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GEOMETRY OF ISOGRADIC, ISOTHERMAL, AND ISOBARIC SURFACES: INTERPRETATION AND APPLICATION

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Abstract

An isograd represents a line on a map resulting from the intersection of an isogradic surface with the topography. It is inferred to represent a metamorphic reaction and is inherently diachronous because of the time required to move heat, fluid, and reactions through the rocks. Relief of 500 m or more or reconstruction of post-metamorphic faulting and folding will be essential to estimate the orientation of an isogradic surface. Ductile rocks require that isobaric surfaces dip gently during metamorphism, and they must do so in restored sections. Isotherms can be constructed into cross-sections because the angle between the isograds and isotherms are a function of the P–T slope of univariant reaction curves. Near Mica Creek, British Columbia, we can infer an 1100-bar difference in pressure along a kyanite–sillimanite (ky–sil) isograd, based upon structural relief. The experimentally determined ky–sil P–T curve suggests a P/T slope of ~20 bars/°C. We calculate the apparent variation in P and T along the isograd and reconstruct the isotherm geometry. Dehydration-reaction curves, at relatively high P, have steep P–T slopes, and the associated isogradic surfaces can approximate isothermal surfaces. Some dehydration isograds are "smeared out", but for regional scales, these latter isogradic surfaces at high P still approximate the isothermal surface geometry. Data on isogradic surfaces can be used to set limits on parts of the P–T grids for pelitic rocks. Locally, bathozone-defining isobaric surfaces can be reconstructed; we suggest a ΔP of 2 kbar for the garnet – biotite – kyanite bathozone.

Keywords: isograd, isogradic surface, isobaric surface, isothermal surface, P–T grids, pelitic rocks, kyanite–sillimanite isograd, dehydration isograd, bathozone, diachronism.

Sommaire

Un isograde représente une ligne sur une carte résultant de l'intersection d'une surface isograde avec la topographie. Elle représenterait une réaction métamorphique et serait implicitement diachrone à cause du temps requis pour mobiliser la chaleur, les fluides, et les réactions dans les roches. Un relief de 500 m ou davantage ou une reconstruction des failles et des plissements post-métamorphiques seront essentiels afin d'estimer l'orientation d'une surface isograde. Les roches ductiles impliquent une surface isobare à faible pendage au cours d'un épisode de métamorphisme, et c'est essentiel qu'une telle surface ait cet aspect dans les coupes restaurées. On peut reconstruire les isothermes en coupes transversales parce que l'angle entre les isogrades et les isothermes dépend de la pente P–T des courbes de réactions monovariantes. Près de Mica Creek, en Colombie-Britannique, nous pouvons supposer une différence de 1100 bars en pression le long de l'isograde kyanite–sillimanite (ky–sil), compte tenu du relief structural. La courbe P–T de la réaction ky–sil indique une pente P/T d'environ 20 bars/°C. Nous calculons une variation apparente en P et en T le long de l'isograde, et nous reconstruisons la géométrie des isothermes. Les courbes des réactions de déshydratation, à pression relativement élevée, possèdent une pente près de la verticale, et les surfaces isogrades associées peuvent simuler des surfaces isothermes. Dans certains cas, les isogrades de réactions de déshydratation sont en fait "flous", mais sur une échelle régionale, la géométrie des surfaces isogrades de telles réactions à pression élevée ressemble encore à celle des surfaces isothermes. Les données portant sur les surfaces isogrades peuvent servir à délimiter certaines parties de réseaux de réactions pour les roches pélitiques. A l'échelle locale, on peut reconstruire les surfaces isobares aptes à définir une bathozone; nous préconisons une valeur de ΔP de 2 kbar dans le cas de la bathozone grenat – biotite – kyanite.

(Traduit par la Rédaction)

Mots-clés: isograde, surface isograde, surface isobare, surface isothermale, réseau P–T, roches pélitiques, isograde kyanite–sillimanite, isograde de déshydratation, bathozone, diachronisme.

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Introduction

The term *isograd* was defined by Tilley (1924): "This term may be used in the same sense as isotherm or isobar. It may thus be defined as a line joining points of similar P,T values, under which the rocks now constituted originated." Since that time there have been a number of definitions of isograds. Our preferred definition is from Carmichael (1970), "a line on a map across which there is a change in metamorphic mineralogy." The implication in this latter definition is that the mineral assemblages on either side of the isograd can be mass balanced, *e.g.*, Greenwood (1968).

Our model for isograds, isogradic surfaces, isothermal surfaces, and isobaric surfaces is presented in Figure 1. Our interpretation is that an isograd is a line representing the intersection of an isogradic surface with the topography. An isogradic surface is the three-dimensional surface that separates the different mineral assemblages that represent the "isogradic reaction," that is, there is a mass balance of mineral assemblages across the isogradic surface. *Isothermal surfaces* are surfaces of constant temperature. They intersect the isogradic surface as lines of constant temperature. *Isobaric surfaces* are surfaces of constant pressure. They intersect the isogradic surface as lines of constant pressure. It is possible to consider other intensive variables within the isogradic surface, *e.g.*, fugacity of H_2O. The isogradic surface is not in general the locus surface of points with similar pressure and temperature, except in special cases such as isothermal isograds.

In this paper, we present some petrological interpretations of the geometry and nature of isogradic surfaces. We begin by establishing that isobaric surfaces must have primary dips limited to a few degrees. There are no such restrictions on the dip of isothermal surfaces. The diachronous nature of isograds and the occurrence of "smeared out" isograds place limitations on quantitative interpretation. We discuss how to deal with these limitations. Isogradic surfaces are intersected by isobaric and isothermal surfaces to produce isobaric and isothermal lines. We discuss applications of this concept with respect to a kyanite–sillimanite isograd near Mica Creek, British Columbia. Dehydration isograds can be approximated by univariant P–T curves, which can have steep slopes on a P–T diagram. This implies that these dehydration isogradic surfaces approximate isothermal surfaces. We discuss the complexities and the applications of this relationship. In the area in southeastern British Columbia that we have studied, we can compare the field relationships of the isograds to published petrogenetic grids (Carmichael 1978, Davidson *et al.* 1990, Pattison 2001). An important conclusion is that understanding the geometry of isogradic surfaces not only enhances structural and tectonic analysis, but also enhances petrological understanding.

Geometrical Analysis of Isobaric, Isothermal, and Isogradic Surfaces

Fyfe *et al.* (1978) and Carmichael (1978) argued that a primary isobaric surface should be smooth and have a low dip, because of the relatively low strength and ductile behavior of rocks at depth. We illustrate this with a cross-section of the Himalayas modified from Searle (1999; our Fig. 2). The long-term strength of near-surface rocks is only some 25% of their short-term strength (Price 1967). This low strength and the instability of high steep slopes due to weathering and the Earth's gravitational field limit local relief to that seen in the Himalayas. The ductility and low strength of rocks at depth permit only small transient differential stresses and lead to lithostatic pressures. Isobaric surfaces will be subhorizontal unless later tilted by deformation. In the cross-section of the Himalayas (Fig. 2, see Searle 1999), we show that the maximum primary dip of isobaric surfaces will be found in the upper crust at the margins of the highest mountain ranges. We estimate that these isobaric surfaces have a dip of about 8° at the southern, steep side of the Himalayas.

We cannot make similar inferences about isothermal surfaces. We should note that the isogradic surfaces can have a primary dip; they may be nearly vertical or even overturned ("hot-side up"). Examples of "hot-side up" isogradic surfaces include those described by Ghent & Stout (1981), Ghent *et al.* (1980), Arita (1983), and Swapp & Hollister (1991). We have demonstrated in earlier papers that isothermal surfaces may have significant primary curvatures and dips (Ghent *et al.* 1980, Digel *et al.* 1998). Streckeisen & Wenk (1974) documented steep isogradic surfaces in the Simplon area of the Central Alps. They inferred the presence of near-horizontal isobaric surfaces and, for the isothermal surfaces, they suggested average dips, not due to subsequent tilting, of 55 to 90°.

The geometry of isogradic surfaces and their relationship to associated isothermal and isobaric surfaces have been discussed by several authors (*e.g.*, Chinner 1963, Streckeisen & Wenk 1974, Carmichael 1978, Thompson 1976, Day 1987, Ghent *et al.* 1980). Determining the 3-D geometry of these surfaces is difficult, and much remains to be done. We discuss here some of the fundamental geometrical relationships that we will use in this paper.

The dip of an isogradic surface cannot be measured with an instrument; information must be obtained for some variant of the three-point solution. This is best obtained where the isogradic surface is exposed as a sharply defined isograd in an area of high topographic relief. Post-metamorphic faulting, folding and regional plunge lead to exposure of an isograd at different structural levels. If the structures are well understood, important 3-D control may be obtained and may permit

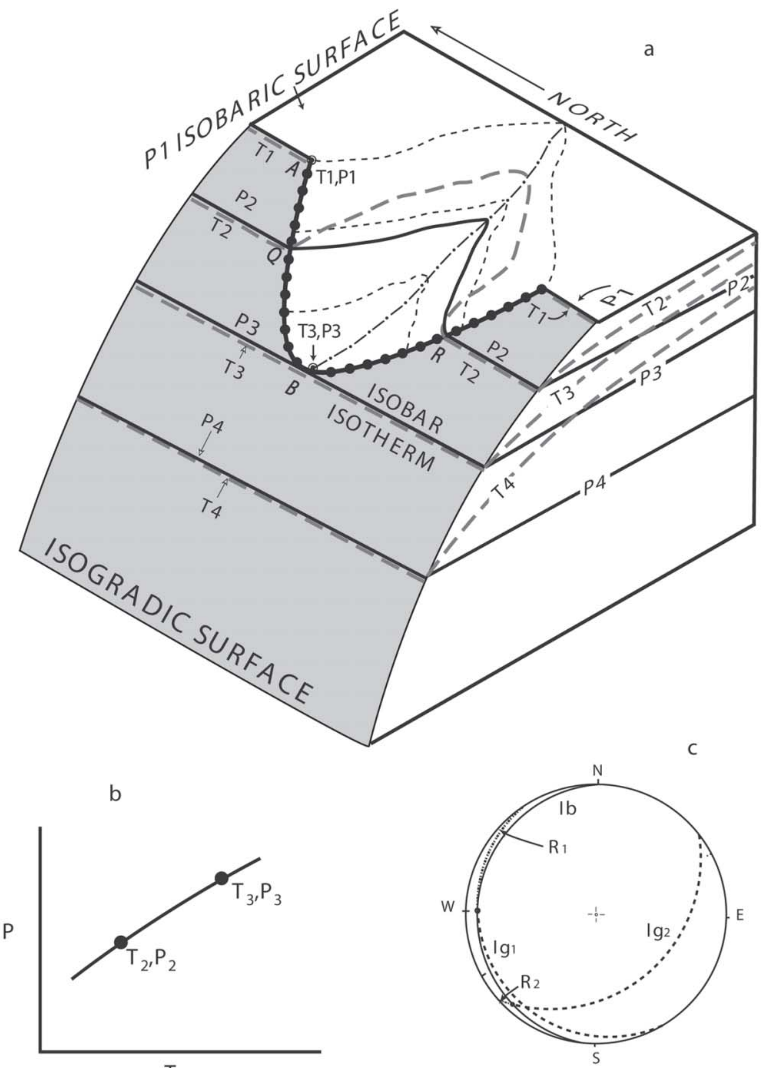

FIG. 1. a) Block diagram illustrating a univariant-reaction isogradic surface and its intersections with horizontal isobaric surfaces P1, P2, P3, P4 and gently curved, westerly dipping isothermal surfaces, T1,T2,T3,T4. A valley has been eroded into the top to the block by a stream (dot-dash line), and the valley sides are shown by topographic contours (short dashes). On the valley sides, the T2 isotherm is exposed (long heavy dashes) as well as the P2 isobar (solid line). The isograd is the line (with large dots) on the erosion surface. b) Univariant reaction curve in P–T space related to the isogradic surface in 1a. Points T2,P2 and T3,P3 correspond to univariant lines on the isogradic surface. c) Stereographic net with gently dipping isobaric surface, Ib, intersecting two isogradic surfaces, Ig1 and Ig2, to illustrate the possible variations in rake (R1 and R2) of the intersection lines in the isogradic surface.

defining an isogradic surface at depth even where topographic relief is low.

Isothermal and isobaric surfaces intersect the isogradic surface and, for isograds related to univariant reaction curves, the isotherms and isobars *on the isogradic surface* must all be parallel and have the same plunge and rake (Fig. 1a). We can think of an isogradic surface as being defined by a series of parallel lines that

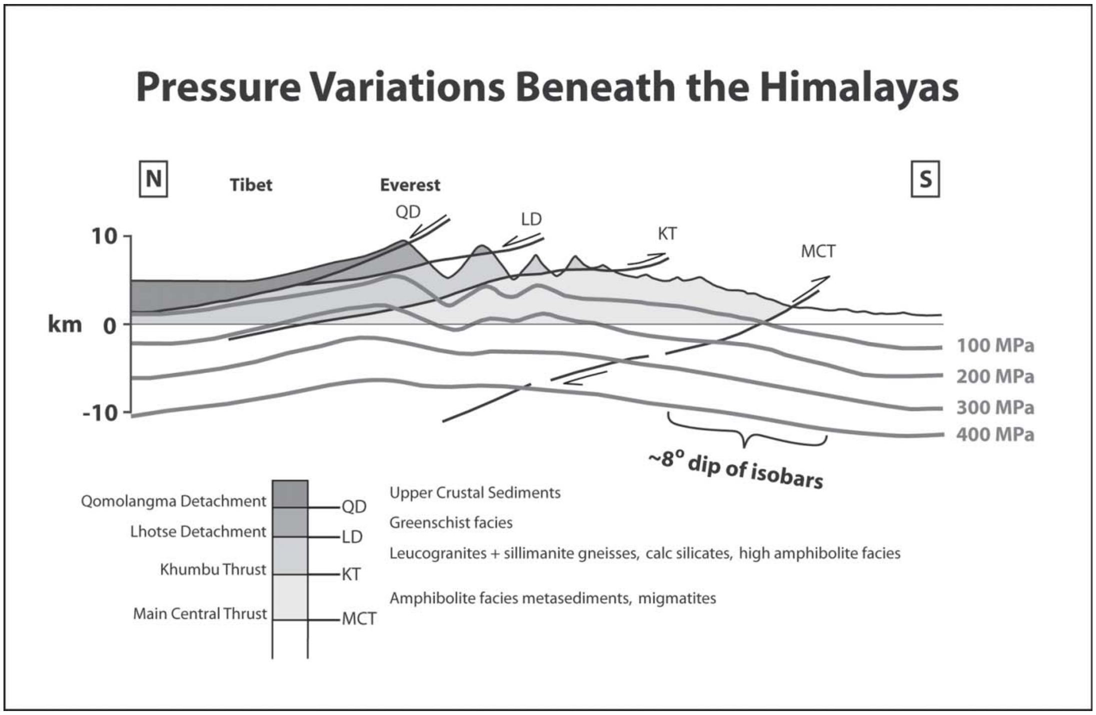

FIG. 2. Cross-section through the Himalayas showing inferred orientation of isobaric surfaces. Cross-section modified from Searle (1999). See text for explanation.

are at once isotherms and isobars with P and T values that correspond to P,T points on the equilibrium curve. We refer to such lines as PT lines, and we illustrate them in Figures 1a and 1b. Where isobaric surfaces are horizontal, as in Figure 1a, or where isothermal, isobaric and isogradic surfaces have the same strike, the rake of the isobars and isotherms will be zero *in the isogradic surface*. Because of these relations, the gentle dip of isobaric surfaces requires that PT lines have gentle plunges, no steeper than the dip of the isobaric surface. As illustrated in Figure 1c, there can be a much greater variation in the rake of the PT lines; where the isogradic and isobaric surfaces have similar but not identical orientation, rakes close to 90° can occur, but where isogradic surfaces have moderate to steep dips, rakes are typically restricted to the 0–20° range.

We introduce the notion of "rake" because geothermobarometry along an isograd may be used to estimate the rake of PT lines. Obtaining the trend and plunge directly is very difficult. Isotherms and isobars need to be parallel in the isogradic surface only for truly univariant reactions. For reaction curves that are in fact divariant because of the influence of an additional intensive variable, temperature can vary along an isobar, and therefore isotherms within the isogradic surface need not parallel isobars, over the range allowed by the divariance.

In the foregoing discussion, we have assumed that post-metamorphic deformation has been insignificant and that the original or primary dips of isogradic, isobaric and isothermal surfaces have been approximately preserved. If the post-metamorphic deformation is simple, with only one phase of buckle folding, simple brittle faulting, simple tilting, *etc*., then accurate palinspastic restoration may be possible. The kyanite–sillimanite isograd near Mica Dam, British Columbia (Ghent *et al.* 1980) is one such example, and we discuss it later. The subhorizontal primary orientation of isobaric surfaces and of bathozones (Carmichael 1978) and their "lower-pressure-side-up" sequence provide, in principle, the same basis for "unrolling" folded and tilted metamorphic complexes as do Steno's principles of original horizontality and of superposition (Friedman *et al*. 1992) for the restoration of simply folded and tilted sedimentary sequences. Where post-metamorphic deformation involves superposed folding and complex histories with ductile strain, restoration will be non-unique at best and impossible in general.

There are some simple relationships between the slope of reaction curves in P–T space and the angle between isothermal and isogradic surfaces. For reaction curves that are isothermal, the isogradic surfaces are isothermal, and they must parallel isothermal surfaces, but the angle they make with isobaric surfaces is indeterminate. The isogradic surface that corresponds to an isobaric reaction-curve is isobaric, but its angle with isothermal surfaces is indeterminate. Where an isogradic surface that is not isobaric curves into parallelism with isobaric surfaces, the isothermal surfaces must do the same if the corresponding reaction-curve is univariant, and constant temperature must correspond with constant pressure. Suppose that in Figure 3, we are looking northward, the isogradic surface is then dipping moderately to the east. If the corresponding univariant reaction curve has a positive slope in P–T space and the higher-temperature metamorphic "high" is to the west, then the isothermal surfaces will also dip eastward, but less steeply because the temperature must increase with increasing pressure. If the slope of the reaction curve changes from positive to negative, like the staurolite-out reaction curve in Figure 4, then the isothermal surfaces must change from dipping less steeply than the isogradic surface to dipping more steeply. Use of these qualitative principles significantly constrains the construction of isotherms and isograds on a metamorphic cross-section and were used by Thompson (1976), Ghent *et al.* (1980) and by Digel *et al.* (1998).

The relationship between the slope of the univariant curves and the angle between isothermal and isogradic surfaces can be quantified, as illustrated in Figure 3. Thompson (1976) derived an elegant and very general solution that begins with an estimate of the angle α between the temperature and pressure gradients. In the problems within our experience, the angle α could not be estimated until the problem was solved. We developed a different approach. We found that after palinspastic restoration, we could estimate ϕ, the angle between the isogradic surface and the (subvertical) pressure gradient normal to the (subhorizontal) isobaric surfaces. We then calculate θ, the angle between the isogradic and isothermal surfaces, using equation 1 (see below). Its derivation and use are illustrated in Figure 3. The plane of the figure is normal to the PT lines and therefore to the isothermal, isobaric and isogradic surfaces that all intersect in them. The dimensions in Figure 3 are in meters and, for purposes of illustration, the spacing between two adjacent subhorizontal isobaric surfaces is taken to be ~3700 m, corresponding to a pressure difference of 1 kbar and a reciprocal pressure-gradient of 3.7 m bar^{-1} resulting from a rock density of ~2700 kg m^{-3}. The spacing of the corresponding isothermal surfaces that pass through T_1 and T_2 is given in metres by $(T_2–T_1)$ m $°C^{-1}$. It is a function of the local temperature-gradient, normal to the isothermal surfaces, prior to quenching (this is neither the geothermal gradient, nor the metamorphic field-gradient) expressed as the reciprocal temperature-gradient in m $°C^{-1}$. As can be seen from the solution of the two right triangles in

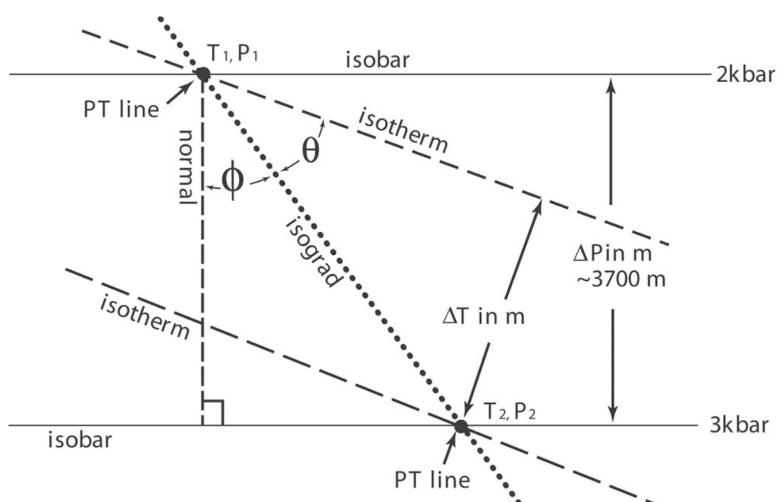

FIG. 3. Angular relationships of isotherms and isobars with univariant-reaction isograds. The plane of the diagram is normal to the (T1,P1) and (T2,P2) intersection lines and is therefore suitable for measuring the angle θ between the isograd and the isotherm, as well as the angle ϕ between the isograd and the pressure gradient, normal to the isobars. The difference in temperature between the two isotherms is a function of the T/P gradient of the metamorphic reaction. The dimensions in the diagram are in meters as a function of the local reciprocal T and P gradients.

Figure 3 that share the segment of isograd T_2–T_1 as their common hypotenuse, the angle θ between the isothermal and isogradic surfaces is given by:

$$\sin\theta = \cos\phi \cdot \frac{\Delta T}{\Delta P} \quad (1),$$

where ϕ is the angle between the isogradic surface and the normal to the isobaric surface, ΔT/ΔP is the reciprocal slope of the univariant-reaction curve and ΔP and ΔT are expressed in meters, as explained above. A sketch must be made, and the user must decide whether a clockwise or counterclockwise θ is more reasonable given the relative positions of the metamorphic "highs" and "lows". The following quantities all have to be known or at least estimated: the dip of the isogradic and isobaric surfaces, the rake of the PT lines in the isogradic surface, ΔT/ΔP for the reaction curve, the local temperature-gradient normal to the isothermal surfaces, and the pressure gradient normal to the isobaric surfaces. It is rare, however, to have accurate estimates for all these quantities, but instructive results are obtained even with parameters that are merely rough estimates. In rare circumstances, the trend of the thermal structure in a metamorphic complex may be known well enough to yield a strike for the isothermal surfaces. It may be possible to estimate their dip if the rake of the PT lines in the isogradic surfaces is significant, say 20°, and the angle between the trend of the PT lines and strike of isothermal surfaces is large enough to permit a robust solution.

Diachronism of Isograds

Metamorphic isograds are inherently diachronous because of the time required to heat the rocks and to complete metamorphic reactions. We can envisage a set of isogradic surfaces advancing through a rock mass. It is unlikely that different isograds, *e.g.*, the garnet and kyanite isograds, would be quenched at the same time. In Figure 1, if the isobaric surfaces have been established, consider the case where the isothermal surfaces are migrating up and to the west. At some instant in time, isotherm T_3 intersects isobar P_3, and the line of intersection reaches point B; the isograd will have just reached point B. It is unlikely that isotherm T_1 would intersect isobar P_1, and that the intersection line would

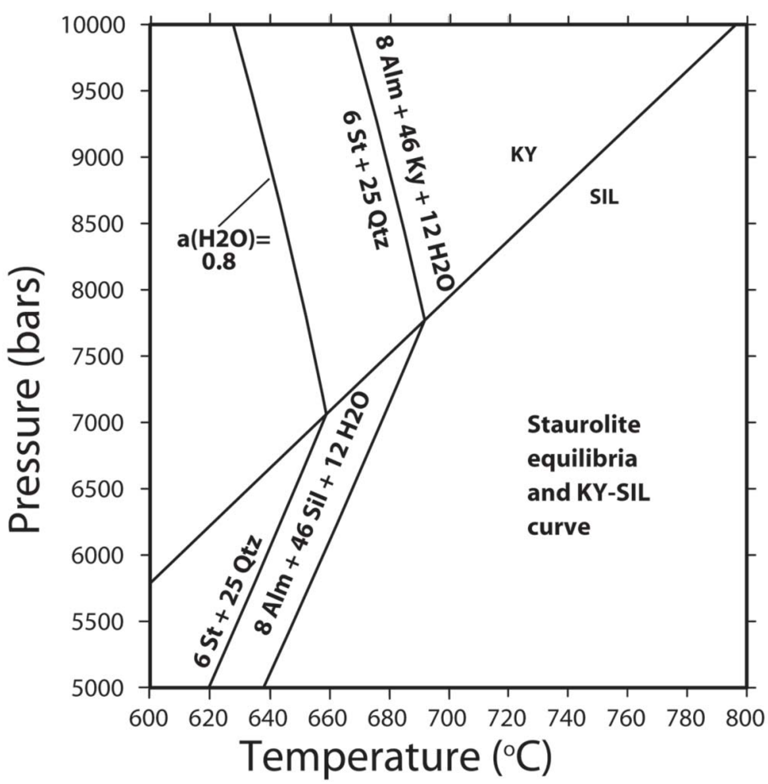

FIG. 4. Pressure – temperature diagram showing ky = sil and st + qtz = Al_2SiO_5 + alm + H_2O equilibria, calculated from Berman (1988).

reach point A at the same instant at which the isograd reached point B. The isograd at A may be younger than the isograd at B, and isograds may be diachronous along their length.

We next calculate the degree of diachronism both across the isograd and along the length of an isograd. It is possible to make rough estimates of the degree of diachronism using the simple model presented by Walther & Orville (1982). We propose that their model will apply to diachronism both across and along isograds because diachronism in both cases is the result of the same relations between process and time. They calculated the rate of advance of a dehydration reaction through a section of rock. We apply this model to the progress of a reaction producing an isograd. The input data we used are: the enthalpy per mole of a dehydration reaction (20 kcal mol^{-1}), the average heat capacity (0.25 cal/g °C), regional heat-flow (2.5 μcal $cm^{-2}s^{-1}$), and density of the rock (2.8 g cm^{-3}); the fluid is lost over an interval of 200°C. The heat required to heat the rocks and drive the dehydration reactions is ~90 kcal per kg of rock (Walther & Orville 1982). To advance the reactions through 1 kg/cm^2 of rock requires ~90 kcal, of which 40 kcal is for dehydration. Using the density given above, we calculate the reaction progress through 360 cm of rock. The expression for the time required for the advance of the reaction is (2.5 μcal $cm^{-2}s^{-1}$) * (360 cm kg^{-1}) / 90 kcal kg^{-1}) = ~3.3 km Ma^{-1}, where there are 3.15×10^{13} s per 10^6 a. It is difficult to evaluate the accuracy of such a calculation, but it would imply that samples ~3.3 km apart along a metamorphic isograd would be at the limits of discrimination of many geochronometers, *e.g.*, ±1 m.y., and would be indistinguishable from being coeval. Over a distance of ~15 km along an isograd, the degree of diachronism would be about 4.5 m.y.

An implication of these calculations is that two isogradic surfaces that clearly belong to the same metamorphic episode can be considered approximately synchronous (±1–2 m.y.) if they are no more than ~3–6 km apart. In this case, we can use the thickness of the metamorphic zone separating the isograds in petrological arguments.

Dehydration Isograds

Dehydration isograds present an important type of reaction in P–T space. Chinner (1963) argued that at moderate to high pressure, the dP/dT for dehydration reactions would be very steep. He suggested that to a first approximation, they could be treated as being isothermal. If the dehydration isogradic surfaces approximate isothermal surfaces, the primary morphology of isotherms in the metamorphic complex can be visualized. Metamorphic "highs" and "lows" with primary relief of several km in the northern Selkirk, Monashee, and Cariboo mountains indicate a relief of several km for the isothermal surfaces during peak metamorphism (Figs. 5, 6a).

It is worth examining the assertion about isothermal dehydration-type reactions in more detail. Consider the reaction

6 staurolite + 25 quartz = 8 garnet
+ 46 kyanite + 12 H_2O (a).

Using the database and program of Berman (1988), the slope of the reaction is about 45 bar $°C^{-1}$ at high pressure below the kyanite–sillimanite curve (Fig. 4). Reaction (a) crosses the kyanite–sillimanite curve at a unique temperature, and above that curve, the slope reverses to ~–140 bar $°C^{-1}$. Suppose a staurolite-out isogradic surface, as represented by model reaction (a), has a dip of 65° on the steep flank of a thermal high with a local temperature-gradient of 30°C km^{-1} and suhorizontal isobaric surfaces. Using equation (1), we calculate the angle between the isogradic and isothermal surfaces to be only 9° in the sillimanite zone and 3° in the kyanite zone. For all practical purposes, this could be treated as being isothermal. The effect of variation in the activities of the phase components in this reaction could cause this ideal univariant reaction to become at least divariant (Fig. 4). For example, varying $a(H_2O)$ from 1.0 to 0.8 at a pressure of 8000 bars would cause the temperature to vary by ~40°C from the univariant curve. The P–T curve would still be steep.

The Problem of "Smearing Out" of Isograds

In some cases, isograds appear to be "smeared out" over distances of several hundred meters, as suggested by the occurrence of a mineral assemblage that appears to be univariant for a limited chemical system, *e.g.*, KFMASH, but is actually multivariant in the natural chemical system. Of course, there is the possibility that the isogradic surface intersects the surface topography at a low angle. This latter interpretation should be tested by careful structural and petrological analysis. If this interpretation were correct, it would permit an estimate of the dip of the isogradic surface.

Among the many examples is the kyanite isograd in Glen Cova, Angus, Scotland (Chinner 1965), where the assemblage kyanite – staurolite – garnet – biotite – muscovite – plagioclase – quartz – graphite persisted over 600 meters. On the basis of the Gibbs phase rule for KFMASH, the variance would be one. Chinner (1965) pointed out that with vertical isogradic surfaces, a 50°C/km gradient would represent a 30°C range. It should be pointed out that there was little structural control on the orientation of the isogradic surface. A lower dip would decrease the temperature range.

Evans & Guidotti (1966) reported the assemblage orthoclase – muscovite – sillimanite – plagioclase – quartz, coexisting over a distance of 11 km up grade of

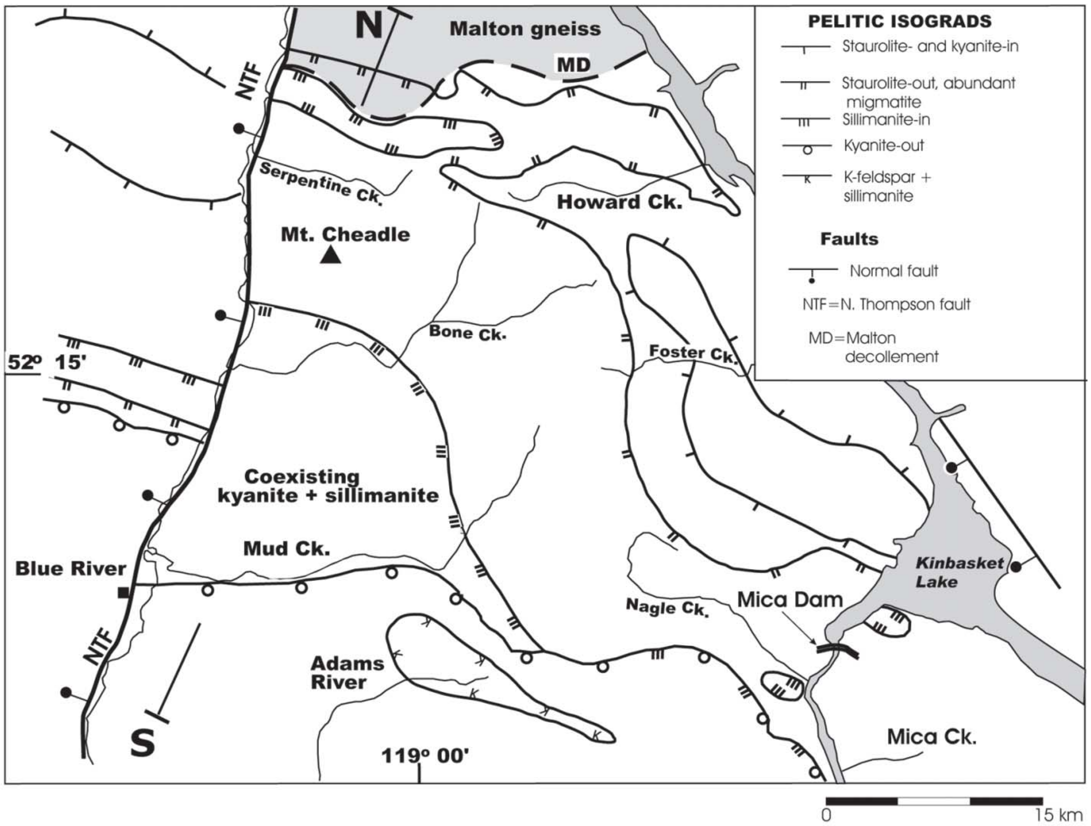

FIG. 5. Simplified map, modified from Digel *et al.* (1998), showing the pattern of isograds in the northern Monashee Mountains between Kinbasket Lake in the southern Rocky Mountain Trench and the North Thompson normal fault (NTF). The ductile Malton décollement (MD) marks the southern boundary of the Malton basement gneisses. S–N marks the line of section for Figures 6a and b.

the first appearance of orthoclase + sillimanite. They argued that phase-rule considerations suggest a variance for this assemblage of not less than two. They suggested that P(H_2O) may have been "buffered" by the assemblage and controlled by local values of P and T. Another suggestion was that temperature gradients "up-grade" of the isograd were minimal because of the onset of fractional melting, so that in the phase-rule sense, temperature was no longer a variable.

Carmichael (1970) found that the assemblage staurolite – biotite – quartz – garnet – chlorite – muscovite persisted 400 m up grade from the first appearance of staurolite – biotite – quartz. Since this case also represents a dehydration isograd, it is similar to the situation described by Chinner (1965). Carmichael found similar problems with other dehydration isograds.

The problem of "smeared out" isograds depends in part on the scale of observation and the purpose of the investigation. Contrast the scale of observation of Carmichael's maps of the Whetstone Lake area (1970) *versus* his map of northern New England (1978). If we are interested in using the isograds for large regional tectonothermal reconstructions, the problem of "smearing out" becomes less important.

VARIATION IN P AND T ALONG A KYANITE–SILLIMANITE ISOGRAD

Where palinspastic restoration yields subhorizontal isobaric surfaces and moderate to steeply dipping isogradic surfaces, the regular increase in pressure, vertically with depth and therefore down-dip of the isogradic surface, can be calculated from the known mean density of the rocks in the area. If the isograd corresponds to a simple univariant reaction, such as the kyanite–sillimanite reaction with a P–T curve having a moderate slope, then regular increments in temperature can be ascribed to the pressure increments. If accurate geothermobarometry produces a metamorphic P and T for a point such as A(T_1,P_1) in Figure 1a, the tempera-

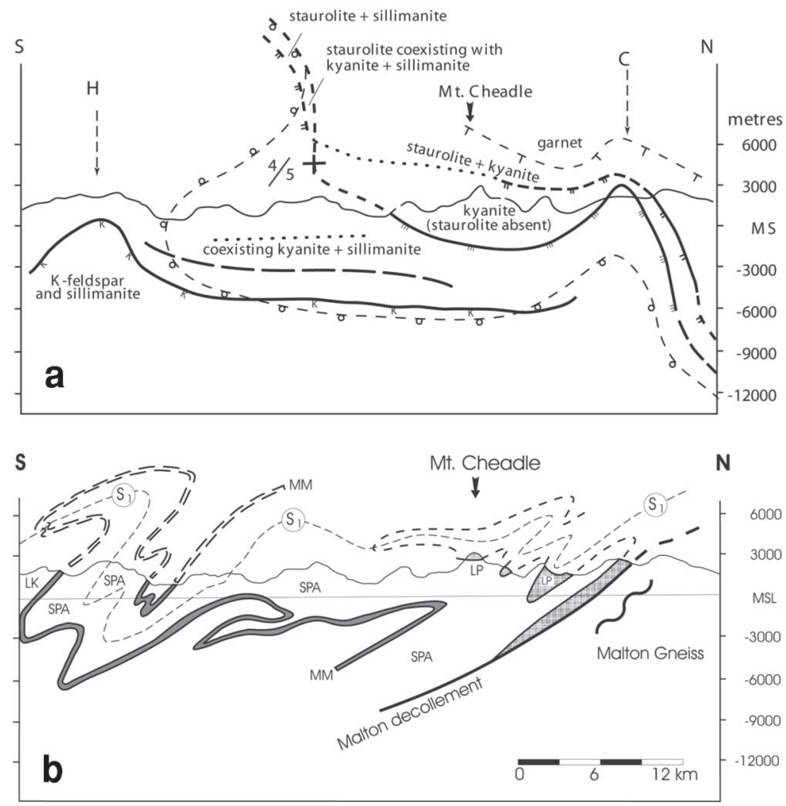

FIG. 6. a) Metamorphic cross-section S–N (Fig. 5). looking west-northwest, modified from Digel *et al.* (1998). Isograd symbols are the same as in Figure 5. C marks the crest of the northern metamorphic "high." 4/5+ is the lowest possible position for the invariant P–T line on the isobaric surface separating bathozones 4 and 5. Heavy dashed line is the highest reasonable level for the K-feldspar-in isograd and the 5/6 boundary surface. The dotted line above the word "coexisting" marks the level predicted for the 5/6 boundary by a ΔP of 1.5 kbar for bathozone 5. b) Simplified structural cross-section S–N (Fig. 5) looking west-northwest, modified from Digel *et al.* (1998). Markers in the Neoproterozoic succession outline an early fold nappe refolded by later, premetamorphic structures. MM: Middle Marble, LP: Lower Pelite, SPA: Semi-pelite Amphibolite.

tures and pressures can be calculated for other points such as Q, B, and R in the isogradic surface. These points lie on P–T lines, and if their orientation can be approximated in the isogradic surface, a set of lines of estimated pressures and temperatures can be established, and we know their orientation in three dimensions. Such P–T lines can be used as projection lines in the same way as axial linear structures are used in the projection of cylindrical folds. This permits quantitative extrapolation of geothermobarometric data from the starting point to any desired point on the surface. This also permits the projection of metamorphic data onto a cross-section of a metamorphic complex. If an isothermal dehydration isograd, such as the one discussed earlier for the staurolite-out isograd, is present in the vicinity of the kyanite–sillimanite isograd, then we not only have the spacing of the isotherms along the kyanite–sillimanite isograd in our cross-section, but we also have the shape of the isothermal surfaces, given by the shape of the nearby staurolite-out isogradic surface (provided we account for the displaced activities). The fact that the slope of the reaction curve may be very steep is not as much of a problem. Mapping of additional isograds in the region, in conjunction with additional geothermobarometry, can further refine this approach and ultimately permit construction of a 3-D model of the thermal structure of the metamorphic complex.

We illustrate this type of analysis of the variation in P and T in an isogradic surface with the kyanite–sillimanite isograd in the Mica Creek area south of Mica Dam (Fig. 5). It has been the subject of numerous studies (Ghent *et al.* 1980, Simony *et al.* 1980, Ghent & Valley 1998, Ghent & Gordon 2000) and can be used as a model system.

The kyanite–sillimanite isograd is well exposed on ridge crests and is sharp, with a 10- to 50-m-wide zone of kyanite–sillimanite coexistence (Fig. 5). The isograd was traced virtually continuously along the well-exposed ridge complex above ~2000 m altitude south of Nagle Creek. It was then followed down the timbered slope across scattered cliff outcrops and across Columbia Valley, where large roadcuts along the highway and logging roads provided critical control. Petrographic study confirmed the hand-lens identification of the kyanite and sillimanite porphyroblasts and the fibrolitic coating on biotite. The minimum structural relief on the isograd, based upon topographic relief alone, is about 1.5 km, which corresponds to a pressure difference of about 400 bars (Ghent *et al*. 1980). The slope of the kyanite–sillimanite univariant curve is about 20 bar $°C^{-1}$ (Fig. 4). This slope suggests a difference of about 20°C along the part of the isograd that can be sampled owing to the present topographic relief. The *primary* structural relief along the isograd, that is, the relief that existed prior to postmetamorphic deformation, can be conservatively estimated to be about 4 km. This figure is derived by using mapping data from the Monashee Mountains adjacent to Mica Creek and Mica Dam and restoring the cross-section (Simony *et al.* 1980, Ghent *et al.* 1980). As discussed previously, we removed the effects of post-metamorphic faulting, simple buckling, and flattening strain. This produced an original gentle dip of the isobaric surfaces (Ghent *et al.* 1980). Figure 7, modified from Ghent *et al.* (1980), illustrates the approach described above. We estimated a pressure of 5.8 kbar and a temperature of 600°C (P–T points on the kyanite–sillimanite equilibrium curve) at a high-elevation point on the isograd. Evenly spaced PT points were then located down the dip of the steeply dipping isograd using 20 bar $°C^{-1}$. The staurolite-out isograd, located 7 km north of Nagle Creek, lies too far away to help with the dip of the isotherms near the kyanite–sillimanite isograd, other than showing that the isothermal surfaces have to dip under the garnet-zone "low" north of Mica Dam (Fig. 5). The construction of the isotherms was primarily guided by: (1) the shape of the subsidiary "high" under Nagle Creek, (2) the 4-km structural relief on the isograd, and (3) the fact that the isothermal surfaces have to rise southwestward to pass over the major thermal "high" outlined by the steeply dipping K-feldspar-in isogradic surface (Sevigny & Simony 1989). The structural relief on the isograd produces a pressure range of 1100 bars and a temperature range of 55°C. A conservative estimate of the uncertainty in geothermobarometry is ±25 °C and ±1 kbar. Thus geothermobarometry alone would not allow the construction of the details of isothermal and isobaric surfaces.

Within the kyanite–sillimanite isogradic surface, the temperature gradient normal to the isobars must be ~50°C $kbar^{-1}$. Because the PT lines typically have small rakes, this temperature gradient can be expressed as ~14°C per vertical km. Where the isogradic surface has a very steep dip, this value must be the vertical temperature-gradient in the vicinity of the isogradic surface. South of Nagle Creek, on the flank of the metamorphic "high," the isogradic surface is very steep over a depth range of ~4 km. This fact suggests a temperature gradient of 14°C km^{-1} over that depth range. With this input and a likely range of values of the angle θ between isothermal and isogradic surfaces, we can propose likely values for the temperature gradient normal to the isothermal surfaces. The exact dip of the isothermal surfaces is not known, but the isograd geometry and spacing require a shape for the isothermal surfaces similar to that shown in Figure 7 (Ghent *et al.* 1980). This shape suggests a θ angle near 30°. Substituting in equation (1) yields temperature gradients normal to the isothermal surfaces near 30°C km^{-1}. The likely range of θ between 20°and 50° yields a range of temperature gradients between 35 and 20°C km^{-1}. Values of θ angles much larger than 50° are unlikely since they would be inconsistent with isograd shape and spacing. The metamorphic "highs" were probably centered on zones of focused higher heat-flow. It is likely that the estimates given above of the temperature gradient normal to the isotherms on their flanks are conservative. We consider this in the next section.

Petrogenetic Grids and Isograds

Petrogenetic grids for pelitic rocks have been presented by numerous researchers, *e.g.*, Albee (1965). One of the more widely used P–T grids is that of Carmichael (1978), with later modifications, *e.g*., in Davidson *et al.* (1990). Another P–T grid was prepared by Pattison (2001). We now apply some of the approaches developed earlier in this paper and relate isograd geometry to petrogenetic grids. The data on isograds from the Mt. Cheadle – Blue River – Adams River areas (Fig. 5) can be compared to those used in the grids. To illustrate the relation of the isograds to the rock structure, we show the isograd geometry in Figure 6a and the fold geometry in Figure 6b. Both sections are along the same line and on the same scale, and are modified from Digel *et al*. (1998). Peak metamorphism and quenching took place after the large phase-1 and phase-2 folds had formed (Sevigny & Simony 1989, Digel *et al.* 1998). Post-metamorphic folding, as seen in the Mica Dam area, is minimal between Mount Cheadle and Adams River, and the isograd geometry illustrated in Figure 6a is largely primary and imprinted across the large folds. The broad zone of coexisting kyanite and sillimanite is interpreted (Digel *et al.* 1998) to represent a volume of

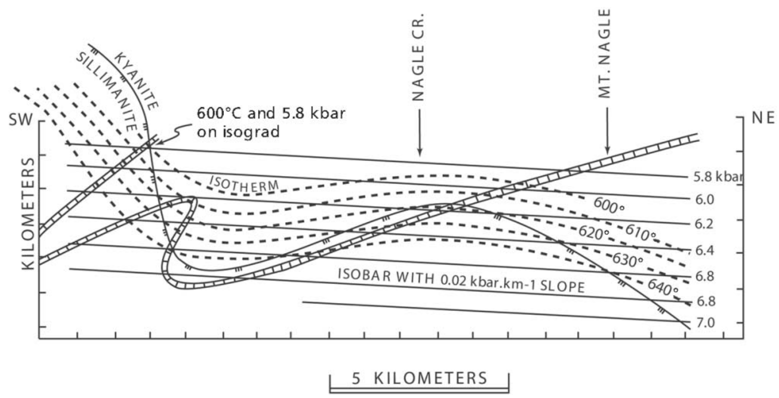

FIG. 7. Metamorphic cross-section in the Mica Creek area, modified after Ghent *et al.* (1980), restored by unrolling post-metamorphic folds. The restoration of isobars and the construction of isotherms are explained in the text and in Ghent *et al.* (1980).

rock where isobaric and isothermal surfaces were both subhorizontal and so spaced as to give a vertical P–T gradient equal to the 20 bar $°C^{-1}$ of the kyanite–sillimanite reaction curve. Whereas metamorphism in this huge volume of coexisting kyanite and sillimanite was probably diachronous, we suggest here that it is reasonable to consider vertical columns, 1 to 2 km on the side, within which there was equilibrium throughout the column during some period of a steady-state thermal regime. The vertical temperature-gradient was not merely a time-integrated metamorphic field-gradient, but a true thermal gradient normal to the isothermal surfaces. Knowing that gradient allows us to compare the metamorphic geology to the petrogenetic grids. Our justification is that the area is a portion of a regional metamorphic complex, 300 km long and locally 100 km wide, dominated by kyanite–sillimanite-type metamorphism. It was perhaps underlain in the lower crust or upper mantle by a "tarm" (Jamieson *et al.* 1998) that continued to produce heat that was focused up into the regional complex for a time span of 10–20 m.y., allowing a steady-state scenario to develop during peak metamorphism and prior to quenching. Digel *et al.* (1998) suggested that the regional metamorphism was quenched, and the isograds were deflected from their regional trend near the Malton complex as a consequence of thrust tectonics with ramps. There would not only have been cooling and decompression in the upper levels as a consequence of uplift and erosion, but thrust displacement would also tend to insert cooler crust below the complex. This development would lead to refrigeration from below, damage the heat connection between the tarm and the complex and, ultimately, quenching. The prograde metamorphism produced staurolite, kyanite and sillimanite porphyroblasts and bodies of leucosome. It is unlikely that complete re-equilibration could have taken place during cooling prior to quenching, because this would imply that the isograds could move without leaving a trace of their former position during the "steady-state" period. Neither Digel *et al.* (1998) nor Sevigny & Simony (1989) reported widespread evidence of partial re-equilibration with decreasing temperature and pressure along the isograds they mapped. We interpret that, in the Mount Cheadle – Blue River – Adams River area, refrigeration from above and below led to quenching and the approximate preservation of the thicknesses of metamorphic zones formed during the "steady-state" period.

In the Mount Cheadle – Blue River – Adams River area, the isograds that help to define Bathozone 5 (Carmichael 1978) are well exposed and have been traced in some detail. We have found three locations where isograd geometry can be meaningfully compared to petrogenetic grids: (1) in the vicinity of Mount Cheadle, (2) in the region north of Blue River in the hanging wall and footwall of the North Thompson normal fault (NTF), and (3) in the Adams River area. The region of the northern metamorphic "high" indicated by C in Figure 6a adjacent to the Malton gneiss complex is unfortunately not suitable despite good mapping control. We cannot make a good estimate of the thermal gradient there, and post-metamorphic shear strain and tilting adjacent to the Malton gneiss during thrust tectonics do not allow unambiguous restoration.

In the Mount Cheadle area, isograds are defined by continuous tracing in well-exposed mountain ridges; a network of logging roads with rock cuts provides good control in the forested lower slopes and valleys. The staurolite-out isograd was traced at high elevation across the well-exposed headwaters of Howard, Foster and

Bone creeks. The isogradic surface has to dip north and east under the garnet zone in the metamorphic "low" (Fig. 5). Trondhjemitic leucosome appears gradually upgrade of (structurally below) the isogradic surface. The staurolite-out isogradic surface must pass just above the summit of Mount Cheadle because leucosome occurs in the mountain with kyanite but not staurolite. The dip of the sillimanite-in isogradic surface is constrained on a slope north of Serpentine Creek, where it must have a southerly dip that is steeper than the slope. The trace of the isograd out of the Bone Creek Valley and across the slope of a low ridge north of Bone Creek requires a moderate northward dip into the "low" under Mount Cheadle. On Figure 6a, we measure vertically from the staurolite-out isogradic surface down through the summit of Mount Cheadle to the sillimanite-in isogradic surface. We have thus obtained a "true" thickness of the staurolite-absent kyanite zone that falls in the range of 4.5 to 5.8 km because of uncertainties in the elevations of the isogradic surfaces. We will use the round number of 5 km, which corresponds to a pressure range of 1.4 kbar. To compare our result in the field to petrogenetic grids, we note that in the opinion of Digel *et al.* (1998), a vertical measure in the Mount Cheadle area is along a line with the 20 bar °C^{-1} gradient of the kyanite–sillimanite reaction, and that in the previous section, we found the same vertical gradient south of Mica Dam. We therefore lay off the 1.4 kbar along a line close to, and with similar slope as, the kyanite–sillimanite reaction curve. We will show later that the isobaric surface separating bathozones 4 and 5 lies not much higher than the staurolite-out surface above Cheadle summit. Our line on the grid therefore starts at the staurolite-out curve just above the kyanite–sillimanite curve (Figs. 8a, b). The 1.4 kbar line must intersect that curve 1.4 kbar uppressure from the starting point and, in the absence of K-feldspar, distinctly short of the K-feldspar-in curve that marks the boundary between bathozones 5 and 6 where it crosses the kyanite–sillimanite line (Carmichael 1978). We conclude, therefore, that the thickness of the staurolite-absent kyanite zone at Mount Cheadle suggests a pressure range (ΔP) for bathozone 5 that is distinctly greater than 1.4 kbar.

In the area north of Blue River (Fig. 5), the sillimanite-in and the staurolite-out isograds outcrop as parallel, almost straight lines in the hanging wall of the NTF (North Thompson, west-side-down, normal fault). In contrast to what is seen in the footwall, the staurolite-out isograd is in between the kyanite-out and sillimanite-in isograds. The isograds have the same strike and dip steeply. They must intersect underground. Solution of the fault displacement and restoration of the 4- to 5-km west-side-down dip slip on the NTF constrain the isograd geometry shown above the mountain tops in Figure 6a. In this cross-section, information from the hanging wall and from the footwall have been projected together. This method permits location of the isograd intersections.

To help envisage this in three dimensions in the rock mass, we consider the isogradic surface in Figure 1a to be the sillimanite-in isogradic surface. We can also consider the isothermal surface T_2 to represent the staurolite-out isogradic surface because we have already shown that it is approximately isothermal (Fig. 4). As is the case in the Blue River area, both isogradic surfaces have the same strike, and their line of intersection must be horizontal. In three dimensions, that intersection, like other PT lines, is an invariant line, but it is special in that it lies on both isogradic surfaces and is the manifestation of the intersection of the kyanite–sillimanite reaction curve with the staurolite-out curve. It also lies on the isobaric surface that defines the boundary between bathozones 4 and 5 (Carmichael 1978; our Fig. 8a). We will refer to such a special line as a *defining pressure–temperature* (DPT) line. It does not occur as a mappable line on the ground surface, but instead it pierces it at isolated points like Q and R in Figure 1a, marked by patches of the invariant assemblage and the intersection of isograd pairs. The DPT line helps in the tracing of bathozone-defining isobaric surfaces or DIB surfaces. In Figure 1a, the DIB surface is horizontal, passes through points Q and R, and is exposed on the valley sides (the solid line parallel to the topographic contours). It separates bathozone 4 above from bathozone 5 below. We do not call this isobaric surface the bathogradic surface in deference to Carmichael's (1978) insistence that a bathograd does not have to be an isobar and that, by extension, a bathogradic surface does not have to be an isobaric surface, although we do hope that it approximates one.

In the Blue River area, the intersection of the sillimanite-in with the staurolite-out isogradic surface gives the subhorizontal DPT line 4/5, 1 to 2 km underground in the hanging wall of the NTF and just above the elevation of Mount Cheadle in the footwall. The horizontal DPT line gives the west-northwesterly strike of the 4/5 DIB surface. That surface cannot have a significant northward dip or staurolite or sillimanite (or both) would occur on Mount Cheadle. The dip is more likely to be southward, but it has to be very gentle because the DIB surface cannot be far above the crest of the northeastern metamorphic "high," marked by C in Figure 6a, where the sillimanite-in and staurolite-out isogradic surfaces are near each other at an elevation of ~3000 m. This observation gives confirmation, if not hard proof, of the proposal of Digel *et al.* (1998) that the isobaric surfaces were subhorizontal in the region between Mud Creek and Serpentine Creek (Fig. 5).

Having constrained the attitude and elevation of DIB surface 4/5, we now explore the possibility of constraining the DIB surface 5/6. The K-feldspar-in and the kyanite-out isogradic surfaces are well exposed on mountain ridges and on their steep slopes in the Adams River area (Fig. 5). The map and cross-sections of Sevigny & Simony (1989) show: (1) the crest of the metamorphic "high" outlined by the K-feldspar-in

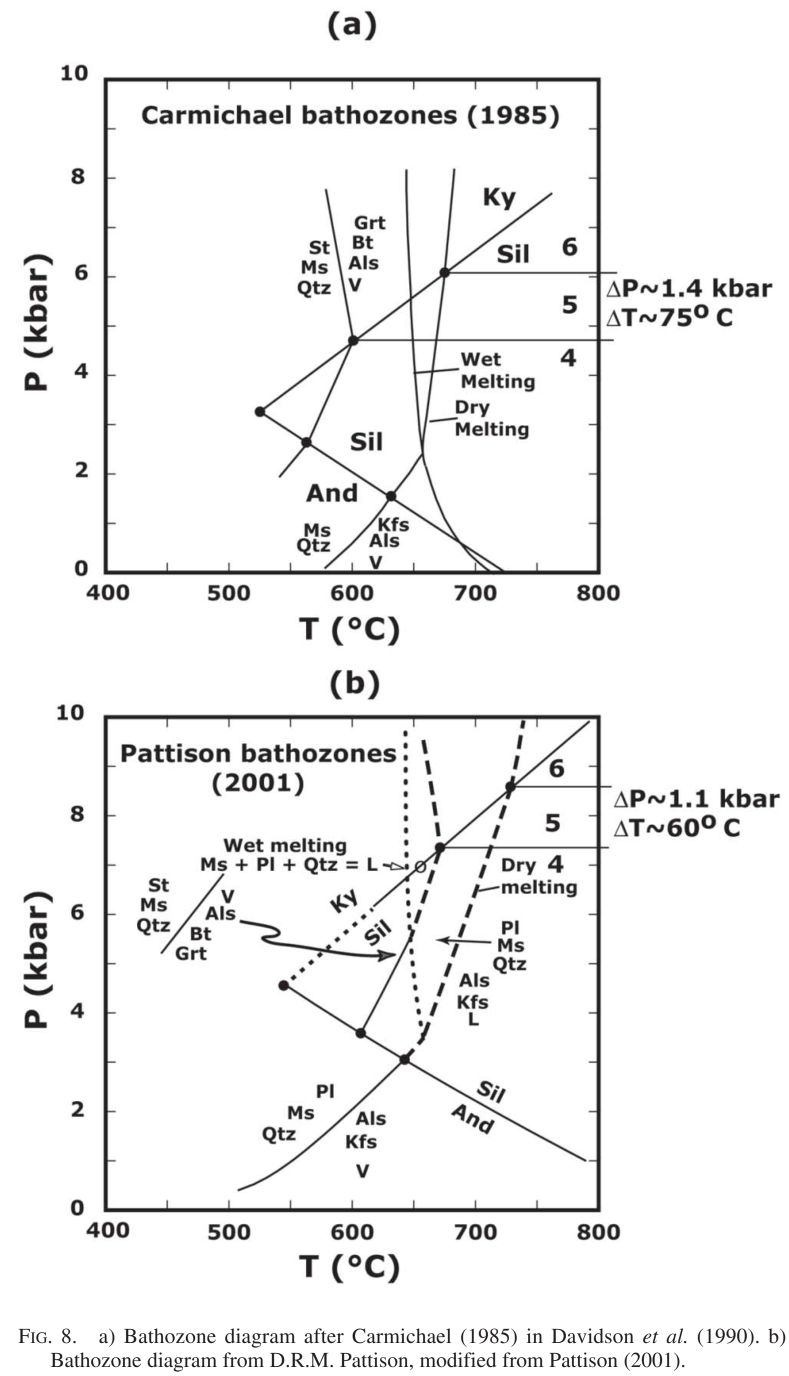

FIG. 8. a) Bathozone diagram after Carmichael (1985) in Davidson *et al.* (1990). b) Bathozone diagram from D.R.M. Pattison, modified from Pattison (2001).

isogradic surface and (2) the kyanite-out isogradic surface, which curves downward from overturned, to subvertical and to a north-northeasterly dip. Following Digel *et al.* (1998), we projected that information into Figure 6a using the reasonable and conservative estimate of a ~3° west-northwesterly plunge for the crest of the metamorphic "high" marked by A in Figure 6a. This places the K-feldspar-in isogradic surface just above sea level and below the floor of the deepest valley in the footwall of the NTF. Sevigny & Simony (1989) showed the control on the configuration of the isograds for 2 to 3 km downward from the crest of the "high". The map trace of the kyanite-out isograd from the headwaters of Adams River into and then along Mud Creek Valley is consistent with the subvertical dip of the isogradic surface proposed by Campbell (1968). Digel *et al.* (1998) showed that three km below the crest of the "high", the kyanite-out isograd curves smoothly, through a northerly dip, to the horizontal in the metamorphic "low". They showed the kyanite-out isograd approaching the K-feldspar-in isograd, as it must with depth, given the different positive slopes of the two corresponding reaction-curves in P–T space. In Figure 6a, we show the two isogradic surfaces intersecting to locate the DPT line on the 5/6 DIB surface, which here coincides with the K-feldspar-in surface. The construction we show is geologically and geometrically plausible, but one could draw the DPT line, the DIB surface and the K-feldspar-in isogradic surface at a higher level. With a heavy dashed line, we show in Figure 6a the highest level at which they can be drawn without contradicting the information from Adams River and Mud Creek. We also show with a + the lowest level at which the DPT line 4/5 can be placed on the sillimanite-in isogradic surface, given the uncertainties of fault solution and projection. The vertical distance between the + and the dashed line is 7.5 km. That is not the thickness of bathozone 5; it is a minimal estimate of that thickness, and it corresponds to a minimum pressure range, ΔP, of 2 kbar for Bathozone 5 in the Blue River area.

In the Adams River area, the K-feldspar-in and the kyanite-out isograds are separated by about 2 km. In the cross-section of a well-exposed ridge (Sevigny & Simony 1989, Fig. 3), the K-feldspar-in isogradic surface has a north-northeasterly dip of 50–55°, and the kyanite-out isogradic surface has a north-northeasterly dip of 60–70°. Using the approach of Digel *et al.* (1998), we project this information into Figure 6a, and we use this geometrical information (Fig. 9) to estimate the difference in temperature between two isothermal surfaces that each intersect their respective isogradic surface in a PT line at the same pressure. We use the conservatively estimated temperature-gradient of 20°C km^{-1} normal to the isothermal surfaces on the north-northeasterly flank of the metamorphic "high" in order to relate distances to temperature differences. The kyanite–sillimanite reaction curve has a T–P gradient of 50°C $kbar^{-1}$; the K-feldspar-in reaction curve has a T–P gradient of 16°C $kbar^{-1}$. We substitute these values in Equation (1) for each of the two reaction curves and obtain the θ angles between the isogradic surfaces and their associated isothermal surfaces. For the kyanite–sillimanite surface (here the kyanite-out surface), θ is approximately equal to 40°; for the K-feldspar-in surface, θ is close to 10°. The spacing between the two isothermal surfaces illustrated in Figure 9 is ~1.5 km, which corresponds to a temperature difference of 30°C if we use the 20°C km^{-1} temperature gradient. From Figure 6a, we see that we measured that temperature difference at a level in the crust where the pressure must have been at least 1 kbar greater than at the 4/5 DPT line, marked by 4/5+ in Figure 6a.

We can now plot the 30°C temperature difference from the Adams River area on the petrogenetic grids in Figures 8a and 8b by plotting 30°C between the kyanite–sillimanite curve and the K-feldspar-in curve. We do this at 1 kbar above the pressure of the invariant point 4/5, where the staurolite-out reaction curve crosses the kyanite–sillimanite curve. To have room for the ΔT of 30°C requires that the ΔP of Bathozone 5 be about 2 kbar. Depending on the grid used, the required ΔP falls between 1.8 and 2.3 kbar.

We have used three different pairs of isograds and three different approaches in three locations spread out in a transect 60 km long and involving different parts of a stratigraphic succession at least 2 km thick, and yet we have obtained results that are internally consistent and point to a ΔP of ~2 kbar for Bathozone 5. D.M. Carmichael, in Davidson *et al.* (1990), showed a ΔP of 1.4 kbar, and Spear & Cheney (1989) did not draw bathozones, but from their KFMASH grid, one can infer a ΔP for Bathozone 5 in the range of 1.5 to 2.5 kbar. Pattison (2001) showed a ΔP of 1.1 kbar, but in a personal communication (2004), he suggested to us that if his staurolite-out curve were recalculated for garnet with X(Mn + Ca) = 0.1, typical of garnet from the Mica Dam area, the staurolite-out curve would be shifted 30°C to the left, such as to pass through point 0 in Figure 8b. As a consequence, the ΔP of Bathozone 5 on his grid would increase to ~1.5 kbar.

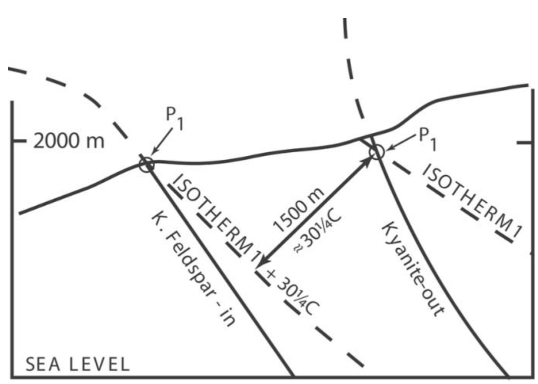

FIG. 9. Simplified metamorphic cross-sections of a ridge in the Adams River area, based on a section by Sevigny & Simony (1989), to illustrate the estimation of true spacing and difference in temperature between two isotherms associated at the same pressure, P1, with two adjacent isograds. P_1 is taken to be 1 kbar more than the pressure at the bathozone 4/5 boundary.

Given that a ΔP of 1.5 kbar could be inferred from the grids mentioned above, we examined, for the area south of Mount Cheadle, the predictions based on a ΔP of 1.5 kbar. If we measure 1.5 kbar $\times$ 3.7 km kbar^{-1} or 5.6 km down from the + in Figure 6a, we predict a level for the DIB surface 5/6 that coincides with the dotted line on top of the word "coexisting". Such a configuration is not really consistent with the observations at Adams River (Sevigny & Simony 1989) and brings the K- feldspar-in isogradic surface so close to the sillimanite-in isogradic surface as to be inconsistent with mapping of isograds in the metamorphic complex.

Our aim here is neither to compare different grids with each other nor to critique a particular grid on the basis of our field observations. The exact trajectories of the dehydration curves depend on compositional and intensive variables. Given that our results seem to be consistent through some 30,000 km^3 of rock, we suggest that if a new "rock-adjusted" petrogenetic grid, in the style of Carmichael (1978), were to be constructed, Bathozone 5 on that grid should have a ΔP of some 2 kbar.

Conclusions

1) Obtaining the three-dimensional geometry of isogradic surfaces is difficult in a region of low topographic relief and scattered outcrops. A very rough and incomplete picture may be all that can be obtained. We would suggest that even in such situations, testing plausible isograd geometries and their implications for the isothermal and isobaric surfaces is worthwhile. Construction of metamorphic cross-sections is a powerful tool.

2) The possibility of diachronism between adjacent isograds and along individual isograds will affect the petrological interpretation. We have argued that over distances of a few km, the effect would be small. In large regional metamorphic complexes, a steady state could be established, with equilibrium established in large volumes of rock.

3) "Smearing-out" of dehydation isograds is another problem, but such isograds may still be useful in outlining the regional thermal structure of an area, as at high pressures, the structure of these isogradic surfaces will approximate the thermal structure.

4) Geothermobarometry alone is not necessarily the best way to outline the thermal structure of an area. Over a large metamorphic complex, the detailed analysis of a large number of samples may not be feasible and may not yield a clear model of the thermal structure. Using the isotherm geometry inferred from the isograd geometry, and using geothermobarometry to obtain values of ΔP and ΔT on selected samples within an area, rather than "absolute" values of P and T (Worley & Powell 2000), are approaches likely to be more successful alternatives to determine the thermobarometric structure of an area.

5) Bathozones and bathograds (Carmichael 1978) are a useful method for geobarometry on a regional scale. We have shown that geometrical analysis of isogradic surfaces can lead to the definition of isobaric-isothermal P–T lines and, with luck, even isobaric surfaces.

6) Finally, we have shown that in a well-studied complex, we can provide constraints on the spacing of key reaction curves on P–T petrogenetic grids. In southeastern British Columbia, we have obtained consistent results to suggest that Bathozone 5 of Carmichael has a ΔP of ~2 kbar and a ΔT of ~80°C along the kyanite–sillimanite reaction curve.

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