Metallogeny of tin in central Thailand: A genetic concept

Bernd Lehmann
Institut für Angewandte Geologie, Freie Universität Berlin, Wichernstrasse 16, D-1000 Berlin 33, Federal Republic of Germany

Chamrat Mahawat
Department of Mineral Resources, Geological Survey, Rama VI Road, Bangkok 10400, Thailand

ABSTRACT

Tin mineralization in central Thailand is associated with granitic rocks of the Thai-Burmese border range (western group). Granitic intrusions east of Bangkok and near the Kampuchea border (eastern group) have no tin. Fractional crystallization is the fundamental petrogenetic process that controls the evolution of both groups of granites. The tin-bearing alkali-feldspar aplogranites of the western group display an extreme degree of differentiation that has no petrological equivalent in the eastern group. These aplogranites are the product of a combination of magmatic fractionation (primary tin enrichment trend) modified by fluid interaction. The latter process is responsible for a secondary geochemical tin deficiency that is balanced by redistribution of tin in fracture systems—i.e., tin mineralization. The pattern of tin depletion in the aplogranites provides an indication of the tin potential in a given ore-forming system.

INTRODUCTION

Tin deposits are generally associated in time and space with granitic intrusions (Ferguson and Bateman, 1912; Taylor, 1979). The Southeast Asian tin province (Fig. 1) covers parts of Indonesia, Malaysia, Thailand, and Burma and contributes about 40% of the current world tin production. Mineralization is associated with granites of both Permian-Triassic (mainly in Indonesia and Malaysia) and Cretaceous-Tertiary age (particularly in Burma and Thailand). Central Thailand displays a remarkable polarity in the distribution of tin mineralization. Granitic rocks east of Bangkok have no tin, whereas the granites of the Thai-Burmese border range in western central Thailand host numerous and important tin ore deposits (Fig. 1).

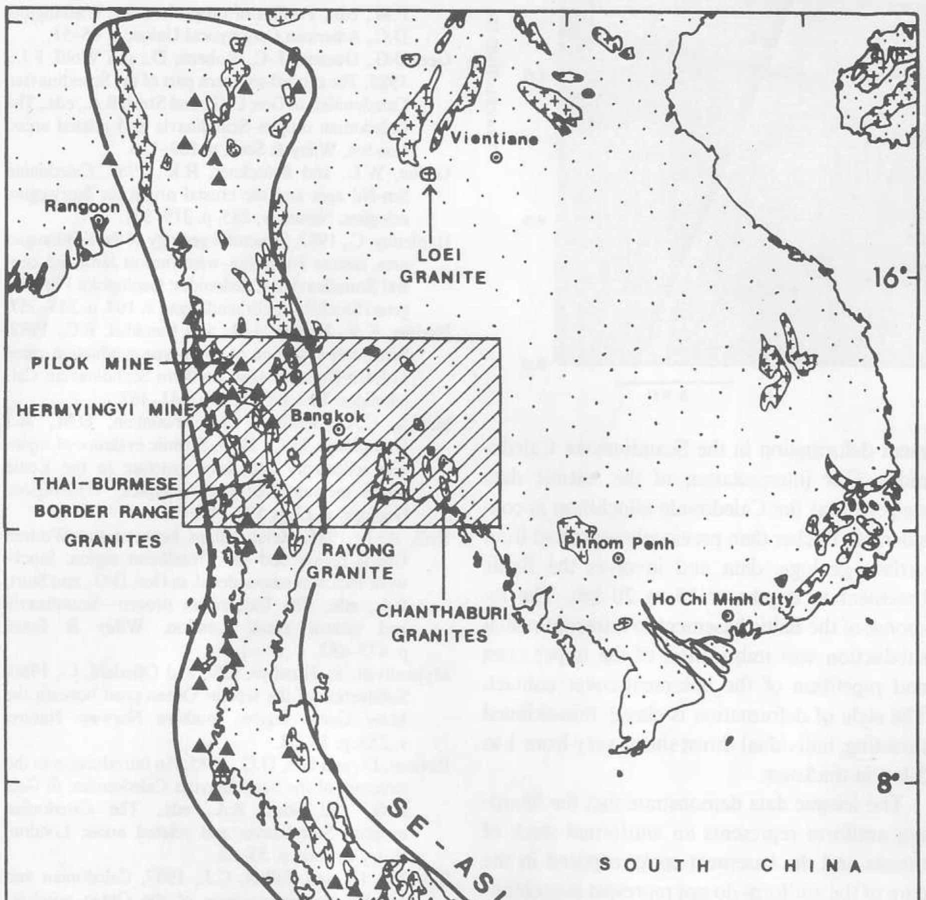


Figure 1. Outline of Southeast Asian tin province. Black triangles locate major tin and tin-tungsten ore deposits with more than 5000 t of Sn metal content for production plus reserves; crosses indicate larger granite terranes (adapted from UNESCO, 1985). Little-known tin deposits in central Sumatra and northeast of Vientiane (Laos) could eventually enlarge traditional tin belt.

This circumstance provides a starting point for a petrographic-geochemical comparison aimed at explaining the difference between tin-bearing and tin-barren granites and the critical factors leading to the formation of a tin deposit.

GEOLOGIC SITUATION AND SAMPLING

Three different granite terranes have been sampled in an east-west transect across central Thailand.

1. Tin-barren, I-type granites of the Chanthaburi region near the Kampuchea border (Permian-Triassic age). These rocks consist mainly of K-feldspar megacrystic biotite and biotite-hornblende granites, with subordinate amounts of fayalite-hornblende granite and some subunits of nonporphyritic biotite granite. The Chanthaburi intrusions form a compositionally extended rock suite with SiO_2 66 to 76 wt% and metaluminous to weakly peraluminous composition. They plot over the full length of thermal minima from 1 to 10 kbar in the experimentally investigated granitic system (Tuttle and Bowen, 1958; James and Hamilton, 1969).

2. The tin-barren, S-type Rayong batholith, east of Bangkok, consists mainly of K-feldspar megacrystic biotite granite with variable amounts of secondary muscovite. It has a Rb-Sr isochron age of 221 ±11 Ma; $^{87}Sr/^{86}Sr_i$ = 0.7263 ±6 (Nakapadungrat et al., 1984). The Rayong batholith shows little variation of major elements, and it plots near the thermal minimum at 1 kbar pressure in the experimentally determined hydrous granite system.

3. Granites of the Thai-Burmese border range in western central Thailand are composed chiefly of K-feldspar megacrystic biotite granites with variable amounts of muscovite of subsolidus formation. They are intruded by small alkali-feldspar aplogranite stocks. Modal compositions and major-element content of the K-feldspar megacrystic granites are similar to those of the Rayong batholith; their age, however, is Late Cretaceous (Beckinsale et al., 1979). The tin-tungsten mining areas of Pilok in Thailand and of neighboring Hermyingyi in Burma are centered on apical parts of alkali-feldspar aplite stocks. The aplogranites are of transitional magmatic-hydrothermal origin; they have the typical mineral assemblage quartz-microcline-albite-muscovite-tourmaline-garnet-fluorite-beryl. A Rb-Sr isochron age from the Hermyingyi stock is 59.5 ±1.4 Ma; $^{87}Sr/^{86}Sr_i$ = 0.727 ±10 (P. Müller, 1988, personal commun.).

Mineralization consists of disseminations, stockworks, and veins with an ore association composed mainly of arsenopyrite, chalcopyrite, sphalerite, pyrite, cassiterite, and wolframite. Minor components are pyrrhotite, stannite, bismuthinite, bismuth, molybdenite, and scheelite. The gangue assemblage is quartz-muscovite-tourmaline-beryl-fluorite-apatite.

TABLE 1. ARITHMETIC MEANS OF CHEMICAL DATA FOR GRANITIC ROCKS OF CENTRAL THAILAND AND BURMA

	Loei granodiorites (n = 7)	Chanthaburi granites (n = 29)	Rayong granite (n = 25)	Border range granites (n = 20)	Pilok aplogranite (n = 17)	Hermyingyi aplogranite (n = 6)
Oxides (wt%)						
SiO_2	63.34	70.28	72.60	73.42	76.18	76.00
TiO_2	0.59	0.41	0.31	0.25	0.03	0.03
Al_2O_3	15.86	14.34	13.80	13.53	13.16	12.83
Fe_2O_3	4.99	3.38	2.08	1.88	0.52	0.99
MnO	0.09	0.06	0.05	0.06	0.07	0.23
MgO	2.20	0.46	0.66	0.35	0.01	0.01
CaO	4.62	2.06	1.26	1.00	0.30	0.50
Na_2O	3.43	3.76	2.74	2.92	3.92	3.45
K_2O	2.99	3.96	5.00	5.11	4.43	4.38
P_2O_5	0.17	0.09	0.16	0.09	0.04	0.01
LOI	1.22	0.68	0.83	0.88	0.73	0.98
Trace elements (ppm)						
Ba	538	368	476	255	13	33
Ce	45	79	66	85	5	47
Cr	29	<15	20	<15	<15	<15
Cu	20	15	6	5	30	18
La	<20	39	26	34	11	81
Nb	7	9	15	24	47	36
Ni	15	8	15	8	9	<5
Pb	11	34	49	87	90	81
Rb	99	207	351	442	625	979
Sn	3	7	10	14	27	72
Sr	381	118	81	65	17	4
Th	10	23	24	43	21	37
U	<5	7	8	19	31	24
V	109	24	25	19	<15	<15
Y	22	51	42	63	102	190
Zn	49	68	32	47	69	135
Zr	147	256	146	149	53	75
D.I.	64	82	86	89	95	93

Note: Analyses by X-ray fluorescence spectrometry. Fe_2O_3 is total iron. D.I. is Thornton-Tuttle differentiation index.

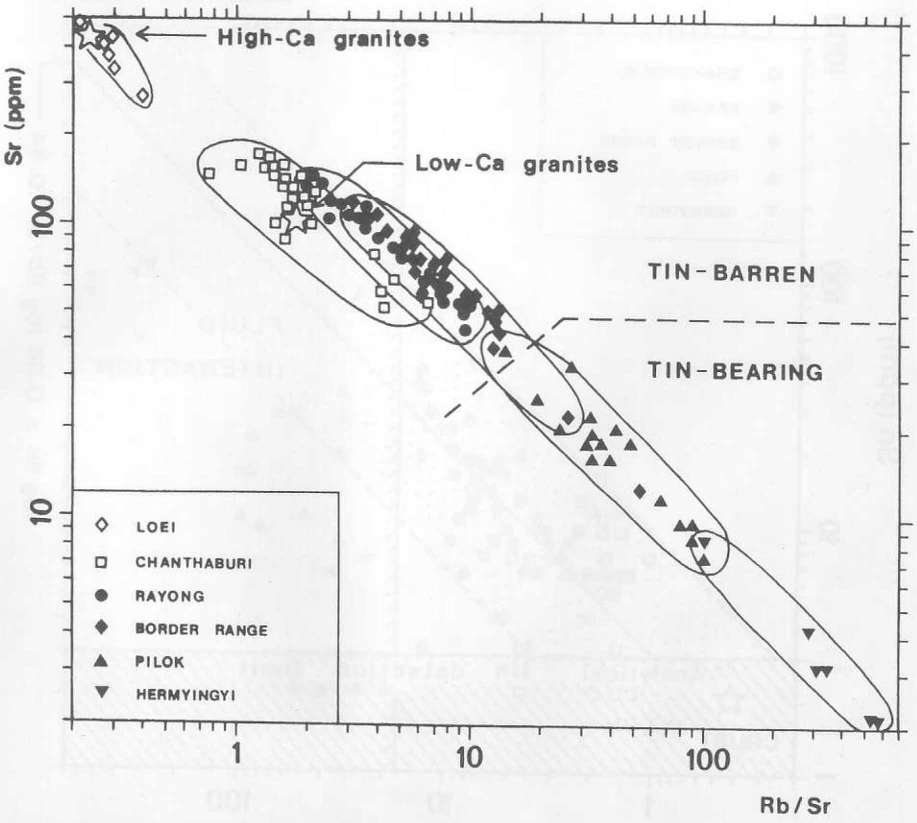
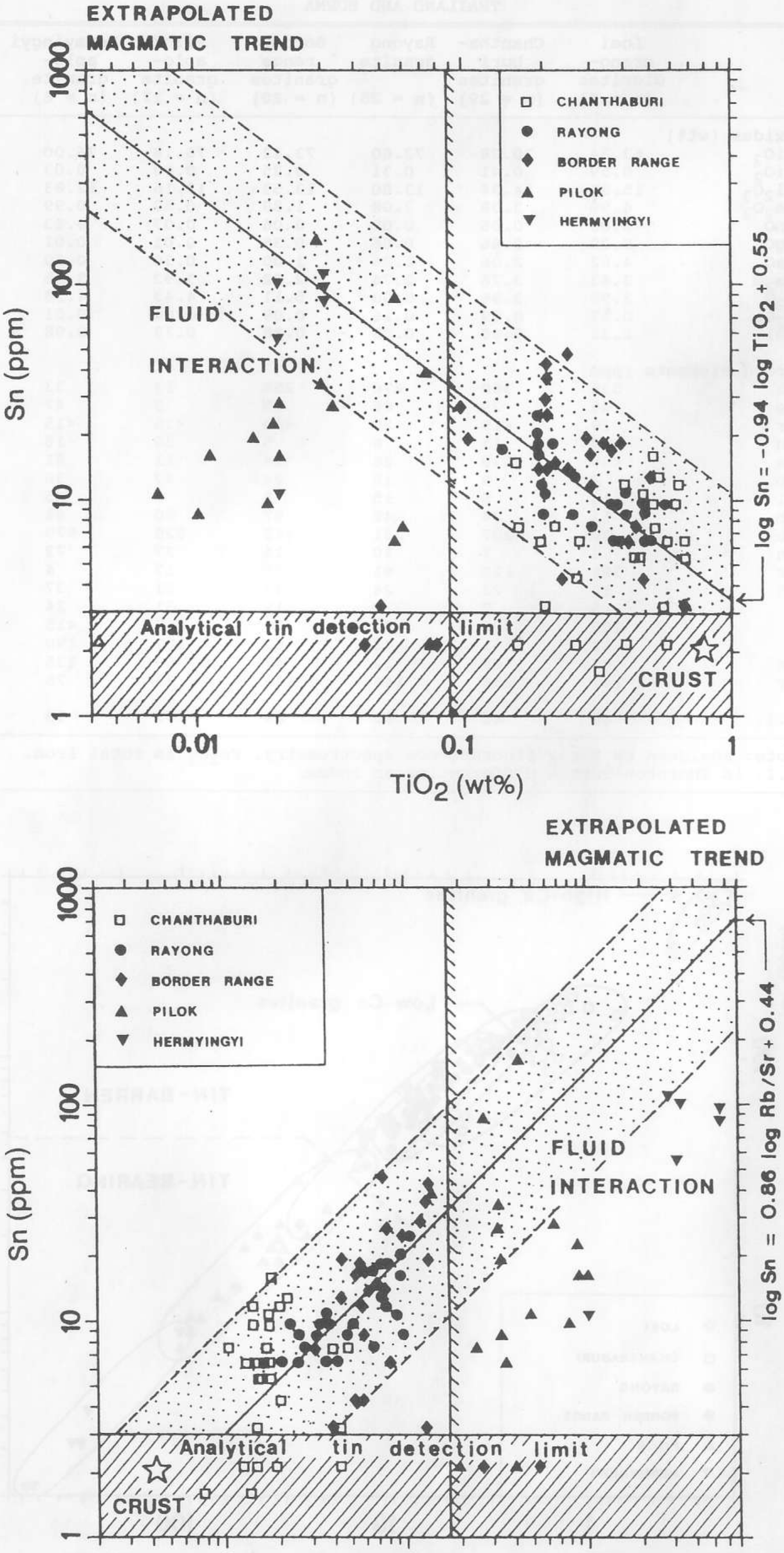


Figure 2. Rb/Sr-Sr variation diagram for central Thailand granitic rocks. Stars locate position of average low-Ca and high-Ca granites (Turekian and Wedepohl, 1961).



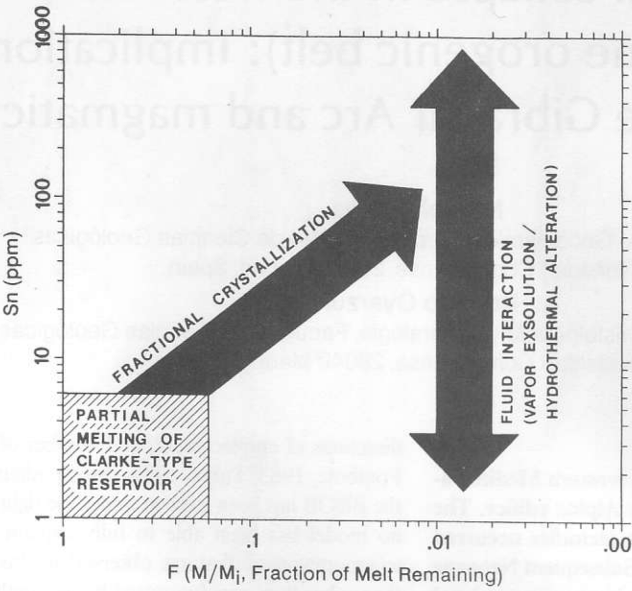
RESULTS

Chemical data for each rock group are given in Table 1. In both the tin-barren granitic rocks from eastern central Thailand and the tin-bearing granitic rocks from the western part, trace-element trends can be defined that imply fractional crystallization as the dominant petrogenetic process controlling magmatic evolution. This is deduced from linear correlation trends in log-log plots of various pairs of compatible and incompatible elements. The log Sr vs. log Rb/Sr diagram in Figure 2 defines a general fractionation pattern of the different magma series. The hydrothermally overprinted populations of samples from the Pilok and Hermyingyi aplogranites form an extension of the general trend of magmatic differentiation to extreme levels, indicative of a Rb-Sr system that has not been disturbed by fluids from external sources. This diagram, of course, provides no evidence of cogenetic relations between geographically separate rock groups, but it does give information about the relative degree of magmatic evolution of defined groups of granites and points to the fact that tin mineralization is associated only with the most fractionated rocks of these series.

The tin content of the rock in relation to the differentiation indices Rb/Sr and weight percent TiO_2 is shown in Figure 3. The samples from the Rayong and border range granites display a systematic trend that can be interpreted in terms of progressive magmatic enrichment of tin (Lehmann, 1982) which is statistically significant at a confidence level of >99.9% with a correlation coefficient $r_{Rb/Sr-Sn}$ = 0.73 and r_{TiO_2-Sn} = 0.63, respectively (53 samples). The Chanthaburi sample group has a relatively large scatter attributed to the margin of analytical error near the tin detection limit, but these data could also be fitted to the pattern of progressive tin enrichment during magmatic fractionation. The alkali-feldspar aplogranite samples from Pilok and Hermyingyi are characterized by scatter distributions. The behavior of tin in this case reflects the influence of external factors in an open system. The tin concentration of these samples is anomalously low relative to their degree of differentiation, interpreted to be due to removal of tin by fluid interaction. This mobilized tin is then deposited in fracture systems that are also the channels for fluid movement.

Figure 3. TiO_2-Sn (upper part) and Rb/Sr–Sn (lower part) variation diagrams for central Thailand granites. Star indicates average crustal composition (Taylor and McLennan, 1985). Diagonal-rule area is region of compositions below analytical detection for Sn. Hachured line separates least altered granite samples from Pilok and Hermyingyi aplogranite samples that are modified by fluid interaction. Note tin deficit between extrapolated magmatic trend and fluid-modified aplogranite field.

Figure 4. Metallogenic model for tin mineralization. Magmatic enrichment of tin as function of degree of fractionation given favorable bulk distribution coefficient D_{Sn} <1 at low oxygen fugacity, and mineralization as result of subsequent fluid interaction with highly evolved magmatic or transitional magmatic-hydrothermal system.



A geochemical balance of the system can be made when the tin mineralization is taken into account. The original mean content of tin of the Pilok aplogranites can be estimated from the general magmatic correlation trend in Figure 3. A primary content of 85 ppm Sn in the magma results (standard deviation 35–269 ppm). Compared to the actual mean content of tin, which is 27 ppm (range 0–64 ppm Sn), there is a difference of 58 ppm Sn. This figure provides a basis for estimation of the potential for tin ore of the Pilok mining area, in which there is a volume of about 1 ±0.5 km^3 of alkali-feldspar aplogranite. The tin potential of $1.5 \pm 0.7 \times 10^5$ t (tonnes) Sn, calculated on this theoretical basis, compares reasonably well with the cumulative production plus reserve figures for this area, which total approximately 5×10^4 t Sn.

MODEL

Figure 4 incorporates the principles of this simple two-stage model of tin metallogenesis: fractional crystallization under conditions in which the bulk distribution coefficient for tin D_{Sn} (crystals/melt) <1 (Lehmann, 1982) leads to Sn levels high enough to load a cogenetic-magmatic and/or an externally derived fluid phase with sufficient metal to form ore-grade mineralization. It is a requirement of this model that tin deposits be restricted to very small volume fractions of large-scale granite systems. A volume estimate based on the geologic circumstances of the Pilok area and assuming perfect conditions of fractional crystallization with an ideal value of $D_{Sn} = 0$ leads to a minimum total melt volume of 28 ±14 km^3. A more realistic estimate for natural conditions would give an order of magnitude of about 100 km^3.

The bulk distribution coefficient for tin seems to be dependent on oxygen fugacity (Ishihara, 1977). Tin granites are generally ilmenite-bearing and have low Fe^{3+}/Fe^{2+} ratios, which suggests a more incompatible behavior of Sn^{2+} as compared to Sn^{4+}. Molybdenum, in contrast, has an opposite $D_{Mo} - f_{O_2}$ relation (Tacker and Candela, 1987), which provides an explanation for the overall bipolar metal distribution in the petrogenetically related Sn-W-Mo ore-deposit spectrum.

Oxygen fugacity also plays a critical role for the hydrothermal mobility of tin, with the solubility of cassiterite near the quartz-fayalite-magnetite buffer about three log units greater than at the hematite-magnetite buffer (Eugster, 1986). Fluid-rock interaction in highly fractionated low-f_{O_2} granitic rocks may produce a very efficient removal of tin, leading to anomalously low background levels of Sn, balanced by hydrothermal tin enrichment in zones of extreme chemical focusing. Therefore, granites affected by large-scale hydrothermal tin depletion may be regarded as good choices for prospecting of tin deposits.

REFERENCES CITED

Beckinsale, R.D., Suensilpong, S., Nakapadungrat, S., and Walsh, J.N., 1979, Geochronology and geochemistry of granite magmatism in Thailand in relation to a plate tectonic model: Geological Society of London Journal, v. 136, p. 529–540.

Eugster, H.P., 1986, Minerals in hot water: American Mineralogist, v. 71, p. 655–673.

Ferguson, H.G., and Bateman, A.M., 1912, Geologic features of tin deposits: Economic Geology, v. 7, p. 209–262.

Ishihara, S., 1977, The magnetite-series and ilmenite-series granitic rocks: Mining Geology, v. 27, p. 293–305.

James, R.S., and Hamilton, D.L., 1969, Phase relations in the system $NaAlSi_3O_8$–$KAlSi_3O_8$–$CaAl_2Si_2O_8$–SiO_2 at 1 kilobar water vapour pressure: Contributions to Mineralogy and Petrology, v. 21, p. 111–141.

Lehmann, B., 1982, Metallogeny of tin: Magmatic differentiation versus geochemical heritage: Economic Geology, v. 77, p. 50–59.

Nakapadungrat, S., Beckinsale, R.D., and Suensilpong, S., 1984, Geochronology and geology of Thai granites, *in* Proceedings, Conference on Applications of Geology and the National Development: Bangkok, Chulalongkorn University, p. 75–93.

Tacker, R.C., and Candela, P.A., 1987, Partitioning of molybdenum between magnetite and melt: A preliminary experimental study of partitioning of ore metals between silicic magmas and crystalline phases: Economic Geology, v. 82, p. 1827–1838.

Taylor, R.G., 1979, Geology of tin deposits: Amsterdam, Elsevier, 543 p.

Taylor, S.R., and McLennan, S.M., 1985, The continental crust: Its composition and evolution: Oxford, Blackwell, 312 p.

Turekian, K.K., and Wedepohl, K.H., 1961, Distribution of the elements in some major units of the Earth's crust: Geological Society of America Bulletin, v. 72, p. 172–202.

Tuttle, O.F., and Bowen, N.L., 1958, Origin of granite in the light of experimental studies in the system $NaAlSi_3O_8$-$KAlSi_3O_8$-SiO_2-H_2O: Geological Society of America Memoir 74, 153 p.

UNESCO, 1985, Metallogenic map of south and east Asia 1:5,000,000: Paris and Tokyo, Commission for the Geological Map of the World, 4 sheets.

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