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Provenance and tectonic setting of deposition of metagreywackes in the Nan River Suture, Northern Thailand

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Abstract: Provenance and tectonic setting of deposition of metagreywackes from the Sirikit Dam area in northern Thailand which covers part of the Nan River Suture were reconstructed on the basis of geochemical and petrographic data. The metagreywackes belong to the Pha Som Metamorphic Complex that consists of a coherent unit of multiply-deformed pumpellyite-actinolite facies metasedimentary rocks and tectonic slices of ophiolitic mafic-ultramafic rocks. The lithology, deformation history, and metamorphism of the Pha Som Metamorphic Complex are consistent with those observed in ancient and modern accretionary complexes in many parts of the world.

Geochemically, the metagreywackes are divided into two categories: the PSM-1 and PSM-2 groups. The PSM-1 group is characterised by relatively low average concentrations of TiO_2, Al_2O_3, Fe_2O_3*, and V, a low Zr/Th ratio, relatively high abundances of Pb, Th, light rare-earth elements (La, Ce, and Nd), and high Th/Sc and Ce/V ratios. The PSM-2 group is characterised by relatively high average concentrations of TiO_2, Al_2O_3, and Fe_2O_3*, a high Zr/Th ratio, relatively low abundances of Pb, Th, light rare-earth elements (La, Ce, and Nd), and low Th/Sc and Ce/V ratios. Immobile trace element characteristics suggest that the PSM-1 metagreywackes were derived from a continental island arc source and were probably deposited in a submarine fan setting at a subduction zone. In contrast, major and trace element characteristics suggest that the PSM-2 metagreywackes represent sediments derived mainly from an oceanic island arc source.

On the basis of modal compositions of the framework grains, the metagreywackes can be divided into quartz-rich greywackes, which are comparable to the sandstone of modern and ancient accretionary complexes, and quartz-poor greywackes, which have a transitional magmatic arc source.

This study further supports the existence of an ancient accretionary complex prior to the amalgamation of the Shan-Thai and Indochina terranes in Late Triassic-Early Jurassic time.

INTRODUCTION

It has long been known that sandstone compositions are influenced by the character of the sedimentary provenance, the nature of the sedimentary processes within the depositional basin, and the kind of dispersal paths that link the provenance to the basin (Dickinson and Suczek, 1979). The provenance of a particular sedimentary suite includes all aspects of the source area, such as source rocks, climate, and relief (Pettijohn *et al.*, 1972). In areas of intense tectonic and/or magmatic activity, source-rock type has a stronger influence upon sediment compositions than climate and relief (Dickinson, 1970; Dickinson and Suczek, 1979). The compositional and chemical variations of sandstone have been utilised to determine of the provenance of sedimentary suites and in palaeotectonic and palaeogeographic reconstruction.

For sandstone that retains its original sedimentary texture, the use of a modal composition as an indicator of the provenance type has long been established (Dickinson, 1970; Crook, 1974; Dickinson and Suczek, 1979; Ingersoll and Suczek, 1979; Valloni and Maynard, 1981; Dickinson *et al.*, 1983; Marsaglia and Ingersoll, 1992). Later, geochemistry of clastic sediments was used for a similar purpose (Bhatia and Taylor, 1981; Maynard *et al.*, 1982; Bhatia, 1983) and its use became increasingly prominent during the last decade (Bhatia and Crook, 1986; Roser and Korsch, 1988; McLennan and Taylor, 1991; Mortimer and Roser, 1992).

On the basis of major element geochemistry, several discrimination diagrams were derived for determining provenance of sandstones (Bhatia, 1983; Roser and Korsch, 1988). Some workers (Bhatia and Taylor, 1981; Bhatia and Crook, 1986) utilised trace element geochemistry in a similar fashion as that used in the tectonic discrimination of volcanic rocks (Pearce and Cann, 1973; Winchester and Floyd, 1976). The basic concepts of these discrimination schemes were based on observations made from geochemical characteristics of several suites of sandstone with known provenance and tectonic settings.

Several studies including by Bhatia (1983) and Roser and Korsch (1988), led to the recognition of major elements that are useful discriminating parameters. The parameters recognised by Bhatia (1983) include TiO_2, Al_2O_3/SiO_2, and $Fe_2O_3* + MgO$. These parameters decrease progressively from oceanic island arc to continental island arc to active continental margin to passive margin settings. Roser and Korsch (1988) proposed discriminant functions that give effective separation between four provenance groups: P1, primarily mafic and lesser intermediate igneous provenance; P2, primarily intermediate igneous provenance; P3, felsic igneous provenance; and P4, recycled provenance.

Trace elements, especially the immobile elements, have also been used for the same purpose as major elements. In general, there is a systematic increase in the light rare-earth elements (La, Ce, and Nd), in Th and Nb, and in a La/Y ratio and a decrease in V and Sc in greywackes from oceanic island arc to continental island arc to active continental margin to passive continental margin settings (Bhatia and Crook, 1986). On these grounds, the discrimination plots were proposed, such as ternary plots of La-Th-Sc and Th-Sc-Zr/10 and a binary plot of Ti/Zr-La/Sc. Roser and Cooper (1990) emphasised the use of immobile element ratios as guides to tectonic setting and provenance because dilution effects can be avoided. They applied discrimination plots, Ti/Zr-La/Sc and Y/Nb-Th/Sc, to distinguish lithologies from two different tectonic settings, the Torlesse and Caples terranes in the Haast Schist terrane in New Zealand. The Torlesse terrane greywackes were interpreted as being derived from an active volcano-plutonic continental margin arc source and the Caples terrane greywackes as being derived from an intra-oceanic island arc (Coombs *et al.*, 1976; MacKinnon, 1983) with some input from a continental source area (Mortimer and Roser, 1992). In addition, Mortimer and Roser (1992) proposed a ratio plot, Ce/V-La/Y, to delineate the Torlesse-Caples terrane boundary in the Otago Schist. In this study, these proposed schemes for discriminating provenance and tectonic settings of sedimentary and metasedimentary rocks were applied to the metagreywackes from the Sirikit Dam area. The result provided a further constraint to the accretionary model for the formation of the metagreywackes in the Nan River suture zone.

REGIONAL GEOLOGY

The Pha Som Metamorphic Complex lies within the Nan River suture zone (Fig. 1) that separates the Shan-Thai terrane on the west and the Indochina terrane on the east (Bunopas and Vella, 1978; Bunopas, 1981). The Pha Som Metamorphic Complex is characterised by a belt of ophiolitic mafic-ultramafic rocks tectonically enclosed within low-grade metasediments of Carboniferous to Permian age (Hess and Koch, 1975).

The Permian-Triassic Pak Pat Volcanics (Bunopas, 1981) occur as a relatively small body east of the Pha Som Metamorphic Complex (Fig. 2). A sequence of volcaniclastic conglomerate and turbidites of the Triassic Nam Pat Group occur east of the Pak Pat Volcanics. Lying unconformably on top of the Nam Pat Group are the Middle Jurassic Phra Wihan Formation continental red beds. These spread across the suture. They are relatively less deformed than the older rock units in this region.

West of the Nan River suture zone a discontinuous belt of Permian-Triassic volcanic and volcaniclastic rocks extends from north of Tak to Lampang. Two major turbidite sequences, one of the Triassic Lampang Group (Piyasin, 1972) and the other of the Permian Phrae Group (Bunopas, 1981) occur in the region between the Permian-Triassic volcanic belt and the Carboniferous-Permian Pha Som Metamorphic Complex. These turbidite sequences have been intruded by Upper Triassic-Lower Jurassic post-tectonic granites. In several areas, Upper Triassic-Lower Jurassic felsic volcanic rocks unconformably overlie these turbidite sequences. Middle Tertiary-Quaternary strata occur in intermontane basins formed during the Late Oligocene. Small bodies of Pliocene-Pleistocene basalts are scattered throughout the region.

STRATIGRAPHY

The Pha Som Metamorphic Complex is used here as a collective name for the Pha Som Ultramafics and the Pha Som Group of Bunopas (1981). As these two names do not comply with formal stratigraphic nomenclature, the informal terms ophiolite association and metasediments are used for the Pha Som Ultramafics and the Pha Som Group respectively. The metagreywackes in the present study belong to the metasediments of the Pha Som Metamorphic Complex.

The ophiolite association

The ophiolite association of the Pha Som Metamorphic Complex was originally defined as a suite of mafic and ultramafic igneous rocks (Bunopas, 1981). However, this rock unit has a sedimentary component (MacDonald and Barr, 1984; Panjasawatwong, 1991; Singharajwarapan and Berry, 1993). It comprises a variety of rocks, ranging from metavolcanic rocks, mafic-ultramafic plutonic rocks and amphibolite to metamorphosed pelagic-hemipelagic sediments. The mafic-ultramafic igneous rocks that are the dominant rock types include basalt, dolerite, microgabbro, gabbro, hornblendite, pyroxenite, and peridotite. Muscovite-quartz schist, piemontite-bearing quartz

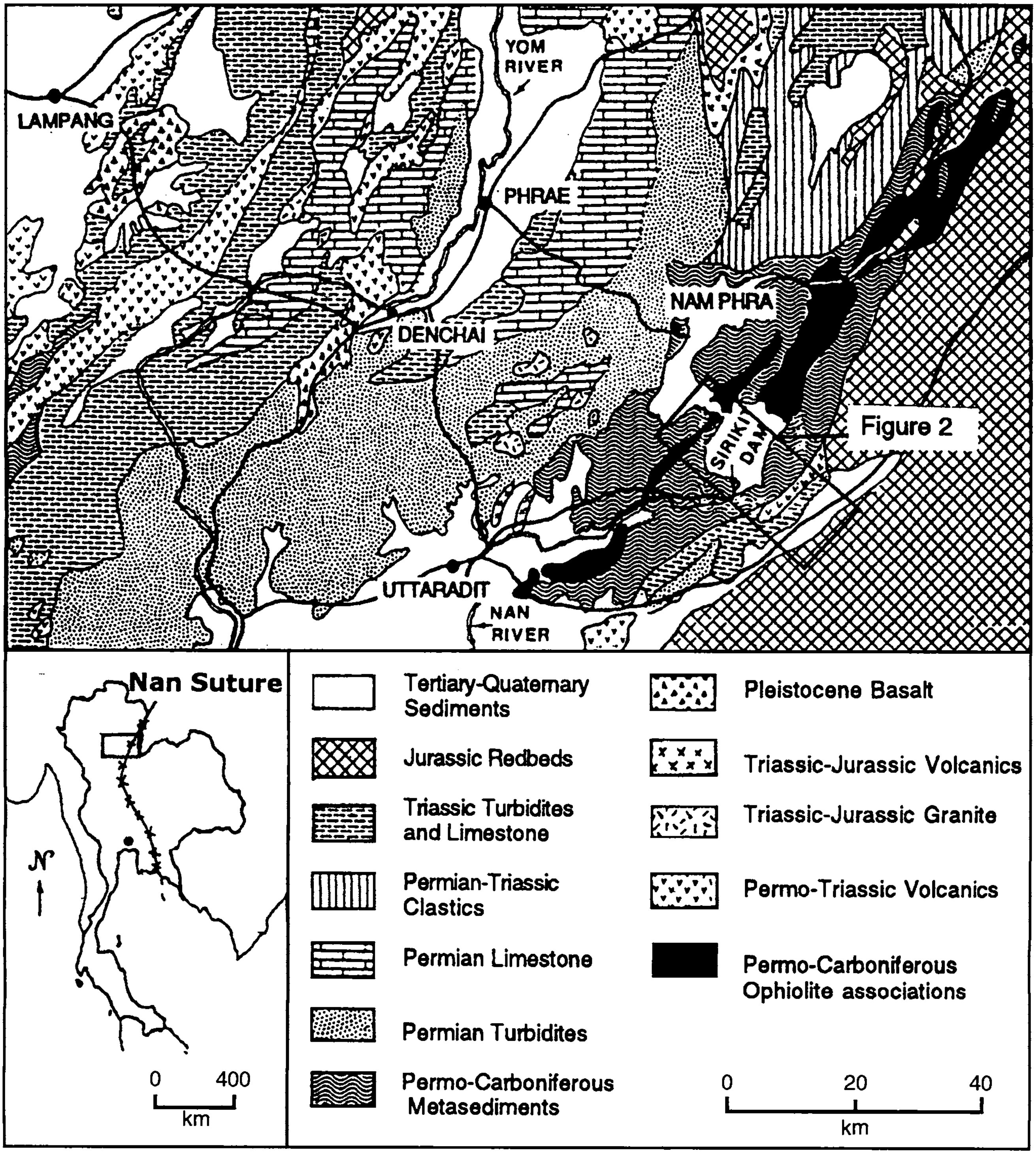

Figure 1. Generalized geological map of the southeastern part of northern Thailand showing major rock units. The Nan River suture zone is shown in the index map.

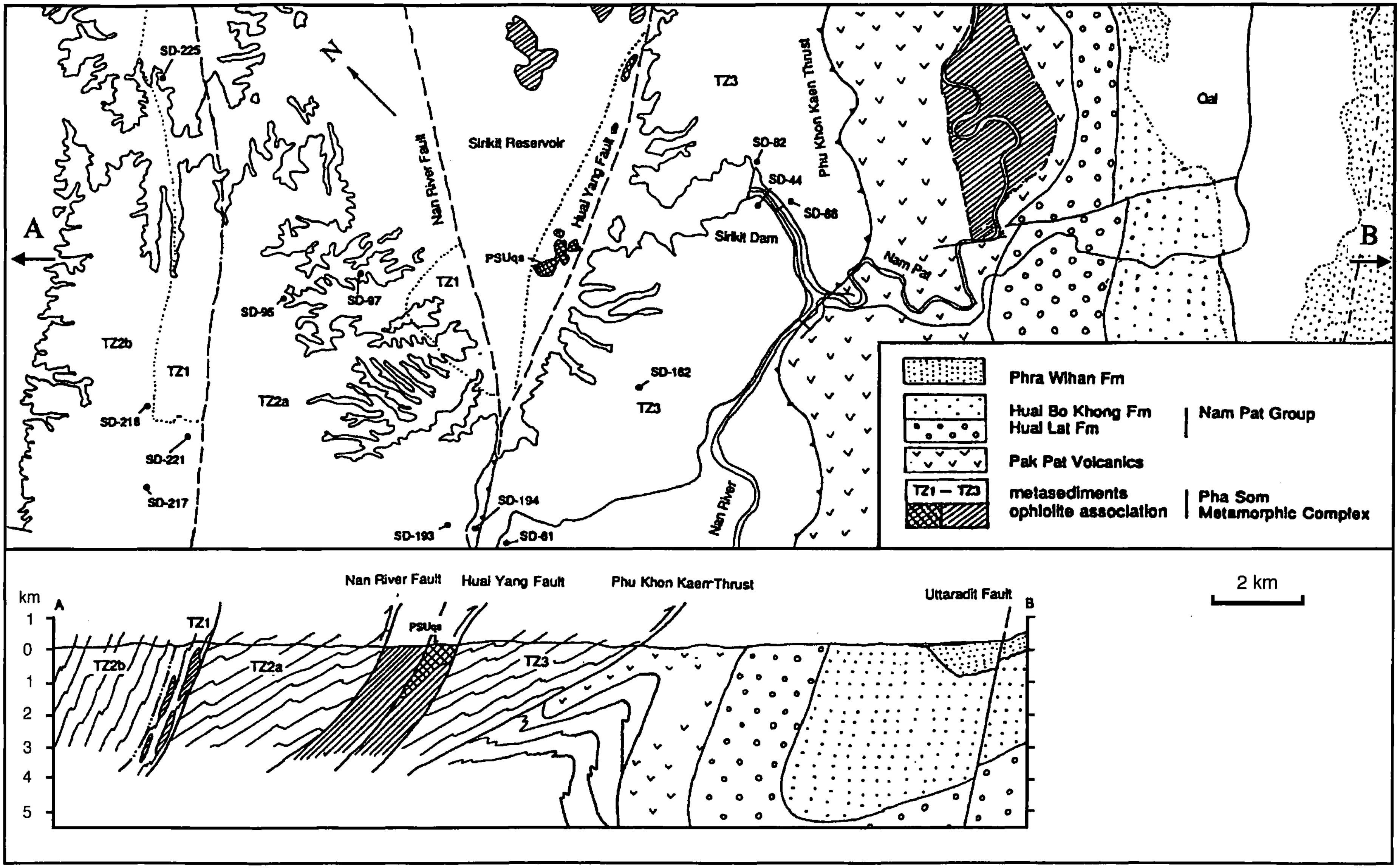

Figure 2. Simplified geological map and cross-section of the Sirikit Dam area showing distribution of rock units and major structures. Also shown are sample locations.

schist, chert, greywacke, argillite, and marble are the sedimentary and metasedimentary rocks associated with the mafic and ultramafic rocks (Singharajwarapan and Berry, 1993).

The internal structure of this unit is rather complex, due to extensive shearing and faulting. Panjasawatwong (1991) described the dismembered mafic-ultramafic-dominated bodies in this area and elsewhere in the Nan River region as a serpentinite melange. Bodies of ophiolite association are commonly found as thrust slices enclosed in the metasediments.

The metasediments

Recrystallisation and complex deformation of rocks in the metasedimentary unit of the Pha Som Metamorphic Complex have destroyed most of the sedimentary features and, hence, restrict the sedimentological interpretations for the metasediments. Detailed stratigraphic subdivision of the metasediments is also impracticable due to the monotony of the succession, the structural complexity, and the scarcity of marker horizons.

The dominant rock type of the metasediments is metagreywacke. Phyllite is a minor component. The term metagreywacke used here includes various rocks described by previous workers in the Nan River area as banded quartzite, muscovite-quartz schist, epidote-quartz schist, and actinolite-quartz schist (Thanasuthipitak, 1978; Bunopas, 1981). Epidote-crossite schist interlayered with quartzite in the Doi Phuk Sung area about 70 kilometres northeast of the Sirikit Dam (Barr *et al.*, 1985) was correlated with this unit.

Texturally, the metagreywacke can be classified as slightly sheared greywacke, TZ1; semischist, TZ2a and TZ2b; and fine-grained schists, TZ3, following the scheme devised by Turner (1938) in which four textural zones, Chl 1 through Chl 4, reflecting increasing intensity of deformation were used as subdivisions of the chlorite zone of the greenschist facies Otago Schist in the south island of New Zealand. The TZ3 textural zone is widespread throughout the area east of the Nan River fault. In the area west of the Nan River fault, the TZ1 textural zone is bounded within the TZ2a and TZ2b textural zones (Fig. 2).

Bunopas (1981) estimated that the thickness of the metasediments was at least 2 kilometres. However, the complex deformation places restriction on the accuracy of this estimate.

The metasediments are thrust over the Pak Pat Volcanics along the Phu Khon Kaen thrust (Fig. 2) and enclose the ophiolite association where the boundary between the two rock units is marked by the Nan River fault on the west side. The contact with the overlying Permian turbidite sequence, the Phrae Group, farther to the west is probably a thrust fault.

The age of the metasediments remains debatable due to the lack of fossils. On the basis of regional stratigraphy, Bunopas (1981) suggested a Silurian-Devonian age for the metasediments; whereas Hess and Koch (1975) assigned a Carboniferous-Permian age. Barr and MacDonald (1987) later suggested mid-Permian (269 ± 12 Ma) as a minimum metamorphic age according to a K-Ar date of actinolite-quartz schist in the metasediments. This metamorphic age implies that the sedimentation of the metasediments took place during Late Carboniferous to Early Permian time.

STRUCTURE

Structural study of the Pha Som Metamorphic Complex was restricted to the metasediments due to the coherent nature of the unit in contrast to the disrupted ophiolite association. Four deformation phases, D_1-D_4, were recognised in the metasediments (Singharajwarapan and Berry, 1993). D_1 to D_3 events in the metasediments pre-dated deformation of the overlying Permian-Triassic turbidites. D_4 structures in the metasediments are probably correlated with the cleavage in the Triassic volcanic rocks and upright folds in the Triassic turbidites.

The earliest stage in the structural evolution of the metasediments is represented by the compositional layering, S_1, which is probably associated with the first generation folds, F_1. D_2 structures are interpreted to be the results of ductile thrusting where F_2 folds, stretching lineation, L_2, and cleavages, S_2, developed. F_3 open folds with associated crenulations and crenulation cleavages produced by D_3 deformation are asymmetrical features. The crenulations and crenulation cleavage are apparently the result of shortening of the S_2 foliation. The D_3 deformation event probably corresponds to the shortening of the accretionary wedge.

The structural succession, D_1-D_3, of the Pha Som Metamorphic Complex are similar to those observed in the Late Cretaceous Kodiak accretionary complex in Alaska (Sample and Fisher, 1986; Sample and Moore, 1987; Paterson and Sample, 1988).

D_4 kink and angular folds are interpreted as the result of late thrusting, which is strongly variable in movement direction. The D4 thrusts and related structures are probably correlated with the cleavage formation in the Permian-Triassic Pak Pat Volcanics and upright folds and thrusts in the Triassic Nam Pat Group turbidite sequence.

LITHOLOGY AND TEXTURAL DEVELOPMENT

Metagreywackes are the principal component of the metasediments. Lithologically, they are mostly quartzofeldspathic, though in a few localities they contain abundant volcanic rock fragments. Systematic textural change from clastic sandstone to fine-grained schist with increasing deformation and metamorphism occurs. Regardless of textures, metagreywackes contain a typical lower-greenschist facies mineral assemblage, quartz + albite + phengitic muscovite + chlorite ± calcite ± epidote ± actinolite ± pumpellyite. In terms of texture, they can be classified as greywacke, semischist, and fine-grained schist (Spry, 1969) corresponding to psammitic rocks of the Chl1, Chl2 and Chl3 textural zones of Turner (1938) respectively. To avoid metamorphic connotation of the abbreviation Chl which is derived from a chlorite zone, textural zones, TZ1, TZ2, and TZ3 are used here instead of the Chl1, Chl2, and Chl3 textural zones of Turner (1938). The TZ2 zone is subdivided into TZ2a and TZ2b subzones based on variation in textural development. The distribution of each textural zone is shown in Figure 2.

Greywackes (TZ1 textural zone)

Greywackes contain framework grains in a partially recrystallised matrix. On the basis of mineralogical composition, greywackes can be divided into two distinct types, quartzose lithic or feldspathic greywacke and quartz-poor lithic greywacke.

Quartzose lithic or feldspathic greywacke (Fig. 3a) is chiefly monocrystalline and polycrystalline quartz with subordinate schist and phyllite fragments, small amounts of albitised plagioclase and chert. Quartz grains show either straight or slightly undulatory extinction. Grains are poorly to moderately sorted and angular to subangular, with mean grain size of 250-500 µm and are largely intact with weakly developed mortar texture. A partially recrystallised matrix is made up of microcrystalline quartz, fine-grained muscovite, albite, chlorite, and epidote. The arrangement of platy muscovite flakes is either random or defines cleavage. Schistosity has not developed.

Quartz-poor lithic greywacke consists chiefly of volcanic lithic fragments and subordinate albitised plagioclase and monocrystalline and polycrystalline quartz. Grains are moderately sorted and subangular, with mean grain size of 400-600 µm. Grains commonly have lobate grain boundaries. A partially recrystallised matrix is made up of microcrystalline quartz, fine-grained muscovite, albite, and chlorite. Epidote, calcite, and fine-grained muscovite largely replace plagioclase.

Semischists (TZ2 textural zone)

The semischists are metagreywackes that have slight to moderate recrystallisation of the original clastic grains and correspond to the metagreywackes of Chl2 textural zone of Turner (1938). The TZ2a semischists (Fig. 3b) are distinguished from the TZ2b semischists (Fig. 3c) on the basis of the degree of recrystallisation of clastic grains. The framework grains of both TZ2a and TZ2b semischists are chiefly monocrystalline and polycrystalline quartz with small amounts of chert, albitised plagioclase, muscovite, and chlorite. Grains are poorly sorted and angular to subangular, with mean grain size of 400 µm. A sheared and partially recrystallised matrix probably includes deformed unstable grains. A weakly developed schistosity is defined by parallel to subparallel alignment of fine-grained platy muscovite in combination with dimensional-preferred orientation of quartz and albite.

Fine-grained schist (TZ3 textural zone)

The fine-grained schist textured rocks (Fig. 3d) developed more pronounced schistosity and have undergone more intense recrystallisation than semischists. They are characterised by a strongly sheared rock consisting of porphyroclasts of quartz and plagioclase set in a recrystallised and schistose matrix of microcrystalline quartz, phengitic muscovite, chlorite, epidote, actinolite, calcite, and rare pumpellyite. Asymmetrical quartz grains commonly have undulatory extinction and possess serrated grain boundaries. In the matrix, fine-grained platy muscovite invariably shows strong parallelism and wrap around flattened porphyroclasts of quartz and plagioclase.

PROVENANCE AND TECTONIC SETTING OF DEPOSITION

Modal composition and interpretations

Intense deformation together with recrystallisation of the original constituents, rendered the metagreywackes unuseful for modal analysis. The modal analysis relies on the sandstone. Five Pha Som Metamorphic Complex greywacke samples that have little textural modification as a result of deformation and recrystallisation were chosen for modal analysis using the Gazzi-Dickinson method (Ingersoll *et al.*, 1984). The thin sections studied were stained to aid identification of K-feldspar. Sandstone samples of the Pha Som Metamorphic Complex

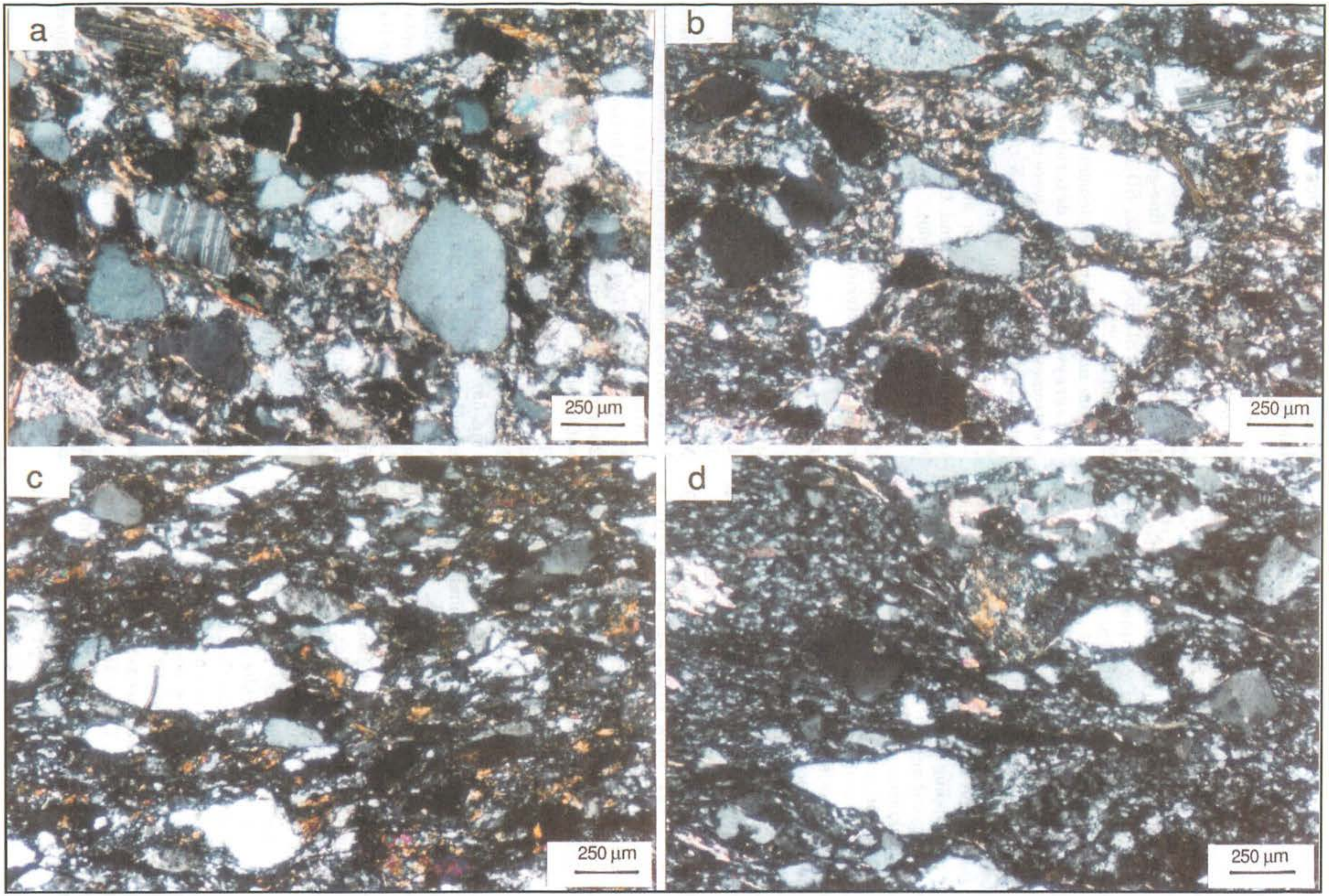

Figure 3. Photomicrographs showing textural development of the metagreywackes of the Pha Som Metamorphic Complex: (a) TZ1 greywacke; (b) TZ2a semischist; (c) TZ2b semischist; (d) TZ3 fine-grained schist.

metasediments can be divided into two types, quartz-rich greywacke and quartz-poor greywacke.

Quartz-rich greywacke samples, 2/8291, 3/8291, and SD-91, are classified as immature, fine- to medium-grained, slightly calcite cemented lithic greywackes (Pettijohn *et al.*, 1972). They have the average composition $Q_{51}F_{14}L_{35}$ and $Qm_{33}F_{14}Lt_{53}$ (Table 1), which are comparable to those of modern and ancient subduction complex sandstone (Dickinson and Suczek, 1979). The ratios of grain parameters, Qp/Q (0.35) and P/F (1.00) and Lv/L (0.27) are also very similar to the values given for the subduction complex sandstone (Dickinson, 1985). However, on the QFL triangular plot (Fig. 4a), they fall within a recycled orogenic provenance field and on the QmFLt diagram (Fig. 4b), they occupy overlapping fields between the transitional recycled orogenic and the dissected arc provenance types of Dickinson *et al.* (1983). The QpLvmLsm plot of Ingersoll and Suczek (1979) indicates that these sandstone samples have come from either magmatic arcs or subduction complexes (Fig. 4c).

The compositional characteristics of the detrital framework modes of the three quartz-rich greywacke samples suggest that they represent sediments derived from an accretionary complex mixed with detritus from a magmatic arc source.

The two quartz-poor greywacke samples, SD-225, and SD-227, show strong affinity towards a volcanic source. Sample SD-225 is an immature, coarse-grained, lithic greywacke. The framework grains consist chiefly of volcanic (microlithic and lathwork) lithic fragments and subordinate albitised plagioclase and monocrystalline and polycrystalline quartz.

The quartz-poor greywackes have the average compositions of $Q_{30}F_{22}L_{48}$ and $Qm_{14}F_{22}Lt_{64}$ (Table 1), which are comparable to transitional magmatic arc sandstone (Dickinson and Suczek, 1979). The ratios of grain parameters, P/F (0.92) and Lv/L (0.91) are also very similar to the values for the magmatic arc sandstone (Dickinson, 1985). On the QFL triangular diagram (Fig. 4a), they plot within transitional and dissected arc provenance fields and on the QmFLt diagram (Fig. 4b), they occupy a transitional arc provenance field of Dickinson *et al.* (1983). The QpLvmLsm plot (Fig. 4c) of Ingersoll and Suczek (1979) indicates that these sandstone samples have a mixed provenance type between magmatic arcs and rifted continental margins (backarc basins) but they plot near the field for magmatic arc (forearc areas) on the LmLvLs diagram (Fig. 4d). These discriminatory plots suggest that these samples were derived from a magmatic arc source.

Geochemical characteristics and interpretations

Sixteen metagreywacke samples were analysed for major and trace elements. These samples included three greywackes (SD-61, SD-97, and SD-225), five semischists (SD-95, SD-193, P-102, P-104, and P-107) and eight fine-grained schists (SD-44, SD-82, SD-86, SD-162, SD-194, SD-217, SD-218, and SD-221).

The major and trace element compositions of metagreywackes were determined by XRF spectrometry. The analyses were carried out by an automated Philips PW 1480 X-ray fluorescence spectrometer at the Department of Geology, University of Tasmania at Hobart, using the technique of Norrish and Chappell (1967) and Norrish and Hutton (1969).

The metagreywackes were divided into two groups, PSM-1 and PSM-2, on the basis of their chemical characteristics.

PSM-1

The PSM-1 group includes two greywackes (SD-61 and SD-97), two semischists (SD-95 and SD-193) and three fine-grained schists (SD-82, SD-162, and SD-194).

Major elements: PSM-1 samples are characterised by relatively low average concentrations of TiO_2 (0.57±0.07 wt %), Al_2O_3 (11.64±0.70 wt %), and Fe_2O_3* (4.75±0.47 wt %) compared to those of PSM-2 samples as shown in Table 2. These samples plot within the felsic igneous rock provenance and the quartzose recycled provenance on the discrimination diagram of Roser and Korsch (1988), as shown in Figure 5. On the TiO_2 versus Fe_2O_3*+MgO diagram (Fig. 6a), these samples plot within the continental island arc field of Bhatia (1983). On the Al_2O_3/SiO_2 versus Fe_2O_3*+MgO plot of Bhatia (1983), the majority of these samples fall within the continental island arc field but a few samples overlap into the field for active continental margin (Fig. 6b).

Trace elements: PSM-1 samples are characterised by relatively low average concentrations of V (88±8 ppm), a low Zr/Th ratio (16.0±2.2), relatively high abundances of Pb (9±4 ppm), Th (12±3 ppm), light rare-earth elements such as, La (27±3 ppm), Ce (52±8 ppm), and Nd (24±2 ppm), and high ratios of Th/Sc (1.0±0.2) and Ce/V (0.6±0.1) compared to those of PSM-2 samples (Table 2).

Comparison with greywackes from various tectonic settings from eastern Australia (Bhatia and Crook, 1986) suggests that the PSM-1 samples are similar to the greywackes derived from continental island arc settings that were deposited

Table 1. Recalculated framework modes of Pha Som metamorphic complex metagreywackes.

Sample No.	QFL (%)			QmFLt (%)			QpLvmLsm(%)			LmLvLs (%)			Qp/Q	P/F	Lv/L
	Q	F	L	Qm	F	Lt	Qp	Lvm	Lsm	Lm	Lv	Ls			
Quartz-rich greywackes															
2/8291	50.7	8.5	40.8	29.7	8.5	61.8	34.0	8.3	57.7	87.4	12.6	0.0	0.41	1.00	0.13
3/8291	47.0	17.7	35.3	31.0	17.7	51.4	31.2	27.1	41.7	59.4	39.4	1.2	0.34	1.00	0.39
SD-91	55.8	15.1	29.1	38.8	15.1	46.2	36.9	18.2	44.9	66.9	28.8	4.2	0.31	1.00	0.29
Mean	51.2	13.8	35.1	33.2	13.8	53.1	34.0	17.9	48.1	71.2	26.9	1.8	0.35	1.00	0.27
Standard Deviation	4.4	4.7	5.9	4.9	4.7	7.9	2.9	9.4	8.5	14.5	13.5	2.2	0.05	0.00	0.13
Quartz-poor greywackes															
SD-225	34.6	23.1	42.2	16.9	23.1	60.0	29.6	66.7	3.7	5.3	94.7	0.0	0.51	0.95	0.95
SD-227	26.3	20.9	52.8	10.6	20.9	68.5	23.0	67.5	9.5	11.3	87.6	1.1	0.60	0.86	0.88
Mean	30.5	22.0	47.5	13.8	22.0	64.3	26.3	67.1	6.6	8.3	91.2	0.6	0.56	0.91	0.92
Standard Deviation	5.9	1.6	7.5	4.5	1.6	6.0	4.7	0.6	4.1	4.2	5.0	0.8	0.06	0.06	0.05

Note:
Q = Qm+Qp, F = P+K, Lt = L+Qp, L = Lm+Lv+Ls, Lvm = Lv+Lm, Lsm = Ls+Lm
Q = total quartz grains, Qm = monocrystalline quartz, Qp = polycrystalline quartz, F = total fedspar grains, P = plagioclase, K = potassium-feldspar
Lt = total lithic grains, L = unstable lithic grains, Lm = metamorphic lithic grains, Lv = volcanic lithic grains, Ls = sedimentary lithic grains
Lvm = volcanic-metavolcanic lithic grains, Lsm = sedimentary-metasedimetary lithic grains

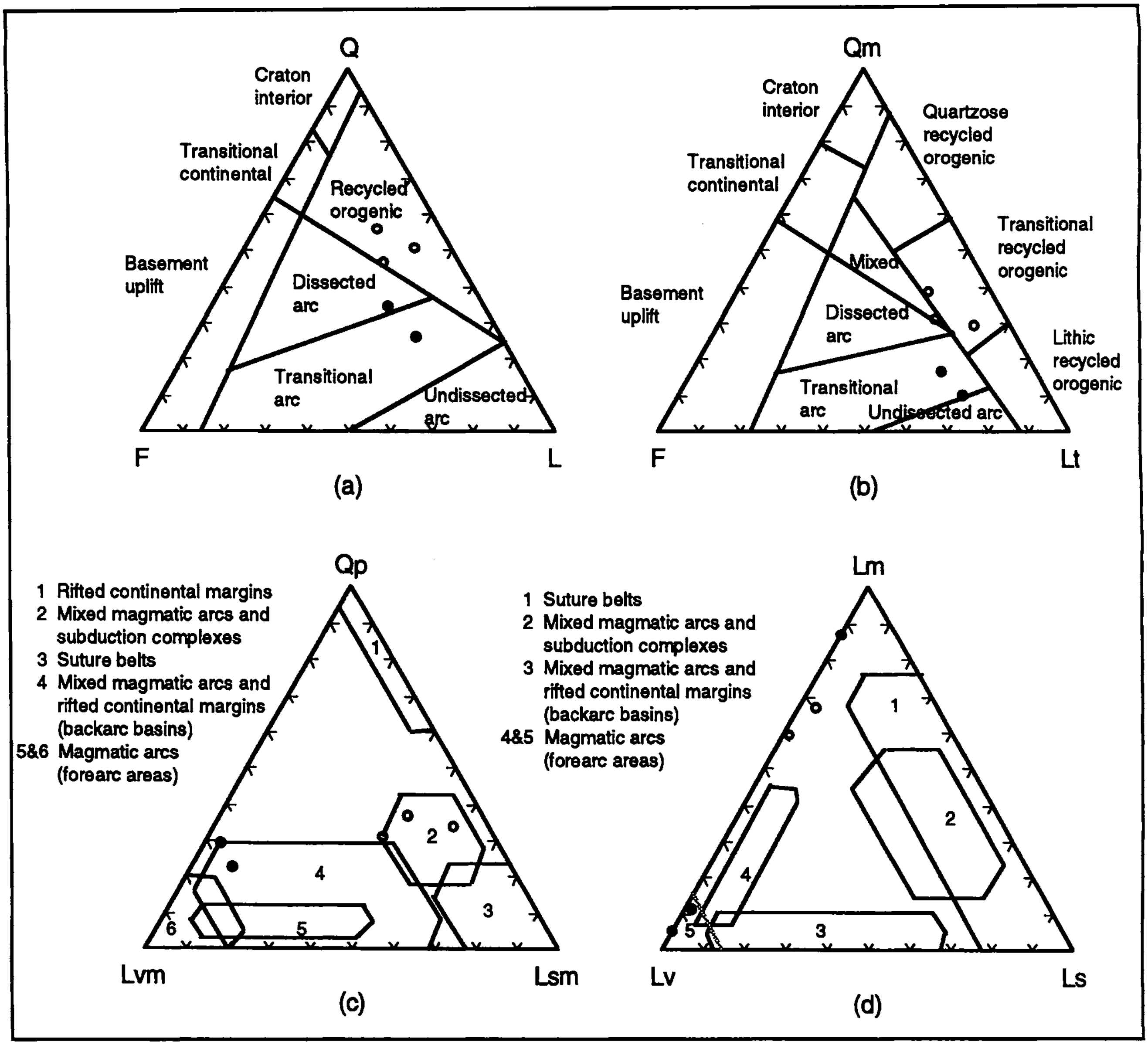

Figure 4. Ternary diagrams for the metagreywackes. Provenance fields are after Dickinson *et al.* (1983) for (a) QFL plot and (b) QmFLt plot, Ingersoll and Suczek (1979) for (c) QpLvmLsm plot and (d) LmLvLs plot. Symbols: open circles = quartz-rich greywackes and solid circles = quartz-poor greywackes.

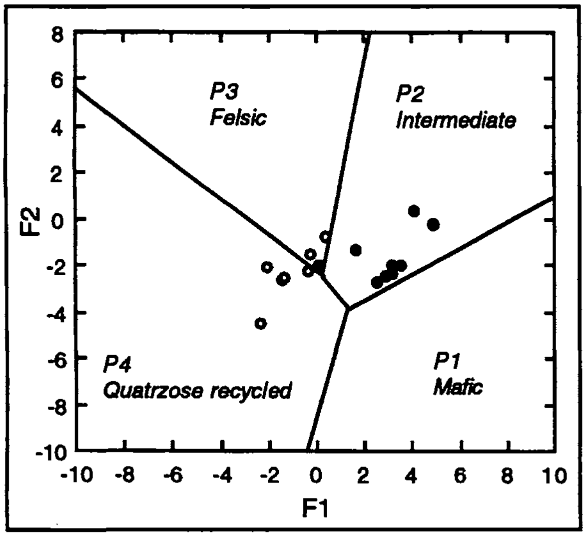

Figure 5. Major element discrimination plot for the metagreywackes. Discrimination functions (F1 and F2) and provenance fields (P1, P2, P3, and P4) are after Roser and Korsch (1988). Sample scores are calculated from anhydrous normalized data in Table 2. Symbols: open circles = PSM-1 and solid circles = PSM-2.

$F1 = 1.773\ TiO_2 + 0.607\ Al_2O_3 + 0.76\ Fe_2O_3^* - 1.5\ MgO + 0.616\ CaO + 0.509\ Na_2O - 1.224\ K_2O - 9.09$

$F1 = 0.445\ TiO_2 + 0.07\ Al_2O_3 - 0.25\ Fe_2O_3^* - 1.142\ MgO + 0.438\ CaO + 1.475\ Na_2O - 1.426\ K_2O - 6.681.$

Table 2. Whole-rock XRF analyses and ratios of major and trace elements of Pha Som Metamorphic Complex metagreywackes.

Chemical Group	PSM-1							PSM-1	Standard	PSM-2									PSM-2	Standard
Sample Mo.	SD-61	SD-82	SD-95	SD-97	SD-162	SD-193	SD-194	Mean	Deviation	P-102	P-104	P-107	SD-44	SD-86	SD-217	SD-218	SD-221	SD-225	Mean	Deviation
Major elements (wt %)																				
SiO_2	71.00	70.73	74.31	73.73	73.30	76.20	71.01	72.90	2.06	66.11	67.04	64.14	65.34	62.73	70.21	62.60	58.10	68.57	64.98	3.62
TiO_2	0.59	0.53	0.49	0.51	0.58	0.60	0.69	0.57	0.07	0.78	0.73	0.83	0.85	0.87	0.56	0.70	0.77	0.65	0.75	0.10
Al_2O_3	12.61	11.85	11.33	10.51	12.24	11.79	11.17	11.64	0.70	12.91	14.39	13.88	15.98	17.21	14.18	15.01	17.53	14.94	15.11	1.54
Fe_2O_3*	4.90	4.40	4.09	4.42	4.85	5.44	5.16	4.75	0.47	6.58	6.22	6.59	6.53	6.96	5.69	7.42	7.97	5.78	6.64	0.74
MnO	0.06	0.07	0.04	0.07	0.05	0.04	0.06	0.06	0.01	0.10	0.09	0.09	0.08	0.07	0.06	0.13	0.11	0.07	0.09	0.02
MgO	2.33	2.12	2.08	2.11	2.39	2.20	2.50	2.25	0.16	2.88	2.96	3.22	2.47	2.77	2.40	3.40	3.99	2.53	2.96	0.51
CaO	4.19	6.28	3.68	5.33	2.32	0.25	5.82	3.98	2.13	7.09	4.36	7.28	2.32	3.68	2.09	6.65	6.68	2.17	4.70	2.24
Na_2O	2.57	2.23	2.22	1.81	2.93	2.26	2.04	2.30	0.36	2.96	3.91	3.16	6.06	4.87	3.23	2.78	2.77	4.36	3.79	1.13
K_2O	1.58	1.64	1.63	1.37	1.20	1.09	1.35	1.41	0.22	0.46	0.13	0.65	0.23	0.67	1.50	1.16	1.88	0.83	0.83	0.58
P_2O_5	0.15	0.14	0.13	0.14	0.14	0.13	0.17	0.14	0.01	0.15	0.16	0.16	0.16	0.18	0.08	0.16	0.20	0.10	0.15	0.04
Total#	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	0.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	0.00
LOI	5.12	6.39	4.86	5.99	3.72	2.73	6.02	4.98	1.34	1.72	2.63	1.93	3.99	3.46	3.34	7.56	7.62	3.18	3.94	2.19
Trace elements (ppm)																				
Nb	10	8	8	8	9	9	10	9	1	5	6	5	5	5	3	3	2	3	4	1
Zr	172	162	165	166	212	176	290	192	46	147	167	155	144	153	105	107	86	116	131	28
Y	22	25	22	22	28	22	32	25	4	23	25	24	27	28	18	27	29	21	24	4
Ba	257	268	293	233	200	176	251	240	40	85	33	174	39	144	229	170	323	161	151	92
Sr	171	198	162	193	107	52	203	155	56	252	325	358	163	454	238	263	328	314	299	83
Rb	71	74	75	65	57	50	64	65	9	11	3	12	8	19	38	39	51	21	22	16
Pb	16	14	7	9	5	4	9	9	4	6	5	6	9	7	6	13	4	6	7	3
Th	12	10	11	12	12	9	18	12	3	5	5	5	4	5	3	3	2	3	4	1
Ni	28	24	23	23	22	29	26	25	3	25	25	29	15	18	16	35	54	16	26	13
Cr	64	57	56	61	62	67	78	64	7	72	59	80	45	58	49	103	213	59	82	52
V	92	84	79	81	88	87	103	88	8	136	109	138	152	161	117	166	227	145	150	34
Sc	14	13	11	12	13	12	13	13	1	16	15	17	18	18	14	23	34	16	19	6
La	28	26	21	28	27	24	32	27	3	17	12	14	13	12	7	12	12	10	12	3
Ce	55	48	43	53	51	44	67	52	8	26	29	29	30	32	16	29	22	20	26	5
Nd	24	25	21	25	25	23	28	24	2	15	17	18	17	18	10	16	15	11	15	3

Table 2. Whole-rock XRF analyses and ratios of major and trace elements of Pha Som Metamorphic Complex metagreywackes (cont'd).

Chemical Group	PSM-1							PSM-1	Standard	PSM-2									PSM-2	Standard
Sample No.	SD-61	SD-82	SD-95	SD-97	SD-162	SD-193	SD-194	Mean	Deviation	P-102	P-104	P-107	SD-44	SD-86	SD-217	SD-218	SD-221	SD-225	Mean	Deviation
Major element ratios																				
Fe_2O_3*/MgO	7.23	6.52	6.17	6.54	7.24	7.64	7.66	7.00	0.59	9.45	9.17	9.81	9.00	9.73	8.08	10.82	11.96	8.31	9.59	1.21
Al_2O_3/SiO_2	0.18	0.17	0.15	0.14	0.17	0.15	0.16	0.16	0.01	0.20	0.21	0.22	0.24	0.27	0.20	0.24	0.30	0.22	0.23	0.04
K_2O/Na_2O	0.61	0.73	0.73	0.75	0.41	0.48	0.66	0.63	0.13	0.15	0.03	0.21	0.04	0.14	0.46	0.42	0.68	0.19	0.26	0.22
$Al_2O_3/(Na_2O+CaO)$	1.86	1.39	1.92	1.47	2.33	4.70	1.42	2.16	1.17	1.28	1.74	1.33	1.91	2.01	2.67	1.59	1.86	2.29	1.85	0.44
Trace element ratios																				
Ti	3542.5	3183.1	2956.0	3053.2	3490.9	3572.1	4147.7	3420.8	403.9	4691.2	4398.7	5005.5	5066.7	5218.4	3342.2	4195.9	4586.7	3904.1	4489.9	605.6
Ti/Zr	20.6	19.6	17.9	18.4	16.5	20.3	14.3	18.2	2.3	31.9	26.3	32.3	35.2	34.1	31.8	39.2	53.3	33.7	35.3	7.6
Ti/V	38.5	37.9	37.4	37.7	39.7	41.1	40.3	38.9	1.4	34.5	40.4	36.3	33.3	32.4	28.6	25.3	20.2	26.9	30.9	6.2
Nb/Y	0.4	0.3	0.4	0.4	0.3	0.4	0.3	0.4	0.0	0.2	0.2	0.2	0.2	0.2	0.2	0.1	0.1	0.1	0.2	0.0
Zr/Nb	17.7	19.5	20.6	21.3	23.0	20.2	28.7	21.6	3.5	30.6	30.4	29.8	32.0	31.9	36.2	35.7	39.1	40.0	34.0	3.9
Zr/Y	7.9	6.6	7.5	7.5	7.5	8.1	9.2	7.8	0.8	6.4	6.8	6.6	5.4	5.5	5.9	3.9	3.0	5.7	5.5	1.2
Zr/Th	13.9	15.5	15.3	14.0	17.2	20.2	15.8	16.0	2.2	27.0	34.4	33.3	35.1	31.5	35.0	38.2	39.1	36.3	34.4	3.6
La/Y	1.3	1.1	1.0	1.2	1.0	1.1	1.0	1.1	0.1	0.7	0.5	0.6	0.5	0.4	0.4	0.5	0.4	0.5	0.5	0.1
La/Th	2.3	2.5	1.9	2.3	2.2	2.8	1.7	2.3	0.3	3.0	2.5	3.0	3.1	2.5	2.4	4.4	5.5	3.0	3.3	1.0
La/Sc	2.0	2.0	1.9	2.3	2.1	2.0	2.5	2.1	0.2	1.0	0.8	0.8	0.7	0.7	0.5	0.5	0.4	0.6	0.7	0.2
Th/Sc	0.9	0.8	1.0	1.0	1.0	0.7	1.4	1.0	0.2	0.3	0.3	0.3	0.2	0.3	0.2	0.1	0.1	0.2	0.2	0.1
Ce/V	0.6	0.6	0.5	0.7	0.6	0.5	0.6	0.6	0.1	0.2	0.3	0.2	0.2	0.2	0.1	0.2	0.1	0.1	0.2	0.1

* Total Fe as Fe_2O_3*

Analyses were recalculated and normalized to 100% anhydrous

LOI = Loss on ignition

in interarc, backarc, and forearc basins adjacent to felsic-dominated island arcs, that formed on well-developed continental crust. The examples include the Lau Basin and the Japan Sea (Bhatia, 1983; Bhatia and Crook, 1986). On the ternary plots La-Th-Sc (Fig. 7a) and Th-Sc-Zr/10 (Fig. 7b) of Bhatia and Crook (1986), these samples all plot within the continental island arc field.

On the Ti/Zr-La/Sc and Y/Nb-Th/Sc diagrams (Figs. 8a, 8b) of Roser and Cooper (1990), these samples plot within the fields for the Permian-Cretaceous Torlesse terrane in New Zealand, which is dominated by quartzofeldspathic strata considered to have been derived from an active continental magmatic arc and deposited in a trench or submarine fan setting at the subduction margin (MacKinnon, 1983; Roser and Korsch, 1988). The Ce/V-La/Y plot (Fig. 8c) of Mortimer and Roser (1992) also indicates the similarity between PSM-1 samples and those of the Torlesse terrane.

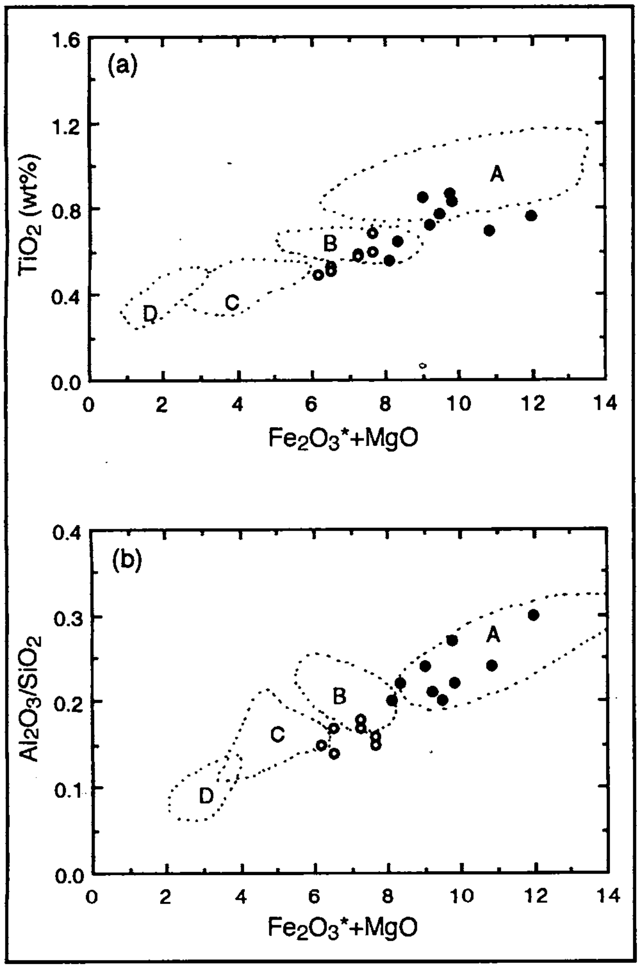

Figure 6. Discrimination plots for the metagreywackes: (a) TiO_2 versus Fe_2O_3* + MgO and (b) Al_2O_3/SiO_2 versus Fe_2O_3* + MgO. Fields: A = oceanic island arc, B = continental island arc, C = active continental margin, D = passive margin (after Bhatia, 1983). Symbols: open circles = PSM-1 and solid circles = PSM-2.

From the major element characteristics of the PSM-1 samples, a continental island arc or quartzose recycled terrain cannot be distinguished using the Roser and Korsch diagram (Fig. 5). This is probably due either to the effect of metamorphism on some of the major elements, particularly Na, K, Ca, and Si, or to the limitation of this diagram. However, this limitation could not be assessed. The Bhatia diagrams (Figs. 7a, 7b), in contrast, clearly delineate the continental arc source of the PSM-1 psammites.

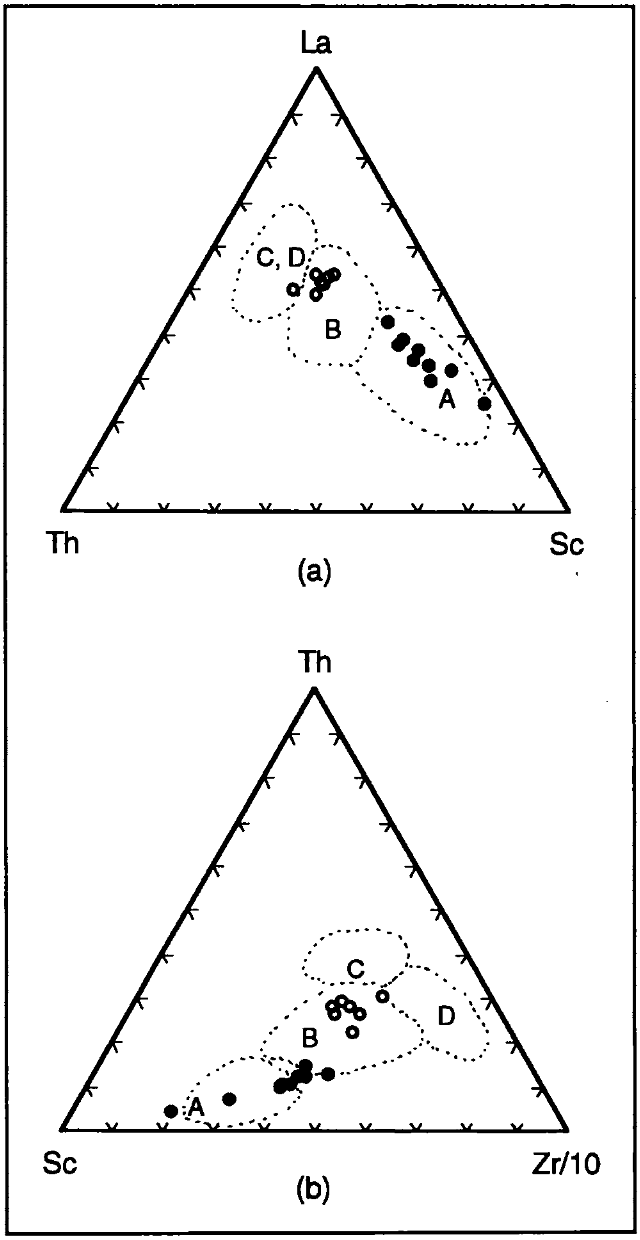

Figure 7. Discrimination plots for the metagreywackes: (a) La-Th-Sc and (b) Th-Sc-Zr/10. Fields: A = oceanic island arc, B = continental island arc, C = active continental margin, D = passive margin (after Bhatia and Crook, 1986). Symbols: open circles = PSM-1 and solid circles = PSM-2.

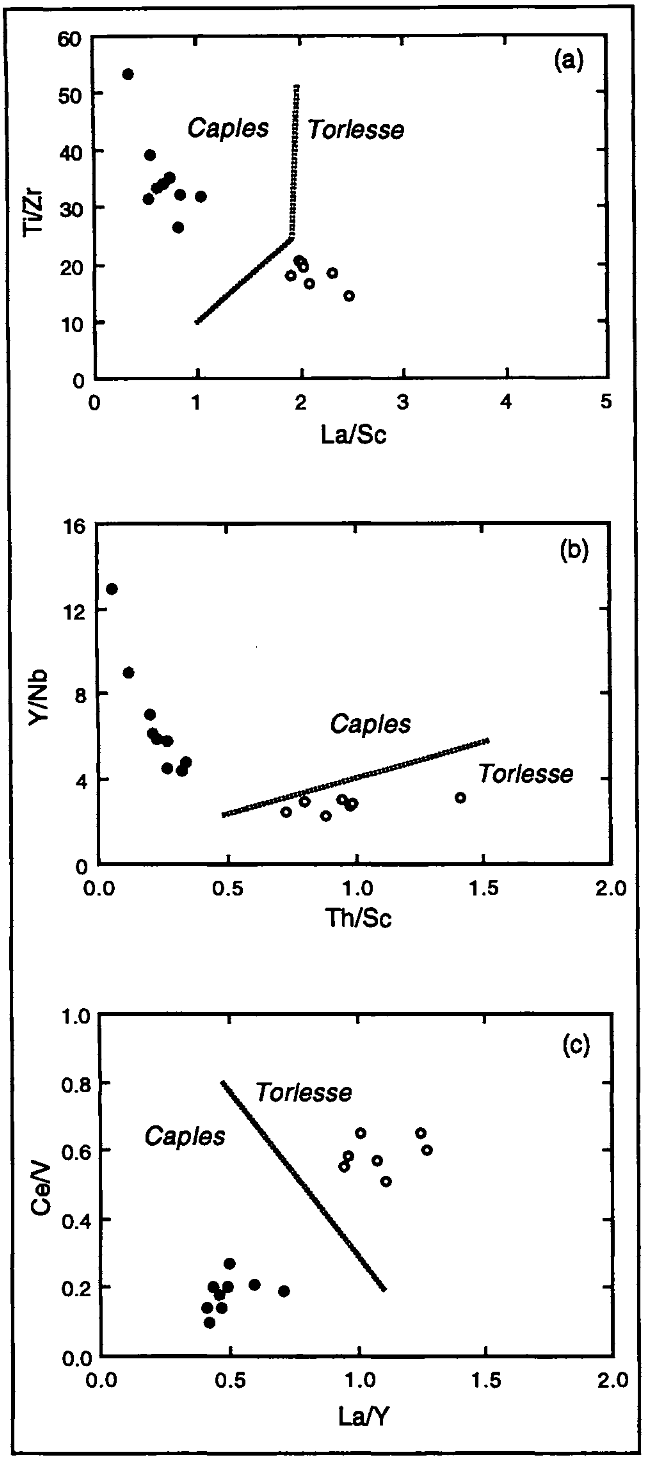

Figure 8. Discrimination plots for the metagreywackes: (a) Ti/Zr versus La/Sc, (b) Y/Nb versus Th/Sc, and (c) Ce/V versus La/Y. The lines separating the compositional fields of the Torlesse and Caples terrane rocks in New Zealand are after Roser and Cooper (1990) and Mortimer and Roser (1992). Symbols: open circles = PSM-1 and solid circles = PSM-2.

The immobile trace element characteristics (Figs. 7a, 7b) clearly point to the continental island arc source for the PSM-1 psammites. The similarity in terms of trace element geochemistry between the PSM-1 samples and those of the Torlesse terrane in New Zealand strongly supports that the PSM-1 samples represent sediments that were derived from an active continental magmatic arc, as do the Torlesse sediments (MacKinnon, 1983). It is probable, despite the circumstantial nature of the evidence, that these two suites were deposited in a similar setting, this being a trench or submarine fan setting at the subduction margin. In addition, the geochemical characteristics of the greywackes and metagreywackes of the PSM-1 group lend support to the interpretation that the quartz-rich greywackes were probably deposited in a slope basin formed on top of the accretionary complex.

PSM-2

The PSM-2 metagreywackes include one greywacke, SD-225); three semischists, P-102, P-104, and P-107; and five fine-grained schists, SD-44, SD-86, SD-217, SD-218,and SD-221.

Major elements: PSM-2 samples are characterised by relatively high average concentrations of TiO_2 (0.75±0.1 wt %), Al_2O_3 (15.11±1.54 wt %), and Fe_2O_3* (6.64±0.74 wt %), as shown in Table 2. These samples plot within the intermediate igneous rock provenance and overlap into the mafic igneous rock provenance on the discrimination diagram of Roser and Korsch (1988), shown in Figure 5. This suggests a provenance transitional between intermediate and mafic island arcs. On the TiO_2 versus Fe_2O_3*+MgO and Al_2O_3/SiO_2 versus Fe_2O_3*+MgO plots of Bhatia (1983), these samples all fall within the fields for oceanic island arc (Figs. 6a, 6b).

Trace elements: PSM-2 samples are characterised by relatively high average concentrations of V (131±28 ppm) and a high ratio of Zr/Th (34.4±3.6) and by relatively low abundances of Pb (7±3 ppm), Th (4±1 ppm), light rare-earth elements such as, La (12±3 ppm), Ce (26±5 ppm), and Nd (15±3 ppm), and the ratios of Th/Sc (0.2±0.1) and Ce/V (0.2±0.1), as shown in Table 2.

Comparison with greywackes from various tectonic settings from eastern Australia (Bhatia and Crook, 1986) suggests that the PSM-2 metagreywackes are similar to those from an oceanic island arc setting, this being a sedimentary basin adjacent to an oceanic island arc, like the Mariana Islands, or an island arc partly formed on thin continental crust, like the Aleutian Islands, where sediments are mainly derived from subalkaline volcanic rocks (Bhatia, 1983; Bhatia and Crook, 1986). On the ternary plots La-Th-Sc (Fig. 7a) of Bhatia and Crook (1986), the PSM-2 samples plot within the oceanic island arc field but plot near the boundary between the oceanic island arc and continental island arc fields on the ternary plot Th-Sc-Zr/10 (Fig. 7b).

On the Ti/Zr-La/Sc and Y/Nb-Th/Sc diagrams (Fig. 8a, 8b) of Roser and Cooper (1990), these samples plot within the fields for the Caples terrane in New Zealand, which is dominated by volcanogenic sediments. The Ce/V-La/Y plot (Fig. 8c) of Mortimer and Roser (1992) also indicates the similarity between PSM-2 samples and those of the Caples terrane.

From their major and trace element characteristics, all discrimination plots show that the PSM-2 metagreywackes represent sediments derived from oceanic-island arc rocks. As with the PSM-1 samples, an intermediate or mafic igneous provenance of the PSM-2 samples cannot be distinguished using the Roser and Korsch diagram (Fig. 5). This limitation made the general applicability of the diagram uncertain. The similarity between the PSM-2 metagreywackes and those of the Caples terrane in New Zealand lends strong support to the volcanic arc source for the PSM-2 metagreywackes. The geochemical characteristics of sample SD-225 and equivalent metagreywackes of the PSM-2 group suggest that the quartz-poor greywackes possibly represent the sediments of a slope basin formed on top of the accretionary complex. Alternatively, they may have been sediments in forearc basins deposited on top of, and later incorporated into, the accretionary complex in a manner similar to that of the slope-basin sediments.

TECTONIC IMPLICATIONS

The Pha Som Metamorphic Complex metagreywackes were derived from continental and oceanic island arc sources during Permian to Middle Triassic time. The process responsible for the mixing or juxtaposition of these metagreywackes of the two sources are still unclear. The probable scenario would be tectonic mixing during subduction accretion and/or terrane collision. Alternatively, the mixing might be related to the change in tectonic setting through time, a change from oceanic arc setting to continental arc setting. However, this problem could not be resolved in this study. The modern analogs for such island arc sources are the Alaska peninsula, representing a continental island arc setting, and its continuation in Pacific Ocean, the Aleutian arc, representing an oceanic island arc setting. This implies the subduction of one plate beneath the other and the existence of a major ocean between the continental terranes during the Permian (probably older) to Middle Triassic. These continental terranes have been referred to as the Shan-Thai and Indochina terranes. The subduction stage is represented by the formation of the Pha Som Metamorphic Complex interpreted as the accretionary complex built on the west-dipping subduction zone (Singharajwarapan and Berry, 1993; Singharajwarapan, 1994). The destruction of this major ocean probably began in Middle Triassic time and culminated in Late Triassic-Early Jurassic time via the collision between the Shan-Thai and Indochina terranes. The timing of collision is well supported by the folding-thrusting event recorded in the Triassic turbidite sequence (Singharajwarapan, 1994), the extensive intrusions of Upper Triassic-Lower Jurassic post-orogenic granites (Cobbing *et al.*, 1986), and the post-orogenic deposition of Jurassic-Cretaceous red beds across the suture (Department of Mineral Resources, 1987). The regional structures formed during the collisional event were later overprinted by extensive normal and strike-slip faulting related to crustal extension during Middle-Late Tertiary (Polachan and Sattayarak, 1989) that resulted in the formation of a large number of extensional basins and in the uplift of Paleozoic and Mesozoic rocks in Thailand.

CONCLUSIONS

Metagreywackes of the Pha Som Metamorphic Complex are of two types on tha basis of modal composition of framework grains: quartz-rich greywackes and quartz-poor greywackes. The quartz-rich greywackes are interpreted to have been derived from an accretionary complex mixed with detritus from a magmatic arc source and were deposited in a slope basin formed on top of, and later incorporated into, the accretionary complex. The quartz-poor greywackes were probably derived from a magmatic arc source.

Geochemically, metagreywackes are divided into two categories, the PSM-1 group and the PSM-2 group. Immobile trace element characteristics suggest that the PSM-1 group was derived from continental island arc source. Compositional similarities with those of the Torlesse terrane in New Zealand suggest that the PSM-1 group metagreywackes were probably derived from a similar source, this being an active continental magmatic arc. Deposition was probably in a trench or submarine fan setting at a subduction margin. The PSM-2 samples are interpreted to represent sediments derived mainly from an oceanic island arc source. Strong compositional similarities between the PSM-2 samples and those of the Caples terrane in New Zealand further point toward an intra-oceanic arc source.

The process responsible for the mixing or juxtaposition of these metagreywackes of the two sources could not be clarified in this study. However, the results firmly support the existence of an ancient accretionary complex prior to the collision of the Shan-Thai and Indochina terranes in Late Triassic-Early Jurassic time.

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REFERENCES

BARR, S.M. AND MACDONALD, A.S., 1987. Nan River suture zone, northern Thailand. *Geology, 15*, 907-910.

BARR, S.M., MACDONALD, A.S., YAOWANOIYOTHIN, W. AND PANJASAWATWONG, Y., 1985. Occurrence of blueschist in the Nan River mafic-ultramafic belt, northern Thailand. *Warta Geologi, 11*, 47-50.

BHATIA, M.R., 1983. Plate tectonics and geochemical composition of sandstones. *Journal of Geology, 91*, 611-627.

BHATIA, M.R. AND CROOK, K.A.W., 1986. Trace element characteristics of greywackes and tectonic setting discrimination of sedimentary basins. Contributions to *Mineralogy and Petrology, 92*, 181-193.

BHATIA, M.R. AND TAYLOR, S.R., 1981. Trace-element geochemistry and sedimentary provinces: A study from the Tasman geosyncline, Australia. *Chemical Geology, 33*, 115-1125.

BUNOPAS, S., 1981. *Paleogeographic History of Western Thailand and Adjacent Parts of South-East Asia — A Plate Tectonic Interpretation.* Unpublished Ph.D. thesis, Victoria University of Wellinton, 810p (Reprinted 1982, *Geological Survey Paper 5*, Geological Survey Division, Department of Mineral Resources, Thailand).

BUNOPAS, S. AND VELLA, P., 1978. Late Palaeozoic and Mesozoic structural evolution of northern Thailand: a plate tectonic model. *In*: Nutalaya, P. (Ed.), *Proceedings of the Third Regional Conference on Geology and Mineral Resources of Southeast Asia, Bangkok*, 133-140.

COBBING, E.J., MALLICK, D.I.J., PITFIELD, P.E.J. AND TEOH, L.H., 1986. The granites of the Southeast Asian Tin Belt. *Journal of the Geological Society, London, 143*, 537-550.

COOMBS, D.S., LANDIS, C.A., NORRIS, R.J., SINTON, J.M., BORNS, D.J. AND CRAW, D., 1976. The Dunn Mountain Ophiolite Belt, New Zealand, its tectonic setting, constitution, and origin, with special reference to the southern portion. *American Journal of Science, 276*, 561-603.

CROOK, K.A.W., 1974. Lithogenesis and geotectonics: The significance of compositional variation in flysch arenites (greywackes). *In*: Dott, R.H. and Shaver, R.H. (Eds.), Modern and Ancient Geosynclinal Sedimentation. *Society of Economic Paleontology and Mineralogy Special Publication, 19*, 304-310.

DEPARTMENT OF MINERAL RESOURCES, 1987. *Geological Map of Thailand* (1:2,500,000 scale), Department of Mineral Resources, Bangkok.

DICKINSON, W.R., 1970. Interpreting detrital modes of greywacke and arkose. *Journal of Sedimentary Petrology, 40*, 695-707.

DICKINSON, W.R., 1985. Interpreting provenance relations from detrital modes of sandstones. *In*: Zuffa, G.G. (Ed.), Provenance of Arenites. *NATO Advanced Study Institute Series*, D. Reidel, 331-361.

DICKINSON, W.R., BEARD, L.S., BRAKENRIDGE, G.R., ERJAVEC, J.L., FERGUSON, R.C., INMAN, K.F., KNEPP, R.A., LINDBERG, F.A. AND RYBERG, P.T., 1983. Provenance of North American Phenerozoic sandstones in relation to tectonic setting. *Geological Society of America Bulletin, 94*, 222-235.

DICKINSON, W.R. AND SUCZEK, C.A., 1979. Plate tectonics and sandstone compositions. *American Association of Petroleum Geologists Bulletin, 63*, 2164-2182.

HESS, A. AND KOCH, K.E., 1975. *Geological Map of Nan* (1:250,000), Federal Institute of Geosciences and Natural Resources, Hannover.

INGERSOLL, R.V., BULLARD, T.F., FORD, R.L., GRIMM, J.P., PICKLE, J.D. AND SARES, S.W., 1984. The effect of grain size on detrital modes: A test of the Gazzi-Dickinson point-counting method. *Journal of Sedimentary Petrology*, 54, 103-116.

INGERSOLL, R.V. AND SUCZEK, C.A., 1979. Petrology and provenance of Neogene sand from Nicobar and Bengal fans, DSDP sites 211 and 218. *Journal of Sedimentary Petrology, 49*, 1217-1228.

LUDDECKE, S., CHONGLAKMANI, C. AND HELMKE, D., 1991. Analysis of pebble associations from the marine Triassic of northern Thailand. *Journal of Thai Geosciences, 2*, 91-101.

MACDONALD, A.S. AND BARR, S.M., 1984. The Nan River mafic-ultramafic belt, northern Thailand: Geochemistry and tectonic significance. *Bull. Geol. Soc. Malaysia, 17*, 209-224.

MACKINNON, T.C., 1983. Origin of the Torlesse terrane and coeval rocks, south Island, New Zealand. *Bull. Geol. Soc. America, 94*, 967-985.

MARSAGLIA, K.M. AND INGERSOLL, R.V., 1992. Compositional trends in arc-related, deep-marine sand and sandstone: A reassessment of magmatic provenance. *Bull. Geol. Soc. America, 104*, 1637-1649.

MAYNARD, J.B., VALLONI, R. AND YU, H.S., 1982. Composition of modern deep-sea sands from arc related basins. *In*: Legget, J.K. (Ed.), Trench-Forearc Geology: Sedimentation and Tectonics on Modern and Ancient Active Plate Margins. *Geological Society Special Publication No. 10*, 551-561.

MCLENNAN, S.M. AND TAYLOR, S.R., 1991. Sedimentary rocks and crustal evolution: tectonic setting and secular trends. *Journal of Geology, 99*, 1-21.

MORTIMER, N. AND ROSER, B.P., 1992. Geochemical evidence for the position of the Caples-Torlesse boundary in the Otago Schist, New Zealand. *Journal of the Geological Society, London, 149*, 967-977.

NORRISH, K. AND CHAPPELL, B.W., 1967. X-ray fluorescence spectrography. *In*: Zussman, J. (Ed.), *Physical Methods in Determinative Mineralogy*. Acadamic Press, London, 161-214.

NORRISH, K. AND HUTTON, J.T., 1969. An accurate X-ray spectrographic method for the analysis of a wide range of geological samples. *Geochemica et Cosmochimica Acta, 33*, 431-455.

PANJASAWATWONG, Y., 1991. Petrology, geochemistry and tectonic implications of igneous rocks in the Nan suture, Thailand and an empirical study of the effects of Ca/Na, Al/Si and H_2O on plagioclase-melt equilibria at 5-10 kb pressure. Unpublished Ph.D. thesis, University of Tasmania, 239p.

PATERSON, S.R. AND SAMPLE, J.C., 1988. The development of folds and cleavages in slate belts by underplating in accretionary complexes: A comparison of the Kodiak Formation, Alaska and the Calveras Complex, California. *Tectonics, 7*, 859-874.

PEARCE, J.A. AND CANN, J.R., 1973. Tectonic setting of basic volcanic rocks determined using trace element analyses. *Earth and Planetary Science Letter, 19*, 290-300.

PETTIJOHN, F.J., POTTER, P.E. AND SIEVER, R., 1972. *Sand and Sandstone*. Springer-Verlag, New York, 618p.

PIYASIN, S., 1972. Geology of Lampang. *Report of Investigation No. 14, Department of Mineral Resources, Bangkok*, 98p.

POLACHAN, S. AND SATTAYARAK, N., 1989. Strike-slip tectonics and the development of Tertiary basins in Thailand. *In*: Thanasuthipitak, T. and Ounchanum, P. (Eds.), *Proceedings of the International Symposium on Intermontane Basins: Geology and Resources, Chiang Mai University, Chiang Mai*, 243-253.

ROSER, B.P. AND COOPER, A.F., 1990. Geochemistry and terrane affiliation of Haast Schist from the western Southern Alps, New Zealand. *New Zealand Journal of Geology and Geophysics, 33*, 1-10.

ROSER, B.P. AND KORSCH, R.J., 1988. Provenance signatures of sandstone-mudstone suites determined using discriminant function analysis of major-element data. *Chemical Geology, 67*, 119-139.

SAMPLE, J.C. AND FISHER, D.M., 1986. Duplex accretion and underplating in an accretionary complex, Kodiak islands, Alaska. *Geology, 14*, 160-163.

SAMPLE, J.C. AND MOORE, J.C., 1987. Structural styles and kinematics of an under plated slate belt, Kodiak and adjacent islands. *Bull. Geol. Soc. America, 99*, 191-213.

SINGHARAJWARAPAN, S., 1994. *Deformation and Metamorphism of the Sukhothai Fold Belt, Northern Thailand*. Unpublished Ph.D. Thesis, University of Tasmania, 385p.

SINGHARAJWARAPAN, S. AND BERRY, R.F., 1993. Structural analysis of the accretionary complex in Sirikit Dam area, Uttaradit, Northern Thailand. *Journal of Southeast Asian Earth Sciences, 8*, 233-245.

SPRY, A., 1969, *Metamorphic Textures*. Pergamon Press, Oxford, 350p.

THANASUTHIPITAK, T., 1978. Geology of Uttaradit area and its implications on tectonic history of Thailand. *In*: Nutalaya, P. (Ed.), *Proceedings of the Third Regional Conference on Geology and Mineral Resources of Southeast Asia, Bangkok*, 187-197.

TURNER, F.J., 1938. Progressive regional metamorphism in Southern New Zealand. *Geological Magazine, 75*, 160-174.

VALLONI, R. AND MAYNARD, J.B., 1981. Detrital modes of recent deep-sea sands and their relation to tectonic setting: a first approximation. *Sedimentology, 84*, 195-212.

WINCHESTER, J.A. AND FLOYD, P.A., 1976. Geochemical magma type discrimination: application to altered and metamorphosed basic igneous rocks. *Earth and Planetary Science Letters, 28*, 459-469.

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