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Nd-Sr ISOTOPIC COMPOSITION AND GEOCHEMISTRY OF SEDIMENTS FROM TAIWAN AND THEIR IMPLICATIONS

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ABSTRACT

The Nd isotopic composition and geochemistry of the earliest Cenozoic to Oligocene metasedimentary and sedimentary rocks together with those of metasedimentary rocks of the Tananao Schist in Taiwan were studied. Most rocks demonstrate geochemical and Nd isotopic characteristics typical to those of the upper continental crust in the South China region. These results imply that most rocks are recycled continental crustal material. However, Nd isotopic compositions seem to show secular variation of decreasing ε_{Nd} value with deceasing stratigraphic age for both the pre-Eocene metasedimentary rocks and the Tertiary sedimentary rocks. The high ε_{Nd} values for the Eocene rocks compared to other Tertiary rocks are probably due to the incorporation of sediments from Cretaceous I-type rocks of Southeast China. The Jurassic metapelites of the Tailuko belt exhibit the highest ε_{Nd} values among all metasedimentary rocks. This suggests that either the source material of the metapelites of the Tailuko belt had received mantle inputs (arc material) or that the metapelites were later metasomatized during a granitization event which occurred in the Cretaceous Period.

Key words: Nd-Sr isotope, geochemistry, sediment, Taiwan, South China

INTRODUCTION

Sediments and granitoids provide an excellent opportunity to foster our understanding of the formation and evolution of continental crust through geological time. Chen *et al*. (1990)

conducted Sm-Nd isotopic and geochemical studies on late Paleozoic to Miocene sedimentary and metasedimentary rocks of Taiwan and found no obvious secular variation with respect to the deposition age of those rocks. They suggested the sources of the sediments were primarily recycled pre-existing continental crust and derived from typical continental crust. A few late Paleozoic metasedimentary rocks might have been influenced by fresh mantle inputs to their provenance. Lan *et al*. (1995) carried out a Sr-Nd-O isotopic study of mid-Cretaceous granitoids and associated metapelites of the basement complex (Tananao Schist) of Taiwan. They concluded that both granitoid and metapelites received not only recycled continental crustal material but also fresh mantle input. Based on published data, Lan *et al*. (1996) summarized that late Paleozoic to early Mesozoic metasedimentary rocks of the Tananao Schist (Old Taiwan) have higher ε_{Nd} values (-12 to -6) than those (-15 to -9) of sedimentary rocks ranging from the late Mesozoic to Miocene of Taiwan (Young Taiwan). Sun *et al*. (1998) examined the Sr-Nd isotopic and geochemical studies on Cretaceous meta-igneous rocks and blackschists of Yuli belt from the Tananao Schist of Taiwan. They indicated that T_{DM} ages of blackschists are identical to Taiwan sediments and are derivatives of the basement strata of the Eurasian continental margin.

Extended metasedimentary and sedimentary rocks in Taiwan from the earliest Cenozoic to Oligocene age were studied. The geochemistry of the metapelites of the Tailuko belt, not discussed in Lan *et al*. (1995), is presented here. The main purpose of this paper is to document the new isotopic and geochemical characteristics of these metasedimentary and sedimentary rocks. Combined with previous data, the authors intend to describe the secular trends of Nd isotopic composition for these rocks. Such a feature was not observed in Lan *et al*. (1996). We will also provide one rationale for the occurrence of such a phenomena.

SAMPLES

The new samples collected in this study are one phyllite of Chulai Formation, one quartzitic sandstone of Szeleng Sandstone, one sandstone of Meichi Sandstone, one argillite of Kankou Formation, two sandstones of Tsuku Formation and one argillite of Tatungshan Formation. Their sample localities are shown in Figure 1.

The depositional age of several of the formation is problematic due to the lack of diagnostic fossils. However, the sequence of stratigraphic units is accurate according to the detailed field investigations of many geologists and is described by Ho (1988). The basement complex of Taiwan, the Tananao Schist, has experienced a complicated metamorphic and tectonic history. It has been divided into a western Tailuko belt and an eastern Yuli belt (Yen, 1963). The metapelite of the Tailuko belt belongs to the Tienhsiang Formation, which lies stratigraphically below the blackschist of Yuli Formation of the Yuli belt (Wang, 1982). The two belts represent accretionary complexes of different ages - the Tailuko belt being Jurassic and the Yuli belt being Cretaceous (Chen, 1989; Yui *et al*., 1990, 1998). The Chulai Formation was proposed by Stanley *et al*. (1981) during their field study along the Southern Cross-Island highway. It rests unconformably on the Yuli Formation of the Tananao Schist and was overlain unconformably by the Hsinkao Formation. The Szeleng Sandstone, the Kankou Formation and the Tatungshan Formation are widely exposed in the northern part of the Hsuehshan Range belt. The Kankou Formation overlies the Szeleng Sandstone and grades upward into the Tatungshan Formation. Thick sandstone beds are abundant in the lower part of the Tatungshan Formation and were named the Tsuku Sandstone, which serves as a well-defined marker that separates the

Tatungshan Formation from the underlying Kankou Formation. Southward towards central Taiwan, the Szeleng Sandstone is replaced by the Meichi Sandstone in the eastern part of the Hsuehshan Range belt.

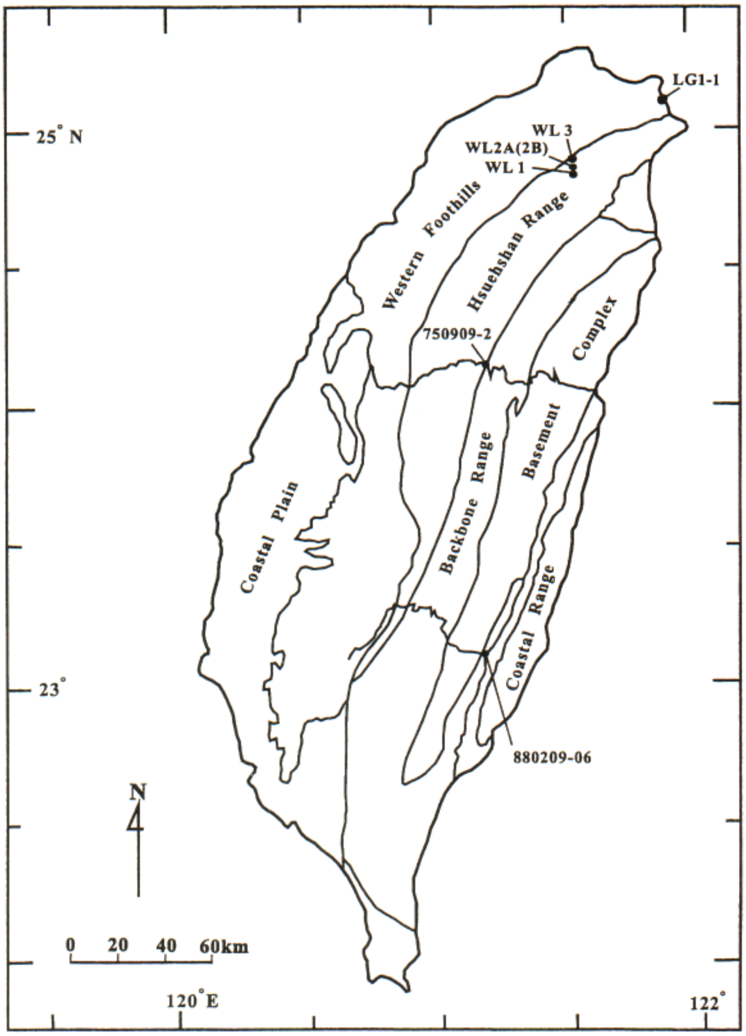

Figure 1. Sample localities for the rocks in this study. The various lithotectonic belts of Taiwan are illustrated from west to east: (1) Coastal Plain consisting of poorly consolidated, clastic sediments from Pleistocene to Recent in age; (2) Western Foothills containing shallow marine detrital units of Miocene to Pleistocene age; (3) Hsuehshan Range consisting of Eocene and Oligocene metasandstones, argillites and slates; (4) Backbone Range consisting mainly of Paleocene, Eocene and Miocene slaty and phyllitic meta-clastic rocks; (5) Pre-Cenozoic Basement Complex consisting of Permian to Mesozoic pelitic schists, marble and metavolcanics; (6) Miocene-Pleistocene arc-related Coastal Range.

The Hsinkao Formation is equivalent to the Pilushan Formation and, based on nannofossils and large foraminifers of *Assilina*, is Eocene in age (Ho, 1988). The Chulai Formation is ascribed to pre-Eocene but post-Cretaceous, and tentatively assigned to the earliest Cenozoic Period on the basis of stratigraphic relationship. Based on the foraminiferal fauna (Huang and Cheng, 1983) and nannofossils (Huang, 1977), the Kankou Formation and Tatungshan Formation have been ascertained to be Oligocene. The Szeleng Sandstone and Meichi Sandstone are tentatively thought to be Eocene to early Oligocene in age on the basis of inferred stratigraphic sequence. For simplicity, the following text denotes both as Eocene.

ANALYTICAL PROCEDURES

Sr and Nd separation was achieved using conventional cation-exchange chromatography (Lan *et al*., 1986; Shen *et al*., 1993). Isotopic ratios were determined on a VG354 mass spectrometer at the Institute of Earth Sciences, Academia Sinica, Taipei, and were corrected for mass fractionation by normalizing to $^{86}Sr/^{88}Sr$=0.1194 and $^{146}Nd/^{144}Nd$=0.7219, respectively. Values for the NBS987 Sr standard yielded $^{87}Sr/^{86}Sr$=0.710226 with a long-term reproducibility of 0.000038 (95% confidence level) and for the La Jolla (UCSD) Nd standard, yielded $^{143}Nd/^{144}Nd$=0.511845 with a long-term reproducibility of 0.000020.

Geochemical analyses were conducted at the Department of Geosciences, Franklin and Marshall College, U. S. A. using X-ray fluorescence (XRF) techniques. Fused glass disks (0.4000 grams rock powder to 3.6000 grams lithium tetraborate) and pressed powder briquettes (7.0000 grams rock powder to 1.4000 grams copolywax) were used, for major- and eleven trace-elements (Rb, Ba, Sr, Zr, Y, Cr, V, Ni, La, Ce, Yb) respectively. An ICP-AES spectrometer was used for three trace elements (Be, Sc, Co). The amount of ferrous Fe was determined using a modified Reichen and Fahey (1962) method. Analytical uncertainties range from 1% to 5% for major elements and from 2% to 10% for minor elements. Boyd and Mertzman (1987) and Mertzman (2000) report the analytical details. For metapelites of the Tailuko belt in the Tananao Schist, the concentrations of nine rare-earth elements (REE) along with Cs, Th, U, Hf, Ta and Sb were analyzed at the Department of Geology, University of Western Ontario, Canada, using instrumental neutron activation analysis, while concentrations of Pb, Nb, Cu, Zn and Ga were determined by XRF. Reproducibility varies from better than 5% to 15%. Details of the analysis are reported in Lan *et al*. (1991).

RESULTS

Isotopic compositions and major and trace element concentrations for the earliest Cenozoic to Oligocene metasedimentary and sedimentary rocks are presented in Table 1. Major and trace element concentrations for the Jurassic metapelites in the Tailuko belt are listed in Table 2.

The present ε_{Nd} values of the earliest Cenozoic to Oligocene metasedimentary and sedimentary rocks (Tab. 1) range from -16.2 to -11.1 and $^{87}Sr/^{86}Sr$ values range from 0.71678 to 0.72216. The sample from the earliest Cenozoic Chulai Formation has the lowest ε_{Nd} value (-16.2), irrespective of the high error range of $\pm 1\varepsilon$. Two samples from the Eocene have the highest ε_{Nd} values ranging from -11.8 to -11.1. Four samples from the Oligocene show intermediate ε_{Nd} values ranging from -12.2 to -13.8. By contrast, Sr isotopic ratios do not show any restricted values between the aforementioned stratigraphic units.

Table 1. Major and trace element concentrations and Sr and Sm-Nd isotopic data of the earliest Cenozoic to Oligocene metasedimentary to sedimentary rocks from Taiwan.

Stratigraphy	Chulai	Szeleng	Meichi	Kankou	Tsuku	Tsuku	Tatungshan
Age	E. Cenozoic	Eocene		Oligocene			
Sample No.	880209-06	LG1-1	750909-2	WL1	WL2A	WL2B	WL3
SiO_2 (wt%)	80.61	95.02	86.50	58.75	60.34	67.06	66.43
TiO_2	0.55	0.04	0.44	0.81	0.90	0.74	0.76
Al_2O_3	10.11	3.49	7.04	17.36	17.97	12.81	14.44
Fe_2O_3	1.09	0.01	0.24	1.32	2.14	1.73	1.61
FeO	1.13	0.07	0.46	4.66	3.65	3.90	3.58
MnO	0.10	0.00	0.01	0.09	0.07	0.07	0.05
MgO	0.40	0.00	0.32	3.00	2.49	2.50	2.22
CaO	0.22	0.03	0.64	2.53	1.22	2.00	1.35
Na_2O	2.32	0.00	0.50	0.99	1.41	1.76	1.71
K_2O	2.03	0.66	2.02	3.47	3.84	2.05	2.71
P_2O_5	0.05	0.00	0.04	0.11	0.13	0.10	0.11
LOI	1.38	0.90	1.81	7.50	6.14	5.31	5.29
Total	99.99	100.22	100.02	100.59	100.30	100.03	100.26
La (ppm)	34	4	31	42	45	30	32
Ce	106	8	97	83	89	68	73
Nd[1]	5.33						
Sm[1]	30.24						
Yb	1.5	0.1	2.4	2.7	3.0	2.2	2.3
Rb	71	23	78	157	169	89	112
Ba	566	80	415	483	567	317	365
Sr	48	2	89	92	95	102	93
Zr	387	33	593	202	211	225	242
Y	10	8	27	27	31	24	25
Be	1.4	0.3	0.9	2.9	3.3	1.7	2.3
Cr	78	118	66	78	89	72	74
V	49	3	25	99	110	73	78
Sc	6	1	3	14	15	10	10
Ni	14	1	6	39	36	31	31
Co	8	2	4	14	12	11	12
$(La/Yb)_N$	14.9	25.1	8.5	10.3	9.9	9.0	9.2
$^{87}Sr/^{86}Sr$	0.71840	0.72216	0.71867	0.71995	0.72030	0.71678	0.71878
$\pm 2\sigma$	0.00007	0.00004	0.00004	0.00004	0.00004	0.00004	0.00004
$^{143}Nd/^{144}Nd$	0.511807	0.512069	0.512033	0.511940	0.511945	0.512013	0.511932
$\pm 2\sigma$	0.000061	0.000020	0.000020	0.000021	0.000025	0.000021	0.000021
$\varepsilon_{Nd}(0)$[2]	-16.2	-11.1	-11.8	-13.6	-13.5	-12.2	-13.8
T_{DM}[3] (Ga)	1.9						

[1] Sm and Nd concentrations obtained by isotope dilution method with uncertainties of 0.5%

[2] $\varepsilon_{Nd}(0) = [(^{143}Nd/^{144}Nd)_{sample}/0.512638 - 1] \times 10^4$

[3] crustal residence model age assuming derivation from a depleted mantle source with present ε_{Nd} of +10

$T_{DM} = 1/\lambda \times \ln\{1 + [(^{143}Nd/^{144}Nd)_{sample} - 0.51315] / [(^{147}Sm/^{144}Nd)_{sample} - 0.2137]\}$

$\lambda = 0.00654 Ga^{-1}$

Table 2. Major and trace element concentration of Jurassic metapelites in Tailuko belt, eastern Taiwan.

Sample No.	TCS25	TCS42A	TCS65	TCS67	TCS74	TCS82	CP7-2	CP11-1
SiO_2 (wt%)	68.85	74.76	84.80	61.32	63.08	64.92	85.10	66.58
TiO_2	0.57	0.31	0.10	0.72	0.72	0.68	0.26	0.69
Al_2O_3	14.60	12.68	7.03	17.71	16.40	16.29	6.65	16.12
Fe_2O_3	1.18	0.44	0.12	2.29	2.80	1.52	0.71	1.62
FeO	3.38	1.46	0.53	3.82	4.00	3.84	1.80	3.49
MnO	0.17	0.03	0.05	0.08	0.09	0.11	0.17	0.10
MgO	1.69	0.62	0.05	1.90	2.31	1.97	1.11	1.95
CaO	1.17	0.96	1.92	1.30	1.37	1.70	0.53	0.90
Na_2O	1.67	3.08	2.96	2.10	1.42	2.22	0.00	1.66
K_2O	3.52	3.78	0.32	3.68	3.60	3.14	0.83	3.34
P_2O_5	0.08	0.06	0.02	0.08	0.11	0.10	0.03	0.08
LOI	2.75	1.25	1.78	4.57	3.85	3.47	2.60	3.68
Total	99.63	99.43	99.68	99.57	99.75	99.96	99.79	100.21
La (ppm)	36.0	27.9	12.1	36.0	17.5	33.4	16.2	31.9
Ce	78.1	55.4	23.5	60.5	35.0	68.5	33.8	65.3
Nd	28.1	23.8	9.6	32.1	15.3	28.1	15.9	27.3
Sm	5.40	3.39	1.53	5.73	2.96	5.30	2.67	4.61
Eu	1.09	0.83	0.39	1.26	0.73	1.14	0.70	0.97
Gd	4.77	2.60	1.32	5.05	3.06	4.52	2.46	4.28
Tb	0.73	0.37	0.19	0.77	0.52	0.68	0.42	0.66
Yb	2.43	1.08	0.71	2.44	2.16	2.40	1.20	2.41
Lu	0.36	0.15	0.11	0.36	0.34	0.40	0.17	0.36
Cs	7.83	2.09	0.46	5.36	6.29	6.44	0.51	3.80
Rb	150	83	7	149	153	141	28	133
Ba	601	1034	110	685	612	614	177	553
Pb	32	22	11	15	25	27	7	20
Sr	143	291	177	203	188	254	22	81
Th	16.5	9.9	3.8	16.0	10.0	14.9	3.6	13.9
U	2.9	1.9	0.5	2.0	1.5	3.0	1.4	4.1
Zr	141	164	48	177	152	181	57	190
Hf	5.12	5.23	1.76	5.61	5.42	5.22	1.33	5.34
Nb	18	10	5	17	18	16	9	18
Ta	2.05	6.19	0.29	6.72	1.19	1.00	0.29	0.91
Y	23	4	8	22	15	21	16	24
Be	2.6	1.6	1.0	2.5	2.1	2.6	1.1	2.3
Cr	115	72	150	122	76	110	128	66
V	101	36	12	128	123	110	24	88
Sc	11	5	2	13	12	12	9	12
Ni	21	8	4	17	12	15	41	30
Co	12	5	3	10	7	6	13	11
Cu	21	7	6	20	12	23	63	34
Zn	120	57	37	124	23	122	62	83
Ga	27	16	2	32	32	29	9	21
Sb							0.21	0.26
$(La/Yb)_N$	9.8	17.1	11.3	9.7	5.3	9.2	8.9	8.7
Th/Sc	1.5	2.0	1.9	1.2	0.8	1.2	0.4	1.2
Th/U	5.7	5.2	7.6	8.0	6.7	5.0	2.6	3.4

The earliest Cenozoic to Oligocene metasedimentary and sedimentary rocks show a wide range of chemical composition (Tab. 1). Two samples of Eocene Szeleng and Meichi Sandstones have the highest SiO_2 content (86 - 95 wt%), followed by the earliest Cenozoic Chulai Formation (81 wt%) and Oligocene formations (58 - 67 wt%). Obviously the TiO_2, Al_2O_3, Fe_2O_3, FeO, MgO, K_2O and P_2O_5 contents increase with decreasing SiO_2 content. Although the Szeleng and Meichi Sandstones have the highest SiO_2 content and lowest contents of other major elements, they show different trace element behavior. The Szeleng Sandstone has the lowest trace element contents, except that Cr is the highest, while the Meichi Sandstone has a trace element content comparable to that found in other rocks. The Oligocene formations show higher Rb, Sr, Be, V, Sc, Ni and Co content than samples of other geologic ages. They all have light REE (LREE) enriched chondrite-normalized patterns (Masuda *et al*., 1973). The Szeleng Sandstone is most enriched with $(La/Yb)_N$=25.1, followed by the Chulai Formation (14.9), the Oligocene formations (9.0 to 10.3) and the Meichi Sandstone (8.5).

The metasedimentary rocks in the Tailuko and Yuli belts of the Tananao Schist have different silica contents: 61 to 85 wt% for the former (Tab. 2) and 52 to 82 wt% for the latter (Sun *et al*., 1998). All samples generally exhibit the LREE enriched chondrite-normalized patterns which are characteristic of sediments and continental crustal material, though the enrichment varies with $(La/Yb)_N$, ranging between 5.3 - 17.1. The Eu-depletion is significant for the blackschists of the Yuli belt (Eu/Eu*= 0.60 - 0.70) and varies for the metapelites of the Tailuko belt (Eu/Eu*= 0.65 - 0.83). All have similar Th/Sc ratios (excluding CP7-2), which are close to or greater than the upper continental crust value of 1.0 (Taylor and McLennan, 1985) or 0.8 (revised by McLennan, 2001). The Th/U ratios (in the range of 5 to 8) of both belts (excluding CP7-2 and CP11-1) are higher than the upper continental crust value of 3.8 (Taylor and McLennan, 1985). This is probably due to U being readily oxidized to the soluble U^{+6} state and lost to the oceans during sedimentation. The metapelites in the Tailuko belt contain lower Zr, Hf, Y and Ni content than those in the Yuli belt.

DISCUSSION

Secular Variation of ε_{Nd} Value

The compiled data summarizing the stratigraphic age, SiO_2 content, present ε_{Nd} value and T_{DM} ages for the sedimentary and metasedimentary rocks discussed in this study are presented in Table 3. Secular variation of decreasing ε_{Nd} values with decreasing stratigraphic age is observed for both pre-Eocene and Tertiary rocks.

Present ε_{Nd} values (Tab. 3) for ten samples of metapelites from the Tailuko belt in the Tananao Schist vary from -7.0 to -11.9 (Chen *et al*., 1990; Jahn *et al*., 1990; Lan *et al*., 1995). Present ε_{Nd} values for eleven samples of blackschists from the Yuli belt in the Tananao Schist range from -11.1 to -14.5 (Sun *et al*., 1998). The ranges for the two belts overlap slightly. A T-test was carried out for samples from the Tailuko and Yuli belts that had overlapping ε_{Nd} values, and those results are presented in Table 3. The results show that the mean ε_{Nd} value is -9.4±1.8 for the metapelites of the Tailuko belt, which is quite distinct from the mean ε_{Nd} value (-13.1 ± 1.2) of the blackschists of the Yuli belt.

The metasedimentary rocks of both belts show a wide range in silica contents (Tab. 3). It is interested to note that for the blackschists of the Yuli belt, the ε_{Nd} values are inversely proportional with the silica content. The correlational coefficient is 0.73. Therefore, the rocks with the lowest ε_{Nd} value (-14.5) exhibited the highest silica content (80 wt%). However, such a relationship does not exist for those of the Tailuko belt. Rocks with the lowest ε_{Nd} value (-11.9) do not have the highest silica content (85.1 wt%), but rather a silica content of 84.8 wt%. Similarly, the rock with the highest silica content (85.1 wt%) shows the second highest (-7.1) ε_{Nd} value.

Table 3. Stratigraphic age, silica content, ε_{Nd} , model age and data sources for the sediments from Taiwan.

Sample No.	Stratigraphic age	SiO_2	$\varepsilon_{Nd}(0)$*	T_{DM}(Ga)	Date sources
TCS25	Jurassic (Tailuko belt)	68.85	-9.4	1.4	Lan *et al*., 1995
TCS42A		74.76	-11.7	1.3	This study
TCS65		84.80	-11.9	1.5	
TCS67		61.32	-9.1	1.4	
TCS74		63.08	-9.9	1.6	
TCS82		64.92	-8.6	1.5	
CP7-2		85.10	-7.1	1.2	
CP11-1		66.58	-8.2	1.3	
S87-13	Jurassic (Tailuko belt)	57.34	-11.3	1.5	Chen *et al*., 1990
S87-107	Jurassic (Tailuko belt)	68.81	-7.0	1.4	Jahn *et al*., 1990
HY-901	Cretaceous (Yuli belt)	78.03	-13.3	2.0	Sun *et al*., 1998
HY-902		76.48	-13.1	1.8	
HY-1008		69.34	-12.8	2.2	
HY-1009		80.08	-14.5	1.8	
JU-904		52.56	-12.2	1.8	
JU-1007		79.70	-13.9	1.8	
JU-4701		63.14	-11.8	2.0	
HO-1006		67.53	-12.3	2.0	
TS-1003		61.23	-11.1		
WU-1010		78.34	-14.2	1.8	
WU-1102		80.24	-14.5	1.9	
880209-06	Earliest Cenozoic (Chulai F.)	80.61	-16.2	1.9	This study
LG1-1	Eocene (Szeleng S.S.)	95.02	-11.1		This study
750909-2	Eocene (Meichi S.S.)	86.50	-11.8		
S87-06	Eocene (Hsinkao F.)	75.03	-11.6	1.9	Chen *et al*., 1990
WL1	Oligocene (Kankou F.)	58.75	-13.6		This study
WL2A	(Tsuku F.)	60.34	-13.5		
WL2B	(Tsuku F.)	67.06	-12.2		
WL3	(Tatungshan F.)	66.43	-13.8		
TK2	Oligocene (Tsuku F.)	70.79	-12.8	1.9	Chen *et al*., 1990
S87-02	Miocene (Changshan F.)	67.67	-15.6	2.0	Chen *et al*., 1990

*All data have been adjusted to $^{143}Nd/^{144}Nd$=0.511845 for La Jolla standard

We note that the mean ε_{Nd} values for the metasedimentary rocks of the two belts in the Tananao Schist (-9.4 and -13.1) together with the ε_{Nd} value of the Chulai Formation (-16.2) clearly demonstrated that the younger the stratigraphic age, the lower the present day ε_{Nd} value is. This feature also applies to the lowest ε_{Nd} value for each unit, i.e. -11.9, -14.5 and -16.2; and holds true for the highest ε_{Nd} value for each unit, i.e. -7.0, -11.1 and -16.2. For a group of data, it is better to take the ε_{Nd} value of rocks with the highest silica content of each unit, i.e. -7.1, -14.5, -16.2. This consideration holds true for rocks from the late Jurassic to earliest Cenozoic Periods.

Four samples from the Oligocene age in this study present restricted ε_{Nd} values of -13.8 to -12.2. The sample with the highest silica content possessed the highest ε_{Nd} value of -12.2. The ε_{Nd} value of the only Oligocene sample (TK2) studied by Chen *et al*. (1990) was -12.8, which is within the range of ε_{Nd} values of Oligocene samples in this study. As presented in Table 3, the TK2 sample has the highest silica content among all Oligocene samples but not the lowest ε_{Nd} value.

The Miocene sample S87-02, which has the highest silica content among all Miocene rocks studied by Chen *et al*. (1990), presents an ε_{Nd} value of -15.6. Similar to the pre-Eocene metasedimentary rocks, the ε_{Nd} values of Tertiary sedimentary rocks shown in Table 3 decreases with stratigraphic age. Thus the ε_{Nd} values for the highest silica content of each unit decrease from -11.1, -12.8 to -15.6, from the Eocene through to the Miocene age.

Similar ε_{Nd} Values for the Correlative Stratigraphic Unit

Chen (1976) named the Meichi Sandstone when he was mapping the geology of the Puli-Wushe area in central Taiwan. The Meichi Sandstone is proposed to replace the Szeleng Sandstone, the outcrop of which is confined to northern Taiwan (Ho, 1988). The Meichi Sandstone and the Szeleng Sandstone are different in lithologic character. The former is composed mainly of well bedded, gray, fine- to coarse-grained compact sandstone with alternating interbeds of sandstone and dark argillite. The latter is characterized by thick-bedded, light gray to whitish gray, quartzitic sandstone or quartzite intercalated with dark gray argillite or slate. Such differences are also noted in Table 1, which display their chemical composition. In comparison with the Szeleng Sandstone, the Meichi Sandstone has lower silica and Cr contents and higher contents of other elements. Although the Meichi Sandstone is limited to central Taiwan and the Szeleng Sandstone is confined to the northern Taiwan, both show differences in whole rock chemistry. However, their ε_{Nd} values (-11.8 and -11.1) are similar and overlap within 2σ.

It is surprised to note that the ε_{Nd} value (-11.6) of the highest silica content sample (S87-06) of "Eocene" rocks in Chen *et al.* (1990) is similar to those of Meichi and Szeleng Sandstones (Tab. 3). That particular sample from Chen *et al*. (1990) is thought to be from the Hsinkao Formation outcrop along the Southern Cross-Island Highway. The Szeleng and Meichi Sandstones were correlated with rocks from the upper part of the Hsinko Formation (Chou, 1990). Note that these three correlated stratigraphic units have similar ε_{Nd} values (average of -11.5) irrespective of differences in scattered area and rock chemistry.

Trace Element Characteristics and Tectonic Setting Discrimination

Variations in major and trace element concentrations reflect distinct provenance types and tectonic settings for various suites (Bhatia, 1983; Bhatia and Crook, 1986). The metasedimentary rocks in the Tailuko and Yuli belts have been subjected to at least two stages of recrystallization. Only concentrations of immobile elements such as La, Ce, Nd, Th, Zr, Nb, Y, Sc, Co and Cr are useful as discriminant parameters to assess their tectonic/paleotectonic environment. The tectonic setting discrimination diagram in Bhatia and Crook (1986), which plots La/Y versus Sc/Cr, is applied here for all samples (Tables 1 and 2 and those of Sun *et al*., 1998). As shown in Figure 2, most of the samples have La/Y ratios ranging from 1 to 1.8 (except the sample from the earliest Cenozoic Chulai Formation with 3.3) and Sc/Cr ratios from 0.01 to 0.18, which are characteristic values for the passive margin. However, as shown in the La-Th-Sc triangular diagram (Fig. 3), metasedimentary rocks of the Tailuko and Yuli belts are related to the tectonic environment not only at the passive margin, but also the active continental margin and the continental island arc. In this diagram, the passive margin and the active continental margin are indistinguishable. 75% of the metapelites of the Tailuko belt belong to the tectonic environment of continental island arc, while 33% of the blackschists of the Yuli belt belong to that setting. The application of this discrimination diagram is for sandstone (Bhatia and Crook, 1986) and may not be suitable for pelitic rocks analyzed in this study. The discrepancy between the continental margin and the continental island arc for the metapelites of the Tailuko belt in a paleotectonic environment is interpreted as due to the involvement of continental island arc material in the metasediments of the Tailuko belt. This is further discussed below.

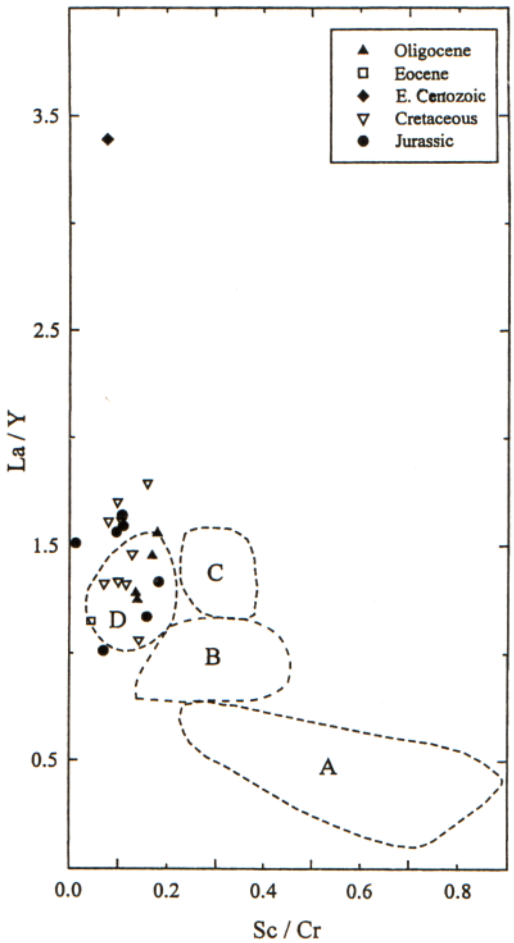

Figure 2. La/Y versus Sc/Cr plots for sedimentary and metasedimentary rocks of the Jurassic Tailuko and Cretaceous Yuli belts as well as the earliest Cenozoic Chulai, Eocene Szeleng, and Oligocene Kankou, Tsuku and Tatungshan formations. Also shown are the tectonic settings after Bhatia and Crook (1986). A: oceanic island arc; B: continental island arc; C: active continental margin; D: passive margin.

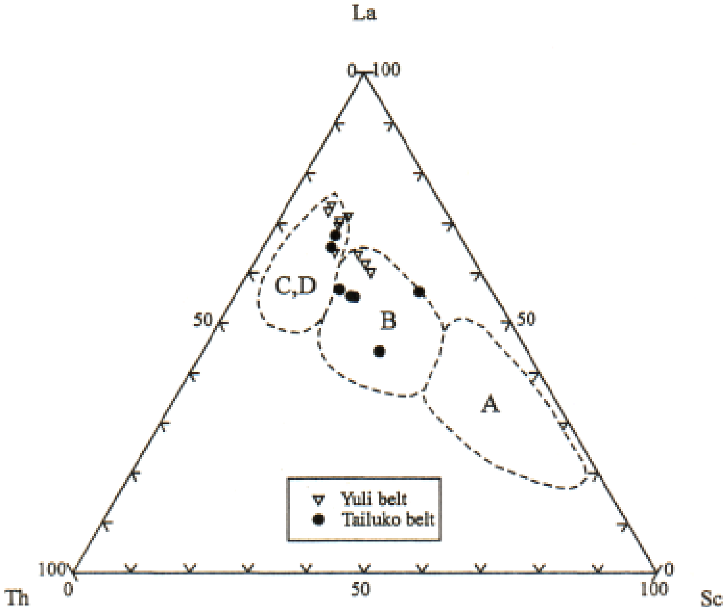

Figure 3. Plot of La-Th-Sc triangular diagram for the metasedimentary rocks of the Tailuko and Yuli belts. Also shown are the tectonic settings after Bhatia and Crook (1986). A, B, C and D are the same as in Figure 2.

Source Provenance

The present $^{143}Nd/^{144}Nd$ and $^{147}Sm/^{144}Nd$ values for the sedimentary and metasedimentary rocks in Chen *et al*. (1990), Jahn *et al*. (1990), Lan *et al*. (1995), Sun *et al*. (1998) and this study are plotted in Figures 4a and b. Also shown are those values for the Cretaceous I-type rocks (granitoids and volcanics from Southeast China as reported in Chen and Jahn (1998) and granitoids from Taiwan as reported in Lan *et al*. (1995)), post-Archean sedimentary and metasedimentary rocks from South China (Chen and Jahn, 1998) and Archean basement rocks of the Yangtze block (Gao *et al*., 1999). Although there are overlapping T_{DM} ages and ε_{Nd} values, the reported Cretaceous I-type rocks tend to have younger T_{DM} ages and higher ε_{Nd} values than those reported for post-Archean sedimentary and metasedimentary rocks from South China.

The sedimentary and metasedimentary rocks of Miocene, Oligocene and Eocene formations (Fig. 4a), as well as those from the earliest Cenozoic Chulai Formation and the Cretaceous Yuli blackschists (Fig. 4b) have early Proterozoic T_{DM} ages (1.4 to 2.2 Ga) and low ε_{Nd} values (-16 to -11). They all fall within those values reported for post-Archean sedimentary and metasedimentary rocks of South China, and are different from those of Archean basement rocks of the Yangtze block (with oldest T_{DM} ages of 2.5 to 3.5 Ga and lowest ε_{Nd} values of -37 to -24). Their Nd model age is similar to those of modern fluvial sediment from a variety of rivers (about 1.7 Ga) (Goldstein *et al*., 1984) and many post-Archean sedimentary rocks (about 2.0 Ga) (McLennan *et al*., 1990). Their ε_{Nd} values are not far from the average value of -15.8 ($^{143}Nd/^{144}Nd$=0.511827) for the upper continental crust of South China (Liu *et al*., 1990).

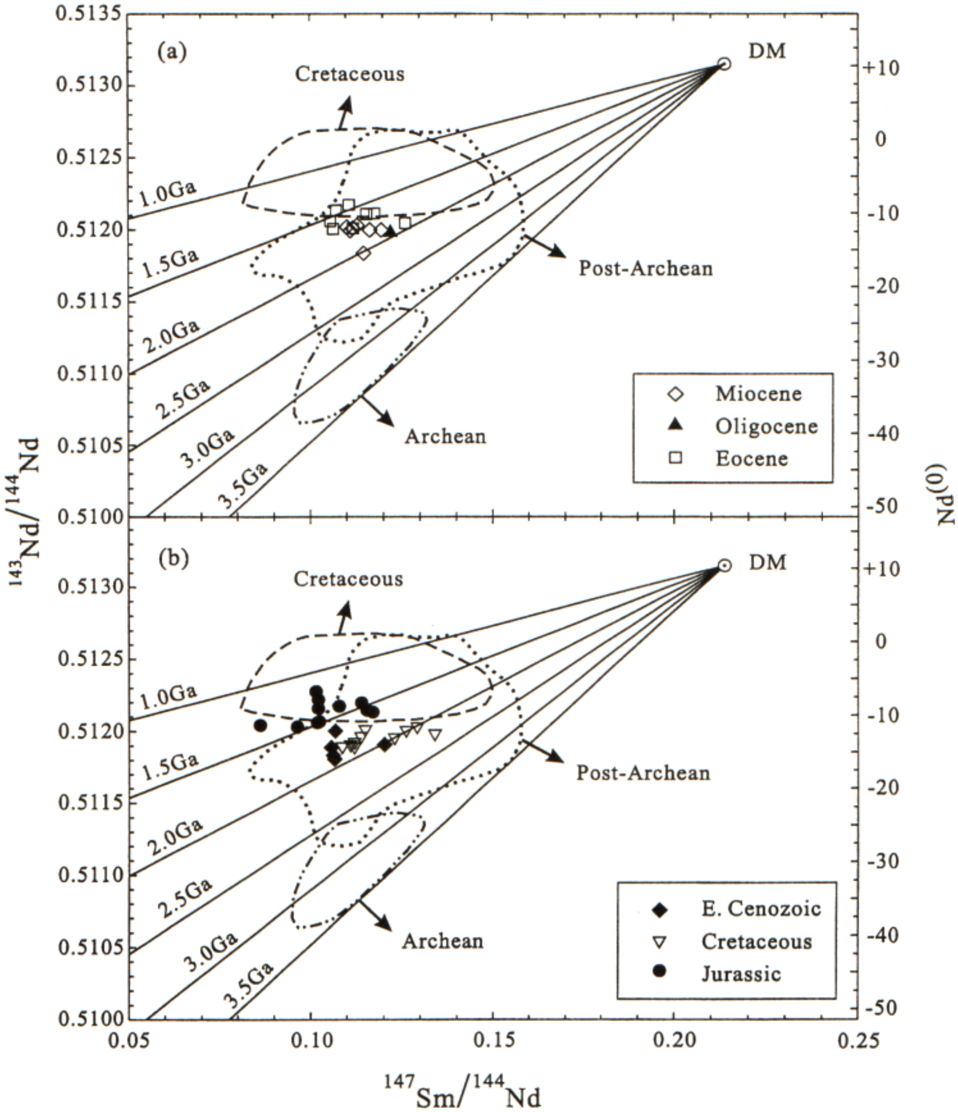

Figure 4. Sm-Nd isotopic composition of Taiwan's sedimentary and metasedimentary rocks of (a) Miocene to Eocene formations and (b) Pre-Eocene formations. Model ages, assuming depleted mantle sources (DM), can be calculated from the slope of the tie-line connecting DM and any individual data point. Six reference lines corresponding to model age of 1.0, 1.5, 2.0, 2.5, 3.0 and 3.5 Ga are shown. Data sources are Chen *et al*. (1990), Jahn *et al*. (1990), Lan *et al*. (1995), Sun *et al*. (1998) and this study. Also depicted are fields which enclosed data concerning the post-Archean sedimentary and metasedimentary rocks of South China (post-Archean) reported in Chen and Jahn (1998), data concerning the Archean basement rocks of the Yangtze block (Archean) reported in Gao *et al*. (1999) and data concerning the Cretaceous I-type rocks of Southeast China and Taiwan (Cretaceous) reported in Lan *et al*. (1995) and Chen and Jahn (1998).

However, the Jurassic Tailuko metapelites (Fig. 4b) have slightly younger, late to middle Proterozoic T_{DM} ages (1.1 to 1.6 Ga) and higher ε_{Nd} values (-12 to -7). The values fall within those reported for Cretaceous I-type rocks and overlap with those reported for post-Archean sedimentary and metasedimentary rocks from South China, particularly those rocks with young T_{DM} ages and high ε_{Nd} values. The relatively depleted nature of the Nd isotopic composition and the younger Nd model age for the metapelites of the Tailuko belt indicate that greater proportions of juvenile material have been involved in the petrogenesis. The metapelites of the Tailuko belt do not plot (Fig. 4b) toward the upper right in the direction of direct mixing with the mantle material (DM). Arc material can have a Nd isotopic composition similar to DM and considerably lower Sm/Nd. This serves as better mantle input material for the purpose of combining with recycled crust to produce the metapelites of the Tailuko belt during the Jurassic Period. Alternatively, there are suggestions that the low-P/T Tailuko and high-P/T Yuli belts of the Tananao Schist are paired metamorphic belts (Yen, 1963; Biq, 1971) resulting from a late Cretaceous subduction process (Yui and Lo, 1989; Lo and Yui, 1996). During the late Cretaceous subduction, the arc material represented by the andesitic rock or its metamorphic equivalent (Lo and Liu, 1984; Yui and Wu, 1991; Yui *et al*., 1998), together with the granitoid, was formed in the Tailuko belt. The granitoids usually possess higher ε_{Nd} values (+0.1 to -9.2, except one with -12.9) (Lan *et al*., 1995) than those of the associated metapelites. Metasomatism during the granitization may have occurred in the metapelites of the Tailuko belt such that the ε_{Nd} values increase from ≤ -15.8 (recycled upper continental crust of South China) to -11.9 and up to -7.

The ε_{Nd} values and T_{DM} ages of metasedimentary rocks of Eocene age depict a mixed source signature (Figs. 4a and b) overlapping partly with those of the metapelites of the Tailuko belt, the Cretaceous I-type rocks, and the post-Archean sedimentary and metasedimentary rocks of South China. Paleo-current and sedimentation studies suggest that the source material of Eocene rocks in Taiwan as came from the northwestern direction (Chou, 1990). This precludes the possibility that the metapelites of the Tailuko belt are the source. It appears that the Eocene rocks of Taiwan contain not only recycled old continental crustal material from South China but also material from the Cretaceous I-type granitoids and volcanics of Southeast China. Late Mesozoic transtentional tectonics induced the rapid cooling and fast exhumation in Southeast China (Yang *et al*., 1997, 1998). The primary source material for Eocene rocks in Taiwan is recycled continental crust. The weathering of the Cretaceous I-type volcanics and the exposed I-type granitoids in Southeast China makes the I-type rocks the secondary source material, which is necessary to increase ε_{Nd} values of Eocene rocks in Taiwan.

The Chulai Formation, with early Proterozoic T_{DM} ages and lowest ε_{Nd} value (-16.2), falls within those reported for post-Archean sedimentary and metasedimentary rocks of South China (Fig. 4b). Such a correlation implies that the Chulai Formation received almost entirely recycled continental crustal material from South China. Thus, our isotopic constraints do not support the idea suggested by Stanley *et al*. (1981), namely, that the Chulai Formation represents volcanic-arc derived material deposited in a fore-arc basin over parts of the accretionary sequence.

The Relation between Isotopic and Geochemical Compositions for the Metasediments of the Tananao Schist

The relationship between the trace element and isotopic composition of the metasedimentary rocks in the Tailuko and Yuli belts are shown in Figure 5 with ε_{Nd} value plotted against Th/Sc ratio (McLennan *et al*., 1990). The neodymium isotopic composition distinguishes provenance components of various ages, whereas the Th/Sc ratio provides a sensitive index of mafic versus felsic composition. Also shown on the diagram are compositions of various major geochemical reservoirs, including the average upper continental curst, average arc andesite and typical mid-ocean ridge basalt (MORB) (Taylor and McLennan, 1985). The Th/Sc ratio is taken as 0.8 for the upper crust according to the revised value of McLennan (2001). The average ε_{Nd} value of the upper continental crust of South China is -15.8 (Liu *et al*., 1990). A mixing line between arc andesite and upper crust is also shown as a reference. Metasedimentary rocks of both belts have Th/Sc ratios similar or higher to the upper continental crust. Rocks of the Yuli belt tend to have ε_{Nd} values close to that of the upper continental crust, while rocks of the Tailuko belt have higher ε_{Nd} values than those of the Yuli belt. The high ε_{Nd} values indicate the incorporation of a greater proportion of mantle-derived components in the metasediments of the Tailuko belt than in the Yuli belt. This observation is comparable with data presented in Figure 3, which indicates the incorporation of a significant portion of arc material in the formation of the metapelites of the Tailuko belt.

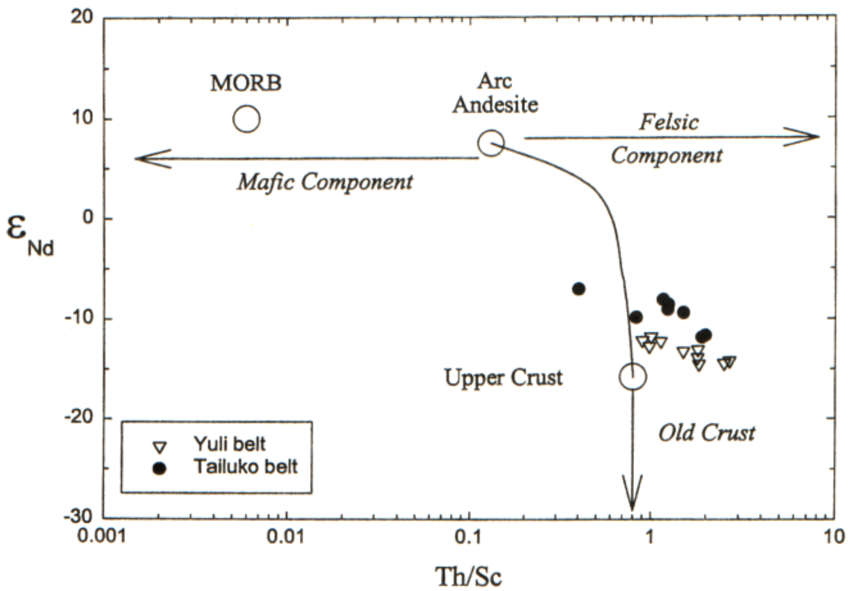

Figure 5. Plot of ε_{Nd} versus Th/Sc ratio for the metasedimentary rocks of the Tailuko and Yuli belts. Also shown are compositions of various geochemical reservoirs (Taylor and McLennan, 1985) and mixing relationships between average island arc andesite and upper continental crust. The ε_{Nd} value of the upper continental crust of South China is -15.8 according to Liu *et al*. (1990).

CONCLUSIONS

The geochemical and Nd isotopic data from Mesozoic to Miocene metasedimentary and sedimentary rocks of Taiwan presented in this study support the following conclusions:

(1) The chondrite-normalized REE pattern and Sc/Cr-La/Y trace element relation indicate that these rocks exhibit characteristics of continental margin crustal material. By contrast, continental island arc material was involved in the formation of the metapelites of the Tailuko belt on the basis of La-Th-Sc trace element data.

(2) The ε_{Nd} values of sediments of the same stratigraphic age are quite similar but not identical. There is a 4.9 to 0.7ε difference reported in this study. Only the blackschists of the Yuli belt show ε_{Nd} values that vary inversely proportionally with SiO_2 content.

(3) Secular variation with decreasing ε_{Nd} value and decreasing stratigraphic age has been documented in both the pre-Eocene metasedimentary and the Tertiary sedimentary rocks of Taiwan. The low ε_{Nd} values of the studied rocks approach those of the upper continental crust of South China and overlap with those of post-Archean sedimentary and metasedimentary rocks from South China. This implies that most of the sedimentary and metasedimentary rocks of Taiwan are recycled continental crustal material from South China.

(4) The relatively high ε_{Nd} values for the Eocene metasedimentary rocks of Taiwan suggests Cretaceous I-type rocks of Southeast China must have been involved in the formation of these rocks in addition to recycled continental crustal material. This is consistent with the rapid cooling and exhumation tectonics that characterize Southeast China during the middle Cretaceous Period, such that the exposed I-type granitoids may have been another source material to increase the ε_{Nd} values of Eocene rocks in Taiwan.

(5) The highest ε_{Nd} values for the Jurassic metapelites of the Tienhsiang Formation in the Tailuko belt are similar to those of Cretaceous I-type rocks and arc-derived sediments. A significant amount of mantle input in the form of arc material must have been involved in the formation of the metapelites of the Tailuko belt. This indicates that either the sedimentation occurred on the Eurasian continental margin, which received mantle inputs (arc material) during the Jurassic Period or that the rocks had been metasomatized via the granitization of the Tailuko belt during Cretaceous low-P/T metamorphism.

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