

6 Exhumation of the Grampian mountains

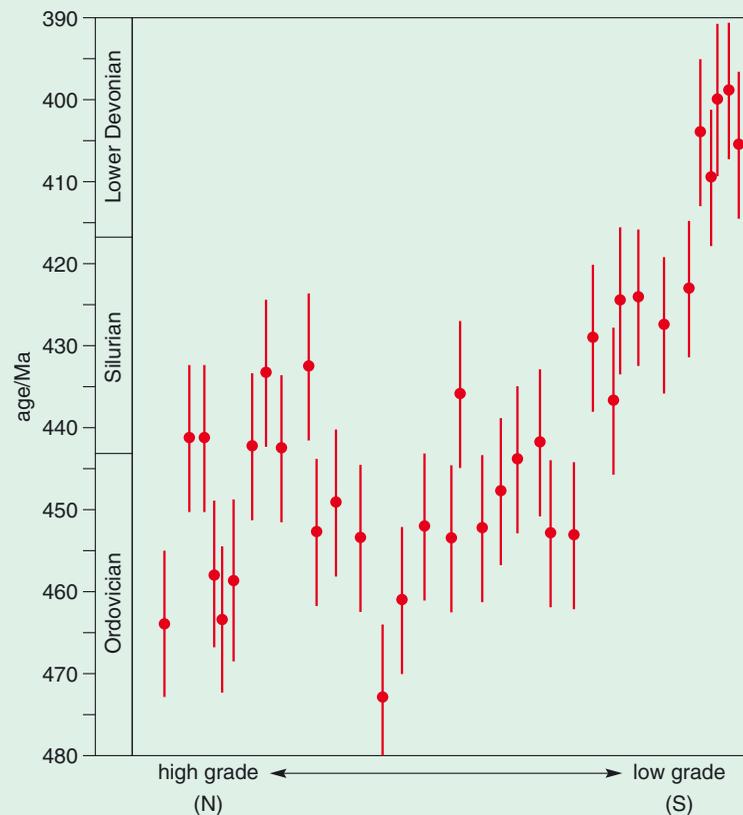
6.1 Introduction

Section 5 discussed the collision of an island arc with the margin of Laurentia, which led to the formation of a major mountain belt, the Grampian mountains, to the north of the Highland Boundary Fault – Fair Head–Clew Bay Line. Sections 5.3 and 5.4 concentrated primarily on the crustal thickening processes that were induced by the collision and led to deformation and metamorphism of the Dalradian Supergroup. After a major phase of crustal thickening the crust is mechanically unstable. Erosion also causes isostatic readjustments that lead to the uplift and erosion of the deeply buried rocks. Section 5.4.5 established that rocks of the Dalradian Supergroup were tectonically buried to a variety of depths, as indicated by the range of pressure estimates (*c.* 200–1000 MPa) obtained from rocks outcropping across the Grampian Highlands. Looking at this in another way, these pressure estimates identify the extent of uplift and erosion, or exhumation, and indicate the amount of overburden that has been removed from various parts of the belt. This Section investigates the exhumation of the deeply buried rocks. Section 6.2 looks at the uplift and cooling history of the metamorphosed Dalradian rocks that are exposed in the Grampian Highlands. In addition, Section 6.3 describes a suite of post-kinematic granites and examines how their generation and intrusion may have been related to exhumation. Section 6.4 investigates how provenance studies can help to determine the source and timing of sediment dispersal into the surrounding basins. Section 6.5 summarizes the nature and time span of the Grampian mountain-building phase.

6.2 Uplift and cooling history of the Grampian mountains

One constraint on the timing of exhumation comes from determining the uplift and cooling history of the metamorphosed Dalradian rocks by dating different metamorphic minerals. As explained in Box 6.1, the radiometric ages of metamorphic minerals define the times at which they cooled through particular temperatures, so they can be used to indicate when deeply buried rocks were exhumed and uplifted towards the surface. One such set of results from the south-eastern Highlands is shown in Figure 6.1, and illustrates that metamorphic biotites began to cool through their closure temperature at *c.* 473 Ma. Interestingly, this was shortly after the obduction of the Ballantrae ophiolite (dated at *c.* 478 Ma; Section 5.2.1). Whereas the high-grade rocks started passing through their closure temperatures at *c.* 470 Ma, the more southerly, lower-grade, rocks cooled much later (*c.* 410–400 Ma). Similar results have been established from the application of K–Ar and Rb–Sr methods to biotite and muscovite micas from across the orogen. These data suggest that the exhumation of rocks metamorphosed during the Grampian phase was in the Ordovician and occurred almost immediately after the peak of metamorphism (*c.* 470–465 Ma).

Figure 6.1 The cooling ages of Dalradian biotites (K–Ar method) from N–S traverses across metamorphic zones in the south-eastern Highlands. The cooling ages can be seen to decrease with decreasing metamorphic grade (grade decreases southwards, towards the Highland Boundary Fault, see for example Figures 5.12 and 5.13).



Box 6.1 Determining metamorphic cooling ages using Rb–Sr and K–Ar isotope data

The radioactive decay of parent isotopes (e.g. ^{87}Rb , ^{40}K) to produce daughter isotopes (in this case ^{87}Sr , ^{40}Ar) provides geochronometers that are used to date minerals according to the amount of daughter isotope that has accumulated.

Above a certain temperature, however, isotopes can diffuse into or out of minerals, so the ‘radiometric clock’ only starts to operate once the mineral has fallen below the temperature at which the mineral becomes a closed system – the closure temperature. Geochronological information is frozen into the mineral as it cools through the closure temperature, hence the radiometric age obtained can be referred to as the cooling age.

In single cycle orogens, that is orogens that have only experienced a single heating or orogenic event, it is possible to take advantage of radiometric isotopes in minerals that have not been reset by subsequent heating events to establish the timing of events during the later part of orogenic development, when the rocks of the orogen are cooling and uplifting.

Each geochronological method records slightly different information about the exhumation history of a rock. This is because different minerals have different closure temperatures, as the examples in Table 6.1 illustrate. So, if a rock contains hornblende, biotite and muscovite, then we can use these minerals to tell us the times at which the rock was at different levels in the crust.

Table 6.1 Examples of closure temperatures.

Parent–daughter system	Biotite	Muscovite	Hornblende
K–Ar	300 °C	320 °C	525 °C
Rb–Sr	uncertain	550 °C	uncertain

For example if a muscovite was dated using K–Ar methods to give an age of 400 Ma, then the rock containing the muscovite would have been at 320 °C 400 million years ago. If we assume that the Earth’s crust has a geothermal gradient of 30 °C km⁻¹, then the rock that gave us the 400 Ma age must have been at a depth of *c.* 10.7 km in the crust.

6.3 Magmatism during exhumation

Following the Grampian phase, post-kinematic magmatism throughout the Grampian Highlands formed a suite of undeformed granites and lavas. To help identify the magma generation processes and the source of these magmas, geologists looked at the initial ⁸⁷Sr/⁸⁶Sr ratios of the granites (Figure 6.2). Two groups are apparent from the Sr isotope data: a group with relatively high ratios (0.712–0.733), which suddenly give way, at *c.* 435 Ma, to a group with lower ratios (0.704–0.708). The young, low ⁸⁷Sr/⁸⁶Sr, group will be discussed in Section 8.7, but here the *c.* 460–435 Ma post-kinematic granites (located in Figure 6.3) are of interest because of the timing of their emplacement and the similarity of their isotope ratios to those of the syn-metamorphic, syn-kinematic granites. The high initial ⁸⁷Sr/⁸⁶Sr ratios of the granites indicate that they were most likely to have

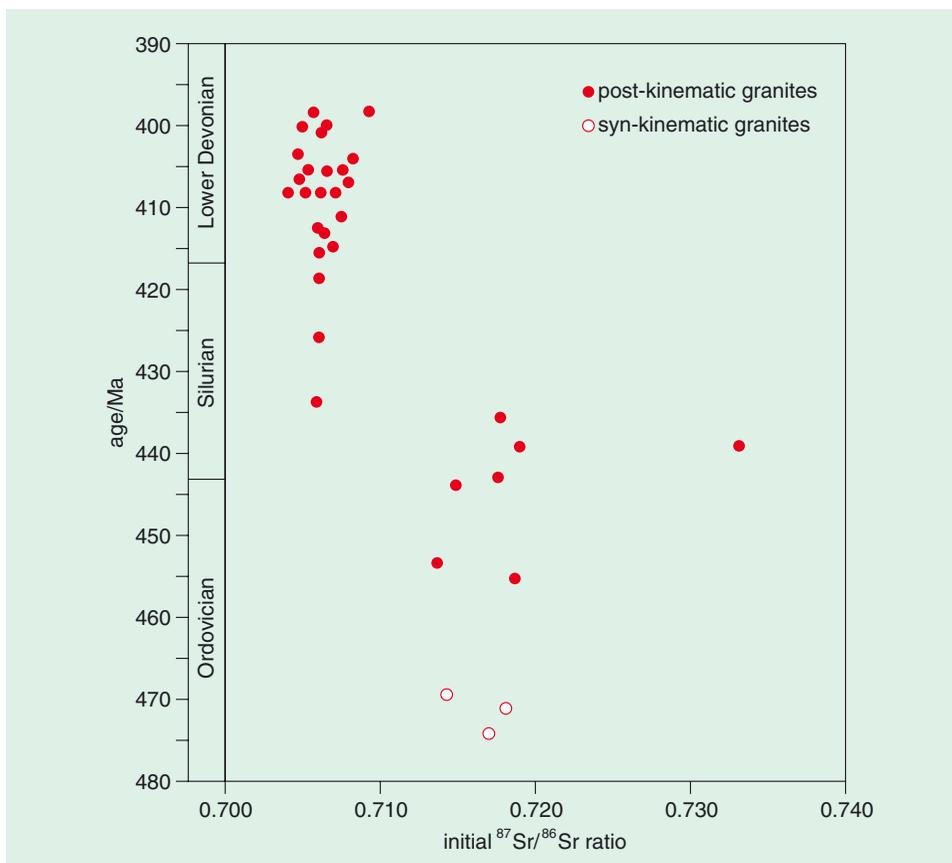


Figure 6.2 Ages and initial ⁸⁷Sr/⁸⁶Sr ratios of syn- and post-kinematic granites and lavas from the Grampian Highlands.

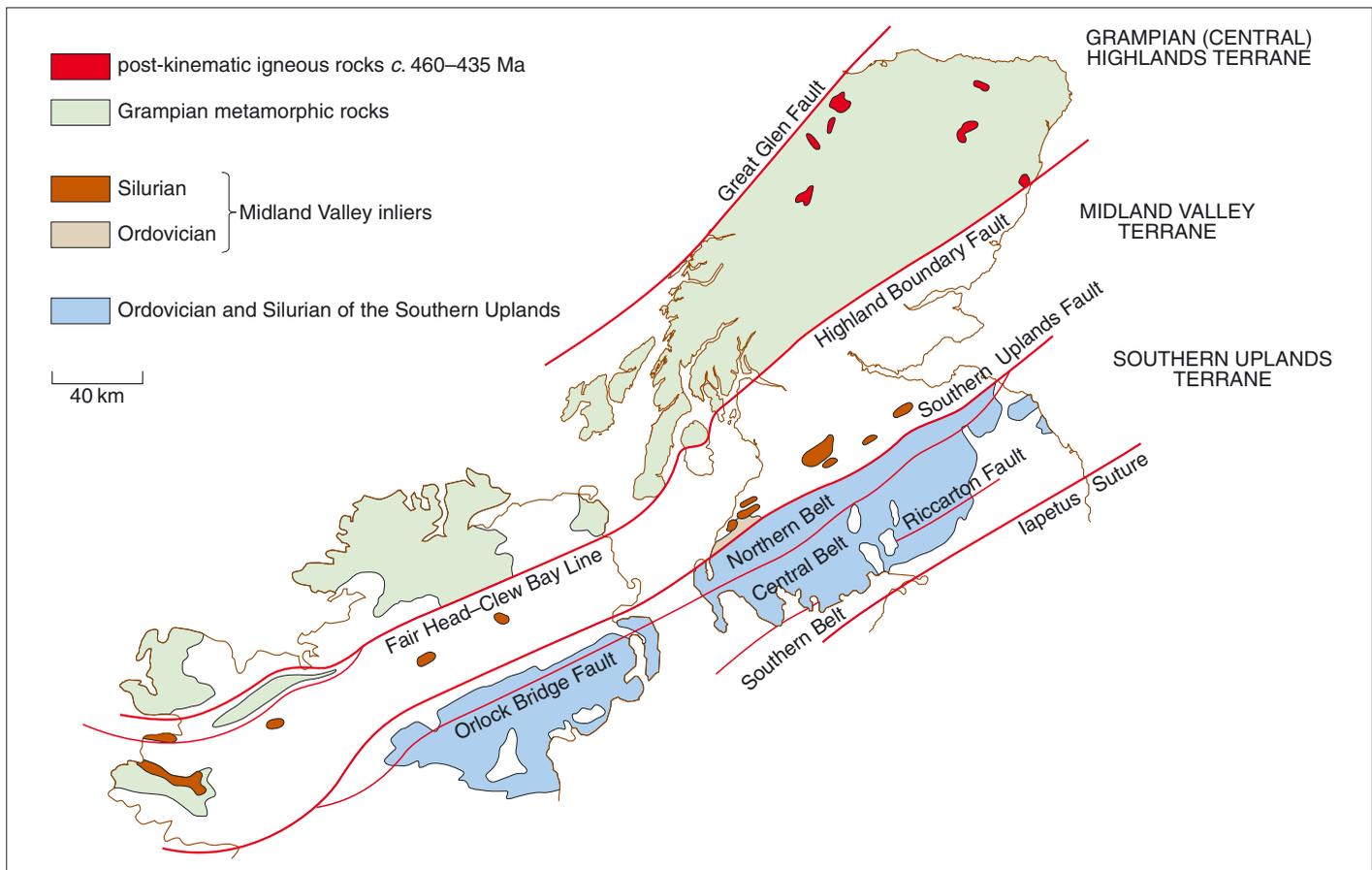
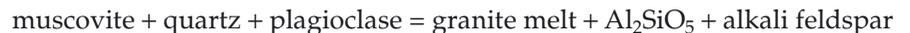


Figure 6.3 Map showing the location of Ordovician and Silurian igneous and sedimentary rocks.

been derived from the partial melting of Dalradian metasediments. The age of the high $^{87}\text{Sr}/^{86}\text{Sr}$ post-kinematic granites overlaps with the time during which the high-grade metamorphic rocks of the Dalradian Supergroup were uplifting and cooling, so we are led to ask a simple question: how can granite magmas be generated from metasediments during uplift and erosion of a mountain belt?

A reaction that can produce granitic magmas by the melting of metasedimentary rocks is:



The approximate slope and location of this reaction in P – T space is illustrated in Figure 5.14 (reaction labelled MM). It has a positive slope on the P – T diagram, and a granitic melt is generated on the high-temperature, low-pressure side.

- What would be the consequences of a near-isothermal decompression P – T – t path, the result of substantial uplift and erosion, on a rock that had been (tectonically) buried to 700 MPa and 700 °C?
- Decompression of at least 200 MPa (representing 6 km of erosion) at 700 °C crosses the melting reaction, implying the partial melting of the metasediments and the formation of migmatites. During uplift the melts will segregate or separate from their source rocks and ascend through the crust, eventually crystallizing as larger plutonic granite bodies at shallower crustal levels.

The c. 460–435 Ma post-kinematic granites may have been generated in this way during exhumation.

6.4 The record of exhumation in sedimentary basins

We have already seen in Sections 2, 3 and 4 how the composition and age of detrital minerals and rock fragments can be used to establish the provenance of sediments and in some cases identify the nature of missing source terranes. Garnet is a useful indicator of provenance because it can withstand transport in fluvial and deltaic environments, it is resistant to chemical modification and low-grade metamorphism, and its chemical composition can be specific to its source region. Capitalizing on this last point, the record of an orogen's exhumation may be read in a sedimentary succession from an adjacent basin by matching the chemical compositions of detrital garnets to the compositions of garnets in the sedimentary source region. The results of a study of the composition of detrital garnets extracted from sediments deposited in the Midland Valley and Southern Uplands Terranes are shown in Figure 6.4. Also shown in this figure are the compositional ranges or fields of garnets from various potential source rocks.

The composition of detrital garnets in *c.* 465–460 Ma (mid-Llanvirn) sediments that overlie the Ballantrae Complex of the Midland Valley (Figure 6.4a) plot within the compositional field of garnets from the Barrovian zones of the Dalradian. These data suggest that the neighbouring Grampian mountains were eroding and supplying sediment into the Midland Valley as early as *c.* 465 Ma. Of additional interest is that some garnets have compositions identical to those from blueschist-facies rocks; the source of these rare garnets is unclear, but they may have been sourced from a nearby subduction zone.

Figure 6.4b shows the compositions of detrital garnets from sediments of *c.* 457 Ma (early Caradoc) and *c.* 450 Ma (late Caradoc) from the Southern Uplands Terrane. Several important points emerge from the figure. Firstly, the samples contain a few eclogite- and blueschist-facies garnets from the subduction zone complexes. Secondly, the majority of garnets are from a Barrovian source, but interestingly, the earlier garnets have compositions similar to low-grade garnet whereas the younger garnets include compositions that are

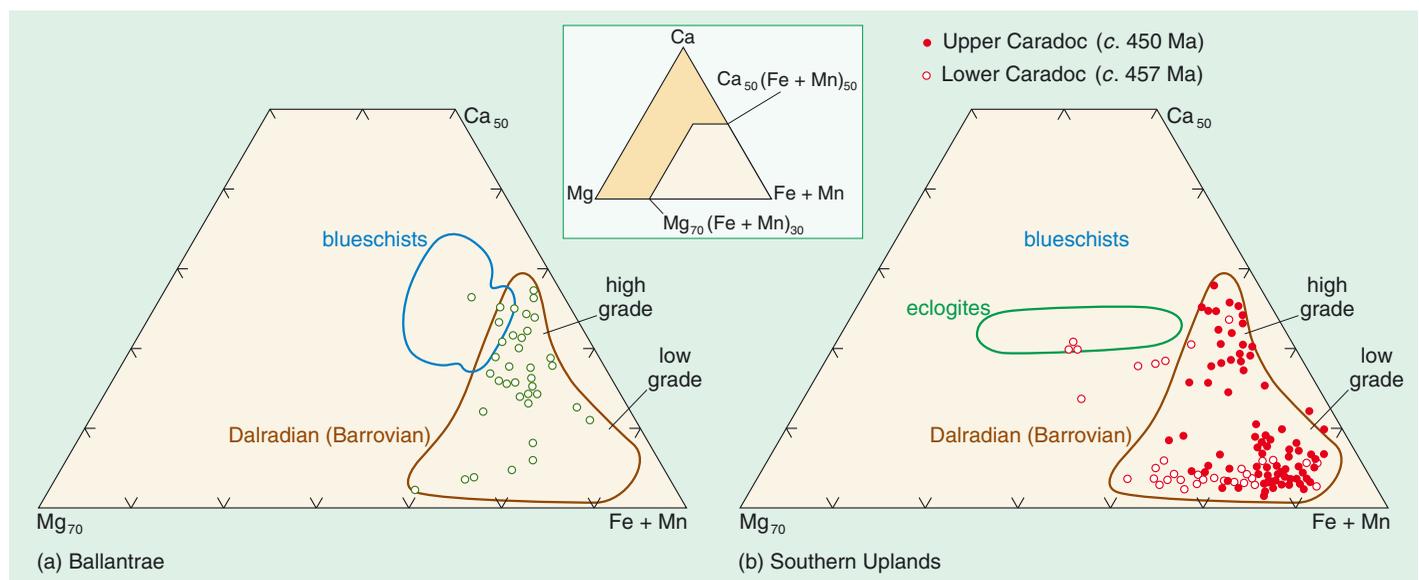


Figure 6.4 The composition of garnets from various sources shown on Ca–Mg–(Fe+Mn) discrimination diagrams. The compositional ranges of garnet from blueschists, eclogites and Dalradian metasediments are indicated. (a) The composition of detrital garnets from the *c.* 465–460 Ma sediments overlying the Ballantrae Complex of the Midland Valley. (b) The composition of detrital garnets from *c.* 457 Ma and *c.* 450 Ma sediments from the Southern Uplands. The inset shows the location of the plots on the full Ca–Mg–(Fe+Mn) diagram.

more typical of higher-grade compositions. An interpretation of this trend is that it represents a simple unroofing sequence: first low-grade then high-grade garnets were exhumed. Thus by the end of the Caradoc (*c.* 450 Ma) the Southern Uplands Terrane was receiving detritus from the roots of the adjacent Grampian mountains and an associated subduction complex.

The data from the detrital garnet studies indicate that the Grampian Highlands were undergoing significant uplift and erosion and providing metamorphic detritus that was being dispersed southwards by *c.* 465 Ma. Uplift and erosion must have occurred rapidly after the peak of metamorphism, as the detritus is nearly the same age as the sediment in which it lies. In other words, the metamorphic and igneous rocks from the roots of the Grampian mountains had crystallized, cooled, exhumed, eroded and been transported within a period of 5 million years.

6.5 Synthesis: time constraints on the Grampian phase

A constraint on the onset of collision is provided by a cooling age of *c.* 480 Ma obtained on the metamorphic sole of the Ballantrae ophiolite. Age constraints on the end of the Grampian collision event are provided by cessation of collision-related deformation and the onset of isostatic uplift in the Grampian Highlands, and by the arrival of the first erosive products from the mountain belt in nearby sedimentary basins. As direct dating of collision-related deformation fabrics is difficult, an age of *c.* 458 Ma, obtained from the oldest post-kinematic granite yet dated, can only provide an upper limit. The first arrival of metamorphic debris in the surrounding sedimentary basins is dated at *c.* 465 Ma and indicates that at this time the orogen was uplifting and eroding: collision had ceased. The Grampian phase in Scotland was therefore a short-lived, <15 million years (*c.* 480–465 Ma), ‘catastrophic’ event that resulted from the collision of an island arc with the Laurentian margin, an event that was coincident with ophiolite obduction, nappe tectonics, crustal thickening, metamorphism and magmatism.

6.6 How high were the Grampian mountains?

The metamorphic rocks that outcrop across the Grampian Highlands contain mineral assemblages that were formed at pressures of up to 1000 MPa (Figure 5.12), equivalent to crustal depths of some 35 km. Does this mean that these mountains once stood 35 km higher? Well, no. If the eroded 35 km of crust were to be put back in place, its weight would load the crust, and much of the added thickness would be accommodated by the crust being pushed down into the mantle rather than being simply added to the topographic height above sea-level. Because continental crust is less dense than the mantle, and is therefore buoyant, the crust behaves like an iceberg floating in the sea. Thick crust (like large icebergs) lies higher above sea-level and extends further below sea-level than thinner crust. This effect leads to an expected correlation between crustal thickness and mean elevation. The total thickness of crust in the Central Highlands Terrane would have comprised the present thickness (*c.* 30 km) plus the eroded 35 km, making *c.* 65 km in total. This is similar to the thickness of crust in Tibet (*c.* 55–70 km) and the Altiplano of South America (65 km), where the mean elevations above sea-level are 5.5 km and 4 km respectively. Following this argument, it is conceivable that the Grampian mountains, some 465 million years ago, were as high as the Himalaya are today.

6.7 Summary of Section 6

- Isotopic dating indicates that the rocks of the Dalradian Supergroup that were metamorphosed during the Grampian phase began to cool through their closure temperatures at *c.* 473 Ma and continued to cool until *c.* 400 Ma. The majority of the high-grade rocks passed through their closure temperatures at *c.* 470 Ma, shortly after the peak of Grampian metamorphism.
- Uplift following tectonic burial led to partial melting of metasediments, a process that culminated in the emplacement of a suite of post-kinematic *c.* 460–435 Ma granites.
- Detrital garnets in sediments from the Midland Valley and Southern Uplands Terranes have Barrovian-type compositions. These data indicate that the Grampian mountains were eroding and supplying metamorphic detritus as early as *c.* 465 Ma.
- The Grampian phase in Scotland was therefore a short-lived, <15 million years (*c.* 480–465 Ma), catastrophic event that resulted from the collision of an island arc with the Laurentian margin.