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Low–pressure subsolidus and suprasolidus phase equilibria in the MnNCKFMASH system: Constraints on conditions of regional metamorphism in western Maine, northern Appalachians

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ABSTRACT

The peak of regional metamorphism in western Maine was reached at ca. 404 Ma during the waning stage of Devonian Acadian deformation. Regional metamorphic mineral assemblages in metapelitic rocks range from greenschist to upper amphibolite facies. Subsolidus rocks are characterized by the association andalusite + staurolite; at the highest grades, anatectic migmatites are developed. Results of thermodynamic modeling in the MnNCKFMASH system are consistent with field data and imply a metamorphic field gradient that extends from 3.5–4.0 kbar at lower grades (500–520 °C) to > 4.5 kbar at suprasolidus temperatures that exceeded 700 °C. Regional isotherms that are inferred to have been shallowly inclined at lower grades are closely spaced around synmetamorphic granites and at the migmatite front, consistent with advection-controlled intracrustal redistribution of heat within the regionally extensive thermal high. Peak pressures vary both along and across the strike of the Central Maine belt, which is interpreted to record differential thickening during syntectonic metamorphism. Contact metamorphism associated with the Mooselookmeguntic igneous complex occurred ca. 35 million years after the regional metamorphic peak, and records higher pressure conditions than the regional event. We suggest that the final increment of late-Acadian thickening accounts for the pressure increase, consistent with regional cooling prior to the emplacement of the Mooselookmeguntic igneous complex. Pluton emplacement at deeper levels ca. 35 million years after the peak of Acadian metamorphism reflects lowering of the brittle-viscous transition zone, a level at which ascending magma is trapped, consequent on regional cooling and a steeper geotherm. An overall counter-clockwise *P-T-t* evolution is implied in the Central Maine belt, consistent with that proposed for Acadian metamorphism in western New Hampshire.

INTRODUCTION

Accurate characterization of the pressure (*P*) conditions of metamorphism in moderate- to high-temperature (*T*), low-*P* (andalusite-sillimanite) terranes is problematic. In part this is a consequence of the poorly constrained boundary between the stability fields of andalusite and sillimanite based on experimental or extrapolated thermodynamic data (e.g., Pattison et al. 2002). Furthermore, most of the commonly used *P*-sensitive net-transfer reactions involve garnet, which may be absent in metapelitic rocks metamorphosed at low-*P* conditions, or which may contain an insufficient concentration of the relevant component (e.g., grossular in the GASP barometer) to avoid errors that are large (> or >>1 kbar). In such cases, a powerful method for constraining the *P-T* evolution of terranes characterized by low-*P* metamorphic field gradients is by comparison of inferred stable parageneses with equilibrium phase diagrams constructed in *P-T*-composition *(X)* space for suitable bulk compositions (pseudosections) using internally consistent thermodynamic data sets and associated software (e.g., Berman 1988; Powell and Holland 1988; Spear 1988, 1990; Holland and Powell 1998).

Although the KFMASH (K_2O-FeO-MgO-Al_2O_3-SiO_2-H_2O) model system is a reasonable analogue for metapelitic rocks (e.g., Thompson 1957), additional components that are commonly present in minor quantities, such as Na_2O, CaO, MnO, TiO_2, Fe_2O_3 (O_2), C (CO_2), and ZnO, have important implications for the stability of additional (non-KFMASH) phases such as plagioclase, zoisite, Fe-Ti oxides and graphite, as well as KFMASH modeled phases, particularly garnet, biotite, staurolite, and the supercritical fluid. Incorporating all of these components into a single model system is currently not possible, although the continuing refinement of thermodynamic data and mixing models for pertinent phases has enabled the modeling of metapelitic phase relations in increasingly complex systems, and under both subsolidus and suprasolidus conditions (e.g., White et al. 2001, 2002; Tinkham et al. 2001; Johnson et al. 2003). We compare natural assemblages developed in metapelitic rocks with pseudosections in the MnNCKFMASH (KFMASH + MnO-Na_2O-CaO) model system to provide phase-

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equilibrium constraints on the conditions of syntectonic low-*P* regional metamorphism in western Maine.

REGIONAL SETTING

The Central Maine belt (CMB) comprises a discrete northeast-southwest oriented tract of deformed and metamorphosed Siluro-Devonian metasedimentary rocks and voluminous, predominantly granitic, plutonic bodies. The CMB is one of a number of similarly oriented lithotectonic assemblages that together comprise the northern Appalachian orogenic belt that extends to the northeast into Maritime Canada, and to the south and southwest into New Hampshire, Vermont, Massachusetts and Connecticut (Fig. 1, inset). To the northwest, the CMB is bounded structurally by the Bronson Hill Belt that was deformed and metamorphosed during the Ordovician Taconian orogeny; to the southeast, the Norumbega shear zone system marks the transition between the CMB and the Neoproterozoic-to-Silurian Avalon Composite terrane (Fig. 1, inset). The main deformation, metamorphism, and plutonism within the CMB were the result of Devonian Acadian orogenesis.

The penetrative deformation recorded within the CMB rocks reflects bulk transpression (Solar and Brown 2001a). Oblique (dextral) southeast-side up contraction of the belt was largely accommodated within the broad Central Maine belt shear zone system (e.g., Brown and Solar 1998a); strong dextral transcurrent movement that continued into the Carboniferous was partitioned into the narrower Norumbega shear zone system (e.g., West and Hubbard 1997). The grade of regional metamorphism within the CMB ranges from greenschist to upper amphibolite facies; granulite-facies assemblages occur in Massachusetts (Chamberlain and Robinson 1989). In Maine and New Hampshire, regional metamorphism occurred at low *P*; andalusite is abundant in rocks of suitable grade and bulk-composition. At the highest grade (upper sillimanite zone), anatectic migmatites are developed in metapelitic rocks. The CMB is intruded by composite, late syn- to post-Acadian granites that may be concordant with, or discordant to, the regional fabrics (e.g., Solar et al. 1998; Solar and Brown 1999). Contact metamorphic effects of late syn- and post-tectonic plutons modify the pattern of, or overprint the regional metamorphism, respectively (e.g., Solar and Brown 1999, 2000; Guidotti and Johnson 2002).

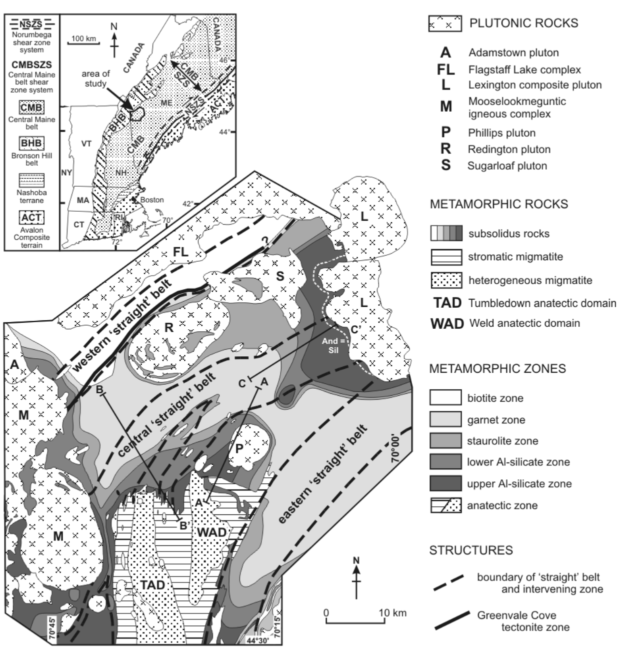

FIGURE 1. Simplified geological map of the study area showing the zonal distrubution of metamorphic rocks and the loction of the major plutons. The limits of the "straight" belts of apparent flattening and intervening zones of apparent constriction are superimposed. The lines (A-A', etc.) show the locations of the metamorphic field gradients discussed in the text. The white dashed line around the Lexington Body marks the And + Sil transiton. The inset shows the location of the field area and the regional context of the Central Maine belt within the northern Appalachians.

GEOLOGY OF WESTERN MAINE

Deformed and metamorphosed sedimentary rocks of the "Rangeley stratigraphic sequence" (Moench 1971; Moench and Hildreth 1976) range from early Silurian to Devonian in age. A basal metaconglomerate fines upwards into a thick sequence of Silurian metaturbidites that are in turn overlain by distal Devonian metasedimentary rocks. Layered and podiform calc-silicate rocks are subordinate. The combined stratigraphic thickness is estimated to be up to 10 km (e.g., Moench et al. 1995). The metaturbidite units dominantly comprise centimeter- to decimeter-scale, compositionally graded layers of metapsammite and schistose metapelite. In rocks that are unmigmatized or weakly migmatized, primary structures such as cross-bedding may be preserved locally. Metamorphic assemblages indicate that the metapelitic rocks are predominantly subaluminous (i.e., plotting on the biotite side of the garnet-chlorite join projected into AFM space).

The stratigraphic succession is folded into kilometer-scale open to tight folds (e.g., Moench et al. 1995). A penetrative moderate to steep, northeast-plunging mineral elongation lineation is ubiquitous. Strain was partitioned heterogeneously. Based on the style and intensity of deformation, Solar and Brown (1999, 2001a) and Brown and Solar (1998a, 1998b, 1999) subdivide the region into kilometer-scale structural zones (Fig. 1). Northeast-southwest trending "straight" belts of apparent flattening, in which a steeply southeast dipping pervasive foliation is strongly developed (S > L fabrics), anastomose around intervening zones of apparent constriction, in which the foliation is only weakly developed and of variable orientation (L >> S fabrics). The heterogeneous distribution of deformation with the Central Maine belt shear zone system has been ascribed to perturbations in the flow regime that resulted from the serial development of thrust-ramp anticlines above Ganderian basement (Solar and Brown 2001a; van Staal and MacNiocaill 2001).

Peraluminous granite bodies are abundant within the CMB, ranging in size from millimeter- to centimeter-scale leucosome segregations and meter-scale sheet- and pipe-like bodies within migmatite (e.g., Solar and Brown 2001b), to kilometer-scale composite plutons of biotite and two-mica granite and granodiorite. Based on the U-Pb method on zircon and monazite, the Phillips and Redington plutons and the central lobe of the Lexington composite pluton (Fig. 1) have yielded ages of ca. 404 Ma, which are interpreted to record the age of crystallization and of Acadian orogenesis (Solar et al. 1998; Brown and Pressley 1999; unpublished data). Schlieric granite and decimeter- to meter-scale granite sheets within the migmatites crystallized synchronously with the ca. 404 Ma plutons (Solar et al. 1998). Components of the Mooselookmeguntic igneous complex (Fig. 1) have younger crystallization ages of c. 390-370 Ma, which record post Acadian magmatism (Solar et al. 1998; unpublished data). The geochemistry of the peraluminous granites suggests derivation from a metapelitic source via volatile-phase-absent melting consuming muscovite (muscovite "dehydration" melting; Brown and Pressley 1999; Solar and Brown 2001b). The three-dimensional geometry of the granites, their relationship to the regional structure, and the close association of smaller bodies, such as the Phillips pluton, with heterogeneous migmatite support a genetic relationship between deformation, granite ascent, and pluton emplacement (Brown and Solar 1998a, 1998b, 1999; Pressley and Brown 1999).

METAMORPHISM IN WESTERN MAINE

There is an abundance of data relating to the metamorphism of western Maine that dates back to the 1960s (see Guidotti and Holdaway 1993 and references therein), and up to five distinct metamorphic events have been proposed (e.g., Holdaway et al. 1988). In this contribution, we are concerned principally with the area shown in Figure 1, in which all metamorphism is of low-*P* facies series.

Subsolidus regional metamorphism

All rocks were affected by a pervasive regional metamorphic event (M1 and M2 of e.g., Guidotti and Holdaway 1993). Over a distance of 20 km or more, the metamorphic field gradient increases from greenschist facies (biotite and garnet zone) in the central part of the region, to upper amphibolite facies (upper sillimanite zone) in the south and northeast of the region (Fig. 1). The age of syntectonic regional metamorphism has been constrained to the interval 405–399 ± 2 Ma using the U-Pb method on monazite considered to have crystallized under staurolite-grade conditions (Smith and Barreiro 1990).

Amphibolite-facies metapelitic rocks are characterized by variably preferentially oriented euhedral to subhedral porphyroblasts of (variably retrograded) staurolite, garnet, and andalusite, within a schistose matrix of muscovite, biotite, quartz, plagioclase, and opaque phases (principally ilmenite, pyrite, and/or graphite). Cordierite of regional metamorphic origin is present in sulfide-rich rocks of the Small Falls Formation (e.g., Henry 1981; Holdaway et al. 1982; Guidotti and Holdaway 1993; Guidotti et al. 1996). The growth of porphyroblasts attributed to regional metamorphism and, by inference, the regional metamorphic peak, was synchronous with the terminal stages of accumulation of plastic strain during Acadian orogenesis (i.e., late-syntectonic; Solar and Brown 1999, 2000, 2001a). Syn-metamorphic shortening of the CMB is interpreted to have been accommodated preferentially within the "straight" belts by tightening of folds and southeast-side up (reverse) shear (Solar and Brown 2001a).

Characteristic low-variance subsolidus assemblages developed in metapelitic rocks across the metamorphic field gradient with increasing grade are:

(i) biotite + chlorite;
(ii) biotite + garnet + chlorite;
(iii) biotite + chloritoid + garnet (rare);
(iv) biotite + garnet + staurolite + chlorite;
(v) biotite + garnet + staurolite + andalusite;
(vi) a: biotite + garnet + andalusite (in the northeast) or b: biotite + garnet + staurolite + sillimanite (in the south); and
(vii) biotite + garnet + sillimanite.

All assemblages include muscovite, quartz, plagioclase, and an assumed H_2O-rich volatile phase [see Holdaway et al. 1982 (their Fig. 1); Dickerson and Holdaway 1989 (their Fig. 2); Guidotti and Holdaway 1993; and Fig. 1 of this paper].

P-*T* estimates of 2.7 ± 0.5 kbar, 575 ± 20 °C (in the northeast) and 3.3 ± 0.4 kbar, 525 ± 30 °C have been proposed for the conditions of staurolite zone peak regional metamorphism (Holdaway et al. 1982; Dickerson and Holdaway 1989). More recent calculations based on new calibrations of the garnet-biotite exchange thermometer suggest temperatures of 570–590 °C (calculated at 3.1 kbar) for staurolite-andalusite assemblages (Holdaway et al. 1997; Holdaway 2000). Guidotti (1989), Guidotti and Holdaway (1993), and Guidotti et al. (1996) consider the prograde regional metamorphic assemblages (their M2) to have developed as a result of heating at a constant *P* of 2.5–3.0 kbar (i.e., along an isobaric metamorphic field gradient), the result of advective pluton-driven metamorphism (DeYoreo et al. 1991). A detailed characterization of the heat source ultimately responsible for driving regional low-*P*, high-*T* metamorphism that reached suprasolidus temperatures in the CMB remains enigmatic.

Regional migmatites

The Weld and Tumbledown anatectic domains (Fig. 1) collectively represent the metamorphic high within the study area and are the northern limit of migmatite in the northern Appalachians. Within these domains, metatexites and diatexites are variably developed in fibrolite- and biotite-rich metapelitic rocks that are now depleted in a granitic component with respect to presumed protolith compositions (Solar and Brown 2001b). The migmatites are subdivided into stromatic and inhomogeneous types that occur as discrete zones at the map scale that correspond with the structural zones (Fig. 1).

Stromatic migmatite occurs at and adjacent to the migmatite front and predominantly within the "straight" belts. Stromatic migmatite is characterized by subparallel, millimeter- to centimeter-scale layers of leucosome and associated marginal melanosome within a melt-depleted mesosome that contains a penetrative foliation that is parallel to and continuous with that developed within lower-grade rocks. Leucosome comprises an average of 3% by volume. Centimeter- to meter-scale concordant to weakly discordant contemporaneous granite sheets are common.

Inhomogeneous migmatite includes vein migmatite and diatexite that commonly lack a strong foliation but which have a strong linear fabric (L > S). In diatexite, up to 15 vol% leucosome occurs within a residual mesosome host rock. Centimeter-scale leucosomes and larger, meter-scale granite bodies have a rod-like or cylindrical form and are elongated subparallel to the regional mineral elongation lineation. Inhomogeneous migmatite tends to be concentrated within the cores of the Weld and Tumbledown anatectic domains, within the intervening zones of apparent constrictional strain. Brown and Solar (1998a, 1998b, 1999) have suggested that the inhomogeneous migmatites record the sites of en masse transfer of melt to higher crustal levels.

At subsolidus grades up to and for a short distance (around 100–200 m) beyond the migmatite front, primary (fabric-forming) muscovite is abundant. Within the cores of the anatectic domains, primary muscovite is largely absent although retrograde, skeletal development of this phase is ubiquitous. Fibrolite and biotite are the primary fabric forming phases in the residual mesosome. K-feldspar, although generally rare, may comprise up to 5 vol% of the leucosome. There is little evidence for extensive incongruent volatile-phase-absent, biotite-consuming melting although, locally, centimeter- to decimeter-scale patches of leucosome within diatexite contain euhedral, inclusion-free garnet that is interpreted as a peritectic reaction product of such equilibria. We have not encountered cordierite, orthopyroxene, or spinel in migmatite.

Evidence for the syntectonic nature of peak regional metamorphism

Solar and Brown (1999, 2000, 2001a) presented several examples of porphyroblast-matrix relations suggesting that the peak of regional metamorphism in western Maine was synchronous with the latter stage of progressive accumulation of plastic strain recorded by the rocks (i.e., late syntectonic). Guidotti (2000) questioned this interpretation and considered peak regional metamorphism as post-tectonic, consistent with previously held views regarding the relative and absolute timing of deformation and porphyroblast growth (e.g., Holdaway et al. 1982; Guidotti and Holdaway 1993; Guidotti et al. 1996). The resolution of this issue has important consequences for tectonothermal models of Acadian orogenesis in western Maine and, in the context of this paper, the cause of the P increase recorded in regionally metamorphosed rocks that are overprinted by contact metamorphism associated with the Mooselookmeguntic igneous complex (Guidotti 1974; Holdaway et al. 1982; De Yoreo et al. 1989; Guidotti and Holdaway 1993; Guidotti and Johnson 2002).

We summarize the evidence for a late-syntectonic thermal peak of regional metamorphism as follows. (1) Regionally metamorphosed (ca. 404 Ma) pelitic rocks up to and beyond the migmatite front have a fine-grained schistose matrix. We have only encountered typical hornfelsic (granoblastic/decussate) microstructures within the innermost aureole (upper Al-silicate zone) of the ca. 370 Ma Mooselookmeguntic igneous complex, within 50 meters of the contact, and at similar distances from the northern lobe of the Lexington mass. Such microstructures, in which the matrix is coarser-grained and shows no pronounced preferred orientation, are typical of post-tectonic contact aureole metamorphism. (2) Moderate to high aspect ratio porphyroblasts attributed to regional metamorphism, particularly andalusite, are weakly to strongly aligned within the penetrative foliation and/or lineation. Detailed measurements of **c**-axis orientations of stubby prismatic staurolite porphyroblasts have demonstrated a statistically valid preferred orientation (Solar and Brown 1999, 2000). Staurolite appears at lower grades (i.e., grew earlier) than andalusite in common metapelite. (3) Equant garnet porphyroblasts commonly have quartz-rich pressure shadows that are either symmetrical or asymmetrical. The phyllosilicate-rich matrix is commonly draped around such porphyroblasts. (4) In suitably oriented sections, inclusion trails within porphyroblast phases, particularly garnet and staurolite, exhibit predominantly low-angle discordance with the matrix schistosity; inclusion trails may swing into parallelism with the matrix at porphyroblast margins. (5) Variably sized sheets and pipe-like bodies of leucosome in migmatite show a close relationship with the structures in lower-grade rocks, suggesting deformation controlled melt migration at the metamorphic peak (e.g., Brown 1994).

Syn-Acadian "contact" metamorphism

Regional metamorphic isograds are locally modified by "contact" metamorphic effects related to nearby syn-metamorphic granites. In a detailed study of metamorphism in the vicinity of the Lexington composite pluton (Fig. 1), Dickerson and Holdaway (1989) proposed three successive metamorphic events and an increase in peak-metamorphic P from the northern lobe (2.35 ± 0.3 kbar), where cordierite is developed in Mg-rich rocks, towards the south (2.7 ± 0.5 kbar), where this phase is absent. Overprinting of regional assemblages around the northern lobe suggest this portion of the Lexington body intruded after the peak of Acadian metamorphism. Metamorphism around the southern and central lobes of the Lexington composite pluton, and around the Redington and Phillips granites is continuous with the regional metamorphic pattern (Fig. 1). The rocks preserve a primary schistosity up to and beyond the migmatite front. The age of crystallization of these granites is synchronous with the regional metamorphic peak (Dickerson and Holdaway 1989; Smith and Barreiro 1990; Solar et al. 1998). Consequently, a distinction between regional metamorphism and that associated with syntectonic granites is unnecessary for the purpose of this study. We call such syntectonic, syn-metamorphic plutons "syn-Acadian" granites.

Post-Acadian contact metamorphism

An extensive aureole is developed around the post-Acadian Mooselookmeguntic igneous complex. Contact metamorphism related to the main leucogranite is dated at ca. 370 Ma (Smith and Barreiro 1990; Solar et al. 1998). Regional assemblages are variably retrograded or prograded depending on proximity to the granite (Guidotti and Johnson 2002). Retrograded regional assemblages imply a source of H_2O-rich volatiles after the regional metamorphic peak. At lower grades, regionally developed biotite is commonly replaced by chlorite in metapelitic rocks distal to the Mooselookmeguntic igneous complex. At higher grades, regionally developed staurolite porphyroblasts may show pseudomorphic replacement by retrograde chlorite + muscovite, or replacement by new, fine-grained staurolite. The regional schistosity is progressively destroyed as the contact is approached. At amphibolite-facies conditions (staurolite and lower sillimanite zone) within the contact aureole, a relict schistosity is preserved, although the matrix is coarser grained than in rocks at similar regional metamorphic grades that were unaffected by subsequent contact metamorphism. Within about 50 meters of the contact, the rocks are hornfelses.

A critical relationship in the contact aureole of the Mooselookmeguntic igneous complex is the presence of sillimanite as the only stable Al_2SiO_5 polymorph. Sillimanite-bearing assemblages, which may overprint andalusite-bearing regional metamorphic assemblages, provide compelling evidence that metamorphism associated with this body, part of M3 of e.g., Guidotti and Holdaway (1993) developed at higher *P* (Guidotti 1974; Holdaway et al. 1982; De Yoreo et al. 1989; Guidotti and Holdaway 1993; Guidotti and Johnson 2002). Cordierite- and sillimanite + K-feldspar-bearing hornfelses are developed within the aureole of the northern lobe of the Lexington composite pluton, suggesting a shallow emplacement level. Metamorphism around the Carboniferous Sebago batholith (293 ± 2 Ma; Tomascak et al. 1996), to the south of Figure 1, is associated with the development of K-feldspar at upper-sillimanite grade; kyanite has been reported from the south side of the body (Thomson and Guidotti 1989).

The hornfelsic nature of the rocks in the aureoles of granites that post-date the peak of regional metamorphism suggest they were emplaced after Acadian thickening of the CMB was complete. These granites are termed "post-Acadian."

MODELING PHASE RELATIONS

We have modeled subsolidus and suprasolidus phase relations of metapelites in the MnNCKFMASH system using THERMOCALC v. 3.1 (Powell and Holland 1988) and the Holland and Powell (1998; updated 05/14/01) data set. Mixing models for NCKFMASH end-members, including interaction parameters to account for non-ideality, largely follow White et al. (2001). The incorporation of Mn into biotite, chlorite, chloritoid, cordierite, garnet, and staurolite follows Tinkham et al. (2001); Mn is particularly important in stabilizing garnet to lower pressures than is predicted by modeling in the KFMASH system, consistent with field observations (e.g., Mahar et al. 1997). The melt was modeled in NCKFMASH on an 8-oxygen basis following Holland and Powell (2001) and White et al. (2001). Based on the results of melting experiments on natural Mn-bearing metapelitic starting compositions of Stevens et al. (1997) and Droop et al. (2003), there is no partitioning of Mn into melt (G.T.R. Droop, personel communication). The data files used in this study, which include *a-X* relations for non-ideal phases, are available as a deposit item[1].

We have constructed pseudosections in *P-T-X*-space based on two bulk compositions recalculated from data in Solar and Brown (2001b): (1) an average metapelite composition (the mean of thirteen major oxide element analyses of Rangeley and Perry Mountain Formation metapelitic rocks; and (2) an SiO_2-richer, Fe-rich [i.e., low X_{Mg}, where X_{Mg} = molar Mg/(Fe + Mg)] Perry Mountain Formation subaluminous metapelite (Sp 95-97) in which staurolite porphyroblasts are abundant. Analyses are given in Table 1. In THERMOCALC, molar proportions of all phases are recalculated on a 1-oxygen basis; consequently, mole percent can generally be considered to approximate volume percent.

Al-silicate stability

Before detailing phase relations, it is important to address the stability of the Al_2SiO_5 polymorphs and, in particular, the relative stability of andalusite and sillimanite. The location of the andalusite-sillimanite transition, which is sensitive to small changes in the free energy of either polymorph, remains a contentious issue that has important consequences for low-*P* phase equilibria in metapelitic rocks (see Pattison 1992 and references therein). The Al_2SiO_5 triple point, as calculated using the Holland and Powell (1998; updated 05/14/01) data set, occurs at 3.8 kbar, 505 °C, similar to the experimental determination of Holdaway (1971). However, this position clearly contradicts most natural assemblage data (cf., Pattison 1992; Tinkham 2001).

The problem is illustrated with reference to Figure 2a, which shows a *P-T* pseudosection for the average metapelite composition constructed using the Al-silicate data in the Holland and Powell data set without modification. The important association andalusite + staurolite is only predicted to be stable within the narrow divariant field {Bt Grt St Chl Ms And} between 3.0 and 3.2 kbar; the assemblage is stable over <0.1 °C at fixed *P* (Fig. 2a), inconsistent with the abundance of andalusite + staurolite in the CMB (e.g., Guidotti et al. 1996) and in other low-*P* metamorphic terranes [e.g., the type locality in the NE Dalradian (Hudson 1980)].

Pattison (1992) used petrological criteria from metapelitic rocks within the Ballachulish aureole, Scotland, to constrain the position of the Al-silicate triple point to 4.5 ± 0.5 kbar, 550 ± 35 °C. The expansion of the andalusite stability field relative

TABLE 1. Major oxide analyses of bulk compositions used in the calculation of pseudosections

	Average		Sp 95-97	
	wt%	mol%	wt%	mol%
SiO_2 (S)	63.37	73.64	67.74	77.71
TiO_2	0.91		0.78	
Al_2O_3 (A)	17.43	11.94	15.77	10.66
FeO* (F)	7.23	5.53	6.48	4.92
MnO (Mn)	0.10	0.10	0.05	0.04
MgO (M)	2.28	3.95	1.66	2.83
CaO (C)	0.43	0.35	0.24	0.01
Na_2O (N)	1.26	1.41	0.81	0.90
K_2O (K)	4.15	3.07	3.99	2.92
P_2O_5	0.11		0.21	
LOI	2.43		1.74	
TOTAL	99.69	100.00	99.47	100.00

Notes: Mol% values are normalized MnNCKFMAS (anhydrous) compositions and take account of FeO (=TiO) in ilmenite and CaO (=3.33P_2O_5) in apatite. The small amount of CaO assigned to Sp 95-97 is required for the model calculations
* All Fe as FeO

[1]For a copy of the data files, document item AM-03-033, contact the Business Office of the Mineralogical Society of America (see inside front cover of recent issue) for price information. Deposit items may also be available on the American Mineralogist web site at http://www.minsocam.org.

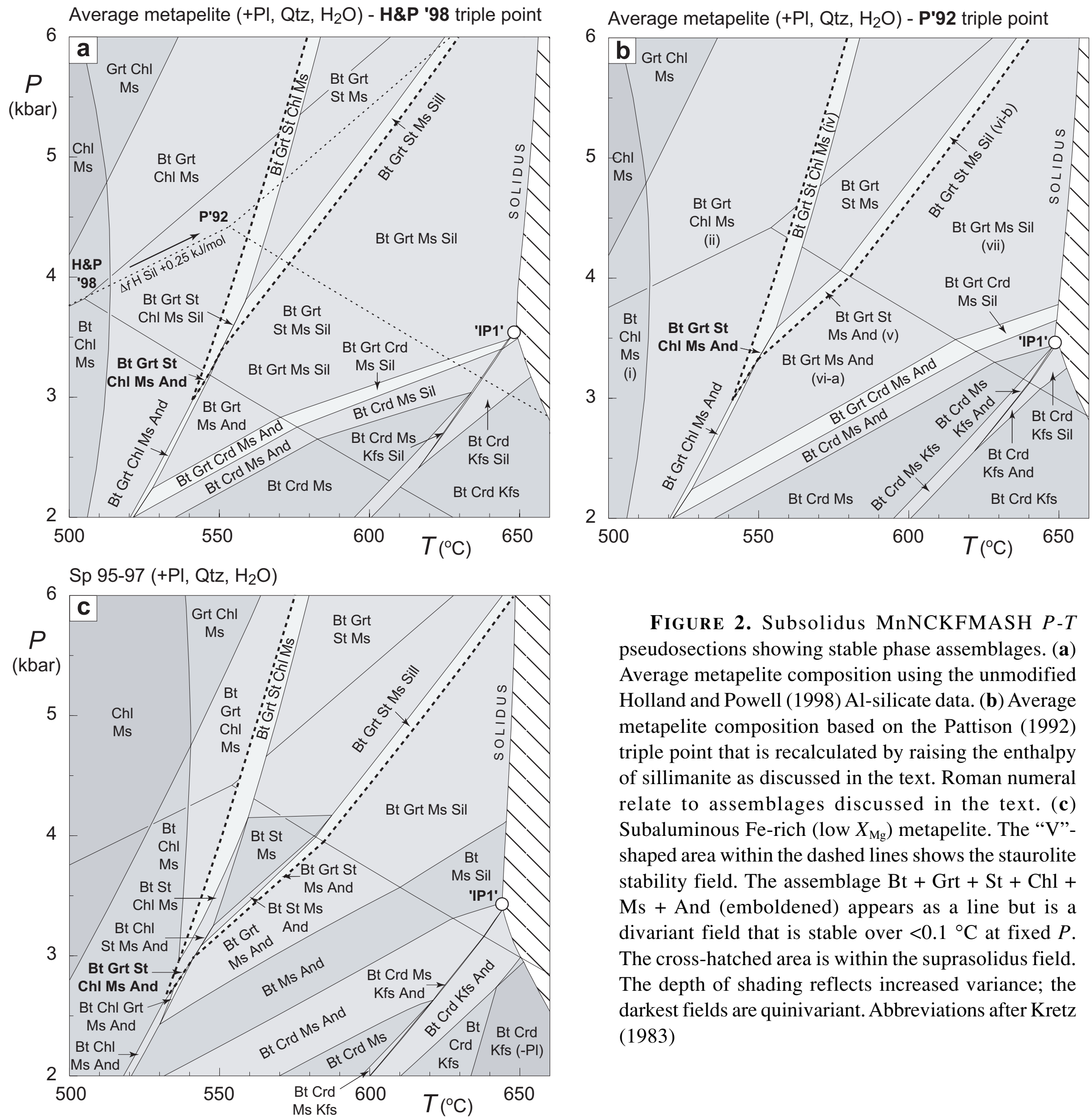

FIGURE 2. Subsolidus MnNCKFMASH *P-T* pseudosections showing stable phase assemblages. (**a**) Average metapelite composition using the unmodified Holland and Powell (1998) Al-silicate data. (**b**) Average metapelite composition based on the Pattison (1992) triple point that is recalculated by raising the enthalpy of sillimanite as discussed in the text. Roman numeral relate to assemblages discussed in the text. (**c**) Subaluminous Fe-rich (low X_{Mg}) metapelite. The "V"-shaped area within the dashed lines shows the staurolite stability field. The assemblage Bt + Grt + St + Chl + Ms + And (emboldened) appears as a line but is a divariant field that is stable over <0.1 °C at fixed *P*. The cross-hatched area is within the suprasolidus field. The depth of shading reflects increased variance; the darkest fields are quinivariant. Abbreviations after Kretz (1983)

to that of sillimanite allows a more realistic stability field for andalusite-staurolite-bearing assemblages (e.g., Fig. 2b), and is here preferred. Figure 2a shows that the Pattison (1992) triple point occurs essentially along the metastable extension of the andalusite = kyanite reaction. Consequently, we have adopted the principle of parsimony and have modified the Holland and Powell (1998; updated 05/14/01) data to fit the Pattison triple point by making a small adjustment in the enthalpy of formation (ΔH_f) of sillimanite, which we have increased by 0.25 kJ/mol, within the quoted error of 0.7 kJ/mol (1σ). The triple point calculated using the modified data, at 4.42 ± 0.1 kbar, 554 ± 8 °C, is within error of that favored by Pattison (1992). Our discussion of subsolidus and suprasolidus phase equilibria in the remainder of this paper is based on calculations using this modified data set.

Subsolidus phase equilibria

In the subsolidus pseudosections, assemblages are SiO_2-saturated and are considered to have equilibrated in the presence of a pure H_2O supercritical volatile phase. Figure 2b shows a *P-T* pseudosection for the average metapelite composition (X_{Mg} = 0.42). The prograde appearance of biotite is pressure sensitive and its early growth is favored by lower-*P*. Subsolidus assemblage i, biotite + chlorite without garnet, is stable at *P* < 4.8 kbar. This assemblage, in which biotite is commonly retrograded (e.g., Holdaway et al. 1982), is widely developed throughout the lower-grade rocks in the CMB. The assemblage biotite + garnet + chlorite (assemblage ii) is common in low-grade rocks of suitable composition except in the extreme NW of the study area (e.g., Holdaway et al. 1982; Guidotti et al. 1996; Fig. 1). Garnet is predicted to be stable over most of

Figure 2b at temperatures in excess of around 510 °C; the prograde onset of garnet growth is essentially *P*-independent. The abundance of garnet is proportional to the bulk Mn content, which is typical of metapelitic rocks (mean of 0.10 wt%; Mahar et al. 1997). Chloritoid (assemblage iii) is not predicted to be stable in the average metapelite composition.

The stability of staurolite (shown bounded by the dashed lines in Fig. 2) is of particular interest. The staurolite stability field is "V"-shaped and, for the average metapelite composition, this phase is only stable at $P > 3.0$ kbar. An increase in the width (essentially *T* stability) of staurolite-bearing rocks across the metamorphic field gradient (Fig. 1) is favored by higher *P*. Assemblage iv, in which staurolite co-exists with biotite, garnet and chlorite, is stable at the low-*T* end of the stability field at $P > 3.0$ kbar. The important association biotite + staurolite + andalusite [assemblage v] is stable between 3.0 and 4.1 kbar. However, below 3.3 kbar, assemblage v is only stable over less than 0.1 °C at fixed *P*.

At *T* in excess of the upper stability limit of staurolite + andalusite in the northeast of the study area (i.e., to the south and west of the Lexington composite pluton; Fig. 1), andalusite is stable with biotite and garnet (assemblage vi-a; Dickerson and Holdaway 1989; Guidotti and Holdaway 1993), implying $P < 4.0$ kbar. To the south of the area, around the Phillips pluton and at the margins of the anatectic domains, assemblage v is superceded by assemblages in which sillimanite co-exists with biotite, garnet and staurolite (assemblage vi-b; Holdaway et al. 1982), implying $P = 4.0$–4.1 kbar at the assemblage v-vi transition (Fig. 2b). The appearance of assemblage vii marks the andalusite–sillimanite polymorphic transition in the south (Fig. 1), and the disappearance of staurolite in the northeast of the study area respectively; assemblage vii occupies a large *P*-*T* stability field.

At about 650 °C, the solidus is crossed and partial melting begins, consistent with the appearance of migmatite in the field. Up to and at the migmatite front, primary muscovite is abundant in the matrix, implying that the regional metamorphic field gradient in western Maine passed above the low-variance point "IP1" on Figure 2b (i.e., $P > 3.4$ kbar; Spear et al. 1999). Cordierite is predicted to be stable at the solidus in the average metapelite composition at $P < 3.7$-3.8 kbar; below about 3.6 kbar, garnet will be absent. Cordierite of regional derivation is only present in sulfide-rich rocks of the Small Falls Formation and garnet is common in all but the lowest grade rocks.

Figure 2c shows a *P*-*T* pseudosection for an iron-rich subaluminous metapelite (Sp 95-97; $X_{Mg} = 0.37$). Such compositions, which contain abundant staurolite at suitable grades, are common in the CMB. Phase relations are similar to those described for the average metapelite composition with some notable differences. The garnet stability field is smaller (due to the lower Mn content of the rock), and this phase is only predicted at $T > 530$–540 °C. The staurolite field is larger and extends to lower *P* (> 2.6 kbar). The stability of staurolite + andalusite (assemblage v) extends from 2.6–4.0 kbar, although below 3 kbar this paragenetic association has an unrealistically small *T*-stability to account for its distribution in the field. Immediately beyond the stability of staurolite + andalusite, biotite + garnet + andalusite (assemblage vi-a) is stable at $P <$ 3.9 kbar; staurolite + sillimanite (assemblage vi-b) implies $P >$ 3.9 kbar.

At higher grades approaching the onset of anatexis, the lower *P* limit of garnet extends to higher *P*, intersecting the solidus at approximately 4.1 kbar. The solidus is depressed by 5–10 °C relative to the solidus for the average metapelite composition. The *P* of low-variance point "IP1", at around 3.4 kbar, does not change significantly, suggesting it is relatively insensitive to changes in bulk composition. Cordierite stability is suppressed marginally towards lower *P* relative to its stability field in the average metapelite composition, intersecting "IP1". At $P < 3$ kbar, near-solidus rocks will lack plagioclase, reflecting the lower Na and Ca content of Sp 95-97.

As X_{Mg} exerts a first-order control on the stable phase assemblages in metapelitic rocks, and as the *P* of metamorphism in western Maine is poorly constrained, it is useful to examine phase relations in *P*-X_{Mg} space. Figure 3 shows an isothermal ($T = 640$ °C) *P*-X_{Mg} pseudosection based on the average metapelite composition that is appropriate for conditions a few degrees (about 10 °C) below that of the solidus. The vertically dashed lines show the range of X_{Mg} appropriate for common metapelitic rocks in the area (0.30–0.45; Solar and Brown 2001b). At low *P* (< 3.2 kbar), andalusite is the stable Al-silicate, and common metapelitic rocks will be K-feldspar- and cordierite-bearing but lack muscovite; at $P < 2.9$ kbar, garnet will be absent. The stability of Al-silicate is increased within Fe-richer rocks. At $P > 3.2$ kbar, K-feldspar is absent. The up-*P* stabilities of garnet, cordierite, muscovite, and sillimanite are strongly dependent on X_{Mg}. Rocks with (regionally) extreme Fe-rich compositions ($X_{Mg} < 0.30$) will contain garnet but lack cordierite at $P > 3.2$ kbar. Mg-rich rocks ($X_{Mg} > 0.45$) will not

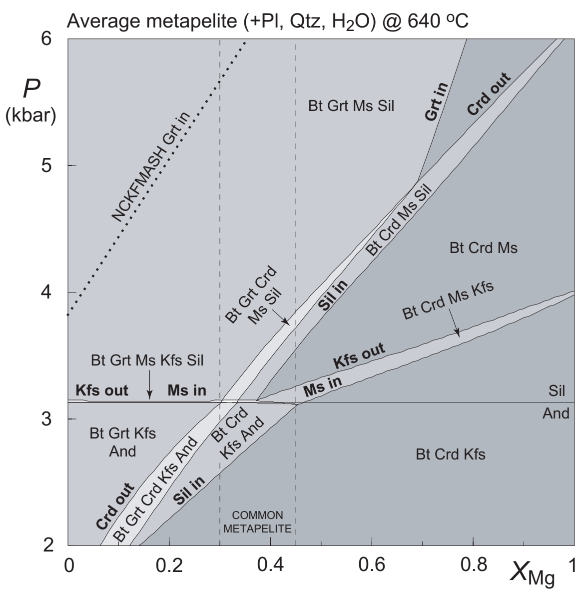

FIGURE 3. *P*-X_{Mg} projection for the average metapelite composition. The appearance or disappearance of phases is shown in an up-*P* sense. The region within the dashed lines reflects the range in X_{Mg} of common metapelitic rocks in the area. The darkest fields are quinivariant.

develop garnet unless P > 3.7 kbar; below around 3.8 kbar, Mg-rich rocks will be cordierite bearing and at P < 3.6 kbar will lack sillimanite.

In western Maine, the abundance of garnet, muscovite, and sillimanite and the absence of cordierite and K-feldspar in common metapelitic rocks close to the migmatite front imply P > 3.8 kbar. Rare samples that are more magnesian than common metapelites (i.e., X_{Mg} > or >> 0.45) will contain cordierite at these pressures. This is consistent with the rare occurrence of cordierite in metapelitic rocks in which much of the Fe is contained within sulfides and, consequently, the effective bulk composition for silicate phases is Mg-rich (e.g., Henry 1981).

Suprasolidus phase equilibria

Figure 4a shows a P-T pseudosection for the average metapelitic composition with quartz and plagioclase in excess. The pseudosection extends from high-grade subsolidus conditions into the volatile-phase-absent melting field. At P < "IP1," K-feldspar rather than muscovite is stable at T below the solidus, inconsistent with the abundance of the latter phase up to and at the migmatite front. Garnet is stable only at P > 3.6 kbar; below 3.7–3.8 kbar, cordierite is predicted.

As rocks attain the T of the solidus, they will produce a small quantity of silicate liquid by volatile-phase-present congruent melting, exhausting free H_2O from the assemblage. The amount of melt generated will be proportional to the quantity of available H_2O; in the absence of any externally derived volatile phase, such a quantity will be small (<< 1 mol%; Fig. 4a). With continued heating beyond the solidus, garnet-bearing, cordierite-absent protoliths produce a small quantity of melt (< 2 mol%) until they reach the incongruent, volatile-phase-absent, muscovite-breakdown reaction (e.g., Patiño Douce and Harris 1998; Fig. 4a),

$$\text{Ms} + \text{Pl} + \text{Qtz} \leftrightarrow (\text{Bt}) + \text{Kfs} + \text{Sil} + \text{L} \quad (1)$$

(biotite is a minor product and is shown in parentheses), which produces 8–9 mol% melt within a narrow T interval (Fig. 4a). Reaction 1 marks the appearance of peritectic K-feldspar [present albeit uncommonly in the migmatites; most K-feldspar is presumed to have back reacted to muscovite (e.g., Kohn et al. 1997; Spear et al. 1999; Brown 2001)] and the disappearance of muscovite, and has been proposed as the principal melt-forming reaction in the migmatites of the current study (Solar and Brown 2001b).

A few additional mol% melt will be produced with continued heating within the field {L Bt Grt Kfs Sil} by the reaction,

$$\text{Bt} + \text{Sil} + \text{Pl} + \text{Qtz} \leftrightarrow \text{Grt} + \text{Kfs} + \text{L}. \quad (2)$$

Euhedral, inclusion-free garnet-bearing leucosomes within the cores of the anatectic domains are consistent with the operation of reaction 2. The principal volatile-phase-absent, biotite-consuming melting reaction in metapelitic rocks is:

$$\text{Bt} + \text{Sil} + \text{Pl} + \text{Qtz} \leftrightarrow \text{Grt} + \text{Crd} + \text{Kfs} + \text{L}. \quad (3)$$

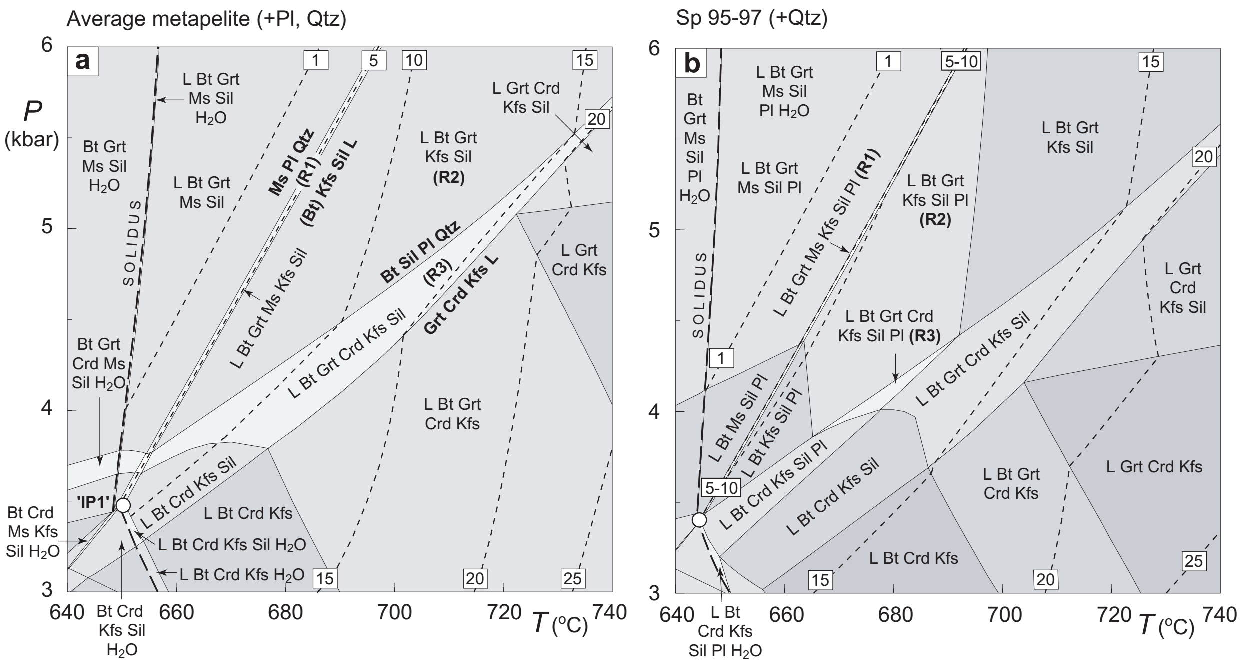

FIGURE 4. Suprasolidus MnNCKFMASH P-T pseudosections for (**a**) the average metapelite composition and, (**b**) Sp 95-97 showing stable assemblages and molar melt proportions (in mol%; dashed lines). Significant quantities of melt (>2 mol%) are not produced until reaction 1 (R1) is encountered. The bulk compositions contain sufficient H_2O to just saturate the solidus at 6 kbar; the amount of added H_2O (~6 mol%) was adjusted so that both compositions produce an identical amount of melt (0.2 mol% at 6 kbar) by H_2O-present melting. The darkest fields are (a) quinivariant and (b) sexivariant.

Reaction 3 occurs across a trivariant field that extends over a greater temperature interval than reaction 1 (Fig. 4a). Reaction 3 results in garnet + cordierite + K-feldspar-bearing melts (and leucosomes) and will exhaust sillimanite from the rocks if temperatures remain sufficiently high for it to run to completion. Evidence for extensive biotite-breakdown is lacking and there is an abundance of primary (fabric-forming) fibrolitic sillimanite and biotite within these rocks. Cordierite is not present in migmatite.

Figure 4b shows suprasolidus phase relations for the subaluminous Fe-rich metapelite composition (Sp 95-97). Relative to the average metapelite composition, the T of the solidus and reaction 1 are lowered (by 5–10 °C); the generated melt fraction at a specified P-T point in the suprasolidus region is larger by a few mol% (Fig 4a and 4b). At suprasolidus conditions prior to the onset of reaction 1, garnet is only stable at P > 4.1 kbar. Beyond this, garnet stability extends to lower P as peritectic garnet is produced (e.g., by reaction 2). Sp 95-97 is depleted in both CaO and Na_2O relative to the average metapelite composition and plagioclase is consumed by melting at T < 700 °C. Plagioclase is consumed at lower T with decreasing P, and the trivariant field that records reaction 3 is consequently much smaller than for the average metapelite.

Discussion: Constraints on metamorphism in western Maine

The spatial distribution of mineral assemblages developed within common, subaluminous metapelitic rocks in western Maine are well constrained (Holdaway et al. 1982; Dickerson & Holdaway 1989; Fig. 1). The important lowest-variance phase associations developed along the regional metamorphic field gradient with increasing grade are:

(I) chlorite + muscovite
(II) garnet + chlorite + muscovite,
(III) garnet + staurolite + chlorite + muscovite,
(IV) garnet + staurolite + muscovite + andalusite,
(V) a: garnet + muscovite + andalusite (in the northeast), and
b: garnet + staurolite + muscovite + sillimanite (in the south),
(VI) garnet + muscovite + sillimanite,
(VII) garnet (subsolidus) + muscovite + K-feldspar + sillimanite + leucosome/melt, and,
(VIII) garnet (peritectic) + K-feldspar + sillimanite + leucosome/melt,

with biotite, plagioclase, and quartz, and an assumed supercritical H_2O-rich volatile phase in subsolidus assemblages. Any model for the regional metamorphism of western Maine must be able to reproduce these parageneses.

Bathograds revisited

In a seminal paper, Carmichael (1978) defined six bathozones based on ten diagnostic amphibolite-facies mineral assemblages within metapelitic rocks. The bathozones were subdivided by five bathograds based on invariant reactions in the model KFMASH system. Carmichael (1978) demonstrated the applicability of the concept by mapping bathograds in the Appalachians, the Alps, and the Scottish Dalradian using compiled assemblage data. The constraints on metamorphic P in western Maine can be illustrated with reference to the bathograd concept extended into the MnNCKFMASH system.

As an example, Figure 5 shows phase relations for the average metapelite composition with the important bathograd-defining equilibria highlighted. Six bathozones are shown and numbered to be consistent with the original notation of Carmichael (1978). The lower-P bathograds separating bathozones 1 from 2 and 2 from 3 are defined by the intersection of the reaction andalusite = sillimanite with reaction 1 and the equilibria:

$$\text{(Crd) + Ms + (Pl) + Qtz} \leftrightarrow \text{(Bt) + Kfs + Al-silicate + } H_2O \quad (4)$$
$$\text{St + Ms + Pl + Qtz} \leftrightarrow \text{Bt + Grt + Al-silicate + } H_2O \quad (5)$$

all of which are trivariant in the MnNCKFMASH system. In reaction 4, plagioclase, cordierite and biotite (shown in parentheses) have small reaction coefficients and the reaction occurs over < 1 °C at fixed P. For the purposes of the bathozones for the average metapelite composition, these phases can be ignored and reaction 4 can be reduced to its univariant KASH equivalent; consequently, bathograds that are dependent on reaction 4 remain essentially invariant. Reaction 5 is a continuous reaction that runs over 5–10 °C at fixed P (Figs. 2 and 5). Consequently, bathograds that are constrained by reaction 5, [i.e., separating bathozones 2 from 3 and 5 from 6 (Carmichael 1978)] are also continuous, and define a narrow P range (i.e., transitional bathograd 2-3t in Fig. 5). The bathograd separating bathozones 3 and 4 defines whether rocks followed a P-T evolution that passed at P lower than or greater than the Al_2SiO_5 triple point.

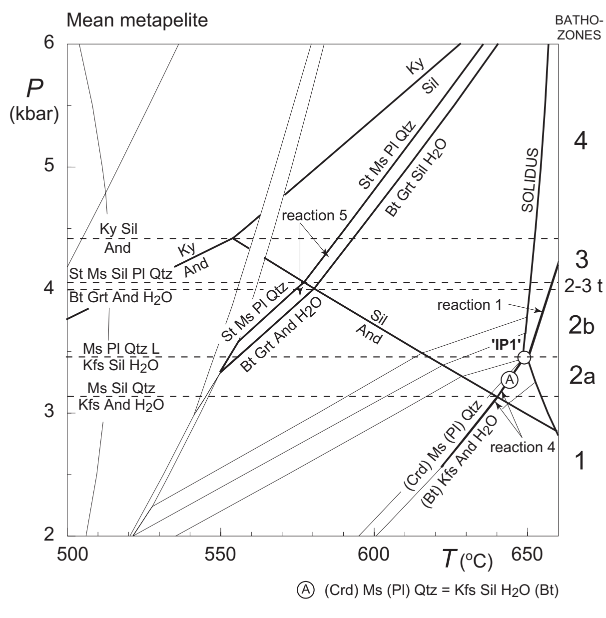

Figure 5. MnNCKFMASH bathozones (cf. Carmichael 1978). Emboldened lines are the bathograd-defining equilibria.

In addition to the original bathgrads, we have subdivided bathozone 2 on the basis of the essentially compositionally independent low-variance point "IP1" (Fig. 2), which represents the intersection of reactions 1 and 4 with the "wet" solidus. The congruent melting reactions that define the solidus are variably di- tri- or quadrivariant in MnNCKFMASH. However, in the absence of an external supply of H_2O, these reactions run over < 1 °C and can be regarded as univariant; the bathograd separating bathozones 2a and 2b is essentially invariant. Importantly, the *P-T* conditions of reactions 1, 3, and 4 and the solidus show some compositional dependence (Fig. 2; Fig. 6a).

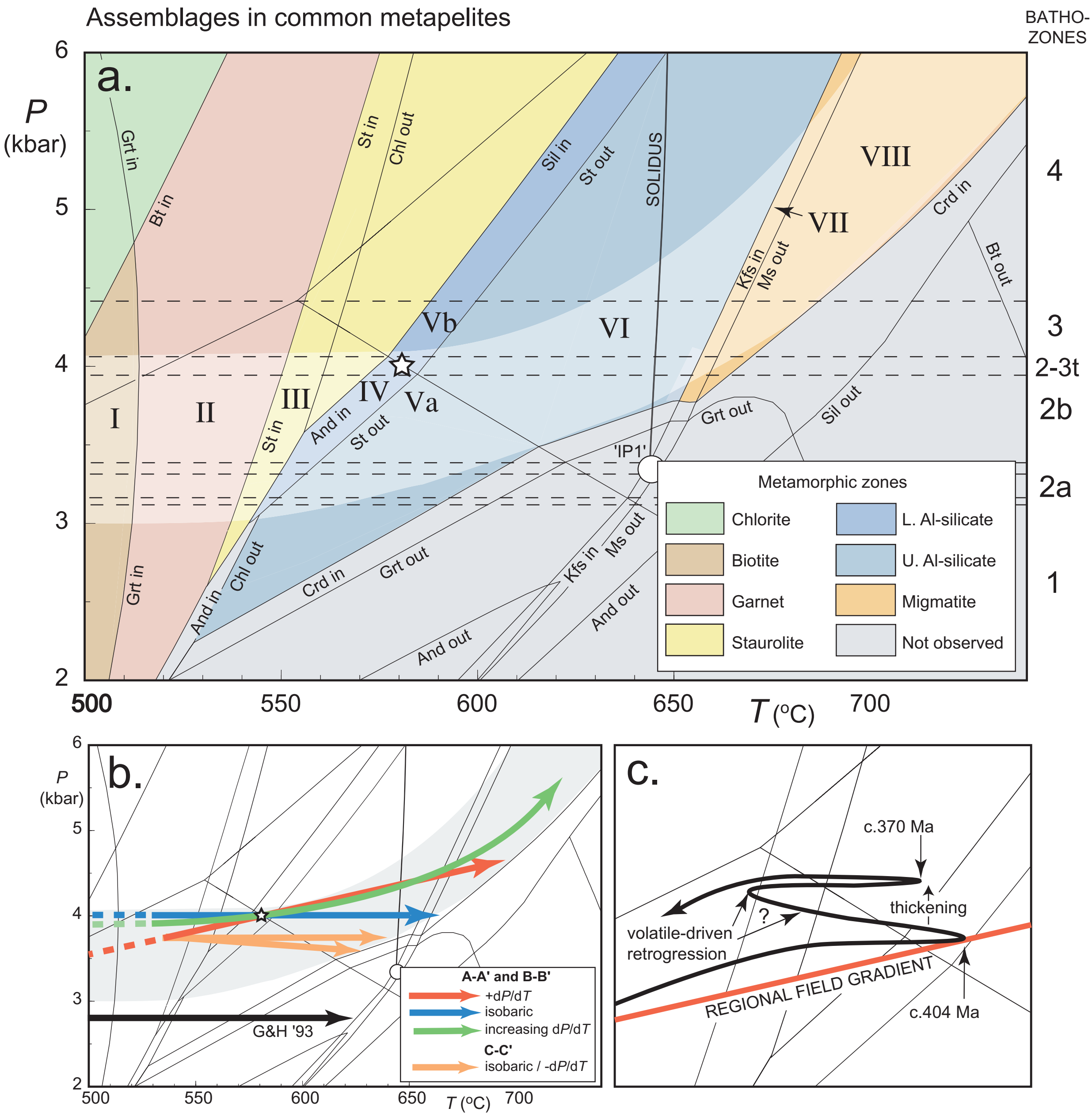

FIGURE 6. MnNCKFMASH model constraints for common metapelitic rocks. (**a**) *P-T* stablility of metamorphic zones and associated assemblages. (**b**) Exemplar metamorphic field gradients. (**c**) Schematic *P-T-t* evolution. This figure, discussed in detail in the text, combines data from both the average metapelite composition and the Fe-rich metapelite and is NOT an equilibrium phase diagram. The appearance or disappearance of phases in (**a**) is shown in an up-*T* sense; the regional metamorphic field gradient is constrained to the pale band. Bold roman numbers refer to diagnostic assemblages discussed in the text. In (**b**), the regional field gradient proposed by Guidotti and Holdaway (1993) is shown for reference.

Assemblages in common metapelitic rocks

Figure 6a shows a *P-T* diagram on which are projected the maximum stability fields of the important phase associations (assemblages I-VIII) as deduced from combining data from calculations on both the average and Fe-rich bulk compositions (i.e., the distribution of metamorphic zones expected in common metapelitic rocks in the area). Figure 6a is not an equilibrium phase diagram and does not adhere to Schreinemakers constraints. Bathozones, in which transitional boundaries are smeared out over a range of *P* due to bulk compositional variation, are shown along the right-hand edge of Fig. 6a.

Subsolidus assemblages within metapelitic rocks in western Maine, which are characterized by andalusite + staurolite and in which K-feldspar does not occur, are essentially constrained to bathozone 2a and higher *P* bathozones ($P > 3.1$ kbar). The lowest grade, biotite zone rocks (assemblage I) imply $P <$ 4.8 kbar. The garnet zone assemblage II occupies a broad stability field that is stable over an increasing *T*-range with increasing *P*. Such assemblages are widespread in the field (Fig. 1). The association staurolite + chlorite (staurolite zone assemblage III) is stable at *P* in excess of about 2.6 kbar.

The most important relationship for the purposes of defining *P* in subsolidus rocks in western Maine is the assemblage garnet + biotite + staurolite + andalusite (lower Al-silicate zone assemblage IV) and its transition to the upper Al-silicate zone assemblage Va or Vb. In the northeast of the region, staurolite disappears and assemblage Va is stable (e.g., Dickerson & Holdaway 1989); in the south, around the Phillips pluton and the migmatites, staurolite remains stable and andalusite is replaced by sillimanite in assemblage Vb (Holdaway et al. 1982).

Assemblage IV is characteristic of bathozone 2 in the KFMASH system (Carmichael 1978), but may also occur within the transition between bathozones 2 and 3 in the expanded system (bathozone 2-3t in Figs. 5 and 6a). Assemblage Va is diagnostic of bathozone 2b, whereas assemblage Vb is diagnostic of bathozone 2-3t and 3. Consequently, at the lower Al-silicate to upper Al-silicate transition (Figs. 1 and 6a), *P* conditions in the northeast of the study area occur entirely within bathozone 2 ($P < 3.9$ kbar, below the star in Fig. 6a). In the south, the lower Al-silicate to upper Al-silicate transition is constrained to bathozone 2-3t (P = 3.9–4.1 kbar, intersecting the star in Fig. 6a). The highest-grade subsolidus rocks in all areas contain assemblage VI that occupies a large *P-T* stability field.

The presence of primary fabric-forming muscovite at the migmatite front implies $P >$ "IP1" (bathozone 2b or higher). Cordierite is not encountered in common metapelitic rocks at any grade. The absence of this phase at the migmatite front implies $P > 3.75$ kbar. Primary muscovite is absent within the cores of the Tumbledown and Weld anatectic domains and a small quantity of peritectic garnet-bearing leucosome occurs. The majority of the suprasolidus segment of the metamorphic field gradient is therefore constrained to the muscovite-absent melting field in which assemblage VIII is stable. This field is "V"-shaped, and is stable over an increased *T*-range with increasing *P*. The migmatites are rich in fabric-forming biotite and sillimanite and cordierite does not occur (i.e., there is no evidence for reaction 3). Although a minimum *P* of 3.75 kbar is implied, the distance from the migmatite front to the core of the anatectic domains is 5–10 kilometers (Fig. 1). Consequently, the areal extent of the stability of assemblage VIII is consistent with higher *P* (> 4.5 kbar).

Regional metamorphic field gradients and idealized *P-T* vectors

The pale band through Figure 6a shows the reasonable permissible range of *P-T* conditions for regional metamorphic rocks in the study area (i.e., assuming a near-linear or curvilinear metamorphic field gradient). In Figure 6b, exemplar *P-T* vectors are shown (as colored arrows) that are qualitatively consistent with the observed assemblages. The *P-T* vectors are discussed with reference to three natural metamorphic field gradients, defined by line-segments A-A', B-B,' and C-C' on Figure 1, that are near-orthogonal to regional isograds.

The overall pattern of regional metamorphism is for grade to increase along the strike of the CMB from northeast to southwest. Line A-A' (Fig. 1) illustrates such a metamorphic field gradient that extends from the garnet zone into the anatectic zone. Around the Phillips pluton and the migmatites, the field gradients are constrained to pass through the star on Figures 6a and 6b, at 3.9–4.1 kbar, 580 °C.

The red arrow on Figure 6b shows a linear *P-T* vector with a positive d*P*/d*T* (approximately 30 °C/km) that is qualitatively and quantitatively consistent with field gradient A-A' and, consequently, with the overall pattern of regional metamorphism in the southern part of the study area. Along the modeled field gradient, staurolite is stable over the *T* range 550–590 °C. The predicted upper stability of staurolite + andalusite compares well with temperatures of 580 ± 8 °C calculated by Holdaway (2000) for staurolite- and andalusite-bearing rocks from west-central Maine. The field gradient crosses the solidus at around 4.3 kbar and 650 °C.

In the absence of any external supply of H_2O, minor quantities of melt (<< 1 mol%) will be produced as the solidus is crossed. The former presence of such small volumes of H_2O-saturated melt might be difficult to demonstrate in the rocks, given that the melt is unlikely to segregate and will react on cooling to subsolidus matrix phases. Major melting will only occur at the onset of reaction 1 by volatile-phase-absent melting consuming muscovite (Fig. 4). We interpret the migmatite front, a short distance beyond which primary muscovite is consumed, to approximate the crossing of reaction 1 at conditions of 4.5–5.0 kbar and ≥ 670 °C.

As there is no evidence for major volatile-phase-absent melting consuming biotite and sillimanite (i.e., by reaction 5), the migmatites are predicted to be stable over 30–40 °C. At T_{max}, approximately 700 °C, melt fractions approach 15 mol%, similar to independent estimates by Solar and Brown (2001b). Higher melt fractions are generated if the metamorphic field gradient extends to higher *P* (Figs. 4a and 4b) and/or in rocks into which an influx of H_2O occurred. An "external" supply of H_2O from proximal crystallizing granite is possible, although we have no evidence for such an influx. The positive d*P*/d*T* of the red *P-T* vector implies increasing *P* towards the south and southwest. This suggests a greater amount of post-peak exhumation towards the southwest (e.g., Holdaway et al. 1988; De Yoreo et al. 1989; Dickerson and Holdaway 1989) and a smaller overburden at the metamorphic peak in the northeast.

The modeled phase equilibria along the *P-T* vector described by the red arrow in Figure 6b are equally consistent with the line segment B-B' in Figure 1, which is essentially orthogonal to the trend of the CMB and extends into the migmatites at its high-grade end, implying an across-strike *P* increase. Consequently, a model of post-tectonic tilting of the CMB with greater exhumation of rocks towards the southwest (e.g., DeYoreo et al. 1989) is an oversimplification. Across-strike variations in *P* are consistent with late-syntectonic metamorphism, the structural southeast side-up kinematics and flattening (Solar and Brown 2001a).

The green *P-T* vector on Figure 6b is a plausible alternative for regional metamorphic field gradients that cross into the anatectic zone (i.e., A-A', B-B'). This *P-T* vector is curved with d*P*/d*T* increasing in a prograde direction. Such a field gradient is attractive in that it extends to higher *P* within the melting field and consequently will produce a greater volume of melt at given *T* (Figs. 4a and 4b). The implication from the shape of the field gradient described by the green *P-T* vector is that rocks within the anatectic zone were thickened more relative to subsolidus rocks at the metamorphic peak. Such a conclusion is consistent with preferred partitioning of plastic strain into rheologically weaker migmatites.

The blue arrow on Figure 6b shows an isobaric (P = 4.0 kbar) *P-T* vector that is most consistent (albeit at higher *P*) with the regional metamorphic field gradient previously proposed for the area (Guidotti 1989; Guidotti and Holdaway 1993; Guidotti et al. 1996). At lower grade, the model predictions match field observations well; however, at higher grades this is not the case. The distance (*T*-range) from the onset of volatile-phase-absent melting by muscovite-breakdown (reaction 1) to the onset of major biotite-consuming, cordierite-producing melting (reaction 5) is unrealistically small (only 10 °C) to account for the areal extent of migmatite. Predicted melt fractions at such low *P* (9 mol%) conflict with the estimates of Solar and Brown (2001b).

A near-isobaric metamorphic field gradient is not consistent with the overall pattern of regional metamorphism in western Maine that culminates in the development of migmatites. However, it is consistent with the pattern of metamorphism in the north of the area, around the Redington pluton and south-central lobes of the Lexington body, in which the prograde metamorphic field gradient (towards the north or northeast; C-C' on Fig. 1) is the reverse of the overall regional metamorphic trend. At the lower-Al-silicate to upper-Al-silicate transition, the field gradient is constrained to bathozone 2b, below the star in Figures 6a and 6b. The *P-T* vector(s) most consistent with the field gradient defined by the line C-C' are shown in orange in Figure 6b, and may be isobaric or have a shallow negative d*P*/d*T*.

A near-isobaric (P = 2.7 kbar) regional metamorphic field gradient, as previously proposed for western Maine (Holdaway et al. 1982; Dickerson and Holdaway 1989; Guidotti 1989; Guidotti and Holdaway 1993; Guidotti et al. 1996; Fig. 6b), would lie within bathozone 1 as calibrated by the calculations herein (Fig. 6a). Along such an isobaric *P-T* vector at 2.7 kbar, staurolite + andalusite is not predicted in common metapelite (Fig. 6a). At higher grades along this vector, cordierite and K-feldspar should be abundant, garnet will be absent, and muscovite will not be stable at the solidus.

Reaction sequence

The sequence of prograde reactions predicted in common metapelitic rocks along the red *P-T* vector (Fig. 6b) is given below. The reactions were determined by comparing the abundance of phases within the pertinent multivariant fields at relatively high and low *T*:

Biotite zone (stable over > 50 °C) Chl + Ms ↔ Bt + (Pl) + Qtz + H_2O

Garnet zone (35 °C) Chl + Ms ↔ Bt + (Pl) + Grt + Qtz + H_2O

Staurolite zone (25 °C) Grt + ***Chl*** + Ms ↔ Bt + St + Pl + Qtz + H_2O

Lower Al-silicate zone (10–15 °C) ***St*** + Ms + (Qtz) ↔ Bt + Grt + Al-silicate + (Pl) + H_2O

Upper Al-silicate zone (60 °C) Grt + Ms + Qtz ↔ Bt + Sil + Pl + H_2O

Solidus (< 1 °C) (Bt) + (Grt) + Ms + Sil + Pl + Qtz + $\boldsymbol{H_2O}$ ↔ L

Ms-breakdown melting (5 °C) ***Ms*** + Pl + Qtz ↔ (Bt) + Kfs + Sil + L.

T > Ms-breakdown melting (<30 °C) Bt + Sil + Pl + Qtz ↔ Grt + Kfs + L.

Reactants shown in bold italics are consumed by the reaction; those in parentheses are minor participants (i.e., have low reaction coefficients).

Implications for the distribution of regional isotherms

A comparison of the width (essentially *T*-range) of the stability fields of assemblages I-VIII along the red *P-T* vector with the areal distribution of isograds in the field (Fig. 1) is instructive. Garnet-zone assemblages are stable over about 35 °C but are widely distributed in the field and stable over many tens of kilometers at map scale (Fig. 1). The most extensive modeled stability field is the upper-Al-silicate zone (assemblages Va and VI), which, including the segment of the *P-T* vector beyond the solidus and up to the onset of reaction 1, is stable over some 80 °C. The upper-Al-silicate zone in the south of the region is generally less than 5 km wide (Fig. 1). The implication is that at lower-grade, regional palaeo-isotherms are sub-horizontal and widely spaced, whereas at high-grade, under subsolidus conditions, isotherms around the margins of syn-metamorphic granite plutons and the anatectic domains are closely spaced and/or steep (Holdaway et al. 1982). Such a conclusion is consistent with a pluton-enhanced thermal structure in subsolidus rocks (e.g., Guidotti and Holdaway 1993). A wider areal extent of the Al-silicate zone in the northeast of the region (Fig. 1) suggests more shallowly inclined higher-grade isotherms and, consequently, that the central and southern lobes of the Lexington composite pluton have a shallow southwesterly dip.

The fundamental source of the heat necessary to drive low-*P* regional metamorphism that culminates in melting at mid-crustal depths in western Maine is currently poorly understood. However, the peraluminous nature of the voluminous syn-metamorphic granites implies derivation from a metasedimentary source. The energy required for anatexis suggests that the granites are an effect, rather than the cause, of the crustal-scale thermal anomaly. Upon generation of large volumes of partial melt, the granites segregated from source, advecting heat that was locally redistributed within the regionally extensive thermal high (e.g., Brown and Solar 1999).

Retrogression of regional assemblages

Most regional metamorphic assemblages exhibit varying degrees of retrograde reaction that implies some volatile phase influx following the peak of regional metamorphism and preceding the intrusion of the Mooselookmeguntic igneous complex (e.g., Guidotti et al. 1996; Foster and Dutrow 2000; Guidotti and Johnson 2002). Retrograde assemblages (e.g., chlorite + white mica after staurolite) suggest that temperatures had cooled close to the ambient (non advection-enhanced) geotherm. We suggest that the required H_2O was liberated following crystallization of granite derived from within the anatectic zone as regional temperatures fell below the solidus (Solar and Brown 2001b). Some melt may have remained broadly in situ, as implied by the abundance of retrograde skeletal muscovite and the general absence of K-feldspar within migmatite (cf. Kohn et al. 1997), although a large portion of the generated melt must have segregated to higher levels as syn-Acadian granites. The Tumbledown and Weld anatectic domains are the surface expression of the anatectic zone, which we suggest underlies much of the region at depth.

Contact metamorphism around the Mooselookmeguntic igneous complex

In the contact aureole of the late Devonian Mooselookmeguntic igneous complex, sillimanite is the only stable Al_2SiO_5 polymorph. Consequently, the contact metamorphic field gradient associated with the complex is constrained to bathozone 3, at $P > 4.1$ kbar (i.e., above the star in Figs. 6a and 6b), implying an increase in P after the regional metamorphic peak. Holdaway et al. (1982) and Guidotti et al. (1996) postulated that such a P increase may have been the result of post-tectonic extrusion of volcanic rocks or pluton emplacement at levels above that of the current exposure. Given the evidence from porphyroblast-matrix relations for the ongoing accumulation of plastic strain at and immediately after the metamorphic peak (e.g., Solar and Brown 1999, 2000, 2001a), we suggest that an equally plausible explanation for the P increase is the final increment of tectonic thickening during the waning stage of Acadian orogenesis. Furthermore, following the peak of Acadian regional metamorphism, the brittle-viscous transition zone will be displaced downwards as the orogen cools (Handy et al. 2001). Since this zone is a likely trap for ascending melt (Brown 2001), such an interpretation is consistent with the ascending melts of the Mooselookmeguntic igneous complex being trapped at a deeper crustal level in comparison with the syn-Acadian plutons. The previous P estimate of around 3.1 kbar for metamorphism associated with the Mooselookmeguntic igneous complex (e.g., Guidotti and Holdaway 1993) cannot be reconciled with the results of our study (Fig. 6).

P-T-t evolution

Quantifying the *P-T-t* (time) evolution of rocks in western Maine, as in many low-*P* terranes, is problematic. However, the qualitative constraints are (1) the synchronous age of regional metamorphism and crystallization of syn-Acadian granites (ca. 404 Ma); (2) the evidence for advection-driven redistribution of heat; (3) the evidence for the accumulation of plastic strain and consequent thickening at and beyond the regional metamorphic peak; (4) extensive volatile-phase-present retrograde reaction as rocks cooled close to the ambient geotherm; (5) subsequent post-Acadian (ca. 370 Ma) contact metamorphism that occurred at higher-*P* than the regional peak and following cessation of thickening of the CMB.

Figure 6c shows an idealized and schematic *P-T-t* path around the staurolite stability field that is consistent with these constraints. The increase in *P* beyond the regional peak implies an overall counter-clockwise *P-T-t* evolution, consistent with that inferred in western New Hampshire and central Massachusetts (e.g., Winslow et al. 1994; Kohn et al. 1997; Thomson 2001).

A metapelitic rock following the exemplar *P-T-t* path shown in Figure 6c develops the lower Al-silicate zone assemblage biotite + garnet + staurolite + sillimanite (replacing andalusite) at the regional metamorphic peak and thickening continues on cooling (i.e., along a counter-clockwise path). As the rocks cool to ambient or near-ambient temperatures (e.g., DeYoreo et al. 1989; Guidotti and Holdaway 1993; Guidotti et al. 1996), H_2O-rich volatile phase-influx causes retrogression (e.g., chlorite + white mica after staurolite; chlorite after garnet; muscovite after Al-silicate). Following this, the rock is affected by the intrusion of the Mooselookmeguntic igneous complex at c. 370 Ma. In this example, the peak contact metamorphic temperature experienced by the rock (staurolite grade) is lower than that attained during the regional event; new staurolite develops but no stable Al-silicate remains (e.g., Guidotti and Johnson 2002).

The *P-T-t* path is drawn for the case where intrusion of the Mooselookmeguntic igneous complex occurred at maximum *P*, implying minimal exhumation of the rocks prior to 370 Ma. We have no constraints on the relative or absolute timing of the cessation of thickening, only that it occurred in the interval 404–370 Ma. Consequently *P-T-t* paths may have more complex looped geometries, a feature that may be common in low-*P*, high-*T* metamorphic terranes (Williams and Karlstrom 1996). The precise nature of the *P-T* path for a particular rock depends on its depth of burial, structural location (i.e., within "straight" belts or intervening zones), and proximity to both syn-Acadian and post-Acadian plutons.

Model limitations

Additional components that are not included in the model system but which are commonly present in minor quantities in metapelitic rocks will influence phase equilibria to varying degrees. TiO_2 and Fe_2O_3 will tend to expand the biotite stability field. Increased biotite stability will reduce the modal abundance of K-bearing phases (muscovite and K-feldspar) and ferromagnesian phases (principally staurolite). The staurolite field may be enlarged by the presence of Zn (averaging 91 ppm in the metapelites; Solar and Brown 2001b), although such effects are probably small (e.g., Pattison et al. 1999).

The prograde decomposition of graphite, variably present in small amounts in the subsolidus rocks, will tend to dilute the supercritical volatile phase, lowering a_{H_2O}. The principal effect is that the stability fields of cordierite- and andalusite-bearing assemblages are slightly extended to higher P, and the breakdown of muscovite to K-feldspar + aluminosilicate occurs at lower T at any particular P (Pattison 1989; Pattison et al. 2002). The minimum P constraints on the position of the subsolidus portion of the metamorphic field gradient, in rocks that lack cordierite and subsolidus K-feldspar, are consequently raised (by around 0.5 kbar). As the pertinent stability fields lie at much lower P (by about 1.0 kbar; Fig. 6), a reduced a_{H_2O} does not significantly affect our proposed constraints on the metamorphic field gradient.

The modeled pseudosections predict that the cordierite field has a shallow positive slope and implies that, along a low P (<3.5 kbar) isobaric heating path, cordierite + muscovite will be produced from the breakdown of biotite + andalusite; such a conclusion is at odds with many examples of reactions inferred from microstructural relations within natural metapelitic rocks (cf. Pattison et al. 2002). The model calculations presented here do not account for rare assemblages that are developed in uncommon bulk compositions. The effect of an increased X_{Mg} beyond that of common metapelites accounts for the occurrences of cordierite (Fig. 3). Chloritoid is stable in particularly Fe-rich rocks; compositions in which chloritoid is predicted to be stable (e.g., from calculations on Ds 96-16) are reported by Solar and Brown (2001b).

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REFERENCES CITED

Berman, R.G. (1988) Internally-consistent thermodynamic data for minerals in the system Na_2O-K_2O-CaO-MgO-FeO-Fe_2O_3-Al_2O_3-SiO_2-TiO_2-H_2O-CO_2. Journal of Petrology, 29, 445–522.

Brown, M. (1994) The generation, segregation, ascent and emplacement of granitic magma: The migmatite-to-crustally derived granite connection in thickened orogens. Earth Science Reviews, 36, 83–130.

———(2001) Orogeny, migmatites and leucogranites: A review. Proceedings of the Indian Academy of Science (Earth and Planetary Sciences), 110, 313–336.

Brown, M. and Pressley, R.A. (1999) Crustal melting in nature: prosecuting source processes. Physics and Chemistry of the Earth A, 24, 305–316.

Brown, M. and Solar, G.S. (1998a) Shear zone systems and melts: feedback relations and self organization in orogenic belts. Journal of Structural Geology, 20, 211–227.

———(1998b) Granite ascent and emplacement during contractional deformation in convergent orogens. Journal of Structural Geology, 20, 1365–1393.

———(1999) The mechanism of ascent and emplacement of granite magma during transpression: a syntectonic granite paradigm. Tectonophysics, 312, 1–33.

Carmichael, D.M. (1978) Metamorphic bathozones and bathograds: a measure of the depth of post-metamorphic uplift and erosion on the regional scale. American Journal of Science, 278, 769–797.

Chamberlain, C.P. and Robinson, P. (1989) Styles of metamorphism with depth in the central Acadian high, New England. Department of Geology and Geography, University of Massachusetts, Amherst, Contribution 63.

De Yoreo, J.J, Lux, D.R., Guidotti, C.V., Decker, E.R., and Osberg, P.H. (1989) The Acadian thermal history of western Maine. Journal of Metamorphic Geology, 7, 169–190.

De Yoreo, J.J., Lux, D.R., and Guidotti, C.V. (1991) Thermal modeling in low-pressure/high-temperature metamorphic belts. Tectonophysics, 188, 209–238.

Dickerson, R.P. and Holdaway, M.J. (1989) Acadian metamorphism associated with the Lexington batholith, Bingham, Maine. American Journal of Science, 289, 945–974.

Droop, G.T.R., Clemens, J.D., and Dalrymple, D.J. (2003) Contact anatexis of metapelites, melt escape and restite formation in the Huntly Gabbro Complex, N. E. Scotland: an integrated investigation. Journal of Petrology, in press.

Foster, C.T. and Dutrow, B.L. (2000) Evidence for separate hydration and thermal pulses during M3 regional-contact metamorphism in western Maine. Geological Society of America – Abstracts with Programs, 32, 54.

Guidotti, C.V. (1974) Transition from staurolite to sillimanite zone, Rangeley quadrangle, Maine. Geological Society of America Bulletin, 85, 475–490.

———(1989) Metamorphism in Maine: an overview. In R.D. Tucker and R.G.Marvinney, Eds., Studies in Maine Geology, Volume 3: Igneous and Metamorphic Geology, p. 1–19. Maine Geological Survey.

———(2000) The classic high-T–low-P metamorphism of west-central Maine, USA: Is it post-tectonic or syn-tectonic? Evidence from porphyroblast-matrix relations: Discussion. Canadian Mineralogist, 38, 1007–1026.

Guidotti, C.V. and Holdaway, M.J. (1993) Petrology and field relations of successive metamorphic events in pelites of west-central Maine. In J.T. Cheney and J.C. Hepburn Eds., Field trip guidebook for the northeastern United States, Volume 1, L1-23. 1993 Boston Geological Society of America, USA.

Guidotti, C.V. and Johnson, S.E. (2002) Pseudomorphs and associated microstructures of western Maine, USA. Journal of Structural Geology, 24, 1139–1156.

Guidotti, C.V., Foster, C.T., Hames, W.E., Henry, W.E., Kinner, D.A., and Lux, D.L. (1996) Ploymetamorphism in western Maine: mineralogic, petrologic, and textural manifestations and regional implications. In M.V. Van Baalen, Ed., Guidebook to fieldtrips, 88, 171–202. New England Intercollegiate Geological Conference.

Handy, M.R., Braun, J., Brown, M., Kukowski, N., Paterson, M.S., Schmid, S.M., Stöckhert, B., Stüwe, K., Thompson, A.B. and Wosnitza, E. (2001) Rheology and geodynamic modelling: the next step forward. International Journal of Earth Sciences, 90, 149–156.

Henry, D.J. (1981) Sulfide-silicate relations of the staurolite grade pelitic schists, Rangeley Quadrangle, Maine. Ph.D. thesis, University of Winsconsin, Madison, Wisconsin. 437 p.

Holdaway, M.J. (1971) Stability of andalusite and the aluminium silicate phase diagram. American Journal of Science, 271, 97–131.

———(2000) Application of new experimental and garnet Margules data to the garnet-biotite geothermometer. American Mineralogist, 85, 881–892.

Holdaway, M.J., Guidotti, C.V., Novak, J.M., and Henry, W.E. (1982) Polymetamorphism in medium- to high-grade pelitic metamorphic rocks, west-central Maine. Geological Society of America Bulletin, 93, 572–584.

Holdaway, M.J., Dutrow, B.L., and Hinton, R.W. (1988) Devonian and Carboniferous metamorphism in west-central Maine: The muscovite-almandine geobarometer and the staurolite problem revisited. American Mineralogist, 73, 20–47.

Holdaway, M.J., Mukhapodhyay, B., Dyar, M.D., Guidotti, C.V., and Dutrow, B.L. (1997) Garnet-biotite geothermometry revised: new Margules parameters and a natural specimen data set from Maine, American Mineralogist, 82, 582–595.

Holland, T.J.B. and Powell, R. (1998) An internally consistent thermodynamic data set for phases of petrological interest. Journal of Metamorphic Geology, 16, 309–343.

———(2001) Calculation of phase relations involving haplogranitic melts using an internally consistent thermodynamic dataset. Journal of Petrology, 42, 673–683.

Hudson, N.F.C. (1980) Regional metamorphism of some Dalradian pelites in the Buchan area, N.E. Scotland. Contributions to Mineralogy and Petrology, 73, 39–51.

Johnson, T.E., Gibson, R.L., Brown, M., Buick, I.S. and Cartwright, I. (2003) Partial melting of metapelitic rocks beneath the Bushveld Complex, South Africa. Journal of Petrology, 44, in press.

Kohn, M.J., Spear, F.S. and Valley, J.W. (1997) Dehydration-melting and fluid recycling during metamorphism: Rangeley Formation, New Hampshire, USA. Journal of Petrology, 38, 1255–1277.

Kretz, R. (1983) Symbols for rock forming minerals. American Mineralologist, 68, 277–279.

Mahar, E.M., Baker, J.M., Powell, R., Holland T.J.B., and Howell, N. (1997) The effect of Mn on mineral stability in metapelites. Journal of Metamorphic Geology, 15, 223–238.

Moench, R.H. (1971) Geologic map of the Rangeley and Phillips quadrangles, Franklin and Oxford Counties, Maine. U.S. Geological Survey Map I-605.

Moench, R.H. and Hildreth, C.T. (1976) Geologic map of the Rumford Quadrangle, Oxford and Franklin Counties, Maine. U.S. Geological Survey Map GQ-1272.

Moench, R.H., Boone, G.M., Bothner, W.A., Boudette, E.L., Hatch, N.L., Jr., Hussey, A.M., II, Marvinney, R.G., and Aleinikoff, J.N. (1995) Geologic map of the Sherbrooke-Lewiston area, Maine, New Hampshire, and Vermont, United States, and Quebec Canada: U.S. Geological Survey Map I-1898-D.

Patiño Douce, A.E. and Harris, N. (1998) Experimental constraints on Himalayan anatexis. Journal of Petrology, 39, 689–710.
Pattison, D.R.M. (1989) P-T conditions and the influence of graphite on pelitic phase relations in the Ballachulish thermal aureole, Scotland. Journal of Petrology, 30, 1219–1244.
———(1992) Stability of andalusite and sillimanite and the Al_2SiO_5 triple point: Constraints from the Ballachulish aureole, Scotland. Journal of Geology, 100, 423–446.
Pattison, D.R.M., Spear, F.S. and Cheney, J.T. (1999) Polymetamorphic origin of muscovite + cordierite + staurolite + biotite assemblages: implications for the metapelitic petrogenetic grid and for P-T paths. Journal of Metamorphic Geology, 17, 685–703.
Pattison, D.R.M., Spear, F.S., Debuhr, C.L., Cheney, J.T., and Guidotti, C.V. (2002) Thermodynamic modeling of the reaction muscovite+cordierite Al_2SiO_5 + biotite+quartz+H_2O: constraints from natural assemblages and implications for the metapelitic petrogenetic grid. Journal of Metamorphic Geology, 20, 99–118.
Powell, R. and Holland, T.J.B. (1988) An internally consistent thermodynamic dataset with uncertainties and correlations. III. Application methods, worked examples and a computer program. Journal of Metamorphic Geology, 6, 173–204.
Pressley, R.A. and Brown, M. (1999) The Phillips pluton, Maine, USA: evidence for heterogeneous crustal sources for granite ascent and emplacement mechanisms in convergent orogens. Lithos, 49, 335–366.
Smith, H.A. and Barreiro, B. (1990) Monazite U-Pb dating of staurolite grade metamorphism in pelitic schists. Contributions to Mineralogy and Petrology, 105, 602–615.
Solar, G.S. and Brown, M. (1999) The classic high-T–low-P metamorphism of west-central Maine, USA: Is it post-tectonic or syn-tectonic? Evidence from porphyroblast-matrix relations. Canadian Mineralogist, 37, 311–333.
———(2000) The classic high-T – low-P metamorphism of west-central Maine, USA: Is it post-tectonic or syn-tectonic? Evidence from porphyroblast-matrix relations: Reply. Canadian Mineralogist, 38, 1007–1026.
———(2001a) Deformation partitioning during transpression in response to Early Devonian oblique convergence, northern Appalachian orogen, USA. Journal of Structural Geology, 22, 1043–1065.
———(2001b) Petrogenesis of Migmatites in Maine, USA: Possible Source of Peraluminous Granite in Plutons. Journal of Petrology, 42, 789–823.
Solar, G.S., Pressley, R.A., Brown, M., and Tucker, R.D. (1998) Granite ascent in convergent orogenic belts: Testing a model. Geology, 26, 711–714.
Spear, F.S. (1988) The Gibbs method and Duhem's theorem: The quantitative relationships among P, T, chemical potential, phase composition and reaction progress in igneous and metamorphic systems. Contributions to Mineralogy and Petrology, 99, 249–256.
———(1990) Petrologic determination of metamorphic pressure-temperature-time paths. In F.S. Spear and S.M. Peacock, Eds., Metamorphic pressure-temperature-time paths, p. 1–55. 28th International Geological Conference Short Course in Geology, 7, Washington, D.C.
Spear, F.S., Kohn, M.J. and Cheney, J.T. (1999) P-T paths from anatectic pelites. Contributions to Mineralogy and Petrology, 134, 17–32.
Stevens, G., Clemens, J.D., and Droop, G.T.R. (1997) Melt production during granulite-facies anatexis: Experimental data from "primitive" metasedimentary protoliths. Contributions to Mineralogy and Petrology, 128, 352–370.
Thomson, J.A. (2001) A counterclockwise P-T path for anatectic pelites, south-central Massachusetts. Contributions to Mineralogy and Petrology, 141, 623–641.
Thomson, J.A. and Guidotti, C.V. (1989) Carboniferous Barrovian metamorphism in southern Maine. Maine Geological Survey, Studies in Maine Geology, 3, 35–51.
Thompson, J.B., Jr (1957) The graphical analysis of mineral assemblages in pelitic schists. American Mineralogist, 42, 842–858.
Tinkham, D.K., Zuluaga, C.A., and Stowell, H.H. (2001) Metapelitic phase equilibria modeling in MnNCKFMASH: The effect of variable Al_2O_3 and MgO/(MgO + FeO) on mineral stability. Geological Materials Research, 3, 1–42.
Tomascak, P.B., Krogstad, E.J., and Walker, R.J. (1996) U-Pb monazite geochronology of granitic rocks from Maine: implications for late Paleozoic tectonics in the northern Appalachains. Journal of Geology, 104, 185–195.
van Staal, C. R. and MacNiocaill, C. (2001) Arc magmatism in the Appalachians-Caledonian Orogen. Geological Society of America Abstracts with Programs, 33, 204.
West, D.P., Jr. and Hubbard, M.S. (1997) Progressive localization of deformation during exhumation of a major strike-slip shear zone: Norumbega fault zone, south-central Maine. Tectonophysics, 273, 185–202.
White, R.W., Powell, R., and Holland, T.J.B. (2001) Calculation of partial melting equilibria in the system Na_2O-CaO-K_2O-FeO-MgO-Al_2O_3-SiO_2-H_2O (NCKFMASH) Journal of Metamorphic Geology, 19, 139–153.
White, R.W., Powell, R., and Clarke, G.L. (2002) The interpretation of reaction textures in Fe-rich metapelitic granulites of the Musgrave Block, central Australia: constraints from mineral equilibria calculations in the system K_2O-FeO-MgO-Al_2O_3-SiO_2-H_2O-TiO_2-Fe_2O_3. Journal of Metamorphic Geology, 19, 139–153.
Williams, M.L. and Karlstrom, K.E. (1996) Looping *P-T* paths and high-T, low-P middle crustal metamorphism: Proterozoic evolution of the southwestern United States. Geology, 24, 1119–1122.
Winslow, D.M., Bodnar, R.J. and Tracy, R.J. (1994) Fluid inclusion evidence for an anticlockwise metamorphic *P-T* path in central Massachusetts. Journal of Metamorphic Geology, 12, 361–371.

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