2 Regional Geology of the Ballachulish Area

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2.1 Introduction

The purpose of this chapter is to describe the stratigraphy, structure and regional metamorphism of the host rocks to the Ballachulish Igneous Complex. The chapter opens with a description of the geography of the Ballachulish area, and concludes with a discussion of pre-intrusion and post-intrusion uplift in the area.

2.2 Physical Geography

The Ballachulish Igneous Complex is located in Argyllshire on the west coast of Scotland, 20 km south of Fort William and immediately southeast of the junction of Lochs Linnhe and Leven. The area is dominated by Beinn a' Bheithir (see Fig. 2.1), a northward-opening, horseshoe-shaped mountain comprising two main peaks, Sgorr Dhearg (1024 m) and Sgorr Dhonuill (1001 m; see Map 2). To the southeast, across the head of Gleann an Fhiodh, is Sgorr a' Choise (658 m); to the south, across Glen Duror, is Fraochaidh (879 m); and to the west, across Strath Duror, is Ardsheal Peninsula (261 m). The main villages in the area are Ballachulish, by the abandoned slate quarries on the south shore of Loch Leven (see Fig. 2.2), Onich, on the north shore of Loch Leven, Kentallen, northeast of Ardsheal Peninsula, and Duror, in Strath Duror.

Glaciation has moulded the topography of the area. The hills and mountains contain arete ridges, cols, hanging valleys and truncated spurs. The glens are U-shaped valleys. Glacial moraine floors the glens up to an elevation of about 400 m.

Annual rainfall is about 100 in., with the driest period being mid-April to mid-June. Coniferous forest has been planted up to an elevation of 350 m in all of the glens except Gleann an Fhiodh (see Fig. 2.1). The high ground consists of grass, heather and bracken. Outcrop is good in the high ground, but poor in the forested glens.

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Equilibrium and Kinetics
in Contact Metamorphism

8.9 Summary

A concentric sequence of pelitic and semipelitic mineral assemblage zones has been mapped around the Ballachulish Igneous complex. The width of the aureole, as defined by the outer development of Zone II, varies from 400 m (NE contact) to 1700 m (E and W contacts). The width of individual subzones in the aureole are generally proportional to these variations. The widest zones are adjacent to or enclose large expanses of quartzite.

The prograde reactions in the aureole produce profound textural contrasts in the metapelites. In Zone I-III, the pelites are relatively fissile, whilst in Zone IV and at higher grades, assemblages with substantial modal development of K-feldspar and cordierite are classic massive hornfelses.

The petrography of the mineral assemblages, including contact metamorphic overprints of regional grade assemblages, have been described in detail. Schreinemakers' analysis of the main phases in the model pelitic system KFMASH has been done on the assumption of H_2O-bearing assemblages below the onset of anatexis, and H_2O-absent, melt-bearing assemblages in the anatectic zone. The modelled reactions may be linked to provide a continuous schematic petrogenetic grid that accounts for all of the assemblages in the Ballachulish aureole, and is also applicable to other thermal aureoles.

Above the Ms + Qtz breakdown, separate prograde sequences of quartz-bearing and quartz-absent assemblages are developed. The development of these relatively uncommon quartz-absent assemblages is due to passage through prograde reactions which consume large modal amounts of quartz.

The chemical variations of pelitic minerals from 60 contact and regional specimens below the onset of anatexis, and 8 specimens from the anatectic zone, have been examined. With the exception of specimens from the graphitic Ballachulish Slate and those with F-rich biotite, the changes in Mg/(Mg + Fe) ratios for chlorite, cordierite and biotite at different grades are consistent with those predicted by continuous Fe-Mg reactions in the petrogenetic grid. Specimens that contain F-rich biotite are anomalously magnesian, consistent with the theory of Fe-F avoidance in biotite. Graphitic specimens in assemblage IVa are anomalously magnesian because of the relative shift to more magnesian compositions of reaction P2a due to lowered $a(H_2O)$ (see Pattison, Chap. 16, this Vol.).

The Tschermak exchange, (Fe,Mg)Si = 2 Al, operates sympathetically in coexisting chlorite, muscovite and biotite in the various metamorphic zones. By treating (Fe,Mg)Si = 2 Al as a general exchange vector that operates in all amenable phases, an isobaric T-X(Al-Si) diagram may be constructed that accounts for the distribution of low grades assemblages in the Ballachulish area, and for the variation in Si content of chlorite, muscovite and biotite in a variety of regional and contact metamorphic assemblages.

A range of textural features in the pelites indicate localized hydrous retrogression in the aureole. Several of the textures suggest retrograde operation of a number of the prograde reactions [e.g., (P1), (P2b) and (P4a)], and indicate that hydrous fluids were variably present during cooling of the aureole, although not everywhere at the same time and not necessarily in very large volumes. Pelites on the west flank (the Chaotic Zone) are the most extensively retrogressed as well as showing the greatest melting. Release of water from the underlying quartz diorite may be responsible directly for their extensive melting, and both directly and indirectly responsible for their extensive retrogression.

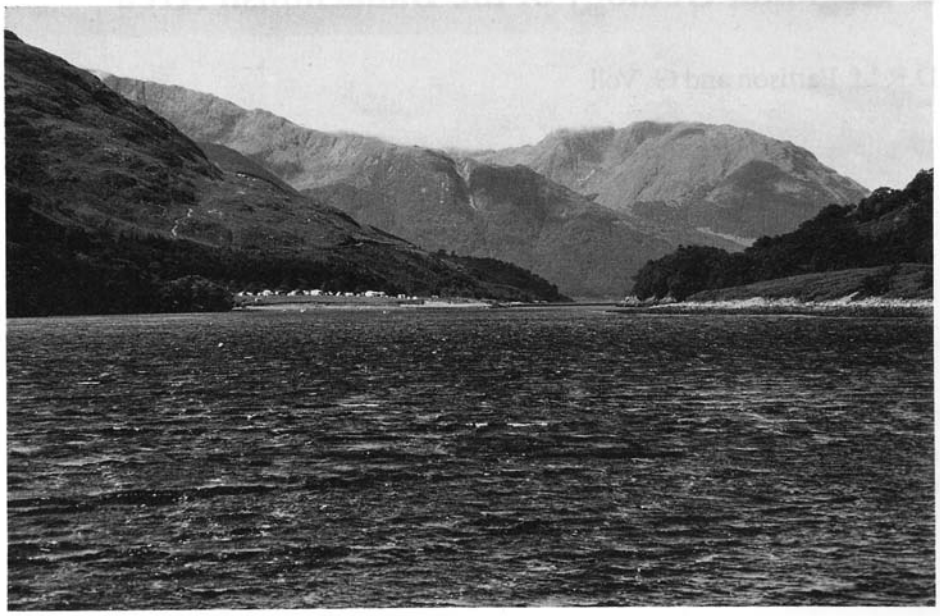

Fig. 2.1. View looking west down Loch Leven to the Ballachulish area. On the *right-centre* skyline is the rounded shoulder of Creag Ghorm, underlain by porphyritic granite. On the *centre* skyline is Meall a' Chaolais, with a sharp ridge running up towards Sgorr Dhearg, to the *left* out of the picture. This ridge is underlain by Appin Quartzite, Appin Phyllite and Appin Limestone striking into the igneous complex. The prominent white scar running down through the trees below Meall a' Chaolais is the gouge zone of the Ballachulish Fault

2.3 Stratigraphy

The Ballachulish Igneous Complex intrudes Lower and Middle Dalradian metasediments of the Appin and Argyll Groups (Bailey and Maufe 1960; Harris and Pitcher 1975; Litherland 1980). In the study area, the Appin Group comprises the Lochaber, Ballachulish and Blair Atholl Subgroups, whilst the Argyll Group comprises the Creran Succession (see Table 2.1). There has been considerable debate about various aspects of the stratigraphy of the Dalradian (see for example Bailey and Maufe 1960; Voll 1964; Litherland 1970, 1980, 1982; Hickman 1975; Roberts and Treagus 1977; Anderton 1985). This chapter focuses on descriptive aspects of the stratigraphic units in the study area, relying principally on Bailey and Maufe (1960), Litherland (1980) and the authors' observations.

Table 2.1 lists the stratigraphic units in the study area. No fossils have been found in these units. High-precision zircon age dating by Rogers et al. (1989) on the Ben Vuirich Granite, emplaced during regional Caledonian orogenesis that followed Dalradian sedimentation, gives an age of 590 ± 2 Ma; this restricts Lower and Middle Dalradian sedimentation to the late Proterozoic or earlier.

Below, each stratigraphic unit is described briefly, starting from the stratigraphically lowest unit (refer to Map 2).

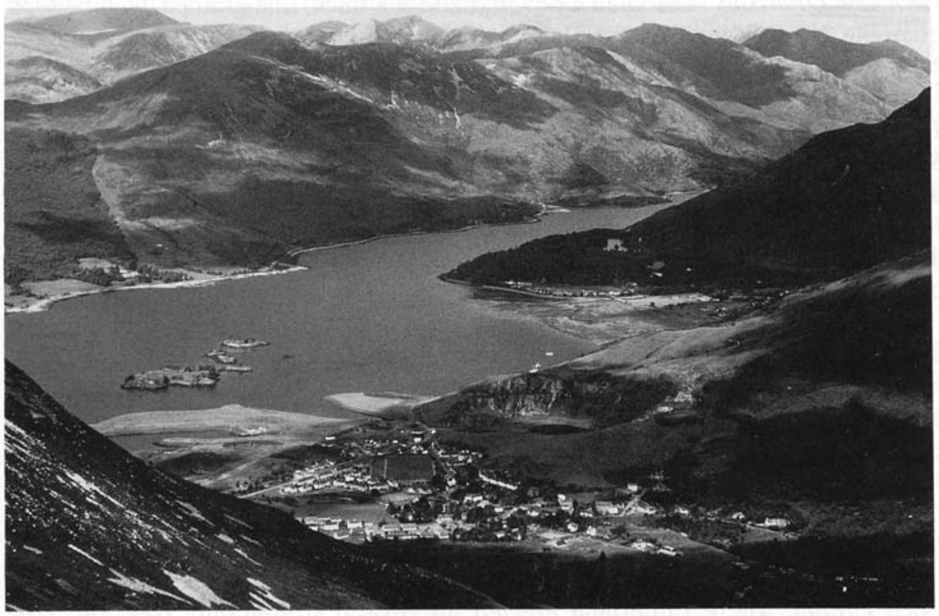

Fig. 2.2. View looking northeast along Loch Leven from Beinn Bhan. The town of Ballachulish and the abandoned slate quarries are prominent *bottom-centre*, with the village of Glen Coe visible further east along the loch. *Top left* is Ben Nevis, with the Mamore range stretching away to the east

Table 2.1. Stratigraphic units in the Ballachulish area

Group	Subgroup	Formation
Middle Dalradian Argyll Group	Creran Succession	('Banded Leven Schists'[a])
Lower Dalradian Appin Group	Blair Atholl	Cuil Bay Slate[b]
	Ballachulish	Appin Phyllite and Limestone Appin Quartzite Transition Series Ballachulish Slate Ballachulish Limestone
	Lochaber	Leven Schist ('Pelitic Leven Schists'[a]) Glen Coe Quartzite

[a]The terms in parentheses are from Bailey and Maufe (1960).
[b]The Benderloch slide forms a tectonic boundary between the Cuil Bay Slate and Creran Succession.

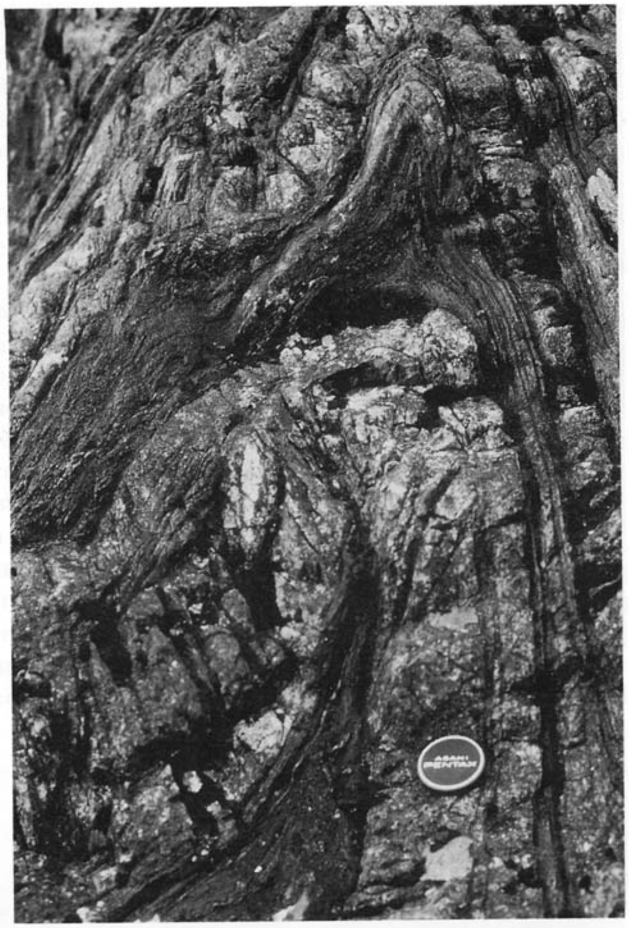

Fig. 2.3. Tight D_1 minor folds in interbedded quartzite-pelite, Appin Phyllite, Coire Guibhsachain. Note the fanned fracture cleavage in the quartzite, and the thickening of the pelite in the fold hinge. The characteristic axial planar slaty cleavage in the pelite has been obscured by contact metamorphic recrystallization

In the Ballachulish area itself, there is divided opinion about the timing and significance of the major folds and faults and small-scale deformation features. The consensus view, held in general but not in detail, by Bailey and Maufe (1960), Roberts (1976), Treagus (1974), Roberts and Treagus (1977) and Litherland (1982), is that the main NE-SW structures and accompanying penetrative cleavage are D_1 features associated with early nappe development in the southwest of Scotland. Deformation during further nappe evolution resulted in refolding of the earlier NE-SW structures, forming the Stob Bhan Synform to the east of the area and the overprinting crenulation cleavage in the southeast of the area (Bailey and Maufe 1960; Roberts and Treagus 1977). Roberts and Treagus (1977) call this later deformation D_3, following an intervening minor D_2 deformation. In contrast, Hickman (1978) considers that

2.4.3 Post-Intrusion Structures

Crosscutting the Ballachulish Igneous Complex is the Ballachulish Fault (Pattison 1985; Weiss 1986), which has a sinistral displacement of about 700 m (see Fig. 2.6). The physiographic expression of the fault can be seen in Figs. 2.1 and 2.5. Prominent fault gouge occurs along its trend. A smaller sinistral strike-slip fault crosscuts the igneous complex to the southeast of the Ballachulish Fault, with a displacement of about 100 m (Weiss 1986; see Fig. 2.6); this is probably related to the Ballachulish Fault.

The Ballachulish Fault was not fully recognized until the present study. Aligned 'shatter belts' were noticed in other areas (Bailey and Maufe 1960; Hickman 1975; Roberts 1976), but with the exception of Litherland (1982), these were generally assumed to predate the igneous complex. The Ballachulish Fault and associated shatter belts line up with a wrench fault near Loch Laggan identified from Landsat Imagery by Johnson and Frost (1977). Continuity with this fault gives a total fault length of at least 80 km. Sinistral stratigraphic displacement along the zone of shatter belts both north and south of the Ballachulish area is consistently in the range 600–1000 m, further suggesting that they join up with the Ballachulish Fault (Pattison 1985). The fault makes about a 15° angle with the Great Glen Fault shear zone, which occupies Loch Linnhe immediately west of the study area (see Fig. 2.6). The orientation, sense of movement and amount of displacement suggest that the Ballachulish Fault is a P-type Reidel shear that splays off the main Great Glen shear zone

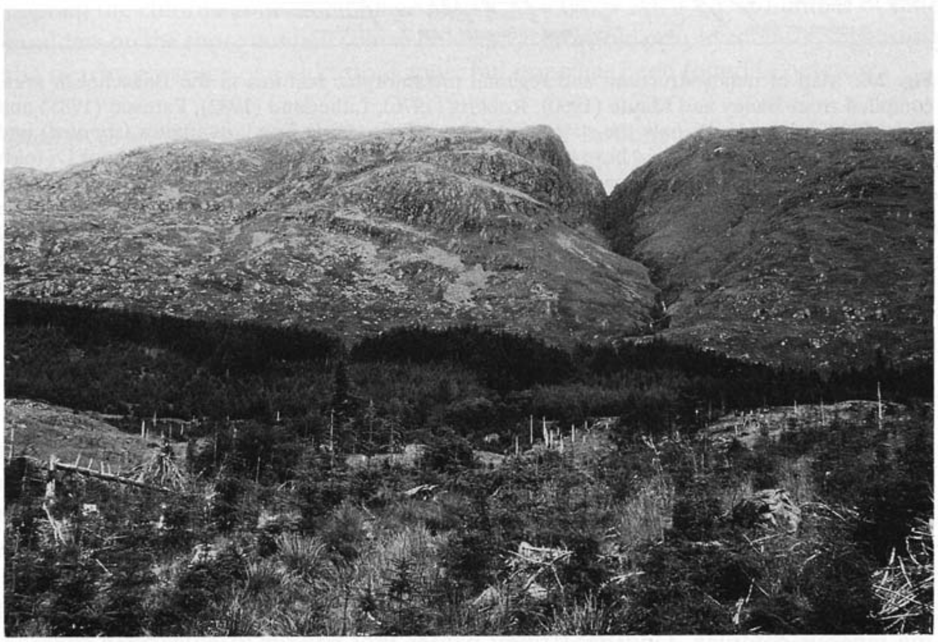

Fig. 2.5. Prominent gorge (Eas nam Meirleach) formed by the Ballachulish Fault crosscutting the Ballachulish Igneous Complex, Glen Duror, looking northeast. To the *left* of the gorge is light-coloured porphyritic granite, whilst to the *right* is darker, low-weathering hypersthene diorite

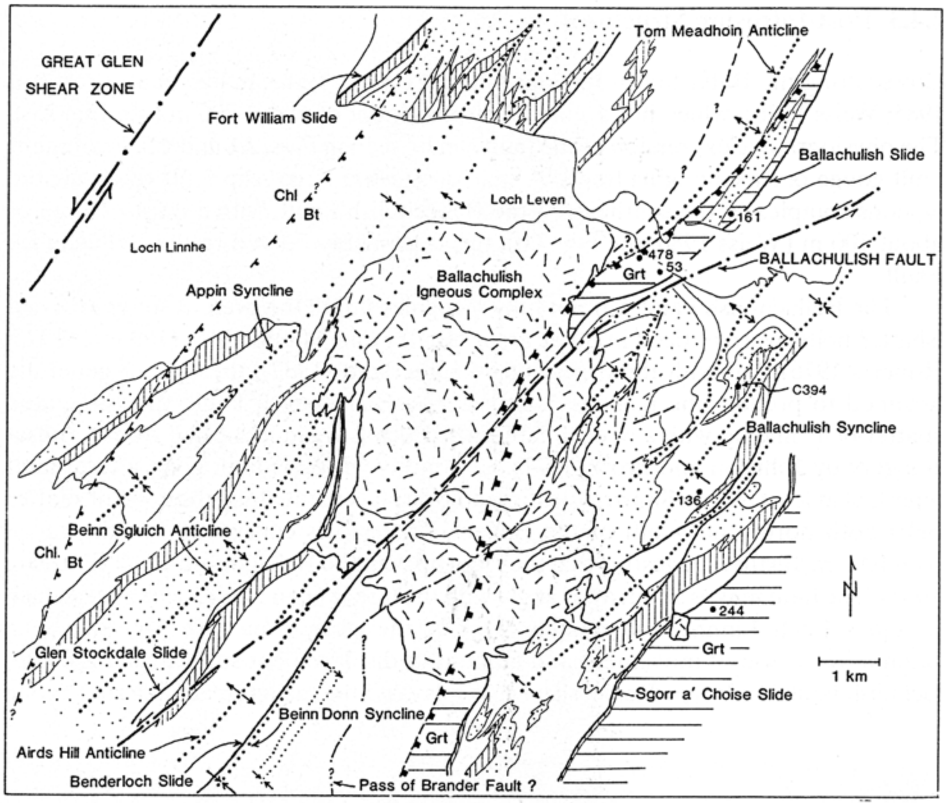

Fig. 2.6. Map of major structural and regional metamorphic features in the Ballachulish area, compiled from Bailey and Maufe (1960), Roberts (1976), Litherland (1982), Pattison (1985) and Weiss (1986). For clarity, only the stratigraphic boundaries (*light lines*), quartzites (*stippled*) and limestones (*vertical line pattern*) have been drawn (for stratigraphy, refer to Map 2). Major D_1 folds (*dotted*) and slides (*medium heavy lines*) have been extrapolated through the Ballachulish Igneous Complex and across Loch Leven. *Ornamented dashed lines* are regional metamorphic isograds (*dots*: biotite isograd; *squares*: garnet isograd), with the ornaments on the high grade side. The *horizontal ruled pattern* refers to garnet-bearing pelites. *Dot-dash lines* represent post-intrusion faults. *Numbers* refer to specimens discussed in text; *numbers with no prefix* are pelitic specimens, whilst C394 is a metacarbonate specimen (see text)

(Johnson 1985 and pers. comm.). Litherland (1982) speculated that the Pass of Brander Fault to the southeast might be the southern extension of the Ballachulish Fault; this seems unlikely, given the straight, well-defined NE-SW trend of the fault south of the igneous complex, in contrast to the speculated arcuate trend of the Pass of Brander Fault (see Fig. 2.6).

It is likely that the Ballachulish Fault was active before and after intrusion of the igneous complex. Unusual striped pelites that appear to have been severely sheared occur in a 10-m-wide zone in the fault zone south of the igneous complex. These have been recrystallized during contact metamorphism to cordierite-bearing

Table 2.2. Regional garnet-biotite geothermometry

Rock	Garnet[a]				Biotite[b]		Temperatures (°C)[c]			
	X_{Fe}	XMg	X_{Ca}	X_{Mn}	X_{Fe}	X_{Mg}	T	HL	FS	HS
D 53	0.606	0.040	0.200	0.154	0.615	0.385	483	477	435	506
D161	0.650	0.042	0.207	0.095	0.618	0.382	480	473	431	504
D244	0.723	0.033	0.166	0.076	0.745	0.255	533	521	494	556
D478	0.628	0.031	0.228	0.112	0.635	0.365	445	441	390	467

All Fe assumed to be Fe^{2+}.
[a]Garnet: $X_i = X_i/X_{Fe} + X_{Mg} + X_{Mn} + X_{Ca}$.
[b]Biotite: $X_i = X_i/X_{Fe} + X_{Mg}$.
[c]Calibrations: T, Thompson (1976); HL, Holdaway and Lee (1977); FS, Ferry and Spear (1978); HS, Hodges and Spear (1982). The preferred calibration is Hodges and Spear. Garnet compositions are rim compositions. P = 6 kbar. Chemical data from Pattison (1985).

of contact metamorphic cordierite in pelites, but its development concentric to the cordierite isograd (see Map 2) suggests that it is of contact rather than regional metamorphic origin (Masch and Heuss-Aßbichler, Chap. 10, this Vol.).

2.5.4 Pressure-Temperature Conditions of Regional Metamorphism

P-T stabilities of the model biotite- and garnet-forming reactions in pelites have not been experimentally constrained. The petrogenetic grid of Harte and Hudson (1979) suggests garnet-forming reaction (R5) occurs at about 570 °C in the Fe-Mg end-member system, but this is a maximum temperature because Ca and Mn in the natural garnets (see below) shifts the reaction to lower temperatures.

Garnet-biotite geothermometry was applied to four specimens (Pattison 1985); three from near the garnet isograd west of the Ballachulish Slide on Loch Leven, and one from the southeast of the area (see Fig. 2.6). Garnet analyses are from the rims of normally zoned, or 'growth-zoned' (Tracy 1982) crystals, whilst biotite analyses come from fresh, unzoned crystals. The mineral chemical data and derived temperatures are listed in Table 2.2. The calibration of Hodges and Spear (1982) is favoured because this is based on the experimentally reversed calibration of Ferry and Spear (1978) with a correction for Ca and Mn in garnet. Assuming a pressure of 6 kbar (see below), a temperature range of 467–506 °C was recorded for the three northerly specimens. This approximately represents the temperature of the garnet isograd. For the southeast specimen, 556 °C was recorded, consistent with the overall southeasterly increase in grade across the area. Uncertainty in the temperature estimates is estimated as ±50 °C (Hodges and Spear 1982).

In carbonates, a calcite-dolomite thermometry estimate of 500 °C (minimum) was obtained from a Dol + Qtz-bearing sample C394 in the pelitic garnet zone (Masch and Heuss-Aßbichler, Chap. 10, this Vol.; see Fig. 2.6). Although it is possible that 500 °C reflects contact metamorphism (see thermal profiles in Pattison, Chap. 16 and