

The Search for Tin

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*Accepting the necessity of locating new sources of cassiterite, the author emphasises the necessity for scientific exploration. Prospecting programmes should be based on knowledge of the geochemistry of tin and its fundamental distribution, as well as on the general characteristics of tin deposits.**

SEVERAL years ago a point was reached at which the world's demand for tin ceased to be met by metal currently produced from natural sources. It seems reasonable to believe that in the foreseeable future more rather than less tin will be required by industry. Whilst this demand can in part be satisfied by an increased recovery of secondary metal, by the retreatment of tailings dumps, and from the working of known deposits at present considered sub-economic, the extent to which these sources will be exploited must, basically, be determined by the cost of production of the metal and its market price. Clearly, however, the soundest policy is to attempt to meet increasing need by searching for further deposits of a grade which can be worked profitably at the present price of tin and without having to await the development of new and more efficient recovery processes. Such deposits must be looked for in and adjacent to known fields and in new fields which possess characteristics suggesting that they might contain economically important deposits of the metal in question.

The object of the present paper is to review the characteristics of tin deposits generally and then to suggest how these data, together with known prospecting techniques, can best be used to locate new sources.

Whether the object of the search is to locate a new tinfield or further deposits in and around a much exploited field, the exploratory work, if it is not to be "wild-catting", must be governed by the fundamental chemical, mineralogical, size and shape characteristics of tin deposits, and the spatial and genetic relationships existing between such deposits and neighbouring geologic units. The nature of the work must also be dictated by the exploration techniques available. In addition, the quality and quantity of available geological and historic data concerning the region to be prospected will also control, to a variable extent, the form of the exploration programme.

Geochemistry of Tin

Considering first, both the general distribution characteristics of tin and its chemical properties which govern, to no small degree, how the element behaves in either deep and superficial environments, attention can be called to a number of empirical rules proposed by Goldschmidt (1937)[†] by means of which it is possible to predict how a given element

will behave during crystal development in a multicomponent system. The application of these rules not only enables one to foretell in which minerals, other than the species in which tin occurs as a major component, the element is likely to occur in significant amounts, but it also makes it possible to give persuasive reasons why tin ore deposits are genetically related to acid- and not basic-igneous rocks, and why certain granitic masses in a tin province may be devoid of economically interesting concentrations of the metal in question.

Goldschmidt's rules as summarised by Mason (1956, p. 114) are as follows:

- (1) If two ions have the same radius and the same charge they will enter a given crystal lattice with equal facility.
- (2) If two ions have similar radii and the same charge the smaller ion will enter a given crystal lattice more readily.
- (3) If two ions have similar radii and different charges the one with the higher charge will enter a given crystal lattice more readily.

From Table 1 it will be clear that the ionic radii of tin and those heavy elements (W, Nb, Ta, and Mo) which are commonly concentrated in the same ore deposits, differ significantly from those of the elements (Na, K, Ca and Si) which are major components of the feldspars and quartz, which make up the bulk of acid igneous rocks. On the other

TABLE 1
IONIC RADII AND VALENCIES OF CERTAIN
ELEMENTS RELEVANT TO THE GEOCHEMISTRY OF TIN

Sn ⁴⁺	W ⁶⁺	Nb ⁵⁺	Ta ⁵⁺	Bi ⁶⁺	Mo ⁴⁺
0.73	0.67	0.70	0.68	0.74	0.67
	Na ¹⁺	K ¹⁺	Ca ²⁺	Al ³⁺	
	0.98	1.33	1.01	0.57	
		Fe ²⁺	Mg ²⁺		
		0.79	0.75		
		Si ⁴⁺			
		0.41			

* A revised version of a paper originally appearing in *Trans. Cornish Inst. Eng.*, N.S. Vol. XVII.

† A list of references is given at the end of this paper.

Epithermal & Xenothermal Deposits. Veins, stockworks, breccia pipes. SnO_2 + several Sn-bearing sulphides. Bolivia; Mexico; New Brunswick.

Pyrometamorphic Deposits. Skarns with SnO_2 and/or tin sphene, and Sn-bearing garnets. Yala (Thailand); Red-a-ven (n/r Okehampton, England).

Pegmatites. Wamba District (Nigeria); Congo; S.W. Africa; Kamativi (S. Rhodesia).

Large complex hypothermal lodes & replacements (carbonates, in granite of St. Ives, Cornwall) flanking granite ridges. Cornwall. SnO_2 , minor stannite.

Greisen-bordered vein swarms in granite cusps (Cligga & Kit Hill, Cornwall) and cusp- & ridge-haloing stockworks (Mulberry, Cornwall; Bois Vert, Brittany).

Lodes, stockworks & ladder veins associated with granitic dykes. Wherry & Parbola mines, Cornwall. (Hypothermal).

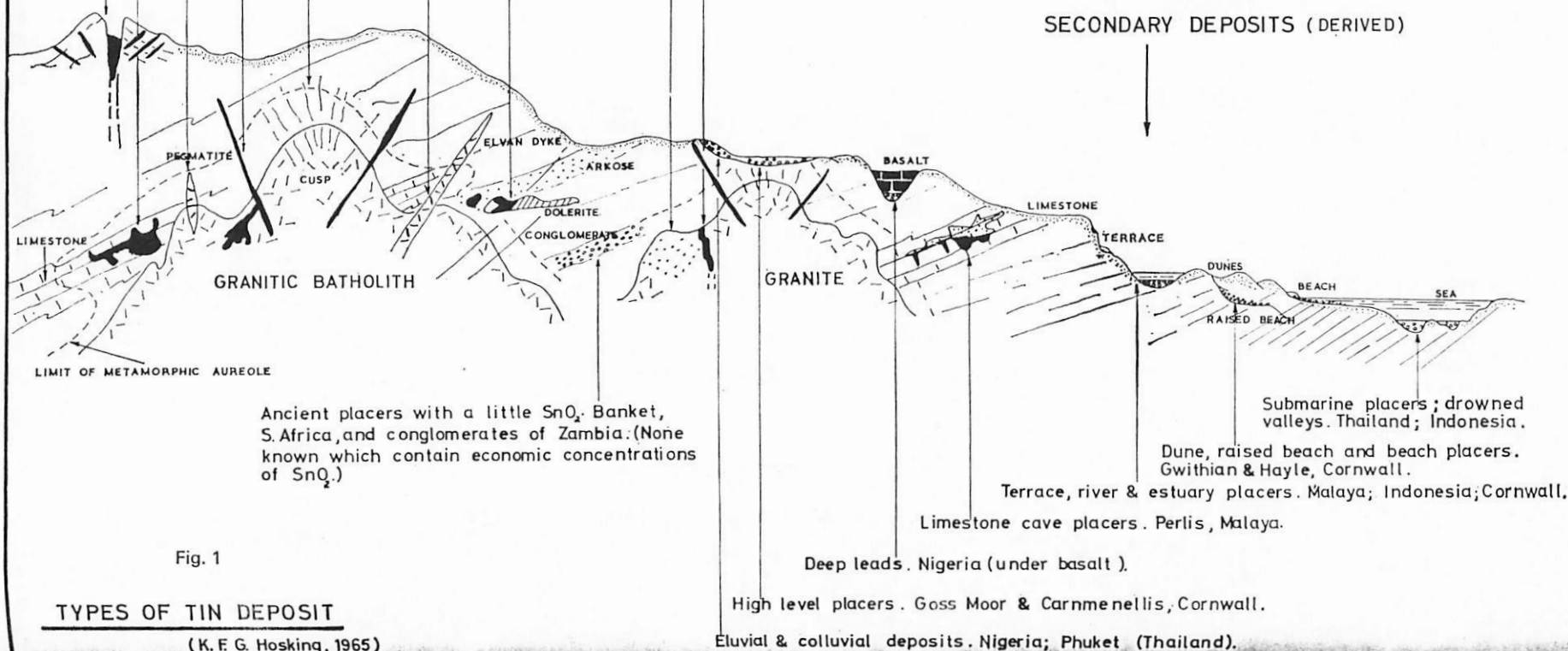
Replacements in dolerite (skarn like), Magdalen mine, W. Cornwall, and in arkose (within met. aureole) Rooiberg, S. Africa.

Magmatic disseminations (SnO_2) in granite, N. Nigeria. Segregations: minor Sn in Merensky Reef, S. Africa.

SnO_2 -bearing pipes in granite, S. Africa & E. Australia (Hypothermal).

PRIMARY DEPOSITS

SECONDARY DEPOSITS (DERIVED)



hand they are not far removed from those of Mg and Fe which are major components of the ferromagnesian minerals. It is, therefore, understandable that of the major minerals of any igneous mass, any ferromagnesian which may be present contain the maximum concentration of tin (and probably also of Nb, Ta and Mo).

However, despite the fact that the concentrations of Fe and Mg increase as the igneous rocks become more basic, the greatest concentrations of tin are found in the acidic and the least in the ultrabasic (Table 2). The data in Table 1 also make it clear why the titanium mineral sphere may contain much tin and rutile more than 2 per cent; why spinels may contain above 2 per cent and wolframite of the order of 1 per cent. On the other hand sphalerite, galena and chalcopyrite, because of certain structural relationships between them and stannite (Ofstedal, 1939) may be tin-bearing, but pyrite and pyrrhotite are free of the element.

During the development of sedimentary rocks tin becomes enriched in aluminium-rich hydrolyzates (70 p.p.m. Sn have been reported in bauxites and 40 p.p.m. in shales). Tin has also been reported in oysters, and in the tissues of most higher animals and plants, and it is sometimes "notably enriched in coal ashes". According to Sahama and Rankama (1952, p. 737)—from whose work much of the above geochemical data have been derived—some bacteria are thought to be able to abstract tin from thermal waters.

Geological Considerations

The economic tin deposits of the world are genetically—and closely spatially—related to granitic intrusives and effusives (Fig. 1). The major deposits are pegmatites, pneumatolytic/hypothermal, epithermal and xenothermal veins and replacements, and eluvial, colluvial and alluvial accumulations which have developed by the concentration of the dense resistate fractions of the primary deposits. It has been suggested that mesothermal tin deposits also occur, but these are probably best thought of as hypothermal tin deposits which have been invaded at a later stage by mesothermal mineral-forming agents. Occasionally, as in Malaya and Thailand, economically important deposits occur in metamorphosed limestone adjacent to granite; these, by virtue of their mineral assemblage, can be fairly termed pyrometamorphic. In addition, cassiterite is sometimes found as magmatic disseminations in granite (as in the Jos/Bukuru and Odegi fields of Northern Nigeria) but such deposits are not important direct sources of tin, although as a result of deep secular erosion they may contribute significantly during placer development.

In the primary deposits cassiterite, SnO_2 , is normally the dominant tin-bearing species present but, on occasion, stannite, $2(\text{Cu}_2 \text{Fe Sn S}_4)$, may assume a major role, and in

some of the Bolivian-type deposits other tin-bearing sulphides (such as teallite, $2(\text{Pb Sn S}_2)$, cylindrite, $\text{Pb}_2 \text{Sn}_4 \text{Sb}_2 \text{S}_{14}$ (?), and franckeite, $\text{Pb}_5 \text{Sn}_3 \text{Sb}_2 \text{S}_{14}$ (?)) may be economically important constituents. A number of exotic tin species has been recorded, but as they are of little relevance to the question in hand they will not be discussed. In the secondary deposits cassiterite alone occurs in economically important amounts.

Tin and Granitic Rocks.

Whereas some granitic regions contain important tin deposits others possess only minor ones or none at all, while within a given tin province much of the granitic intrusives or effusives and adjacent country rock is devoid of tin deposits. It is obviously important to consider the nature of any differences which may exist between the "tin granites", etc., and their barren equivalents, and to consider what facts and postulates are at present available to account for the distributional characteristics of the element.

At the outset it must be said that it is probable that granitic regions vary in their total tin content because of the original erratic distribution of the element in the crust. If this is so then those parts of the globe now occupied by South-west England, Malaya and Bolivia have always been unusually rich in the element. In such tin-rich regions it is probable that the element has been involved in the same cycle of events on a number of occasions. Broadly speaking each cycle involves the development of granitic rocks and genetically related primary tin deposits, destruction of the deposits and associated rocks by processes of weathering, transportation of the products of weathering to a centre of deposition, and completion of the cycle by conversion of the sediments into granite and primary tin deposits.

"Tin Granites"

Considerable work has been devoted to determining what, if any, are the differences between granitic masses with which tin deposits are genetically and closely spatially related and those which lack such an association. Clearly, if a granite mass could be readily classified as likely to have tin deposits associated with it, or unlikely to have them, this could expedite the selection of areas worthy of intensive prospecting.

Jones (1925, pp. 54-55) makes the point that the tin-bearing granites are of the acid type and states that in this connection "it is interesting and instructive to compare very briefly the granites of two mountain ranges near to one another, one granite range being highly stanniferous and the other barren, or almost barren, of tin minerals. The Benom Range in Penang, Federated Malay States, runs approximately parallel to the Main Range of the Peninsula . . . , the foot of one range being only about 12 miles from that of the other. Practically no tin deposits have ever been found in the Benom Range, whereas tin deposits are worked extensively in innumerable parts of the Main Range, and within 13 miles of the foot of the Benom Range. Colourless and pale coloured mica, muscovite and lepidolite, are rare or absent in the granite of the Benom Range, and are very abundant in that of the Main Range; and hornblende is a common constituent over large areas of the Benom granite, and is rare or absent from that of the Main Range . . . the granite of the latter range is of more acid type than that of the Benom Range."

Table 2

The Tin Content of Igneous Rocks

(After Rankama, K. and Sahama, T. G. p. 732, 1952.)

Rock	Sn (g/ton)
Dunite	0
Plateau basalt	4
Gabbro, average	8
Granite, average (Goldschmidt and Peters)	80
Granite, average (Ottemann)	56
Nepheline syenite	8-40
Greisen, average	800-8,000

Edwards and Gaskin (1949, p. 236) hold views similar to those of Jones; they contend that the granites with which tin deposits are associated are truly magmatic and of a special type. They assert that "tin granites" are conspicuously tin-rich, even among "acid" granites, and are abnormally high in Mg and Ca... typical "tin granites" in New South Wales (New England) contain from 74 to 76.5 per cent silica, those of Queensland (Stanthorpe) from 76.5 to 77 per cent silica, and those of Tasmania (Blue Tier) from 74.5 to 77 per cent silica. The "tin granites" of Saxony, Cornwall and the Azores are comparatively rich in silica."

The above remarks invite the following comments: It is not true that tin deposits are generally associated with very acid granitic rocks though it is probable that those which have tin deposits associated with them are not invariably truly magmatic.

Certain tin granites contain a far smaller percentage of tin than those quoted by Edwards and Gaskin, and the host rocks are not necessarily unusually low in Ca and Mg. Thus, the tin granite of Lagares-do-Estanho, Portugal, only contains 67.96 per cent SiO_2 (0.29 per cent MgO , 1.87 per cent CaO) (Cotelo Neiva, 1944, p. 8) and at Caracoles, Bolivia, the tin ore is associated with a quartz monzonite containing 65.39 per cent SiO_2 , 1.87 per cent MgO , and 7 per cent CaO (Lindgren, 1933, p. 648).

Metallogenic Provinces

In a given metallogenic province tin deposits are not necessarily developed within or in the close vicinity of the most acid granites. In the South-west of England, for example, one of the most acid granites yet analysed is from the Cornubian (it contains 75.09 per cent SiO_2 , 0.74 per cent MgO , and 0.66 per cent CaO) and though this mass has tin deposits they have been of little importance when compared with, say, those associated with the Carnmenellis granite, which, judging by the analyses available, has a silica content of 72 to 73 per cent (see Ghosh, 1934).

It is also to be noted that highly acid granitic rocks may be completely devoid of tin deposits (for reasons noted earlier): the soda leucogranite of Mountsorrel, Leicestershire, which contains 76.70 per cent SiO_2 , 0.65 per cent MgO and 0.6 per cent CaO falls into this category (Hatch *et al.*, 1949, p. 192).

Sullivan (1948, p. 485) holds that, provided tin is available in a given province, it will only concentrate in ore deposits that cannot be incorporated in the lattices of the granitic minerals and he states that "in the presence of abundant ferromagnesian minerals, the large scale concentration of these elements (*i.e.* Sn, W, Ta and Nb) may be practically impossible because of the similar ionic radii of iron... and magnesium... to those of the elements (tin, etc.) under discussion, and because of the relatively low valency of iron and magnesium". This is a very attractive suggestion and might well account for the paucity of ore in the vicinity of the Cornubian Range which has been noted earlier; it also again emphasises that considerable tin might occur in the biotites of certain granites—a question which is taken up later, and that ferromagnesian-rich alluvial samples may contain appreciable amounts of chemically-determinable tin and yet

have originated from a granitic region which is devoid of cassiterite-bearing deposits.

Barsukov (1957) claims that tin-barren granites do not differ essentially from the tin granites either in age or in mineralogical composition. However, whereas the barren granites only contain from 3.5 p.p.m. Sn, those associated genetically with tin deposits contain from 4 to 5 times as much of the element in the rock varieties which are not altered by post-magmatic processes. He also asserts that the marginal zones of the tin granites, due to assimilation of country rock, contain concentrations of tin which are approximately the same as those of the barren types, but any slates or sandy deposits adjacent to these granites are enriched in tin and contain from 15 to 25 p.p.m. of the element: this enrichment decreases as the distance from the granite increases.

Jedwab (1955) claims that the concentrations of certain trace elements in some of the mineral species of tin-barren granites are appreciably less than those of tin granites. He investigated the lithium content of feldspars and the tin content of muscovite and biotite micas from two granite masses of Morbihan, France. The one at Guehenno is barren whilst the other, at La Villeder, has tin lodes associated with it. The highest and lowest concentrations of the elements under review which were found in the mineral specimens obtained from the two masses are indicated in the following table:

		Guehenno	La Villeder
Li in feldspars	No. of samples analysed	11	30
	Extreme concentrations (p.p.m.)	0-110	0-450
	Arithmetrical mean (p.p.m.)	36	141
Sn in biotites	No. of samples analysed	10	25
	Extreme concentrations (p.p.m.)	50-85-(165)	32-165
	Arithmetrical mean (p.p.m.)	67(77)	110
Sn in muscovites	No. of samples analysed	9	23
	Extreme concentrations (p.p.m.)	10-130-(245)	60-400
	Arithmetrical mean (p.p.m.)	71(90)	120

Jedwab draws the following conclusions from this study:

(i) Tin is never absent from the micas of granites, regardless of whether they are tin granites or not: at least this is so as far as the Hercynian granites are concerned.

(ii) The two granites studied show a much more marked difference in the tin content of their biotites than in that of their muscovites.

(iii) The tin content of the micas increases as lodes are approached.

(iv) The lithium content of the feldspars is markedly different in the two granites.

(v) The tin content of the feldspars increases significantly (up to 280 p.p.m.) in the vicinity of lodes.

(vi) All the work demonstrates the importance of determining the concentration of oligo-elements in individual minerals.

It is quite probable that an analysis of total granite would not enable differentiation to be made between tin granite and barren granite. For example, the high concentration of lithium in the micas would mask the differences in the lithium concentration in the feldspars from the two masses, and it is these latter differences which permit material from one granite to be distinguished from that of the other. Jedwab (see Hawkes and Webb, 1962, p. 52) subsequently claimed that "a granite containing commercial pegmatite vein deposits can be distinguished from an associated, barren

granite by the trace-element content of the biotite. He found that the biotite from the productive granite contained on the average 10 p.p.m. Ni, 455 p.p.m. Sn, and 3,450 p.p.m. Li compared with 30 p.p.m. Ni, 200 p.p.m. Sn, and 380 p.p.m. Li in the biotite from the barren granite". Hawkes and Webb (*op. cit.*, p. 52) comment that "care must be taken when applying this type of criterion in the field, as variations in trace-element distribution may arise solely as a result of progressive differentiation of the host rock. For example, successive phases of the granite constituting the Carnmenellis intrusion in the heart of the Cornish tin field have widely differing trace metal characteristics (see table below) despite the geographical proximity of all phases to mineralisation".

Trace element variation in the various phases of the Carnmenellis granite. (After Hawkes and Webb, 1962, p.52)

Element	Content in fresh rock (p.p.m.)		
	Phase I granite	Phase II granite	Phase III granite
Co	8	4	2
Ni	10	4	2
Sn	25	5	30
Li	700	1,500	3,000

If a small number of samples are analysed from a comparatively large lithologic unit the results are likely to lead to wrong conclusions. Jedwab's samples were too few, and as sampling was not carried out on a grid a subconscious bias may well have entered into the operation.

Although the writer agrees entirely with the above observations of Hawkes and Webb, which are based on Webb's very limited, quoted, Carnmenellis analyses, the latter, in fact, demonstrate that an erroneous picture can be obtained from too few results as there is now strong evidence that Ghosh's Phases I and 2 granites are one phase. Chayes (1955), as a result of modal analyses of samples of Carnmenellis granites, and Cameron (1958) having investigated the specific alpha-particle activity of zircons from the mass, found strong reason for believing that Ghosh's Phase I and 2 granites were identical; this conclusion was also supported by the analyses of stream sediments (Hosking, K. F. G., Hosking, J. A. and Thomas, G. B. unpublished studies, 1964) which are discussed later. The danger of drawing conclusions from too few analyses is further emphasised by noting the marked variations which have been revealed in the granites of each of Ghosh's phases (see Table 3) when a comprehensive sampling and analytical programme is employed.

Table 3
Analytical Data for the Carnmenellis Granite

(Hosking, K.F.G., Roberts, A. and Ahmad, U. Unpublished Studies, 1964.)
(Values are given in parts per million)

Samp. Site	As	Be	Cr	Co	Cu	Fe	Pb	Mn	Mn	Ni	P ₂ O ₅	Sn	W	V	Zn	Location	Ghosh Phase
1	30	12	5	2	70	12,000	250	275	3	34	935	60	8	20	120	Quarry near dyke	I
2	16	12.5	2.5	1	1600	18,000	60	275	4	24	935	60	16	20	400	Shaft, lode area	I
3	5	15	6	4	15	9,000	10	350	4	30	1400	10	8	80	60	Quarry near dyke	I
4	10	10	20	3	20	14,000	15	550	3	36	1400	12	10	40	100	Shaft, lode area	I
5	7.5	5	2.5	1	12	14,000	10	500	1	36	1400	4	4	80	60	Dump	I
6	20	8.5	12.5	2	4	10,000	25	300	2	20	2100	2.5	3	60	100	Old Quarry	I
7	45	8.5	7.5	2	4	12,000	10	350	3	20	2100	10	3	160	48	Old Quarry	I
8	12.5	12.5	10	1	8	12,000	20	350	3.5	30	1865	3	3	160	200	Old Quarry	I
9	20	12.5	5	1	8	14,000	10	325	2	26	2100	20	4	120	60	Quarry	I
10	5	12.5	1.2	2	6	10,000	30	450	2.5	26	1630	20	4	200	68	Old Quarry	I
11	25	15	10	1	6	13,000	15	400	2	30	1165	2.5	2	160	60	Old Quarry	I
12	5	15	5	1	2	10,000	30	200	2	16	1630	2.5	4	20	56	Quarry	I
13	15	20	12.5	4	20	11,000	15	350	3	30	1260	5	8	20	120	Old Shaft, lode area	I
14	2.5	15	1.2	1	120	15,000	40	325	3	20	700	20	6	20	112	Shaft, lode area	I
15	20	8.5	15	2	16	11,000	35	500	2	30	1630	50	12	120	92	Quarry	I
16	70	20	2.5	1	20	11,000	75	350	3.5	44	1400	30	8	80	92	Old Quarry	I
17	15	12.5	17.5	1	25	14,000	55	250	3.5	16	1490	20	14	60	120	Shaft	I
18	17	15	12.5	3	20	10,000	70	200	3.5	26	1400	20	8	20	92	Old Quarry near dyke	I
19	15	15	7.5	1	18	10,000	40	350	4	30	1165	30	6	60	80	Old Quarry	I
20	2.5	12.5	6	1	12	10,000	35	400	3	16	1630	15	6	320	1500	Old Quarry	I
21	15	8.5	7.5	2	10	11,000	50	350	2	20	1490	30	4	30	104	Quarry	I
22	15	8.5	20	6	12	20,000	10	450	2	20	1630	2.5	4	240	100	Outcrop	I
23	25	12.5	10	5	20	15,000	30	325	3	30	1400	35	8	80	100	Quarry near dyke	I
24	25	12.5	6	1	70	17,000	65	250	2	14	1630	40	6	20	140	Dump	Ia
25	5	12.5	38	2	20	20,000	35	600	2	26	1865	40	8	60	160	Dump	Ia
26	5	12.5	7.5	2	6	15,000	35	400	2	26	1630	5	4	240	100	Old Quarry	II
27	20	15	20	1	4	14,000	25	400	4	20	2100	3	6	400	88	Quarry near dyke	II
28	7.5	7.5	5	1	4	5,000	140	325	2	14	1400	2.5	12	20	60	Old Quarry	II
29	135	8.5	30	4	7	15,000	55	400	2	30	1400	2.5	10	600	60	Old Quarry near dyke	II
30	55	15	12.5	1	8	15,000	35	425	3	30	1165	4	6	280	88	Quarry	II
31	30	15	17.5	1	6	15,000	25	400	2	30	1630	3	8	320	80	Outcrop	II
32	5	20	7.5	2	6	14,000	25	250	4	20	1630	3	6	240	84	Old Quarry	II
33	65	8.5	12.5	8	4	12,000	20	350	3	30	1165	3	6	240	60	Quarry	II
34	17.5	20	7.5	4	4	14,000	5	4000	2	30	1865	4	8	240	72	Old Quarry	II
35	65	12.5	12.5	4	80	9,000	125	200	4	41	935	50	10	20	120	Quarry near dyke	III
36	20	8.5	0.25	0.6	20	8,000	30	200	3	20	1260	25	2	20	92	Quarry	III
37	12.5	12.5	7.5	1	4	11,000	10	400	3.5	20	1490	2.5	4	60	40	Shaft, lode area	III
38	35	20	10	2	6	10,000	25	325	3	30	1865	10	8	20	100	Quarry, lode area	III
39	5	8.5	2.5	10	40	35,000	50	1400	5	34	1400	500	45	20	160	Shaft, lode area	III
40	2.5	15	3.7	6	800	14,000	35	400	3	20	935	120	4	20	120	Shaft, lode area	III
41	2.5	12.5	6	2	300	10,000	15	300	2	20	700	25	10	20	160	Shaft, lode area	III

Granite Controversy

From the foregoing it will be apparent that there are still many conflicting views concerning the differences, etc., between tin granites and their barren counterparts. However there seems good reason for believing that generally (though not invariably) tin granites are most likely to be found closely associated with hornblende-free, acid granites, and that of the biotite granites of a given region, those most likely to have tin deposits associated with them can, if Jedwab is right, be selected by considering the concentration of tin in the biotites and of lithium and tin in the feldspars of the various masses.

However, again, within a granite mass the variation in trace element content between different samples of whole granite is matched by that of the micas and the feldspars so that a comprehensive unbiased sampling programme is still required if Jedwab's views are to be tested. Carrying out such a sampling programme may be fraught with difficulty. In Cornwall, for example, large alluvium-filled basins occupy considerable areas of the surfaces of the larger granite outcrops and within such basins samples of fresh granite can only be obtained by drilling. Furthermore, the trace-element content of two samples of granite collected only a few yards from each other may vary markedly due to inherent differences, differences induced by post-consolidation hypogene agents, or to varying degrees of weathering not apparent to the naked eye.

If then an easier alternative to sampling and analysing hard rock exists which will enable tin-barren and tin granites to be differentiated it would facilitate exploration, and there is an alternative which can be employed in many geologic and climatic environments. Stream sediments are homogenised samples of the hard-rock units across which the streams flow (unless the region happened to be a dumping ground for recently far-transported glacial debris) hence their trace element content should reflect local lithologic variations though the reflections may be somewhat distorted. That this is so is indicated by experiments carried out in Malaya by Webb and Tooms (see Hawkes and Webb 1962, p. 374) who, by "using a rapid field method of analysis, have shown that the tin content of fine stream sediment can be used in regional reconnaissance for distinguishing stanniferous and non-stanniferous granites." The writer and others (Hosking, K. F. G., Hosking, J. A. and Thomas, G. B. unpublished studies, 1964) by analysing the minus 80 mesh (B.S.S.) fraction of sediments from the radial drainage system of the Carnmenellis Mass and then analysing the results by a grid deviation method, were able to delineate the tin lode zones, to develop a picture of the structure of the mass, and to show that tin and lithium were related antipathetically. This unexpected Li/Sn relationship has also been found to hold in some, at least, of the Kamativi tin-bearing pegmatites of Southern Rhodesia (Bellasis and van der Heyde, 1963, p. 49). The reason for this relationship in the Cornish fields is discussed later, sufficient is it to note here that if this relationship is general it permits potential tin areas to be delineated even though the lodes themselves may not sub-outcrop.

Finally it should be noted that the stream sediment approach to the problem under discussion is also better than the hard-rock one in that sediments are easier to collect and

do not require the time consuming pre-analytical treatment which rock samples need.

Tin Bearing and Barren Pegmatites

In a tinfield in which economically interesting concentrations of cassiterite are confined to pegmatites it is usual to find that only some of the bodies are tin-bearing. Furthermore, even those pegmatites which contain substantial quantities of cassiterite may have outcrops which are devoid of the mineral, and as it cannot be predicted just where in a given pegmatite any cassiterite present is likely to be concentrated, a reasonable amount of drilling cannot be relied on to differentiate between the possibly productive and the barren bodies. Obviously, any means of making this differentiation which depends on examination of outcropping material could be of considerable value, and the results of a number of workers suggest that such means exist.

Ginzburg (1954) states that in pegmatites dark blue and green tourmalines are widespread in cases of intensive albitisation which accompanies tantalum/niobium and tin ores, whereas those pegmatites which have not been subject to ore-forming replacement processes generally contain only black tourmaline. It must, however, be stated categorically, that tin, tantalum and niobium minerals are not always present in pegmatites that have been albitised and which contain coloured tourmalines. At Meldon Quarry, Okehampton (Devon), such altered pegmatites and aplites occur, and despite the fact that they have been much worked and carefully examined on many occasions, of the Nb, Ta and Sn suites of minerals only columbite has been recorded, and only a few minute crystals of this species has ever been found. Ginzburg also remarks that small quantities of tin are always present in the micas of pegmatites, partly as very small grains of cassiterite and in part as an isomorphous mixture in the crystal lattice. The micas in pegmatites rich in cassiterite contain up to 0.4 to 0.5 per cent SnO_2 , whereas in barren pegmatites the amount of tin in the micas is negligible.

Ahrens and Liebenberg (1950) also conclude that tin-rich micas are characteristic of pegmatites with a possible cassiterite potential. The same workers also state that "the other common pegmatite minerals, albite, microcline and quartz invariably do not contain detectable amounts of tin, and would therefore be useless as possible tin prospecting indicators". Jedwab (1953), has severely criticised these observations. Briefly, he claims that his work in this field allows the following conclusions to be drawn:

- (i) Micas from both "tin-mineralised" and "tin-barren" pegmatites contain tin.
- (ii) The muscovites of both syntectonic, non-mineralised, and post-tectonic, mineralised pegmatites may contain comparable concentrations of tin.
- (iii) Although the tin content of the feldspars is always very much lower than that of the micas it enables differentiation to be made between barren and tin-mineralised pegmatites with a much greater degree of certainty than is possible when the tin-content of micas is used as an indicator.

However, the choice of feldspar to be analysed is most important, as those which developed before the cassiterite (microcline principally) are richer in tin than those (usually

albites) which developed contemporaneously with, or after the cassiterite. Despite certain differences in the above views they are all "in accord with a long suspected relationship between the presence of trace elements and accompanying minerals (in pegmatites) and the presence of concentrations of these elements in their own minerals: namely, that in order to crystallise these minerals at all, the concentrations of their elements must be sufficiently high so that the entire system is relatively 'saturated' by them. Therefore, abnormally high concentrations of these elements will appear not only in discrete form as their 'own species' but will also be camouflaged in accompanying species vicariously" (Heinrich, 1962, p. 618).

Horning (1962) has recently demonstrated that in Southern Rhodesia differentiation between lithium-, niobium-, and beryllium-rich pegmatites and those containing comparatively small amounts of these elements can be made by consideration of the concentration of these elements in the wall rocks. He does not concern himself with the possibility of using a similar technique to differentiate between tin-rich and tin-poor pegmatites but clearly this is a possibility worthy of consideration. Indeed, Horning concludes his paper (p. 1129) saying "it is felt that in any large scale pegmatite investigation a study of the wall rocks should be made, particularly when pegmatites are emplaced into host rocks of a very contrasting composition, where any alteration is most pronounced. The absence of any halo around an individual pegmatite will not in itself indicate a lack of economic minerals, but in a regional study, the presence of striking enrichments around certain pegmatites will clearly establish a need for further investigation."

To summarise, the evidence at present available suggests that a study of the tin content in the micas and feldspars of pegmatites and in the host rock is likely to enable, in a given area, differentiation to be made between "tin-rich" and "tin-poor" pegmatites and so to limit the targets to be drilled. On occasion the degree of albitisation and the presence of coloured tourmalines may also facilitate the selection of such targets.

Time and Space Considerations

When assessing the possibilities of an area, the absolute age of the granite rocks within it is not nearly as important as its geologic history, since tin-bearing deposits are known which are genetically related to granitic rocks varying in age from Precambrian to Tertiary. However, as tin deposits occur in the vicinity of the tops of batholithic masses the greater the extent to which a given granitic body has been uncovered and destroyed by erosion the smaller the chance of finding worthwhile primary deposits associated with it. In this sense there is possibly less chance of finding primary deposits in the vicinity of early granites than in that of later ones, but there are, of course, other important controlling factors to be considered. It is also to be remembered that at least in part because the original surface of a given batholith may be very irregular, at a given time erosion may have partly or entirely eliminated deposits originally associated with those parts of the mass which were emplaced of the highest horizons whilst deposits associated with more deeply emplaced parts of the batholithic surface remain virtually intact.

This is well seen, for example, in Malaya where only roots of lodes are found near the top of the Main Range (as at Sangkha Dua) on the west, whereas on the east, where the granite was emplaced at a much lower horizon, the lodes (as at Pahang Consolidated mine) are still largely intact. As an important corollary it follows that in Malaya major alluvial cassiterite deposits (the small ones of the Bundi Mine area cannot be classed as such) are unlikely to be found in the east coast region occupied by North Pahang and Trengganu, and little more than the roots of lodes are likely to occur in and about the tin-rich alluvial tract of the Kinta Valley. Generally, also, erosion leading to the exposure of the high spots of a granite batholith means that reasonably intact primary tin deposits are most likely to be located near the granite/country rock contact, not well inside the granite: this is well exemplified in the Carn Brea/Carnmenellis area of Cornwall. There, along the northern granite/slate contact are to be found the deep mines of Dolcoath, South Crofty, East Pool, etc., whereas in the centre of the Carnmenellis granite mass only comparatively shallow mines occur: of these Porkellis and Polhigey are typical.

Because orebodies genetically related to rhyolites are developed near the surface it follows that they are likely to be destroyed fairly rapidly by erosion and so it is very unusual to find such bodies which are pre-Tertiary in age. Occasionally, however, fortunate circumstances have prevented the destruction of such older deposits and the xenothermal tin deposit of Mount Pleasant, New Brunswick, which is of Mississippian age (Hosking, 1963) is such a one.

Time and Emplacement

That the time at which a granitic or rhyolitic mass was emplaced within a geosyncline determined whether or not it should have tin deposits associated with it (provided, of course that tin was available) has been suggested by Bilikin (1955). He believes that within a mobile belt events always follow the same sequence. Tectonic changes follow a set pattern and at fixed points in time particular types of igneous and volcanic rocks are developed and characteristic mineral deposits are formed. Although granitic rocks and rhyolites may develop on a number of separate occasions within such a belt, tin, according to Bilikin, is only likely to be deposited in association with ultra-acid potassic granites, alaskites, aplites and pegmatites in the middle (M3) stage and with the granites, and their hypabyssal and volcanic equivalents, of the late (L2) stage. Furthermore, he suggests that whilst the middle stage tin may be associated with W, Mo, Bi, F, Li, Be, Ta and Nb, that of the late stage tends to occur with Pb, Zn, Ag, As, and possibly W and Mo. Obviously if the Russian's conclusions are valid they can be used to considerable advantage to select targets in those areas whose geology is reasonably well known but in which little prospecting for tin has been carried out. McCartney and Potter (1962, p. 87) claim that the Russian findings are applicable to the Canadian Appalachians and make the significant comment that "had this paper been written a few years ago, we would have listed the sulphide-cassiterite assemblage (L2) expected in the late phase (Mississippian in the Appalachians) as 'missing', yet the recent recognition of tin at Mount Pleasant, New Brunswick, is exactly the mineral assemblage expected and, if mineralisation is roughly synchronous with the rhyolitic wall rocks, it is of the correct age."

Distribution Patterns.

The distribution patterns of tin deposits in the vicinity of granite batholiths possess certain recurring features which may facilitate the search for "new" deposits. The most intense tin mineralisation appears to be found in the vicinity of the widest (i.e., the central) section (in plan) of an elongate lenticular batholith. In the South-west of England, for example, the most intense tin mineralisation occurs within the central quadrangle bounded by the batholithic "high-pots" of St. Agnes, Carn Marth, Carnmenellis, and Godolmaston. As the batholith is traced to the N.E. and S.W. from this zone the mineralisation gradually decreases so that in the extreme N.E. area of Dartmoor it is very slight and in the south-western extremity, in the Scilly Isles, the only indication of hypothermal tin mineralisation is the occasional crystal of cassiterite seen in a small quartz vein.

The distribution of tin deposits which are associated with the lenticular "sub-batholiths" of Malaya and Thailand shows somewhat similar patterns. In Malaya the maximum mineralisation occurs in the widest central section which embraces the Kinta Valley and the fields in the vicinity of Pahang Consolidated Mine. In Malaya, however, the pattern differs a little from that of the S.W. of England in that mineralisation again increases somewhat at the extremities (in Kelantan and Johore) where the granite ridges coalesce.

Tin Provinces

Within a tin province in which the deposits are genetically related to a granite batholith, well-developed lodes are usually (probably invariably) spatially closely associated with clearly-defined, steep-sided cusps (or cupolae), and in an area of limited extent the strongest lodes are usually associated with cusps of the above type which have penetrated to the highest horizons above a given datum. Such cusps, which tend to surmount granite ridges, are often characterised by possessing at their apices a series of greisen-bordered veins containing cassiterite, wolframite, arsenopyrite, etc.: alternatively they may be haloed by a swarm of narrow mica-margined veins whose mineralogical characteristics are similar to the greisen-bordered type. (Both these types of vein swarm are commonly sub-economic unless the country rock is so decomposed that they can be mined by open-cast methods involving little but the use of mechanical shovels. It is also worth noting that greisen-bordered vein swarms, particularly when they occur in kaolinised granite, have much in common with the porphyry coppers, and some of them could fairly be called porphyry tin deposits.)

Pegmatites and hypothermal lodes and replacement deposits of major economic importance tend to flank or halo these cusps and these deposits may be equally well developed in either the granite or the country rock adjacent to it. Thus, exposed cusps with apical greisen-bordered veins containing cassiterite should be regarded as pointers to the possibility that economically important flanking lodes may be present. Conversely, the general lack of well-defined cusps in areas where it is clear that had they been present they would not have been completely eliminated by erosion, may well mean that strong lodes are unlikely to occur, though numerous

small tin-bearing veinlets may be present which if subject to deep secular erosion may provide sufficient cassiterite for extensive and important alluvial deposits.

This is precisely what appears to have happened on the Plateau of Northern Nigeria where, though there are many large placer deposits, there is almost a complete absence of large tin veins. The writer agrees entirely with Mackay *et al.* (1949, p. 57) when they say that at least in part this paucity of lodes may have been due to the fact "that the Plateau Granites may have had relatively flat tops, which would ... contribute to the dispersion of mineralisation."

Examples

Often the relationship between lodes and well-defined cusps has been partly, or entirely, obliterated by erosion, and so the most convincing examples must be looked for in those areas in which the granite is still largely, or entirely, uncovered. Typical among such examples are the following:

Pahang Consolidated Mine (Malaya) (Fitch, 1947). Here the lodes cluster about a series of buried cusps: no values occur in the granites of the mine.

Tronoh (Malaya). A rich lode was discovered flanking a small granite cusp which is situated at the limestone/slate contact. (Hosking. Unpublished notes.)

Aberfoyle Mine (Tasmania) (Lyon, 1957). The lodes of this mine which contain cassiterite and wolframite, halo a buried, slightly greisenised cusp, and maximum values occur at the points where the lodes intersect anticlines.

St. Agnes (Cornwall). A suite of important tin lodes fringes a barely-exposed granite cusp which locally contains small greisen-bordered tin-bearing veins.

Phuket (Thailand). This small island off the west coast of peninsular Thailand consists essentially of non-calcareous sediments which have been invaded by granite which is locally exposed as a series of N.-S.-trending ridges. Tin mineralisation is confined to the central third of the island where the granite occurs as large cusps, and maximum mineralisation occurs near the western coast where the cusps are most strongly developed and where they were emplaced at the highest horizon. Although some of the cassiterite occupies veins and pegmatites much of it has been liberated by erosion and has concentrated at the base of the hills where it is recovered by dredging and open-cast mining methods. The fact that further submerged cusps with associated mineralisation might occur offshore to the east and west of the known belt of mineralisation in part dictated the areas to be searched for submarine placers: a search which has proved outstandingly successful (Hosking, K. F. G., Private reports).

Cligga (Cornwall). Here a small granitic cusp containing numerous greisen-bordered cassiterite- and wolframite-bearing veins forms a part of the coast. To the landward side it is flanked by a number of sizeable copper-bearing veins which locally may well be tin-bearing in depth. In the author's view it is likely that tin-bearing veins also flank the cusp on the seaward side.

Carn Brea (Cornwall). This N.E.-S.W.-trending elongate cusp is capped by a few small greisen-bordered cassiterite/wolframite/arsenopyrite-bearing veins. It is flanked on both sides by major tin- and copper-bearing lodes whose strikes approximately parallel that of the long axis of the granite.

Mawchi Mine (Burma) (Hobson, 1940). Here tin/tungsten lodes are closely associated with a prominent granite cusp which has penetrated slates and limestones.

Mumba—Numbi—Nyamukubi Region (Kivu, Congo). (Agassiz, 1954). In this region both stanniferous pegmatites and hypothermal veins flank the granite cusp of Mont Hango.

(To be continued)