environment. Stone toolmaking dates back to about 2.5 million years ago, and fire was being used in Africa about a million years later. The question of how far prehistoric hunters contributed to the demise of certain species of animals is a vexed one, as is the related question of the role of burning in bringing about plant extinctions. With the advent of Neolithic food production,
and accelerated clearing of the natural vegetation, the
degree of human impact upon the biosphere and
hydrosphere began to increase dramatically (Turner
et al. 1990; Mamion and Bowly 1992; Roberts
1994; Middleton 1995; Brown 1997). By altering
plant cover, we may increase runoff, and thereby
accelerate soil erosion. There is a delicate balance
between the different components of the hydrosphere
(Fig. 1.5) and the atmosphere (Fig. 1.6). Since the
Industrial Revolution, in particular, we have begun to
interfere with that balance by unwittingly altering
some of the feedback loops which are an integral part
of the global climate system (Fig. 1.5). Chapter 13
discusses these issues in greater detail.

QUATERNARY CHRONOLOGY

There has long been controversy over the exact dura-
tion of the Quaternary. Some workers espouse a long
chronology starting as early as 3.5 Ma. Others prefer
a shorter chronology, beginning at 2, 1.8 or 1.6 Ma.
We tentatively opt for 1.8 Ma (Fig. 1.1), which also
coincides reasonably well with the Olduvai palaeo-
magnetic event, an interval with normal magnetic
polarity bracketed by K–Ar dates of 1.87 and 1.67
Ma (see Appendix). An equally good case may be
made for placing the Pliocene–Pleistocene boundary
at 2.5 Ma, when there was a rapid build-up of ice in
the northern hemisphere. Sue and colleagues (1997)
have recently argued very persuasively that the
Pliocene–Pleistocene boundary should be placed at
the Gauss–Matuyama reversal at 2.58 Ma. There is
much merit in this proposal, since it fulfills the neces-
sary geological criteria and would be relatively easy
to identify both on land and in ocean cores. The
choice of Quaternary boundary is very much a matter
of personal taste (Vita-Finzi 1973), and has often
generated more heat than light. We likewise favour
a simple four-fold subdivision of the Quaternary
(Fig. 1.7) into Lower Pleistocene (1.8 to 0.75 Ma),
Middle Pleistocene (750 to 125 ka), Upper Pleis-
tocene (125 to 10 ka) and Holocene (10 to 0 ka),
while noting that none of these somewhat arbitrary
divisions or ages is particularly sacrosanct.

RECONSTRUCTING QUATERNARY
ENVIRONMENTS

A knowledge of past events and processes can offer
useful insights into both present and future environ-
mental changes, but a few preliminary words of
caution are necessary here. Earth history is a tale of
constantly varying interactions over time between
lithosphere, atmosphere, hydrosphere (including
cryosphere) and biosphere. Present world landscapes
reflect the influence of past as well as present-day

![Diagram of the hydrosphere](image)

**Fig. 1.5** The hydrosphere. (After Bloom 1978; Strahler and Strahler 1987)
processes. Theoretical constructs about the relation between present-day weathering processes and climate (or latitude) are only useful if we are fully aware of their limitations.

Table 1.1 shows some of the types of evidence commonly used to reconstruct Quaternary environments and climates. Each is useful for a specific purpose, and for a particular area or time (Leroy Ladurie 1972; Vita-Finzi 1973; Lowe and Walker 1984; Bradley 1985; Bradley and Jones 1995; Benda 1995; Wadia et al. 1995). Difficulties arise immediately when we use Procrustean tactics to force the data to yield palaeo-environmental information at particular scales in space or time for which those data are totally inappropriate. It is essential always to take due note of the time-scales at which the different processes involved in environmental change normally operate (Fig. 1.8).

A related issue is the precision available in dating the proxy data or samples used in reconstructing past events (Fig. 1.9). In many cases we are still limited by the imprecision of existing dating methods, which is often a function of the half-life length of the particular radioactive isotopes involved (see Appendix). Given all of the above caveats, it would seem that the task of Quaternary environmental reconstruction is still more of an art than a science. Such a conclusion is in no way dismissive of some of the excellent progress made in quantifying past fluctuations in temperature and salinity, on land and in the sea, using stable isotopes and trace element composition of the calcareous shells of ostracods and forams. However, we still have a very long way to go to gain the spatial and temporal resolution necessary to test existing models of global atmospheric circulation in the Quaternary (Chapter 12).

QUATERNARY ENVIRONMENTAL ANALOGUES

It is always tempting to use past climatic events as analogues for possible future climatic changes. For example, some workers have suggested that future global warming linked to the greenhouse effect may have an early Holocene climatic analogue. We consider that such claims should be treated with considerable caution, especially since the early Holocene boundary conditions, including sea-level, the extent of the cryosphere, terrestrial albedo, and sea surface temperatures, may have been very different from those used to model future change. Of greater value in understanding possible future change is the geological and biological evidence of past hydrological
Table 1.1 Sources of data used to reconstruct Quaternary environments

<table>
<thead>
<tr>
<th>Proxy data source</th>
<th>Variable measured</th>
</tr>
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<tbody>
<tr>
<td><strong>Geology and geomorphology – continental</strong></td>
<td>Soil types</td>
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<tr>
<td>Relict soils</td>
<td>Lake level</td>
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<tr>
<td>Closed-basin lakes</td>
<td>Varve thickness</td>
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<tr>
<td>Lake sediments</td>
<td>Age</td>
</tr>
<tr>
<td>Aeolian deposits – loess, desert dust, dunes, sand plains</td>
<td>Stable isotope composition</td>
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<tr>
<td>Lacustrine deposits and erosional features</td>
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<tr>
<td>Evaporites, tufas</td>
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<td>Speleothems</td>
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<tr>
<td><strong>Geology and geomorphology – marine</strong></td>
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<tr>
<td>Ocean sediments</td>
<td></td>
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<tr>
<td>Continental dust</td>
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<tr>
<td>Biogenic dust: pollen, diatoms, phytoliths</td>
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<tr>
<td>Marine shorelines</td>
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<td><strong>Fluvial inputs</strong></td>
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<tr>
<td><strong>Glaciology</strong></td>
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<tr>
<td>Mountain glaciers, ice sheets</td>
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<tr>
<td>Glacial deposits and features of glacial erosion</td>
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<tr>
<td>Periglacial features</td>
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<td>Glacio-eustatic features</td>
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<tr>
<td>Layered ice cores</td>
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<tr>
<td><strong>Biology and biogeography – continental</strong></td>
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<tr>
<td>Tree rings</td>
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<tr>
<td>Fossil pollen and spores</td>
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<td>Plant macrofossils</td>
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<td>Plant microfossils</td>
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<td>Vertebrate fossils</td>
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<tr>
<td>Invertebrate fossils: mollusca, ostracods</td>
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<tr>
<td>Diatoms</td>
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<tr>
<td>Insects</td>
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<tr>
<td>Modern population distributions</td>
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<tr>
<td><strong>Biology and biogeography – marine</strong></td>
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<tr>
<td>Diatoms</td>
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<tr>
<td>Foraminifera</td>
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<tr>
<td>Coral reefs</td>
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<tr>
<td><strong>Archaeology</strong></td>
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<tr>
<td>Written records</td>
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<tr>
<td>Plant remains</td>
<td></td>
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<tr>
<td>Animal remains, including hominids</td>
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<tr>
<td>Rock art</td>
<td></td>
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<tr>
<td>Hearths, dwellings, workshops</td>
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<tr>
<td>Artefacts: bone, stone, wood, shell, leather</td>
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</tbody>
</table>

*Source: After National Academy of Sciences (1975), Bradley (1985) and Williams (1985a)*

events. Rather than seeking past climatic analogues to a warmer Earth, it may be more useful for us to focus on how various elements of the biosphere and hydrosphere have responded to former climatic fluctuations. What were the directions and rates of response? What were the thresholds? Was the response synchronous or time-transgressive? How did one set of changes (e.g. deforestation) repercuess upon the rest of the landscape? If we adopt this approach then it is possible to argue that an appreciation of past
Quaternary events can provide us with insights about possible future events which are unattainable by any other means.

**PRACTICAL RELEVANCE OF QUATERNARY RESEARCH**

The Quaternary legacy is ubiquitous. Many of our soils formed during the Quaternary, as did many of the depositional features created by moving ice, wind and rivers. Human activities in the last few centuries have served to accelerate many natural processes, including soil erosion by wind and water. Some modern rates of soil erosion are several orders of magnitude greater than the long-term geological rates for those regions. One reason for this discrepancy may simply be the ease with which unconsolidated Quaternary sediments can be mobilised by present-day runoff, but another may be destruction of the vegetation cover, which increases the vulnerability of the
soil surface to the erosive impact of rainsplash and runoff.

A knowledge of the rates and magnitudes of past and present environmental change is essential to our understanding of the world we live in. Planners and policy-makers are becoming increasingly attuned to the relevance of Quaternary studies to agricultural and resource management. For instance, Quaternary research can contribute its unique historical perspective to a sensible policy of long-term management of soil erosion, desertification, salinisation, coastal erosion, floods and droughts, and biological conservation. Recent experience shows all too well that to ignore the past is to court future land-use problems. Present rates of plant and animal population changes mean very little unless set in a historical context, in this case Quaternary palaeocology. The long-term development and preservation of our soil, plant and groundwater resources thus require a balanced understanding of recent Quaternary environmental changes as well as a thorough knowledge of present-day geomorphic, ecological and hydrological processes.

FURTHER READING


QUATERNARY ENVIRONMENTS

Second Edition

MARTIN WILLIAMS
Mawson Graduate Centre for Environmental Studies
University of Adelaide, Australia

DAVID DUNKERLEY
Department of Geography, Monash University, Australia

PATRICK DE DECKKER
Department of Geology, Australian National University

PETER KERSHAW
Department of Geography, Monash University, Australia

AND

JOHN CHAPPELL
Research School of Earth Sciences, Australian National University

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