Source and tectono-metamorphic evolution of mafic and pelitic metasedimentary rocks from the central Quetico metasedimentary belt, Archean Superior Province of Canada.

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Abstract

A study of the Jean Lake area of the Quetico metasedimentary belt, Superior Province, Canada, was conducted in order to evaluate the origin, source and evolution of sedimentary rocks, including mafic rocks previously mapped as ultramafics rocks. Bulk chemical compositions of these rocks show a mixing with two end members: quartzo-feldspathic sediments and komatiitic basalts. High CaO and MgO contents of the rocks suggest a proximal source of komatiitic basalts, probably from the southern Wabigoon subprovince.

The rocks in the Jean Lake area record a pressure-temperature (P-T) path with three tectono-metamorphic stages. The first stage formed staurolite (500-700°C) under medium P-T (MP-MT) metamorphic conditions shortly after the sedimentation. The second stage yielded the biotite-sillimanite-garnet assemblage under the peak condition of 0.6 ± 0.1 GPa and 700 ± 70°C during transpressional deformation. The third stage, low P- medium T (0.25 ± 0.11 GPa, 540 ± 80°C) metamorphism, was associated with regional south-southeast compression and its timing is constrained by a new U-Th-Pb monazite age of 2667 ± 20 Ma. Combining the regional deformation events, we suggest that the sediments in the Jean Lake area were buried up to MP-MT conditions during the D1 deformation at 2698-2689 Ma. They attained the peak metamorphic condition during the regional transpressive D2-D3 deformation (2689-2671 Ma), and retrograded to LP-MT condition during the south-southeast compression of the regional D4 at 2671-2667 Ma.

The tectono-metamorphic history of the study area is consistent with the sedimentation in an accretionary prism followed by its docking to the Wabigoon subprovince to the north and Wawa greenstone belt to the south. The P-T-time path of this Archean accretionary prism is similar to that in modern arc accretion systems, except for a higher temperature gradient, ~ 30°C/km, recorded in the Quetico belt compared to ~10°C/km in modern counterparts. The high temperature gradients in the Quetico belt explain the lack of high-pressure metamorphic rocks, such as blueschist, that are common in modern accretionary prisms.

Key words: Archean accretionary prism, provenance, geochemistry of clastic sedimentary rocks, cratonization, geothermal gradient, subduction zone, monazite geochronology.

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1. Introduction

The Archean Superior Province contains linear arrays of granite-greenstone belts and metasedimentary belts. Successive accretion of volcanic arcs in late Archean time (Card, 1990; Thurston and Chivers, 1990; Fig. 1) is considered as a likely process for the formation of the Archean craton. This is supported by “frozen subduction zones” shown in seismic reflection profiles across the Canadian Shield (Ludden et al., 1993; Calvert et al., 1995; Cook et al., 1999). Metasedimentary belts between greenstone belts are considered to represent accretionary prisms developed during subduction and collision of arcs (Percival, 1989; Card, 1990; Williams, 1990).

The Quetico Subprovince is one such metasedimentary belt in the western Superior Province and is bounded by two volcanic belts: the Wabigoon Subprovince to the north and by the Wawa Subprovince to the south (Figs. 1, 2). The Quetico Subprovince consists mostly of turbiditic quartz-rich metasedimentary rocks with minor banded iron formations. In this monotonous sedimentary belt, a lens of “ultramafic rocks”, ~ 2 km long and 400 m wide, crops out near Jean Lake, north of Lake Superior (Williams, 1988; 1991; Fralick et al., 1992; Fig. 2). Earlier work suggested that this lens was formed by weathering of ophiolites or serpentinite diapirs (Williams, 1988, 1990; Fralick et al., 1992). Ophiolites and serpentinite diapirs are common in modern convergent margins (Nicolas, 1989; Fryer et al., 1995), but their occurrence of Archean age is in debate (e.g., Hamilton, 1998; DeWit, 1998). Therefore, the “ultramafic” unit in the Quetico belt may provide information relevant to Archean tectonics, and may shed additional light on the evolution of the Quetico metasedimentary belt. In addition, the deformational of the Quetico sedimentary rocks are poorly dated and their metamorphic evolution has not been studied. Such a study will contribute to better understanding of the origin of the belt. Consequently, a study of the “ultramafic” rocks was conducted with four objectives: (i) to characterize the “ultramafic” rocks, (ii) to evaluate their origin and source, (iii) to examine the structural and metamorphic evolution of the “ultramafic” and surrounding rocks, and (iv) to compare the Quetico belt with modern accretionary prisms.

2. Geological setting

The Quetico Subprovince is a linear belt of dominantly quartz-rich, turbiditic metagraywackes (Ojakangas, 1985) that has a relatively consistent width of about 70 km and extends approximately 1200 km from longitude 70°W up to 96°W (Williams, 1991). The timing of sedimentation is constrained, by the youngest U-Pb age of zircon in the sedimentary rocks and the oldest age of intrusions. There is a difference in the youngest ages of zircon between the north and south: 2698 Ma in the northern part and 2690 Ma in the southern part of the Quetico belt. The oldest U-Pb zircon intrusion age is 2696 Ma in the northern Quetico belt (Zaleski et al., 1999) and ~2670 Ma for granitic intrusions in the south Quetico belt (Percival, 1989; Williams, 1991). The data indicate that the sedimentary rocks in the southern part of the belt deposited significantly later than the northern part.

Igneous rocks are volumetrically minor in the Quetico belt. They include rare felsic volcanic rocks (Williams, 1991), tonalitic-granodioritic intrusions dated at 2696 Ma (Davis et al., 1990; Zaleski et al., 1999), a suite of carbonate-bearing alkaline complexes of 2680 ±_1 Ma (Hattori and Percival, 1999; Lassen et al., 2000), and large aluminous granites dated between ~2670 and ~2650 Ma (Percival, 1989; Williams, 1991).

The Wabigoon Subprovince to the north consists of igneous rocks formed during several magmatic pulses: 3005-2990 Ma mafic-felsic volcanic and tonalite complexes, 2750-2700 Ma mafic-felsic volcanic rocks and ~2690 Ma monzodiorite-diorite and mafic-ultramafic suites

(Sutcliffe et al., 1989; Blackburn et al., 1991). The Wawa Subprovince to the south is composed of 2750-2690 Ma old ultramafic, mafic and felsic volcanic rocks and related intrusions (Williams, 1990).

3. Occurrence of mafic rocks in the Jean Lake area

3.1 Distribution and lithology

The "ultramafic" lens is well exposed on the shores and on small islands in the Jean Lake (Fig. 2). Rocks contain millimetre-size clasts of quartz aggregates and exhibit sedimentary textures, including climbing ripples, flame structure, loading and stratification (Figs. 3a, 3b and 3c). These observations suggest a sedimentary origin of these rocks. Bedding and foliation strike east, dip mainly south (between 85° north and 50° south) and the "ultramafic" lens is surrounded by quartzo-feldspathic metasedimentary rocks similar to those in the remainder of the Quetico belt.

The quartzo-feldspathic rocks consist of two lithological units, a volumetrically dominant semi-aluminous unit (45-25 vol % of Qtz, 50-30 vol % of feldspar, 35-10 vol % of Bt, < 35 vol % of Chl, < 10 vol % of Ms and < 10 vol % of Grt, abbreviations are from Kretz, 1983) and a minor aluminous unit (40-25 vol % of Qtz, 40-30 vol % of feldspar, 30-20 vol % of Bt, 30-5 vol % of St, < 10 vol % of Chl, < 5 vol % of Ms and < 5 % of Grt). The "ultramafic lens" contains three units; biotite-amphibole-rich unit, amphibole-rich unit, and felsic unit. All units contain more than 10 vol% of felsic minerals (quartz and feldspars) and are thus mafic rather than ultramafic. The biotite-amphibole-rich unit is made of 40-10 vol % of Qtz, 35-10 vol % of feldspar, 50-5 vol % of amphibole, 40-5 vol % of Bt, < 40 vol % of Chl. The amphibole-rich unit contains 90-40 vol % of amphibole, 20-5 % of Qtz, 20-5 % of feldspar, < 10 vol % of Chl.

The felsic unit is identical to the surrounding quartzo-feldsparthic rocks. Unit names instead of rock names are used in this manuscript because the unit names can best characterize the studied rocks which are highly heterogeneous in mineral abundance.

The decametre to metre lenses of amphibole-rich rock unit occurs parallel to the bedding and form high relief on the weathered surface of the hosting, biotite-amphibole-rich unit. South and north of the Jean Lake, sedimentary rocks are cut by granitic dykes and sills, which originated from the voluminous, two mica granite of 2670-2650 Ma (Percival, 1989; Williams, 1991).

3.2 Chemical composition and source of the mafic sedimentary rocks

The mafic sedimentary rocks show significant compositional variations (Table 1). The contents of SiO_2, Al_2O_3, MgO, and Cr vary from 53.9.wt% to 65.5.wt%; 9.8 to 17.9 wt%, 3.0 to 12.5 wt%, and 149 to 866 ppm, respectively (Table 1). The contents of Al, Ti, Mg, and Cr form linear arrays with high correlation coefficients ($r > 0.95$), suggesting that they were immobile after sedimentation (Rollinson, 1993). Linear arrays of Ca, Ga, V, Zn, Co, and Ni against these immobile elements suggest that they too were relatively immobile. The plot of two immobile elements, such as TiO_2 vs Al_2O_3, shows a linear array between the felsic unit and the amphibole-rich unit. The biotite-amphibole-rich unit plot between the two units (Fig. 4).

There are three possible causes to form the linear arrays; constant sum effect, hydraulic sorting, and mixing of two end-members. The constant sum effect is rejected because elemental ratios, such as Ti/Mg and Al/Mg, also show linear arrays (Fig. 5a). Hydraulic sorting from a single source was suggested for the cause of compositional variation of sedimentary rocks from the area between the Beardmore and Jean Lake area (Fralick and Kronberg, 1997). The high Cr content (up to 866 ppm) and the positive correlation of the contents between Cr and Ca require a contribution of chromite and Ca-minerals with similar proportions to the sediments. This is a highly unlikely process because two have very different densities. Therefore, the linear correlations of elements are attributed to mixing between two end-member components.

The amphibole-rich unit contains high MgO (up to 12.5 wt%), Cr (up to 866 ppm), and high PGE (20 ppb Pt, 17 ppb Pd, 3 ppb Ir). These values are all greater than those of most basaltic igneous rocks, suggesting a contribution from more Mg-rich rocks such as komatiitic basalts, komatiites and mantle peridotites. The latter two possibilities are rejected because komatiites and mantle peridotites contain low CaO to account for our samples (Fig. 5b). This leaves komatiitic basalts as the source. The amount of the komatiitic basalts is evaluated to be nil in the felsic unit and up to ~ 90 % in the amphibole-rich unit using the level rule (Fig. 5b).

4. Deformation in the Jean Lake area and correlation with regional deformation

Four tectono-metamorphic events have been recognized in the Quetico Subprovince (Williams, 1991, and references therein). The first regional deformation (D1) included slumping, and recumbent folding shortly after sedimentation (2698-< 2690 Ma; Table 4; Sawyer, 1983; Williams, 1991; Zaleski et al., 1999). This event was followed by mainly strike-slip deformation (D2), with lineations plunging east at 10-30°. The D2 deformation resulted in layer-parallel dextral strike-slip shearing and a Subprovince scale west-trending planar (vertical) and linear fabric (Williams, 1991). The subsequent deformation was also transpressive (D3), and produced upright folds (F3) that affected both the bedding and the earlier-formed planar fabrics (Sawyer, 1983; Williams, 1991). The D4 deformation corresponds to minor shearing under a south-southeast compression (Sawyer, 1983).

The study area shows three stages of deformation. The first stage of deformation in the Jean Lake area produced a foliation defined by Bt and St. The foliation was later folded during the main deformation event in the area, producing decimetre-scale tight folds with an axial trace of N95 80S. The later foliation, which is defined by Bt, Grt and Sil, is locally oblique to the axial surface because of larger-scale upright folds (Fig. 2). Similar upright folds are common in the Quetico belt and considered to have formed under the regional transpressive D3 deformation (part 4; Williams, 1991), suggesting that this late foliations and upright folds in the Jean Lake area are most like a product of the regional D3 deformation. It implies that the earlier foliation in the Jean Lake area formed during either D1 or D2 regional deformation.

The final deformation in the Jean Lake area produced minor shear zones, which are defined by Chl± Bt ± amphibole, strike N110°, dip steeply to the south (Fig. 2). They cut earlier planar and folded fabrics (pre-S3 and S3) and bedding planes and east-trending pre-S3 and S3 foliations rotate into the shear planes, forming hectometre-scale dextral sigmoïds. Z-folds, suggesting dextral strike-slip motion. The location of these asymmetric folds suggests that they are not drag folds of F3 folds, thus unrelated to the D3 deformational event. Z-folds of narrow (up to 1 cm width) Qtz veins inside the shear zones likely developed during this strike slip deformation (Fig. 6a). The geometry of centimetre-wide kink bands of Chl is also consistent with dextral shearing along a N110° direction. A conjugate set of the dextral shear is sinistral shear planes striking N50°. Indeed, Pye (1964) identified such shear planes in the Jean Lake area (Fig. 2), confirming that the dextral shear planes formed during north-south compression.

The final deformation in the Jean Lake area corresponds to the regional D4 deformation. Similar deformation features, such as shears and kink bands, formed during the D4 are recorded in the Kashabowie area (~ 200 km south-east of the Jean Lake area; Sawyer, 1983).

5. Metamorphism in the Jean Lake area

5.1 Mineralogy and mineral chemistry

We conducted a detailed petrographic and thermobarometric study of the felsic and amphibole-rich units, which represent the end members of the compositional variations in the study area. The purpose is to evaluate the thermobarometric evolution of the metasedimentary rocks in the study area and to relate this evolution to the regional deformational events.

5.1.1 Aluminous unit

The rocks are defined by the following minerals: Qtz + Pl + Bt + St ± Grt ± Sil ± Chl ± Ilm ± Tur. Both Qtz and Pl, ranging from 0.05 to 0.1 mm in size, are anhedral in shape and Pl is homogenous in composition (An25-27). Bt (up to 2 mm in length) defines the pre-S3 foliation, subsequently deformed by F3 folds. Later Bt, Bt_2, crystallized parallel to the axial surface, forming the main S3 foliation. Bt_2 in contact with Grt and St have similar composition as those in the matrix, with X_{Fe} (= Fe/(Fe+Mg) atomic ratio) of 0.47-0.49 (Table 2).

St (up to 0.5 cm; 30-5 vol %, X_{Fe} from 0.82 to 0.84) is anhedral with corroded rims and belongs to the pre-S3 foliation. Some folded crystals, outline fold limbs of centimetre-scale tight F3 folds (Fig. 6c).

Rare fibrous Sil occurs parallel to the S3 foliation between corroded St and euhedral Bt and Grt (Fig. 6d). The texture suggests the following KFMASH reaction;

St + Qtz + Bt_1 = Bt_2 + Sil + Grt + H_2O (Reaction 1)

Grt porphyroblasts (0.2-1.0 mm) are euhedral, contain Qtz inclusions, and are syn-kinematic with respect to the main S3 foliation. They are solid solutions of $Alm_{0.72-0.78}$, $Prp_{0.10-0.14}$, $Grs_{0.03-0.07}$ and $Sps_{0.07-0.08}$, and show increasing Alm component toward the rims (Fig. 7). The Sps component decreases towards the 70 µm thick rims and starts increasing within the rims (Fig. 7). The bell shaped profile of Ca and Mn with a gentle increase in X_{Fe} towards the rims is commonly formed during crystal growth (Spear, 1993; Reaction 1). The sharp enrichment of Fe in the outermost rims is probably related to late diffusion of Fe from Bt_2, as suggested by Spear (1993).

Bt grains are homogeneous, probably because of fast diffusion of elements in Bt (Spear, 1993). Bt_2 is partially replaced by Chl.

5.1.2 Semi-aluminous unit.

This unit consists of Qtz + Pl + Bt ± Grt ± Chl ± Ilm ± Tur. Anhedral Qtz (0.05-0.1 mm) is predominant and Pl crystals (0.05-0.2 mm) are anhedral and commonly contain Qtz inclusions. Individual grains do not show compositional zoning, with $An_{0.24-0.31}$ (An; 100*[Ca]/([Ca]+[Na]+[K])) and $An_{0.14}$ in sample 244 and $An_{0.22-0.27}$ in sample 262b.

Bt (0.1-0.3 mm) defines the main S3 foliation and re-crystallized in D4 shear bands (Fig. 6b). Some Bt surrounding Grt define delta micro-structures. Bt grains in contact with Grt have similar compositions as those in the matrix, with X_{Fe} of 0.48-0.49.

Euhedral Grt grains (0.3-1.2 mm) contain rounded Qtz inclusions and were rotated by the late dextral strike-slip shear deformation (D4), suggesting crystallization before or during D4. In sample 262b, Grt crystals (~ 1 mm) have Alm component ranging from 0.78-0.84, whereas Grt (~ 0.7 mm) in sample 244 contains between 0.67 and 0.73 Alm component (Table 2). Sps, Grs and Prp components vary from 0.17 to 0.13, 0.06 to 0.04 and 0.12 to 0.10, respectively. The Grs and Sps components and X_{Fe} decrease from core to rim. The 80 µm-thick rims record a reverse trend; an increase in Sps and X_{Fe}, and a decrease in Prp component (Fig. 7).

The bell-shaped zoning pattern suggests that the zoning is a result of crystal growth without subsequent modification by diffusion (Fig. 7). The reverse zoning in the outer rim implies a consumption of Grt during retrogression (Spear, 1993).

Anhedral Kfs crystals identified in one sample occur around Grt porphyroblasts in association with Chl suggest the following reaction:

Grt + Bt + H_2O = Kfs + Chl (Reaction 2)

Chl crystallized along the dextral shear planes that formed during the south-southeast compression (D4) and replaces Bt under retrograde greenschist facies conditions.

5.1.3 Amphibole-rich unit

This unit consists of amphibole + Pl + Qtz + Ilm ± Chl ± Tur. Amphibole (0.05-1 mm), the predominant mineral, is euhedral to subhedral (Fig. 8) and does not display a preferred orientation. The compositions of the amphiboles plot near the boundary between magnesiohornblende and Tr, following the classification of Leake et al. (1997). They plot an array of solid solutions between Tr-Ts and Tr-Prg (Fig. 9), suggesting a typical Act-Hbl exchange reaction (Spear, 1993). Individual grains in sample 268a show an enrichment of Hbl component whereas those in sample 252a show an enrichment of Tr component towards the rims (Fig. 10). The P-T evolution reflected on the zoning pattern will be discussed in part 5.3.

Pl grains are subhedral to anhedral in shape and range in size from 0.1-0.6 mm. They contain inclusions of Qtz and amphibole, and show Ca-enrichment towards the rims ranging from $An_{0.32}$ to $An_{0.38}$ in sample 252a and from $An_{0.33}$ to $An_{0.52}$ in sample 268a.

5.1.4 The felsic unit

This unit contains Qtz + Pl + Bt ± Ilm ± Tur. It is similar in mineralogy and texture to the surrounding semi-aluminous unit of quartzo-feldsparthic rocks.

5.2 Thermobarometric methods

The felsic rocks have low MnO and TiO_2 contents and feldspar is the only Na- and Ca-bearing phase. Therefore, we used KFMASH petrogenetic grids of Spear and Cheney (1989), together with the aluminosilicate triple point by Richardson et al. (1969) to represent the metamorphic assemblages. We used two Fe-Mg exchange thermometry; Grt-St thermometry of Perchuk (1989) and Grt-Bt thermometry (GARB thermometer) of Pigage and Greenwood (1982) and Williams and Grambling (1990). The classical GARB thermometers of Ferry and Spear (1978) and Indares and Martignole (1985) were not used because Bt compositions in our samples are outside the range accepted for the thermometry (Bt with $(Al^{VI}+Ti)/(Al^{VI}+Ti+Mg+Fe) < 0.15$). Furthermore, the Ti-Al substitution of Bt in our samples is different from Bt used by Indares and Martignole (1985). Pressures were estimated using the Grt-Pl-Sil-Qtz (GASP) barometer of Hodges and Crowley (1985) and Koziol and Newton (1988), and the empirical Grt-Pl-Qtz (GPQ) barometer of Hoisch (1990). We also used the THERMOCALC computer program by Powell et al. (1998) in order to identify possible reactions among given end-member phases and to calculate the pressure and temperature of sub-systems.

The amphibole-bearing rocks contain low TiO_2, MnO, and K_2O and plot on the ACFM+SiO_2 petrogenetic grid defined by Spear (1981). Complementary P-T estimates of the amphibole-rich unit were obtained using the thermometer based on the cation exchange reaction of edenite (Holland and Blundy, 1994). Thermobarometers based on the contents of Ti and Al (VI) in amphibole were not used because of the absence of Zo and Ep in our samples (Raase, 1974; Plyusnina, 1982; Hammarstrom and Zen, 1986).

5.3 Metamorphic conditions

5.3.1 Aluminous unit

The KFMASH P-T grid of Spear and Cheney (1989) suggests early formation of St at 500 to 700°C (Fig. 11). This is consistent with the mineral assemblage of our samples. The second metamorphic stage is characterized by the assemblage of Sil + Grt + Bt, suggesting a metamorphic condition on the high temperature side of Reaction 1, greater than 600°C (Spear and Cheney, 1989; Fig.11). The absence of Kfs and the occurrence of Sil suggest temperatures lower than 800°C and pressures between 0.2 and 1 GPa. Sample 251 yielded 628 ± 35 °C and 0.64 ± 0.16 GPa using the THERMOCALC program. These results are consistent with the estimate of 600 ± 70 °C using the GARB thermometer, and also with 625 ± 50°C and 0.54 ± 0.09 GPa using the independent GS thermometer and the GASP barometer. The estimates are all comparable considering uncertainties of the estimated values (Table 3a), but the estimated temperatures represent a minimum because of possible late re-equilibration of Bt and Grt rims.

5.3.2 Semi-aluminous unit

The assemblage of Grt + Bt + Pl suggests a metamorphic temperature greater than 500 °C (Spear and Cheney, 1989), as Grt can not crystallise on the low temperature side of the reaction:

Fe-Cld + Ann + Qtz = Alm + Ms + H_2O (Reaction 3)

In sample 262b, the GARB thermometry and GPQ barometer on Grt cores yielded 610 ± 70°C and 0.56 ± 0.12 Gpa. In sample 244, Grt cores yielded 585 ± 70°C and 0.71 ± 0.08 GPa, whereas rims with Pl and Bt show a retrograde condition of 540 ± 80°C and 0.25 ± 0.11 GPa (Table 3b).

5.3.3 Amphibole-rich unit.

Metamorphic temperatures are estimated using the amphibole-Pl geothermometer (Holland and Blundy, 1994). Amphibole shows compositional zoning from Hbl in the cores to Tr in the rims. Tr commonly crystallizes under greenschist facies condition, whereas Hbl forms under amphibolite facies condition. Therefore, the zoning of amphibole (sample 252a) likely reflects the retrograde path. The core composition of Hbl and Pl yields a temperature of 700 ± 70°C, comparable to the peak metamorphic temperature (T > 650°C) for the quartzo-feldspathic rocks.

Amphibole grains, that are free from any evidence of retrogression, in sample 268a record a prograde path, increasing Hbl component towards the rims. The rims yielded a maximum temperature of 600 ± 70°C using the amphibole-Pl thermometer.

In summary, the rocks in the Jean Lake area underwent a metamorphic event starting with the crystallization of St in the aluminous unit and the increasing Hbl component in amphiboles in the amphibolite unit. The peak metamorphic P-T, 0.61 ± 0.10 GPa and 700 ± 70 °C, was attained during the D3 regional transpressive deformation (Fig. 12). This was followed by retrogression forming Chl and Tr during D4 south-southeast compression at 0.25 ± 0.11 GPa, 540 ± 80°C (LP-MT event; Fig. 12).

6. Tectono-metamorphic evolution of the study area and the Quetico Belt

The first regional deformation (D1) took place shortly after sedimentation and involved burial of sediments, producing moderate P-moderate T (MP-MT) metamorphism (Tabor et al., 1989; Pan and Fleet, 1999). This tectono-metamorphic event was followed by mainly strike-slip deformation (D2). This deformation and subsequent deformation (D2-D3) mainly involved strike-slip deformation, implying no significant change in P conditions. Therefore, the crystallization of

St and Hbl-rich amphiboles under the MP-MT metamorphism in the Jean Lake area occurred before the regional D2 transpressional deformation. It is most likely related to the regional D1.

The second stage deformation in the Jean Lake area, which corresponds to regional D2-D3, is accompanied by the peak metamorphic. The final deformation in the Jean Lake area includes local shearing during south-southeast compression, accompanied by LP-MT metamorphism. The metamorphic condition, 0.25 GPa and 540°C in the Jean Lake area, is in agreement with the conditions expected from the Subprovince-wide metamorphism. There is a systematic increase in metamorphic conditions, from 0.2 GPa and 500°C at the U.S.A.-Canada border in the west to 0.5-0.6 GPa and 780°C in the eastern part of the Quetico belt (Pirie and Mackasey, 1978; Percival, 1989). Greenschist facies retrogression is recorded at the end of D4 deformation in the Jean Lake area. Similar retrogression is observed in many other places in the Quetico belt (Percival, 1989; Pan et al., 1994; Pan and Fleet, 1999).

The last two regional deformation events (D3 and D4) were described by Sawyer (1983) and Williams (1991), but their timing is not well established. Furthermore, the timing of the regional D2 (and then D1) deformation and its relationship with regional metamorphism are in debate. Based on ages of intrusive rocks and detailed structural study in Shebandowan and adjoining Quetico belt (Fig. 2), Percival (1989 and references therein) suggested the regional D2 bracketed between 2689 and 2684 Ma and the LP-MT event at 2671-2667 Ma. On the other hand, Pan et al. (1998) suggested that the regional D2 deformation ended after 2666 Ma because pegmatitic rocks of this age were concordant to the penetrative S2 foliation. This implies that the D2 was associated with the regional metamorphism. This is not consistent with our data from the Jean Lake area, where the LP-MT metamorphism was synchronous with the D4 deformation. To confirm this time relationship, we dated monazite that crystallized during the LP-MT metamorphic stage (D4).

7. Dating of monazite

Thirty six grains of monazite were examined in sample 251. Monazite shows no compositional zoning, contains high U (up to 0.8 wt%), Th (up to 5 wt %) and light rare earth elements (REE). Chondrite-normalized REE patterns of all grains are similar, suggesting a single population of monazite (Fig. 13). The age was calculated from the concentration of U, Th, and Pb assuming no Pb at the time of crystallization following the method of Montel et al. (1996; see caption for Fig. 14). The calculated mean age is 2667± 20 Ma with a mean square of weighted deviates (MSWD) of 0.36. The error is estimated following the method described in Montel et al. (1996). The narrow range of MSWD supports a single generation population of monazite in the sample (Fig. 14).

8. Discussion

8.1 Pressure-temperature-time path

The age of 2667± 20 Ma for the D4 and LP-MT metamorphism is in good agreement with the time span of 2671-2667 Ma suggested by Percival and Sullivan (1988) and 2668± 6 Ma of the U-Pb age of metamorphic titanite reported by Pettigrew et al. (2001). For the D2 deformation, we adopt 2689-2684 Ma suggested by Percival (1989). The pegmatite of 2666± 1 Ma dated by Pan et al, (1998) likely intruded along the pre-existing S2 foliation.

Combining our data with those of previous workers, we propose the P-T-t path for the central part of the Quetico metasedimentary belt described below. The rocks were buried to form a MP-MT mineral assemblage under amphibolite facies P-T conditions during the D1 shortly after the sedimentation bracketed between 2698 and <2690 Ma (Zaleski et al., 1999). Transpressive deformation (D2-D3) started at 2689 Ma and was accompanied by peak metamorphic conditions of $P= 0.61 \pm 0.10$ GPa and $T= 700 \pm 70$ °C. The subsequent south-southeast compression, D4, was accompanied by east-west extrusion under LP-MT metamorphic conditions (0.25 ± 0.11 GPa, 540 ± 80 °C) at 2671-2667 Ma (Fig. 12). This deformation likely continued under retrograded greenschist-facies conditions, forming lineations of Chl and Tr .

8.2 Tectonic setting of the sedimentation of the Quetico belt

A variety of tectonic settings have been proposed for the deposition of the sediments in the Quetico belt. We briefly present the evidence for and against several possible settings.

Ensialic basin

Given the elongate shape of the Quetico metasedimentary belt, an aborted rift basin in sialic crust was suggested for the depositional environment (Percival, 1989). As discussed by Percival (1989) and Williams (1990), the turbiditic character of the Quetico sedimentary rocks is markedly different from alluvial conglomeratic sequences that commonly develop in a continental extensional basin.

Back-arc basin or intra-arc basin

The evidence against this model is essentially the same as for the ensialic rift environment described above. In addition, the Quetico belt does not contain rift-related mafic igneous rocks that are common in a back-arc or intra-arc basin.

Forearc setting

This was first suggested by Devaney and Williams (1988) based on a sedimentological-structural study in the Beardmore-Geraldton area (Fig. 2) in the southern margin of the Wabigoon Subprovince. They outlined north-dipping thrust slices of volcanic-sedimentary rocks and interpreted the area as a forearc basin in an accretion model. Sediments in modern forearc basins are thin (Lallemand, 1999), which is not consistent with the observed 20 km of burial corresponding to MP-MT metamorphism established shortly (< 9 My) after sedimentation.

Accretionary prism

This model, proposed by Percival (1989) and Williams (1990), suggests that submarine fans and abyssal turbidites were first deformed during their accretion onto the active Wabigoon arc (D1) and later during docking to the Wawa arc (D2-D3). The younging age of sedimentation toward the south part of the Quetico belt (Zaleski et al., 1999) is compatible with a southward propagation of the active front as observed with a north dipping subduction (Platt, 1986). An oblique component of this convergence likely contributed to the observed transpressional structures, dextral wrench zones, and transcurrent faults along subprovince boundaries. Thermal relaxation after cessation of subduction could account for the late LP-MT metamorphism.

Seismic reflection profiles from the Superior Province illustrates crustal reflections dipping toward the centre of the craton and the remnant of the subducting lithosphere from within the crust to 80-100 km in the mantle (Ludden et al., 1993; Calvert *et al.*, 1995). Island arcs were continuously accreted to a continent to the north through subduction and collision. This is further supported by petrological and structural studies in the Superior Province (Desrochers et al., 1993; Tomlinson et al., 1996; Davis, 1998). Thus, we suggest that an accretionary prism setting best explains the sedimentologic, metamorphic, tectonic and geophysics characterics of the Quetico belt.

8.3 Source and evolution of the Quetico accretionary prism

The sedimentary rocks in the Jean Lake area formed by mixing of quartzo-feldspathic rocks and komatiitic basalts. Three types of possible geological setting are considered for the komatiitic basalts; an oceanic island that accreted to the Quetico belt, igneous rocks in the Quetico belt, and the adjacent southern Wabigoon Subprovince. An oceanic island and a volcano inside the Quetico belt are unlikely simply because there are no komatiites or komatiitic basalts in the Quetico belt. There are abundant mafic igneous rocks in the southern Wabigoon subprovince that are contemporaneous with the sedimentation of the Quetico sediments. They include a suite of sanukitoids of ~ 2690 Ma in the Wabigoon Subprovince (Stern and Hanson, 1991; Stevenson et al., 1999), and voluminous mafic-ultramafic rocks ~ 2692 Ma in the southern Wabigoon belt along the boundary with the Quetico belt (Sutcliffe et al., 1989; Blackburn et al., 1991; Pettigrew and Hattori, 2002).

High contents of MgO and CaO suggest a proximal source, since these elements are easily leached during weathering and transportation (Nesbitt and Young, 1989). Immature sediments may be formed during sudden uplift and erosion of a source terrane, or by discharge of pyroclastic material from a volcano. The compositions of the mafic sedimentary rocks are still too immature to have originated from such a distal source as the southern Wabigoon Subprovince. The study of modern accretionary prisms suggest that the sediments may have deposited close to the Wabigoon Subprovince.

In modern accretionary prisms, sediments are thickened through repeated underplating and near-horizontal thrusting (Platt, 1986; Lallemand, 1999; Hashimoto and Kimura, 1999). Continued underplating at the base of the wedge is compensated by extension in the shallow part of the wedge (Platt, 1986; Lallemand, 1999). This extension in the rear of the prism causes lateral movement of material and thrusting toward the prism front (Platt, 1986; Fig. 15). Our structural analysis in the Jean Lake area shows that the mafic sediments were most likely buried during the D1 deformation under compressional regime. Taking the structural development of modern accretionary wedges as an example, we suggest that the rocks in the Jean Lake area were deposited close to the Quetico-Wabigoon boundary and were displaced towards the south, subsequently buried by rapid underthrusting along a MP-MT metamorphic gradient to amphibolite facies P-T conditions. Subsequent dominant dextral transpressive deformation (D2-D3) displaced the sedimentary rocks to the west from the original depositional site. The dextral component during D2-D3 was likely caused by strain partitioning in an oblique convergent system as described in many modern subduction zones, such as the Ryukyu, Higurangi, Aleutian, and western North American subduction zones (Lallemand, 1999). This is also consistent with an earlier suggestion by Percival (1989) that the Wawa arc collided obliquely with the Wabigoon arc to the north.

The rocks were then uplifted during the D4 deformation. This exhumation was likely accompanied by the development of LP-MT metamorphism and voluminous granitic plutonism. This has been interpreted previously as a result of thermal relaxation (Percival, 1989; Williams, 1991).

8.4 Comparison with modern subduction zones

Our data suggest the burial of sedimentary rocks to a depth of about 20 km and their metamorphism up to amphibolite facies conditions in less than 9 M.y., and their exhumation up to LP-MT conditions within about 15 M.y. In Phanerozoic orogenic belts, the typical burial rate of sediments in prisms is about 3 to 8 cm/yr (Demets et al., 1990) and their exhumation rate is about 0.2 to 1 mm/yr (Duchêne et al., 1997; Schwartz et al., 2000; De Sigoyer et al., 2000). Using these burial and exhumation rates, our P-T path suggests that the Quetico rocks would have been buried in less than ~ 1 M.y. and exhumed within 12 to 60 M.y. The estimates from the Quetico metasedimentary rocks are thus compatible with those from modern subduction zones, suggesting that the Neoarchean tectonic regime was essentially similar to the modern analogs.

Modern subduction zones commonly contain HP-LT metamorphic rocks, such as blueschists and eclogites. They formed under low geothermal gradients, ~ 10°C/km (Fig. 12; Ernst, 1988; Ernst and Liou, 1999; Schwartz et al., 2000). Like many other Archean sedimentary terranes, the Quetico belt does not contain HP-LT rocks. The lack of such metamorphic rocks in Archean terranes has been in debate (e.g., De Wit, 1998). This may be attributed to high geothermal gradients (~ 30°C/km) during Archean time possibly caused by local effects such as magma emplacement and ridge subduction, as proposed to account for high geothermal gradients of several Phanerozoic accretionary prisms (Sakaguchi, 1999). Upwelling of magmas may be supported by the occurrence of small, yet numerous intrusions in the belt including 2680+-1 Ma alkaline igneous rocks (Hattori and Percival, 1999).

9. Conclusion

Our study in the Jean Lake area suggests that the Quetico sedimentary rocks formed in an accretionary prism above a north-dipping slab subducting underneath the Wabigoon Subprovince. Oblique convergence of the prism and the Wawa volcanic belt resulted in transpressional deformation within the prism. The geodynamic setting and tectono-metamorphic evolution of the accretionary prism is comparable to those of modern examples. The sedimentary rocks were buried along a gradient of about 30°C/km, which is significantly higher than modern counterparts (10°C/km). The lack of HP-LT rocks, such as blueschists, in the Quetico belt is attributed to such high geothermal gradients.

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FIGURE CAPTIONS

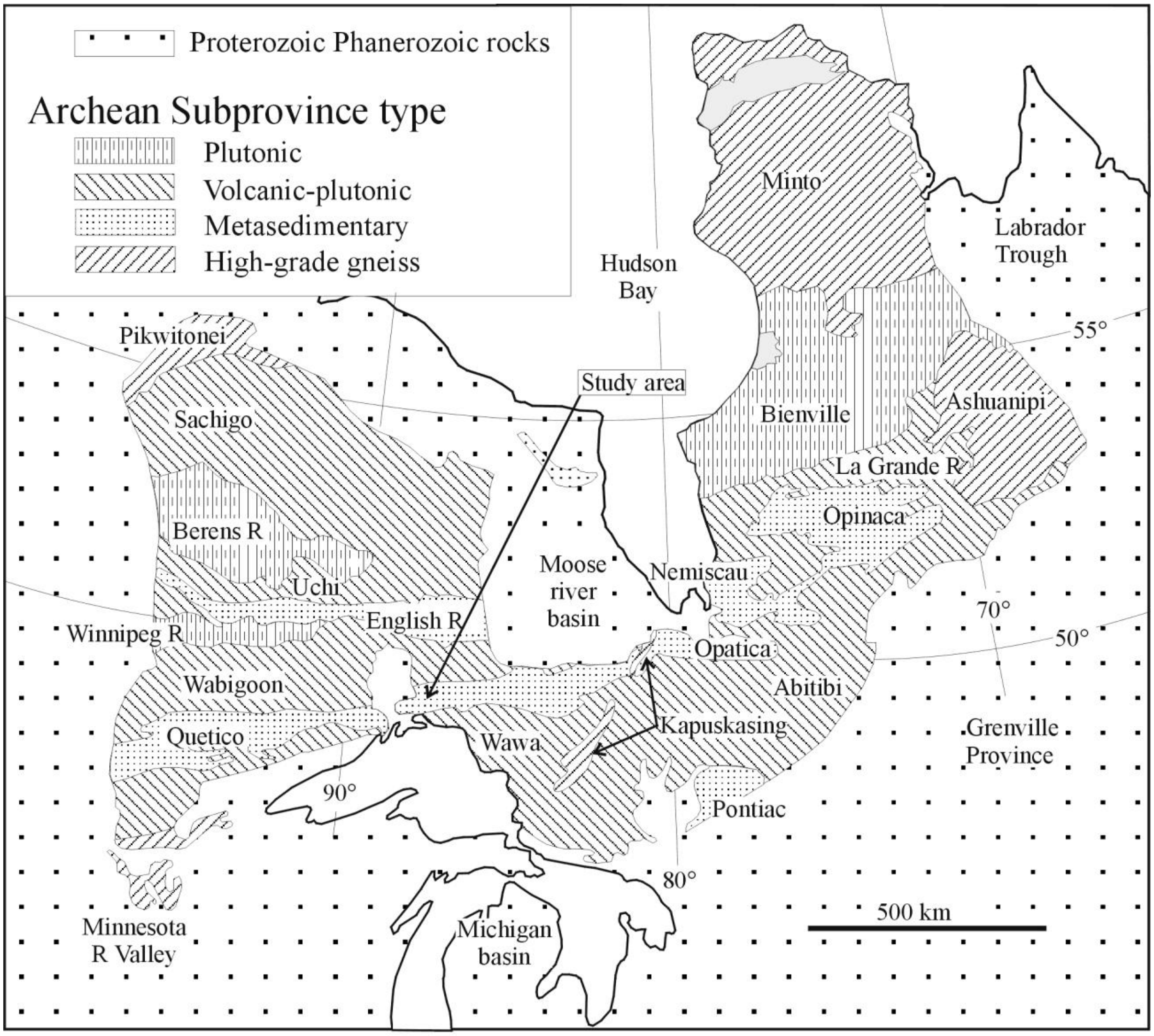


Figure 1. Simplified geological map of the Superior Province with the names and locations of Subprovinces and the location of the study area shown in Figure 2, modified after Card (1990).

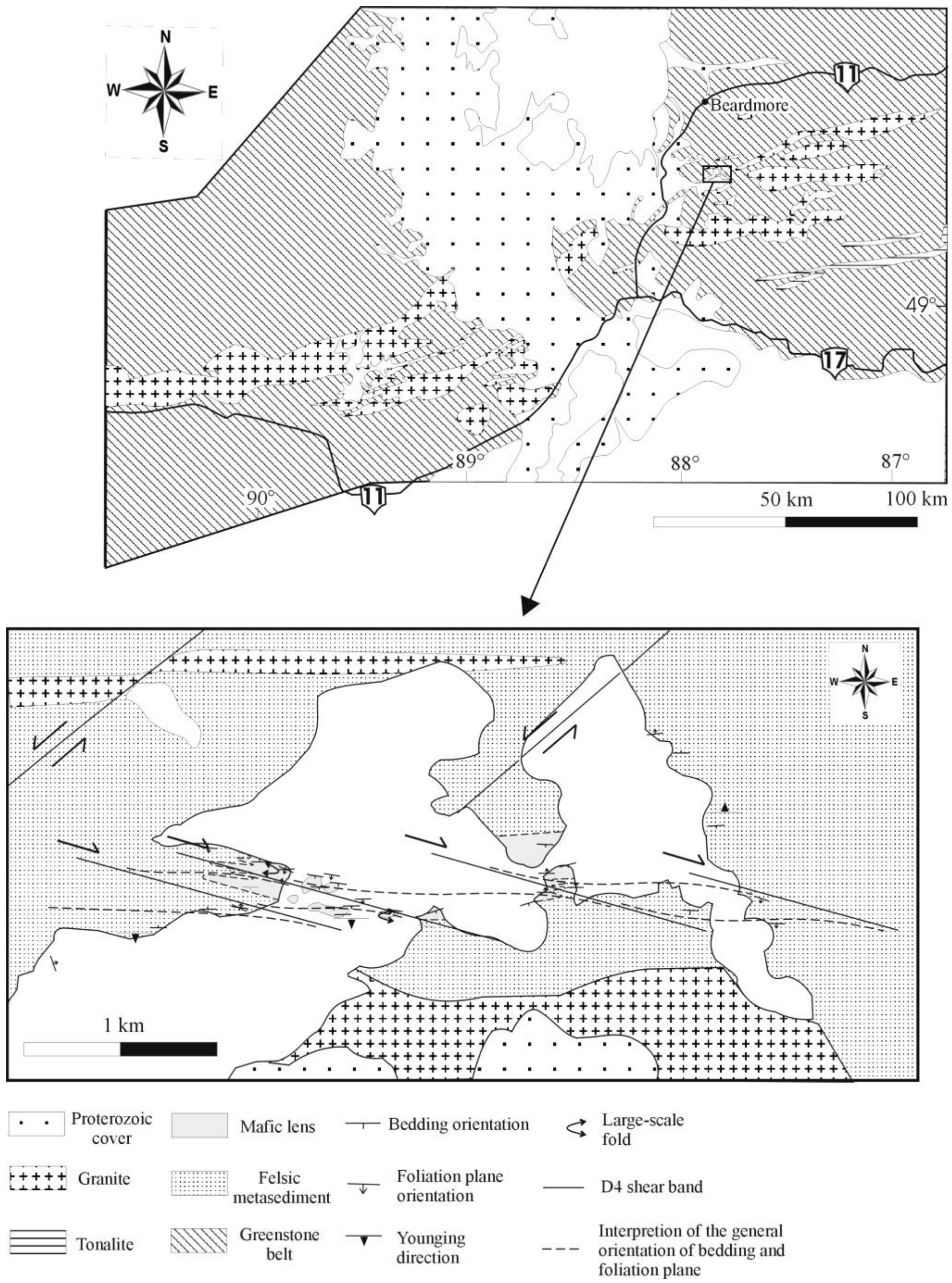


Figure 2a. Geological map of the central Quetico metasedimentary belt (modified after map 2542 from Ontario Geological Survey, 1991) and the location of the study area.

2b. Geological map of the study area (modified after map 2056 by Pye (1964)).—If you have added your structural measurements, you should say so.

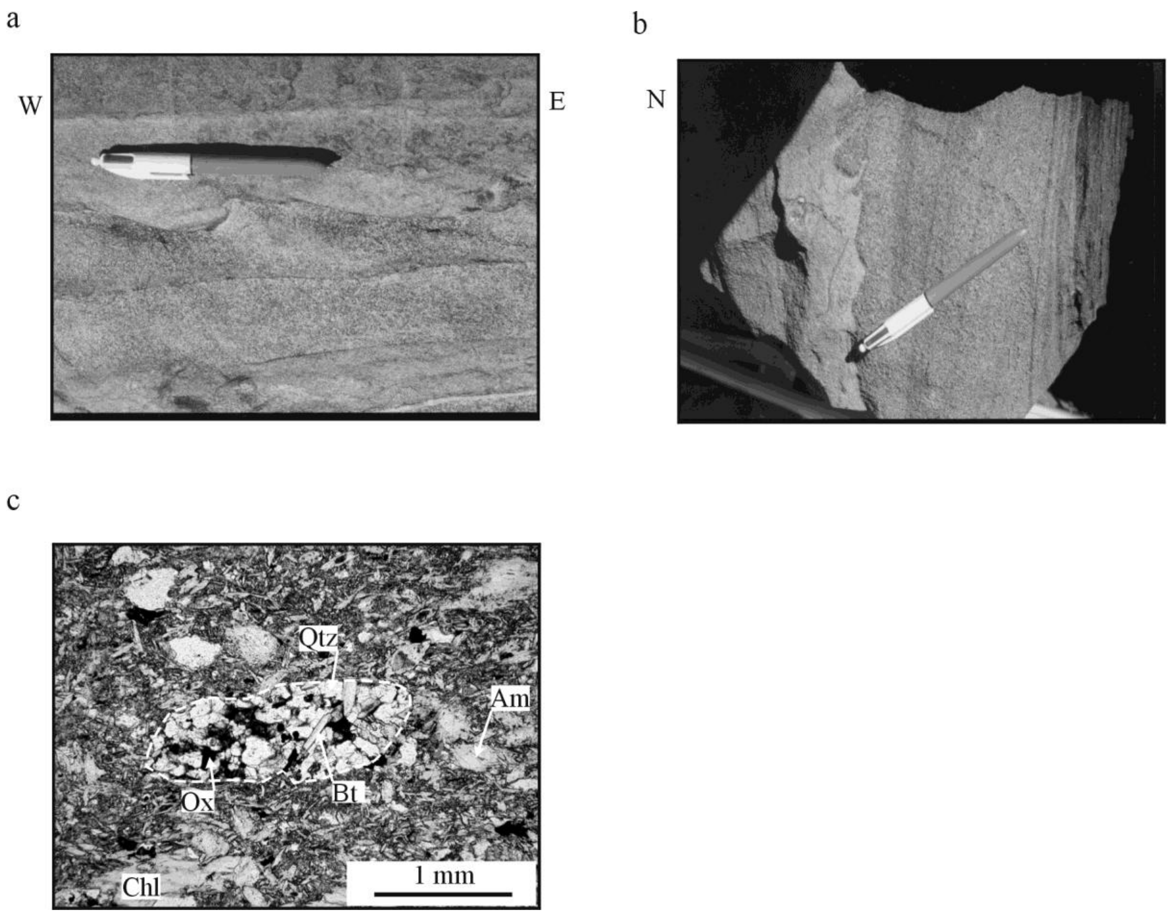


Figure 3a: Flame structure in the quartzo-feldspathic host rock. Pen is 14 cm long.
3b. Loading structure in the biotite-amphibole-rich unit.
3c. Photomicrograph showing a quartz-rich clast in the amphibole-rich unit.

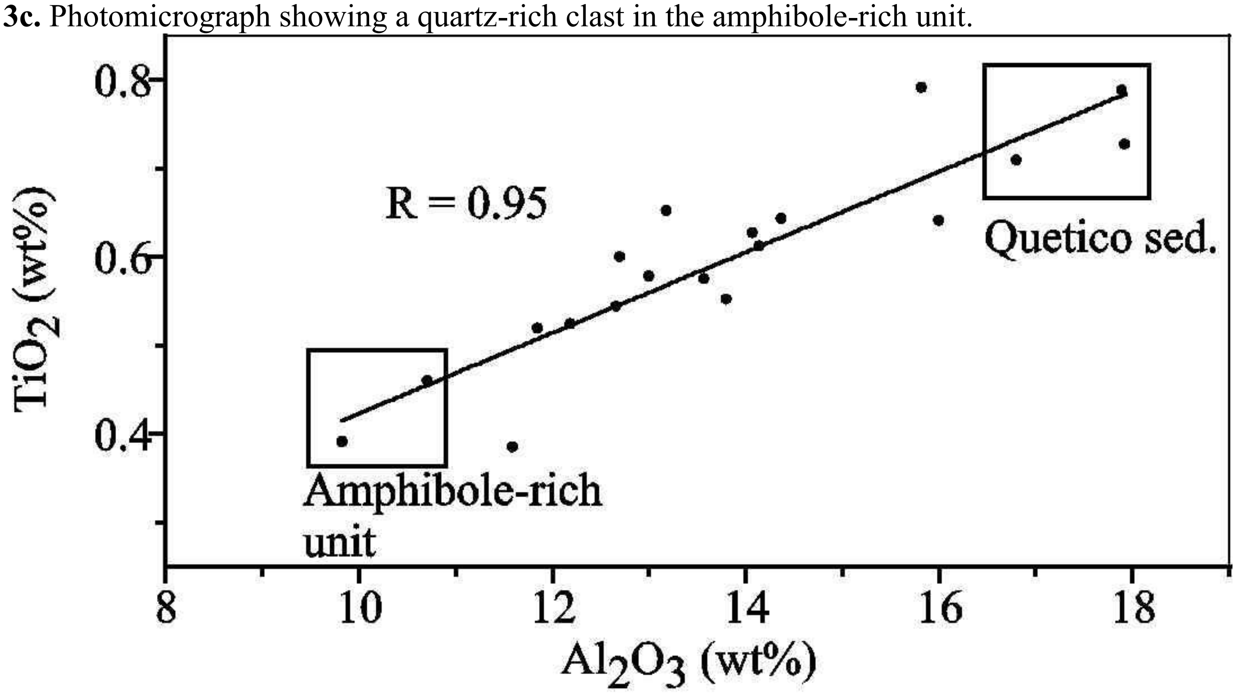


Figure 4. TiO_2 vs. Al_2O_3 wt% of mafic rocks in the Jean Lake area. Circles correspond to the rocks from the biotite-amphibole-rich unit, triangle to the rocks from the amphibole-rich unit, squares to the felsic unit in the mafic lens and the quartzo-feldsparthic rocks surrounding the mafic lens.

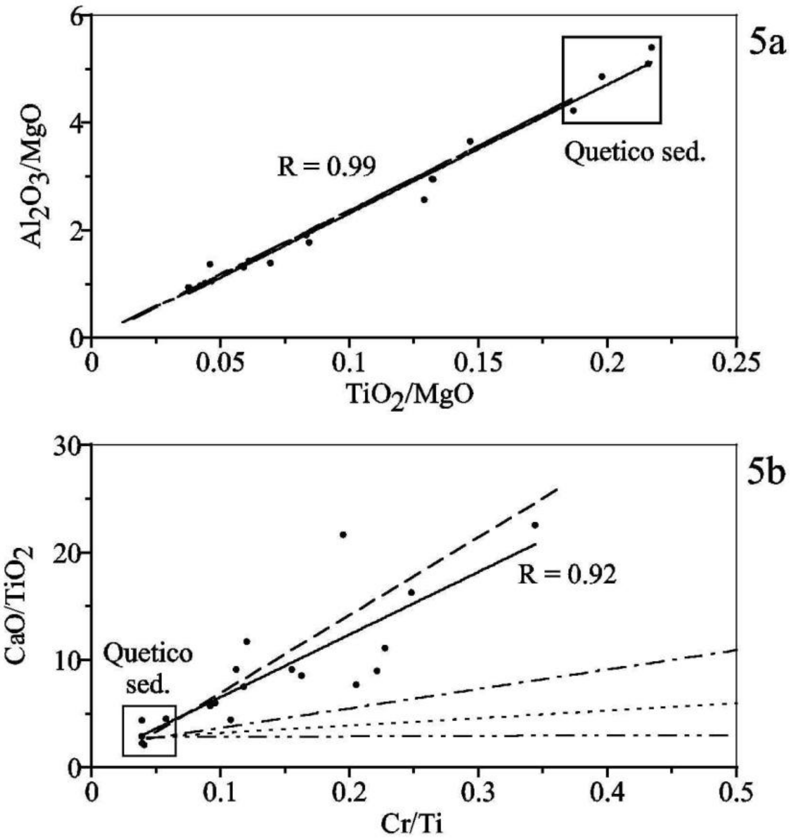


Figure 5a. Weight ratios of Al_2O_3/MgO vs TiO_2/MgO for rocks from the mafic lens in the Jean Lake area. The regression line (solid line) of sedimentary rocks from the mafic lens compared to various mixing lines between an averaged composition of the Quetico felsic sedimentary rocks (host rocks and felsic-unit rocks) and possible ultramafic and mafic rocks; komatiitic basalt (dashed line; Ayer, 1999), komatiite (dash-dot line; Ayer, 1999) in the southern Wabigoon Subprovince, harzburgite (dash-double-dot line; Yamamoto et al., 1992) and lherzolite (dotted line; Ballantyne, 1992).

5b. Weight ratios of CaO/TiO_2 vs Cr/Ti for rocks from the mafic lens in the Jean Lake area. Lines are described in Figure 5a.

6a

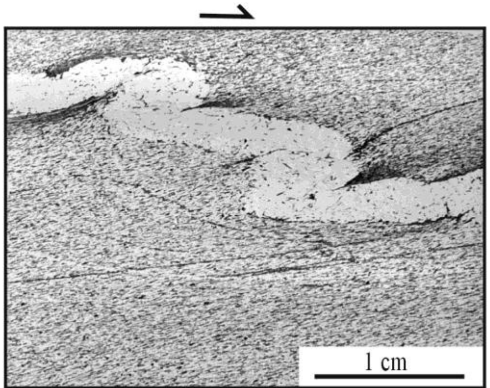
W  E

Figure 6a. Horizontal photomicrograph showing a Z-folded Qtz vein parallel to D4 shear planes in the semi-aluminous unit (sample 219). What is this? What is horizontal?

6b

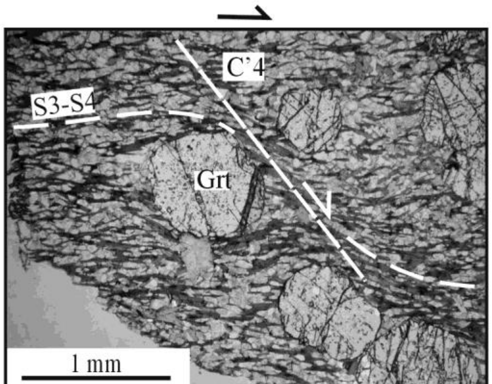
W  E

Figure 6b. Horizontal photomicrograph of the semi-aluminous unit (sample 262b). S2-S3 foliation defined by biotite is transposed into dextral C4 shear bands

6c

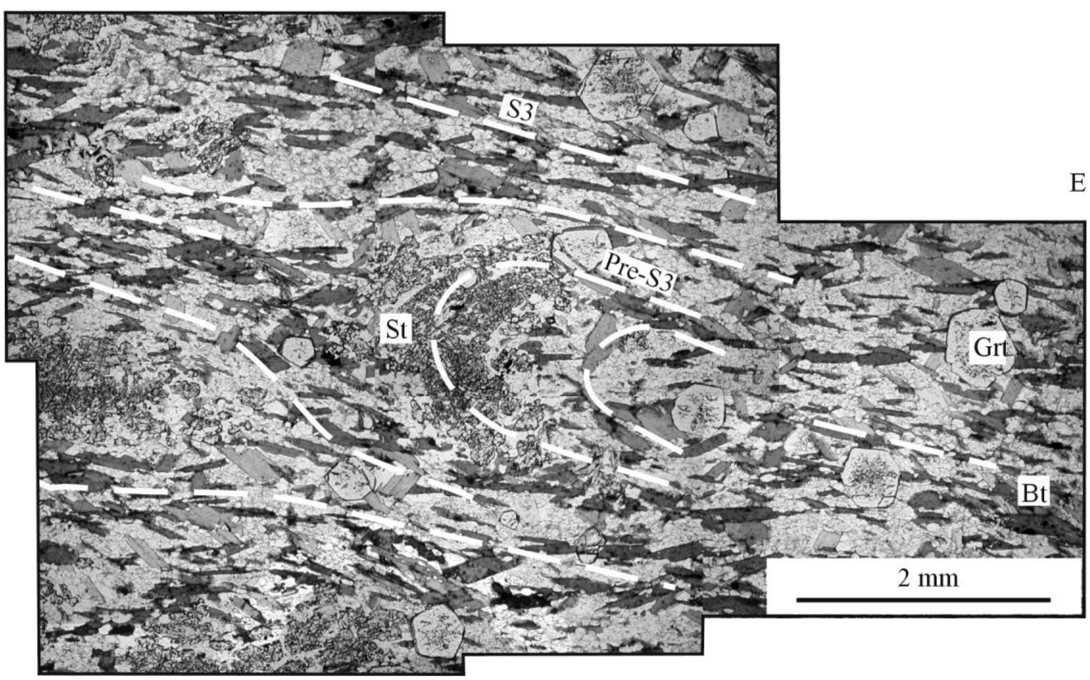
W  E

Figure 6c. Photomicrograph of the aluminous unit (sample 251). Staurolite (St) and earlier formed biotite (Bt) are folded by D3 event. A new foliation (S2-S3), which is defined by later biotite, develops in parallel to the axial plane.

6d

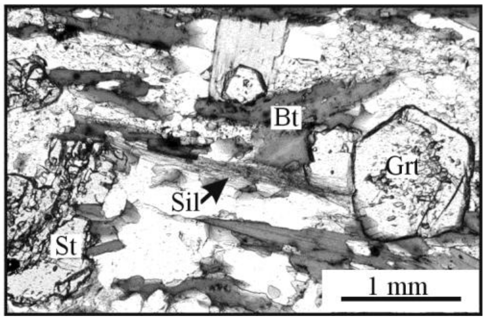
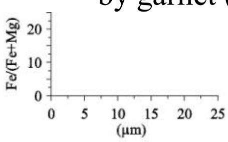


Figure 6d. Photomicrograph of the quartzo-feldsparthic unit (sample 251). Staurolite is replaced by garnet (Grt), biotite (Bt) and sillimanite (Sil).



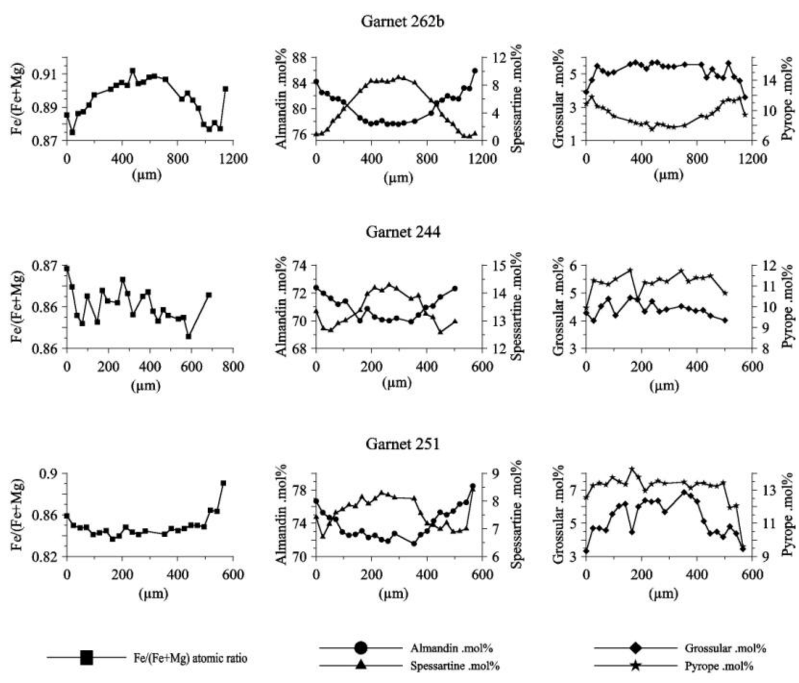
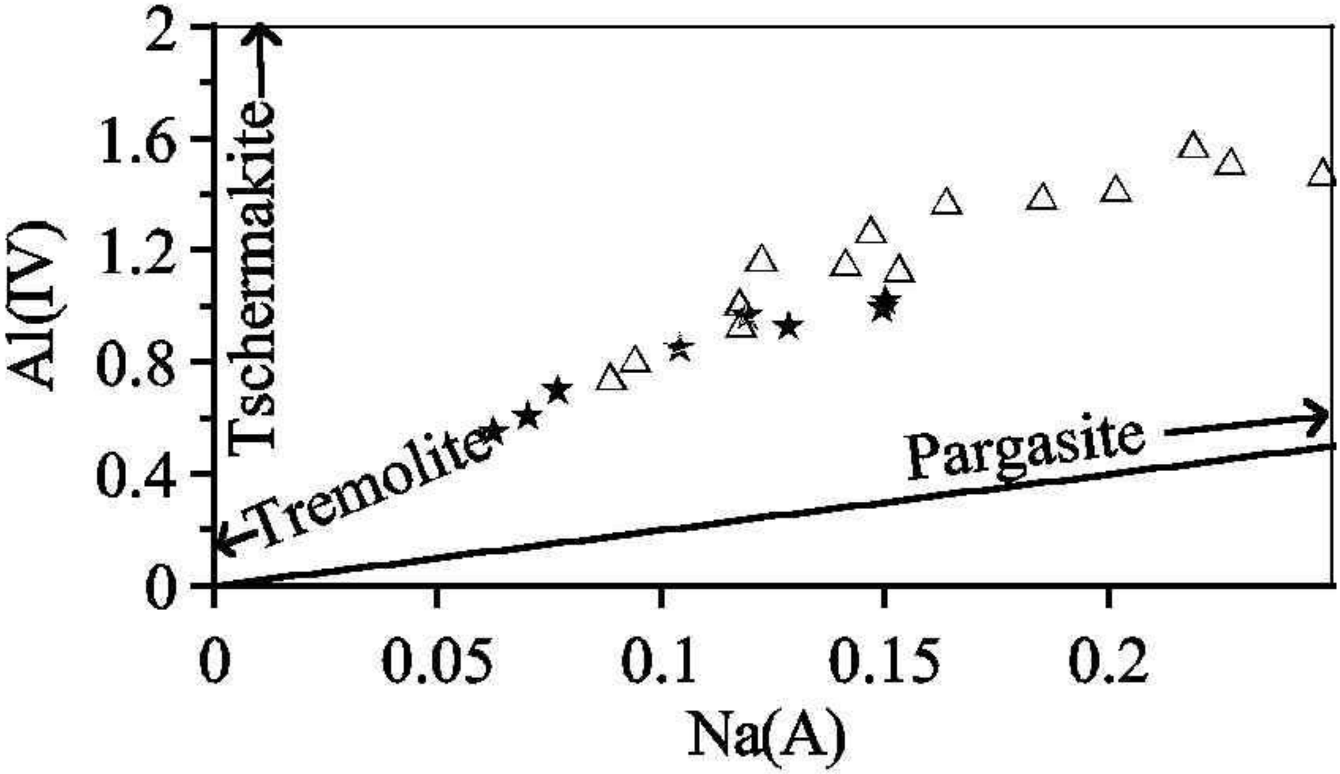
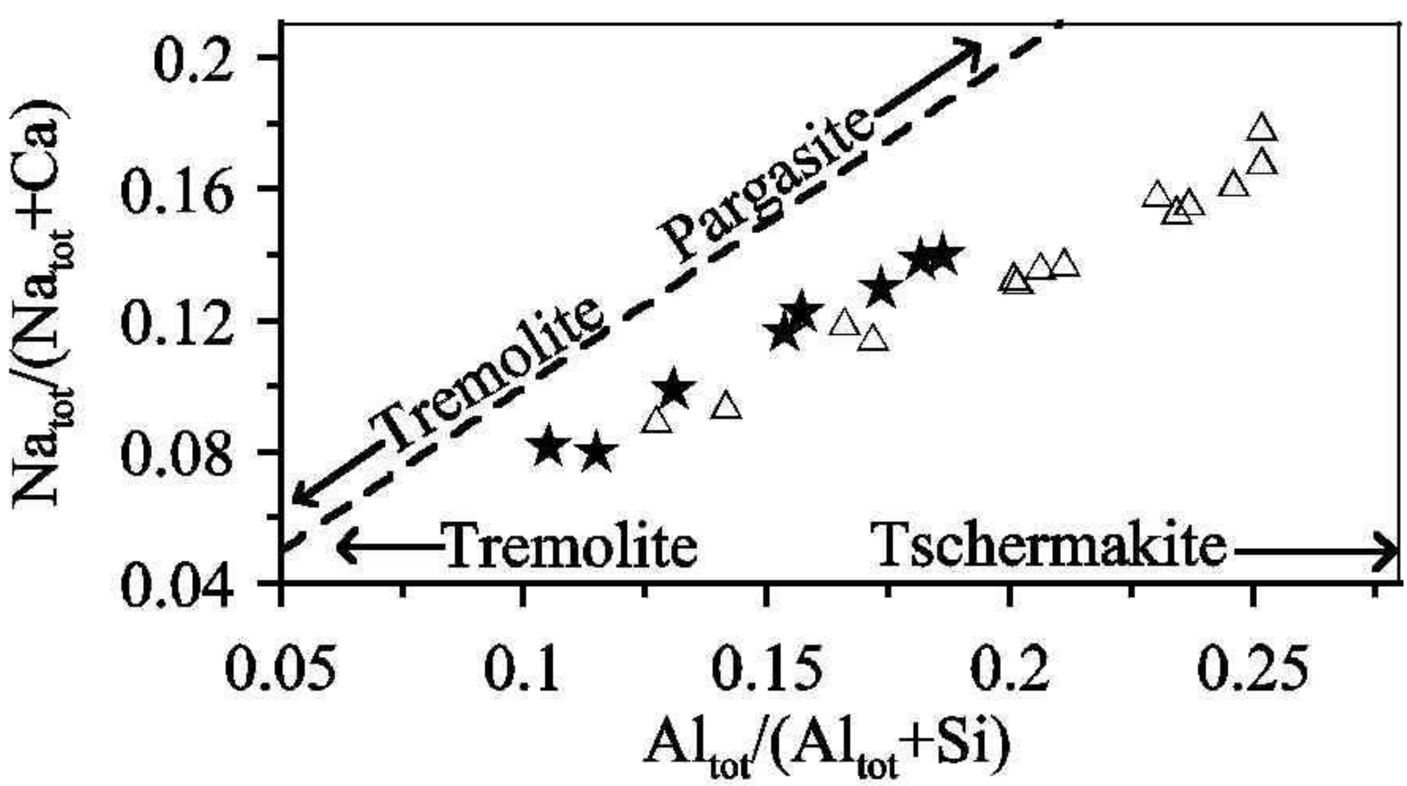


Figure 7. Compositional zoning of selected garnet crystals are presented on rim-core-rim sections. Garnet 262b and 244 pertain to the semi-aluminous unit, and garnet 251 to the aluminous unit. Alm = 100*Fe/(Fe^{2+} + Mg + Ca + Mn), Prp = 100*Mg/(Fe^{2+} + Mg + Ca + Mn), Grs = 100*Ca/(Fe^{2+} + Mg + Ca + Mn), Sps = 100*Mn/(Fe^{2+} + Mg + Ca + Mn) (abbreviations are from Kretz, 1983).

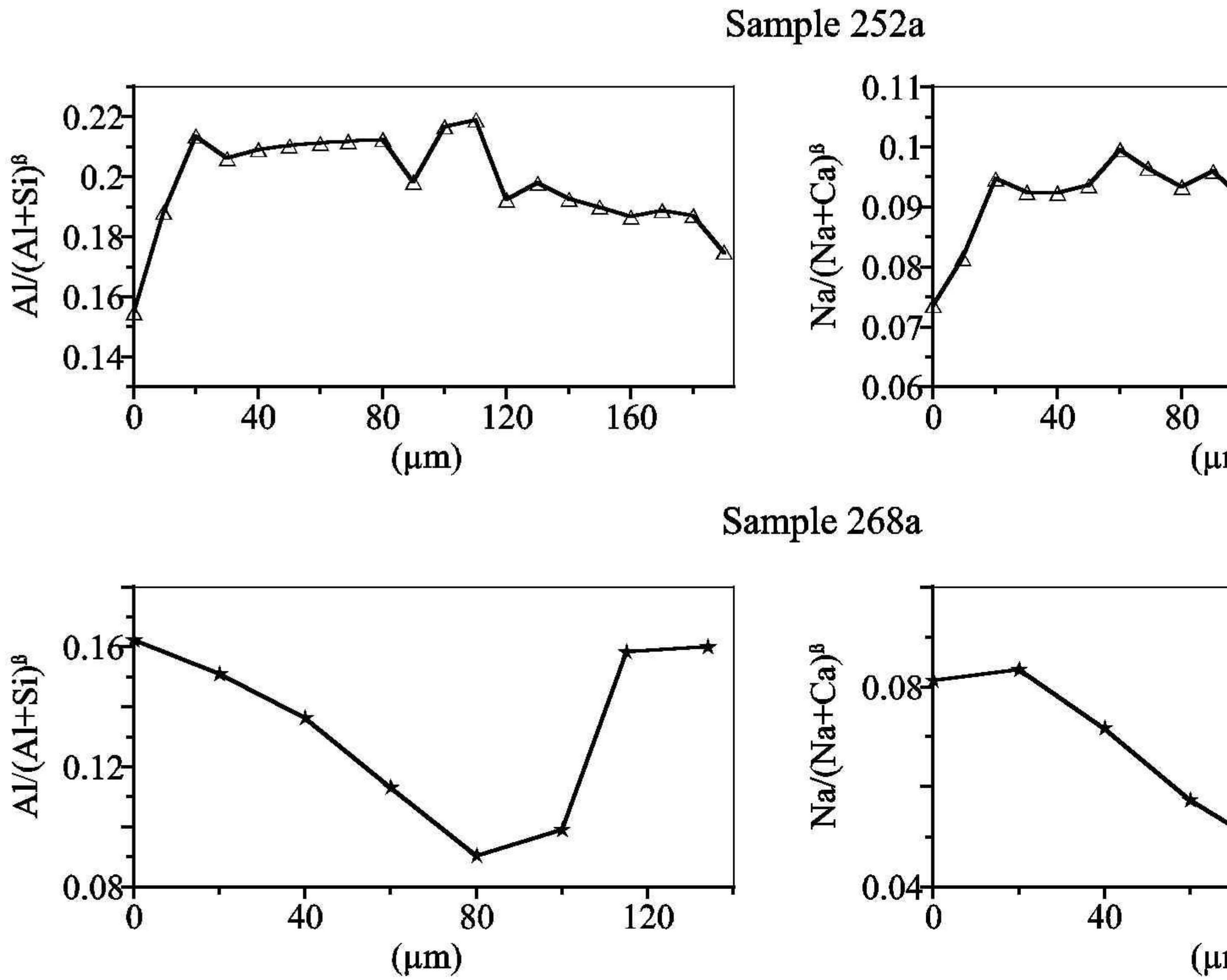


Tschermakite
Tremolite
Pargasite
Al(IV)
Na(A)
0
0.4
0.8
1.2
1.6
2
0
0.05
0.1
0.15
0.2



Pargasite
Tremolite
Tremolite
Tschermakite
$Na_{tot}/(Na_{tot}+Ca)$
$Al_{tot}/(Al_{tot}+Si)$
0.04
0.08
0.12
0.16
0.2
0.05
0.1
0.15
0.2
0.25

Figure 8. Photomicrograph showing amphibole crystals in samples 252a (left) and 268a (right). Black lines represent the compositional profiles reported in Fig. 9.



ß: atomic ratio

Figure 9. Compositional profiles of representative amphibole grains in sample 268a (stars) and sample 252a (triangles).

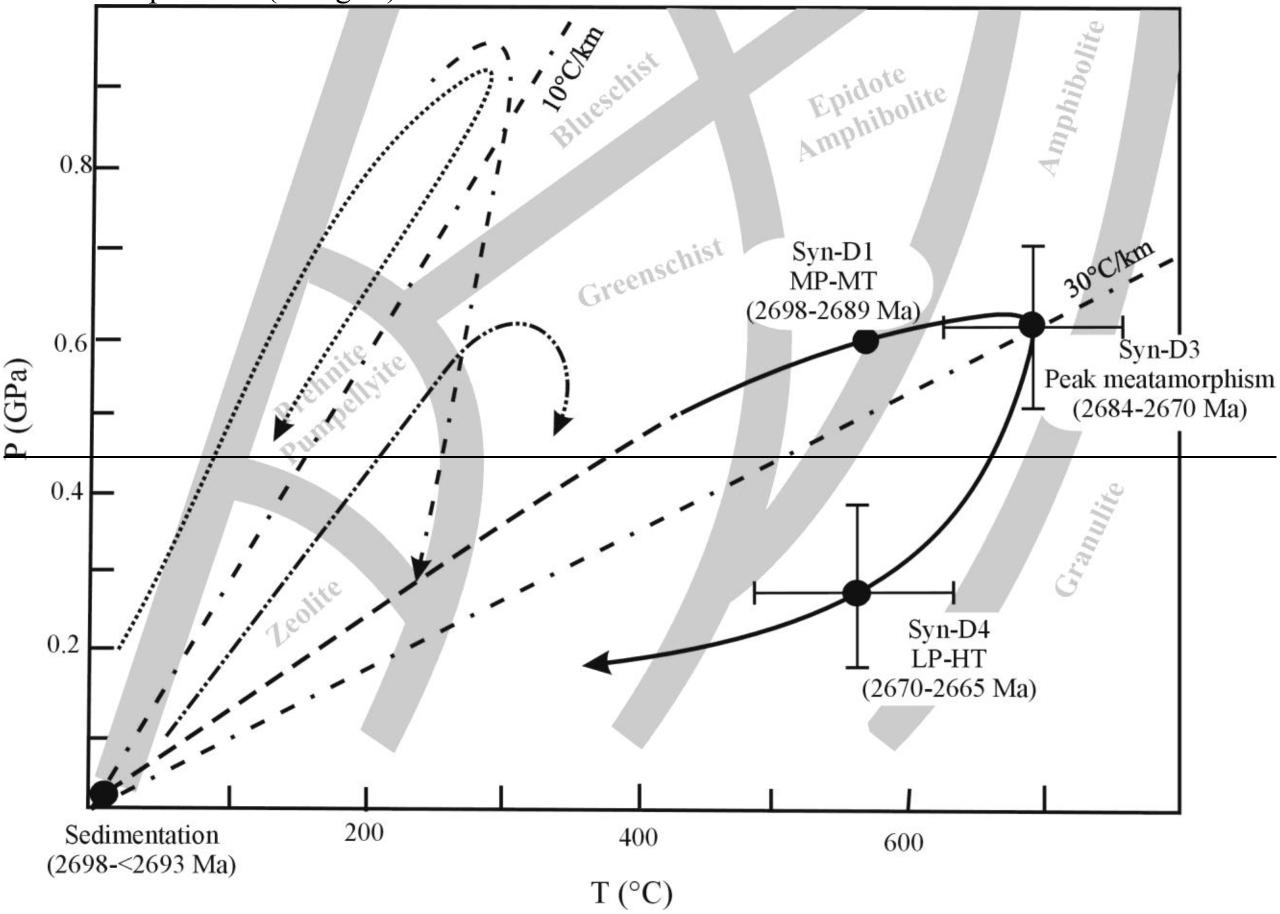


Figure 10. Compositional zoning of amphibole grains in sample 268a (stars) and sample 252a (triangle) from the amphibole-rich unit. Each profile represents an individual grain from rim to rim through the centre of the grain. The grain was selected from four representative grains used for the compositional analysis in each sample. The ratios are atomic.

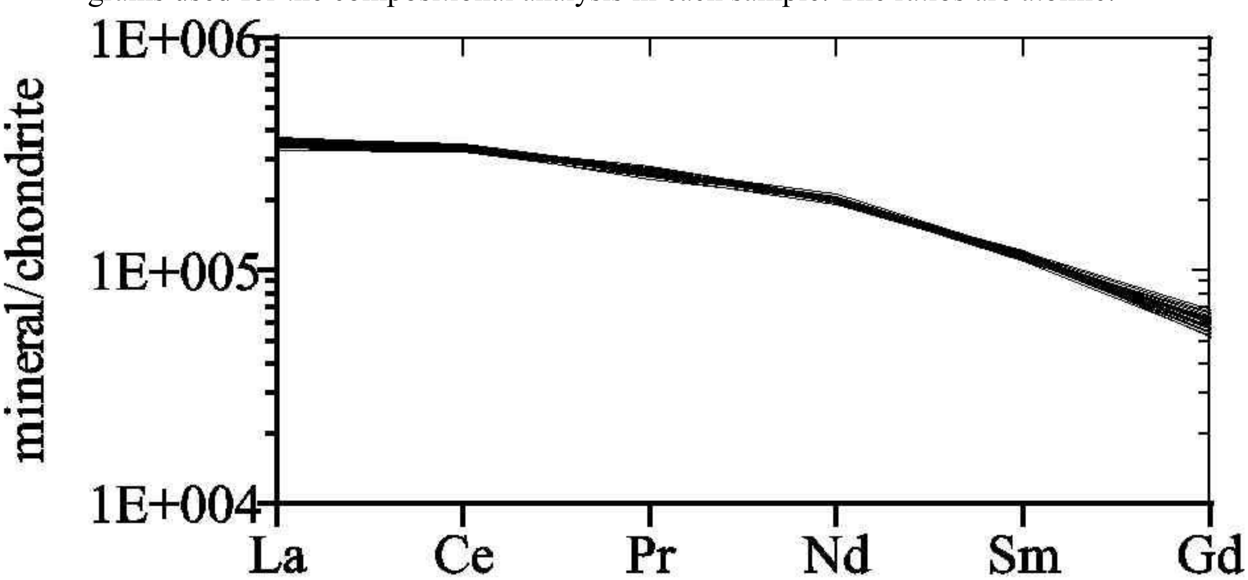


Figure 11. Simplified P-T grid for pelites in the KFMASH system (modified from Spear and Cheney, 1989). "As" refers to Aluminosillicate, other abbreviations of minerals are from Kretz (1983).

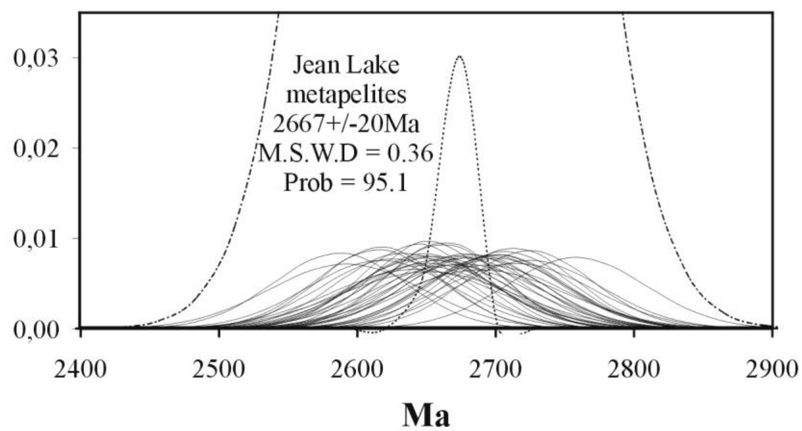


Figure 12. Estimated P-T-t path (solid curve) for the rocks in the Jean Lake area compared to the paths of modern accretionary prisms. Queyras (Schwartz et al., 2000); Sambagawa (Ernst, 1988); and Franciscan (Ernst, 1988). The metamorphic facies are from Spear (1993). Dot-double-dash lines represent geothermal gradients.