THE GEOLOGICAL FIELD GUIDE SERIES

The Field Description of Igneous Rocks

SECOND EDITION

Dougal Jerram and Nick Petford

Contents

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The Field Description of Igneous Rocks

SECOND EDITION

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WILEY-BLACKWELL

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This book is dedicated to Bob Hunter, and his great contribution to our understanding of rock textures.

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PREFACE

Igneous rocks in the field present a bewildering array of lithiologies formed not just from cooling and crystallisation of intrusive material but also by sedimentation and surface flow from volcanic eruptions. This concise guide is designed to give students, professionals and keen amateurs of igneous geology the key tools needed to help understand and interpret better the origin and evolution of complex igneous systems in a focused way. This extensively revised and reorganised colour guide builds on the original version by Richard Thorpe and Geoff Brown of the Open University (both now deceased) and published in 1985 as part of the Geological Society of London Field Guide Series. Since then much has changed in igneous petrology including significant advances in our understanding of the physical processes that govern the emplacement of volcanic and plutonic material both on the surface and within the solid earth. For example, new models for the emplacement of pyroclastic flows have helped explain the origin of some of the more enigmatic features of ignimbrites, while magma emplacement studies now draw heavily on techniques used routinely in structural geology. It is thus not enough just to know how to identify minerals in the field – multidisciplinary skills borrowed from other branches of field geology, and even engineering, are not desirable aspirations, but essential must haves. As our understanding of the subject has increased, we have tried in this first colour revision to incorporate much of this new thinking. At the same time we have remained true to the original philosophy of a portable guide that explains clearly and concisely the basic concepts underpinning igneous geology in the field. To this end we hope that the inclusion of new colour images and a colour-coded index system make basic identification of rock types and structure a slightly easier task. Both of us grew up with the original version and it has been a pleasure to revise and build from the start on a text so well laid out. We hope you find the new colour guide as great a companion as we did the old, and that in revised form it is even more of an essential aid when confronted, perhaps for the first time, with igneous rocks in the field.

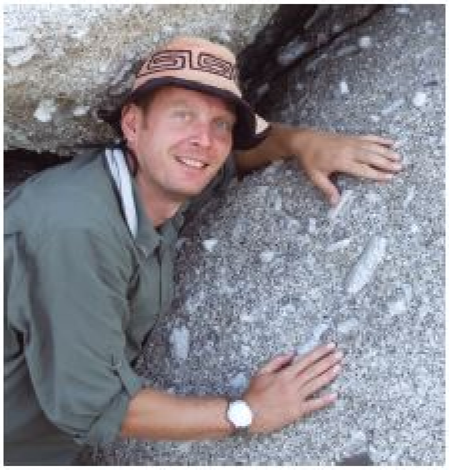
As we write, the Eyjafjallajokull volcano is erupting in Iceland, causing severe disruption to air traffic across Europe and beyond while generating unexpected but welcome global media interest in volcanology. This excitement will die down soon enough, but a raised awareness and respect for volcanoes will linger in the public psyche for years to come. Its aftermath will present new opportunities to those willing to grapple with the complexity and scientific challenges of ‘next generation’ igneous petrology. Our hope is that this book will in small measure inspire new entrants into the field, just as the original did for us.

Dougal Jerram and Nick Petford

April 2010

Meet the Authors

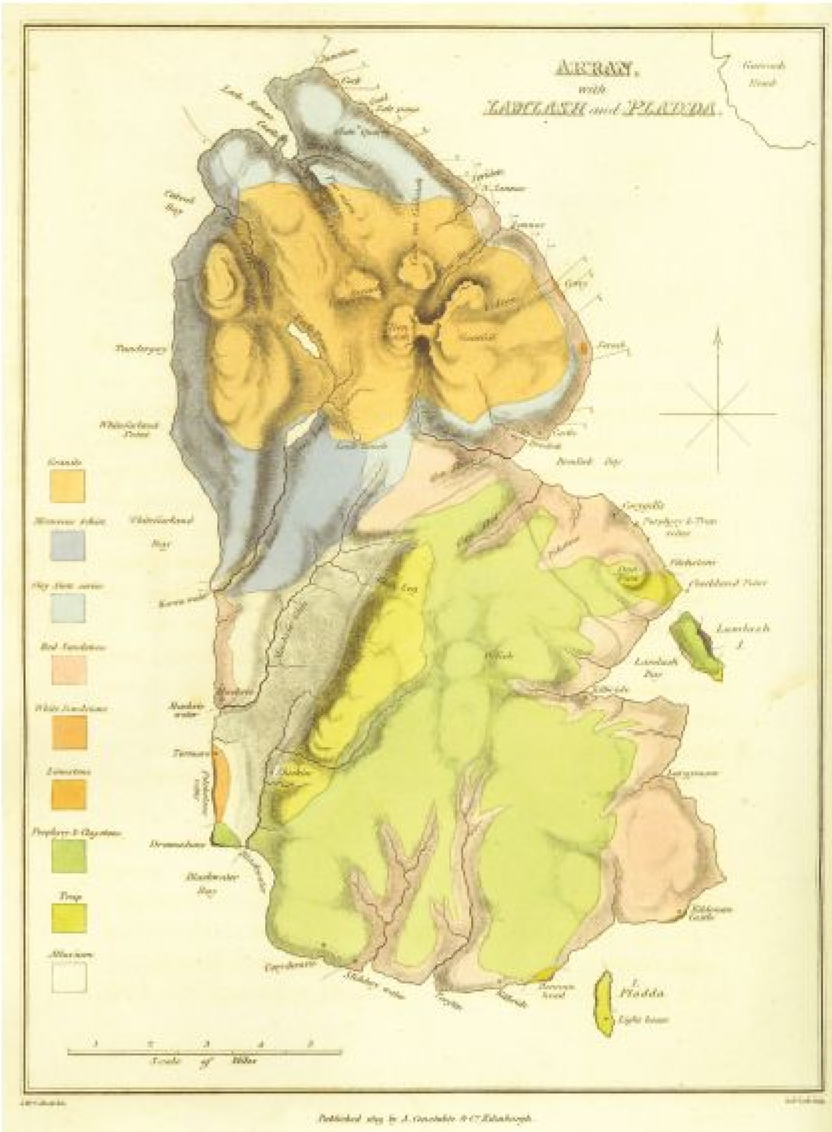
Dougal is currently at the Department of Earth Sciences, Durham University where he is involved in research and teaching, particularly of field geology. His main expertise is in rock microstructure and textural analysis, 2D–3D modelling of rock textures and volcanic basins, volcanology, sedimentology and field geology. In recognition of his early significant contribution to Earth Sciences he was awarded the Murchison Fund of the Geological Society in 2006. Recently Dougal has developed a keen eye for science outreach, and has appeared on national and inter-national TV (BBC, Discovery, National Geographic, History Channel, Channel 4) promoting aspects of the Earth, and has developed a popular web presence through www.dougalearth.com.



Dougal Jerram

Nick has published extensively on both field and theoretical aspects of igneous geology. After completing a PhD on Andean magmatism and geochemistry he switched to work more on the physical mechanisms governing the ascent and emplacement of granitic magmas and magma rheology. Other research themes include melt segregation in meteorites, the geotechnical properties of volcanic rocks and volcano tourism and economic regeneration. Nick began his research career as a Royal Society University Research Fellow and has worked at the Universities of Liverpool, Cambridge, Kingston and Bournemouth. He was awarded the Murchison Fund of the Geological Society in 1999 and has held visiting professorial appointments in Europe, USA and Australia. Like Dougal he makes the occasional TV appearance. In 2010 he was appointed Vice Chancellor of the University of Northampton.


Nick Petford



Early map of Arran from John Macculloch's Western Islands of Scotland 1819 book.

1

INTRODUCTION AND OCCURRENCE

Igneous rocks occur in almost all environments at the Earth's surface as volcanoes and their dispersed products, and within the crust and mantle as they form the pathway from which the Earth cools from it's hot interior. The products of igneous activity not only provide key information about the evolution of the Earth through time, they can be used as key stratigraphic markers, form the basis of our understanding of the Earth's chronology and can be found to have striking effects on our planets climate. From the beauty of diamonds, the wonders of erupting volcanoes and the polished rocks which adorn buildings all over the world, man has had a fascination with igneous rocks as far back as we can trace. The key basis from which we can understand igneous rocks and their systems is from detailed fieldwork and observation. This guide aims to provide the basic information and tools to enable earth and engineering scientists from a variety of backgrounds to investigate the wonderful world of igneous rocks in the field.

1.1 The Importance of Fieldwork

The most fundamental observations that you can make within the earth sciences are in the field. Here we are able to characterise the occurrence of earth materials *in situ*, in relation to their surroundings and within the context that will underpin any further investigations of the rocks in the lab. In short – *Fieldwork is the basis of all geological studies*. As such it is important that a person who wishes to understand rocks is proficient in the field. Whether one is studying igneous, sedimentary or metamorphic rocks the fundamentals of the fieldwork are more or less that same and indeed one may need to address all three major types of rock in the same field locality. It should be noted that there are many instances in which expensive geochemical and geophysical data have been misinterpreted through incomplete knowledge of basic field relationships. Therefore, *if the appreciation of field geology is poor, then all studies based on collected samples and field measurements will be equally poor*. Conversely, *good appreciation of field geology forms the basis of good geological interpretation*.

As a good field scientist you will need to have a background of basic skills to enable you to make the correct detailed observations that will in turn lead to clear and well thought out interpretations of the geology. The study of igneous rocks might also include petrological and mineralogical investigation, geochemical and isotopic analysis to determine the age and origin of the rocks and the use of geophysical measurements in the field to determine the distribution of rock-types below the ground. Also, many igneous rocks are associated with distinctive types of economic mineralisation and these are generally discovered and evaluated by fieldwork. Key to the success of these approaches will be the detailed understanding of the rocks in the field.

In this handbook we explain how to observe igneous rocks in the field, from the scale of outcrops down to hand specimens and to tie observations into basic interpretations of how the igneous rocks formed. Before embarking on the details of igneous rocks in the field it is valuable to consider the role of igneous rocks in a global framework and to consider the main occurrence of igneous rocks.

1.2 The Global Picture – Igneous Rocks in Relation to Regional Tectonics

Igneous rocks are materials that have solidified from molten or partially molten material, termed *magma*. Such rocks may be classified as *extrusive rocks*, which were erupted at the surface of the Earth, and *intrusive rocks* that crystallised beneath the surface. Igneous rocks of different compositions and field relationships exist at specific regions on the Earth associated with the plate tectonics in general. This reflects the mode of formation and emplacement of igneous rocks in the context of regional tectonic patterns. Below we briefly describe the key plate margin and within plate associations where patterns of igneous activity can be recognised.

The Earth's crust forms the uppermost part of the outer rigid shell, or lithosphere, of the Earth and is divided into large coherent 'plates' that move in relation to one another. This process termed *plate tectonics* (continental drift) reflects our cooling planet and the convection of the mantle beneath. The plates themselves are split into two types of crust which are defined by their composition and thickness, *oceanic and continental* and the configuration of the plates leads to different types of plate margins (boundaries) where specific igneous associations exist.

The boundaries between plates are of four types (summarised Table 1.1, see also Figure 1.7).

1. Constructive plate margins or ocean ridges, where two plates are moving apart and the upwelling and solidification of magma forms new oceanic crust.
2. Destructive plate margins, where two plates are converging so that one plate sinks below the other and is eventually resorbed into the mantle or 'destroyed'. This process is accompanied by formation of a range of magmas. Such plate margins may occur on oceanic (island arcs) or continental lithosphere (active continental margins).
3. Conservative plate margins, are faults where two plates slide past each other (transverse faults), so that lithosphere is neither created nor destroyed, and igneous activity is minor.

4. Collision zones, where two island arcs and/or continents have collided so that subduction of oceanic material has ceased. Such areas are characterised by widespread extrusive and intrusive igneous activity which commonly continues for a considerable time after collision.

Over 99% by volume of igneous activity occurs at constructive and destructive plate margins and at collision zones and some occurs at locations *within* the plates, for example volcanoes such as those of Hawaii and those associated with the East African rift system.

Igneous activity at constructive plate margins is responsible for the formation of the oceanic crust. The composition and structure of the oceanic crust is known from the study of rocks dredged from the ocean floor, from seismic studies and from studies of onshore exposures of older rocks that are believed to be fragments of the oceanic crust (*ophiolites*). These lines of evidence indicate that the oceanic crust consists of layers of basalt lavas, basalt/dolerite dykes, gabbro and peridotite. These rocks form a distinctive association which may be recognised in ancient orogenic belts, where it is termed the *ophiolite association*. The recognition of such associations is clearly of great palaeogeographic significance and the ophiolite associations are described in detail in Chapter 8.

The oceanic lithosphere moves away from the oceanic ridge by the process of sea-floor spreading and is generally returned to the mantle at a destructive plate margin within circa 200Ma. The descent of oceanic lithosphere into the mantle is accompanied by partial melting above the descending plate where water is driven off at depth. This melting in the overlying mantle forms magmas ranging in composition from basalt, through andesite to rhyolite in composition. These intrude the crust and may be erupted at the surface or emplaced at depth as gabbro, diorite and granite. In some places, the emplacement of such rocks causes melting of the lower crust and this results in the emplacement of intrusions dominantly of diorite, granodiorite and granite composition at destructive continental margins, accompanied by eruption of andesite, dacite and rhyolite. The intrusive rocks emplaced at active continental margins form linear belts of intrusive complexes of diorite-granite composition, often termed batholiths.

The composition of the continental crust broadly resembles that of the igneous rocks of andesite composition. Much of continental crust is thought to have formed as a result of igneous activity of the type seen today at island arcs and at destructive continental margins. The crust has evolved continuously as a result of magmatic and metamorphic activity, uplift, erosion and sedimentation, and hence consists largely of metamorphic and igneous rocks with a thin veneer of sedimentary rocks. Because of it’s greater age and complex geological history, the structure of the continental crust is much more varied than that of the oceanic crust. The continental crust is therefore considered to have a complex structure characterised by rapid lateral and vertical variation, and uplifted sections from which the sedimentary veneer has been eroded expose sections of a wide variety of igneous rocks emplaced at great depth within the crust.

Igneous rocks formed at locations distant from plate margins (locations within-plate, Table 1.1) may have distinctive modes of occurrence, for example as flat-lying sheets of plateau lavas, as discordant plutonic magmatic bodies within continental rifts and as concordant or discordant gabbroic intrusions. Such igneous rocks may have characteristic compositions; indeed, many magmas emplaced at locations within a plate have distinctive alkali-rich chemical compositions which may be reflected in their mineralogy.

1.3 Mode of Occurrence of Igneous Bodies

In general we can split the different types of igneous body into three main sections relating generally to their relative positions within the Earth. Volcanic rocks erupt at and onto the Earth’s surface, minor intrusions tend to occur at shallow depths within the Earth’s crust and plutonic rocks form larger intrusive bodies at a variety of depths. In the context of this field guide we will generally look at these three main modes of occurrence and different subsections of these (for example, Volcanic – lava, Volcanic – pyroclastic, Plutonic – Granite, Plutonic mafic/ultramafic). Most field areas will be dominated by rocks from one of these general levels, though many examples will exist where different styles of occurrence are found (for example, shallow intrusions with lavas) so these basic subdivisions are used as a guide to the main features of each type. Below we briefly describe these major subdivisions.

1.3.1 Volcanic rock units

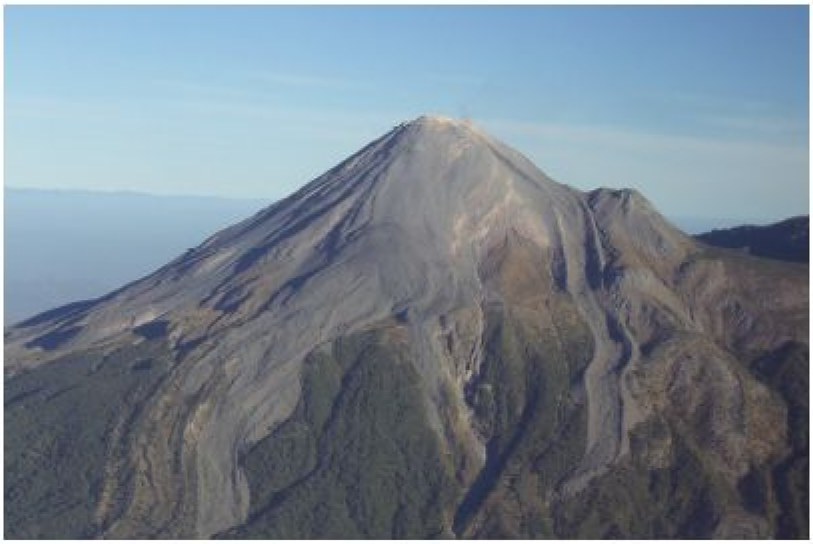
Volcanic rocks are classified as *lavas* and *pyroclastic rocks* (volcaniclastic). *Lava* is the term for molten extrusive rock and its solidified product, and pyroclastic rocks are composed of a mix of materials (lava fragments, pumice and crystals) fragmented by explosive volcanic activity. Within the guide we will deal with lava flows in detail in Chapter 4 and pyroclastic rocks in Chapter 5. Below is a brief summary of the main occurrence of volcanic rock units.

Often lavas and pyroclastics associated with individual volcanoes are concentrated within valleys and depressions around the volcano. The most extensive pyroclastic deposits may form large-scale stratigraphic units that blanket the topography and may form plateau-like features around volcanoes, additionally pyroclastic deposits may be underestimated in volume due to a large proportion of fine ash material which can be carried great distances from the volcano. The largest lavas flows build up thick sequences (plateaus), and construct large igneous provinces of immense volume.

Volcanoes show a wide variety of forms, depending largely upon the composition of the erupted material and hence the style of eruption (cf. Chapters 4 and 5). Basaltic volcanoes such as Hawaii erupt dominantly (over 80%) lava, the dominantly andesitic products of many volcanoes in island arcs and active continental margins have less than 10% lava and over 90% pyroclastic rocks. Further, the erupted proportion of pyroclastic rocks is often underestimated from subsequent field studies because these materials are often rapidly dispersed by the wind, or are eroded after deposition more rapidly than the equivalent volume of solid lava. Hence, bear in mind that lavas might be over-represented in many island arc and continental margin volcanoes.

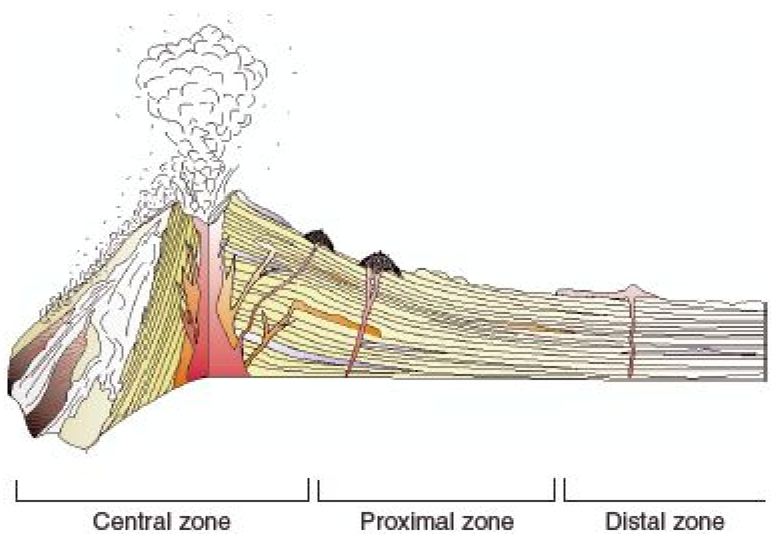
Many volcanoes, particularly of andesite composition are *composite* in the sense that they comprise both lava and pyroclastic materials and have a steep irregular conical form (for example, Figure 1.1). Such volcanoes are built by flow of lava down depressions around the volcanoes and the eruption of pyroclastic materials; they commonly have diameters of 10-40km. Volcanoes associated with mainly basaltic eruptions form relatively low relief shallow sided volcanoes known as shields due to the predominently low viscosity lava, that erupts from them. The smallest volcanic forms result from a single short-lived eruption and comprise a variety of cones and extrusions. These include *pyroclastic/scoria* cones comprised of material of basic and intermediate composition, and steep sided *flows and domes* of more viscous acid lava. Such volcanic forms are generally 1–2km in diameter and may form upon, or near to, larger volcanic forms, when they may be termed *parasitic volcanoes*.

Figure 1.1 *Colima volcano with lava flows and pyroclastic flows which have destroyed parts of the woodland around the mountain flanks*.



From this description of volcanic forms and products, it is clear that a single volcanic area may be characterised by a variety of deposits. These may be contemporaneous and, for a terrestrial composite volcano, may be interpreted in terms of variation of *associations* of deposits with distance from the volcano (for example, Figure 1.2). The central zone (within circa 2 km of the central vent) is characterised by lava conduits (later exposed as volcanic plugs, dykes and sills) associated with coarse, poorly-sorted pyroclastic materials which have been deposited near to the vent. The *proximal zone* (circa 5–15km from the central vent) has a higher proportion of lava flows, with a variety of pyroclastic flow deposits, and the *distal zone* (beyond circa 5–15km from the central vent, and extending beyond the volcano) is characterised by pyroclastic flow deposits associated with fine air-fall deposits dispersed by wind away from the volcano. These may be interbedded with sedimentary rocks such as lacustrine deposits and reworked volcaniclastics (epiclastic) rocks. Pyroclastic cones, flows and domes may occur within any of the three zones. Therefore, even for young volcanoes, it may be difficult to correlate individual lava flows, pyroclastic fall and flow deposits with a single eruption. Debris flows (as distinct from pyroclastic flows) formed when material collapses from volcano sides and unconsolidated deposits, may travel several kilometres around source, and can carry great masses of lava as blocks (for example, around Mount Egmont/Taranaki, in North Island New Zealand).

Figure 1.2 *Schematic internal architecture of a compostie volcano. See text for descriptions of central, proximal and distal zones.*



1.3.2 Intrusive rock units

Intrusions vary widely in size and relationship to the country rock and are generally grouped according to size into

1. **minor intrusions**, which have mean minimum dimensions measured in tens of metres (or less) and were emplaced relatively near to the Earth's surface and

2. **plutonic intrusions**, which are commonly emplaced at greater depth and have sizes measured in terms of kilometres.

Within the guide we deal with shallow/minor intrusions in Chapter 6, granitic plutonic rocks (granitic complexes) in Chapter 7 and mafic/ultramafic complexes in Chapter 8. A brief description of the main modes of occurrence is introduced below.

1.3.3 Minor intrusions

The most common forms of minor intrusions are shown schematically in Figure 1.3 *Dykes* are sheet-like intrusions which were approximately vertical at the time of emplacement and are hence *discordant* to host rocks such as shallowdipping sedimentary rocks. As a consequence of their attitude, the outcrops of dykes are little affected by the topography of the countryside in which they occur and often appear as nearly straight lines on geological maps. The width of dykes ranges from centimetre size to sizes measured in hundreds of metres, but in general the average width is probably in the range 1–5 m. Since this is too small to portray accurately on large-scale geological maps, dykes are often shown with a uniform or 'conventional' width (like roads on geographic maps).

Sheet intrusions that were approximately horizontal at the time of emplacement are termed *sills* (for example, Figure 1.4). These are often emplaced into horizontal or shallow dipping sedimentary rocks, in which case they may be broadly concordant, with the stratification, and appear on a geological map as part of the sedimentary succession. Other forms of intrusion which are broadly concordant with the surrounding strata are blister-shaped masses with a subhorizontal base and elevated upper surface, termed *laccoliths*, and saucer-shaped intrusions, termed *lopoliths* (Figure 1.3); both forms range in size from small bodies with dimensions measured in metres, to enormous masses hundreds of kilometres in size, which are clearly distinct from smaller minor intrusions.

Figure 1.3 *Broad types of shallow level intrusions; sills, dykes, lopoliths and laccoliths (see Chapter 6 for detailed section)*.

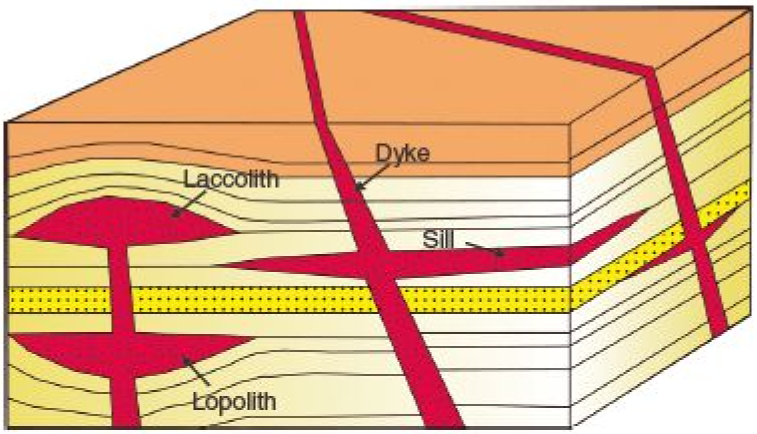
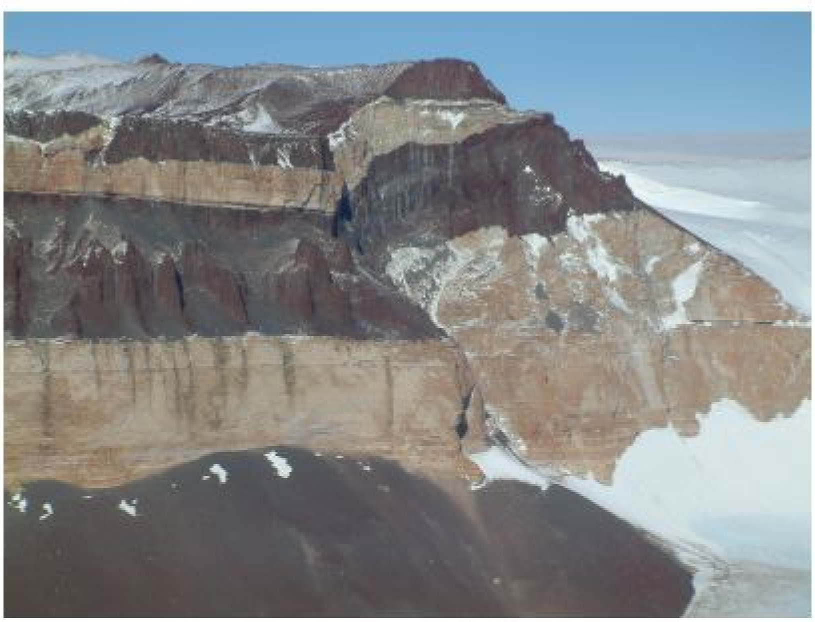


Figure 1.4 *Thick sills (>100m) and dykes cutting through sediments in the Transantarctic mountains, Antarctica (total height of section circa 300m*).



In studying minor intrusions care should be taken to trace contacts and measure stratigraphic sections. Most contacts are complex: minor intrusions and plutons usually show steep contacts and, since the form and areal distribution of such contacts are used to determine the form of the intrusion in three dimensions, it is particularly important to determine the attitude and orientation of all planar contacts in order to determine the overall geometry. For many minor intrusions it should be possible to locate a contact area with sufficient three-dimensional exposure to determine dip and strike.

1.3.4 Plutonic intrusions and igneous centres

At the larger end of the igneous spectrum we have the major igneous intrusions/centres and plutons. Although there is a huge range of sizes and associations that may be regarded as major plutonic intrusions, in this guide we will be grouping the large plutonic intrusions into those which are mainly granitic in composition (Granite complexes – Chapter 7) and those which are mainly mafic/ultra mafic in composition (mafic complexes – Chapter 8). Additional information about magma mixing/mingling which is also often found within the large plutonic intrusions will be dealt with in Chapter 9.

Coarse-grained granitic plutonic rocks occur most frequently within large, elongate belts of intrusions, 50–150km in width and 500–1500km in length, that characterise eroded mountain belts. Such elongate plutonic bodies are termed *batholiths*. They are usually composed of a large number of cross-cutting smaller intrusions, including bodies 5–50km in size with circular outcrop patterns, ring like intrusions and irregular dykes and sills. Circular intrusions with surface areas of less than $100km^2$ are