CHAPTER 21

REGIONAL METAMORPHISM

In the same manner that the structural geometry of eastern Labrador is the result of four orogenic events (Makkovikian, Labradorian, Pinwarian and Grenvillian) so are the metamorphic mineral assemblages. It was noted earlier that, the structural configuration of the region is largely the product of two of them, namely the Makkovikian and Grenvillian orogenies. Structures north of the Grenville front (Makkovik Province) were only weakly impacted by post-Makkovikian orogenesis, whereas, in the Grenville Province, structures produced during Labradorian and Pinwarian orogenesis were incorporated into the Grenville Province during the Grenvillian orogeny. Metamorphic assemblages in the Makkovik Province can be interpreted as the product of Makkovikian metamorphism, but, in the Grenville Province, the situation is much less clear, as there are districts where it is certain that the metamorphic assemblages must be pre-Grenvillian, thus providing windows through Grenvillian orogenesis to earlier events.

This chapter attempts to provide a generalized summary of metamorphic products, conditions under which they formed, and linkage to events that caused them. Results achieved during this study are modest and enormous scope remains for more advanced and rigorous studies. The subject matter is divided into three parts, namely: i) a review of select metamorphic minerals in key rock types, ii) a summary of available geothermobarometric results, and iii) interpretation of metamorphism on a province/terrane basis.

21.1 DISTRIBUTION OF METAMORPHIC MINERALS BY ROCK TYPE

Regional metamorphism in eastern Labrador is most readily summarized from the perspective of four groups of metamorphosed rocks, namely: i) pelitic gneiss, ii) other supracrustal rocks, iii) granitoid rocks (including dioritic rocks), and iv) mafic rocks (excluding mafic dykes). Much information on metamorphism of these rock types has already been given when describing individual units, so this section is focussed on providing a synthesis.

The distribution of minerals is based on thin section evidence, having filtered out cases of uncertain identification, or secondary origin. Note that for minerals easily identifiable in the field (*e.g.*, garnet, sillimanite) data users can achieve higher density coverage by selecting the mineral from field names in the database – at some cost of reliability of identification, of course.

21.1.1 PELITIC GNEISS

Key metamorphic minerals in pelitic rocks are shown in Figures 21.1, 21.2 and 21.3. Figure 21.1 shows the distribution of kyanite *vs.* sillimanite. (Two locations where relict andalusite was equivocally identified in the Mealy Mountains terrane are depicted in Figure 7.10.) Excluding a kyanite occurrence in the Smokey area (White Bear Islands granulite complex – *cf.* Section 21.2.1), kyanite occurs in three settings:

i) Along the southernmost fringe of the Groswater Bay terrane, where it abuts against either the Lake Melville or Hawke River terranes.

ii) Sporadically along the eastern flank of the Lake Melville terrane, where it is in contact with the Hawke River terrane (*see* also Figure 7.9C), and

iii) Within the Paradise metasedimentary gneiss belt in the Hawke River terrane.

Along the southernmost fringe of the Groswater Bay terrane, kyanite is part of the stable high-grade metamorphic mineral assemblage. In contrast, in the eastern flank of the Lake Melville terrane, kyanite occurs as a relict mineral, found in the cores of sillimanite clusters. As suggested earlier (Chapter 7), high-grade metamorphism in pelitic gneiss occurred prior to the emplacement of the White Bear Arm complex, hence the pelitic gneisses of the Lake Melville terrane and Paradise metasedimentary gneiss belts were originally a single high-grade pelitic gneiss unit (early Labradorian or earlier), and mineral assemblages later experienced downgrading during Grenvillian orogenesis (*e.g.*, sillimanite retrogressing to muscovite). Metamorphic assemblages in the Paradise metasedimentary gneiss belt are inferred to have only a mild Grenvillian overprint. Kyanite in the Paradise metasedimentary gneiss belt occurs mostly as a reaction product from cordierite breakdown, rather than being part of a stable high-grade assemblage. It is deemed to be a Labradorian product, developed according to reactions outlined in Chapter 7.

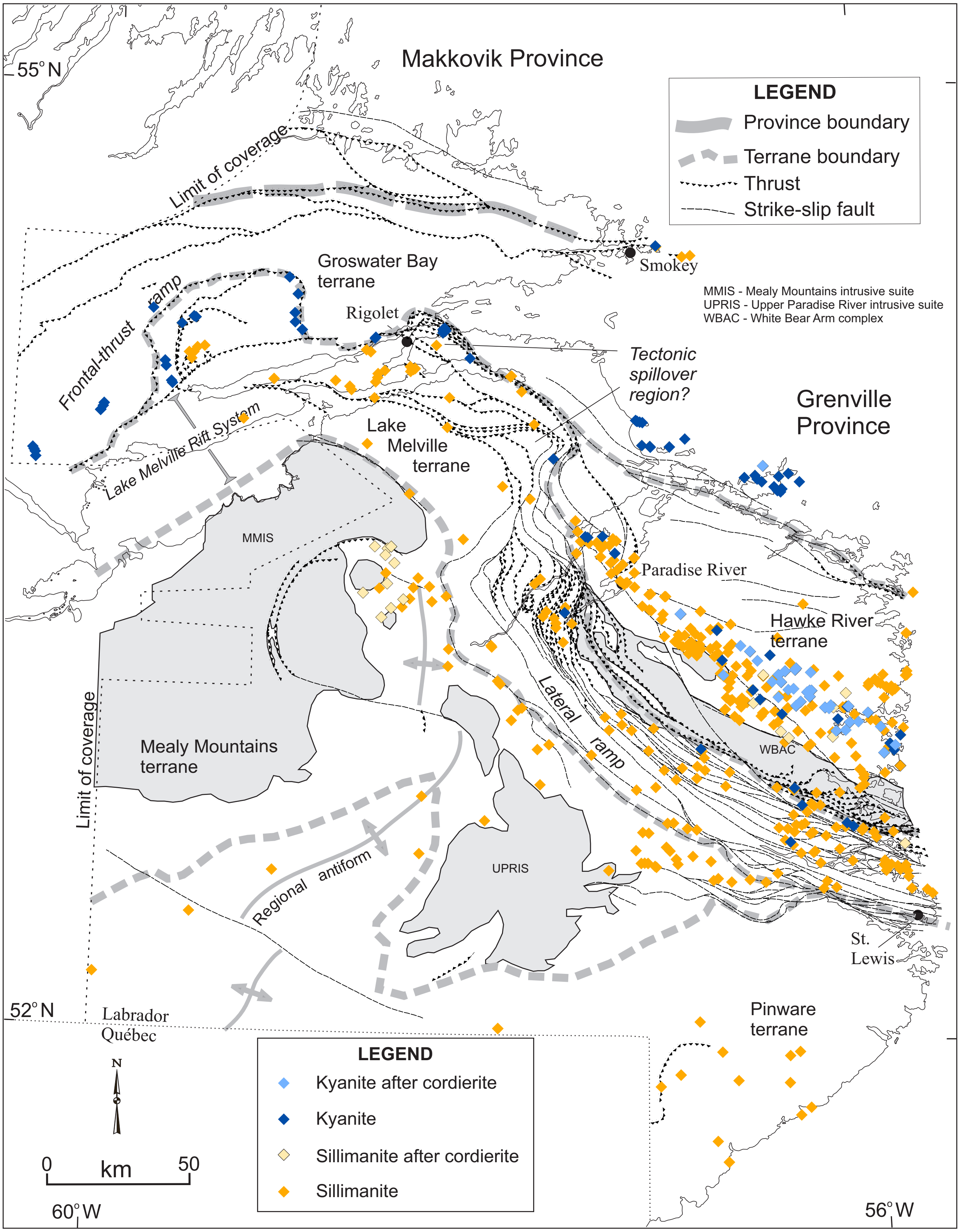


Figure 21.1. *Distribution of sillimanite and kyanite in pelitic rocks in eastern Labrador.*

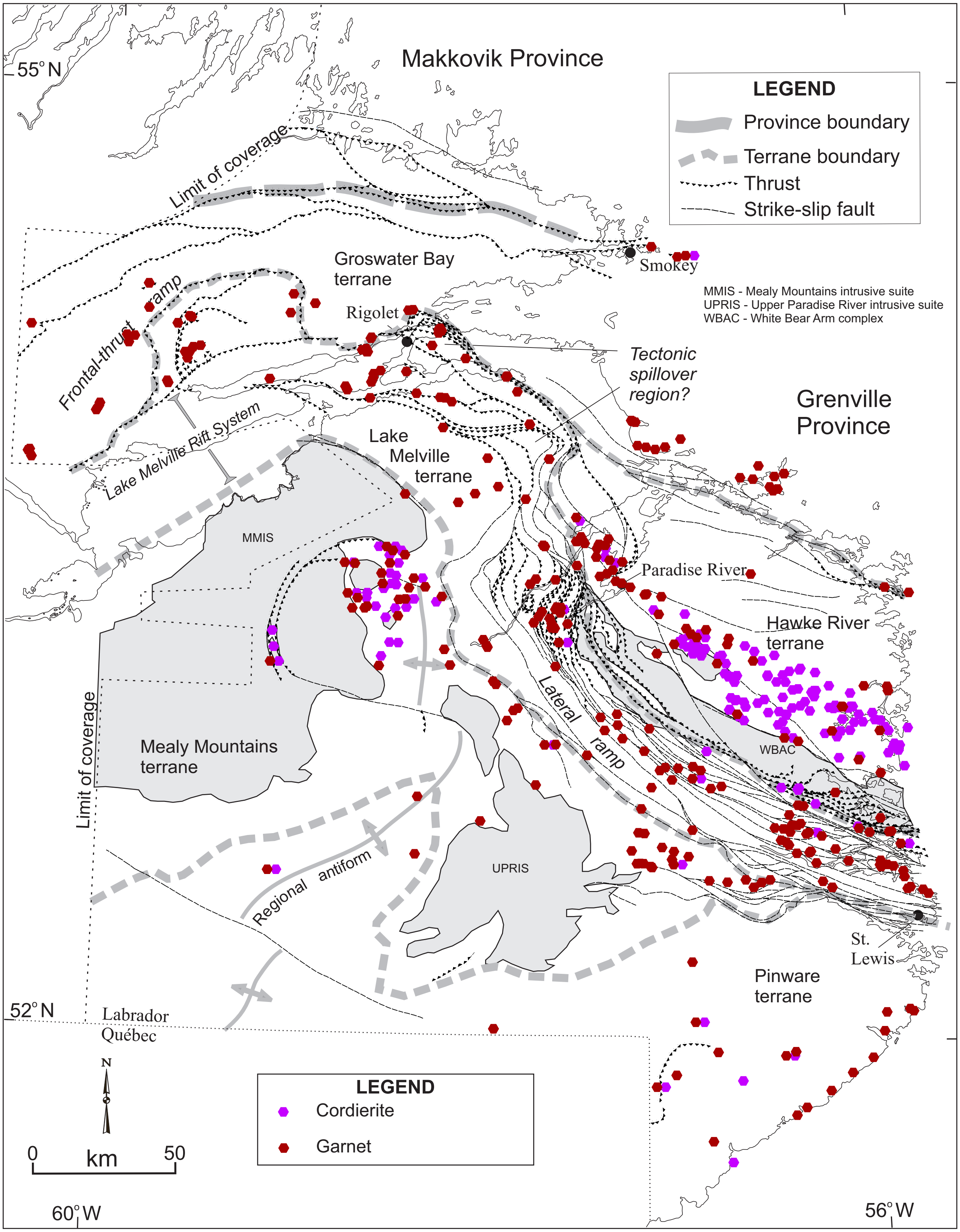


Figure 21.2. *Distribution of cordierite and garnet in pelitic rocks in eastern Labrador.*

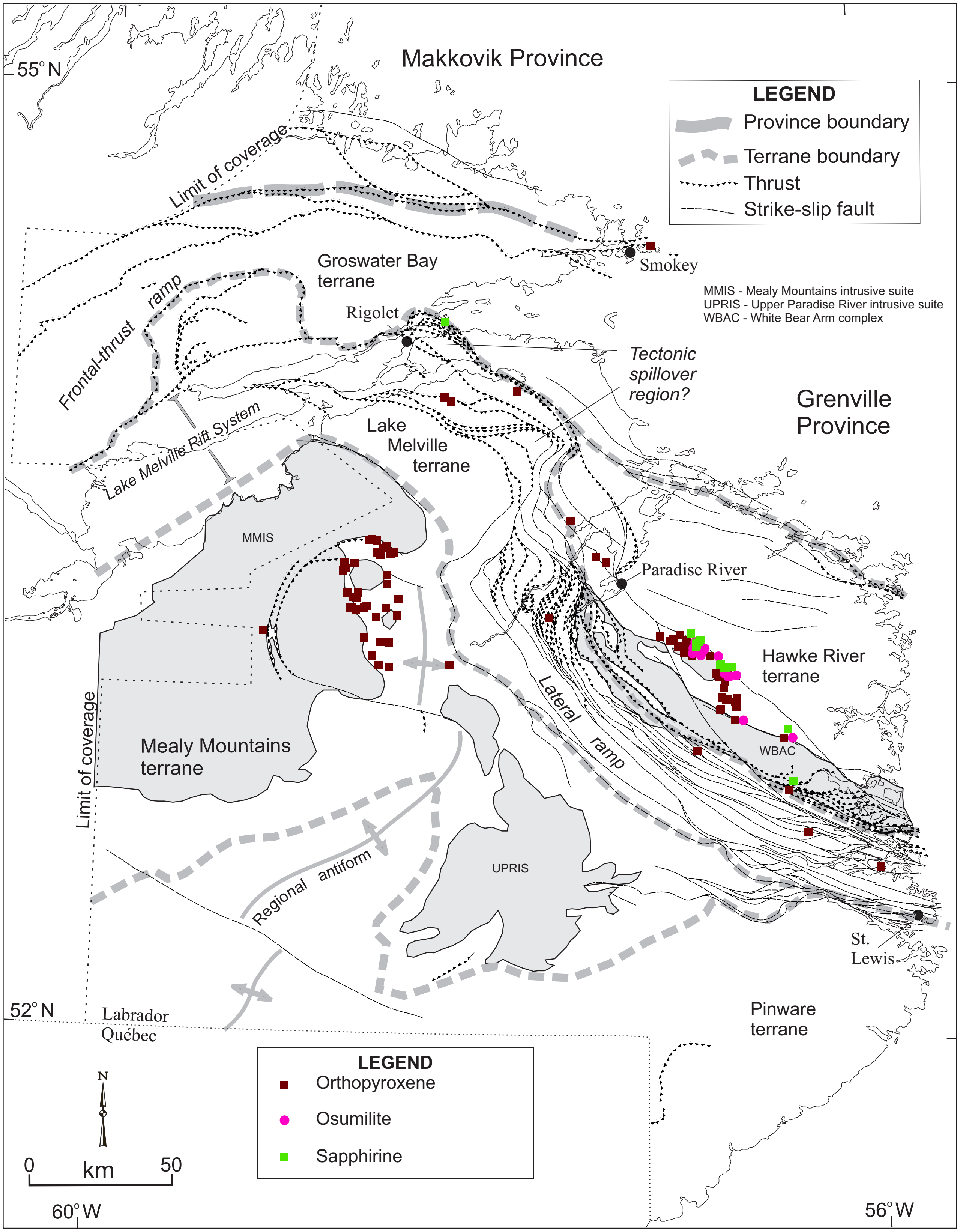


Figure 21.3. *Distribution of orthopyroxene, osumilite and sapphirine in pelitic rocks in eastern Labrador.*

Figure 21.2 shows the distribution of cordierite and garnet. Garnet is concentrated in the Lake Melville terrane and adjoining flanking regions, being sparse and sporadic elsewhere, except north of the boundary between the Groswater Bay and Hawke River terranes. Cordierite is found as a stable mineral in pelitic gneiss in the Paradise metasedimentary gneiss belt, although it is absent from the northern side of its eastern end (where it never formed), and rare in the higher grade northwest end (where it was reacted out) (*cf.* Section 7.3.3.5 and Figure 7.8D). Cordierite is also stable in pelitic gneiss flanking the eastern side of the Mealy Mountains intrusive suite (Section 7.3.6.1). Cordierite is found sporadically in the Lake Melville terrane, but is relict, rather than being part of the stable high-grade parageneses (Figure 7.9C). A few instances of cordierite were also found in the Pinware terrane, where the cordierite is a stable mineral of metamorphic assemblages. Apart from the few scattered occurrences in the Pinware terrane, cordierite in eastern Labrador is part of a regional high-grade mineral assemblage, partly linked to the emplacement of late-Labradorian AMCG suites, and perhaps representative of areas that experienced somewhat lower pressures during high-grade metamorphism.

Figure 21.3 shows the distribution of orthopyroxene, osumilite and sapphirine. Apart from some orthopyroxene occurrences scattered along the length of the Lake Melville terrane, their presence is clearly spatially related to either the Sand Hill Big Pond gabbronoritic–anorthositic intrusion in the Hawke River terrane or the Mealy Mountains intrusive suite in the Mealy Mountains terrane. These minerals (plus hercynitic spinel) can be regarded as having formed in contact metamorphic aureoles, but under deep-seated conditions where the distinction between contact and regional metamorphism is rather blurred.

21.1.2 OTHER SUPRACRUSTAL ROCKS

Apart from pelitic gneiss, other metamorphosed supracrustal rocks include felsic volcanic rocks, psammitic gneiss, calc-silicate rocks, and silica-rich rocks (metachert and quartzite). None are as informative as pelitic gneiss because they either: i) lack widespread distribution, or ii) lack a high level of mineral-identification confidence, or iii) lack informative (at least to the author) mineral assemblages. Despite deficiencies regarding materials or investigator, they are not without interest. For example, scapolite in association with a Ca-rich garnet in calc-silicate rocks is common in calc-silicate rocks in the Lake Melville terrane, but lacking elsewhere, except for a few occurrences in the Pinware terrane (Figure 21.4).

21.1.3 GRANITOID GNEISS

The granitoid rocks, as grouped here, include dioritic rocks, having established that the latter, at the reconnaissance level of data evaluation applied here, serve to augment granitoid patterns, rather than differ from them. The ubiquitous distribution of granitoid rocks makes them invaluable in assessing regional metamorphism. Anorthositic rocks are not addressed because they are compositionally distinct, and late- and post-Grenvillian intrusions are also disregarded because they mostly escaped metamorphism.

One of the most striking features regarding metamorphic assemblages in granitoid rocks is the distribution of garnet and epidote (Figure 21.5). Epidote occurrences have been filtered to remove those of obvious secondary origin (*e.g.*, in veins and fractures), with the caveat that judging stability relationships in thin section is very subjective, and some results may have been excluded or retained erroneously. Garnet poses less of a problem in this regard. The distribution of garnet is very similar to that in pelitic gneiss, namely concentrated in the Lake Melville terrane and close to the border between the Groswater Bay and Hawke River terranes, but being rather minor and sporadic elsewhere. Epidote distribution very clearly correlates with the Groswater Bay and Hawke River terranes. Given geochronological evidence for modest Grenvillian metamorphism in these terranes, the distribution of epidote is interpreted by the author to be Labradorian. It would seem likely that epidote is a reactant in garnet-generating reactions, and that some of the garnet in the Lake Melville terrane is the product of Grenvillian metamorphism.

The distribution of clinopyroxene and orthopyroxene in granitoid rocks is plotted in Figure 21.6. During petrographic studies, an attempt was made to distinguish between metamorphic *vs.* igneous pyroxene, mainly on the basis of extent of recrystallization and apparent stability with other minerals. The figure clearly shows the concentration of pyroxene-bearing rocks in the Mealy Mountains and Pinware terranes, with lesser concentration along the outer (eastern) border of the Lake Melville terrane. The figure was plotted to evaluate two features, namely: i) the spatial association between pyroxene-bearing igneous rocks and granulite-facies country rocks, and ii) the distribution of granulite-facies granitoid rocks. Two concentrations of igneous pyroxene-bearing granitoid rocks (having both clino- and orthopyroxene) are in monzonitic (mangeritic) rocks of the Mealy Mountains and Upper Pinware River (AMCG) intrusive suites. Note that the visual integrity of this figure is distorted by the lack of petrographic data for much of the Mealy Mountains intrusive suite. Field descriptions (Emslie's 1975 and 1995 notes) suggest that, had they been at hand, a similar pattern of pyroxene-bearing granitoid rocks would be evident as seen in those areas for which data are available. To some extent, the concentration of pyroxene-bearing granitoid rocks north of Double Mer and the northwest end of the White Bear Arm complex is also an

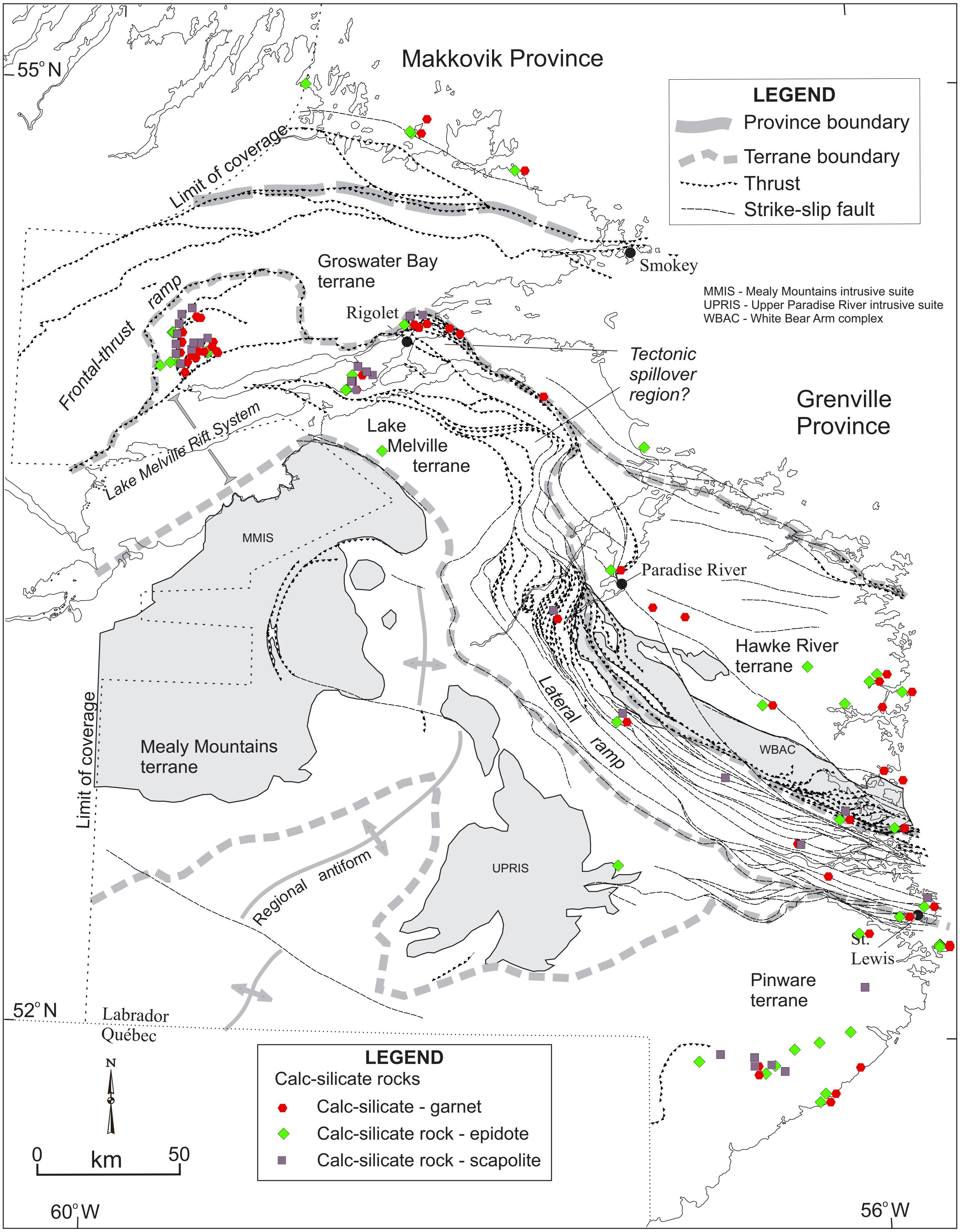


Figure 21.4. *Distribution of garnet, epidote and scapolite in calc-silicate supracrustal rocks.*

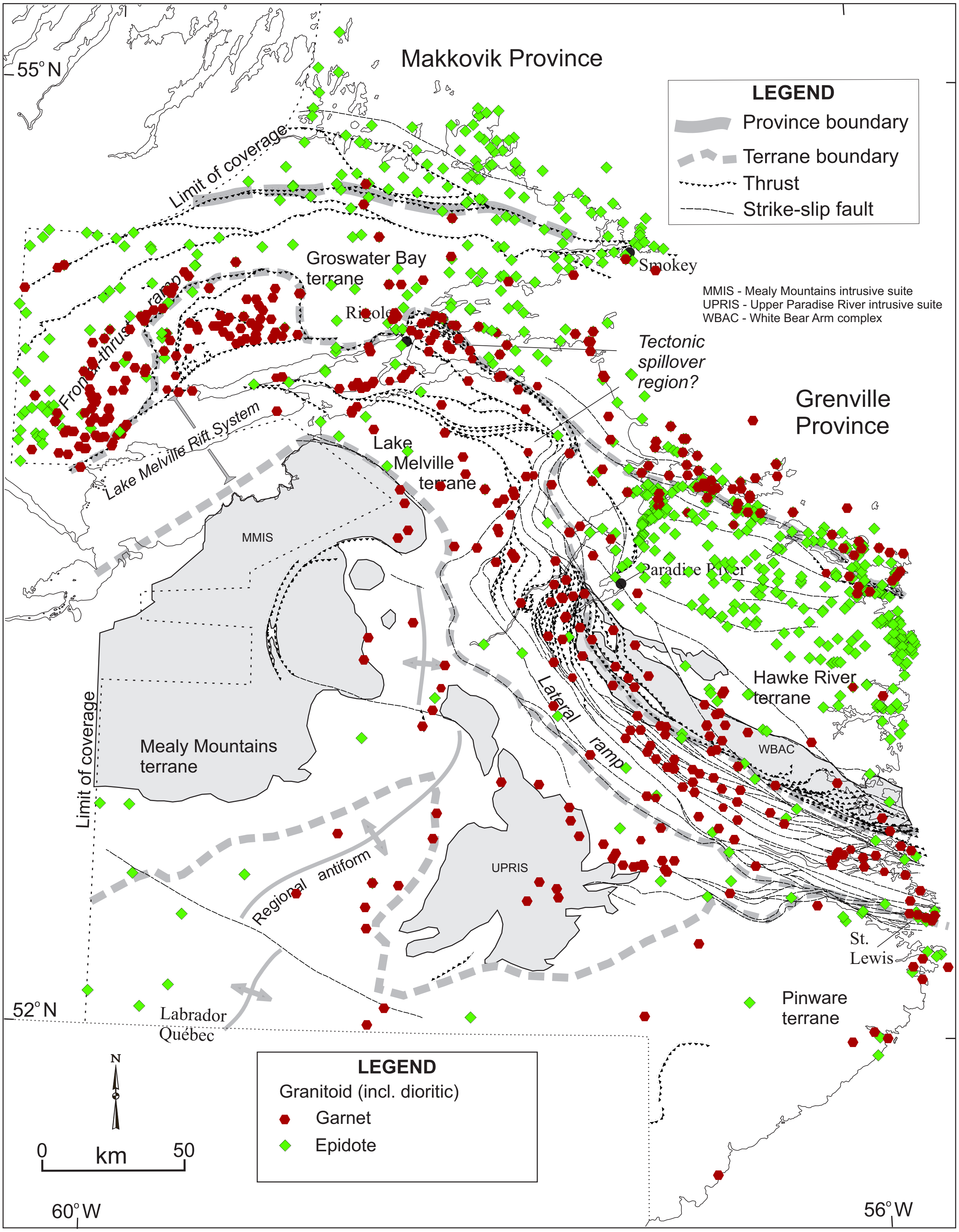


Figure 21.5. *Distribution of garnet and epidote in granitoid gneiss in eastern Labrador.*

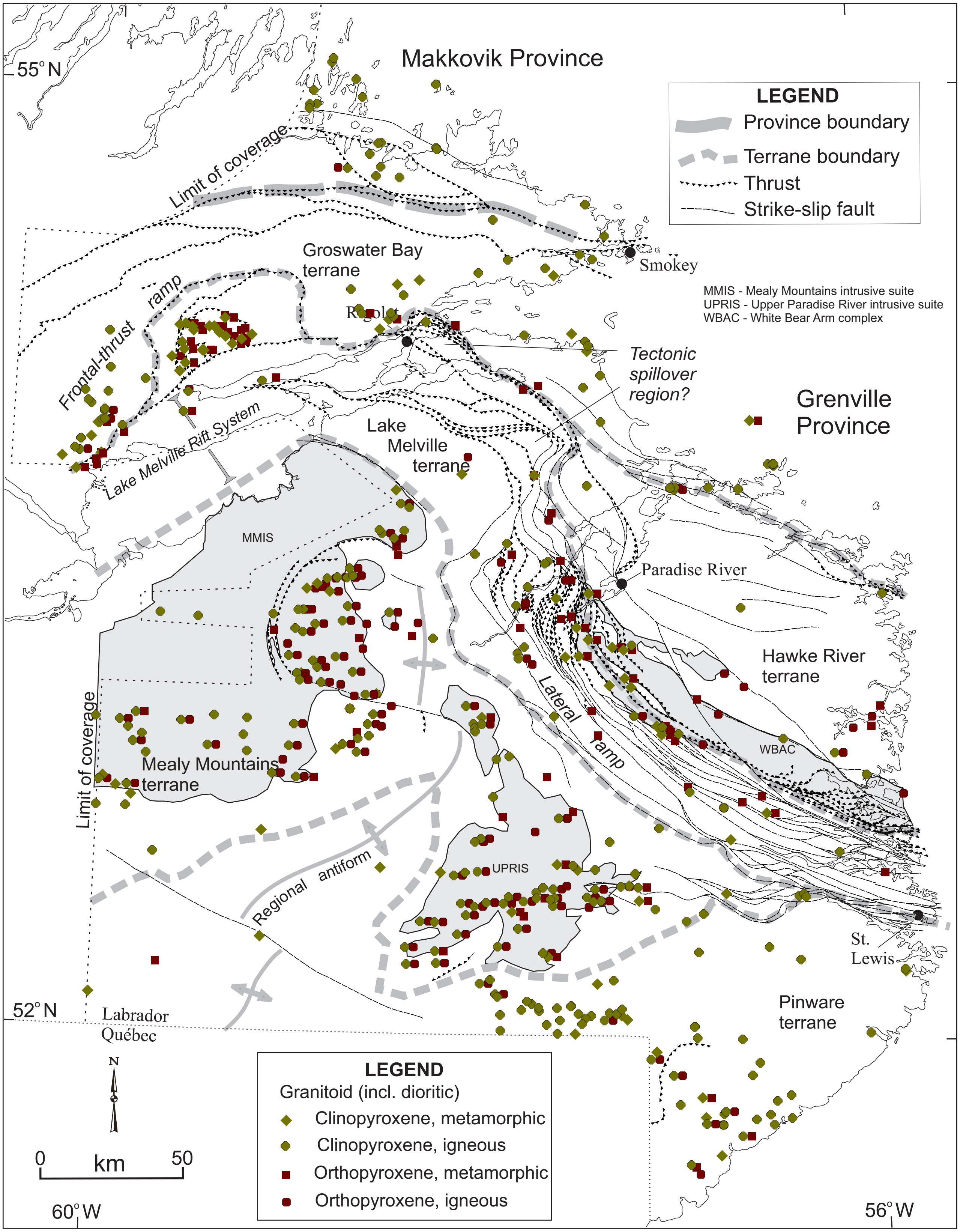


Figure 21.6. *Distribution of clinopyroxene and orthopyroxene (igneous and metamorphic) in granitoid gneiss in eastern Labrador.*

expression of the presence of AMCG-related monzonitic rocks. The granitoid rocks containing igneous pyroxene show a close spatial relationship with those containing metamorphic pyroxene, suggesting a close genetic relationship, which most likely dates from Labradorian orogenesis. A striking exception is a northwest-trending belt of pyroxene-bearing granitoid rocks in the eastern and southern Pinware terrane, which broadly correlate with the distribution of sillimanite ± cordierite ± garnet-bearing pelitic gneiss. Nd isotopic evidence (Moumblow, 2014) suggests that the northern margin of this area correlates with a change in T_{DM} values (<1.80 Ga on the southern side).

Two other, somewhat experimental, figures were constructed for metamorphic minerals in granitoid rocks (Figures 21.7 and 21.8). One shows the distribution of perthite *vs.* microcline and the other the colour of biotite in thin section. The distribution of perthite closely matches that of pyroxene, as do the areas of orange-brown biotite (*vs.* microcline and green biotite, respectively, in pyroxene-absent areas). These features correlate with higher temperature igneous and metamorphic rocks.

21.1.4 MAFIC ROCKS

Mafic rocks addressed here omit mafic dykes because, by virtue of their recognition as discordant intrusions, they typically postdate the metamorphism evident in their host rocks. Late- to post-Grenvillian mafic dykes, the Long Range dykes and Phanerozoic dykes are also excluded. Michael gabbro has been included.

One of the key features in mineral assemblages in mafic rocks is reaction between olivine and plagioclase to yield various coronal minerals. The most characteristic of these are double orthopyroxene–amphibole coronas mantling olivine, which give way to garnet coronas at higher metamorphic grades, and, concomitantly, generate polygonal orthopyroxene in the cores of former olivine crystals. Mafic, granoblastic, (two-) pyroxene, garnet granulites are the high-grade end product of these reactions. Figures 21.9 and 21.10 demonstrate the same conclusion and should be considered together, having only been separated to aid clarity. Figure 21.9 shows the distribution of primary and relict igneous olivine and coronal and non-coronal garnet. The areas of primary igneous olivine represent the lowest grade rocks, *vs.* the areas of non-coronal (*i.e.*, granoblastic) garnet, which represent the areas of highest grade. Figure 21.10 shows the distribution of double orthopyroxene– amphibole-bearing coronitic mafic rocks as well as the distribution of those rocks bearing non-coronal (*i.e.*, granoblastic) orthopyroxene. The double orthopyroxene–amphibole coronitic rocks represent the lower grade mafic rocks, whereas the metamorphic orthopyroxene represent the highest grade mafic rocks. The two figures, between them, show increasing metamorphic grade progressing southward across the Groswater Bay terrane and across the White Bear Arm complex toward the southwest. Regionally, the highest grade mafic rocks are at the outer (eastern) edge of the Lake Melville terrane.

21.2 PRESSURE–TEMPERATURE ESTIMATES

Various studies, some more formal than others, have attempted to provide estimates of metamorphic pressures and temperatures in eastern Labrador (Owen *et al.*, 1988; Gower and Erdmer, 1988; Corrigan *et al.*, 2000; van Nostrand, 1988; Arima and Gower, 1991; T. van Nostrand, personal communication, 1989; Owen and Greenough, 1995; V. Owen, personal communication, 1987). The main focus here is on P–T estimates obtained from pelitic gneiss assemblages, all of which contain either kyanite or sillimanite. These are widespread, and pressure–temperature results can be readily related to mineral assemblages present. Temperature determinations use garnet–biotite exchange thermometry as formulated by Hodges and Spear (1982) or Hodges and Royden (1984). Pressure determinations use garnet–plagioclase–Al_2SiO_5–quartz geobarometry (Newton and Haselton, 1981; Hodges and Royden, 1984).

Some of the investigations also address other rock types, especially mafic rocks. For mafic rocks, temperature determinations mostly applied garnet–clinopyroxene or orthopyroxene–clinopyroxene thermometry (Ellis and Green, 1979; Bertrand and Mercier, 1986), and pressure determinations utilized orthopyroxene–clinopyroxene–plagioclase–quartz (Newton and Perkins, 1982), or garnet–plagioclase–orthopyroxene–quartz (Perkins and Chipera, 1985) barometry. Justification for these choices is given in the original publications. Methods employed by Corrigan *et al.* (2000) for their geothermobarometric study were not reported.

Most of the work was done in the 1980s to 1990s and the author is well aware that the results are inadequate from a present-day perspective. He believes, however, they retain some value, and that there is merit in reviewing and synthesizing extant material, especially as much of it is not generally available.

Results are reviewed from north to south (Figure 21.11), but their interpretation is largely reserved for the next section.

21.2.1 SMOKEY

In the Smokey area, Owen (1985) concluded that pre-Grenvillian granulite-facies conditions may have reached

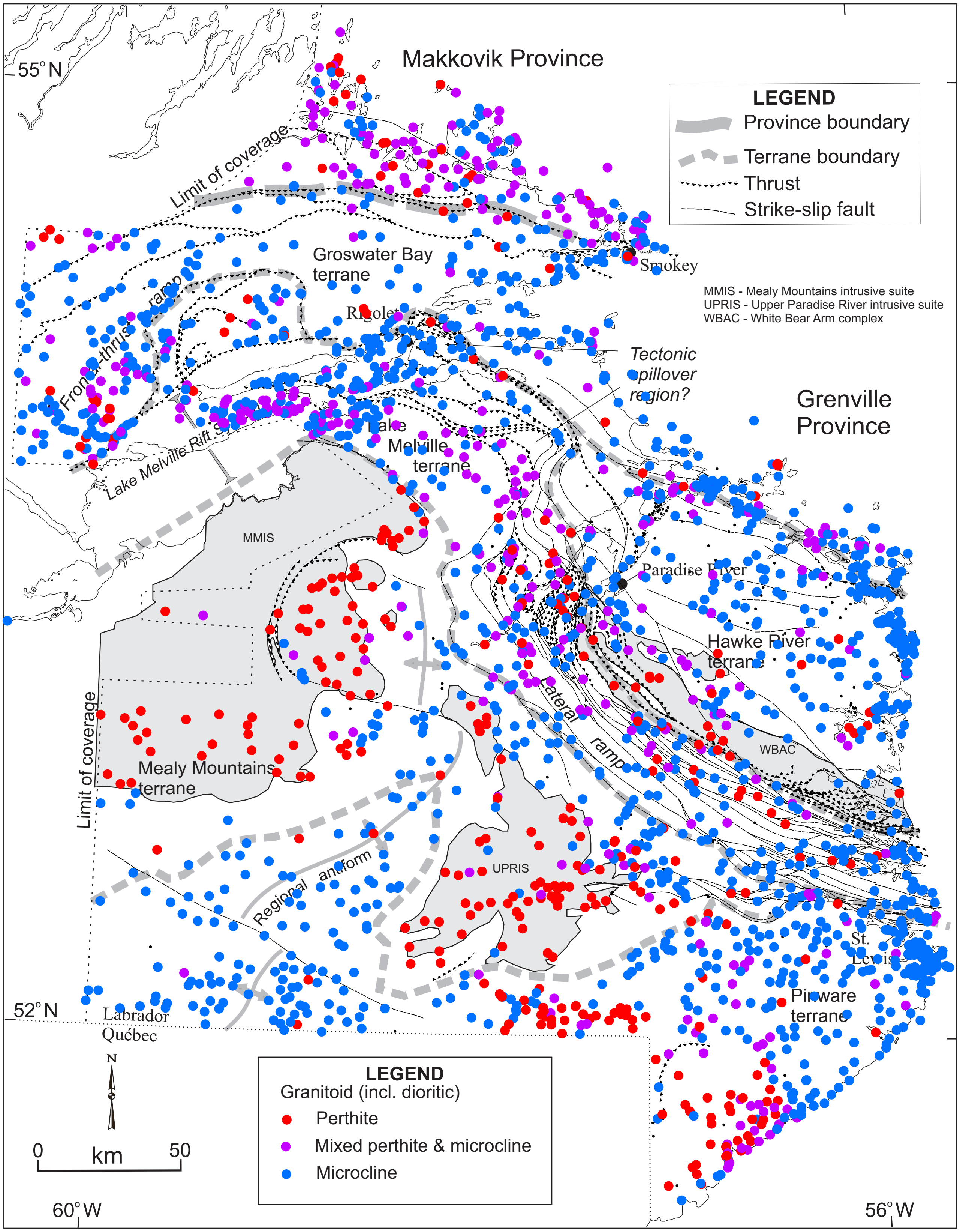


Figure 21.7. *Distribution of perthite* vs. *microcline in granitoid gneiss in eastern Labrador.*

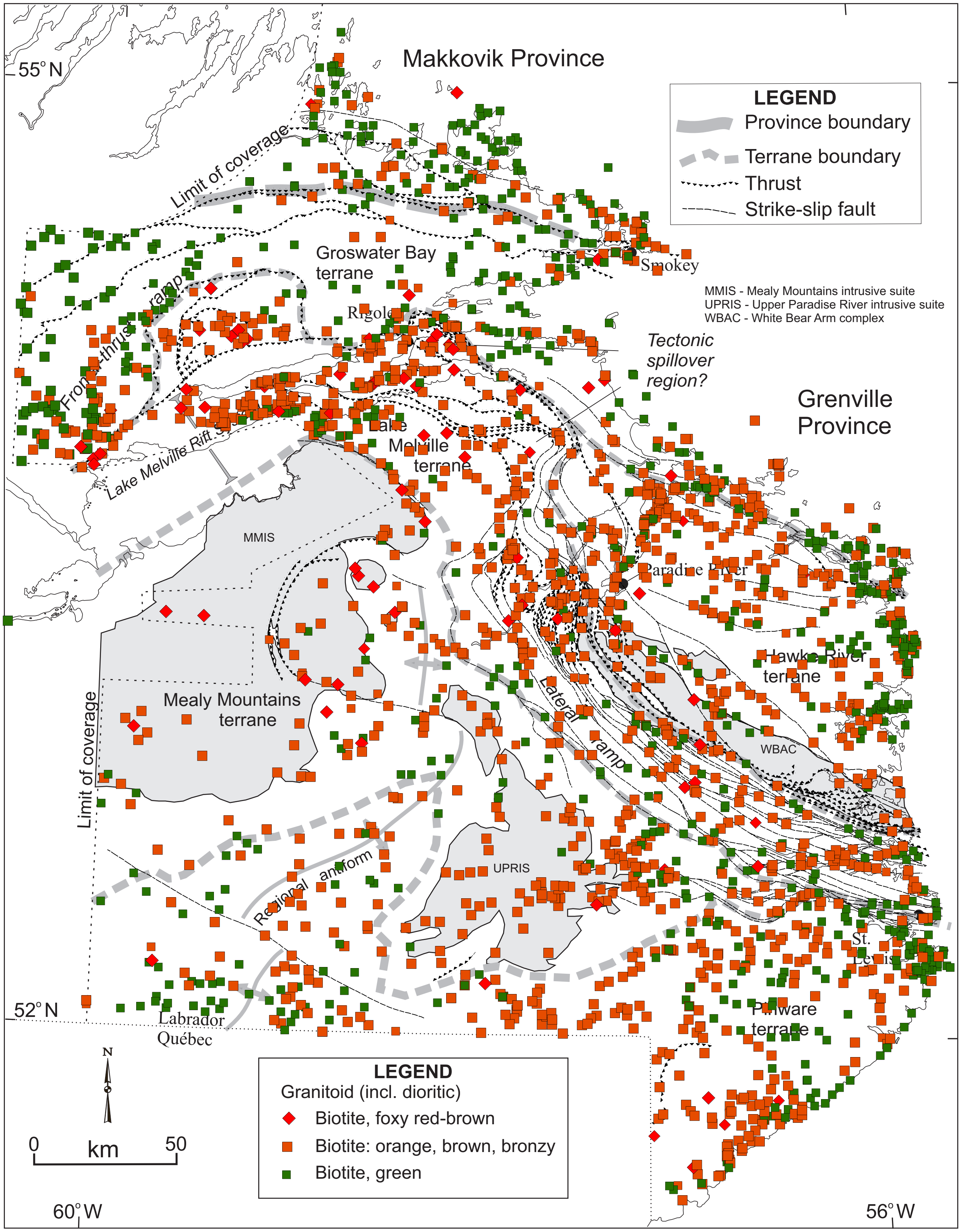


Figure 21.8. *Distribution of orange-brown biotite* vs. *green biotite in granitoid gneiss in eastern Labrador.*

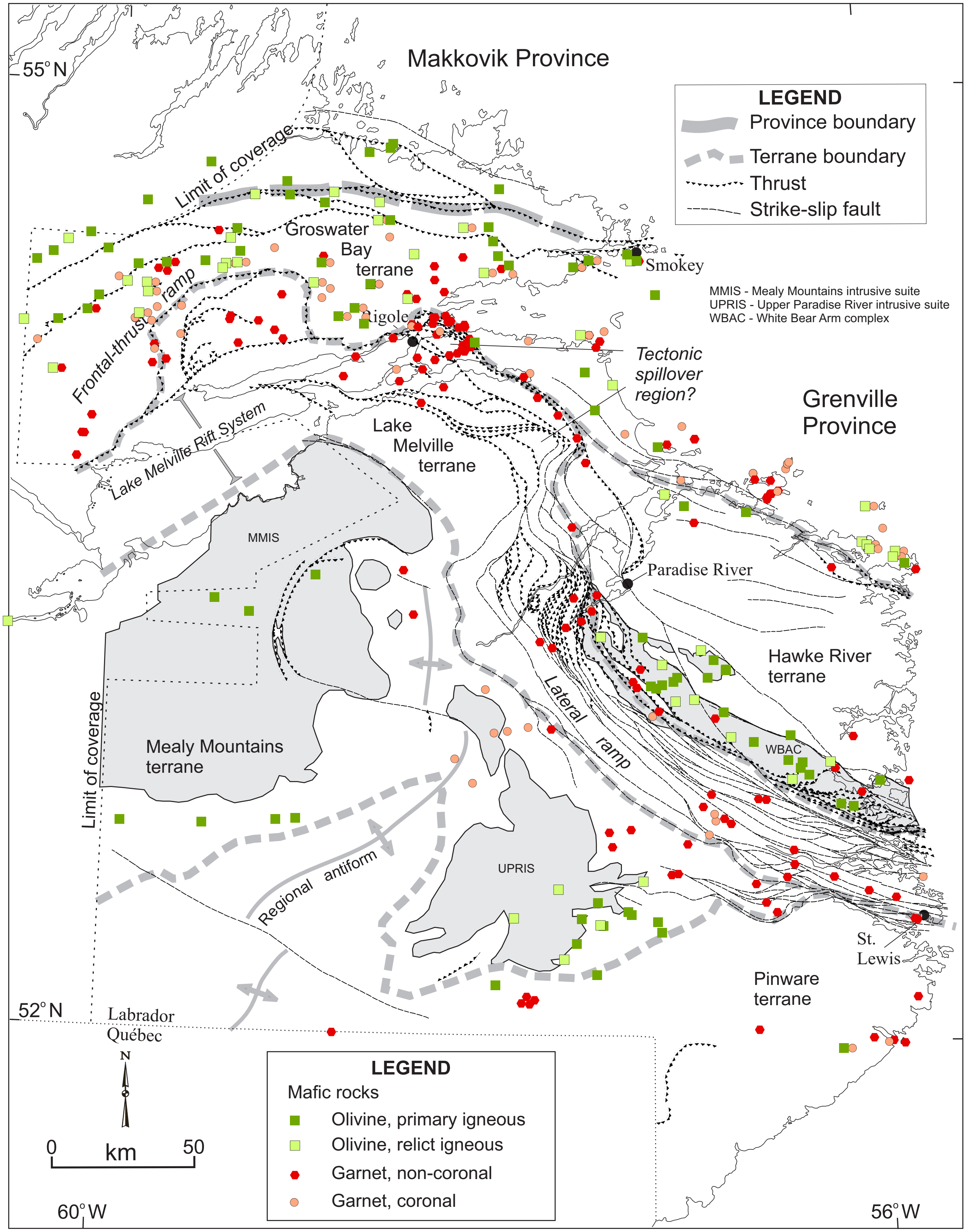


Figure 21.9. *Distribution of primary* vs. *relict igneous olivine and coronal* vs. *non-coronal (granoblastic) garnet in mafic rocks in eastern Labrador. Primary olivine represents lowest grade areas and granoblastic garnet the highest.*

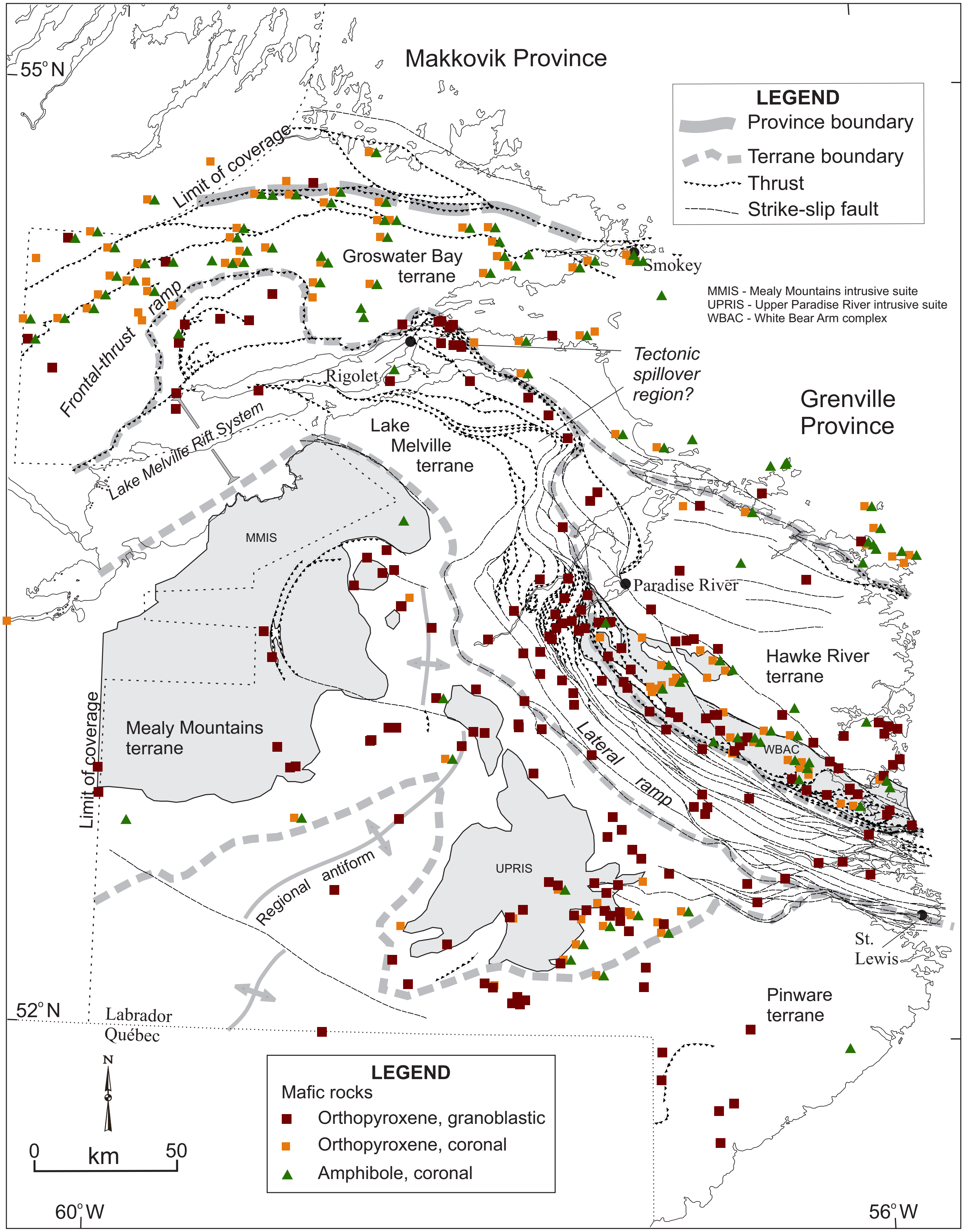


Figure 21.10. *Distribution of granoblastic orthopyroxene* vs. *double coronal orthopyroxene–amphibole (mantling olivine) in mafic rocks in eastern Labrador. This figure is complementary to Figure 21.8.*

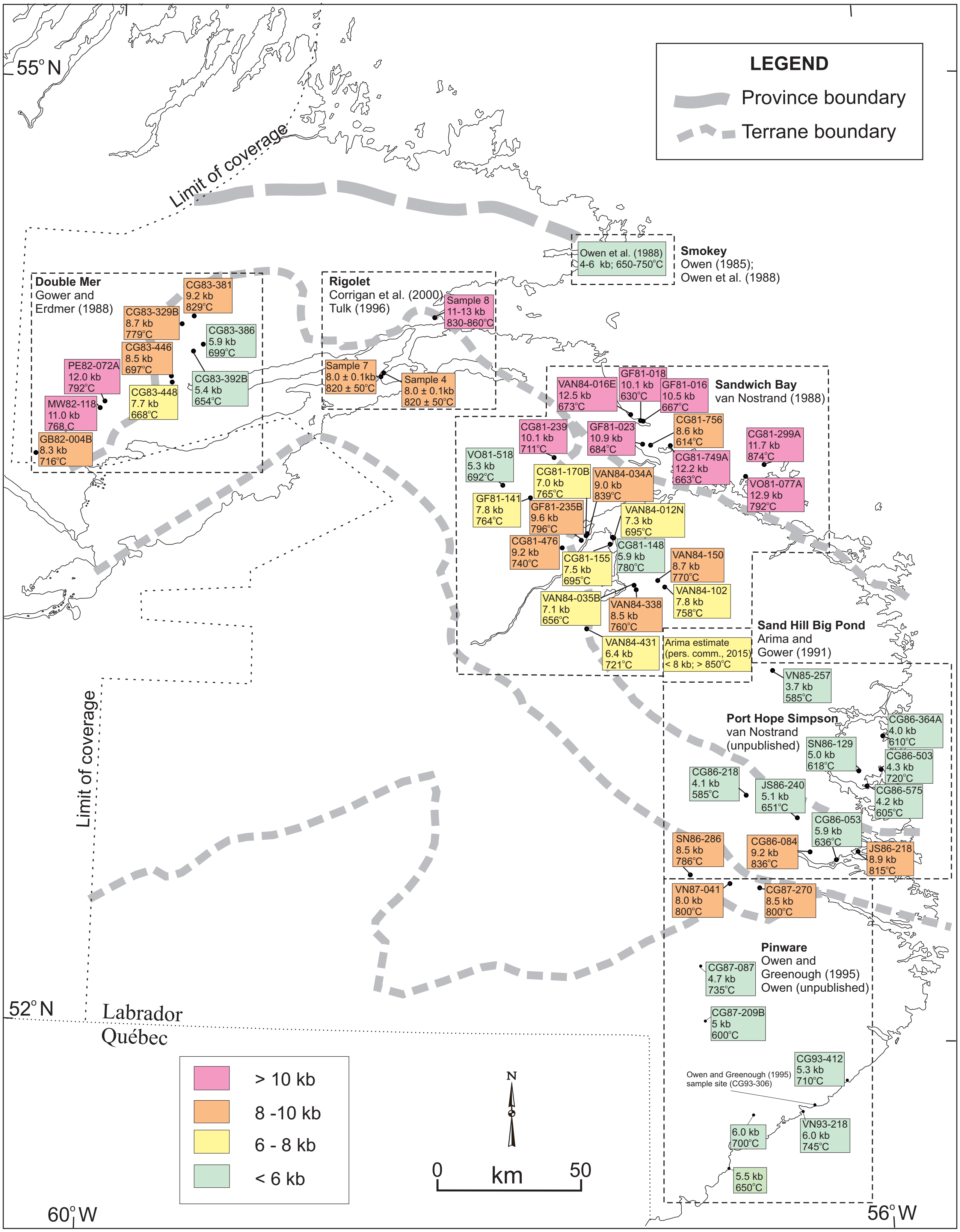


Figure 21.11. *Metamorphic pressure–temperature estimates in pelitic gneiss in eastern Labrador.*

pressures of 7–8 ± 1.5 kb and temperatures of 830°–860°C, followed by pre-Grenvillian retrogression to 5.5 ± 1.5 kb and 650° ± 50°C. Owen *et al.* (1988) revised P–T estimates for the pre-Grenvillian granulite facies event to *ca.* 4–6 kb and 650°–750°C. Their investigation was carried out on the White Bear Islands granulite complex (Section 6.3.3) and included rock types other than pelitic gneiss. Regarding the single kyanite occurrence in the area (Section 7.3.1.8; Figure 21.1), Owen *et al.* (1988) commented that kyanite would not be stable under the determined conditions. Its presence was attributed to either: i) being a xenolith carried from depth during emplacement of the enveloping granitoid rocks, or ii) that mineral re-equilibration (particularly in plagioclase) renders the geobarometric estimates to be no more than minimum values.

21.2.2 DOUBLE MER

In the Groswater Bay terrane, Double Mer area (Figures 21.11 and 7.4), Gower and Erdmer (1988) determined pressure and temperatures for one sample (GB82-004B) of kyanite-bearing pelitic gneiss from the area 34 km west of Mulligan Bay and on two samples (PE82-072A, MW82-118) from the area 16 km northwest of Mulligan Bay. The GB82-004B sample gave 8.3 kb and 716°C, which contrasts with the other two samples having mean values of 11.5 kb and 780°C. Despite having all been grouped in one metamorphic domain by Gower and Erdmer (1988), these results suggest otherwise (and are discussed by Gower and Erdmer), and that sample GB82-004B has closer metamorphic identity to two samples in the Lake Melville terrane (Partridge Point domain; samples CG83-446 and CG83-448; Figure 7.4).

In Lake Melville terrane in the Double Mer White Hills area, two pelitic gneiss samples from domain 3a (CG83-329B, CG83-381; Figure 7.4) gave averaged geothermobarometric pressure–temperature results (Gower, 1986; Gower and Erdmer, 1988) of 8.95 kb and 804°C. Monzonitic granulite samples (CG83-047, CG83-390) from domain 3a gave averaged results of 10.25 kb and 753°C. In domain 3b (Figure 7.4), two pelitic gneiss samples (CG83-386, CG83-392B) show very much lower averaged geothermobarometric pressure–temperature results of 5.65 kb and 677°C. A few kilometres to the east, in domain 3c, two monzonitic granulite samples (CG83-090, CG83-181) gave the highest mean P–T values for the district at 11.35 kb and 711°C.

21.2.3 RIGOLET

Corrigan *et al.* (2000) gave pressure–temperature results for three pelitic gneiss samples from the Rigolet area, although supporting analytical data were not included. One sample (Sample 8), from the Rigolet thrust zone at the Groswater Bay–Lake Melville terrane boundary, was reported as having attained 11–13 kb and 830°–860°C; it has a late Labradorian monazite age. The other two (samples 4 and 7), which come from adjacent sites 30 km southwest of Sample 8, in the Lake Melville terrane, were collectively reported as having 8.0 ± 0.1 kb and 820° ± 50°C; they have early to mid-Grenvillian monazite ages.

Tulk (1996) obtained geothermobarometric data on some coronitic mafic rocks from the same area. Tulk's Sample 12 site is close to Corrigan *et al.*'s (2000) Sample 8 site and gave P–T values of 8.5–11.2 kb and 840°C. Tulk's Sample 52 site is close to Corrigan *et al.*'s Sample 4 and 7 sites and gave P–T values of 9.1 kb and 820°C. This author has reservations regarding the validity of utilizing (demonstrably non-equilibrium) coronitic rocks for geothermometric purposes. The issue was acknowledged by Tulk who, nevertheless argued that local equilibria existed at grain boundaries. In any case, it is evident that broad consistency exists between pressure–temperature results for the two groups of rocks and their assigned terrane.

21.2.4 SANDWICH BAY

In the Groswater Bay terrane in the Sandwich Bay area, van Nostrand (1988) determined pressures from 8 pelitic gneiss samples to be between 8.6 and 12.9 kb and temperatures between 630° and 874°C. With one exception, all samples yielded pressures exceeding 10 kb, and 6 of the 8 samples delivered temperatures below 700°C.

The rest of van Nostrand's samples are from sites farther south, on either side of the boundary between the Hawke River and Lake Melville terranes. The region is interpreted by this author to be a very complex zone of dextral strike-slip faults and northwest-verging thrusts. Results from 15 samples show a pressure range from 5.3 to 10.1 kb and a temperature range from 692° to 839°C. Note, however, only three of the results exceed 9.0 kb and only four of the results show temperatures below 700°C. Clearly, there is a distinct contrast between the Groswater Bay terrane *vs.* the Hawke River/Lake Melville terranes to the south, showing higher pressures and lower temperatures to the north. This distinction is consistent with the distribution of kyanite *vs.* sillimanite.

21.2.5 SAND HILL BIG POND

The study by Arima and Gower (1991) in the Sand Hill Big Pond differs from those mentioned previously in that, although mineral analyses were obtained from all major metamorphic phases, they were not used for quantitative geothermobarometry. Instead, in conjunction with detailed petrographic observations, they were utilized to evaluate the status of various metamorphic minerals (especially osumilite and sapphirine) in the context of a petrogenetic grid. As experimental data were sparse at that time, conclusions regarding pressure and temperature were imprecise. M. Arima (personal communication, 2015) provided an updated pressure–temperature estimate, concluding conditions were (close-to but) less than 8 kb and greater than 850°C. Such an estimate is consistent with that obtained by van Nostrand (1988) farther northwest, with the caveat that temperatures for the Arima and Gower samples are expected to be somewhat higher than in the regional results as the rocks formed in a deep-seated contact metamorphic environment adjacent to the Sand Hill Big Pond leucogabbronorite.

21.2.6 PORT HOPE SIMPSON

Following on from his 1988 study, T. van Nostrand (personal communication, 1989) investigated additional samples of sillimanite-bearing pelitic gneiss from farther southeast, including rocks from the Hawke River, Lake Melville and Mealy Mountains terranes.

Five samples from the Hawke River terrane yield the lowest pressure–temperature results in eastern Labrador, ranging from 3.7 to 5.0 kb and 585° to 720°C. These lower grade pressure–temperature results would seem to be in conflict with the nearby much higher values from the Sand Hill Big Pond area, but two areas are separated by a major northwest-trending, near-strike-parallel fault (downthrown to the northeast) that juxtaposes contrasting metamorphic domains (*cf.* Section 7.3.3.5; Figure 7.7).

Five samples from the Lake Melville terrane can be readily subdivided into two groups. Three show modest P–T values of 4.1 to 5.9 kb and 585° to 636°C, whereas the other two have very much higher values of 8.9 to 9.2 kb and 815° to 836°C. One additional sample (SN86-286) from the Mealy Mountains terrane in the area also belongs to the high P–T group.

21.2.7 PINWARE

The three high-grade P–T results mentioned in the previous section are independently supported by data for two additional sillimanite-bearing pelitic gneiss samples (CG87-270, VN87-041) from the Mealy Mountains terrane analyzed by V. Owen (personal communication, 1997). In fact, the five results show a remarkable consistency, collectively having pressures of 8.0 to 9.2 kb and temperatures of 786° to 836°C. The remainder of Owen's samples (sillimanite–garnet pelitic gneiss) from farther south and all within the Pinware terrane, have pressures between 4.7 and 6.0 kb and temperatures between 600° and 745°C. These are more-or-less comparable with those from the lower grade part of the Hawke River terrane.

One other study has been carried out in the Pinware terrane by Owen and Greenough (1995) on a quartzose paragneiss from Black Bay. The quartzose paragneiss is associated with biotite- and epidote-rich mafic gneiss, and sillimanite- and garnet-bearing pelitic gneiss. The outcome of the study was not so much a determination of metamorphic temperatures or pressures achieved, but, rather, a demonstration that temperatures derived using garnet–biotite geothermometry were dependent on the absolute amount of biotite and garnet present and distances separating them. The authors found that the highest temperatures (*ca.* 700°C) were obtained in the most widely separated grains in leucocratic layers and in the cores of relatively large grains in mesocratic layers. More closely spaced grains in leucocratic layers and smaller grains in mesocratic layers gave lower temperatures (between 700° and 560°C). Integrating the maximum 700°C temperature estimate with information from associated sillimanite–garnet pelitic gneiss implies pressures of *ca.* 5.3 kb.

Going farther afield, mention is also made here of geothermobarometric results by Perreault and Martignole (1988) and Owen and Erdmer (1989) from pelitic rocks in eastern Québec. From the Baie Jacques Cartier area and from the Baie des Ha! Ha!, using oxide and garnet–biotite thermometry, Perreault and Martignole determined that temperatures reached 800°C, except in the Baie Jacques Cartier area, where temperatures in leucosomes attained 900°C. Pressures reached 7.2 kb, based on using ilmenite–sillimanite–quartz–garnet–rutile equilibria. The higher temperatures for the Baie Jacques Cartier leucosomes were explained as due to an external magmatic source. Owen and Erdmer analyzed a suite of 10 samples of pelitic gneiss from an area about 100 km northeast of Baie Jacques Cartier. Temperatures were estimated to be 615°–775°C using garnet–biotite thermometry and core compositions, and a pressure estimate of 5.7 kb was obtained for one sample using garnet–sillimanite–plagioclase–quartz barometry. This sample was also determined to have achieved a temperature of 780°C (based on garnet–biotite thermometry).

21.2.8 GEOTHERMOBAROMETRIC SUMMARY

Geothermobarometric results for pelitic rocks are displayed in pressure–temperature space in Figure 21.12A, B according to Al_2SiO_5 polymorph and according to terrane. Figure 21.12A shows that a large majority of the samples are delivered to their appropriate kyanite or sillimanite fields as indicated by polymorph present in thin section thus lending some credence to the validity of the calculated pressure–temperature values. Six samples contain both kyanite and

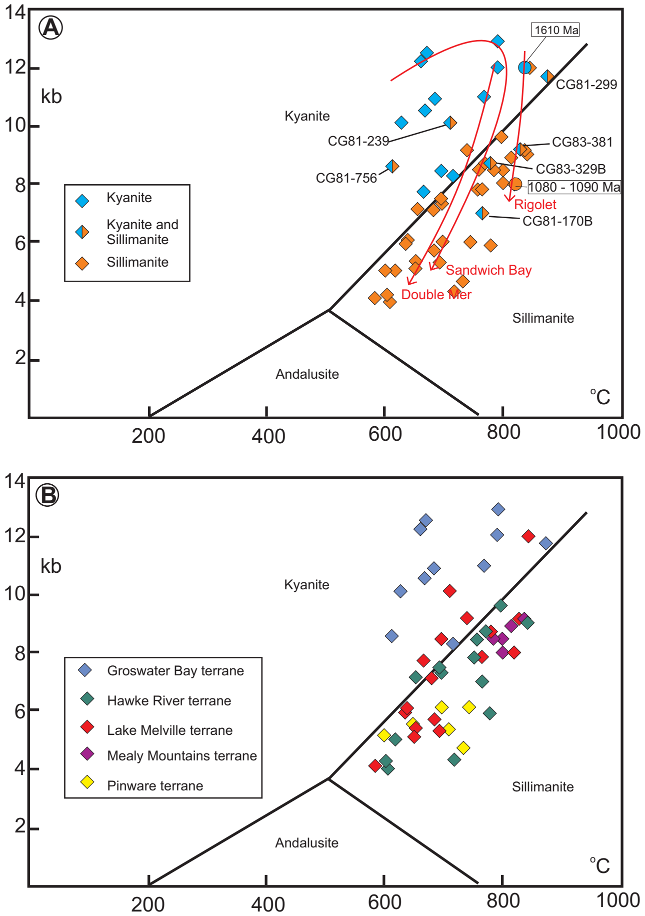


Figure 21.12. *Geothermobarometric pressure–temperature determinations in pelitic gneiss. A. Plotted according to* Al_2SiO_5 *polymorph present, B. Plotted according to assigned terrane.*

sillimanite and are mostly located geographically in kyanite-to-sillimanite stability transition areas, and can be explained as including metastable relict phases.

In Figure 21.12B, the same samples are plotted according to assigned terrane. All the Groswater Bay terrane samples fall in the kyanite stability field, whereas the Hawke River and Lake Melville terrane samples are mostly in the sillimanite stability field, with some overlap into the kyanite stability field, all of which is in accordance with field distribution. The Hawke River and Lake Melville terrane samples mostly both occupy the same P–T space, although there may be a slight bias toward higher temperature for given pressure for the Hawke River terrane samples.

The data show that temperatures in all three terranes were similar, namely between 600° and 800°C, but that pressures in the Groswater Bay terrane (7 to 13 kb) were generally significantly higher than those in the Hawke River and Lake Melville terranes (5 to 9 kb), as previously concluded by Gower and Erdmer (1988) and van Nostrand (1988). There seems to be little difference regarding P–T values in frontal- *vs.* lateral-ramp location in a given terrane.

Various lines of evidence (structural, geochronological) suggest that the Groswater Bay terrane comprises pre-Grenvillian rock assemblages and that it was only modestly affected by Grenvillian orogenesis, whereas the Lake Melville terrane experienced severe Grenvillian tectonism. In the Rigolet area, this has been demonstrated by Corrigan *et al.* (2000) who dated kyanite-bearing pelitic gneiss at the Groswater Bay–Lake Melville terrane boundary to be 1610 ± 4 Ma, and sillimanite-bearing pelitic gneiss (two samples) in the Lake Melville terrane to be 1088 ± 3 Ma and 1080 ± 2 Ma. These are shown on Figure 21.12A.

The suggestion advanced here is that the kyanite-bearing pelitic gneiss was formed during Labradorian or earlier orogenesis and stayed at depth until uplift, equivalent to 4–6 kb (*ca.* 12–18 km), during Grenvillian collisional orogenesis.

An important take-away conclusion from metamorphic studies in eastern Labrador (apart from being a fertile field for future studies), is the huge contrast in pressures experienced by rocks now at the same crustal level, ranging from *ca.* 12 kb in the north to *ca.* 6 kb in the south, which is equivalent to about 18 km of uplift in the north, relative to the south. In contrast, temperatures were much the same both north and south, at 600°–800°C, demonstrating that either north or south did not follow a 'normal' geothermal gradient. Greater heat flux in the south can, perhaps, be linked with widespread Grenvillian magmatism.

21.3 INTERPRETATION OF METAMORPHISM BY PROVINCE/TERRANE

21.3.1 MAKKOVIK PROVINCE (CAPE HARRISON DOMAIN)

Gower (1981) identified two events in the Cape Harrison domain, now equated with the Makkovikian and Grenvillian orogenies, although the effects of the latter are slight. The effects of Makkovikian metamorphism are expressed mainly in the syn-Makkovikian Aillik Group supracrustal rocks, in the mid- to late-Makkovikian Cape Harrison Metamorphic Suite and in the White Bear Islands granulite complex (WBIGC), although the WBIGC can only be equivocally linked with the Makkovik Province. The late- to post-Makkovikian (1800–1790 Ma) and the post-Makkovikian (1720 Ma) granitoid rocks largely have intact igneous assemblages, apart from some recrystallization and retrogression.

In Aillik Group correlatives in the Cape Harrison domain (felsic volcanic rocks, felsic volcaniclastic rocks, or calc-silicate rocks), there is a mild increase in metamorphic grade from west to east. In the west, the felsic volcanic rocks south of Burnt Island (localities indicated on Figure 6.2) are at upper-greenschist facies, having mineral assemblages that include actinolitic amphibole, white mica, chlorite, epidote and prehnite. On nearby Little Double Island, some rocks deemed to have a felsic volcanic protolith include epidote–garnet (*cf.* grossularite/andradite) pods. Farther east, on Double Island, similar rocks, but containing more calc-silicate material, comprise assemblages that include clinopyroxene, garnet, epidote and, possibly, vesuvianite (in CG72-072). Epidote is particularly abundant. The metamorphic grade is estimated to be no higher than lower-amphibolite facies. Continuing east, to south of Deus Cape, the supracrustal rocks are much more strongly deformed and metamorphosed, and show some agmatitic migmatization due to heavy injection by fine-grained felsic material. Metamorphic grade was, at most, lower-amphibolite facies. The easternmost supracrustal rocks occur as minor remnants in the Cape Harrison Metamorphic Suite, the most recognizable of which are calc-silicate pods.

In the Cape Harrison Metamorphic Suite, the dominating granodioritic gneissic rocks are characterized by quartzofeldspathic segregations or are heavily injected by granitic veins. A wide range of agmatitic to nebulitic fabrics is represented. Although the rocks are migmatitic, the metamorphic grade is relatively modest, being no higher than middle-amphibolite facies. Melting was incipient to moderate. In the associated granitoid intrusive rocks, mineral assemblages include relict blue-green hornblende partly pseudomorphed by biotite, epidote, titanite, quartz and opaque minerals. Garnet was recorded sporadically in field notes, but not seen in any thin section. Dating by Ketchum *et al.* (2002) demonstrated that the emplacement of granitoid units, deformation and metamorphism all occurred at *ca.* 1815 Ma. There is no evidence indicating earlier metamorphism affecting the Aillik Group prior to the emplacement of the Cape Harrison Metamorphic Suite.

The White Bear Islands granulite complex contains granulite-facies assemblages in both dioritic–tonalitic gneiss and jotunitic–charnockitic gneiss and remnants of quartzitic to pelitic metasedimentary gneiss, which contain kyanite, sillimanite, garnet and relict cordierite. Granulite-facies mineral assemblages were not found in potentially correlative rocks a few kilometres to the north, so the WBIGC remains the only potentially Makkovikian granulite-facies unit known. As it is situated south of a major east-trending thrust (Cutthroat Island thrust), the rocks may have been exhumed during post-Makkovikian tectonism.

21.3.2 GROSWATER BAY TERRANE

The Groswater Bay terrane is characterized by increasing metamorphic grade, progressing from north to south. This is not well demonstrated in pelitic rocks, which are sparse in the terrane, except near its southern boundary. Nevertheless, sufficient pelitic remnants are available to show change from muscovite-bearing (K-feldspar lacking) pelitic schists in the north to K-feldspar–kyanite–garnet pelitic gneiss in the south (Figures 21.1 and 21.2). The progressive southerly increase is also shown in granitoid rocks, particularly in a change from epidote-bearing to garnet-bearing assemblages (Figure 21.5). The most striking changes are in mafic rocks, particularly in the *ca.* 1450 Ma Michael gabbro, which demonstrates progressive north-to-south change from pristine olivine gabbro in the north, through double orthopyroxene–amphibole coronitic olivine gabbro, to coronitic garnet metagabbro having relict olivine, and, finally, to granoblastic two-pyroxene garnet mafic granulites (Figures 15.2, 21.9 and 21.10). The highest grade rocks experienced P–T conditions of 10–12 kb and *ca.* 800°C.

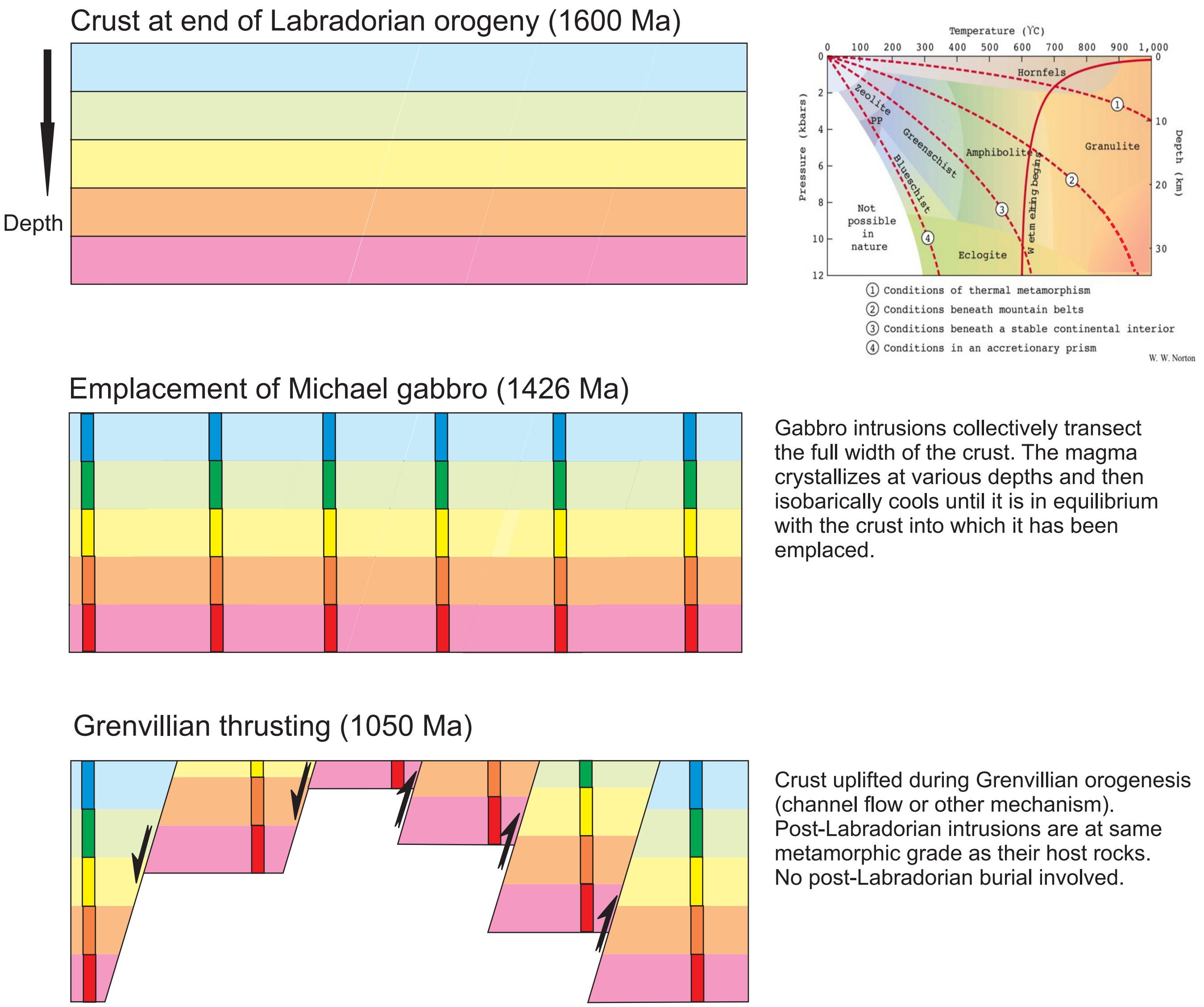
Gower and Erdmer (1988) argued that the high-grade metamorphism was pre-Grenvillian and that the metamorphic grade shown by the rocks is related to the depth from which the rocks were exhumed during Grenvillian orogenesis. The grade of metamorphism evinced by the Michael gabbro was postulated to be a function of variation in crustal level achieved during emplacement, so the present horizontal metamorphic gradient, in effect, now displays the crystallization history of what were once, collectively, vertical columns of mafic magma transecting the full width of the crust (Figure 21.13).

Having advanced this thesis it is as well to keep in mind that questions still remain regarding the extent to which pre-Grenvillian metamorphic mineral assemblages were metastably preserved during Grenvillian exhumation, *vs.* the extent to which such pre-Grenvillian metamorphic mineral assemblages would have re-equilibrated to the lower P–T conditions that such assemblages must have passed through during Grenvillian thrusting.

21.3.3 HAWKE RIVER TERRANE

The metamorphic character of the Hawke River terrane is seen from the perspective of three very different rock groups, namely: i) granitoid rocks of the Earl Island intrusive suite, ii) pelitic gneisses in the Paradise metasedimentary gneiss belt, and iii) mafic rocks of the White Bear Arm complex.

Granitoid rocks of the Earl Island intrusive suite, like their counterparts in the Groswater Bay terrane, are epidote-



W. W. Norton

Gabbro intrusions collectively transect the full width of the crust. The magma crystallizes at various depths and then isobarically cools until it is in equilibrium with the crust into which it has been emplaced.

Crust uplifted during Grenvillian orogenesis (channel flow or other mechanism). Post-Labradorian intrusions are at same metamorphic grade as their host rocks. No post-Labradorian burial involved.

Figure 21.13. *Model to explain metamorphic grade equivalence between Labradorian (or older) host rocks and Mesoproterozoic Michael gabbro that intrudes them, without involving post-Michael gabbro – pre-Grenvillian burial.*

bearing and are sparsely garnetiferous, and provide a compelling reason for conceptually linking the two terranes. A reason for not simply combining them is the contrasting metamorphic character along their common boundary, as indicated by garnet abundance, which implies a higher grade of metamorphism. The presence of Labradorian-age titanite in the Earl Island intrusive suite demonstrates the lack of a severe Grenvillian overprint, and argues in favour of the closely associated epidote also being Labradorian. The status of the garnetiferous granitoid rocks along the GBT–HRT boundary is more problematic. The zone is characterized by severe mylonitization and there is some U–Pb geochronological evidence for localized Grenvillian metamorphic overprint. Regional Ar–Ar and K–Ar geochronological data, however, suggest that Grenvillian overprinting in both the Groswater Bay and Hawke River terranes was not severe (Gower, 2003; Section 22.4). This leads to consideration that, not only must the kyanite-bearing pelitic gneiss in the southern Groswater Bay terrane bordering the Hawke River terrane be Labradorian, but the boundary zone of higher deformation and metamorphism (reaching 10–12 kb and 750°–800°C) between the two terranes is also largely Labradorian.

The pelitic rocks of the Paradise metasedimentary gneiss belt show progressive increase in metamorphic grade both across the belt (increasing to southwest) and along its length (increasing to the northwest) (Section 7.3.3.5). This pattern is modified by a high-pressure, high-temperature contact metamorphic overprint caused by the emplacement of the Sand Hill Big Pond intrusion As this body is Labradorian, it follows that both the contact and regional metamorphism must also be, at latest, Labradorian – a thesis supported by U–Pb geochronological results (Kamo *et al.*, 1996). The only qualifier to this assertion is that uplift of higher grade rocks at the northwest end of the Paradise metasedimentary gneiss belt, where it merges into the Lake Melville terrane (south and west of Sandwich Bay), most likely occurred during Grenvillian orogenesis, as geochronological data indicate a much more significant Grenvillian overprint in this region.

Earlier in this report, the White Bear Arm complex was subdivided into four metamorphic zones, mainly according to coronitic assemblages. These show an increase in grade progressing westward across the body (Figure 11.8). Gower (2005) argued that down-plunge kinematic indicators at the boundary between the Lake Melville terrane and Hawke River terrane indicate north-side-up sense of displacement and that this displacement was Labradorian.

In conclusion, the Hawke River terrane is thus characterized by doubly vergent tectonism (south-side-up on its north flank and north-side-up on its south flank) and that this tectonism is related to Labradorian orogenesis (Gower *et al.*, 1997a). Superimposed on this is an increase in metamorphic grade to the northwest, which is Grenvillian.

21.3.4 LAKE MELVILLE TERRANE

The Lake Melville terrane has an arcuate, dog-legged shape, and is characterized metamorphically by sillimanite- and garnet-bearing pelitic rocks, garnet- and orthopyroxene-bearing granitoid gneisses, and granoblastic, garnet- and orthopyroxene-bearing mafic rocks. The pelitic rocks also have various relict phases (particularly kyanite, cordierite, orthopyroxene). 'Ghost garnet' (*i.e.*, retrograded and pseudomorphed by plagioclase, biotite and quartz) is commonly seen in granitoid, mafic and leucogabbronoritic rocks. Searching on 'ghost' in this report will provide some instances.

It is clear that the rocks achieved granulite facies. U–Pb geochronological data (Schärer *et al.*, 1986; Scott *et al.*, 1993; Corrigan *et al.*, 2000) provide clear evidence for both Labradorian and Grenvillian orogenesis, with a particular emphasis on major Grenvillian metamorphism – in marked contrast to it being modest in the Groswater Bay and Hawke River terranes. Given evidence for progressive prograde metamorphism in Labradorian high-grade rocks in the Groswater Bay terrane and Hawke River terrane as the Lake Melville terrane is approached, it seems likely that the granulite-facies rocks in the Lake Melville terrane also date from Labradorian or earlier times. It seems reasonable to infer that the retrogression that left relict phases mentioned above is Grenvillian. The concentration of garnet in the Lake Melville terrane (*e.g.*, Figure 21.5) coupled with geochronological data suggests that the garnet is, at least partly, a Grenvillian product so, even if Grenvillian metamorphism was not high-grade, it was not trivial either. The two groups of geothermobarometric results determined for the southeastern end of the Lake Melville terrane are interpreted to imply 8–9 kb Labradorian metamorphism and 4–6 kb Grenvillian metamorphism.

21.3.5 MEALY MOUNTAINS TERRANE

Pelitic gneiss in the Mealy Mountains terrane is characterized regionally by sillimanite ± garnet-bearing assemblages, but lacking orthopyroxene. One area that is an exception to this generalization is located on the east flank of the Mealy Mountains intrusive suite. Progressing westward in this area, sillimanite+biotite-bearing assemblages give way to cordierite + garnet-bearing assemblages, which, in turn change to cordierite+orthopyroxene-bearing pelitic gneiss (Figure 7.10). The east-to-west mineralogical gradations in the pelitic gneiss reflect progressively higher temperatures and increasingly anhydrous conditions. The spatial relationship with the Mealy Mountains intrusive suite implies linkage between contact and regional metamorphism during the emplacement of the Mealy Mountains intrusive suite under moderately deep-seated conditions.

Another characteristic of the Mealy Mountains terrane is the presence of two-pyroxene, perthitic K-feldspar monzonitic rocks in both the Mealy Mountains intrusive suite and the Upper Paradise River suite. These bodies postdate Labradorian metamorphism and their mineral assemblages reflect their igneous emplacement conditions. At the same time, the preservation of such assemblages indicates lack of subsequent severe Grenvillian overprint.

Linkage of the pelitic gneiss with the emplacement of the Mealy Mountains intrusive suite clearly indicates that these assemblages were developed during Labradorian orogenesis, although the starting material may well have been pre-Labradorian pelitic gneiss. Lack of a significant younger U–Pb geochronological overprint (Gower *et al.*, 2008b) indicates that Grenvillian metamorphism was mild in the Mealy Mountains terrane.

21.3.6 PINWARE TERRANE

Metamorphic grade increases from northeast to southwest in the Henley Harbour to Red Bay area, and is demonstrated by a range of mineralogical changes, of which muscovite reacting to give sillimanite is one of the more obvious (Figure 13.5). Overall, the mineralogical changes demonstrate gradation from low-amphibolite facies to low-granulite facies. The increase in metamorphic grade was first documented by Bostock (1983), but its characterization is now augmented by more detailed petrographic studies (*cf.* Section 13.1.3.6).

The southwestward increase in metamorphic grade is also evident in granitoid rocks, particularly in the development of two-pyroxene mesoperthitic granitoid rocks (lacking garnet, however). Also, in the western part of the Pinware terrane in eastern Labrador, evidence of increasing metamorphic grade in a southwest direction, is demonstrated by the development of rare orthopyroxene-bearing leucosome segregations in foliated and gneissic granitoid rocks. Although clinopyroxene is widespread in both the Mealy Mountains and Pinware terranes, it is not identical in both regions. In the Mealy Mountains terrane, clinopyroxene is the pale-green variety typical of granulite-facies terranes, whereas in the Pinware terrane it is a brighter, more intense green, characteristic of alkalic rocks. Both titanite and allanite are common in Pinware terrane granitoid rocks, in marked contrast to that seen in comparable rocks in the Lake Melville terrane. Along with other criteria, the presence of these minerals point to somewhat lower grade metamorphic conditions.

In mafic to anorthositic rocks, some recrystallized primary igneous pyroxene is preserved but hydration and recrystallization to amphibole is most common. In the anorthositic and leucogabbronoritic rocks, plagioclase is typically recrystallized and only rarely is any evidence of former coarse-grained igneous texture preserved.

A similar progressive increase in metamorphic grade from amphibolite to granulite facies west-southwest across the Long Range Inlier was identified by Owen and Erdmer (1989). Extrapolation across the Strait of Belle Isle would imply a 50 km dextral offset in the strait, if correlation is made.

The metamorphic assemblages in the pelitic rocks are most likely related to pre-Labradorian or Labradorian metamorphism. The impact of Pinwarian and Grenvillian metamorphism appears to be somewhat variable.

21.4 POST-GRENVILLIAN METAMORPHISM

21.4.1 LATE- TO POST-GRENVILLIAN PLUTONS

Late- to post-Grenvillian granitoid plutons (975–950 Ma) have primary textures and igneous mineral assemblages and are only slightly modified by sericitization of feldspar and chloritization of mafic minerals. Unrecrystallized quartz demonstrates that these rocks escaped the last (*ca.* 990–985 Ma) deformational event to affect the region. The presence of vugs suggests a fairly high level of emplacement. Mafic granulite enclaves within the Upper Michaels River monzonite to granite and Matse River pluton are interpreted as xenoliths of unknown origin.

U–Pb geochronological data from zircon, monazite and titanite (Wasteneys *et al.*, 1997) and K–Ar geochronological data from hornblende and biotite (Gower *et al.*, 1991) were used to estimate a metamorphic cooling rate of *ca.* 3°–4°C per million years for the Pinware terrane between 1040 and 960 Ma.

21.4.2 LATE NEOPROTEROZOIC

The north northeast trending mafic dykes and Lighthouse Cove Formation show moderate, low grade alteration. Olivine is serpentinized, clinopyroxene uralitized, and plagioclase sericitized. Minor hematite-, epidote- or prehnite-filled fractures indicate late-stage, low-grade metamorphism and brittle deformation.