The Canadian Mineralogist
Vol. 37, pp. 359-373 (1999)

KYANITE IN THE WESTERN SUPERIOR PROVINCE OF ONTARIO: IMPLICATIONS FOR ARCHEAN ACCRETIONARY TECTONICS*

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Abstract

Thirteen occurrences of kyanite in Archean supracrustal rocks of the western Superior Province of Ontario are grouped into three distinct lithotectonic associations: I) metapelites close to subprovince and terrane boundaries, II) metapelites near faults within greenstone belts, and III) metamorphosed Al–Si-rich alteration assemblages associated with volcanogenic massive sulfide (VMS) mineralization in greenstone belts. Kyanite of groups I and II is commonly associated with staurolite and texturally predates the main assemblage of metamorphic minerals (Sil + Grt + Bt + Pl + Qtz), indicating that a medium-P, low-T Barrovian metamorphism occurred before the main, regional low-P/T metamorphism that characterizes the western Superior Province. This earlier Barrovian metamorphism (670–730 MPa, 500–560°C) was followed by significant unloading (up to 12 km at the Quetico–Wabigoon boundary) before the development of the main penetrative deformation and the regional low-P/T metamorphism. The results of geothermobarometry and the restricted locations of group-I and group-II kyanite are interpreted to reflect crustal thickening as part of accretionary tectonic processes for the collage of individual greenstone belts and subprovinces for the formation of the western Superior Province. In particular, the three occurrences of kyanite along the Quetico–Wabigoon boundary support the origin of the Quetico Subprovince as an accretionary wedge during northward subduction. Group-III kyanite, on the other hand, reflects unusual whole-rock compositions and hydrothermal fluids, and may be a potentially useful exploration tool for VMS deposits.

Keywords: kyanite, occurrences, Barrovian metamorphism, Archean, accretionary tectonics, western Superior Province, Ontario.

Sommaire

Nous nous proposons de regrouper treize indices de kyanite dans les roches archéennes d'origine supracrustale du secteur ouest de la Province du Supérieur en Ontario en trois associations lithotectoniques distinctes: I) métapélites proches de la bordure d'une sous-subprovince ou d'un socle, II) métapélites situées près de failles dans des ceintures de roches vertes, et III) roches métamorphiques enrichies en Al–Si par altération hydrothermale près des gisements de sulfures massifs volcanogéniques dans des ceintures de roches vertes. La kyanite des groupes I et II, généralement associée à la staurolite, est antérieure selon des critères texturaux à l'assemblage principal de minéraux métamorphiques (Sil + Grt + Bt + Pl + Qtz). Ce fait montre que l'épisode de métamorphisme barrovien de pression moyenne et de faible température a précédé l'épisode principal de métamorphisme régional de faible pression et de faible température qui caractérise le secteur ouest de la Province du Supérieur. Cet épisode barrovien (670–730 MPa, 500–560°C) fut suivi par une érosion importante (jusqu'à 12 km de soulèvement à l'interface entre les socles de Quetico et Wabigoon) avant le développement de l'épisode important de déformation régionale et de métamorphisme de faible température et de faible pression. Les résultats d'une analyse géothermobarométrique et la répartition des indices de kyanite des groupes I et II assez restreint refléteraient un épaississement de la croûte suite aux processus tectoniques accompagnant l'accrétion d'un collage de ceintures individuelles de roches vertes et de sous-provinces pour former le secteur ouest de la Province du Supérieur. En particulier, trois indices de kyanite provenant de l'interface entre les socles de Quetico et de Wabigoon étayent l'hypothèse d'une origine de la Sous-province de Quetico comme prisme d'accrétion lors de la subduction à polarité vers le nord. En revanche, les indices de kyanite du groupe III signaleraient la présence de roches de composition particulière due à l'altération hydrothermale, et serviraient donc de guides utiles dans les programmes d'exploration pour de gisements de sulfures d'origine volcanogénique.

(Traduit par la Rédaction)

Mots-clés: kyanite, indices, métamorphisme barrovien, archéen, tectonique d'accrétion, Province du Supérieur (secteur ouest), Ontario.

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Introduction

There is a growing consensus among investigators (Card 1990, Thurston & Chivers 1990, Williams 1990, Williams *et al.* 1991, Percival *et al.* 1994) that the Archean Superior Province of North America was assembled by accretionary plate-tectonic processes, analogous to those of the modern convergent-plate boundaries of the western Pacific (Hamilton 1988, and references therein). Plate-tectonic activity in the Archean is supported by geochronological, structural, and geochemical evidence, and broad-scale metamorphic patterns of the Uchi, English River, Wabigoon, Quetico and Wawa subprovinces of the western Superior Province (Thurston & Breaks 1978) and the Abitibi subprovince (Jolly 1978). Calvert *et al.* (1995) provided compelling evidence for subduction based on seismic reflection profiles across the Opatica–Abitibi boundary in Quebec. Hamilton (1998), on the other hand, maintained that plate-tectonic processes did not operate in Archean time.

The western Superior Province, which is characterized by a well-defined distribution of alternating, east–west-trending granite–greenstone and metasedimentary belts (Fig. 1), is a classic area where models of plate tectonics for the formation of Archean crust were first introduced (Krogh & Davis 1971, Langford & Morin 1976, Blackburn 1980). Therefore, knowledge of the distribution of metamorphic grade, conditions of peak metamorphism, and metamorphic pressure – temperature – timing – deformation history in the Western Superior Province is critical to our understanding of the tectonic evolution of the Archean Superior Province. In this contribution, we examine the reported occurrences of kyanite in the Western Superior Province (Table 1, Fig. 1) and attempt to provide metamorphic evidence for and P–T constraints on Archean accretionary tectonics responsible for the collage of individual greenstone belts and subprovinces in the Western Superior Province (Percival & Williams 1989, Williams 1990).

Description of Kyanite Occurrences

Thirteen occurrences of kyanite have been reported in the Archean supracrustal rocks of the Western Supe-

TABLE 1. SUMMARY OF KYANITE OCCURRENCES IN THE WESTERN SUPERIOR PROVINCE

No.	Location	Lithotectonic Association	Mineral Assemblage	References
		Group I: Metapelites near subprovince boundaries		
1	Rainy Lake, Minnesota	Metapelites of the Quetico subprovince near the Quetico-Wabigoon boundary	Ky, St, Sil, Grt, Ms, Bt, Pl, Qtz, Ilm	Tabor (1988)
2	Abbess Lake, Atikokan	Metapelites of the Quetico subprovince near the Quetico-Wabigoon boundary	?	Moore (1940)
3	Raith	Metapelites of the Quetico subprovince near the Wawa-Quetico boundary	Ky, St, Sil, Grt, Ms, Bt, Pl, Qtz, Ilm	Percival et al. (1985) This study
4	North Caribou greenstone belt	metapelites near the tectonic boundary of the North Caribou terrane	Ky, And, Crd, St, Grt, Qtz, Pl, Bt	Breaks et al. (1984) Thurston et al. (1991)
5?	Favourable Lake	near the Bear Head Fault	?	Ayres (1978)
		Group II: Metapelites associated with faults within greenstone belts		
6	White River-Hemlo-Black River	metapelites of the Hemlo-Heron Bay greenstone belt near the Hemlo Fault Zone	Ky, St, Sil, Grt, Qtz, Pl, Bt, Ilm	Patterson et al. (1984), Burk et al. (1986), Pan & Fleet (1993; 1995)
		Group III: Al-Si-rich alteration assemblages and veins associated with VMS and Au deposits in greenstone belts		
7	Sturgeon Lake	quartz veins associated with VMS deposits	Ky, Qtz, Prl, Ms, And	Franklin et al. (1975)
8	Savant Lake	Al-Si-rich alteration associated with VMS showings	Ky, Sil, And, St, Ms	Lefebvre (1982)
9	Marshall Lake	Al-Si-rich alteration associated with VMS showings	Ky, Qtz, Sil, Oam, Crd	Ayres (1978), Amukun (1989)
10	Onaman	Headway-Coulee massive sulfide occurrence	Ky, Qtz, And, Ser	Osterberg et al. (1987)
11	Melchett	quartz veins associated with VMS showings	Ky, Qtz	Breaks (1991)
12	Manitouwadge	Al-Si-rich alteration associated with VMS deposit	Ky, Sil, Ms, Bt, Pl, Qtz	Schandl et al. (1995)
13	Hemlo	quartz veins at the Hemlo gold deposit	Ky, Qtz, Ms, Tur, Py	Burk et al. (1986), Kuhns et al. (1994)

See text for discussion on the Favourable Lake occurrence. Mineral symbols after Kretz (1983). VMS, volcanogenic massive sulfide deposits.

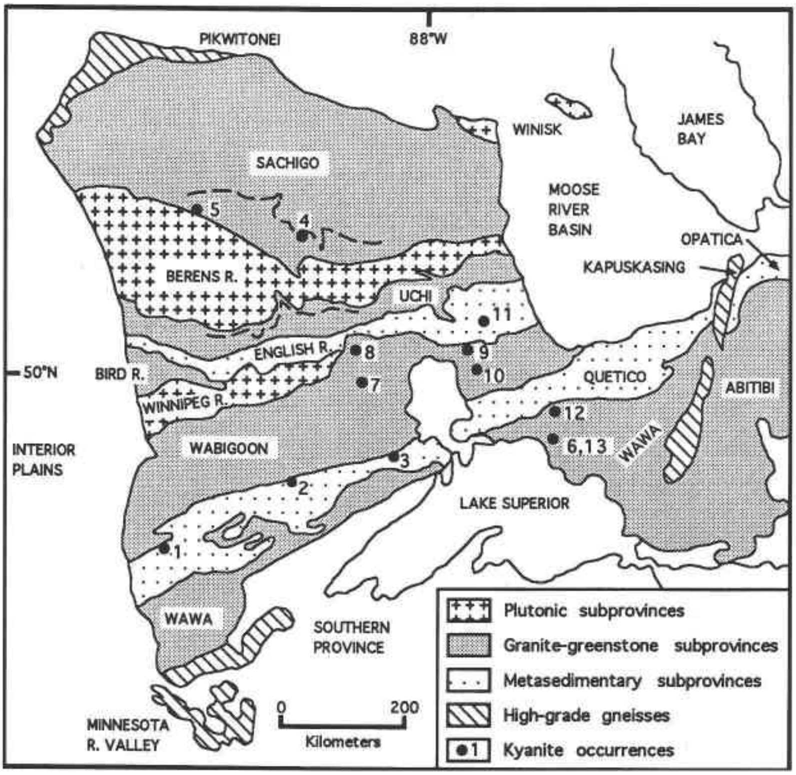

FIG. 1. Occurrences of kyanite in the Western Superior Province [classification of subprovinces after Card & Ciesielski (1986); except for the 2.9–3.0 Ga North Caribou terrane, after Thurston *et al.* (1991), dashed lines]. Numbers correspond to Table 1. Group I: 1–3) Rainy Lake, Abbess Lake (Atikokan) and Raith areas, respectively, of the Quetico Subprovince, 4) North Caribou greenstone belt near the northern tectonic boundary of the North Caribou terrane, and 5) Favourable Lake greenstone belt (see text for discussion). Group II: 6) the Hemlo – Heron Bay greenstone belt of the Wawa subprovince. Group III: 7–10) Sturgeon Lake, Savant Lake, Marshall Lake and Onaman areas, respectively, of the Wabigoon Subprovince, 11) Melchett greenstone belt of the English River subprovince, and 12–13) Manitouwadge greenstone belt and Hemlo gold deposit, respectively, of the Wawa Subprovince.

rior Province (Fig. 1, Table 1). Ayres (1978) listed four of these; three are located in amphibolite-facies terranes near subprovince boundaries, and the fourth one is found in quartz veins associated with metamorphosed volcanogenic massive sulfide (VMS) deposits. Table 1 shows that eight of the nine additional occurrences of kyanite belong to these two groups, whereas the remaining one constitutes a new group in which kyanite occurs in metapelites in close proximity to a major fault in greenstone belt (Table 1, and see below). Also, new data from Amukun (1989) and Thurston *et al.* (1991) warrant a re-appraisal of two of Ayres's (1978) original occurrences (*i.e.*, Favourable Lake, 5 in Fig. 1; Marshall Lake, 9 in Fig. 1).

Group I: kyanite in metapelites near subprovince and terrane boundaries

This group includes three occurrences [Rainy Lake, Abbess Lake (Atikokan), and Raith] in the Quetico Subprovince near the Quetico–Wabigoon boundary (Moore 1940, Percival *et al.* 1985, Tabor 1988; 1–3 in Fig. 1), and another one in the North Caribou greenstone belt close to the tectonic boundary of the North Caribou terrane (4 in Fig. 1; Thurston *et al.* 1979, 1991, Breaks *et al.* 1984).

The boundary between the metasedimentary Quetico Subprovince and the granite–greenstone Wabigoon Subprovince in the Atikokan area (2 in Fig. 1) coincides

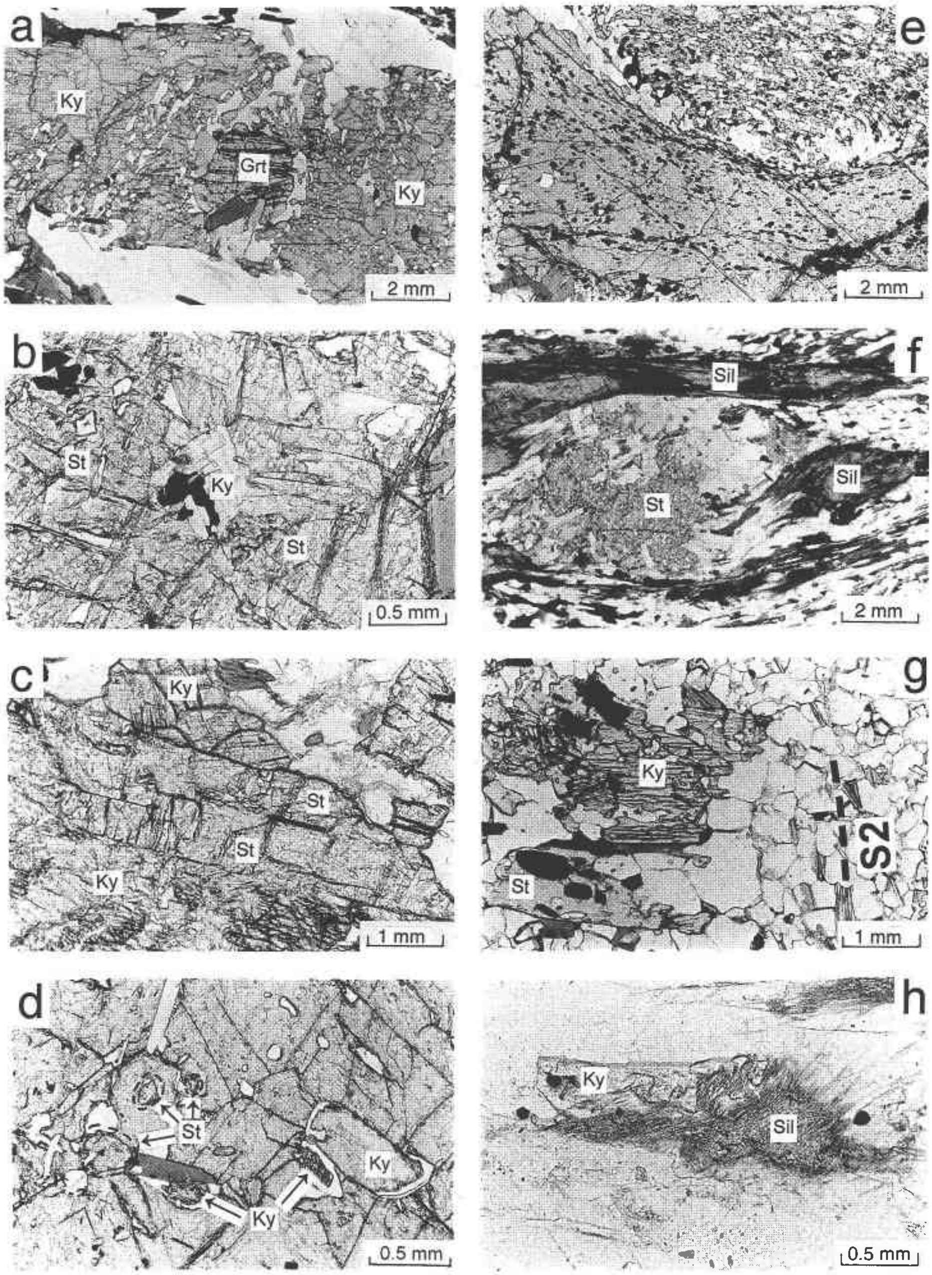

FIG. 2. Photomicrographs illustrating textural relationships and associated minerals in kyanite-bearing metapelites from the Raith (a–e) and Hemlo (f–g) areas of the Western Superior Province. a) Kyanite poikiloblast (Ky); note that the included garnet (Grt), albeit partially surrounded by quartz and plagioclase, is locally in direct contact with kyanite. b) Kyanite inclusion associated with ilmenite in staurolite porphyroblast (St). c) Kyanite intergrown with staurolite. d) Inclusions of kyanite, staurolite (outlined) and biotite in garnet porphyroblast. e) Part of a large garnet porphyroblast (1.2 cm in diameter) illustrating a marked discontinuity between an inclusion-rich core (mainly quartz and plagioclase) and an inclusion-bearing rim (mainly magnetite and ilmenite). f) Staurolite poikiloblast replaced by biotite + sillimanite assemblage in the hanging-wall metapelites. g) Kyanite porphyroblast and associated staurolite, discordant with the main foliation (*S*2; outlined) in the hanging-wall metapelites, h) Fibrous sillimanite after kyanite in the hanging-wall metapelites.

with the Quetico Fault (a regional-scale dextral shear-zone; Williams 1991) that swings into the Quetico Subprovince just west of Raith (3 in Fig. 1). Moore (1940) reported kyanite in metasedimentary rocks northwest of the Abbess Lake in the Atikokan area (2 in Fig. 1), but did not provide any petrographic description or information on the mineral assemblage. Percival *et al.* (1985) reported relict kyanite in plagioclase from a garnet – sillimanite – biotite – plagioclase – quartz schist at Raith. Two of eight metapelitic samples from the Raith area collected by the first author contain kyanite and have a similar assemblage of minerals. Kyanite in these two samples occurs not only as fragments in plagioclase, but also as porphyroblasts or poikiloblasts. The kyanite poikiloblasts are discordant with respect to the main penetrative foliation and contain inclusions of garnet (Fig. 2a), biotite, plagioclase, quartz, muscovite and ilmenite. Kyanite also has been found as inclusions in or intergrown with staurolite porphyroblasts (Figs. 2b, c), which have an assemblage of mineral inclusions similar to the kyanite poikiloblasts. In addition, kyanite and staurolite have been found as inclusions in garnet porphyroblasts (Fig. 2d). Sillimanite, not in textural equilibrium with kyanite (Percival *et al.* 1985), is invariably fibrolitic and is present mainly in knots aligned parallel or subparallel to the main penetrative foliation. Other minerals in apparent textural equilibrium with sillimanite include garnet porphyroblasts and biotite, plagioclase and quartz in the matrix. Although a few of the largest porphyroblasts of garnet (up to 1.5 cm in diameter) show a textural zonation with a marked discontinuity in the internal trails of inclusions (Fig. 2e; indicative of two episodes of garnet growth), most garnet porphyroblasts have internal trails of inclusions consistent with growth during the development of the penetrative foliation and, therefore, are part of the main metamorphic (sillimanite-stable) assemblage.

In the Rainy Lake area, northern Minnesota (1 in Fig. 1), the Rainy Lake – Seine Lake Fault marks the boundary between the Quetico Subprovince to the south and the Wabigoon Subprovince (including the Rainy Lake Wrench Zone, Poulsen 1986) to the north. Tabor (1988) reported that kyanite occurs in metapelites close to the Rainy Lake – Seine Lake Fault at the northeastern corner of Kabetogama Peninsula and increases in abundance from north to south away from the Rainy Lake – Seine Lake Fault to a maximum at the first appearance of sillimanite. Kyanite occurs as porphyroblasts or poikiloblasts showing preferred orientation parallel to $S1$, as are internal trails of inclusions (Tabor 1988). Mineral inclusions in kyanite include muscovite, staurolite, biotite and garnet. Tabor (1988) also noted that some porphyroblasts of kyanite at Rainy Lake are rotated by $S2$ crenulations and that, where both are present, kyanite and sillimanite are not in contact.

The North Caribou greenstone belt is situated close to the northern tectonic boundary of the 2.9–3.0 Ga North Caribou terrane (4 in Fig. 1), and consists of four supracrustal assemblages: the 2980 Ma Aguta Arm assemblage, the Keeyask assemblage, the McGruer assemblage, and the Eyapamikama assemblage (Thurston *et al.* 1991). Thurston *et al.* (1979) reported kyanite in metasedimentary rocks from the southern part of the North Caribou greenstone belt at the Forester Lake area. Breaks *et al.* (1984) reported kyanite in metapelites of the Eyapamikama assemblage at the Miskeesik Lake area (Table 1). Breaks & Bartlett (1991) observed two generations of kyanite at Miskeesik Lake: kyanite-1 as ragged poikiloblasts intergrown with staurolite in aggregates that deflect the enclosing phyllosilicate-defined foliation (*cf.* Figs. 2f, g below), and kyanite-2 truncating the regional foliation. Breaks & Bartlett (1991) also noted the presence of kyanite as an epitactic replacement after andalusite at the Miskeesik Lake area. It is noteworthy that the Miskeesik Lake occurrence of kyanite is also within 0.5 km of a fault boundary between the Eyapamikama and McGruer assemblages.

Ayres (1978) classified an occurrence of kyanite at the Favourable Lake greenstone belt (5 in Fig. 1) as a member of Group I, because of its location near the Bear Head fault (*i.e.,* the Berens River – Sachigo Subprovince boundary in Card & Ciesielski 1986; Fig. 1). Thurston *et al.* (1991) re-interpreted the Berens River Subprovince to represent a 2720 Ma magmatic welt during northward subduction at the Uchi – English River Subprovince boundary. The Bear Head fault is then no longer a subprovince boundary, but is a likely ensialic structure that was active at about 2.7 Ga within the 2.9–3.0 North Caribou terrane (Thurston *et al.* 1991). Unfortunately, classification of this Favourable Lake occurrence of kyanite into Group II or III is not possible owing to the lack of petrological data.

Group II: kyanite in metapelites associated with faults within greenstone belts

There is one example of this group: the Hemlo – Heron Bay greenstone belt of the Wawa Subprovince (6 in Fig. 1; Patterson *et al.* 1984, Burk *et al.* 1986, Pan & Fleet 1993). The Hemlo – Heron Bay greenstone belt consists of two supracrustal assemblages (*i.e.,* the Hemlo – Black River assemblage to the north and the Heron Bay assemblage to the south) separated by the Hemlo Fault Zone, which is part of the regional Lake Superior Fault Zone (Williams *et al.* 1991). Figure 3 illustrates the close spatial association of kyanite occurrences with the Hemlo Fault Zone in the Hemlo – Heron Bay greenstone belt. The kyanite-bearing metapelites at the White River property (6–1 in Fig. 3) are found within a turbiditic metasedimentary sequence (Pan *et al.* 1991), as are the kyanite-bearing rocks at the Padre Resources property (6–3 in Fig. 3; Patterson *et al.* 1984). There are two distinct types of kyanite occurrences at the Hemlo gold deposit (6–2 in Fig. 3): one in hanging-wall and footwall aluminous rocks, and the other in quartz veins within the orebodies (Burk *et al.* 1986, Kuhns *et al.*

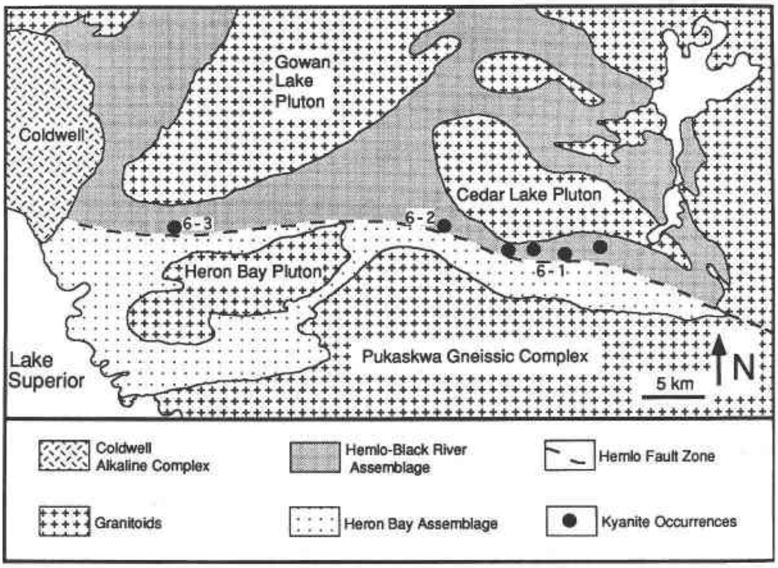

FIG. 3. Details of kyanite occurrence #6 of Figure 1. Kyanite in metapelites of the Hemlo – Black River assemblage in the Hemlo – Heron Bay greenstone belt (Group II): 6–1) White River property, 6–2) Hemlo deposit, and 6–3) Padre Resources property near Black River. Note the close association with the Hemlo Fault Zone.

1994, Pan & Fleet 1995). We consider these hanging-wall and footwall aluminous rocks at the Hemlo gold deposit to be metapelites because of their association with other metasedimentary rocks, similarity in stratigraphy to metapelites along strike at the White River property and the Padre Resources property (Pan & Fleet 1995), and distinctive geochemical characteristics (Fleet *et al.* 1997), although Kuhns *et al.* (1994) interpreted them to represent metamorphosed rocks that had undergone porphyry-style argillic alteration.

Kyanite-bearing metapelites at the White River property and Hemlo gold deposit typically contain kyanite, sillimanite, garnet, staurolite, biotite, muscovite, plagioclase, and quartz (Burk *et al.* 1986, Kuhns *et al.* 1994, Pan & Fleet 1993, 1995). Sillimanite, mainly "fibrolite", usually occurs in knots oriented parallel or subparallel to the main penetrative foliation. Kyanite, on the other hand, typically occurs as prismatic porphyroblasts and poikiloblasts discordant with respect to the main penetrative foliation and is commonly associated with staurolite poikiloblasts (Figs. 2f, g). Staurolite poikiloblasts in augen are commonly replaced by a sillimanite + biotite + muscovite + plagioclase + quartz assemblage (Fig. 2f). The mineral inclusions in kyanite and staurolite poikiloblasts are similar and include garnet, plagioclase, quartz, biotite, ilmenite, zircon, apatite and pyrite. Authors of previous studies have emphasized that kyanite and sillimanite at Hemlo and the White River property, where they commonly occur together, generally do not show any replacement textures (Burk *et al.* 1986, Pan & Fleet 1993, Kuhns *et al.* 1994). In this study, irregular grain boundaries have been observed on kyanite porphyroblasts in direct contact with "fibrolite" knots (Fig. 2h), and may be related to resorption of the former. Kyanite and staurolite from the Hemlo gold deposit commonly exhibit extensive alteration to muscovite, chlorite and epidote along grain fractures and boundaries, but are less affected by such alteration at the White River property. It is noteworthy that petrographic descriptions of kyanite and associated minerals in aluminous rocks (our metapelites) of the Hemlo gold deposit by Burk *et al.* (1986) and Kuhns *et al.* (1994) are similar to those above, although their interpretations differ significantly from ours (see below).

Group III: kyanite in Al–Si-rich alteration assemblages associated with mineralization

This group includes seven occurrences: the Sturgeon Lake (7 in Fig.1; Franklin *et al.* 1975), the Savant Lake (8 in Fig. 1; Lefebvre 1982), the Marshall Lake (9 in Fig. 1; Ayres 1978; Amukun 1989), and the Onaman area (10 in Fig. 1; Osterberg *et al.* 1987) of the Wabigoon Subprovince, the Melchett greenstone belt of the English River Subprovince (11 in Fig.1; Breaks 1991), the Willecho deposit in the Manitouwadge greenstone belt of the Wawa Subprovince (12 in Fig. 1; Schandl *et al.* 1995), and the Hemlo gold deposit in the

Hemlo – Heron Bay greenstone belt of the Wawa Subprovince (13 in Fig. 1; Burk *et al.* 1986, Kuhns *et al.* 1994, Pan & Fleet 1995). The first six occurrences are all associated with base-metal volcanogenic massive sulfide (VMS) deposits or showings. For example, Franklin *et al.* (1975) noted that kyanite at the Mattabi Cu–Zn deposit of the Sturgeon Lake area is restricted to the massive ores or veins in the immediate footwall, whereas andalusite occurs as porphyroblasts in all rock types and in veins. Lefebvre (1982) reported the presence of all three polymorphs of Al_2SiO_5 in Al–Si-rich alteration zones in the Handy Lake metavolcanic rocks at the Savant Lake area. Amukun (1989) also documented all three Al_2SiO_5 polymorphs, staurolite and muscovite in alteration assemblages in close proximity to base-metal sulfide mineralization at the Marshall Lake area. At the Manitouwadge greenstone belt, Schandl *et al.* (1995) reported the presence of relict kyanite in sillimanite knots in altered felsic volcanic rocks from the footwall of the Willecho 3 orebody. The occurrence of kyanite in quartz veins and its association with gold mineralization at the Hemlo gold deposit have been described by a number of authors (Burk *et al.* 1986, Kuhns *et al.* 1994, Pan & Fleet 1995).

Mineral Chemistry and Geothermobarometry

Textural evidence from Group-I and -II occurrences of kyanite at Raith and Hemlo clearly shows two distinct assemblages indicative of two episodes of metamorphism (*M*1 and *M*2): an earlier one consisting of kyanite + staurolite + garnet (inclusions in kyanite and staurolite, Fig. 2a; core of texturally zoned porphyroblasts, Fig. 2e) + inclusions of biotite, plagioclase, quartz, and ilmenite, and the main one in the matrix including sillimanite + garnet + biotite + plagioclase + quartz. In this study, four samples of low-variance, kyanite-bearing assemblages (two from Raith and two from the Hemlo gold deposit) were selected for compositional analysis of minerals (see Pan *et al.* 1994 for analytical details; Table 2) and geothermobarometry (Table 3). Also, geothermobarometric results from kyanite-bearing samples of the Rainy Lake area (Tabor 1988) and White River property (Pan & Fleet 1993) are included for comparison.

The mineral inclusions (*i.e.*, biotite, plagioclase and garnet) in kyanite and staurolite poikiloblasts from both the Raith area and the Hemlo gold deposit are compositionally distinct from their counterparts in the matrix (Table 2). For example, biotite in kyanite poikiloblasts is higher in Mg/(Mg + Fe) values than its isolated counterpart in the matrix, whereas grains of biotite in direct contact with garnet porphyroblasts are intermediate in Mg/(Mg + Fe) and apparently have been affected by re-equilibration during retrogression. Similarly, plagioclase in kyanite and staurolite poikiloblasts is more sodic than its counterpart in the matrix. Chemical zonation has not been detected in the matrix plagioclase of the Raith samples. However, some isolated grains of plagioclase from Hemlo show an outward increase in the anorthite component (up to 5 mol% An). Also, plagioclase inclusions in the margin of zoned porphyroblasts of garnet (Fig. 2e) are slightly higher in An than their counterparts in the core. Garnet inclusions in kyanite and staurolite poikiloblasts from both Raith and Hemlo are enriched in Ca relative to the *M*2 garnet porphyroblasts, whereas the inclusion-rich core of zoned porphyroblasts of garnet (Fig. 2e) has a Ca content similar to that of the

TABLE 2A. COMPOSITIONS OF MINERALS IN KYANITE-BEARING METAPELITE FROM RAITH (SAMPLE RAITH-1)

	Inclusions in Kyanite				Minerals in Matrix						
Minerals	Grt	Pl	Bt	Ilm	Grt^a	Grt^b	St	Pl	Bt^c	Bt^d	Ms
SiO_2 (wt.%)	37.5	63.5	36.1	0	38.1	37.8	27.9	60.2	35.5	35.8	45.5
TiO_2	0.01	0	1.98	52.5	0.02	0.01	0.50	0	2.33	2.21	0.05
Al_2O_3	21.2	22.9	18.6	0	21.9	21.5	53.3	25.6	18.9	19.1	36.8
FeO	33.5	0	17.8	46.6	32.9	34.5	12.1	0	19.1	18.6	0.84
MgO	3.27	0	11.7	0.16	4.02	2.45	1.27	0	10.7	11.3	0.51
MnO	2.12	0	0.01	0.90	1.86	2.57	0.28	0	0.02	0.02	0.05
ZnO	nd	nd	nd	0.03	nd	nd	2.41	nd	nd	nd	nd
CaO	2.17	3.90	0	0	1.21	1.17	0.01	7.12	0	0	0.01
Na_2O	nd	9.23	0.22	nd	nd	nd	0	7.10	0.14	0.18	0.21
K_2O	nd	0.41	9.36	nd	nd	nd	0	0.30	9.18	9.21	10.5
F	nd	nd	0	nd	nd	nd	0	nd	0	0	0
O≡F			0				0		0	0	0
Total	99.8	99.9	95.8	100.2	100.0	100.0	97.6	100.3	95.9	96.4	94.5
Si	3.011	2.808	5.419	0.000	3.022	3.035	8.126	2.670	5.355	5.352	6.083
Ti	0	0	0.224	0.996	0.001	0.001	0.110	0	0.264	0.248	0.005
Al	2.006	1.193	3.291	0.000	2.047	2.033	18.294	1.338	3.360	3.366	5.798
Fe	2.245	0	2.230	0.982	2.178	2.311	2.943	0	2.405	2.321	0.094
Mg	0.391	0	2.619	0.006	0.476	0.293	0.551	0	2.407	2.520	0.102
Mn	0.144	0	0.001	0.019	0.125	0.175	0.068	0	0.003	0.003	0.006
Zn				0.001			0.520				
Ca	0.187	0.185	0	0	0.103	0.101	0	0.339	0	0	0.002
Na		0.792	0.063				0	0.610	0.042	0.052	0.055
K		0.023	1.797				0	0.017	1.771	1.761	1.795
F							0		0	0	0
O	12.0	8.0	22.0	3.0	12.0	12.0	48.0	8.0	22.0	22.0	22.0

TABLE 2B. COMPOSITIONS OF MINERALS IN KYANITE-BEARING METAPELITE FROM HEMLO (SAMPLE HEMLO-1)

	Inclusions in Kyanite				Minerals in Matrix						
Minerals	Grt	Pl	Bt	Ilm	Grt[a]	Grt[b]	St	Pl	Bt[c]	Bt[d]	Ms
SiO_2 (wt.%)	37.2	63.0	35.6	0	36.6	37.1	27.9	61.9	35.2	35.6	45.1
TiO_2	0.01	0	1.89	52.1	0	0.05	0.64	0	1.70	1.81	0.58
Al_2O_3	21.1	23.3	19.5	0.05	21.2	21.2	53.4	24.1	19.8	20.2	36.8
FeO	31.2	0	18.9	45.3	31.3	31.2	13.5	0	19.3	17.5	0.77
MgO	2.36	0	9.55	0.19	2.75	1.88	1.68	0	9.01	9.67	0.54
MnO	6.02	0	0.01	1.50	5.80	7.20	0.35	0	0.12	0.20	0
ZnO	nd	nd	nd	0.01	nd	nd	0.41	nd	nd	nd	nd
CaO	2.43	4.30	0	0	1.44	1.40	0	5.39	0.04	0	0.01
Na_2O	nd	9.35	0.32	nd	0.05	0	0	8.40	0.41	0.25	1.23
K_2O	nd	0.19	9.56	nd	nd	nd	0	0.03	9.36	9.62	9.76
F	nd	nd	0	nd	nd	nd	0	nd	0.04	0	0
O≡F			0				0		0.02		
Total	100.3	100.1	95.3	99.2	99.3	100.0	97.9	99.9	95.0	95.0	94.9
Si	2.997	2.785	5.403	0.000	2.980	3.004	8.091	2.746	5.377	5.393	6.013
Ti	0.000	0.000	0.215	0.997	0.000	0.003	0.140	0.000	0.196	0.206	0.058
Al	2.003	1.214	3.488	0.002	2.034	2.023	18.247	1.260	3.564	3.606	5.782
Fe	2.098	0.000	2.394	0.964	2.127	2.109	3.268	0.000	2.461	2.214	0.086
Mg	0.284	0.000	2.112	0.007	0.334	0.227	0.726	0.000	2.053	2.185	0.107
Mn	0.411	0.000	0.001	0.032	0.400	0.494	0.086	0.000	0.016	0.025	0.000
Zn				0.000			0.089				
Ca	0.210	0.204	0.000	0.000	0.126	0.122	0.000	0.257	0.006	0.000	0.002
Na		0.801	0.048		0.008	0.000	0.000	0.722	0.121	0.073	0.317
K		0.011	1.861				0.000	0.002	1.829	1.863	1.663
F			0.000				0.000		0.019	0.000	0.000
O	12.0	8.0	22.0	3.0	12.0	12.0	48.0	8.0	22.0	22.0	22.0

Mineral symbols after Kretz (1983). 'a' represents the outer portion of M2 garnet porphyroblast with maximum Me/Fe value, 'b', outermost margin of M2 garnet porphyroblast in direct contact with biotite; 'c', isolated grain of biotite; 'd' grain of biotite in direct contact with garnet porphyroblast; wt.%, weight percent.

garnet inclusions (Table 2). The *M*2 garnet porphyroblasts from both Raith and Hemlo exhibit a weak compositional zonation typical of prograde metamorphism (*i.e.*, increase in Mg and decrease in Fe and Mn) from core to rim, except that the outermost margin (<50 μm wide) in direct contact with biotite or chlorite shows reverse trends in Mg, Fe and Mn (Fig. 4), consistent with an exchange of these elements during retrogression. However, the Ca profile of these *M*2 garnet porphyroblasts does not show any apparent changes, even where they are in direct contact with plagioclase (Fig. 4). The two textural varieties of staurolite (*i.e.*, inclusion in kyanite and porphyroblasts or poikiloblasts in the matrix) from the Raith area do not show any compositional differences and are characterized by minor amounts of Zn (up to 2.4 wt.% ZnO; Table 2A). Similarly, minor amounts of Zn (0.4–2.5 wt.% ZnO) are typical of staurolite from Hemlo.

The well-calibrated garnet–biotite geothermometer and garnet – Al_2SiO_5 – quartz – plagioclase (GASP) geobarometer were selected for temperature and pressure calculations to facilitate direct comparison of the two episodes of metamorphism (Table 3). In addition to the experimental calibrations of Ferry & Spear (1978) for the garnet–biotite geothermometer and Koziol & Newton (1988) for the GASP geobarometer, we have also used the TWEEQU software package of Berman (1991), with the internally consistent thermodynamic dataset of Berman (1988) and solution models of Berman (1990) for garnet, McMullin *et al.* (1991) for

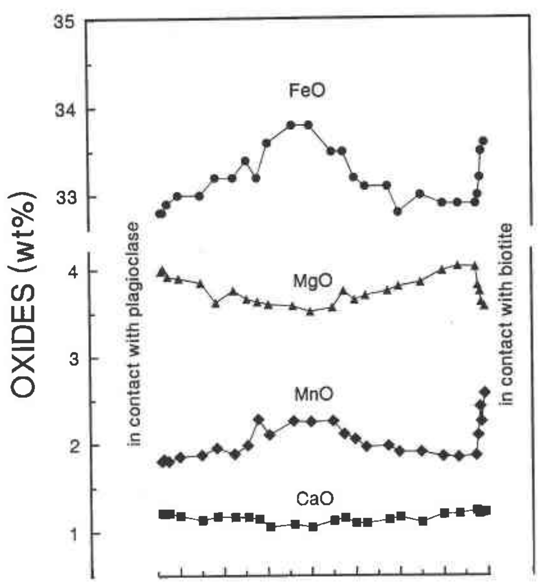

FIG. 4. Compositional profile for a garnet porphyroblast (8 mm in diameter) from kyanite-bearing metapelite of the Raith area. This garnet porphyroblast most likely grew during the *M*2 episode of metamorphism, because its S-shaped internal trail of inclusions is continuous with the main penetrative foliation.

TABLE 3. SUMMARY OF METAMORPHIC PRESSURE-TEMPERATURE RESULTS

M1 Metamorphism

Sample	Garnet				Biotite					Pl	Temperature(°C)		Pressure (MPa)	
	X(Alm)	X(Pyr)	X(Grs)	X(Sps)	X(Mg)	X(Fe)	X(Al)	X(Ti)	X(K)	An	F&S	TWQ	K&N	TWQ
Raith-1	0.757	0.132	0.063	0.049	0.453	0.386	0.123	0.039	0.966	18.5	510	560	690	670
Raith-2	0.710	0.101	0.072	0.117	0.397	0.393	0.169	0.041	0.982	18.1	495	540	730	690
Hemlo-1	0.696	0.095	0.070	0.137	0.382	0.423	0.157	0.038	0.975	20.1	515	560	690	670

M2 Metamorphism

Sample	Garnet				Biotite					Pl	Temperature(°C)		Pressure (MPa)	
	X(Alm)	X(Pyr)	X(Grs)	X(Sps)	X(Mg)	X(Fe)	X(Al)	X(Ti)	X(K)	An	F&S	TWQ	K&N	TWQ
Raith-1	0.756	0.165	0.036	0.043	0.415	0.415	0.123	0.046	0.977	35.0	640	645	320	330
Raith-2	0.712	0.125	0.060	0.103	0.354	0.449	0.157	0.040	0.961	53.0	650	670	340	450
Hemlo-1	0.712	0.112	0.042	0.134	0.363	0.435	0.167	0.035	0.938	26.2	590	600	430	450
Hemlo-2	0.641	0.167	0.058	0.134	0.477	0.353	0.138	0.033	0.958	35.0	595	620	450	520

Retrogression (M3)

Sample	Garnet				Biotite					Temperature (°C)	
	X(Alm)	X(Pyr)	X(Grs)	X(Sps)	X(Mg)	X(Fe)	X(Al)	X(Ti)	X(K)	F&S	TWQ†
Raith-1	0.802	0.102	0.035	0.061	0.434	0.399	0.124	0.043	0.971	450	460
Raith-2	0.725	0.092	0.059	0.124	0.431	0.377	0.151	0.041	0.977	435	455
Hemlo-1	0.714	0.077	0.041	0.167	0.390	0.395	0.178	0.037	0.962	430	440
Hemlo-2	0.661	0.139	0.042	0.158	0.535	0.298	0.135	0.032	0.956	450	455

F&S is the garnet-biotite geothermometer of Ferry & Spear (1978); K&N is the GASP geobarometer of Koziol & Newton (1988) using the solution models of Berman & Koziol (1991) for garnet and Fuhrman & Lindsley (1988) for plagioclase; TWQ is calculated from the TWEEQU method of Berman (1991) using the internally-consistent thermodynamic data set of Berman (1988) and solution models of Berman (1990) for garnet, McMullin et al. (1991) for biotite, and Fuhrman & Lindsley (1988) for plagioclase. †, assuming a pressure of 200 MPa.

biotite, and Fuhrman & Lindsley (1988) for plagioclase, to evaluate the influence of other components (*e.g.*, Ca and Mn in garnet, and Al and Ti in biotite) on the pressure–temperature estimates. These geothermobarometers also were chosen to facilitate comparison with the results of Tabor (1988) for the Rainy Lake area, Percival (1989) for the Raith area, and Pan & Fleet (1993) for the White River property. For both the Raith area and the Hemlo gold deposit, pressures and temperatures of the *M*1 metamorphism were calculated exclusively from the compositions of mineral inclusions in kyanite porphyroblasts or poikiloblasts (Table 3). We calculated the pressures and temperatures of the *M*2 metamorphism by assuming that the outer portion of the *M*2 garnet porphyroblasts with the maximum Mg/Fe value (Fig. 4) was in equilibrium with the isolated grains of biotite and plagioclase in the matrix, where sillimanite is the stable Al_2SiO_5 polymorph (Table 3). In addition, the garnet–biotite geothermometer has been applied to the outermost margin of garnet porphyroblasts and biotite in direct contact with it to constrain the event of retrogression (*M*3; Table 3). The lack of variation in Ca in garnet (Fig. 4) where it occurs in direct contact with plagioclase indicates that the net-transfer reaction involving the breakdown of 3 anorthite to give grossular + Al_2SiO_5 + quartz was not important during the retrogression. Alternatively, the retrograde path may have been parallel to the GASP isopleth.

Geothermobarometric results from the Raith area and the Hemlo gold deposit are given in Table 3 and illustrated in Figure 5. These results confirm the textural relationships for two distinct episodes of metamorphism and a retrograde event. Moreover, the Raith area and the Hemlo gold deposit both have undergone an earlier medium P–T (Barrovian-style) metamorphism and a main low-P/T metamorphism (Table 3, Fig. 5), and hence are discussed together below.

Pan & Fleet (1993) reported pressure and temperature conditions of 600–650 MPa and 500°C for the *M*1 metamorphism at the White River property. The garnet–biotite geothermometer based on the calibration of Ferry & Spear (1978) also yielded 495–515°C for the *M*1 metamorphism at both the Raith area and the Hemlo gold deposit (Table 3). However, the temperature estimates from the TWEEQU calculation are higher (540–560°C; Table 3). Also, pressure estimates of the *M*1 metamorphism from the GASP geobarometer of Koziol & Newton (1988) are slightly higher than those from the TWEEQU calculation (Table 3). It is noteworthy that Bauer & Tabor (1991) also recognized an earlier medium-P, low-T metamorphism in the Rainy Lake area. However, the geothermobarometric results of Tabor (1988) are difficult to evaluate, because he did not differentiate the two episodes of regional metamorphism.

Our pressure and temperature estimates of the *M*2 metamorphism at Raith (Table 3) are almost identical to those obtained by Percival (1989): 650°C from the Ferry & Spear garnet–biotite geothermometer and 330 MPa from the Koziol & Newton GASP geobarometer. Similarly, the results of the *M*2 metamorphism at the Hemlo gold deposit are comparable to those at the adjacent White River property (400–500 MPa and 550–650°C; Pan & Fleet 1993). The temperature estimates for the retrogression event (*M*3) at Raith and the Hemlo gold deposit are similar and range from 430 to 460°C (Table 3).

Pan & Fleet (1993) also used mineral-inclusion geothermobarometry (St-Onge 1987) to construct a metamorphic P–T path involving both *M*1 and *M*2 metamorphism at the White River property. Unfortunately, mineral inclusions in garnet porphyroblasts from the Raith and Hemlo samples examined in this study are not sufficiently developed to permit use of this method. Nevertheless, the compositional zonation of the *M*2 garnet porphyroblasts (*i.e.*, increase in Mg/Fe from core to rim except for the outermost margin; Fig. 4) corresponds to a temperature increase of about 60°C, assuming a constant composition of the coexisting biotite. However, pressure most likely remained constant during the growth of the *M*2 garnet porphyroblasts, because the temperature increase is offset by an increase in the anorthite component of plagioclase inclusions. These results are in agreement with the calculated metamor-

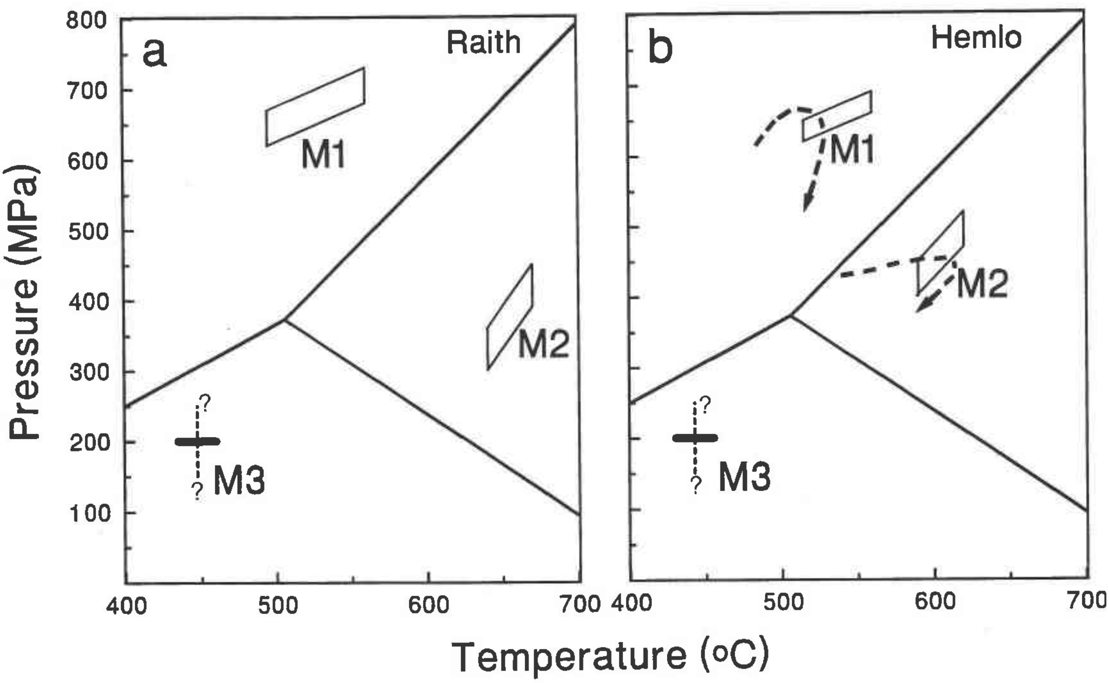

FIG. 5. Summary of metamorphic P–T conditions calculated from kyanite-bearing metapelites for a) the Quetico–Wabigoon boundary at the Raith area, and b) the Hemlo gold deposit; also shown is the calculated P–T path from the White River property (Pan & Fleet 1993; dashed lines). Boundaries of Al_2SiO_5 polymorphs are calculated using the thermodynamic dataset of Berman (1988). *M*1 is the earlier Barrovian metamorphism, *M*2 is the regional low-P, medium-T metamorphism, and *M*3 is the retrogression.

phic P–T path from mineral-inclusion geothermobarometry at the White River property (Pan & Fleet 1993; Fig. 5b). Burk *et al.* (1986) and Kuhns *et al.* (1994), on the other hand, interpreted kyanite as part of the peak metamorphic assemblage and sillimanite as a retrograde phase, although their calculated temperatures of the kyanite-forming event are noticeably lower than those of the sillimanite-forming event. Sillimanite in many parts of the Western Superior Province is clearly part of the prograde assemblage of the regional low-P/T metamorphism (Ayres 1978, Thurston & Breaks 1978, Percival 1989, Thurston *et al.* 1991, Williams *et al.* 1991, Pan & Fleet 1993).

Discussion

Metamorphic significance of Group-I and -II occurrences of kyanite

Most previous studies have emphasized the regional low-P/T metamorphism in the Western Superior Province (Thurston *et al.* 1991, Williams 1991, Williams *et al.* 1991, and references therein). Our textural evidence from the kyanite occurrences in metapelites and quantitative geothermobarometric calculations demonstrate the existence of an early Barrovian-style metamorphism (see also Burk *et al.* 1986, Bauer & Tabor 1991, Pan & Fleet 1993) before the regional penetrative deformation that accompanied the main low-P/T metamorphism. The geothermobarometry also reveals a significant decompression following the Barrovian metamorphism from approximately 700 MPa to about 300 MPa at the Quetico–Wabigoon boundary (Table 3), corresponding to an exhumation of up to 12 km. Exhumation of at least 6 km (*i.e.*, from 700 MPa to 400–500 MPa; Table 3, Fig. 5b) occurred also in the Hemlo – Heron Bay greenstone belt along the Hemlo Fault Zone.

Barrovian metamorphism is common in Phanerozoic orogenic belts, and is related to large-scale thickening of the crust followed by thermal relaxation (Spear 1993, Windley 1995). High-P/T metamorphism (*i.e.*, blueschist and eclogite facies) that characterizes Phanerozoic subduction complexes (Platt 1986, Hamilton 1988), on the other hand, requires anomalously low geothermal gradients (Ernst 1972, Windley 1995). The absence of blueschists and eclogites in Archean terranes has long been attributed to either significant higher geothermal gradients in Archean time or to difficulties in preservation (Ernst 1972, Windley 1995, and references therein). There is ample evidence that the Archean mantle was considerably hotter than today's mantle (*e.g.*, Bickle 1978, Martin 1986, Herzberg 1996); therefore, plate production and rate of oceanic lithosphere spreading may have been greater in the Archean (Bickle 1978, Martin 1986, Condie 1990), resulting in younger, hotter, and thicker oceanic lithospheres in Archean subduction zones. Consequently, the thermal regimes in Archean subduction zones must have been significantly different from their modern counterparts and were not appropriate for high-P/T metamorphism but, instead, might have yielded medium-P/T (Barrovian) metamorphism (including kyanite–staurolite assemblages in metapelites). Therefore, we propose that the Barrovian metamorphism in the Western Superior Province, as revealed by the kyanite occurrences in metapelites, may be directly related to Archean subduction–accretion tectonic processes.

Implications for accretionary tectonics in the western Superior Province

According to accretionary plate-tectonic models (*e.g.*, Percival & Williams 1989, Card 1990, Thurston & Chivers 1990, Percival *et al.* 1994), the subprovinces of the Western Superior Province represent volcanic arcs (granite–greenstone subprovinces), accretionary complexes (metasedimentary subprovinces), and continent–margin magmatic arcs (plutonic subprovinces), assembled by sequential north-to-south accretion (Krogh & Davis 1971, Card 1990, Percival *et al.* 1994). Specifically, Percival & Williams (1989) interpreted the Quetico Subprovince as an accretionary wedge in which sediments of submarine fans and abyssal turbidites were first deformed by accretion onto the active Wabigoon arc and later became compressed by docking of the Wawa arc (Percival 1989, Williams 1990). Percival & Williams (1989) also suggested a northward subduction on the basis of the dominantly northward-facing stratigraphy in the Quetico metasedimentary rocks. However, these authors cautioned that the regional low-P/T metamorphism in the Quetico Subprovince is not consistent with the thermal structure of accretionary wedges. We suggest that the earlier Barrovian metamorphism, and not the main regional low-P/T metamorphism, formed during this early stage of the development of the Quetico Subprovince. Several authors (*e.g.*, Tabor 1988, Percival & Williams 1989, Williams 1990) have documented early thrust- and nappe-like structures at the Quetico–Wabigoon boundary. Underplating and thrusting of sediments would be expected to thicken the accretionary wedge (Platt 1986) and hence create conditions for Barrovian metamorphism in Archean subduction complexes. Platt (1986) also demonstrated that continued underplating at the base of the wedge must be compensated by extension above, thus providing a mechanism for bringing up high-P/T metamorphic rocks to upper levels at the landward margin of the wedge. This combination of continued underplating and extension provides a plausible explanation for the observed uplift of up to 12 km at the Quetico–Wabigoon boundary.

Platt (1986) suggested that preferential uplift in accretionary wedges occurs near the landward margin where high-P/T metamorphic rocks are commonly observed in Phanerozoic accretionary complexes. The restricted occurrences of kyanite in the Quetico Subprovince along the northern (Quetico–Wabigoon) boundary appears strikingly equivalent to the restriction of lawsonite- and jadeite-bearing blueschists to the eastern side of the accretionary prism of the Franciscan Complex in California. This provides further evidence for northward subduction during formation of the Quetico Subprovince (Percival & Williams 1989). On the basis of east–north–east shallowly plunging mineral lineations and indicators of dextral shear, Tabor (1988) suggested southward subduction in the western Quetico subprovince in northern Minnesota and proposed a reversal of the polarity of subduction along the strike of the Quetico Subprovince, similar to the Alpine Fault in New Zealand. However, the occurrence of kyanite in the Rainy Lake area suggests that subduction in the western Quetico Subprovince was northward, as it was throughout the remainder of the subprovince.

The timing of the Barrovian metamorphism at the Quetico–Wabigoon Subprovince boundary has not been directly constrained. Percival & Williams (1989) bracketed the formation of the proposed accretionary wedge from 2750 to 2700 Ma. This was followed by compression as a result of oblique collision with the Wawa arc at 2700–2684 Ma (Corfu & Stott 1986, Percival & Williams 1989, Percival 1989). The *M*2 metamorphism in the Quetico Subprovince has been bracketed at approximately 2670 Ma in amphibolite-facies zones (Percival & Sullivan 1988) and 2666–2650 Ma in a granulite-facies zone (Pan *et al.* 1998), and is interpreted to relate to thermal relaxation following collision with the Wawa arc with additional sources of heat from underplated mantle-derived magmas (Percival 1989, Pan *et al.* 1994).

It has become clear in recent years that many Archean greenstone belts may represent a collage of originally unrelated greenstone fragments assembled by accretionary tectonic processes (*cf.* Williams 1990, Thurston *et al.* 1991). On the basis of two U–Pb zircon age determinations, Corfu & Muir (1989) suggested that the Hemlo – Heron Bay greenstone belt represents a juxtaposition of two originally unrelated fragments (*i.e.*, the 2772 Ma Hemlo – Black River assemblage and the 2695 Ma Heron Bay assemblage) separated by a major structural discontinuity, possibly represented by the Hemlo Fault Zone (see also Williams *et al.* 1991). If this suggestion is valid, the restricted occurrences of kyanite and inferred earlier Barrovian metamorphism in close spatial association with the Hemlo Fault Zone may have recorded an event of crustal thickening related to small-scale accretion that assembled originally unrelated slivers of greenstones (*e.g.*, Williams 1990). It is well known that accretion of allochthonous terranes (by collision) in the Coast Ranges of British Columbia resulted in intense deformation and Barrovian metamorphism followed by rapid uplifting (*e.g.*, Hollister 1982).

Pan *et al.* (1991) had noted that, at the White River property, the sedimentary and mafic volcanic rocks from both sides of the Hemlo Fault Zone are remarkably similar; they suggested that they most likely formed in a single tectonic environment. However, these lithologies are merely typical of Archean island arcs. In light of the present survey of kyanite occurrences, they could well have formed in separate island arcs or indeed could be separate fragments of the same island arc system. Further high-precision U–Pb zircon geochronological analyses of volcanic rocks and associated sedimentary rocks in the Hemlo – Heron Bay greenstone belt are clearly needed to test whether the Hemlo – Black River and Heron Bay assemblages represent two related or unrelated fragments of greenstone.

Thurston *et al.* (1991) proposed the formation of the northwestern Superior Province (*i.e.*, the Berens River and Sachigo subprovinces in Card & Ciesielski 1986) by a northward accretion onto the North Caribou terrane. The occurrences of kyanite in the North Caribou greenstone belt, near the northern boundary of the North Caribou terrane, are consistent with crustal thickening related to this northward accretion. Alternatively, the Miskeesik Lake occurrence of kyanite close to a fault boundary between the Eyapamikama and McGruer assemblages may be related to accretionary processes that assembled the North Caribou greenstone belt. Further research of these North Caribou occurrences of kyanite is needed to establish their relationships with the tectonic events, especially in view of the possible presence of multiple generations of kyanite (Breaks & Bartlett 1991).

Comments on the Group-III occurrences of kyanite

The occurrences of kyanite and other aluminosilicates in Al–Si-rich alteration assemblages associated with VMS and Au mineralization clearly reflect the unusual whole-rock compositions of their host rocks and may represent potential exploration tools for base-metal mineralization (*e.g.*, Franklin *et al.* 1975, Amukun 1989). However, the relationship of these kyanite occurrences to tectonic processes is difficult to decipher because of the high variance of their mineral assemblages. In particular, the presence of two or all three Al_2SiO_5 polymorphs in these alteration assemblages has been suggested by some to represent metastability (*e.g.*, Lefebvre 1982). Franklin *et al.* (1975) suggested that kyanite at the Mattabi deposit formed from the breakdown of pyrophyllite and did not require medium-P metamorphic conditions. Similarly, Fleet & Pan (1995) interpreted kyanite in the quartz veins of the Hemlo gold deposit to have formed during a late low-grade alteration event in a manner equivalent to the formation of kyanite in veins and segregations in the Lepontine Alps, Switzerland (Kerrick 1990). Fleet & Pan (1995) suggested that the P–T–t trajectory locally crossed into the stability field of kyanite, and pyrophyllite stability was suppressed by the high salinity of the fluids. Kyanite in Al–Si-rich alteration assemblages of the Manitouwadge greenstone belt, on the other hand, occurs as a relic within sillimanite (Schandl *et al.* 1995). It is noteworthy that the Manitouwadge greenstone belt is situated closely to the Quetico–Wawa boundary, and the occurrence of kyanite here may still record crustal thickening related to the docking of the Wawa arc onto the Quetico accretionary wedge (Percival 1989). Also, Ayres (1978) classified the Marshall Lake kyanite occurrence as a member of Group I because of its location close to the English River – Wabigoon boundary, although petrographic or geothermobarometric evidence for an earlier Barrovian metamorphism is still lacking there.

Conclusions

Kyanite in the supracrustal rocks of the Archean Western Superior Province falls into three distinct lithotectonic associations: I) metapelites near subprovince and terrane boundaries, II) metapelites near faults in greenstone belts, and III) Al–Si-rich alteration assemblages associated with VMS and Au mineralization in greenstone belts.

Kyanite in Groups I and II indicates an earlier Barrovian metamorphism (670–730 MPa and 500–560°C) before the regional penetrative deformation that accompanied the regional low-P/T metamorphism. The presence of group-I kyanite along the Quetico–Wabigoon boundary and the inferred metamorphic P–T path support the origin of the Quetico Subprovince as an accretionary wedge during northward subduction. Group-II kyanite from the Hemlo – Heron Bay greenstone belt may have recorded accretion that assembled originally unrelated slivers of greenstones. Our results support the two-stage-accretion model of Williams (1990) for the development of the Western Superior Province.

Kyanite in Group III reflects unusual host-rock compositions and hydrothermal fluids, and may be a potentially useful tool for exploration of volcanogenic massive sulfide deposits.

Acknowledgements

We thank A. Indares, T. Rivers and P. Thurston for thorough reviews and helpful suggestions, and R.F. Martin for editorial assistance. We also thank F.W. Breaks, S. Jackson, A.H. Mumin, J.A. Percival, E. Schandl, H.R. Williams, and E. Zaleski for many stimulating discussions on metamorphism and kyanite in the western Superior Province, and G. Zhang for the preparation of Figures 1 and 3. F.W. Breaks and E. Schandl also kindly supplied kyanite-bearing samples from the North Caribou and Manitouwadge greenstone belts, respectively. Financial support to this study was provided by NSERC Research and Lithoprobe Grants.

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Received November 13, 1997, revised manuscript accepted February 15, 1999.