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The Search for Tungsten Deposits

K. F. G. Hosking

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CONTENTS

Preface

This fifth Bulletin in our series is an expanded version of the fifth Presidential Address of the Geological Society of Malaysia, read to the fifth Annual General Meeting on 13 February 1971 in the Lecture Room, Department of Geology, University of Malaya, Previous Presidential Addresses have been separately printed as pamplets or included in a Bulletin together with other papers, but in this case, it was felt that due to its length and content it would be more appropriate to publish it separately in a Bulletin.

This Bulletin containing only one paper is also a departure from our usual practice of presenting a collection of papers as in Bulletins 1, 3 and 4. The next two Bulletins would however revert to our previous trend. Bulletin 6 at present in press is a selection of papers presented at the Regional Conference on the Geology of Southeast Asia held in Kuala Lumpur on 20–25 March 1972 while Bulletin 7 is miscellaneous in content.

B. K. TAN

The Search for Tungsten Deposits

K.F.G. HOSKING[1]
Fifth President, Geological Society of Malaysia

"An obstetrician is a medical specialist who delivers babies; he does not simply make biological studies. An exploration geologist is a specialist who delivers orebodies; he does not simply make geological studies."

(T.W. Mitcham. Discovery Thinking in ore-search. 1955. (Feb.), Mining Engng., 140–141.)

Synopsis

It is pointed out that although now tungsten is a 'feast or famine' metal the time may not be far off when it will be in short supply unless immediate steps are taken to search for further deposits of it.

It is held that realistic search for such deposits must be based, essentially, on an intimate knowledge of the tungsten minerals and particularly of their behaviour in the superficial environment. Furthermore, the nature of all types of tungsten-bearing deposits must be fully appreciated as must be the geologic environment in which they occur. Knowledge of the tungsten distribution patterns in the accessible parts of the Earth is also of fundamental importance. On the other hand, views of the source of the tungsten in the primary deposits, of its mode of transport to the sites of primary deposition and of the chemistry of this deposition are of no consequence, and exploration programmes which owe their design, to an appreciable degree, to consideration of such topics, are suspect, and likely to be of limited value.

Because of the above views the writer has, in this paper, dealt in some detail with tungsten distribution patterns, the tungsten species (and certain field tests for their identification), the nature of the tungsten deposits, the geologic environments in which they occur, and the relationship between some of the primary ores and granitic bodies. He has also examined, at considerable length, the behaviour of tungsten in the surface and near-surface environments, and whilst noting various aids to the search for deposits of the type under discussion, he has given prominence to geochemical ones, because of their special value.

Finally, exploration programmes for tungsten are presented and their content is commented on.

INTRODUCTION

To many of the mining fraternity wolframite, [(Fe, Mn) WO_4] and scheelite ($CaWO_4$), by far the two most important sources of tungsten, are 'feast or famine' minerals. Exploitation of tungsten deposits may result in fortunes for the miner or simply piles of concentrate for which there is either no immediate sale or for which prices are offered which may not even cover the cost of production. This is because, until possibly *very* recently, the value of the element under review has fluctuated in sympathy with the degree of unrest shown by the nations of the world, a fact which has given rise, in the United States, to the expression 'the more tension, the more tungsten' (Bateman, 1950, p. 598). It is also due, to no small degree, to the uncertainty of China's likely behaviour, at any time, in the tungsten market. Of the annual production of tungsten, which varies from c. 20,000–60,000 tons of concentrate, China has, in the past, contributed about a third, most of the balance coming from the 'countries which follow the volcanic chain which skirts the Pacific, (Bateman, op. cit., p. 598). Recently, however, this major producer has not offered tungsten concentrates to the outside world, and whether this is due to the fact that she is stock-piling this

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commodity, or running short of reserves, or for some other reason, remains conjectural.

That the value of tungsten reacts so rapidly to wars and rumours of wars stems from the fact that it plays such an important rôle in metallurgical industries which are of major importance during times of trouble. The element is used, for example, in the production of high-speed cutting steel, guns, projectiles, armour plate, electrical apparatus, and radio. It is also an ingredient of tungsten carbide, a remarkably hard compound used to tip tools for metallurgical processes, and as the cutting parts of rock drills: tungsten filaments are normally those used in electric light bulbs. This list does not exhaust the uses of this element but is sufficiently comprehensive to indicate that it has an important rôle to play in peace as well as in war, and this rôle will increase as more and more countries become industrialised. So, although it is virtually impossible to forecast the price of tungsten-bearing concentrates 5 years hence, that is to say, one does not know what the need will be for such concentrates in 5 years time, taking the long-term view there seems to be no doubt that the world's demand of the element will increase, albeit probably erratically, and it may be, as some think, that by the year 2,000 there may be insufficient tungsten to meet current demands unless new sources are located. Doubtless, as the need arises, new exploitable deposits will be found, and with time improved mining and beneficiation methods, together with an increase in the value of the commodity, will permit progressively lower grade deposits to be mined profitably. Such deposits are known and will be referred to again later. However, in the writer's view, the time is ripe for one to make an inventory of existing knowledge concerning the nature of the tungsten deposits, of the geologic environments in which they occur, of the exploration techniques, etc., which have been employed, or which might possibly be employed during the search for such deposits, and of those geochemical and other data relating to natural phenomena upon which the search for tungsten deposits, if it is not to be of the nature of wild-catting, must be based.

In this paper questions relating to the genesis of primary tungsten deposits will only be discussed if they are relevant to the search for such deposits. The writer holds the view that the search for tungsten or indeed, any 'metallic' deposit, should be founded largely on the results of comparative studies. The types of mineral deposit occurring in a given geologic environment in one part of the world may well be found in the same geologic environment in another part of the world. What happens to a given outcropping tungsten ore body in a given climatic/geomorphological environment in the northern hemisphere is likely to happen to a similar ore body in a similar environment in the southern hemisphere.

WORLD DISTRIBUTION OF TUNGSTEN DEPOSITS

Most of the major tungsten deposits of the world rim the Pacific Ocean but other important ones are found in Burma, Brazil and Portugal, whilst less important deposits, which have been worked solely, or partly for their tungsten content, are considerably more widespread and occur, for example, in Spain, France, Britain, Morocco and Nigeria.

Some idea of the relative importance of the various tungsten producers is indicated by the following remarks by a 'special contributor' to the Mining Annual Review, 1971 (London), p. 67:–

"...... world mine production of tungsten ores rose to 35,837 s. tons in 1970 from 34,838 s. tons in 1969. Communist countries (predominantly China) accounted for roughly half these totals .... The leading Free World producers in 1970 (with 1969 outputs in brackets) were: U.S., as to mine shipments, 5,000 s. tons (4,702), South Korea 2,250 (2,168), Bolivia 2,050 (2,025), Portugal 1,450 (1,308) and Australia 1,487 (1,473)."

To those searching for tungsten deposits it is of some considerable importance to note that they are commonly, but not invariably, found in tin provinces. In addition, tungsten in workable amounts is also not uncommonly found in the same areas, and indeed on occasion in the same ore bodies, as economically important concentrations of molybdenum and/or bismuth minerals. However, at this stage emphasis is placed on the tin/tungsten relationship because the geology and distribution of tin have been more fully investigated than those of tungsten's other common metallic associates.

All tin provinces known to the writer contain tungsten-bearing deposits and the overwhelming majority of the tin provinces contains some deposits in which the tungsten content is such that they can be regarded as tungsten ore bodies. However, the degree of importance of the tungsten deposits in the tin provinces varies enormously. Thus, for example, the tin province of the North Transvaal contains comparatively little tungsten, as does that of the Southwest of England, whereas those of China and the U.S.S.R. appear to contain considerable deposits of both elements. Within mixed tin/tungsten provinces the distribution of tungsten may, or may not broadly coincide with that of tin. In the Southeast Asian tin province, for example, which extends from central Burma, via peninsular Burma, Thailand and Malaysia, to Indonesia, economically important tungsten deposits are much less in evidence in the southern half than in the northern. Furthermore, within such mixed provinces, some of the tungsten deposits may be virtually free from tin, as was the case, for example, at the Castle-an-Dinas wolfram mine, Cornwall, and the Kramat Pulai scheelite mine, Perak, W. Malaysia, or the tin and tungsten minerals may each occur in separate vein systems which are so intimately related that they cannot be mined separately. A typical example of this occurs at South Crofty Mine, Cornwall, where locally, early K-feldspar/quartz/arsenopyrite/wolframite veins are intersected by ones containing quartz, chlorite, fluorite and cassiterite. Finally, both tin and tungsten species may occur in the same ore body and, in the extreme case, as in the Mawchi Mine, Burma, the species may be so intimately admixed that the two can only be effectively separated by resorting to chemical means.

Because of this common tin/tungsten association the maps compiled by Schuiling (1967) showing the distribution patterns of tin occurrences in Europe, Africa, North America and South America are of importance to those searching for further tungsten deposits, and it is of real interest to note that the tin/tungsten deposit of Abu Dom, Sudan (Almond, 1967) which is within a logical extension of one of Schuiling's tin belts, was discovered after the preparation of the maps in question. Clearly, however, the distribution of tungsten deposits needs to be treated in the Schuiling manner, largely because there are major tungsten provinces which are tin-impoverished and the most important of these are the Peruvian, Argentinian, North Brazilian, North American Cordilleran and Korean ones.

If, in addition, one accepts that continental drift has occurred, and who doubts this now, then Schuiling's fig. 8 (op. cit.) showing his tin belts on a 'reconstruction of the continents' offers food for thought for the searcher for tungsten, and a similar one on which tungsten belts were plotted would offer even more food for thought. The position of tin, tungsten and other great ore provinces, 'in the frame of the theory of continental drift' has also been considered by Petrascheck (1960) and his findings concerning the element under review, although too prolonged to be included here, are worthy of study: however, to 'whet the appetite', on page 58, his figure (abb.) 3 indicates that Palaeozoic tin/tungsten deposits may well occur in Antarctica! Elsewhere Petrascheck (1960, p. 576) makes a further remark re the distribution of tungsten and tin which is relevant to the topic under discussion. He says 'the granitophile metals, tin and tungsten, appear in larger amounts in the younger belts': and Petrascheck continues, 'but they apparently were reworked from the ancient shields and incorporated into the younger palingenic magmas around the Pacific''. These views the writer also holds to be correct.

ASPECTS OF THE GEOCHEMISTRY OF TUNGSTEN

Goldschmidt (1954) and also Rankama and Sahama (1952) bemoan the fact that the geochemistry of tungsten is imperfectly known, and certainly much less *is* known about it than that of tungsten's common associate molybdenum, but from which it differs appreciably.

The lack of knowledge about the geochemistry of tungsten doubtless stems, as Ginsburg (1960, p. 176) observes, from the 'relatively low sensitivity of the spectrographic method (for tungsten) (0.01%) or perhaps, as some say, a few thousands of 1 percent.' So it is common to find the results of trace element studies of rocks and even plant material, in which the concentrations of many elements are recorded, lacking those of tungsten, for the reason noted above. Thus, for example, a recent account (Hall, 1969) of the geochemistry of the Cligga Head Granite, Cornwall (a granitic cusp famous for its numerous greisen-bordered cassiterite/wolframite-bearing veins) contains details of the concentrations of 10 trace elements in the granite and greisens but those of tungsten are conspicuous by their absence!

Because some knowledge of the fundamental geochemistry of tungsten is at least a desirable, and, in the writer's view, an essential preliminary to the planning and sound execution of geochemical surveys aimed at locating deposits of the element, it is pertinent to present at this stage certain geochemical data relating to tungsten. For convenience, however, certain aspects of the tungsten content of granitic rocks will be discussed later as also will be the fate of tungsten in the superficial environment.

Rankama and Sahama (1952, pp. 625–626) provide the following information concerning the tungsten content of igneous rocks:–

	g/ton
Igneous rocks	69
Igneous rocks	1.5
Igneous rocks	8
Gabbros and norites	24
Basic rocks, Central Roslagen, Sweden	10
Silicic and intermediate igneous rocks	1.5
Granite, Schwarzwald, Germany	83
Acidic rocks, Central Roslagen, Sweden	7

Goldschmidt (1954, p. 558), commenting on the first two results recorded above, observes that "both results seem rather high......". The present writer is very much in agreement with Goldschmidt's comment and would add that the tungsten content of the Schwarzwald granite recorded by the same workers is surely greatly in excess of its true content. It is relevant to record here the tungsten content of a number of igneous and metamorphic rocks of the Carnmenellis and Lizard areas of South-west England which were obtained by the writer by means of the dithiol method of analysis (Hosking. Unpublished studies).

Rock	Locality	P.P.M.
Chromite serpentine	Kynance	<4
Gabbro	Crousa Downs	<4
Horblende schist	Mullion	<4
Epidiorite	Ponsanooth	<4
'Slate'	Trelowarren	<4
Microgranite	Kennack	4
Biotite granite	Long Downs	4
Biotite granite	Penryn	4

Hawkes and Webb (1962, p. 374) state that the average tungsten content of igneous rocks is 2 ppm and they also note that Green (1959) concludes that limestones contain 1.8 and sandstones 1.6 ppm of the element in question.

Rankama and Sahama (1952, pp. 626–627) note that magmatic sulphides contain an average of 2 g/ton tungsten and that titaniferous iron ores (according to Landergren) contain less than 100 g/ton of this substance. They further observe that rare earth and tantalum/niobium minerals, which typically occur in pegmatites, usually contain some tungsten which in the case of columbite may reach the surprisingly high figure of 13 percent. In view of the fact that the ionic radius of tungsten does not differ greatly from those of niobium, tantalum, tin, bismuth, molybdenum, iron and magnesium it is not surprising to find tungsten closely associated with some or all of these elements in natural environments. One might expect, for example, to find W^{6+} proxying for Ta^{5+} in the lattice of, say, tantalite, and possibly also occurring as 'wolfram' ex-solution bodies in the same species. For similar reasons it might be expected that tungsten might occur in appreciable trace amounts in titanium species (ilmenite, sphene, etc.) and in the ferromagnesian minerals, but the writer has been unable to find any data in the literature relevant to these observations. He, and others, have together determined the tungsten content of biotites from the Carnmenellis granite, but it is convenient to discuss these results later.

That the tungsten content of cassiterite is commonly high is to be expected in view of the similarily of the ionic radii of Sn^{4+} and W^{6+}: it is reasonable to expect that tungsten might be incorporated into the cassiterite lattice and that, in addition, on occasion, exsolution bodies of tungsten species might occur in the tin mineral. Sometimes, however, the tungsten content of cassiterite is largely due to the deposition of the tin species around fragments of earlier deposited wolframite: this is commonly the case, for example, in South Crofty Mine, Cornwall, where earlier wolframite-bearing veins are intersected by later cassiterite-bearing ones (Hosking, 1964).

That tungsten often occurs in cassiterite was amply demonstrated by Venugopal (1952) who subjected samples of the mineral from many fields to semi-quantitative spectrographic analyses. He detected tungsten in 60 per cent of the samples he investigated and noted that those from Cornwall and Bolivia commonly contained tungsten in excess of 1 per cent, whilst the tungsten content of those from Portugal and France varied from c. 3,000 ppm to such a small amount that it was not detected. Specimens from New South Wales, Malaya and South Africa generally contained less tungsten than those of the Cornish/Bolivian group and more than those of the Portuguese/French one. It is also of interest to note that Venugopal never detected more than comparatively small amounts of tungsten in those samples of pegmatite cassiterite which he investigated, and that he concluded that high tungsten ($>$ 10,000 ppm) cassiterites were most commonly found in quartz veins and sulphide lodes, and that the high tungsten values were largely due to inclusions of tungstates. Apart from the levels of concentration these general findings are not, for the most part, greatly at variance with those of Pryor and Wrobel (1950–51, pp. 202–205) who subjected acid-cleaned cassiterite to spectrographic analysis. The reported tungsten content of the cassiterites they studied is given in Table 1, from which it will be at once apparent that this latter work indicated that cassiterites only contain from about a fifth to a tenth of the tungsten which Venugopal found. The findings of Pryor and Wrobel also differ from those of Venugopal in that whilst both parties agree that cassiterite from pegmatites contains not more than a trace of tungsten, Pryor and Wrobel claim that the cassiterite from sulphide veins shows this same characteristic whilst that from quartz and quartz/feldspar veins has a tungsten content which "rises towards 0.3 per cent". (Footnote.)

Table 1. The tungsten content of samples of cassiterite
(Data after Pryor and Wrobel, 1950–1951)

	Source of cassiterite	Tungsten content (percent)
A.	*Cassiterite from pegmatite veins*	
	Amari dyke, N. Nigeria	tr.
	Kota Tinggi, Johore, Malaya	tr.
	Pereiro Mine, Portugal	0.1
	Tambun Mine, Kinta District, Malaya	tr.
	Kaia, Bauchi Plateau	nil
	Herberton, N. Queensland	tr.
B.	*Cassiterite from quartz and quartz-felspar veins*	
	Pulai Mine, Kinta District, Malaya	0.1
	Tekka Mine, Kinta District, Malaya	0.2
	Kacha Mine, Malaya	0.1
	Siputeh Mine, Malaya	0.2
	Zinnwald, Germany	0.1
	Murcia Mine, Spain	0.1
	San Finx Mine, Corunna, Spain	0.1
	Borralha Mine, Portugal	0.1
	Panasqueira Mine, Portugal	tr.
	East Pool, Cornwall	0.1

Footnote: It is relevant to point out that such conclusions are only completely valid if each deposit is correctly classified. Certainly the classification of Pryor and Wrobel (Table 1) is to some extent erroneous although the errors are not, perhaps, sufficiently plentiful to seriously affect their conclusions. The deposits of Kota Tinggi, for example, should be place in group B, whilst those of Geevor and Panasqueira, whilst containing feldspar, are, nevertheless, distinctly sulphidic, and so more properly belong to Group C.

(*Table 1 continued*)

Source of cassiterite	Tungsten content (percent)
South Crofty, Cornwall	0.2
Dolcoath Mine, Cornwall	0.1
Geevor Mine, Cornwall	0.1
Gwithian Sands, Cornwall	0.1
Green Bushes, N. Australia	0.1
Glen Sands, New South Wales	0.05
C. Cassiterite from sulphide veins	
Campiglia Marittima, Italy	0.1
Sungei Way Estate, S. Selangor, Malaya	tr.
Mawchi Mine, Burma	0.05
Sullivan Mine, Canada	0.04
Zaaiplaats Mine, S. Africa	tr.
Llallagua Mine, Bolivia	tr.
Uncia Mine, Bolivia	0.16
Oploca Mine, Bolivia	0.08
Konigsberg, Norway	0.1
Mwirasandu Hill, Ankole, Uganda	0.1

Clearly this particular topic is in need of further study. To the explorationist the magnitude of the tungsten content in cassiterite, a resistate species, is important in that it could have, on occasion, a profound effect on the nature of secondary dispersion patterns of tungsten. It is of further importance in that it *may* throw further light on the type of primary deposit from which the cassiterite in a given sample of, say, stream sediment, was derived, and this, in turn, would shed light on the nature of the primary tungsten deposits to be expected within the drainage system in question. In addition, in view of what will appear in a subsequent section concerning the significance of the iron and manganese content of wolframites, the manganese/tungsten ratio of such panned cassiterite might permit still further deductions to be made concerning the character of some, at least, of the primary tungsten deposits which might occur there.

In conclusion, the search for tungsten deposits by geochemical methods would be facilitated if much more were known, not only about the tungsten content of those primary species, particularly the resistate ones, which are common associates of tungsten minerals in ore bodies, but also about the tungsten content of the major rock forming minerals, perhaps especially the ferromagnesian ones, and of the accessory minerals, in particular perhaps, ilmenite.

THE TUNGSTEN MINERALS (FIG. 1)

As noted earlier, virtually all the tungsten used by man is obtained either from scheelite or from members of the ferberite/wolframite/hübnerite series: this is because the other dozen or so tungsten species are rarely found in economically important quantities. Anthoinite, for example, is only found in workable amounts in Uganda and adjacent countries and there it occurs intimately associated with ferberite and a few other tungsten species.

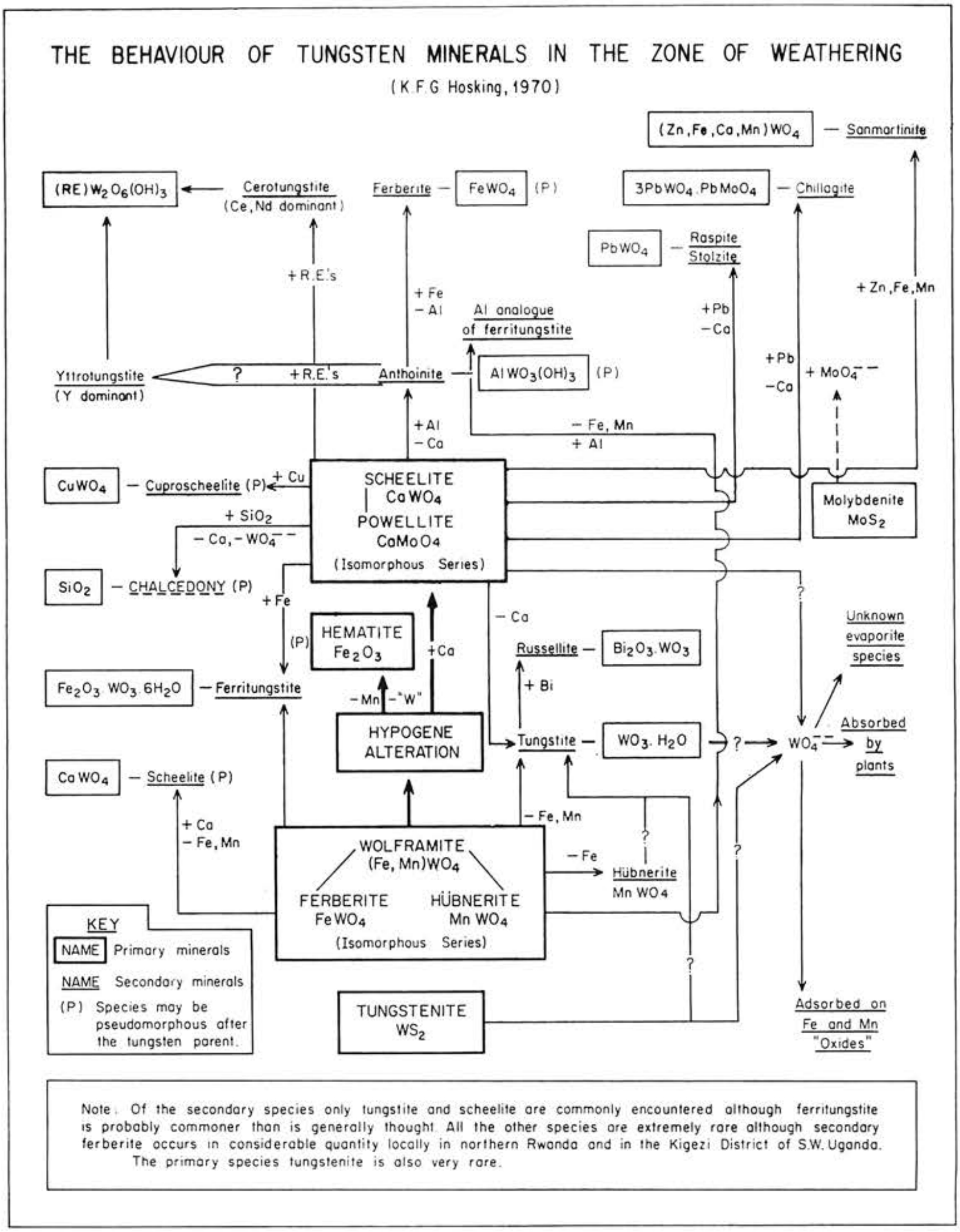


Fig. 1.

From the point of view of the searcher for tungsten deposits the following properties of scheelite and wolframite (the last word is used here, and often subsequently, to indicate the whole isomorphous series noted above) are the most important:–

i. Although both species may be decomposed in the zone of weathering, in many near-surface environments they are sufficiently inert to report in placers.

ii. They are fairly dense (scheelite, 5.8–6.2; 'wolframite', 6.7–7.5) a fact which facilitates their concentration in placers.

iii. Scheelite is not very hard (4.5), is brittle, and has a distinct cleavage (111), whilst the hardness of wolframite varies from 4.5–5.5. Wolframite is also brittle and possesses a perfect (010) cleavage. These facts indicate that both species are likely to disintegrate readily under a number of different but essentially superficial environments.

All these properties will be considered again, in some detail, in a later section. There are other properties, etc., which are conveniently discussed in this section. It is important to note that apart from the species mentioned in the first paragraph of this section there are few tungsten species that are anything but rare. Some of the tungsten species indicated in figure 2 (e.g., tungstenite (WS_2), chilliagite ($3PbWO_4.PbMoO_4$), russellite ($Bi_2O_3.WO_3$), cerotungstite and yttrotungstite (R.E. $W_2O_6[OH]_3$)) have only been recorded from one, or two localities, whilst the number of places in which cuproscheelite and stolzite are known to occur is distinctly limited. Goldschmidt's (1954, p. 559) observation that there is a "rather frequent occurrence of the tetragonal stolzite, $PbWO_4$, as a secondary mineral in cassiterite deposits" is not well founded in the writer's view. Of the definitely secondary species only tungstite (WO_3) is comparatively common although possibly ferritungstite ($Fe_2O_3.WO_3.6H_2O$) may have been often misidentified, and so may be considerably more common than is generally believed. The yellow tungstite (sometimes termed tungstic ochre, particularly when the species is admixed with limonite) is not uncommonly found investing wolframite and scheelite occurring at or near the surface.

Secondary scheelite, developed from members of the wolframite series by supergene processes may be quite common. Perhaps, for example, the scheelite sometimes found on wolframite in the zone of weathering as a film so thin that it may be invisible to the naked eye may be so formed, but it is usually very difficult or impossible to differentiate between scheelite developed from wolframite by supergene processes and that formed from the same parent by hygogene ones.

Returning to the primary tungsten species, it is important to emphasise that members of the wolframite series are usually dominant in ore-deposits occurring in the granitic rocks, in non-calcareous sediments, and metasediments, and that generally the composition of the species present requires that it is termed wolframite: that is to say it contains from 5.9 to 17.6 weight percent of Mn (Betekhtin, 1970 (?), p. 394). Ferberite, whilst much less common than wolframite, is much more common than hübnerite. Scheelite, or perhaps better a tungsten-rich member of the scheelite/powellite isomorphous series, is usually, but not invariably, the only primary tungsten species found in deposits within sedimentary carbonate rocks or their thermally metamorphosed equivalents. Scheelite is also usually the sole primary tungsten representative in skarns developed by the alteration of basic igneous rocks by the addition of heat and chemicals from granitic intrusions. Along the northern edge of the Land's End granite (South-west England), for example, such scheelite-bearing skarns occur. Scheelite, however, is not confined to the above mentioned environments and many instances are known of the species occurring in deposits both within granitic rocks and non-calcareous metasediments. In such circumstances the species is usually, but not invariably, associated with wolframite and developed immediately after the latter and commonly by replacement of it (fig. 2). The writer believes that the calcium necessary for the formation of scheelite is always locally derived, and when the mineral occurs in

COMPLEX LODE OF THE ROSKEAR SECTION OF SOUTH CROFTY MINE, CORNWALL, WHERE INTERSECTED BY THE CROSS-CUT AT THE 2,000 Ft. HORIZON.
3 sketches from thin sections of the Ore

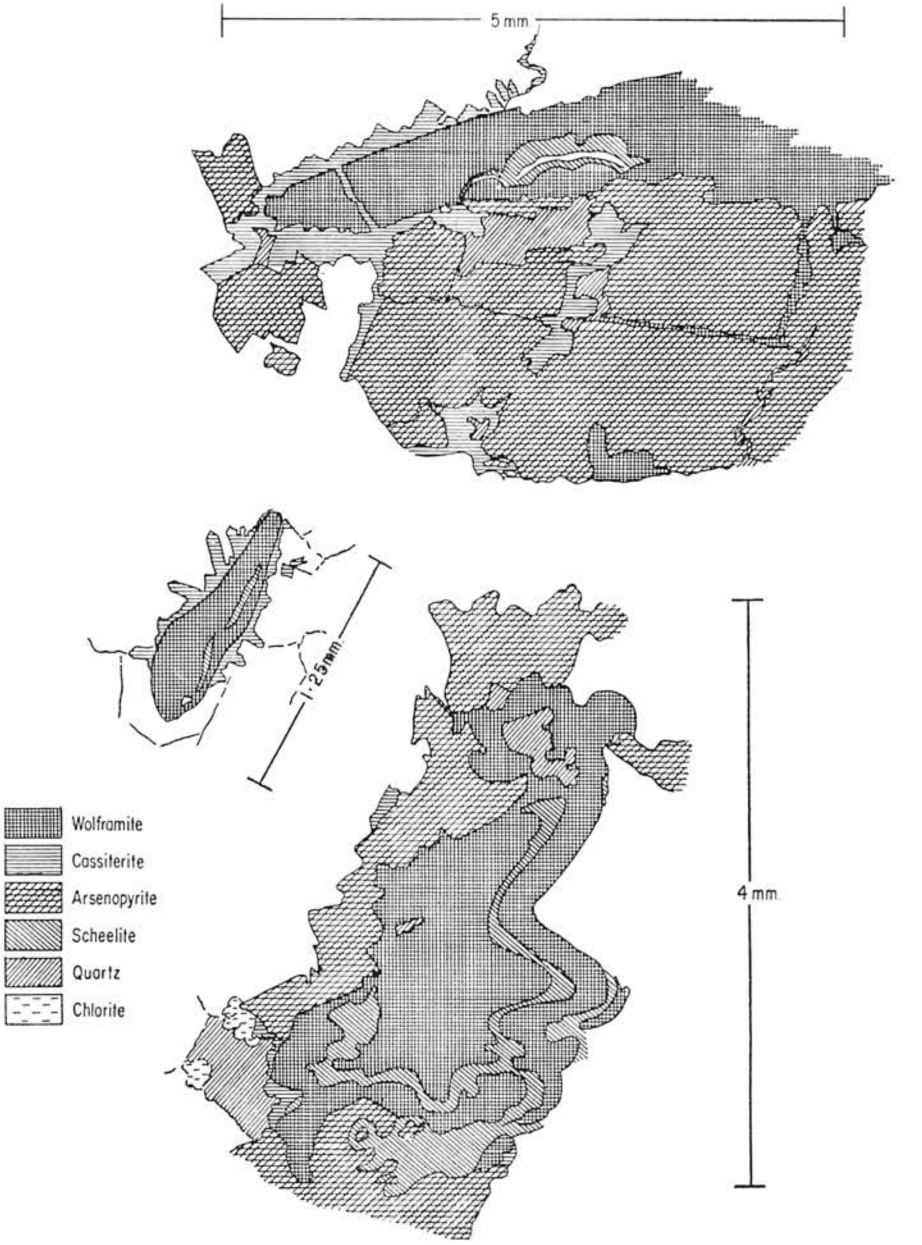


Fig. 2

deposits within granitic rocks the necessary calcium was often that liberated from the plagioclases during wall-rock alteration. The scheelite rim-replacing the wolframite in the early veins far below the granite/"killas" contact at South Crofty Mine (Cornwall) probably owes its lime content to such a process. On the other hand the scheelite locally cementing fragmented components of the greisen-bordered veins of Ulu Langat (Selangor, West Malaysia) (which also contain cassiterite and wolframite) may well be due to calcium liberated from the marble roof which once covered the granites there. (Hosking. Unpublished studies.)

Certain variations encountered in the composition of 'wolframites' within a given tungsten province are also to be noted as these may be of possible value to the explorationist. Briefly, there are now many findings in support of the view that commonly within a given province the 'wolframites' of pegmatites and early felspathic veins tend to have a higher Mn/Fe ratio than those of greisen-bordered veins, whilst the ratios of the latter tend to exceed those of the later hypothermal veins. This was shown, for example, to hold in the South-west of England by Hosking and Polkinghorne (1954) (fig. 3) and although there a few wolframites with anomalous Mn/Fe ratios were found, it was not difficult to account for them. Often, the later the vein the farther is it away from the supposed igneous source, and in such a circumstances it might be expected that in the case of wolframite-bearing ones the Mn/Fe ratios related of the species under discussion should reflect this. This, in fact, has been demonstrated in Maniéma by de Magnée and Aderca (1960, p. 7) who used Varlamoff's (1958 A) wolframite analyses to calculate the $MnWO_4/FeWO_4$ (h/f) ratios. These ratios, as the following table shows, established the marked compositional zoning there which occurs as one goes from the centre of the granite mass outwards and into the country rocks.

h/f ratio	*Location of wolframite*
1.03	At the contact
1.40	In granite
0.86	In granite
0.83	In granite
0.77	In granite
0.46	At the contact
0.10	Near the contact
0.35	In the surrounding rocks
0.43	In the surrounding rocks
0.016	In the surrounding rocks
0.045	In the surrounding rocks
0.022	In the surrounding rocks

de Magnée and Aderca (op. cit., p. 6) also state that the h/f ratio is a very good indicator of the temperature of formation of the deposit and that for wolframites from pegmatites it is greater than 1; from greisens it is between 0.3 and 1.5; from high temperature quartz veins from 0.5 to 1 and from the low temperature hydrothermal veins it is below 0.5.

In the writer's view the 'story' is not always as simple as de Magnée and his co-worker suggest. Wolframites with anomalous ratios may occur because of a deficiency in either manganese or iron in the solutions depositing the tungstate. More than one generation of wolframite may reside in the same deposit, and Ramdohr (1969, p. 1068) notes that "in the bismuth-, silver- and cassiterite-bearing veins of South Bolivia, which grade into the sub-volcanic sequence, varieties (of wolframite) high in Mn or in Fe are

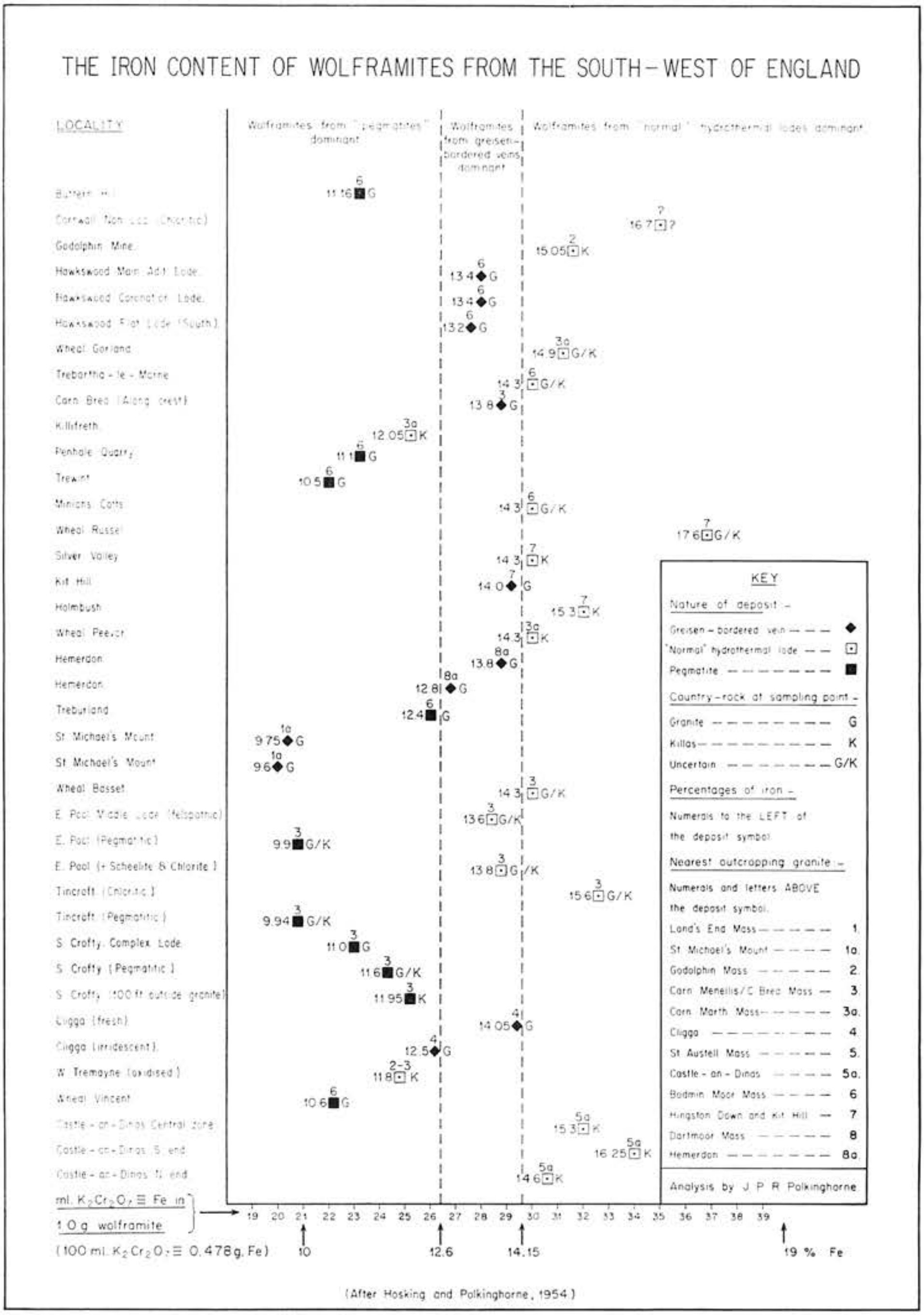

THE IRON CONTENT OF WOLFRAMITES FROM THE SOUTH-WEST OF ENGLAND
LOCALITY
Wolframites from "pegmatites" dominant
Wolframites from greisen-bordered veins dominant
Wolframites from "normal" hydrothermal lodes dominant
Godolphin Mine
Hawkswood Main Adit Lode
Wheal Garland
Carn Brea (Along crest)
Killifreth
Penhale Quarry
Wheal Russel
Silver Valley
Kit Hill
Holmbush
Wheal Peevor
Hemerdon
Treburland
St. Michael's Mount
Wheal Basset
E. Pool (Pegmatitic)
E. Pool (+ Scheelite & Chlorite)
Tincroft (Chloritic)
Tincroft (Pegmatitic)
S. Crofty. Complex Lode
S. Crofty (Pegmatitic)
Cligga (fresh)
Cligga (irridescent)
W. Tremayne (oxidised)
Wheal Vincent
Castle-an-Dinas N. end
ml. $K_2Cr_2O_7 \equiv$ Fe in 1.0 g. wolframite
(100 ml. $K_2Cr_2O_7 \equiv$ 0.478 g. Fe)
19 20 21 22 23 24 25 26 27 28 29 30 31 32 33 34 35 36 37 38 39
10
12.6
14.15
19 % Fe
KEY
Nature of deposit:-
Greisen-bordered vein
"Normal" hydrothermal lode
Pegmatite
Country-rock at sampling point:-
Granite G
Killas K
Uncertain G/K
Percentages of iron:-
Numerals to the LEFT of the deposit symbol
Nearest outcropping granite:-
Numerals and letters ABOVE the deposit symbol
Land's End Mass 1.
St. Michael's Mount 1a.
Godolphin Mass 2.
Carn Menellis/C. Brea Mass 3.
Carn Marth Mass 3a.
Cligga 4.
St. Austell Mass 5.
Castle-an-Dinas 5a.
Bodmin Moor Mass 6.
Hingston Down and Kit Hill 7.
Dartmoor Mass 8.
Hemerdon 8a.
Analysis by J. P. R. Polkinghorne
(After Hosking and Polkinghorne, 1954)

Fig. 3

both common". Recently, also, Taylor and Hosking (1970) have demonstrated that the iron content of wolframites from a comparatively small vein system in South Crofty Mine, Cornwall, varies in such a manner as to emphasise that much more needs to be known "about the possible relationships between the MnO/FeO coefficients of wolframites in general and their temperatures of deposition" before views such as those expressed by de Magnée and noted above can be accepted unconditionally. There is little doubt that generalisations based on the Mn/Fe and similar ratios of wolframites should be used with considerable restraint during exploration work on any scale. However, some years ago, at the suggestion of the writer, a preliminary study of the "iron/manganese" ratios of wolframites from Beralt Tin and Wolfram Mine (Portugal) was carried out in order to see if they varied in such a way as to facilitate the search for further buried granite cusps, as it was in the vicinity of the known cusp within the mine that most of the cassiterite occurred. For various reasons the study was discontinued, but the limited results obtained, although not highly encouraging, were still such that they indicated that the investigation should be resumed.

Simple aids to the identification of tungsten minerals

Whilst there is little point in noting how the tungsten minerals can be recognized in thin or polished section, or in describing the well-known blowpipe and other classical chemical tasts for such minerals, as they can be readily found in the text books, it is pertinent to describe a few simple chemical aids to the identification of tungsten in such species which are not generally known, together with means of staining grains of the more important tungsten minerals in order to facilitate their identification. In addition, the use of the short wave ultraviolet light during the search, etc., for tungsten deposits requires comment.

(i) *The ammonium hypophosphite test* (see Hosking, 1953)

This test may be used as an aid to the identification of any tungsten mineral. Briefly, a little of the powdered substance to be tested is mixed with 3 or 4 volumes of ammonium hypophosphite in a silica crucible. The mixture is heated until a melt is obtained and there is a copious evolution of phosphides of hydrogen (which may ignite and which stink). A few drops of water are then added to the hot turbulent melt and if a product rather like blue ink is obtained tungsten is probably present. The reaction can be carried out in a silica crucible using a candle flame as a source of heat; alternatively a comparatively small quantity of the mixture may be placed in an open tube near one end and heated with the flame of a cigarette lighter or even a match. A few drops of water are finally added to the melt by means of a teat pipette and the product is allowed to run down the tube thus permitting its colour to be readily assessed.

(ii) *The zinc/HCl streak test* (Hosking, 1957)

This test may be used to confirm the presence of tungsten in any species in which it is an essential component except members of the wolframite series. To carry out the test a heavy streak of the mineral is made on a small piece of unglazed tile. A small pile of zinc dust is placed on the streak and several drops of concentrated HCl are added to this by means of a teat pipette and in such a way as to ensure vigorous reaction between the acid and the powder. The powder is then washed off by a jet of water and the presence of tungsten is indicated by the treated streak appearing blue.

A field alternative consists of adding a drop or so of the acid to the surface of the mineral under test and then rubbing the damped surface repeatedly with a zinc nail. A resulting blue solution indicates the presence of tungsten.

(iii) *The staining of wolframite and scheelite grains in concentrates* (Vanden Herrewegen, 1954)

Boil 2 to 5 g. of the concentrate for c. 20 minutes in a solution consisting of 25 ml. HCl, 15 ml. HNO_3 and 60 ml. water. This causes wolframite and scheelite grains to become yellow. The yellow grains may be picked out and their coating can then be removed by treatment with ammonia. Then the white grains can be removed and weighed as scheelite and the dark grains as wolframite.

The short wave ultraviolet light test for scheelite

One cannot conclude this section without reference to the short wave ultraviolet light test for scheelite as it can be said with conviction that no tungsten survey is complete until appropriate material has been scanned under the short wave ultraviolet lamp.

Scheelite fluoresces when irradiated with short-wave ultarviolet light but its fluorescent colour varies with the $(MoO_4)^{--}$ content (scheelite, be it remembered, forms an isomorphous series with powellite, $CaMoO_4$). Pure scheelite fluoresces a strong blue but with an increasing molybdenum content the colour changes to pale blue, through white to yellow. Gleason (1960, p. 176) notes that if scheelite fluoresces whitish it probably contains 0.5 to 1 percent molybdenum; if yellow, more than 1 percent, and if deep orange-yellow, four percent or more. It is also relevant to note here that the comparatively rare cuproscheelite, (Cu, Ca) WO_4, always fluoresces yellow-green according to Gleason (op. cit., p. 177). This semi-quantitative test was perhaps of greater value in the past then now as some years ago comparatively modest amounts of molybdenum in scheelite rendered the latter unacceptable to industry.

It is perhaps hardly necessary to state that the fluorescent colours of certain other minerals, etc., may be similar to those of scheelite and so appropriate confirmatory tests should be employed. Hydrozincite, pabsite, and mineral oil fluoresce bluish, so does the yellow scorpion! Malayaite ($CaO.SnO_2.SiO_2$) usually fluoresces, and when it does the colour is yellowish, a colour which may well have caused it to be mistaken, on occasion, for molybdenum- 'rich' scheelite or powellite during field and other studies of skarns!

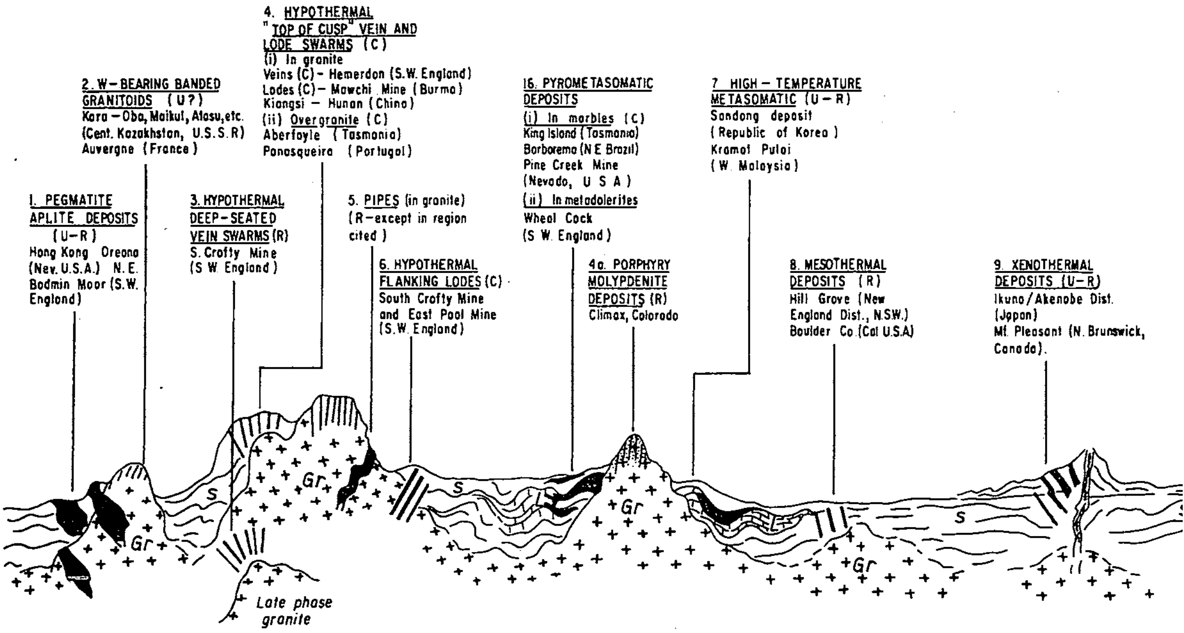
TYPES OF TUNGSTEN DEPOSIT (FIG. 4)

Clearly, he who wishes to search for useful deposits of tungsten would be ill-equipped for the work were he not au fait with the various known types and with their major characteristics. In particular, it is necessary for him to be aware of those types of deposit which are commonly of economic importance and also those which, although they may be tungsten-bearing are rarely, if ever, important sources of the element. It has also to be borne in mind, of course, that although the emphasis in this section will be on tungsten, on many occasions tungsten is obtained from deposits in which other associated elements are recovered which are of equal or greater value, perhaps of much greater value, than that of the element under review.

For the purpose of this paper the tungsten deposits are classified as follows:

1. Tungsten-bearing banded granitoids.
2. Pegmatite/aplite deposits.
3. Pyrometasomatic deposits.
4. Hydrothermal deposits.

TUNGSTEN DEPOSITS :



PRIMARY TUNGSTEN MINERALS / HOST ROCK RELATIONSHIPS				
HOST ROCK	Calcareous rocks (Limestones, dolomites, marbles, calc – silicate hornfels)	Basic igneous rocks (Dolerites, meta – dolerites) Ca from Ca – Na feldspars	Acid/intermediate igneous rocks and metamorphic equivalents	Non – calcareous sediments and metasediments
USUAL DORMINANT PRIMARY TUNGSTEN MINERAL	Scheelite	Scheelite	"Wolframite" (minor scheelite may be present)	"Wolframite" (minor scheelite may be present)

SPECIFICATIONS OF TUNGSTEN CONCENTRATES (after Kreiter, 1968 p. 22)
WO_3, 40 – 65%; P, 0·03 – 0·2%; S, 0·3 – 3·0%; As, 0·04 – 0·2%; Sn, 0·08 – 1·5%; and Cu, 0·1 – 0·22%.

LEGEND

Gr – Granitic intrusives and effusives	S – Non – calcarious sediments and sediments	U – Uncommon
Carbonate rocks: Cal – silicate hornfels	R – Rare	C – Common

INGSTEN DEPOSITS: VARIATIONS OF THE THEME

K. F. G. Hosking, 1971

DATA RE	
Species	
Wolframite (Ferberite–Hübnerite series)	
Scheelite	

7. HIGH – TEMPERATURE METASOMATIC (U – R)
Sandong deposit (Republic of Korea)
Kramat Pulai (W. Malaysia)

11. THERMAL SPRING DEPOSITS (Econ. deposits R)
(W-bearing Fe / Mn oxides)
Wolfram, Golconda, Nevada, U.S.A.). Uncia (Bolivia)

'RY TE R) rado

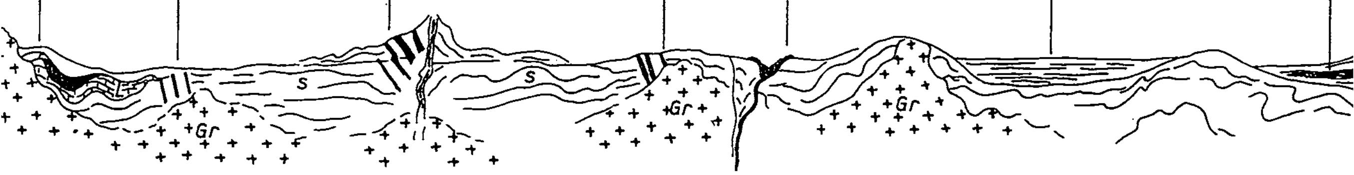
8. MESOTHERMAL DEPOSITS (R)
Hill Grove (New England Dist., N.S.W.)
Boulder Co. (Col. U.S.A.)

9. XENOTHERMAL DEPOSITS (U–R)
Ikuno/Akenobe Dist (Japan)
Mt. Pleasant (N. Brunswick, Canada).

10. EPITHERMAL DEPOSITS (R)
Los Guijos Dist. (Pima Co., Arizona, U.S.A.)
Silver Dyke (Nevada, U.S.A.) (or mesoth.?)

12. ALKALINE BRINES AND/OR EVAPORITE DEPOSITS. (R)
Searles Lake (Calif., U.S.A.) U.S.S.R.

13. STRATAF DEPOSITS
Ruanda. Kle (Eastern



ROCK RELATIONSHIPS		
s olerites) eldspars	Acid/intermediate igneous rocks and metamorphic equivalents	Non – calcareous sediments and metasediments
	"Wolframite" (minor scheelite may be present)	"Wolframite" (minor scheelite may be present)

ECONOMIC IMPORTANCE OF THE VARIOUS				
1. PEGMATITIC	2. W– BEARING BANDED GRANITOIDS	3–11. HYDROTHERMAL	12. ALKALINE BRINES	13. STRATAFORM
Minor importance (wolframite and scheelite types)	Of no direct economic interest, but guides to exploration targets	Very great importance but (4–7 most important) wolframite, scheelite and mixed types.	In U.S.A. a large untapped reserve.	Only important in E (largely ferberite

(after Kreiter, 1968 p. 22)
·2 %; Sn, 0·08 – 1·5%; and Cu, 0·1 – 0·22 %.

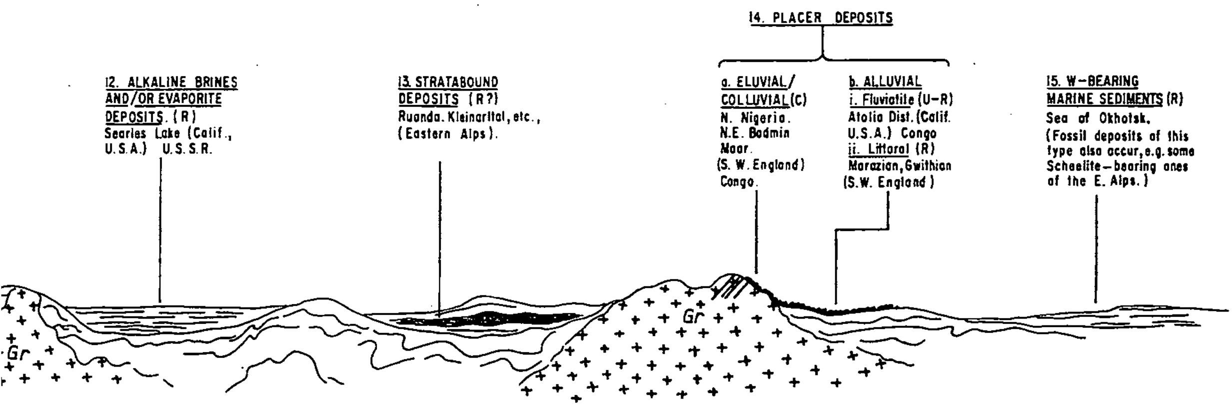
s	U – Uncommon
	C – Common

ECONOMIC TYPES OF TUNGSTEN DEP		
Type	Medium and large veins and vein – like deposits of scheelite skarns in contact deposits of carbonate and granitic rocks.	Small, medium and larg vein zones, and stocl endo – and exo – conta
WO_3 Content, (%)	0·3 — 6·0	0·6 –
Percentage of world output	55	25

Fig. 4

OF THE THEME, ETC.

DATA RE THE MOST IMPORTANT TUNGSTEN MINERALS					
Species	Formula	Hardness	S. G.	% WO_3	Cleavage, etc.
Wolframite (Ferberite–Hübnerite series)	$(Fe,Mn)WO_4$	5 – 5·5	7 – 7·5	c. 76·5	b (010) very perfect. Brittle
Scheelite	$CaWO_4$	4·5 – 5	5·9 – 6·1	80·6	p (111) most distinct e (101) interrupted. Brittle



C IMPORTANCE OF THE VARIOUS TYPES OF DEPOSIT					
11. HYDROTHERMAL	12. ALKALINE BRINES	13. STRATAFORM DEPOSITS	14. PLACER DEPOSITS	15. W–BEARING MARINE	16. PYROMETASOMATIC
great importance but 7 most important) amite, scheelite and d types.	In U.S.A. a large un-tapped reserve.	Only important in East Africa (largely ferberite)	14 a. very much more important than 14 b.i. 14 b.ii. only academic interest. Wolframite and scheelite types.	Sediments Only of academic interest	Very great importance scheelite types usual

IIC TYPES OF TUNGSTEN DEPOSIT: Kreiter's (1968) View.		
e veins and vein-like deposits ns in contact deposits of granitic rocks.	Small, medium and large quartz-wolfram veins, vein zones, and stockworks, most often in endo- and exo-contacts of granitic rocks.	Eluvial and alluvial placers of wolfram and huebnerite
3 — 6·0	0·6 — 4·0	0·03% in thin beds. 0·015% in thick beds.
55	25	20

5. Tungsteniferous brines and evaporites.
6. Stratabound and allied deposits.
7. Placers.

Each of these classes will be discussed below.

1. Tungsten-bearing banded granitoids

The Russians have made the point, according to a report by Alexandrov (1962) that in a number of tungsten fields in the U.S.S.R. and in the Auvergne (France) rhythmically-banded, often dyke-like granitoids occur. The mineralogy and texture of the various bands within such bodies are somewhat variable but they commonly consist of aplite, conventional granite, quartz, and quartz together with such minerals as molybdenite, wolframite, ilmenite, topaz, and fluorite. The cores of such banded dykes may be pegmatitic.

In the view of the author of the paper in question "the formation of banded granitoid intrusions was due to periodical crystallisation of rock from the contacts inward and formation of zones of orientated crystal growth as the result of rhythmical fractional crystallisation of magma rich in rare elements within the magmatic chamber. The formation of topaz (and)—wolframite—may be considered as pneumatolytic during the magmatic stage of crystallisation".

Later it is stated that "the rhythmically banded granitoid bodies are known only in massifs with which tungsten and molybdenum deposits are associated genetically. This may indicate that the banded granitoids represent a regular stage of ore-bearing intrusions. Occurrence of these granitoids may be used as an indicator in prospecting for tungsten and molybdenum deposits".

The following comments on the above are relevant:–

i. Clearly, such deposits are not economic sources of tungsten.

ii. If such were found in a new area one would be encouraged in one's search for tungsten (and/or molybdenum) deposits of economic importance. However, in the writer's experience banded granitoids, either with or without wolframite, etc., are not particularly common in areas in which important deposits of tungsten and/or companion elements occur. Thus, whilst spectacular banded granitoids are known in the South-west of England, they are, nevertheless, very rare, and not a single one contains wolframite, although many, but usually small, tungsten deposits are known and have been worked there. The nearest approach to the type noted by the Russians locally fringes the Godolphin/Tregonning granite and is best exposed in the Tremearne coastal section. The granitoids there consist of bands of granite displaying considerable textural and mineralogical variation, together with occasional bands and clots of quartz. Within these granitoids, isolated and rare patches of loellingite/arsenopyrite, molybdenite, fluorite and apatite, together with much rarer aggregates of chrysoberyl and bertrandite, occur. At Tremearne there is little doubt that the loellingite/arsenopyrite and all the species following it in the above list were deposited from hydrothermal solutions which permeated the granitic host and were preceded by a stage when the composition and texture of the solid granitic body was strongly modified by 'late' potash metasomatism. The writer, therefore, holds that the wolframite recorded by the Russians in banded granitoids was probably introduced during the hydrothermal stage and that the genesis of the mineralised quartz bands is essentially the same as that of the greisen-bordered ones to be described later. There is no good evidence in support of the view that these, or indeed any other types of tungsten deposit, are pneumatolytic.

2. Pegmatite deposits

Generally pegmatites, whether zoned or unzoned, are comparatively small lithologic units, and with few exceptions, when they contain heavy minerals, the content is not great. On those rare occasions when rather high concentrations of heavy minerals occur in them, these minerals, in the writer's opinion, are probably essentially the products of hydrothermal events which occurred after the pegmatite had developed—possibly even a long time, geologically speaking, after. The ease with which a pegmatite fractures by comparison with the rocks in which it is emplaced is well known and hence it follows that a pegmatite is often a preferred site for hydrothermal mineral deposition. Despite this last remark, pegmatites have never contributed more than very modestly to the production of tungsten concentrates, and the over-all declared contribution is greater than it should be, possibly very much greater, because not uncommonly so-called tungsten-bearing pegmatites are simply hydrothermal quartz veins which happen to contain some K-feldspar together with wolframite, arsenopyrite, etc. The so-called wolfram-bearing pegmatites of South Crofty and E.P.A.L. mines of Cornwall fall into this category. It is also of importance to note that it is much less common to find interesting concentrations of tungsten species than of cassiterite in pegmatites, and von Knorring's (1970) recent review of the pegmatites of Africa amply justifies this statement as far as the continent in question is concerned. In addition, in Portugal it is not uncommon to find a little wolframite in pegmatites whose economic importance, such as it is, largely depends on their cassiterite content. The pegmatite of Adoria which has been described by Neiva (1944, pp. 66–89) is quite a good example and its mineral content is shown in figure 5. Neiva (op. cit., p. 88) leaves the reader in no doubt about his views concerning the genesis of this body and he believes that the heavy minerals were deposited within the solid pegmatite by hydrothermal agents.

Perhaps the tungsteniferous pegmatites reach their greatest importance in South China. According to a long abstract in the Mining Magazine (May, 1959, pp. 305–307) of a paper by Davis on tungsten deposits in South China and Hong Kong, in the region in question 'pegmatite veins usually carry wolframite which is often associated with cassiterite'. The following relevant details are also included:– The wolframite "deposits mined (in Kiangsi) are mainly alluvial having been derived from the pegmatites of the Nan Ling Range." "In southern Kwang Si, in the district of Pat Po, wolframite is found in economic quantities associated with cassiterite and gold deposits. It occurs in pegmatites and greisen." "In Hong Kong there are two characteristic occurrences of tungsten-bearing ores. One is in pegmatite that has been formed by the intrusion of the Hong Kong granite into the Tao Mo Chan porphyry ...." "In the Lyemun Black Hill deposit of the New Territories the wolframite-bearing rocks occur where the Hong Kong granite has intruded into the Repulse Bay volcanics. The contact rock here at the base of the roof pendant, is pegmatite. It is highly mineralised ...."

The writer has little doubt that what he has written above concerning the genesis of the tungsten-bearing Portuguese pegmatites applies equally well to their Chinese counterparts. If the reader needs to be further persuaded of the validity of these remarks he needs only to consider how otherwise could the extremely rich tungsten-bearing pegmatites of Oreana, Nevada, have formed. One would need to be a geologic Grimm to suggest, for example, that these developed by progressive crystallisation of a magmatic fraction within a closed system! According to Kerr (1946) at Oreana, scheelite is found both in vertical pegmatite dykes of limited extension in depth and in a series of pegmatite lenses which lie within a metadiorite and parallel to the intrusive/invaded limestone contact. The vertical dykes contain large but erratically disposed masses of scheelite in addition to oligoclase, quartz, fluorite and beryl, whilst the lenses consist essentially of scheelite, oligoclase and phlogopite.

Fig. 5. The mineral content of the Adoria pegmatite (after Cotelo Neiva, 1944)

- Hypogene Minerals
  - Essential
    - Predominant
      - Quartz
      - Orthoclase
    - Subordinate
      - Albite
      - Muscovite
      - Biotite
  - Accessory
    - Silicates
      - Sericite
      - Tourmaline
      - Zircon
    - Phosphates
      - Apatite
    - Oxides
      - Cassiterite
    - Tungstates
      - *Wolframite*
    - Fluorides
      - Fluorite
    - Sulphides
      - Galena
      - Chalcopyrite
      - Sphalerite
      - Arsenopyrite
      - Pyrite
- Supergene minerals
  - Oxides of iron
  - Oxides of manganese
  - Sulphates of iron
  - Covellite
  - Chalcocite
  - Malachite
  - Anglesite
  - *Tungstite*
  - Native sulphur
  - Chlorite
  - Kaolinite

In conclusion it can be stated that beyond reasonable doubt the chances of finding pegmatites containing such tonnages of tungsten minerals that these alone would attract any but small operators are slight. The chances of finding economically interesting stanniferous pegmatites containing minor wolframite which can be recovered as a by-product during the recovery of cassiterite are probably somewhat better, but even these deposits are rarely of interest to large mining companies. Finally, of course, the discovery of a tungsten-bearing pegmatite may be taken as an indication that there are perhaps other types of tungsten deposit in the area which might be of comparatively great economic interest. It is most important to remember that in a given tungsten field the element in question may well occur in a number of different types of deposit.

3. **Pyrometasomatic deposits**

These deposits which are a major source of tungsten, the element being recovered very largely as scheelite, occur in carbonate rocks which have been invaded whilst still deeply buried, by the more basic members of the granitic series. They are never far removed from the 'granite' contact and tend to concentrate around the original high parts (cusps and ridges) of the intrusive. Bateman, (1950, p. 91) speaking of pyrometasomatic deposits, says that they 'are generally scattered irregularly around the contact but tend to be concentrated upon the side of the intrusive that has the gentler dip.'

Such deposits, which individually are not often large as ore-bodies go, show a great variety of shape which stems from the fact that they may be developed by profound mineralogic modification of preferred beds, of shear zones, of carbonate rock adjacent to joints, and of similar rock immediately beneath an impounding body. Fundamentally all these tungsten-bearing deposits consist of scheelite associated with a gangue of so-called calc-silicates of which the more commonly occurring are epidote, vesuvianite, diopside, tremolite, grossularite, andradite, and wollastonite. Other silicates may be present, such as zoisite, almandine, and axinite, together with one or more of a host of other species which includes magnetite, molybdenite, gold, arsenopyrite and pyrrhotite. Recrystallised calcite is rarely, if ever, entirely absent. On occasion the deposit may be worked primarily for one or more of these other species, particularly molybdenite and gold, and scheelite may be recovered as a by-product. The mineralogical character of the deposit must clearly depend in part on the composition of the parent rock and in part on the nature and amount of the components contributed by the invading granite. The final product, whatever its nature, is a product of reactions between the parent rock and substances from the igneous rock which took place at an elevated temperature and usually under considerable pressure. Ore-genesis such as this cannot occur in the absence of an efficient plumbing system as extremely large amounts of material have to be transported to and from the centre of deposition. The character of the plumbing system will depend, to no small degree, on the physical and chemical properties of the 'contact' rocks at the time when ore development is a possibility, and on the magnitude and duration of application of regional forces to which these rocks may be subject at this time. 'Dirty' carbonate beds in a limestone sequence are the most susceptible to skarnification, and changes in volume during this process may make these beds so porous that subsequently ore-forming agents—fractions of the residuum of the consolidating granite—can move relatively easily through them and effect the deposition of scheelite, etc., in favourable sites.

An observation of Kerr (1946, pp. 58–59) perhaps may be cited in support of this suggestion. Kerr states that limestones which have only been subject to 'initial metamorphism' and which consist essentially of pink or cream-coloured garnet (frequently grossularite), wollastonite, pale vesuvianite and recrystallised calcite appear to be low in tungsten. However "where scheelite is most abundant, advanced replacement of limestone appears to form masses which consist largely of a mixture of epidote, quartz, and scheelite—. Garnet may also be present, and, in fact, high-grade quartz-garnet-scheelite ores often occur." Also, it may well be that when such rock sequences are sufficiently heavily loaded, regional stresses may cause the skarns to fracture whilst the neighbouring limestone (or marble) behaves as a plastic body: such would appear to have been the case locally in the Kuala Lumpur area of West Malaysia. There bedded skarn deposits occur and the writer believes that their mineralisation is genetically related to the mesozone Triassic granites of the area. However, also in the Kuala Lumpur area one finds veins in the limestone, containing an impressive suite of minerals (including cassiterite, wolframite, scheelite, stannite, teallite, sphalerite, etc., sometimes with a partial calc-silicate gangue). These are highly telescoped and perhaps should be classified as xenothermal rather than pyrometasomatic, or better still xenothermal/pyrometasomatic. In the writer's view they developed in Tertiary times, when the clean limestone was but little loaded, and behaved, under stress, as a brittle body.

The writer is strongly of the opinion that so-called pyrometasomatic scheelite deposits are simply hydrothermal tungsten deposits which happened to have developed, largely by metasomatic processes, in calc-silicate hornfels. If this is so, then in manner of development they are really little different from those metasomatic scheelite deposits which developed in other rock types and amongst which those of Kramat Pulai (W. Malaysia) and Sangdong (S. Korea) are perhaps the best known. At Kramat Pulai, a rich deposit consisting essentially of scheelite and white fluorite, has replaced marble occurring immediately beneath the crests of two schistose plunging anticlines. The schist, clearly, behaved as an impounding body, albeit not a perfect one, as leak-away veins penetrated it and have been mined for their scheelite content. The writer believes that this deposit, also, developed late, when the then lightly loaded marble fractured even more readily than the adjacent skarns.

The Sangdong deposit of the Republic of Korea is one of the greatest tungsten deposits known. There six parallel bodies are scheelite-bearing, but only one, the Main Bed, has been exploited (Klepper, 1947 and Yong, 1936). These ore deposits, which are lenticular in shape and are "essentially parallel to the bedding of the host rocks" are located in "several calcareous shale beds within Upper Cambrian sediments (Yong, op. cit., p. 1285). The Main Bed, which has an average width of 4.5 metres, and dips from 15 to 30 degrees, possesses a strike length in excess of 1,000 metres, although according to Yong (op. cit., p. 1288) "the economically minable length is about 700 m because of the low ore grade at both margins". When Yong was writing the vertical depth from the outcrop to the present deepest working level was about 300 m, however, diamond drilling has indicated that the ore has a considerably greater extent than this and "the Korea Tungsten Mining Co., in 1966, began a shaft-sinking operation which is planned to increase the depth of mining from 250 metres to 470 metres in 1970." (See 'Industry in Korea, 1970'. Published and compiled by the Korea Development Bank, p. 302.)

The Main Bed, occurring in a hornfelsic slate host, shows in longitudinal section the following three distinct zones (1) a marginal low grade tungsten zone of garnetiferous-diopsidic skarn, (2) an intermediate zone of hornblende-rich hornfelsic ore, and (3) a central zone, rich in biotite and sericite, with the highest metal content, and characterised by an abundance of quartz veins which become progressively less frequent in the outer zones (Yong, op. cit., p. 1288). The grade of the core of the central zone is, according to Yong, greater than 2% WO_3 whilst that of the outer fringe of the siliceous hornfelsic ore is 1 to 2% WO_3 and that of the skarn ranges from 0.2 to 0.3% WO_3.

The ore minerals present are scheelite (by far the most important economic mineral in the deposit), wolframite, molybdenite, bismuthinite and tetradymite. "The other opaque minerals are, in the order of abundance, pyrite, pyrrhotite, chalcopyrite, sphalerite, arsenopyrite and magnetite. A small amount of cassiterite and gold is also associated with the above" (Yong, op. cit., p. 1291).

"Non-opaque gangue minerals are quartz, diopside, andradite, epidote, hornblende, biotite, chlorite, sericite, fluorite, calcite and some apatite. The most abundant gangue mineral is quartz, followed by hornblende, chlorite, diopside, biotite, sericite, andradite, epidote, calcite, fluorite and apatite, roughly in that order of abundance" (Yong, op. cit., p. 1291).

Vertical zoning within the ore-body is not conspicuous although there is a tendency for molybdenum to increase with depth and for bismuth to decrease.

A fact of some genetical interest, which will be referred to later, is that the Main Orebody is "cut in many places" by faults, both normal and reverse, with small displacement, ranging from less than a meter to several meters and which, according to Yong (op. cit., p. 1290) are post-mineralisation features.

It is also of interest to note that the nearest out-cropping sizeable igneous body is about 4 km away from the tungsten deposit. It is a granite porphyry elongated parallel to the strike of the invaded rocks, and is cut by a number of felsite dykes. However, at 2 km from the mine a number of pegmatite dykes occur which consist essentially of "acidic feldspars, quartz, muscovite, and a minor amount of cassiterite (Yong, op. cit., p. 1287). A diamond drill hole, which extended to a vertical depth of 800 metres in the area of the mine, failed to intersect any igneous bodies (Yong, op. cit., p. 1290).

Klepper (1947, p. 474), largely because the Sangdong deposits were so far from outcropping granitic rocks, regarded them as 'high-temperature metasomatic', rather than pyrometasomatic. Yong, on the other hand, believes that the Main Bed was developed, essentially, in two stages. The first was the pyrometasomatic stage in which impure limestones were converted to calc-silicate hornfels and in which some scheelite, molybdenite, magnetite, pyrrhotite, pyrite, bismuthinite, etc., were deposited. The second was a hydrothermal one and was the much more important in that the bulk of the scheelite, and other minerals of economic importance, were then introduced. The hydrothermal mineralisation was, according to Yong (op. cit., p. 1299) made possible by the entry of the mineralising agents which ascended concordant and very persistent fractures near the foot-wall of the ore body and then migrated into the net-work of discordant tension fractures in the ore body which were due to the cooling of the body, and which resulted in the generation of many metal-rich veins, and local intense wall-rock alteration. At this stage scheelite, molybdenite, wolframite, pyrite, arsenopyrite, sphalerite, chalcopyrite, bismuthinite, tetradymite, etc., were deposited.

The present writer is inclined to accept most of Yong's views of the genesis of the Sangdong deposits. He is ,however, inclined to the view that the whole of the scheelite was deposited by hydrothermal agents, and he wonders if the fractures along which these agents moved may have been tension or second order shear faults which developed between pairs of transcurrent faults. Has the final word yet been uttered about the history of fault development in the area in question?

4. **Hydrothermal deposits**

Some would say that hydrothermal tungsten deposits may be sub-divided into hypo-, meso-, epi- and xeno-thermal ones and to this list a case could be made for adding a class to include the tungsteniferous hot spring deposits of Nevada and Uncia

(Bolivia) although these might well be classified as epithermal. There are others who would claim that some, at least, of the so-called hypothermal tungsten deposits are pneumatolytic in origin.

Classifications of ore-deposits are only of use to the mineral explorationist if having obtained only limited data concerning a given deposit he can classify it, and by so doing can foretell, with considerable certainty of being fundamentally correct, some of the other important characteristics the deposit is likely to possess. At present the various classes of tungsten deposit noted above are not so defined that a given deposit will be placed in the same class by two different people. The writer would not classify, for example, the tungsten deposits of the Sudan as xenothermal, as Almond (1967) has done, nor would he regard those of Las Guijas, Pima County, Arizona, as epithermal, as does Sheikh (1970).

As far as the mineral exploration geologist is concerned it would seem of more value to classify the deposits under review as follows:–

i. Tungsten deposits spatially and possibly genetically related to granitic intrusives:
   (a) Early (high-temperature?) ones
   (b) Late (low-temperature?) ones

ii. Tungsten deposits spatially and possibly genetically related to granitic effusives and high-level granitic plutons.
   (a) Xenothermal deposits
   (b) Hot-spring deposits

This is the classification which will be adopted in this section, despite the fact that in figure 4 deposits have been classified in the traditional manner: this has been done in order to emphasise the fact that the "traditional" classification, despite its obvious deficiencies, is still generally employed by those concerned with primary tungsten deposits.

i. *Tungsten deposits spatially and possibly genetically related to granitic intrusives.*

a. *Early (high-temperature?) ones*

Within this class are included vein- and lode-swarms closely associated with granite cusps, and lodes and pipes flanking granite ridges, the former particularly where the ridges are surmounted by cusps. As noted earlier, a strong case can be made for regarding the pyrometasomatic tungsten deposits and, of course, those of the Sangdong and Kramat Pulai type, as hydrothermal, and even without including these obviously metasomatic bodies the members of this class are collectively the major source of the world's tungsten.

The hydrothermal tungsten-bearing deposits occurring within, or close to, granitic cusps and ridges display such considerable variation in size, shape, tenor, mineralogic and structural complexity, etc., that only those characteristics which are of major importance to the prospector can be considered in this paper.

In many tungsten provinces it is common to find veins and/or lodes, a few or many, occupying the apices of some of the granitic cusps, and frequently these ore-bodies are virtually impounded within these granitic features. At Cligga, Cornwall, the veins containing wolframite, cassiterite, etc., die out just outside the granite (Hosking, 1964) whilst at Mawchi Mine, Burma, the richly mineralised tin/tungsten lodes peter out on reaching the granite/marble contact, although some of them persist for some distance beyond the granite where the latter is in contact with schist (Hobson, 1940).

These deposits are commonly steeply dipping and of limited strike length: their strike direction, however, coincides with that of other early hydrothermal lodes, etc., of the district in question (a fact well seen in the Cligga area).

The mineralogy of these bodies is, as noted above, very variable, but the dominant non-metallic gangue mineral is quartz, and the dominant tungsten species is wolframite although scheelite may be present in considerable quantity. Cassiterite and arsenopyrite/loellingite are virtually always present in considerable concentrations, whilst molybdenite is rarely entirely absent, and it also may occur in appreciable concentrations. The porphyry molybdenite deposit of Climax, Colorado, may be regarded as an unusual member of the type of deposit under consideration in that (amongst other things) molybdenite is dominant whilst wolframite is present simply as a minor constituent, nevertheless one worth recovering, primarily because of the scale of the mining operation.

Tourmaline, topaz, fluo-apatite, and sericite and gilbertite micas are common non-metallic gangue minerals in these deposits, which may also contain one or more of a host of other 'non-metallic' and 'metallic' species. The repeated reopening to which the mineralogically more complex of the bodies in question was subject was, for the most part, very gentle, as marked cataclastic texture is not one of their usual characteristics.

The 'ore-bodies' are usually bordered by greisen which predated the development of the veins themselves, but which is, on occasion, appreciably mineralised (Hosking, 1964). Both the greisen and the veins are essentially the products of metasomatic processes: that the veins are primarily due to the infilling of open spaces has been demonstrated to be erroneous (Hosking, 1964).

The granite between pairs of lodes or veins is commonly kaolinised, often largely as a result of hypogene rather than supergene processes.

Marked primary zoning is never seen, although in depth the ore minerals may give way to quartz and tourmaline, as, for example, at Cligga (Hosking, 1964) and Mawchi Mine, Burma (Hobson, 1940).

The mineralisation is restricted to a depth of a few hundreds of feet below the granite contact: a fact established, for example, at Mawchi (Hobson, op. cit.) and at Kit Hill, Cornwall (Hosking, 1964).

Some of the richer veins of the vein-swarms at the tops of cusps in Cornwall have been mined in the past for cassiterite and wolframite, and in Peninsular Burma it was, and perhaps still is, common practice for such deposits, when they outcrop, to be exploited by local miners. Today, vein swarms of the Cornish type would only be of interest to a mining company if they could be mined on a large tonnage basis by opencast methods. This would involve sending both vein material and associated granite to the mill. Such ores, in the South-west of England, grade only grade a few lbs. of SnO_2/WO_3 to the long ton, whilst the marked clay content of some of them militates against a high mill recovery of the valuable components (Dines, 1956).

The Mawchi deposits, however, are very rich tin/tungsten deposits by contrast with the Cornish ones, and were worked profitably by underground methods. Over 60 lodes are known and these have been exploited for their cassiterite and wolframite. The lodes also contained a little scheelite and a number of sulphides have been recorded. Greisen bordering the lodes was not strongly developed, but locally the granite was heavily tourmalinised, and such granite was appreciably mineralised: elsewhere kaolinised granite was much in evidence. The unusual richness of the top-of-cusp Mawchi deposits may well have been due in part to the canalisation of the ore-forming agents, which were liberated during the consolidation of the deep granitic magma, into the cusp by the impounding action of the pre-lode wrench(?) faults which bound the ore zone to the north and south (Hobson, 1940, and Hosking, 1969).

The presence of pairs of pre-lode wrench faults is commonly found in strongly mineralised hydrothermal lode areas and may well be generally necessary for the latter to develop: the writer regards them as important features which should always be looked for, particularly during the earlier stages in the selection of 'likely areas' and when photogeologic studies play an important rôle.

Tungsten-bearing pipes are restricted to a few of the many tungsten provinces of the world. Some of the intriguing pipes and related 'flat lenticular ore-bodies' (Strauss, 1954, p. 51) of the Potgeitersrus tin-fields of South Africa, which have been mined for cassiterite, and whose suite of minerals is much the same as that of the mineralogically complex greisen-bordered veins discussed above, contain a little sporadically distributed wolframite and scheelite, but these tungsten species up to the time when Strauss described the deposits, had not been recovered. The deposits occur within, but at the apices of, the flat domes of Bobbejaankop-Lease granite which is intrusive into the Main granite (Strauss, 1954, p. 1943) and emphasise the important rôle which impounding structures can, and often do, play in determining the location of ore bodies.

Somewhat similar, essentially stanniferous 'pipes', occur at Haad-Som-pan (Thailand) but there they have developed in granite immediately beneath a schist roof. Aranyakan (1961) who described them, regards them as syngenetic and pneumatolytic and in this respect he follows Strauss' views, which do not accord with those of the present writer, re the genesis of the South African deposits noted above.

According to Jones (1925, p. 234) the only mine in Indonesia where wolframite occurs in economic quantities is the Tikus Mine on Belitung. There "tinstone and wolframite are found in an ore pipe consisting mainly of quartz. Topaz is plentiful, some tourmaline is present, and arsenopyrite, pyrite, blende and galena are abundant".

Only in eastern Australia are tungsten-rich pipes in the granite common. There, in addition to pipes in which wolframite is the dominant mineral of economic importance, there are others which are essentially cassiterite-bearing ones and still others which owe their importance primarily to their molybdenite/native bismuth content. Each of these types of pipe commonly contains a certain amount of the species which makes the other types economically important. However, there are areas in which wolfram-bearing pipes are dominant and there are a number of mineralogic differences between the three types of pipe,and the structural controls which operated during their formation were different: for example, unlike the molybdenite/native bismuth pipes, the wolframite ones are located "along well defined joint planes or fractures" (Blanchard, 1947). Also, according to Blanchard (op. cit.) "with few exceptions ...... the pipes (regardless of type) occur close to the contact of the granite with the invaded rock, mostly within a few hundred feet and rarely more than a quarter mile from it, with their general inclination paralleling the dip of the contact without regard to whether the dip is steep or flat. They occur mostly on terrace-like structures or gentle domes along the flanks of the intruding granite, where the mineralising agents appear to have been trapped within the chilled margins of the granite, beneath a generally impermeable roof". This description reminds one of Cligga, Cornwall, where greisen-bordered veins, containing cassiterite, wolframite, etc., and which are impounded in a granite cusp (as noted earlier) appear as concentric 'shells' which parallel the original granite/country rock contact. Greisening accompanies these tungsten pipes and their mineral content is not much different from the Cligga veins: the similarity is, in fact, most striking.

The pipes in question "vary in diameter from 2 to more than 60 feet and in length from 10 to more than 600 feet". The wolframite ore may be "distributed uniformly, or as sporadic shoots throughout the pipe". Shoots "containing from several hundred pounds to 6 or 8 tons of one or more of the metallic ore minerals are most common" but very much larger ones have been recorded (Blanchard, op. cit.). These deposits do not display vertical zoning.

Hydrothermal deposits, however, are not always confined to the uppermost parts of exposed granitic cusps and ridges. At South Crofty Mine, Cornwall, for example, swarms of veins consisting essentially of K-feldspar, quartz, wolframite and arsenopyrite occur at about a thousand feet beneath the granite/killas contact. These veins, which predate the cassiterite bearing lodes are, in the writer's view (Hosking, 1969) probably situated over cusps of the latest granite phase of the polyphase Carnmenellis granite. These deposits, from which wolframite has been recovered, would probably not have been found except by underground methods of exploration and, in any event, their limited size would have prevented their exploitation had they not been closely associated with the tin deposits.

At Hermyingyi Mine, Burma, (the mine which during the period 1913–25 was the largest producer of wolframite in the world) "the mineralised area is on the margin of a granite stock capped by schists and phyllites, and both the granite and the metamorphosed sedimentaries are traversed by quartz veins", from 8 in. to 14 in. in width, "carrying wolframite and tin stone" (Jones, 1925, p. 226).

At Minas da Panasqueira, Portugal, a series of flat dipping vein is associated with a highly greisenised, granitic cusp which was exposed during mining operations. For the most part the veins, which contain wolframite, cassiterite, etc., occur above the granite in the Infra-Cambrian phyllites, but some transect the apex of the cusp. There are a few steeply dipping veins on the property but these are generally poorly mineralised and, in addition, numerous faults—some major ones—occur and these have played an important but not yet well understood rôle in the development of the present vein pattern. The productive 'veins' are, in fact, lenses which average c. 30 cm. in width and which dip at c. 10° to the south-west. These lenses possess dip and strike lengths which vary from "only a few metres up to 100 metres and occasionally more" (Allan et. al., 1946, p. 7). The phase of mineralisation, which was heralded by the intensive greisenisation and local silicification of the granite followed by intense tourmalinisation of the phyllites, particularly in the vicinity of the flat-dipping proto-veins, involved the deposition of the following impressive suite of minerals which are listed in the order of their first appearance:- apatite, muscovite, arsenopyrite, quartz, cassiterite, muscovite, wolframite, beryl, molybdenite, pyrrhotite, sphalerite, loellingite, chalcopyrite, pyrite, siderite, dolomite, calcite, fluorite (Thadeu, 1951). More than one generation of some of the species noted above occurs. Cassiterite is most in evidence in the veins within or close to the granite cusp so that a degree of zoning is apparent. The mineralisation varies markedly from vein to vein, and some of them are sub-economic. Within a given vein the wolframite is "disseminated irregularly, generally as large crystals or as a rib along the foot —or hanging wall" according to Allen et. al. (1946, p. 7) but the writer (unpublished studies) and others have been impressed by the fact that strong mineralisation is commonly found within the domal portions of the veins and also often at the extremities of the lenses (the portions which the miners aptly term cods' tails). Here then is yet another example of the important rôle played by impounding structures in the localisation of ore.

The writer agrees with Clark's view (1964, p. 814) that "flat-lying ...... and, to a lesser extent, steeply inclined joint systems in ... the phyllites ... have controlled the emplacement of the post-tectonic granite cupola (or cusp) and the development of quartz veins bearing wolframite "at Panasqueira". He is also essentially in agreement with Clark's further view (1964, p. 814) "that the granite was intruded as a relatively mobile mush of early magmatic crystals in a rest liquid rich in K, Al, and H_2O, as well as in W, Sn, As, Zn, CO_2, etc., which was impounded in the apical dome and penetrated the jointed phyllites to form the economic vein systems. There is no significant break, either spatially or temporally, in the magmatic-endomagmatic-hydrothermal crystallisation sequence. The apex of the intrusion is a true, though small, emanative centre and, although further centres were probably active at lower levels in the granite it is considered that a large proportion of the hydrothermal ore solutions was immediately derived from the apical zone".

The tin/tungsten picture at Aberfoyle, Tasmania, is similar to that at Panasqueira in several important respects but differs from it in a number of other important ones. At Aberfoyle, according to Edwards and Lyon (1957, p. 93) "the quartz-cassiterite-wolfram veins ...... form a sheeted zone about 200 ft. wide and 1,600 ft. long in slightly contact metamorphosed shales, slates and greywackes, and are associated with a cupola of aplitic granite whose top is about 1,050 ft. below the present surface. Economic mineralisation persists from the surface down to a vertical depth of 1,050 ft. to 1,100 ft., dying away in the vicinity of the cupola. Down to the 9-level there is a progressive increase in wolfram content of the veins, and a decline in cassiterite with increasing depth ..." "The general sequence of deposition of the ore minerals was:

(1) cassiterite, wolfram;
(2) arsenopyrite, pyrite, molybdenite;
(3) pyrrhotite (in part);
(4) blende-group minerals—chalcopyrite, sphalerite, stannite, pyrrhotite (in part)—as solid solutions;
(5) galena, tetrahedrite, matildite, native bismuth, scheelite;
(6) marcasite and secondary pyrite, magnetite and hematite.

The sequence of deposition of the gangue minerals was:–

(1) fluorine-bearing minerals—muscovite, topaz, apatite, triplite, fluorite—more or less contemporaneous with the cassiterite and wolframite;
(2) quartz—contemporaneous with the earlier sulphides;
(3) carbonates—contemporaneous with the later sulphides. The stages overlap somewhat."

The major differences between the Aberfoyle and Panasqueira deposits are then:

(i) The Aberfoyle veins are steep-dipping whilst those of Panasqueira are flat-dipping;
(ii) the tourmaline is much in evidence in the Portuguese mine but lacking in the Tasmanian one;
(iii) cassiterite is most abundant in and near the granite at Panasqueira but tends to decrease as the granite is approached at Aberfoyle; and
(iv) an appreciably greater variety of metallic minerals is present at Aberfoyle than at Panasqueira.

From the point of view of the prospector it is important to note that both these deposits are not far removed from large exposed granitic masses. Such margins in wolfram provinces are, clearly, areas worthy of investigation and such investigations would be greatly facilitated were geophysicists or others able to devise means of locating small granitic cusps buried beneath a considerable sedimentary cover. However, it is relevant to note that a marked radial drainage pattern may indicate a buried cusp as may a local bulge in the metamorphic aureole, coupled perhaps by a local increase in photo lineaments. The former characterises the wolframite-bearing Bukit Lentor (Trengganu) and the latter the wolframite-bearing hill near Sungei Pahoi (Pahang) (Lim, 1971).

It is, also, of importance to note that in both Panasqueira and Aberfoyle major faults exist which probably played a major part in developing those fractures which in due course determined the lodes. In this connection it is relevant to note that Lyon (1957, p. 82) states that "both the Aberfoyle Fault and the cross-course faults were initially *pre-ore*, and produced fractured channelways for the emplacement of the quartz veins which contain the ore."

As a final example of early, high-temperature (?) tungsten deposits associated with granitic intrusives, those flanking the ridged Carnmenellis granitic mass of West Cornwall will be briefly considered. Particularly in the South Crofty and E.P.A.L. mines large structurally complex lodes occur which display marked primary zoning. In their upper horizons wolframite is associated with chalcopyrite and in depth these species gradually give way to cassiterite (Dines, 1956 and Hosking, 1964). Those at South Crofty Mine post-date and locally fault the felspathic wolframite-bearing vein-swarms noted earlier.

b. *Late (low temperature?) deposits*

Deposits are often termed mesothermal or epithermal ones largely because of the dominant minerals they contain, but over and over again examination of epigenetic deposits indicates that it is common place for a given one to contain both early and late species: high, 'medium', and 'low temperature' species may all occur in the same deposit and often in the same hand specimen or section from such a deposit. The presence then of 'wolframite' in a primary deposit which is dominated by what are regarded as lower temperature minerals does not necessarily mean that the wolframite was deposited at a lower temperature than was wolframite occurring in a pegmatite or a greisen-bordered vein. On the other hand, the tungsteniferous hot-spring deposits, to be discussed later, suggest that tungsten may be deposited late from hypogene solutions of modest temperature, and this is to some extent confirmed by the fact that at New Consols Mine, Cornwall, Vokes and Jeffery (1954–55, p. 157) recorded the presence of a vein consisting of quartz, pyrite, siderite and wolframite which was "demonstrably much later" than the quartz/tourmaline/cassiterite/wolframite/etc., lodes occurring there.

Whatever the temperature range of deposition of tungsten species in hydrothermal deposits it is important to note that deposits exist in which tungsten species, on occasion in economically important amounts, occur in a mineralogic milieu which is markedly different from those described in the preceding sub-section. These may be found not only in tungsten provinces which are lacking or impoverished in tin such as those of the Western Cordillera, but also within tin/tungsten provinces where they tend to be considerably removed from the sites of primary tin/tungsten veins, etc., of the types already described. Although there may be considerable variation in the mineralogy of such deposits, perhaps the most typical ones are characterised by the presence of scheelite with gold: stibnite, however, is also not infrequently present. Thus, at Warren, Idaho, quartz veins contain gold "with a small amount of pyrite scattered through scheelite. Chalcopyrite and pyrite were also present" (Kerr, 1946, p. 122). At Yellow Pine, Idaho, deposits formed essentially by replacement along shear zones in quartz monzonite contain workable concentrations of tungsten, gold, silver and antimony. Cooper (1944) notes that the mineralisation can be divided into the following three stages:–

(1) introduction of sericite, quartz, alkali feldspar, pyrite, arsenopyrite and gold;
(2) the carbonate-quartz-scheelite stage;
(3) the deposition of stibnite together with silver, quartz, pyrite and carbonates.

It is of interest to note that scheelite, the most important ingredient of this ore, was only discovered after the drill core had been examined under short-wave ultraviolet light (Kerr, 1946, p. 125). The Raub deposits of Western Malaysia constitute a further example of the type under review. There orebodies which have been worked for gold, occur in intensely faulted carbonaceous shale not far removed from what has been termed, although possibly incorrectly, an elongated cupola of granite-porphyry. According to Coldham (see Mining Mag., 1946, p. 326) the "ore-bodies have been formed by hydrothermal solutions, partly as vein-filling of the compression and tension faults and partly by replacement of the country rock". According to the same worker (op. cit., p. 327) the approximate composition of the ore was as follows:–

(i) quartz and schist—50% to 80%: quartz predominant.
(ii) $CaCO_3$—15% to 30%.
(iii) $MgCO_3$—about 2%.
(iv) Arsenopyrite, chalcopyrite, varieties of pyrite—1.0% to 5%: average about 2.5%.
(v) Carbonaceous matter—max. 0.5%.
(vi) Stibnite and scheelite—small amounts.

This deposit occurs in the approximately N.–S. comparatively little prospected gold belt which separates the eastern and western tin/tungsten belts of West Malaysia and in which belts tin/tungsten deposits occur of the types noted earlier (e.g., pyrometasomatic and metasomatic scheelite-bearing deposits and greisen-bordered wolframite containing veins). Although the scheelite in the Raub deposit may be only of academic interest, its presence suggests that elsewhere in the gold belt somewhat similar deposits, but containing more interesting concentrations of scheelite, *might* exist.

In concluding this sub-section it is pertinent to note that Ramdohr (1969, p. 1068) reports the presence of 'low temperature' wolframite at Neudorf in the Harz Mountains, where it is associated with siderite and galena, and in Butte where it occurs in enargite veins.

ii. *Tungsten deposits spatially and possibly genetically related to granitic effusives and high level granitic plutons.*

a. *Xenothermal deposits*

Xenothermal tungsten deposits are associated with high level plutons and their related effusives. The most spectacular members are associated with Tertiary igneous activity and occur in Japan and Bolivia. The fracture systems to which the ore is related are often complex and the ore consists of a wide variety of high- and low-temperature minerals which are closely associated either as a result of 'dumping' or of 'telescoping' (Park and MacDiarmid, 1970, pp. 381–382).

Typical of such deposits is the Kanagase lode which is the principal ore deposit of the Ikuno Mine, of Japan. This lode, which is locally 25 feet wide, and has been traced for more than two miles along the strike, intersects rhyolite and underlying Tertiary sediments. This texturally and mineralogically complex body is the product of repeated reopening of the associated fracture system and, according to Kato (1927, 1928) four successive stages of mineralisation.

During stage one cassiterite and quartz were deposited together with minor amounts of pyrrhotite, chalcopyrite, pyrite and scheelite.

Wolframite, cassiterite, quartz, and minor amounts of topaz, sulphide and scheelite were introduced during state two.

In the third stage chalcopyrite, quartz, sphalerite, galena, tetrahedrite, and other sulphides made their appearance.

In the final stage quartz, together with some native gold and grains of tetrahedrite, chalcopyrite, pyrite, galena, and other sulphides, were deposited. Some of these sulphides contain gold and silver.

Each deposit such as this yields, of course, a number of products, but the mineralogic characteristerics are such that mineral beneficiation of a very high order is necessary to get high recoveries and clean concentrates.

b. *Hot-spring deposits*

Both at Golgonda and at Sodaville, Nevada, manganese oxide ores, which have been deposited from hot springs and which are tungsteniferous, are known, and are locally capped by tufa. Similar deposits have been recorded by Lindgren (1922) at Uncia, Bolivia. In addition, at Golgonda, blanket deposits of tungsteniferous limonite also occur and the largest of these, the Big Four ore body, which reaches a maximum thickness of 20 feet, has an average WO_3 content of c. 3 per cent (Kerr, 1946, p. 69).

According to Kerr (op. cit., p. 69) ore similar to that forming the blankets—"the outflow lenses of spring accumulation"—also occupies veinlets in the rocks beneath the lenses and these could be of economic value. Kerr, however, further remarks that "the tungsten-bearing minerals in the spring deposits are of colloidal origin and are not amenable to physical methods of separation. While the chemical treatment is simple enough to be applied on a commerical scale, the tungsten content of ore required for the economical operation of this method must be almost double that necessary for the economical operation of gravity extraction".

Whether the tungsten in the hot springs which were responsible for these rare deposits was of direct magmatic origin or whether it was leached by deeply circulating hot ground waters from already deposited tungsten is unknown; however, the writer favours the latter suggestion.

5. **Tungsteniferous brines and evaporites**

Alkaline brines, or evaporites derived from them, and occurring in either present day or in ancient lakes in arid regions, may be enriched in tungsten.

Brines enriched in the element in question occur in the arid regions of the Soviet Union (Boyle, 1969, p. 39) but the most well known example is that of Searles Lake, California. This dry lake consists of a mass of evaporites, about 35 square miles in area, with a thickness which varies from 0–120 ft. and which contains more than 3 billion tons of salt. All but about 8 sq. miles of this deposit is covered by 'mud'. The evaporite deposit is only c. 53 percent solid, the brine being worked for its lithium and boron content. This brine contains 70 parts per million WO_3 "or a total of 170 million lb. of WO_3 (i.e., 8.5 million units") and is the "largest single known deposit of tungsten in the United States" (Carpenter and Garrett, 1959). A commerical method of extracting the tungsten is known but as yet the price of the product is not sufficiently high for it to be put into operation (private communication).

Searles Lake is within the former so-called Owens drainage system within which there are also many primary tungsten deposits. It would seem then that leaching of these primary deposits, probably by alkaline brines, is the reason for the present Searles Lake tungsten content. The mode of occurrence of the element in question in these brines is discussed elsewhere in this paper.

6. **Stratabound and allied deposits**

This is a somewhat unsatisfactory class, but the writer has erected it in order to accommodate certain unusual tungsten deposits of Ruanda and Uganda which have been the subject of considerable study by a number of geologists including Varlamoff (1946–7, 1958), Pargeter (1959), Jedwab (1958), Jeffrey (1959) and de Magnée and Aderca (1960). It is the paper by the last two authors which is most relevant to the present study as it contains findings which stem from all the earlier data plus considerable additions which the writers have themselves contributed. Briefly, in this region there are many mines, generally small, which are recovering ferberite, and locally scheelite, anthoinite and tungstic ochre, from quartz veins and breccia zones within graphitic schist situated in anticlinal formations. This schist is remarkably rich in tungsten, for example, ten samples of it from the Ruhizha ferberite mine (Uganda) contained an arithmetic average of 23 ppm of the element in question and a geometric average of 19 ppm (de Magnée and Aderca, op. cit., p. 43). These figures are staggeringly high when it is remembered that Wilson and Fieldes (1944) claimed that the tungsten content of a 'normal' schist is from 1–2 ppm. This graphitic schist is also of interest in that locally, as at Nyamulilo and at Ruhizha (de Magnée and Aderca, op. cit., p. 10) in layers of the rock in question, nodules of ferberite occur which vary in diameter from several millimeters to one centimeter, and which may be so plentiful that the rock can be mined for its tungsten content.

There are some who would hold that the tungsten deposits in question are truly epigenetic ones which are related to granitic rocks underlying the anticlines—that ascending tungsten was in part precipitated in fracture systems and in part in the adjacent wall-rock and that finally the primary tungsten species were subjected to varying degrees of alteration. Others, notably de Magnée and Aderca (op. cit.) are of the opinion that the source of the tungsten was the regions of ultrabasic rocks, which, according to Jeffery's (1959) analyses contain 10.0 (arithmetic mean) or 5.7 (geometric mean) ppm of the element in question, figures which suggest that these are, indeed, very much more tungsteniferous than the average ultrabasic rock, which contains, according to Vinogradov et. al. (1958), 0.77 ppm W. They further believe that the tungsten, having been brought into solution during weathering, was carried into a marine basin where it was adsorbed by organic matter. After consolidation of the sediments and as a result of folding and regional metamorphism, or as a result of the heat, etc., liberated by invading granites, the tungsten in the sediments was locally mobilised and migrated into fracture systems in which it was redeposited. In support of this 'sedimentary' view de Magnée and Aderca (op. cit., pp. 41–45) further note that marked concentrations of tungsten occur in Searles Lake, and, what is perhaps more important, in view of the fact that the graphic schists of Ruanda, etc., are marine is that tungsten is presently accumulating in the sea of Okhotsk (Issaieva, 1960) where the superficial sediments contain from 15 to 20 ppm WO_3, those at a depth of 5 metres, 20–35 ppm, and those from a depth of 27 metres, 30 ppm.

There are others who have studied these deposits, notably Jeffery (1959, p. 286) who are prepared to keep an open mind concerning the genesis of these remarkable deposits, and this is almost certainly due in part to the fact that there are undisputably epigenetic wolframite-bearing deposits in the granites of the region: it is this same fact, of course, for causing some to hold that all the tungsten deposits of the region are epigenetic.

Whatever the genesis of these deposits, they provide a lesson for the tungsten prospector—one which tells him that those deposits for which he is searching may not always be obviously very closely associated with granitic rocks, and that one must not fail to investigate areas in which the geologic environment is similar to that of the tungsten belt of Ruanda and its neighbouring countries which has been briefly described above.

Finally, one wonders if the only partial correlation between the tungsten belts of the Western Cordillera, as indicated by granitic rocks and known tungsten deposits, with those revealed by geochemical studies (Noble, 1970) is not perhaps due to the widespread occurrence of 'sedimentary' tungsten and the local concentration of some of this into ore deposits as a result of igneous events. (Footnote.)

Aspects of paragenesis, primary zoning, wall-rock alteration, and impounding structures which are of importance in the search for tungsten deposits.

Whilst paragenesis, primary zoning, wall-rock alteration and impounding structures have not been disregarded in the preceding sections there are certain aspects of these topics which deserve special mention on account of their importance to the tung-

Footnote: Since writing this paper the writer has had the opportunity of reading an account of certain recently discovered scheelite-bearing, "sedimentary" deposits of the Eastern Alps (Höll et al., 1972). The textures, etc., of these deposits leave little doubt that the deposits represent accumulations of scheelite in shallow marine basins which were subsequently modified by tectonic and metamorphic processes.

sten prospector, and which are dealt with briefly below and before the placers are discussed.

Paragenesis

Both wolframite and scheelite are usually amongst the earliest minerals to be deposited in a primary deposit. Often they pre-date associated cassiterite, and this is generally so in South-east Asia, but sometimes they are deposited after any cassiterite which happens to be present in the same deposit, and this is often the case in the South-west of England. When scheelite is present in a primary deposit in which wolframite occurs as the dominant tungsten species, the scheelite invariably post-dates the wolframite, often common boundaries between the two minerals are to be seen (as at Carris Mine, Tras os Montes, Portugal) and commonly the scheelite rim-replaces the wolframite (as in the Complex Lode of the Roskear Section of South Crofty Mine, Cornwall). Furthermore, as the primary tungsten minerals are early lode components they are commonly fractured or mylonitized and cemented by one of more of the later introduced minerals. Locally, at E.P.A.L. Mine, Cornwall, for example, the wolframite fragments were often cemented by chalcopyrite: at Cligga Mine, Cornwall, in some of the more complex veins, wolframite is cemented by a number of sulphides including stannite, chalcopyrite, arsenopyrite and sphalerite.

From what has been written above it will be clear that the usual position of the tungsten minerals in the paragenetic sequence means that polymineralic tungsten-bearing primary deposits are often difficult to beneficiate and this may severely restrict their value. Because of the scheelite/wolframite relationship at Carris Mine, for example, there was a period when the wolframite was not aceptable to the American buyers because it contained more than 0.25 per cent CaO. This was due to the fact that during the grinding of the ore, fracture preferentially occurred along the perfect cleavages of the wolframite and extended into the scheelite and hence scheelite-contaminated wolframite grains were reporting with the 'clean' wolframite during magnetic separation (Hosking. Private reports). At Mawchi and Hermingyi Mines, Burma, as noted earlier, the wolframite and cassiterite were so intergrown that it was necessary to sell a mixed concentrate the components of which were subsequently separated by chemical means (Jones, 1925).

Wolframite which occurs in a fine state of division will prove difficult to recover because during the crushing and grinding necessary to effect its liberation a considerable amount of the readily fractured tungsten mineral will be converted to such small sizes that it will report with the tailings.

It is also appropriate to note again here that a high recovery of the wolframite from a stockwork in heavily kaolinised granite may be very difficult to achieve on account of the high concentration of clay in the mill feed: this has been perhaps the major factor preventing the exploitation of the porphyry type cassiterite/wolframite deposit of Hemerdon (South-west England).

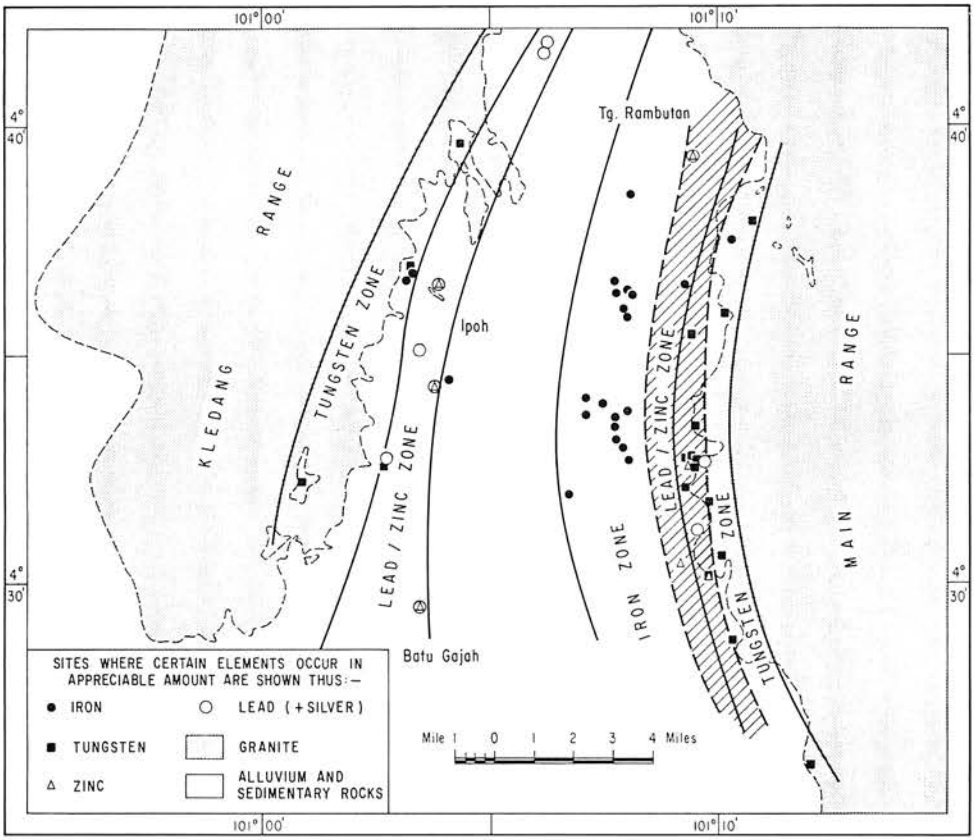
Primary zoning

Two aspects have to be considered namely regional zoning and zoning within single primary deposit.

Regional zoning in tungsten fields is often quite marked and is an aid to exploration. Generally the tungsten-bearing deposits are close to the contact of the genetically (?)—related granitoids and the rocks invaded by the igneous mass. The tungsten deposits may lie wholly within or outside the 'granite', or, on less frequent occasions they may transect the contact. One has to remember, of course, that the tungsten deposit may be several miles from an outcropping granite, as is the Sangdong one, but yet be still close to a buried granite body.

In the Kinta Valley the close relationship between primary tungsten deposits and the granites is clearly seen. The tungsten, iron and lead/zinc zones all parallel the N–S granite contacts of the Main and Kledang ranges, with the tungsten zones restricted to the contact areas (Fig. 6). Locally in West Cornwall, to take a further example, wolframite is restricted to the Cligga cusp and cassiterite is also largely restricted to this granitic body which is fringed by a copper zone and this, in turn, is bordered by a lead/zinc one.

Cornwall is regarded as the type area for primary zoning but the earlier accounts of it, [Davison (1930), Dewey (1948), and Dines (1956)] are all grossly simplified and



METAL ZONES IN THE KINTA VALLEY
BASED ON DATA TAKEN FROM THE MINERAL DISTRIBUTION MAP (1966) OF THE GEOLOGICAL SURVEY OF MALAYSIA
(K. F. G. HOSKING, 1969)

Fig. 6

are often in part such distortions of the truth that were they used as the basis for an exploration programme for tungsten, or other elements, that programme would be hardly likely to yield satisfactory results. The zones do not generally parallel the granite/invaded rock contact as Davison claimed: the mineral zones of a given field cannot be fitted into a single primary zone model, as Dines stated, and lodes showing clearly defined zones are comparatively rare.

In the Camborne-Redruth area of Cornwall, for example, wolframite occurs in a few small greisen-bordered veins at the apex of the Carn Brea granite cusp; in felspathic veins deep inside the granite and in a zone largely above the tin one in some of the great lodes of the district.

In tungsten fields individual bodies may show no zoning and to investigate tungsten areas with the preconceived idea that the primary deposits are certain to be zoned is to risk arriving at all sorts of wrong conclusions and to make costly mistakes. One may think that seasoned geologists would not allow preconceived ideas to influence their work but, of course, they often do, and a perusal of the earlier accounts of the tin/tungsten deposits of South-east Asia will show that on more than one occasion geologists, with preconceived notions, rejected the overwhelming evidence that such deposits were rarely or ever zoned!

Wall-rock alteration

Whilst it is true that tungsten deposits in a granitic or non-calcareous sediment/metasediment environment are commonly bordered by wall rocks which have been subject to one or more of the following types of alteration:– kaolinisation, greisenisation, tourmalinisation, chloritisation, hematitisation, silicification, and that those in a calcareous environment may be associated with calc-silicates, often these facts are not of great help to the prospector because the zones of alteration are commonly very narrow. It is, of course true, that in areas of rock outcrop such alterations are conspicuous and attract one's attention and that in arid regions these may be seen from an aircraft and readily recognized on aerial photographs, particularly if they are associated with vein- or lode-swarms. However, barren veins, etc., may have the same types of wallrock associated with them, and during underground exploration the common narrowness of the altered zone often militates against them being useful guides. However, as noted elsewhere, the increase in the number of fractures and veins as a lode is approached is rendered more obvious by their altered borders and the signs are more significant if the nature of the alteration is similar to that known to accompany the lodes in the mine. Furthermore, such veinlets may give further clues that a lode occurs in the vicinity, as discussed elsewhere, if their trace element content is established.

Aureoles of anomalous concentrations of the ore-components around mineral deposits may be fairly considered as aspects of wall-rock alteration. These, however, are generally very narrow, not more than a few feet, around the tungsten deposits that the writer has investigated, and so are usually of little help to the surface or underground prospector, and thus differ from the veinlets noted above which may be regarded as a series of features which contain anomalous concentrations of ore components due to 'leak away'.

Impounding structures

It is only necessary here to emphasise the fact that impounding structures commonly play a major rôle in localising the sites of development of tungsten, and, indeed, of many other types of deposit. That which has already been written contains sufficient examples to support this view. It follows then that at all stages in the search for tungsten deposits the prospector should be on the look out for such structures.

7. Placers

Tungsten-bearing placers are, for the most part, eluvial and colluvial, they are rarely truly alluvial, and when true alluvial deposits occur they are restricted to those parts of the drainage system which are close to the primary source (Varlamoff, 1971) or to beaches more-or-less backed by primary tungsten deposits. In Cornwall, for example, many of the stream placers have been worked for alluvial cassiterite which was in many instances derived from primary bodies containing both cassiterite and wolframite, yet no example of the presence of wolframite in such placers is known to the writer. In Cornwall, however, wolframite has been recovered from eluvial deposits at, for example, Kit Hill and Belowda Beacon, and from colluvial deposits on, for example, the north-east portion of the Bodmin Moor granite.

In Nigeria (Haag, 1943) derived wolframite was recovered solely from eluvial and colluvial deposits as it was (with one or two exceptions noted below) in Burma (Jones, 1925). At Carris (Portugal) the discovery of a colluvial deposit of wolframite, etc., in a small, high level basin, followed by the find of eluvial deposits on an adjacent mountain-side, led to the discovery of the excellent primary deposit there (Hosking. Unpublished studies).

Jones (1925, p. 229) notes that wolframite and cassiterite were recovered from the beach deposits of Spider Island, Palauk, Burma, where the parent deposits occurred in the neighbouring high ground, and so were close at hand as they are at Cligga, Cornwall. At Cligga, wolframite with cassiterite has been recovered from the finer sizes of the beach were they have been derived in part from the weathering of the primary vein swarm in the backing cliffs and in part from mine tailings derived from the mining operations which have taken place there. Much of the wolframite from the Cligga beach, however, was recovered from portions of the veins in the boulders. Beyond doubt, on a beach, or in a river, wolframite with one surface exposed, but otherwise embedded in a quartz gangue, is not weathered away appreciably faster than the quartz. So it is that one finds wolframite, pebbles and cobbles on the beach of Marazian, Cornwall, which have been derived from the greisen-bordered lode swarm of St. Michaels Mount, and the wolframite has survived to the same extent as the accompanying quartz such mechanical and chemical attacks as a sea which can often be rough has been able to generate. Jones (1925, p. 227) notes that at Hindu Chaung, Tavoy, Burma, pebbles containing wolframite occurred in the stanniferous placers yet no free wolframite was found in the tin concentrates.

Beyond doubt wolframite and scheelite in recoverable sizes can only long survive in an alluvial environment when they are protected by accompanying gangue. When these species are liberated from the parent body they often survive the attack of subaerial agents sufficiently for useful eluvial and colluvial placers to develop. However, they are, even in the subaerial environment, far from inert and their fate in such a circumstance is discussed in a later section.

That 'fossil' tungsten placers of academic interest, at least, can occur has been established by Samama (1971) who found such bodies, from 3 to 40 cm thick, in fine-grained quartzite, in the Fonts-du-Pouzin area, eastern Vivarais, Massif Central (France). These 'placers' contained detrital quartz, apatite, anatase, cassiterite; probably detrital axinite, magnetite, idocrase, ferberite, and non-detrital arsenopyrite, scheelite, chalcopyrite, goethite, lepidocrocite and siderite. Samama's final conclusion is that whilst the cassiterite and ferberite are mechanical concentrations in placers, the scheelite is perhaps due to the alteration of wolframite during metamorphism.

Aspects of the relationship between primary tungsten deposits and granitic rocks

It is convenient to consider aspects of the relationship between primary tungsten deposits and granitic rocks under the following three headings:

(i) Temporal aspects,
(ii) chemical and mineralogical aspects, and
(iii) spatial aspects.

Because tin and tungsten deposits so often have a penchant for developing in the same or similar geologic environments many of the relationships which hold for the one type of deposit and granitic rocks holds equally well for the other: there are, however, some notable differences. As, in recent years, the relationship between tin deposits and granitic rocks has been dealt with in some detail by the writer (Hosking, 1965 and 1967) he proposes, in this paper, to stress only those which apply solely to tungsten and granite and to mention but briefly those which are common to both elements.

i. *Temporal aspects*

Although tungsten deposits range in age from the Pre-Cambrian to the Tertiary there is some eivdence that they tend to become increasingly more abundant as the geological time scale is ascended.

Rankama (1946) has indicated that certain granitophile elements become progressively enriched, in trace amounts, in successively younger granites, and although tungsten was not included in his study there seems to be no good reason why this element should behave in a contrary manner.

That denudation may be in part responsible for the fact that the older granites tend to have fewer tungsten deposits associated with them than younger ones cannot be denied. What are, of course, more important to he who is searching for further tungsten deposits are the effects of denudation on primary tungsten deposits which he may encounter. Locally, exploration may be facilitated by denudation because it has uncovered primary deposits, established tungsten dispersions, etc.: on the other hand it may have effectively destroyed primary deposits which were once of economic grade without the concomitant development of useful secondary ones.

Within a given tungsten province granitic rocks of distinctly different ages may occur, and whilst deposits of the element in question may be associated with granites of one age they may be absent in and about those of another age: alternatively, rich deposits may be associated with granites of one age and poor ones with those of another age.

Both in Thailand and West Malaysia granites of three or possibly more distinct ages occur (Hosking, 1969). However, in Thailand it would appear that the tungsten deposits of interest are largely, perhaps entirely, associated with the believed late-Cretaceous ones. In West Malaysia, whilst some deposits of the type under discussion may well be associated, along the 'East Coast', with granites of Upper Carboniferous age, there are also important deposits associated along the Main Range which seems to be composed largely of Mesozoic granite. The Tertiary granites, which are not well represented, are devoid of tungsten mineralisation, but certain tungsteniferous xenothermal veins and pipes in the limestones, to the west of the Main Range, in the writer's view, are due to Tertiary igneous activity.

In Nigeria, also, the wolframite deposits are confined, essentially, to the younger (Jurassic) granites. It is also probable that even if a large magmatic granitic mass were not the product of granitic invasions separated by considerable periods of time (geologically speaking) that it, at least, owes its origin to a succession of invasions of granitic magma separated by very small periods of time (geologically speaking). In such a circumstance any tungsten deposits associated with it may show a clear spatial relationship and so possibly a closer genetic one to one granitic phase than another. This fact may be not entirely unimportant to the tungsten explorationist. Thus, as noted earlier, at South Crofty Mine, Cornwall, a plexus of wolframite-bearing veins, which predates the spatially closely associated cassiterite-rich veins, are found deep in the granite. The superficial parts of the granite of this mine is the phase I granite of the Carnmenellis Mass: in the writer's view these tungsten (and associated tin) veins are probably related to a high spot of the later phase II granite which forms the core of the Carnmenellis mass. In West Malaysia strong primary tungsten (and tin) mineralisation occurs along the western margin of the granitic Main Range, and this is particularly evident in the Kinta Valley, yet such primary mineralisation is, by comparison, very weak along the eastern side of the Range. May not this mineralisation pattern, like that of the Cornish example noted above, be due, in part, to the emplacement of a late phase elongate Mesozoic granite mass within the earlier granite and in such a manner that its crest line which paralleled that of the earlier phase, was displaced to the west of that of the earlier granite? However, that some of the tungsten deposits are of Tertiary age is, as noted earlier, a distinct possibility, and so the disposition of distinctly late igneous activity might have been a major factor in determining the present day primary mineralisation pattern.

At Castle-an-Dines Mine (St. Columb, Cornwall), a somewhat different picture emerges. There a wolframite/loellingite/quartz lode in tourmaline hornfels has been intersected by a granite tongue. It seems likely that there a lode developed over the apex of an earlier granitic cusp and that a later phase granite then penetrated the area, assimilating the lower portions of the vein and discarding these components which it could not incorporate into the lattices of its minerals. These discarded components were deposited as a wolframite/loellingite/halo (a metallic front) in the original vein zone around the granite. (Hosking, 1964).

A further curious temporal relationship between granitic rocks and mineralised veins, some of which contain wolframite, is found, according to Povilaitis (1962 p. 996) in the ore field of the Kuu granite massif of Central Kazakhstan. There "the order of rock formation and phases of mineralisation are as follows:

(1) granite-porphyries,
(2) granites and aplites with pegmatitic dykes,
(3) quartz veins with wolframite, cassiterite and molybdenite, accompanied by mica-quartz greisens,
(4) dikes of fine crystalline granites and aplites,
(5) quartz veinlets with molybdenite accompanied by quartz-mica greisens,
(6) metasomatic feldspar rocks, and
(7) mica greisens.

Mineral deposits in which what are generally regarded as late forming low temperature species were deposited before those species which are traditionally regarded as early forming 'high temperature' ones may be due to the deposition of minerals related to two different phases of igneous activity in a common site. This may be the case, for example, at Akenobe (Japan) where, in the xenothermal deposits, according to Yoshihiro Sekine (1961, p. 407) "the rather high temperature tin and tungsten minerals were deposited later than the low temperature base metal sulphides". That the history of igneous activity in this area is complex is beyond doubt.

The views of de Magnée and Aderca (1960) concerning the genesis of the tungsten deposits of Ruanda constitute yet another interesting temporal relationship. As noted earlier, he thinks that these tungsten deposits which in his view owed their origin to sedimentary and metamorphic processes may have locally been further modified by invading granite.

In spite of the Castle-an-Dinas case, noted above, and of other similar ones which are known, during a single period of acid igneous activity involving the emplacement of major and minor intrusives (the batholith, granitic dykes, pegmatites, etc.) most of what tungsten mineralisation is going to take place does so when all these granitic bodies have come into being. As stated elsewhere, the writer thinks that most, if not all of the tungsten occurring as wolframite and/or scheelite in pegmatites and aplites are epigenetic with respect to these granitic bodies: he does concede, however, that on occasion the pegmatitic (and aplitic) fractions were tungsteniferous to some slight degree, this seems to be indicated by the high tungsten content of some tantalites from pegmatites, and as yet he has no strong reason for thinking that these tantalites are not products of the pegmatite 'magma'. Also, as stated earlier, he is somewhat sceptical about the Russians' views concerning the genesis of wolframite in certain banded granitoids: such wolframite bands may, in fact, be epigenetic and are originated in much the same way as the greisen-bordered wolframite-bearing veins of granite cusps. It is certain, however, that tungsten species are amongst the earliest of the 'heavy minerals' to be deposited by hydrothermal agents, and although they *may* develop more-or-less simultaneously with cassiterite and, on occasion, after it, as at Cameron Quarry, St. Agnes, Cornwall, (Hosking. Unpublished studies), they are commonly formed before the companion tin species, as, for example, at South Crofty Mine, Cornwall, in many of the Burmese Mines (Morrow Campbell, 1920) and locally at any rate, at Panasqueira, Portugal, where the writer has collected a wolframite crystal, with cassiterite crystals deposited on one of its faces, from a druse (unpublished studies). It is also clear that scheelite is deposited in skarns after the calc-silicates have developed and before any cassiterite has been laid down. Locally in the Kuala Lumpur tin-field, scheelite is seen replacing malayaite (E.B. Yeap. Personal communication).

In a large tungsten province such as that of South-east Asia, which has suffered a number of major granitic invasions which were separated by considerable periods of time, one has to accept the possibility that some, at least, of the primary tungsten deposits may have histories which are considerably more complex than perhaps either their structures or mineral content would, at first sight, suggest. It may well be that some 'early' deposits have been enriched by additions during a later genetically unrelated period of mineralisation, whilst others have been assimilated by 'late' invading magma only to be later largely "discarded" as a telescoped rich body or bodies in much the same manner as seems to have been the case at Castle-an-Dinas. That such modifications exist elsewhere is supported by the work of Druzhinin and Kolesnichenko (1965, p. 186) on the tin/tungsten mineralisation of the Kukel'bey region of Eastern

Transbaikalia. These workers noted that there 'a 110–130 million year old amazonite granite massif formed after the deposition of the tungsten within the 146 million year old biotite granite and preceded tin mineralisation in silicified sandstones and schists'. They also noted that 'the intrusion of the amazonite granite was accompanied by metamorphism which altered the composition of quartz-wolframite veinlets. In a 2–2.5 m zone at the contact with granite, wolframite is replaced by muscovite, and quartz in veinlets is replaced by fluorite and mica'. If these ideas are accepted, then they are important to the tungsten prospector in that, particularly in large tungsten provinces with a complex history of acid intrusion, primary tungsten deposits which may initially appear similar may, in fact, differ greatly in their developmental history and in their tungsten content.

Finally, one cannot terminate a discussion of the temporal relationship between tungsten deposits and granitic rocks without reference to Bilibin's views (1968) of the evolution pattern of endogenetic mineralisation of mobile belts. Bilibin's thesis (op. cit., p. 5–6) is that there exists a "close correlation between the evolution of endogenetic mineralisation, magmatism, tectogenesis, and accumulation of sediment" in such belts, and there is no doubt that his findings have facilitated the search for ore in the U.S.S.R., that it could, if applied earlier, have accelerated the discovery of the tin-sulphide (plus wolframite) deposit of Mount Pleasant, New Brunswick (see McCarthy and Potter, 1962) and that it appears to be applicable to the South-east Asian tin/tungsten province.

It seems likely that Bilibin's geosynclines are better thought of as mobile belts which developed parallel to subduction zones. Acceptance of the concepts of plate tectonics does not invalidate, nor render less valuable to the mineral explorationist, Bilibin's major findings; rather it permits one to acquire, for the first time, the broad pattern of a reasonable mechanism of hypogene ore-deposit development.

Bilibin is of the opinion that both contact-metasomatic and hydrothermal tungsten-bearing deposits may be developed during the early, intermediate and late stages in the evolution of a mobile belt, but that the deposits of major economic importance (both contact metamorphic and hydrothermall) are most commonly developed during the intermediate stage. Whilst it is appropriate to delay further discussion of Bilibin's views concerning the relationships between the compositions of the magmatic rocks and the types of associated tungsten deposits until the next section it is pertinent to note here that the occasions when tungsten-bearing deposits (of widely varying degrees of economic importance) may develop within a mobile belt are, according to Bilibin, considerably more numerous than those when tin-deposits form.

ii. *Chemical and mineralogical aspects*

If the writer interprets Bilibin's (1968) views aright then the latter holds that tungsten-bearing deposits may be spatially and genetically related to intrusives and effusives ranging in composition from those of gabbros to leucogranites, and even members of the syenitic suite may, according to him, have associated with them pyrometasomatic essentially magnetite bodies which frequently contain some scheelite. He does, however, appear to hold the view that the most important hydrothermal and pyrometasomatic tungsten-bearing deposits are associated with granitic rocks (alaskites, leucogranites, grano-diorites, etc.), a view with which few, if any, would disagree. He further notes (op. cit., p. 20) that "there are usually Sn and Sn-W types of mineralisation in metallogenic provinces where complexes of acidic potassic granitoids are developed.

On the other hand W *or* Sn/W mineralisation occurs in provinces with lesser development of these granites''. This observation is a very debatable one.

Although most would hold that there is a genetic relationship between primary tungsten deposits and 'igneous' rocks, which with few exceptions, at any rate, are granitic in composition, such a relationship has not been absolutely established. Indeed, there are some who claim that the common spatial relationship which holds between greisen-bordered wolframite-bearing veins and granitic cusps is simply due to the fact that the invading granite selected an easy passage way towards the surface and this was followed by ore-forming agents from unknown deep sources.

Clearly, if a genetic relationship does exist between such tungsten deposits and the associated intrusive or effusive then if might be expected that such 'igneous' rocks might possess a significantly greater trace tungsten content than their tungsten-barren counterparts. The same argument has already been applied in connection with the relationships between tin deposits and granites and the writer has commented at some length on the problems attendant on investigations carried out to examine the problem (Hosking, 1965 and 1967). It is necessary whether one is studying the tin or the tungsten content of granitic masses with a view to finding answers to some of the problems re the productive granite/barren granite problem to record whether a given sample is taken from a cusp or the area between cusps; whether it is from the core or peripheral portions of the granitic outcrop, etc. It is also necessary to ensure that the sample has not been subject to hypogene alteration, etc. The limitations of the analytical method, also, must be fully appreciated.

During the interpretation of the geochemical data it must be fully recognized that the tungsten deposits may have developed in one igneous mass but be genetically related to another later one: this is of the greatest importance, as most large granitic masses, as has been mentioned earlier, are the product of repeated magmatic invasions and these *may* be separated by considerable periods of time, geologically speaking. Many Russian workers, in particular, appear to be well aware of this possibility, and Kalenov (1967), for example, believes that those tungsten-molybdenum deposits which occur in Triassic granites in the Nakut Daban belt of Eastern Mongolia are genetically related to later granites "the apices of which seldom crop out and in the Yugodzyr have been detected solely in deep mine workings".

Furthermore, variations in the tungsten content of a granite, like those in its tin content, may be due, to no small degree, to the composition of the material from which the magma was derived. (This tin aspect of this problem has been discussed by the writer elsewhere [Hosking, 1967].) The tungsten/granite relationship problem, like the tin/granite one, is filled with complexities, and it is certainly premature to say, as Beus (1969) has done, that if half the granitic samples from a given mass have a tungsten content of 4 ppm or more then it is probable that tungsten-bearing deposits will be associated with it. (The criteria which Beus have published appear in Table 2). Nevertheless, the only other study of the tungsten content of samples from a granitic mass on which the writer can comment was made by him and some of his students in 1964. The tungsten content of these samples from the Carnmenellis granite mass, Cornwall, which has strong wolframite/scheelite-bearing lodes and veins locally along its northern margin (at South Crofty and E.P.A.L. mines), supports Beus' views: of the 41 samples which were analysed for tungsten by the dithiol method (North, 1956) 36 contained four, or more, parts per million of the element in question. The number of times a given concentration was found is as follows:–

Table 2. Geochemical criteria for determination of parent granites of tungsten (after A.A. Beus [1969, p. 74])

Type of deposits and main ore component	Indicatory element and number of samples used in study ( )	Average abundance (ppm)		Contents (ppm) selected as criteria	Probability of the indicatory value in sample populations	
		In ore-bearing granites	In barren granites		In ore-bearing parent granites	In barren granites
Tungsten deposits in quartz veins and greisens (Based on Altai and Transbaikalia regions)	W(40)	5 ± 1	2 ± 0.3	4 and more	0.50 and more	0.03 and less

Number of samples	*ppm*
5	4
9	4
8	6
10	8
4	10
2	12
1	14
1	16
1	45

Some of the samples with the higher concentrations of tungsten *may* have been enriched during the phase of mineralisation as they were taken from areas of mining activity, although in these areas tungsten minerals have not been recorded.

iii. *Spatial aspects*

As noted earlier, tungsten, like several of the elements which commonly associate with it, but particularly tin and molybdenum, tends to concentrate in veins, etc., particularly in and around the 'high spots' (cusps) of granitic masses, and that the original surface of the granitic body should have been characterised by marked ridges, locally surmounted by steep-sided cusps, seems to be a necessary requirement for the development of such primary deposits of real economic worth. Where, as in Nigeria, the plateau granites appeared to have had relatively flat tops, the mineralisation tends to be dispersed (MacKay, et. al., 1949, p. 57) so that there is a paucity of tungsten lodes (as opposed to veins) and none are of outstanding importance.

THE PRIMARY CASSITERITE AND WOLFRAMITE DEPOSITS OF PORTUGAL
(After J. M. Cotelo Neiva, 1943)

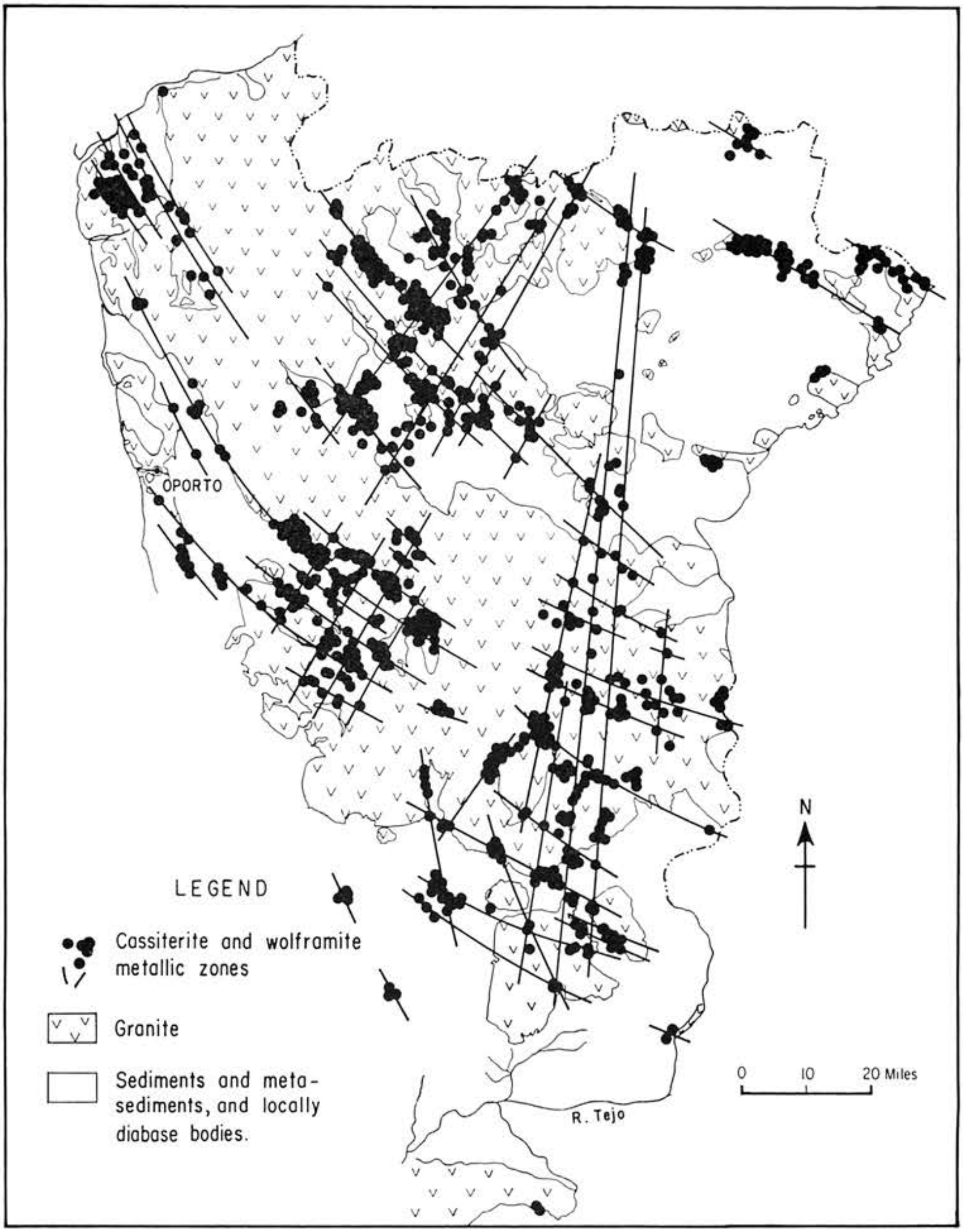


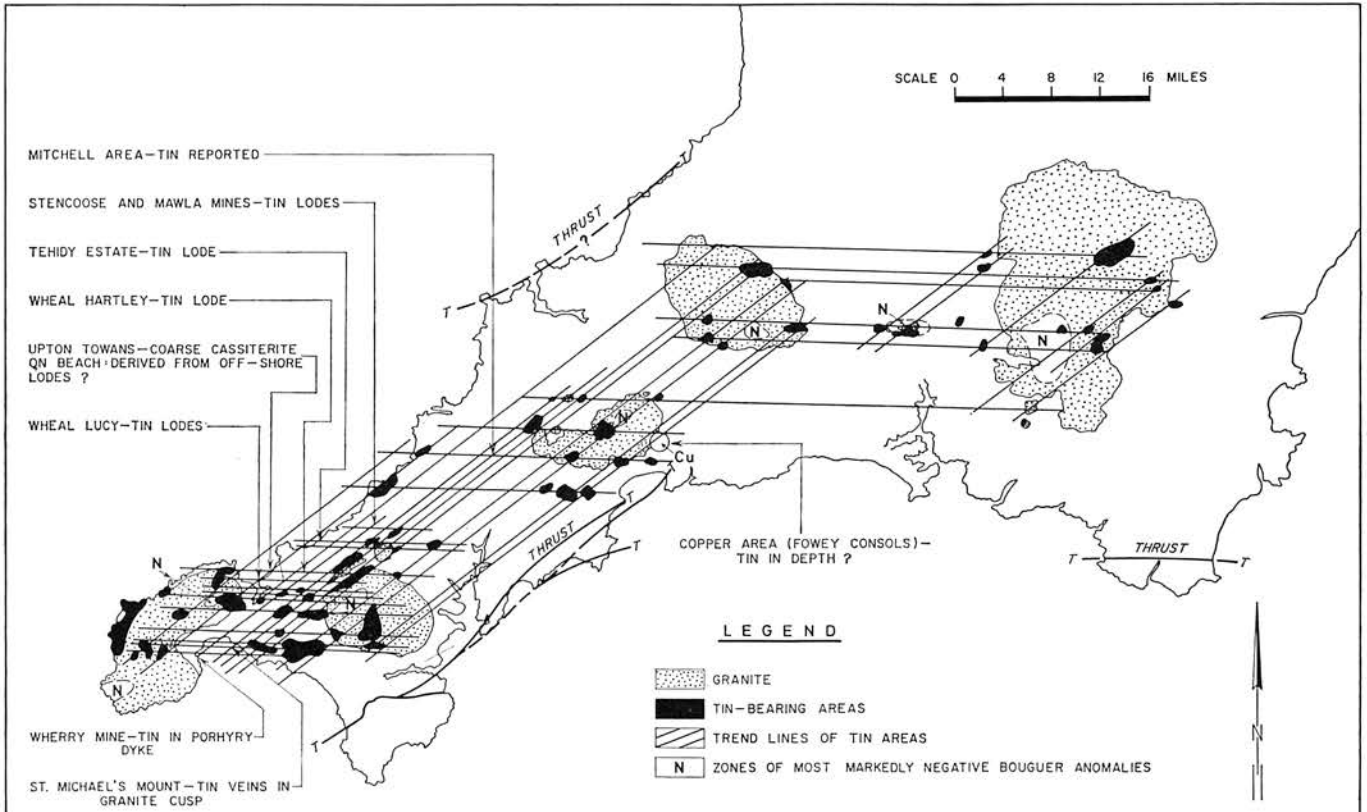
Fig. 7

The writer holds the view that the ridge/cusp pattern on the original surface of a granitic intrusive is due to the invaded rocks behaving as a mould, albeit, a mould capable of being deformed during the intrusive phase. Briefly, he thinks that generally antiforms created the ridges, whilst cusps developed where two antiforms of distinctly different strikes intersected, also less frequently where an antiform was intersected by a major fault with a markedly different strike from it, and perhaps on occasion where two major faults, differing greatly in strike directions intersected each other (Hosking, 1962). That the distribution of the cusps was structurally controlled both in Portugal and in the South-west of England has been demonstrated by Cotelo Neiva (1944) (fig. 7) and Hosking (1962) (fig. 8) respectively. In the South-west of England there is some evidence for believing that the distribution pattern of known cusps can be used to indicate sites of buried cusps, and with which primary mineralisation might be associated, both in unexplored onshore and offshore areas (Hosking, 1962).

From what has been written in earlier sections it is clear that mineralisation may be essentially confined to the apices of the cusps, and take the form of lode and vein swarms (as at St. Michael's Mount, Cligga and Hemerdon in the South-west of England, Mawchi in Central Burma, and in many instances in Peninsular Burma), or it may be partly in the cusps and partly in the invaded rocks (as at Hermingyi, South Burma); lastly, it may be essentially in the rocks overlying the cusps (as at Aberfoyle, Tasmania, and Panasqueira, Portugal). The granite invaded rocks may be igneous, sedimentary, or metamorphic and on occasion the cusp with which the tungsten mineralisation is closely associated may be that of a late granite which has been emplaced within an earlier one. Thus, in the Potgietersrus field of South Africa, the essentially stanniferous pipes which, nevertheless, are occasionally tungsten-bearing, have developed immediately under the roof of an elongate cusp of granite which developed under a cover of earlier granite. As noted earlier, at South Crofty Mine, Cornwall, the wolfram-bearing felspathic vein swarms may well have developed over late phase granite cusps which developed within an earlier phase granite, and a similar state of affairs, apparently, is to be found in East Mongolia.

In areas characterised by xenothermal deposits, some of which contain tungsten, as in Central Bolivia, there is a tendency also for the mineralisation to occur in and around granitic cusps. In the Mount Pleasant (New Brunswick) xenothermal deposit the wolframite occurs in a greisenised pipelike body, which also contains molybdenite, arsenopyrite, etc., and which the writer (Hosking, 1963) believes may have been the site of the main volcanic vent overlying a granitic cusp.

Erosion and inadequate investigation of the geology of the region may each prevent the original relationship between a given primary tungsten deposit and a granitic cusp from being recognized, even though such a relationship exists, or existed initially. Whenever the spatial relationship between tungsten mineralisation and granite rocks can be clearly established, and sometimes, this is difficult, perhaps virtually impossible to do, there is usually, perhaps always, the cusp/mineralisation relationship which emerges. Large, wolframite-bearing lodes flanking granitic ridges, and generally striking approximately parallel to these ridges, are most strongly mineralised in the vicinity of the cusps: this is well seen, for example, in the Camborne-Redruth area of the South-west of England, where tungsten mineralisation is strongest in those major lodes of the district which flank the elongate and prominent Carn Brea granite cusp, and strike approximately parallel to its long axis. It is likely that pyrometasomatic and metasomatic tungsten deposits are also commonly, at least, closely related to high-spots on granitic masses, and perhaps the numerous tungsten-bearing pipes of eastern Australia, which occur in the granite, usually not far from its contact with the invaded rocks, may also owe their disposition to the local migration of tungsten-forming agents into granitic high-spots, the obvious evidence, for which, at any rate, has been eliminated by denudation.



The distribution pattern of the mineralised areas containing tin and commonly tungsten, and of the zones of most markedly negative Bouguer anomalies. The material on which this map is, in part, based, has been derived from Dines (1956, figs. 3a and 3b) and from Bott, Day and Masson–Smith (1958, fig. 2).

Fig. 8

Although, then, the original topography of the granite appears to have played a major rôle in canalising the tungsten-depositing agents, clearly the resulting type of deposit—the minerals it was to be composed of, its shape, etc.—were determined by the nature of the mineralising agents, the chemical/mineralogical character of the invaded rocks, and by structural controls: amongst the latter faulting and impounding bodies are the most important.

Finally, it is not irrelevant to point out here that the emplacement of well-defined granitic cusps (or volcanic piles closely related to them) together with the development of aureoles of thermally metamorphosed rocks, and the establishment of lodes, etc., in and about the invading granite, collectively serve to produce a unit which is likely to be more resistant to erosion than those rocks surrounding it. Hence, such a unit, at some stage in the cycle of erosion, is likely to become a prominant and 'foreign-looking' hill feature. A mineral explorationist might well observe, amongst other laws, one which reads "if you see a foreign hill prospect it". The Hemerdon, Kit Hill and Castle-an-Dinas deposits, of the South-west of England, occupy the spices of such hill features, so also does that of Mount Pleasant (New Brunswick). Indeed, Mount Pleasant can be seen from miles away 'sticking out like a sore thumb' and yet the fact that it should be prospected was not appreciated until after a regional geochemical reconnaissance survey had been completed! It goes without saying that not all strange hills are mineralised, nor is tungsten necessarily present in those that are. It is also obvious that for one reason or another important tungsten deposits may be found in many other geomorphological settings.

The effects of exogenic processes on tungsten-bearing minerals

The behaviour of members of the ferberite/wolframite/hübnerite and scheelite/powellite isomorphous series (which, in what follows will be referred to as the wolframite and scheelite series respectively) in the surficial environment is, clearly, of the utmost importance to the exploration geologist seeking tungsten deposits.

In appropriate environments, in the zone of weathering, the members of both series are capable of taking part in chemical reactions. The extent to which such reactions occur is dependent on many factors which will be discussed after the views of various workers on this topic have been advanced.

Gannett (1919) threw considerable light on this subject, and the more important of his findings are as follows:–

i. Solutions of carbonates have no effect on wolframite and scheelite.
ii. Unacidified salts of lime and soda have no effect on them.
iii. Humic acids do not attack them.
iv. Sulphuric acid alone, and in combination with the sulphates of calcium, sodium, manganous and ferrous iron dissolve a part or all of the sample of all the species under test.
v. When solutions which were tested attacked scheelite, a precipitate of H_2WO_4 was usually formed.
vi. Manganous ions in solution probably replace the calcium ions in scheelite and possibly ferrous ions do likewise.

Morrow Campbell (1920) concluded, from a study of Burmese tungsten species, that sulphuric acid derived from the oxidation of pyrite attacks both wolframite and scheelite. However, the latter is attacked the more readily. The reaction with scheelite causes the generation of calcium and sulphate ions plus a precipitate of WO_3 (or H_2WO_4) whilst that with wolframite results in the generation of manganous, ferrous and sulphate ions and, also a precipitate of WO_3 (or H_2WO_4). Morrow Campbell notes that tungstic hydrate is readily dissolved by ground water containing alkaline carbonates, and that secondary scheelite probably results from the action of calcium sulphate on alkali tungstate in an excess of alkaline carbonate solution.

Haag (1943, p. 10) as a result of studying the genesis and nature of eluvial wolframite deposits in Northern Nigeria, concluded that the presence of magnetite, which does not occur in the parent veins, "and of tungstite or tungstic ochre, the absence of wolfram from the vicinity of outcrops in flats where mechanical disintegration is least, and the absence of fine wolfram from alluvials, prove that chemical decomposition takes place, although rapid mechanical disintegration due to the marked cleavage and rather friable nature of the mineral no doubt plays an important part: the two processes reinforce each other, the disintegration providing larger surfaces on which chemical action can proceed, which emphasises the planes of weakness. It may be supposed that when the wolfram breaks up, the tungstic acid, traces of which are occasionally found in the form of tungstite or tungstic ochre, is washed away in impalpable form with the manganese dioxide and some of the iron that has become oxidised to limonite, the rest of the iron remaining as magnetite".

The writer finds it difficult to believe that magnetite did, in fact, develop as a result of the decomposition of wolframite. He is of the opinion that Haag may well have arrived at this conclusion in the field because the mineral in question was magnetic. It seems more likely that if the magnetic iron species had been developed in the manner Haag postulates that it was maghemite. Clearly it would be most rewarding to carry out studies in Northern Nigeria, similar to those made by Haag, but to supplement the research by detailed mineralogic and analytical work. However, it is interesting to compare Haag's views with those put forward by Varlamoff (1970, pp. 60–61) as a result of a long experience of the tungsten deposits of the equatorial or tropical countries of the Eastern Democratic Republic of Congo, Rwanda, Burundi and Uganda. Varlamoff states that "in the zone of weathering, particularly, in hot, humid and forested equatorial and tropical conditions, the dispersion and migration of tungsten do not start with fresh minerals (i.e., wolframite and scheelite) but with the products of their alteration, namely anthoinite, ferritungstite, hydrotungstite, meymatite and tungstite, which, in this zone, may represent as much as 50 to 75 per cent of all tungsten-bearing minerals".

"The above-mentioned products of alteration strongly affect the mechanical resistance of wolframite and scheelite, such that they cannot survive for more than some hundreds of meters of alluvial transportation. At the same time they facilitate their chemical solubility".

Varlamoff continues, "under equatorial and tropical conditions, during eluvial processes, all the above-mentioned products of alteration are pulvarised almost completely and are partly dissolved and partly mixed with the finest products of eluvium, which absorbs at least part of the solution".

"During the alluvial processes, the products of alteration are dispersed and transported for distances that may be expressed in kilometres and tens of kilometres. They are mixed with the finest products of the river silts and soils. The coarse wolframite and scheelite are concentrated in river beds near the primary deposits over some hundred meters".

"Geochemical haloes of dispersion are produced by these products in regions where granitic cupolas are not reached by erosion. In regions where granitic cupolas outcrop, the tungsten of granites is added to these products."

Whilst the writer believes that there is much that is generally valid in Varlamoff's view it is important to realise that the deposits with which he was concerned are mineralogically distinctly unusual and certainly there are those who would hold that the anthoinite he mentioned is not a product of normal alteration of primary tungsten species in the zone of weathering. In the writer's experience the in situ wolframite and scheelite at or near the surface in West Malaysia and South Thailand rarely display marked chemical attack, and secondary tungstic species have only been seen in appreciable amounts, on very rare occasions. These countries, it must be remembered, are in the tropics! Probably much of the following observation of Betekhtin (1970 p. 394) is one which, although the remark re wolframite is, in part, debatable, is more generally valid. "In the oxidised zone exposed to weathering, wolframite is altered, though with difficulty, into the so-called tungsten ochre. In this process, divalent iron is oxidised into the trivalent modification. As a result, the lattice breaks down and earthy yellow-brown or brown masses are formed, consisting mainly of hydrotungstate of trivalent iron (ferritungstite). Sometimes yellow-green tungsten oxides called tungstite, or meymacite, H_2WO_4, are formed."

"Hübnerite, which breaks down in much the same manner, yields black "psilomelanic" accumulations containing WO_3, It should be noted that the psilomelane nodules present in eluvium, even at a considerable distance from the primary deposit, contain up to a few percent WO_3."

"Commonly, however, in the vicinity of primary deposits, wolframite, as a relatively inert mineral, usually passes into placers. But it is characteristic that with increasing distance from the primary deposits, the fragments of the wolframite minerals are comparatively quickly attrited and finally disappear altogether. This is due to the relative brittleness of the minerals which is enhanced by their perfect cleavage."

Concerning the behaviour, etc., of scheelite in the same environment, Betekhtin (p. 398) observes that in the oxidising zone the species is not very stable and that on the surface quartz veins sometimes have cavities in the place of leached scheelite. Nevertheless, scheelite quite often shows in the heavy concentrates of placer washing." That the components of scheelite may be mobilised during the oxidation of a primary orebody is indicated by the pseudomorphs of quartz and chalcedony after the mineral in question found on the dumps of the abandoned Ramsley Mine of Devon (Kingsbury and Hosking. Unpublished studies).

It is convenient to note here that Zeschke (1961) working in Pakistan, concluded that there, in river sediments, scheelite occurred at 1,100 miles and wolframite at 800 miles from the primary sources of these species. This runs quite counter to the views of Betekhtin, noted above, and indeed of many other geologists with which the writer has discussed this subject. However, before Zeschke's findings are dismissed as nonsense it is well to remember that according to Kuenen (1959, p. 18a) to reduce a quartz cube of 0.4 mm to a sphere solely by mechanical fluviatile abrasion (that is, the body is not subject to chemical attack) "would require a river transport of several million kilometers."

The occurrence of fossil tungsteniferous placers has been noted earlier.

It is clear that wolframite can be part-converted to tungstic oxide or to scheelite (possibly via the oxide) and these reactions are of comparatively common occurrence in some climatic and geologic environments. It is also clear that perhaps not uncommonly scheelite may be converted to tungstic oxide, and that on comparatively rare occasions, which because of their rarity, are of minor importance to the exploration geologist, scheelite may be replaced by other tungsten species, notably ferberite, cuproscheelite, raspite and stolzite. There is, however, little doubt that in appropriate circumstances tungsten, probably as tungstate ions, can be released directly from both wolframite and scheelite or from their secondary solid products and the ions can remain sufficiently long in the mobilised state to be taken up by land plants, from estuarine water by algae, and from sea-water (which, according to Mason, 1958, p. 174, contains 0.0001 parts per million W) by certain marine animals (see Sahama and Rankama, 1952, p. 628). Khristoforov (1955) notes that when intimate mixtures of iron sulphides and wolframite are subject to weathering an intimate mixture of $Fe(OH)_3$ and WO_3 is initially precipitated and manganese is mobilised whilst the environment is a distinctly acid one. As the process continues the "wolframite becomes progressively replaced by a mixture of ferritungstite and $Fe(OH)_3$. As the environment becomes progressively less acid, neutral, and weakly alkaline, while the precipitation of $Fe(OH)_3$ is going on, a precipitate of hydrates of MnO_2 begins. A partial leaching and removal of WO_3 becomes a possibility in this new environment".

Tungsten mobilisation is further confirmed by Ginsburg (1960, p. 71) who notes that on very rare occasions tungsten has been found in dry residues of water and that it is present in the ash of certain plants.

Hawkes and Webb (1962, p. 375) remark that tungsten probably occurs in the aqueous phase as WO_4^{--} and that the mobility of the element may be moderately high but limited by the slow dissolution of the primary minerals. They also note that Carpenter and Garrett (1959) suggest that estimation of the tungsten content of water samples may serve as a geochemical prospecting tool. That their suggestion is correct is supported by the work of Goleva (1971) who records that aqueous dispersion haloes of gold, tungsten and molybdenum were sought and found in Zabaykal'ye and that "the ores, lying below the modern plane of erosion ... were shown to have expressions in geochemical anomalies in ground waters, whether 'blind', as in a deep bore, or outcropping on the surface of the ground as seepages, springs, etc."

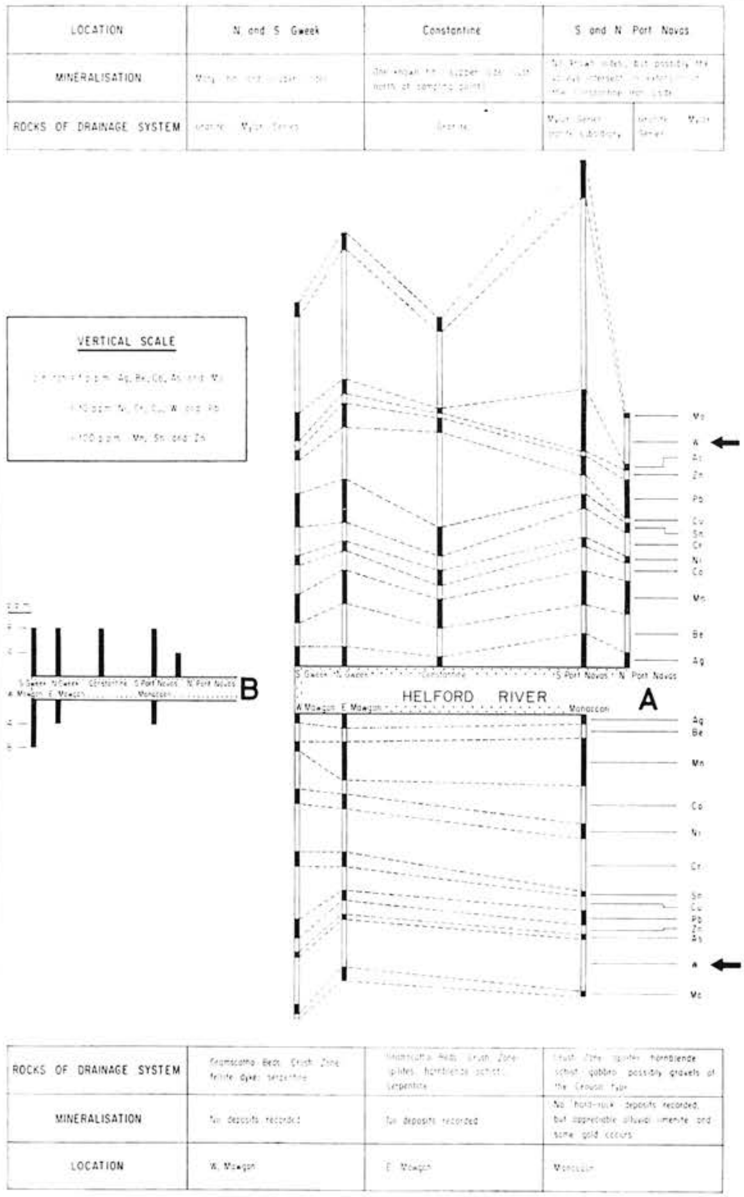
Boyle (1969, p. 39) however, warns that "tungsten compounds are relatively insoluble in natural settings, and hence water surveys are generally not effective as a means of locating tungsten deposits. He further observes that 'exceptions to this may prevail where the waters are alkaline since the element exhibits an increased mobility under such conditions. He also admits at least to a limited mobility of the element in question in soils generally, since he states that "vegetation surveys may also be useful since some plants take up considerable amounts of the element". That the latter statement is valid is supported by Aranyakanon and others. Aranyakanon (1963, p. 30–31) studied the tungsten content of specimens of the plant 'Pak Ped' (a composite whose botanical name is Erectitis hieracifolia Rafin) collected in the vicinity of certain tungsten mines of Northern Thailand, and found that the leaf ash from plants from tungsten mineralised areas contained up to 360 ppm W whereas the background value was not above 12 ppm. The present writer (Hosking. Unpublished studies, 1960) demonstrated that the ash of specimens of the brown alga Fucus ceranoides growing in those creeks of the Helford Estuary (Cornwall) which received their waters from the mineralised areas of the Carnmenellis granite contained 8 ppm W, whereas that from samples of the same species growing in those creeks which drained the ultrabasic rocks of the Lizard Complex contained 4 ppm, or less, of the element in question (fig. 9). The above examples serve to indicate that there is at least the possibility of using to advantage, on occasion, biogeochemical methods of prospecting for tungsten.

That comparatively dilute and inocuous biochemical agents are capable of solubilising wolframite, at any rate, is suggested by the fact that the spectrographic analysis of the lung of a miner who had worked for years in South Crofty (cassiterite/wolframite) mine of Cornwall revealed that it lacked an anomalous concentration of tungsten. Not surprisingly, it did contain an anomalous concentration of tin, but an anomalous concentration of molybdenum was also present, and this is surprising as in this mine not a single grain of molybdenite had ever been recorded (Ray and Salm, 1962). This study suggests that despite the marked differences in the physiologic patterns of man and the lower animals, it may be that tungsten is mobilised as and when minute particles of tungsten minerals are ingested by some of the soil animals. The example also serves to further emphasise the marked difference in the biochemical behaviour of tungsten when compared with that of molybdenum.

The occurrence of aggregates of secondary minerals in druses, as for example the beautiful crystals of cerotungstite described by Sahama et. al. (1970) in druses in Kigezi ferberite, and the occurrence of pellets of russellite, with included flakes of gold, at Castle-an-Dinas (Cornwall), are further evidence of the local presence of mobilised 'tungsten' which later took part in chemical reactions between solutions. Rankama and Sahama (1952, p. 629) have no doubt that waters derived from weathering tungsten deposits commonly contain tungstates in solution, for they note that "when the weathering solutions carrying alkali molybdates and tungstates mingle with waters rich in calcium, the insoluble calcium salts of molybdic, and tungstic acid will be precipitated". This, in their view, causes both these metals to be incorporated in the hydrolyzates (op. cit., p. 630).

It is, of course, as Boyle (1969, p. 39) observed, that in alkaline solutions tungsten may reach the most notable concentrations, and as noted elsewhere, the brines of Searles Lake contain 70 ppm of the element. Carpenter and Garrett (see Mine and Quarry Engineering, 1959, 25, no. 10, p. 469) are of the opinion that the "tungsten in the (Searles Lake) brine probably exists as a large heterapoly ion $(M_xW_yO_2)^{n-}$, where M may be boron, arsenic, or phosphorus and y:x may be numbers between 6 and 12." They further state that "such ions are very soluble in water but will form insoluble precipitates with complex organic compounds, such as proteins and various alkaloids". One wonders if tungsten might not travel more commonly as a heteropoly anion rather than as the comparatively simple WO_4^{--} one. One also wonders if, in particular, the tungsten enrichment in the Central African black schists might not have been due initially to the precipitation of such complex tungsten anions by proteins and/or other organic agents in the sediments.

It would appear that hot acid spring water (and much of it is likely to be meteoric) is capable of transporting tungsten and of obtaining its tungsten load by leaching the element from primary deposits through which it circulated. The evidence for this is to be found at Golgonda (Nevada), where acid spring waters containing a trace of tung-



The distribution of certain minor and trace elements in the top six inches of the estuarine muds in the upper reaches of certain creeks of the Helford River, Cornwall (A), together with the tungsten content of the ash of samples of Fucus ceranoides which were collected from these creeks (B).

(K.F.G. Hosking, 1960) S/71

Fig. 9

sten are found in the vicinity of spring-deposited manganiferous and ferruginous oxidate deposits which locally contain colloidal tungsten components of economic niterest (Kerr, 1946, p. 69).

That tungsten tends to co-precipitate with the oxides of iron and manganese suggests that in arid regions it may occur in desert varnish. Thus in such regions this may provide a means of locating hidden tungsten deposits, particularly as Lakin and others (1963) have demonstrated the validity of this approach for other deposits whose elements are capable of being mobilised in the zone of weathering.

From what has been written it must be clear that the story of the release of tungsten from the primary deposit into the superficial deposits and drainage systems is imperfectly known. Clearly, some of the tungsten may be released as primary species (hence the placers), some as secondary 'insoluble' minerals which have developed in situ from the primary deposits, and some as a component of ions which subsequently may be rapidly adsorbed on to colloidal ferric hydroxide, etc., or may be taken up by plants, or may react with other ions producing secondary insolubles: in alkali brine-rich areas the tungsten may be leached from the primary species, or their secondary products, and remain in a mobile state for a long period of time. Climate, topography, the mineralogical and textural character of the primary deposit and of the host rock must also play important rôles in determining the nature of the tungsten components released, the released mechanisms employed and their relative importance, and the rate of release. Generally in arid regions, both hot and cold ones, disintegration must be the dominant release mechanism, and in such regions it might be expected that oxidation would be reduced to a minimum: in hot and wet regions one would expect decomposition to be dominant, whilst in temperate regions both should be important. However, even in the tropics it is unlikely that a simple vein consisting of wolframite and quartz will show more than the slightest sign of chemical attack. If, however, sulphides, especially pyrite or pyrrhotite, also occur with the wolfram in considerable quantity, then in such a climatic environment the acidic solutions released as a result of the oxidation of the sulphides may well result in the wolframite becoming strongly altered and some of the tungsten mobilised. Again, in such a circumstance the degree to which, in a given time, the wolframite is attacked will depend on the texture of the deposit, that is to say on the wolframite/sulphides spatial relationships, and to what extent the wolframite masses are protected by quartz. It will also depend on the extent to which open fractures and joints occur in the deposit, as these provide passage ways for the attacking agents. Finally, it will depend on topography: if, to take an extreme case, the deposit outcrops on a vertical rock face, the attacking reagents are unlikely to remain long enough in contact with the wolframite to seriously affect the mineral. It would be a mistake to think that the mechanical release of primary tungsten species is unimportant in the tropics. Clearly these are released in such a climatic environment, a fact demonstrated by the sizeable eluvial deposits (essentially wolframite) which have been worked in Burma and by the equally sizeable eluvial wolframite and also scheelite deposits which have recently been discovered by villagers in the Chawang District of Nakhon Si Thammarat, S. Thailand, and near Wieng Papao, N. Thailand respectively (Offices of the Department of Mineral Resources, Thailand. Personal communication). In such regions, marked changes in temperature effected by heavy rains falling on hot rocks may disintegrate a deposit. In addition, and particularly, in steep granitic areas, landslides initiated by water-logged soils and lubricated joints may promote the release and disintegration of large masses of 'ore'. It might also be added that cliff falls are capable of rapidly releasing considerable quantities of wolframite, and, of course, other minerals, on to the beach. This is well seen as hinted earlier, at Cligga, Cornwall, where virtually all the wolframite/cassiterite-bearing boulders which strew the beach have been derived by partial collapse of the adjacent mineralised granite mass.

However, when, as a prospector, one is considering the question of dispersion of tungsten from a given primary deposit, it is not enough to consider it solely in the light of the present day environment. Ideally, one should consider all the geologic events and climatic changes to which the deposit has been subject since it came under the influence of subaerial agents. This is particularly important if the deposit happens to be in an area which has been recently glaciated, as associated with it may well be a dispersion fan, characterised by anomalous concentrations of tungsten, and capable of being established by a boulder survey and/or by chemical analysis of the finer glacial components Such a region might also contain tungsten placers in the upper reaches of buried preglacial drainage systems. Furthermore, any non-residual cover, even if it is quite thin, over the primary deposit, may lack anomalous concentrations either of tungsten or of elements from the companion minerals in the in situ deposit. This situation can accrue from the limited attack of the primary minerals (exposed by the stripping off of the oxidized zone by the ice sheet) in a cold climate since the retreat of the ice.

In many climatic environments residual soil overlying primary tungsten deposits is characterised by anomalous concentrations of the element which enable the sub-outcropping deposit to be delineated by geochemical methods (see, for example, the early but beautiful case history of the work of Holman and Webb (1957) in Uganda). As in the case of many other elements, the shape of the anomalous aureole is largely a function of the shape of the deposit and the topography, although, naturally, the climate is a modifying factor.

The size of the anomalous zone at the surface is dependent largely on the size of the tungsten deposit and the topography, and the size of the zone, in turn, determines the soil sampling interval which can be safely employed during a geochemical soil survey aimed at tracing the extension of the given tungsten deposit and/or in finding similar neighbouring bodies. In Cornwall, when investigating sub-outcropping tungsten vein-swarms, lodes, etc., the writer found it necessary to employ a sample interval of 25 feet or less with a maximum initial traverse interval of 400 feet which often had to be reduced subsequently.

Movement of tungsten-bearing material (soil and/or rock debris) down a valley slope into a river, or the direct release of tungsten species from a deposit intersected by a river will create a dispersion train in the sediments, which can usually be established over a comparatively limited distance by panning or similar gravity methods, but which can be much more readily established over considerably greater distances by the employment of rapid semi-quantitative colorimetric methods of analysis, of which the dithiol one (North, 1956) is the most satisfactory. The tungsten content of such dispersion trains may owe something to the precipitation of tungstate ions by, say, calcium ones, although the writer thinks that this process does not generally provide significant contributions of tungsten to the stream sediments. For reasons noted earlier, the finer fractions of stream sediments are those in which tungsten preferentially concentrates in the lower reaches of a river, and the tungsten content of the minus-80-mesh (B.S.S.) fraction of stream sediments has proved to be quite satisfactory when studying the dispersion of the element in question in Cornwall with a view to establishing tungsten-anomalous areas (figs. 10 and 11).

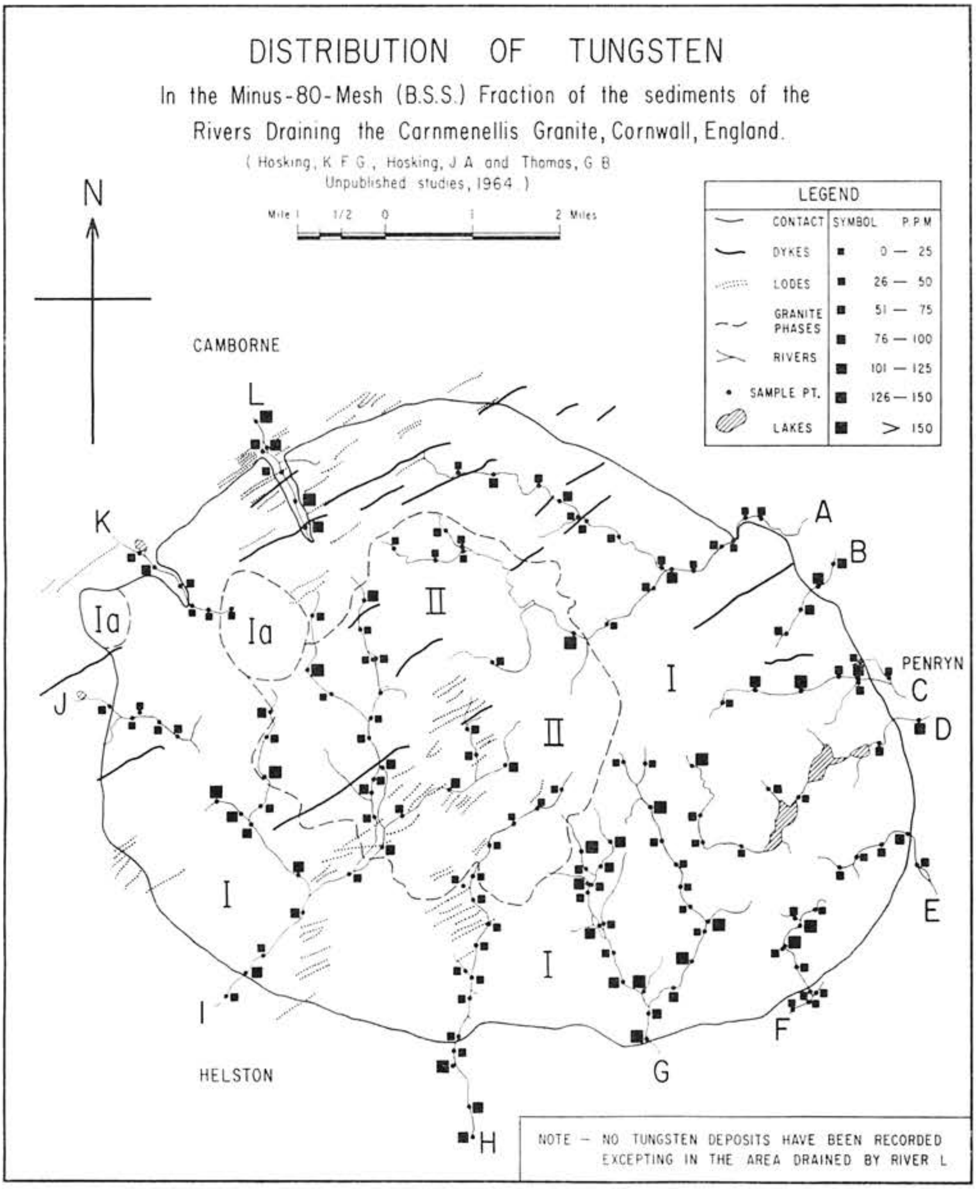
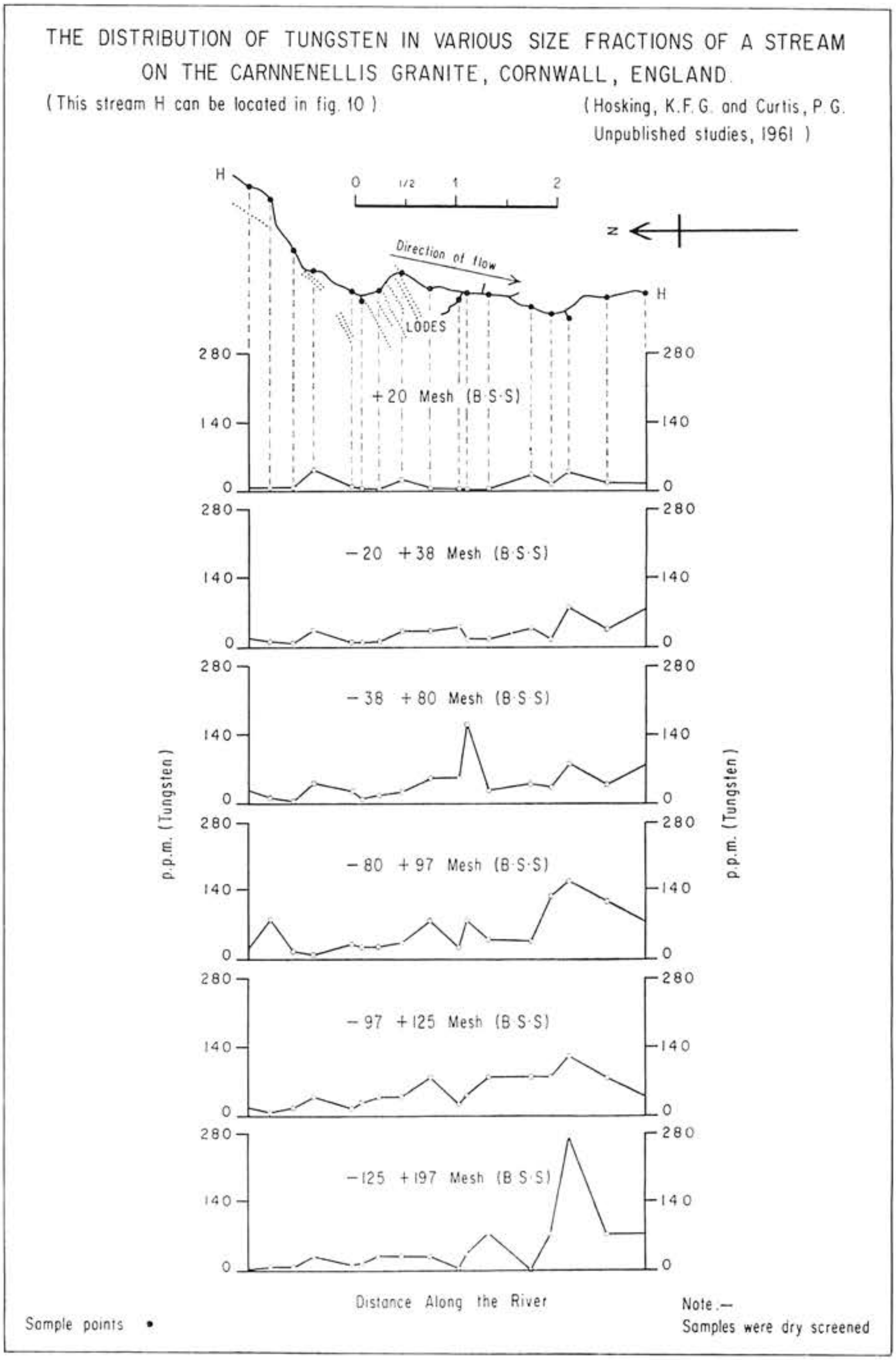


Fig. 10

The distance below a given primary tungsten source beyond which anomalous concentrations of the element in question cannot be established in the sediments of a river receiving contributions from the source must depend on several factors including the sensitivity of the analytical method used (which could include pre-concentration of the tungsten, if the study warranted it and research established that this could be achieved by mechanical and/or chemical methods), the climate, topography, the dis-



THE DISTRIBUTION OF TUNGSTEN IN VARIOUS SIZE FRACTIONS OF A STREAM ON THE CARNNENELLIS GRANITE, CORNWALL, ENGLAND.
(This stream H can be located in fig. 10)
(Hosking, K.F.G. and Curtis, P.G. Unpublished studies, 1961)
H
0 1/2 1 2
N
Direction of flow
H
LODES
+20 Mesh (B·S·S)
−20 +38 Mesh (B·S·S)
−38 +80 Mesh (B·S·S)
−80 +97 Mesh (B·S·S)
−97 +125 Mesh (B·S·S)
−125 +197 Mesh (B·S·S)
280
140
0
p.p.m. (Tungsten)
Distance Along the River
Sample points •
Note.— Samples were dry screened

Fig. 11

tribution and number of tributaries draining barren areas, the amounts of barren material added in unit time by them to the main river, and the mode of occurrence of the tungsten in the sediments. It may well be, as for copper, that tungsten dispersion trains are more limited in length in drainage systems in arid regions where the rivers flow intermittently, or where, at any rate, their flow is often very restricted, than they are in similar drainage systems in wetter climates. Clearly, the nature of the dilution of the tungsten-bearing sediments by barren ones must determine, to no small extent, the distance from the source at which anomalous concentrations of tungsten can be determined by the direct colorimetric analysis of a given sediment fraction. The mode of occurrence of tungsten in the sediments may also be important. It may be, as Zeschke (1961) suggests, that both scheelite and wolframite are remarkably resistant to complete destruction in a fluviatile environment, or it may be, as most believe, that both wolframite and scheelite rapidly become reduced to fine components in such an environment and are then dissolved. Nevertheless, if the latter is the case, then anomalous concentrations of tungsten may still, on occasion, be found far below the primary source, if the heavy mineral fraction of the sediments is appropriately examined, because the element may occur, as noted earlier, in appreciable concentrations in cassiterite and columbite/tantalite.

In the south-west of England anomalous concentrations of tungsten have been established by direct colorimetric analysis of the minus-80-mesh fractions of stream sediments for distances of 5 to 6 miles (Hosking et. al., 1962: Hosking and Ong, 1963–64). In addition, it has been shown that the sediments of those creeks of the Helford Estuary which are 'fed' by rivers draining the mineralised portions of the Carnmenellis granitic mass contain appreciably greater concentrations of tungsten than the sediments of the creeks of the same estuary which are fed by streams from the tungsten barren ultrabasic and other rocks of the Lizard Complex (fig. 9). Whilst these differences in tungsten content are most obvious when the contents of the sediments of the heads of the creeks are compared, they are, nevertheless, still in evidence when a comparison is made between the tungsten contents of samples taken from points near where the creeks join the estuary proper. Although the distribution of tungsten in the Helford estuary proper has not been established, it has been done in the case of the neighbouring estuary termed the Carrick Roads (Figs. 12 and 13). The Carrick Roads is served largely by two rivers, the one originates from the St. Austell area and carries but little tungsten in its sediments, whilst the other, the so-called Carnon stream, contains sediments with high concentrations of a number of elements including tungsten. The high tungsten concentration derives from the constant natural additions of tailings from the widespread mine dumps of the now long abandoned mines of the St. Day copper field. This high tungsten-content is quite remarkable as very little mention, as far as the writer is aware, is made in the literature of the presence of tungsten minerals in the St. Day area, and in accounts of the St. Day mines drained by tributaries of the Carnon stream no mention is made of tungsten! This may well be not because tungsten minerals were absent, but because practically all these mines were abandoned before tungsten was of economic interest. Anomalous concentrations of tungsten in the sediments of the Carnon stream continue into the superficial ones of the Carrick Roads, but quickly decrease seawards. The concentration pattern of the tungsten in the estuarine sediments is such as to indicate quite clearly which river system was the main contributer of the element.

An unpublished study by the writer and another of the concentrations of a number of elements, including tungsten, in the sediments of the streams draining the epithermal (mineralogically speaking) antimony field of North Cornwall, and flowing into

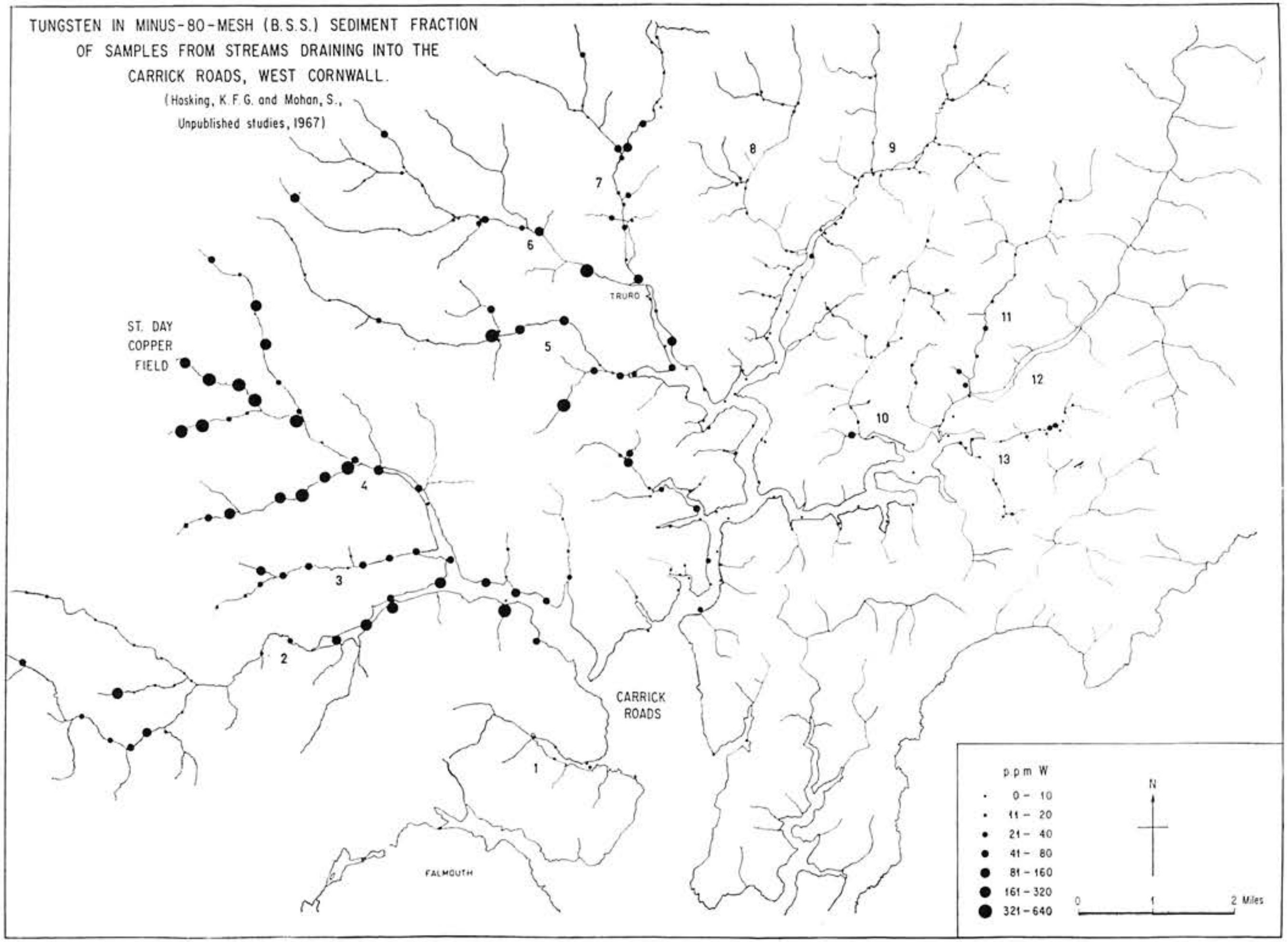
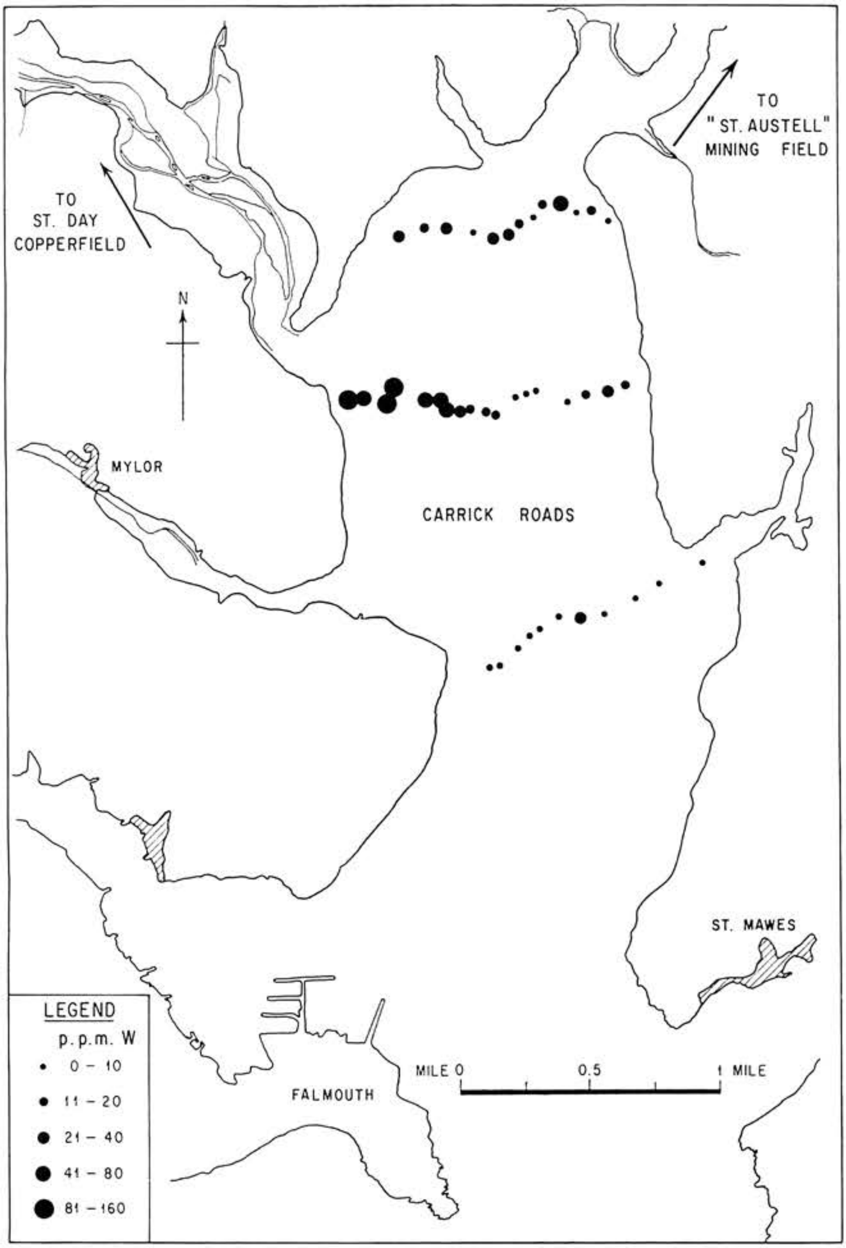

TUNGSTEN IN MINUS-80-MESH (B.S.S.) SEDIMENT FRACTION
OF SAMPLES FROM STREAMS DRAINING INTO THE
CARRICK ROADS, WEST CORNWALL.
(Hosking, K.F.G. and Mohan, S.,
Unpublished studies, 1967)
ST. DAY
COPPER
FIELD
TRURO
CARRICK
ROADS
FALMOUTH
1
2
3
4
5
6
7
8
9
10
11
12
13
p.p.m W
0 - 10
11 - 20
21 - 40
41 - 80
81 - 160
161 - 320
321 - 640
N
0
1
2 Miles

Fig. 12



TUNGSTEN IN THE MINUS-80-MESH FRACTION OF ESTUARINE SEDIMENTS OF THE CARRICK ROADS, WEST CORNWALL
(K. F. G. Hosking and Mohan, S., 1967)

Fig. 13

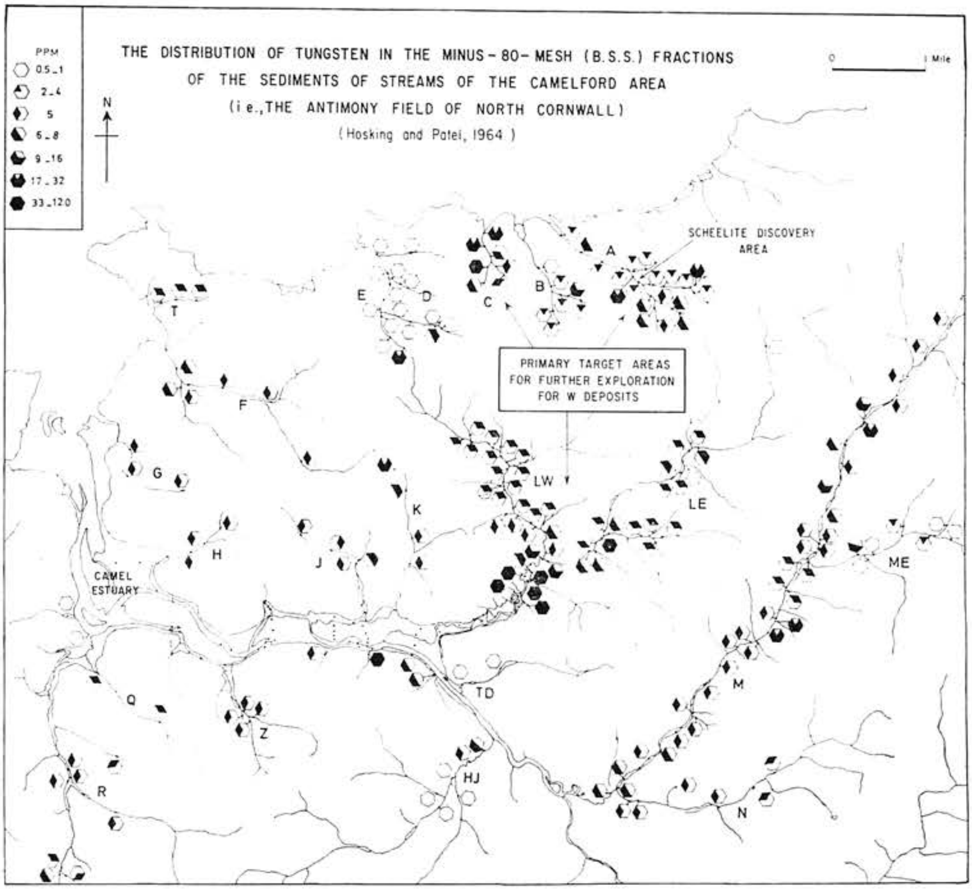
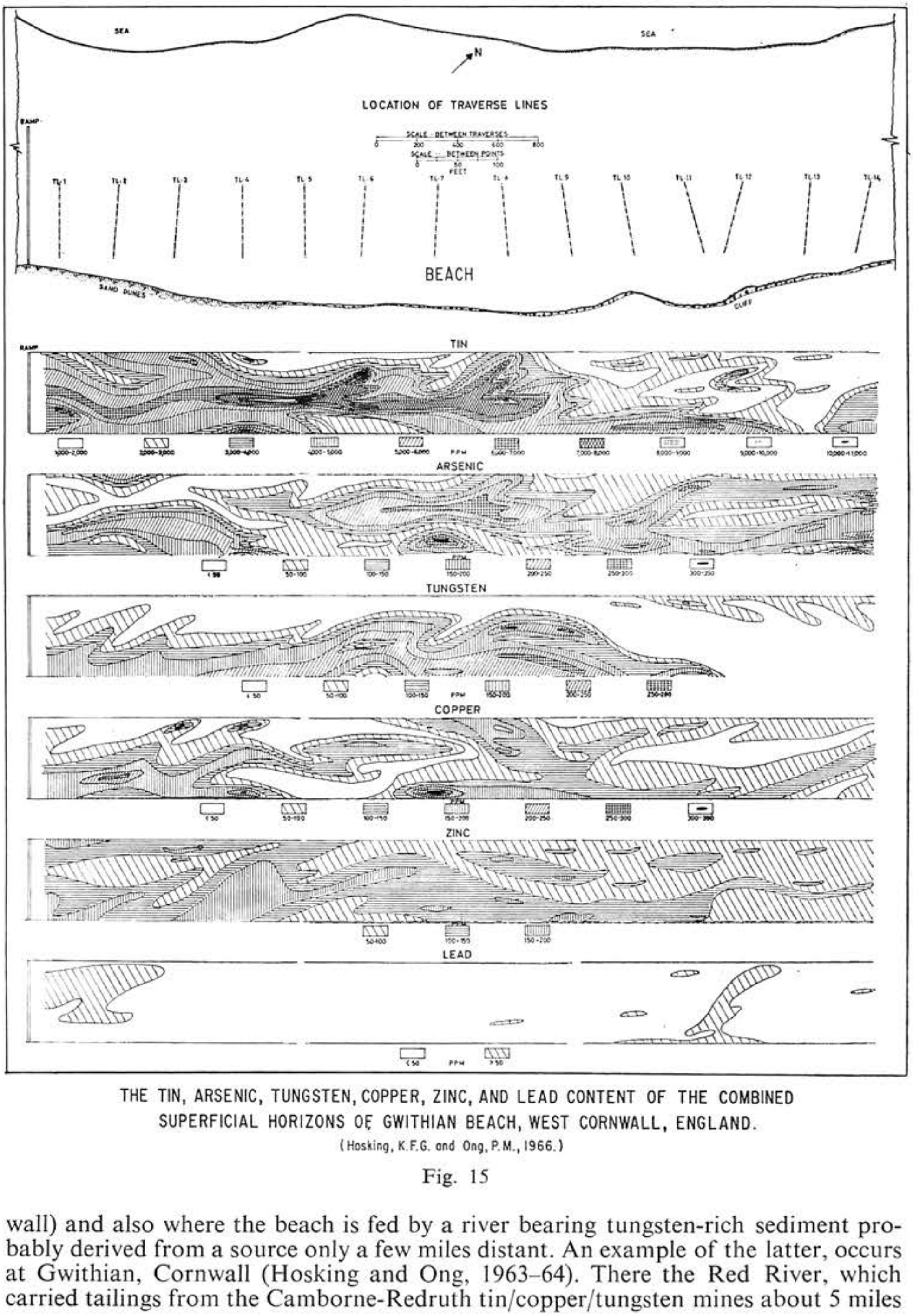


Fig. 14

the Camel Estuary, also established that in several of the streams the sediments contained distinctly anomalous concentrations of tungsten (fig. 14). Further work revealed that this was also true of some of the estuarine sediments. These facts suggest that locally tungsten may occur in the small deposits in which stibnite, jamesonite and galena figure largely, and which are associated with spilites. It may well be that scheelite occurred in these long abandoned deposits: it could easily have been overlooked and, in any event, the miners would have had no interest in it (footnote).

Anomalous concentrations of tungsten may occur in beach deposits where they are backed by cliffs containing deposits of the element in question (as at Cligga, Corn-

Footnote: Confirmation that scheelite does, indeed, occur in this area was obtained quite by chance when the writer was reading a paper by Kingsbury (1964) after the final type script of this paper had been completed. Kingsbury's (p. 249) relevant remarks are as follows: "One quite unusual occurrence of scheelite has also been found, where it is apparently of late, low temperature formation and is associated with pyrite, stibnite, jamesonite, galena, some arsenopyrite, and other sulphides, and gold, in a carbonate matrix in one of the veins in the North Cornwall antimony district near St. Teath. This occurrence recalls the similar but very unusual associations in the Hillgrove District, New South Wales, Australia, and is probably the first and hitherto only such occurrence known in Cornwall." (It is also reminiscent of the Yellow Pine ore noted earlier.)



THE TIN, ARSENIC, TUNGSTEN, COPPER, ZINC, AND LEAD CONTENT OF THE COMBINED SUPERFICIAL HORIZONS OF GWITHIAN BEACH, WEST CORNWALL, ENGLAND.
(Hosking, K.F.G. and Ong, P.M., 1966.)

Fig. 15

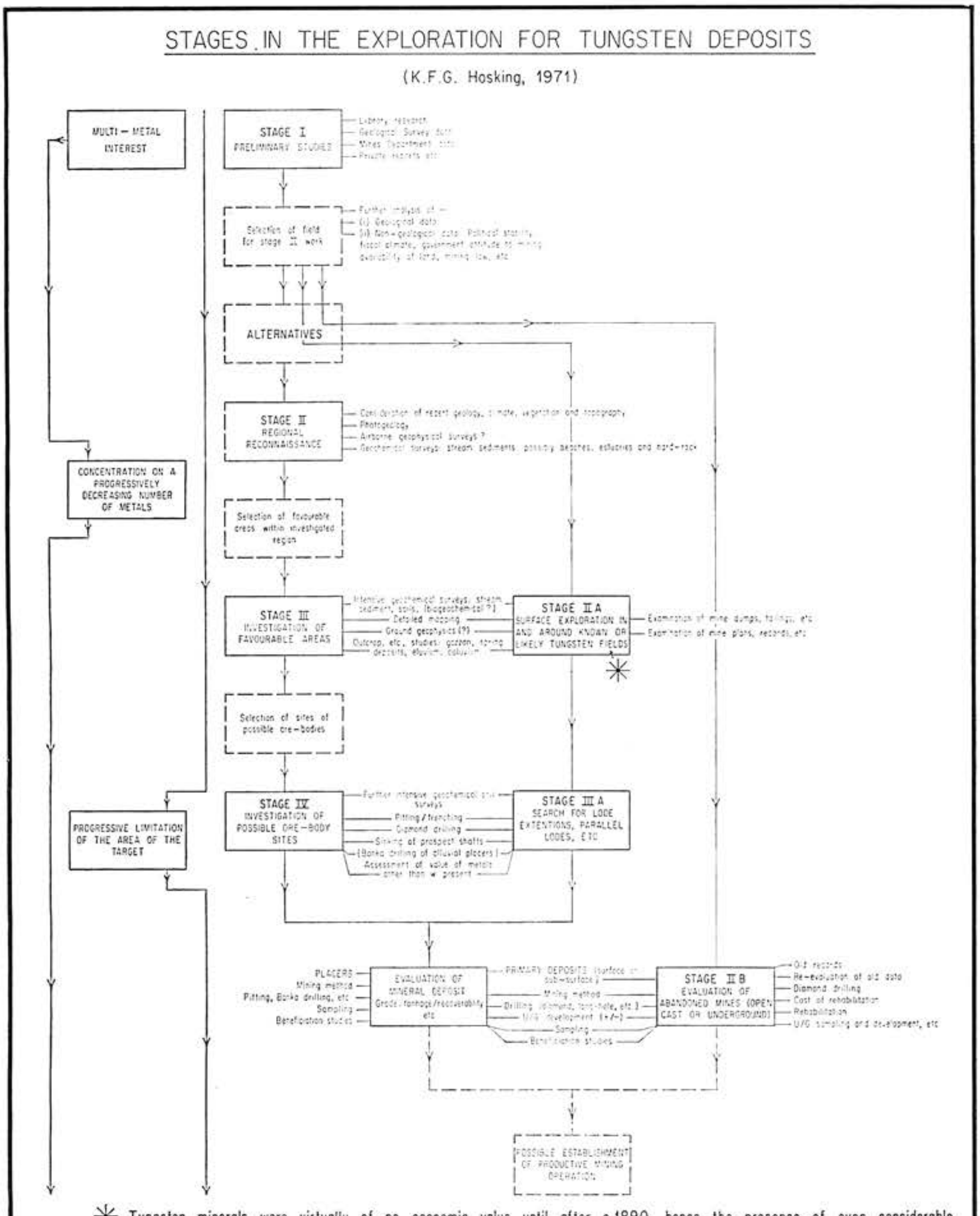
wall) and also where the beach is fed by a river bearing tungsten-rich sediment probably derived from a source only a few miles distant. An example of the latter, occurs at Gwithian, Cornwall (Hosking and Ong, 1963–64). There the Red River, which carried tailings from the Camborne-Redruth tin/copper/tungsten mines about 5 miles away, flows across the beach. The action of the sea has served to concentrate the released cassiterite carried into it by the river in elongate zones below the low-water level and parallel to the shore, whilst cassiterite in composite grains and other cassiterite-free heavy grains have been transported by longshore currents and concentrated in elongate zones on the beach and in such a way that the long axes of the zones parallel the coast-line (fig. 15). Both the tungsten and tin distribution patterns on the beach are similar, but not identical, which suggests that the tungsten pattern cannot be due solely to tungsten 'protected' in cassiterite. Unfortunately, during these and similar studies in Cornwall, the tungsten content in the cassiterite there was not investigated, and what is more important nor was the extent to which any tungsten in cassiterite would be mobilised during the fusion employed in the dithiol method used by him for determining tungsten, but it is thought to be slight. Although in the studies relating to the distribution of tungsten in creek, estuarine, and littoral deposits described above man's activities have been largely responsible for the tungsten content of the rivers feeding these deposits, it seems reasonable to believe that in favourable situations Nature, without man's help, is quite capable of making similar, but perhaps generally less spectacular, contributions. If this is accepted then it follows that determination of the tungsten content, particularly of the sediments of the upper reaches of creeks, and, on occasion, of the sediments of the landward ends of estuaries, and of beaches, may serve to give some indication of the tungsten potential of the hinterland, and this might be strengthened by determining the concentrations in these same sediments of elements which commonly associate with tungsten in primary deposits, notably tin, molybdenum, bismuth, arsenic and copper. Geochemical studies of creek sediments might prove to be particularly valuable during the initial stages of an exploration of a little explored area which was difficult of access but which was bordered by a coastline characterised by the presence of many creeks and estuaries which were fed by comparatively short rivers. Samples could be taken from a small boat and analyzed on board the parent vessel.

EXPLORATION PROGRAMMES FOR TUNGSTEN

The various types of exploration programme for tungsten, together with indications of the nature of the work to be carried out at each stage of these programmes, is indicated in figure 16. Most of this figure should be readily understood in the light of what has already been written in this paper, and so it only remains to make some general comments regarding surface exploration programmes for tungsten, together with somewhat more detailed remarks concerning the search for further tungsten deposits in underground mines.

Exploration programmes in which the search for tungsten figures, vary greatly in content, depending on the extent, accessibility, topography, vegetation and climate of the terrain to be investigated, together with the state of geologic and other knowledge concerning it. At the one extreme it is necessary to devise a regional reconnaissance programme: at the other, one suited to the search for further ore in and about a working or abandoned mine.

During regional reconnaissance tungsten may, or may not, be an element specifically sought at the stage when a geochemical survey involving the analysis of stream sediments from all the drainage systems of the terrain is carried out. However, if areas anomalously high in tungsten are broadly delineated at this stage these should, during subsequent stages be investigated in progressively greater detail. During these stages more intensive geochemical surveys involving first the analysis of stream sediments for tungsten and likely associated elements (e.g., Sn, As, Be and Mo) should be done, and these should be followed by geochemical surveys in which soil samples taken from



* Tungsten minerals were virtually of no economic value until after c.1890, hence the presence of even considerable quantities of tungsten minerals in, say, a copper mine which closed before that date, might well not be recorded. In addition, scheelite was often not recognized as such.

Fig. 16

areas indicated by the preceding studies were analyzed. At this point, or possibly a little earlier, granitic cusps, granite/limestone contacts should be established by map research, photo-geological methods and field studies. Perhaps, also, the tungsten content (and *possibly*, also, the content of certain potential, mineral deposit indicators such as, say, F^-, Cl^-, PO_4^{---} and Sn) of granitic samples might be established and, of course, any mineralised outcrops and skarns should be subject to detailed investigation.

The tungsten content of a thoroughly gozzanised outcrop, which may be determined by rapid semi-quantitative methods, might well give indication as to whether the deposit should, or should not, be regarded as a target for further investigation by the tungsten prospector.

On occasion, geophysical methods may be used to advantage to trace, etc., sub-outcropping tungsten deposits, particularly, when they are sulphide-rich: then I.P. and S.P. methods should be tried and if the results are promising the better geophysical method should be employed in conjunction with appropriate geochemical ones.

The possibility of using geophysical methods to locate buried granitic cusps, around which tungsten, and other deposits, so often congregate, has long been in the mind of the writer. Geophysicists have all claimed the generally the cusp is likely to constitute too small a target to be located, unless it is quite close to the surface. Stumpfl (1963–64) however, claims that geophysical methods *were* successfully employed to locate such targets in the Rooiberg-Leeuwpoort mining area of South Africa!

At the point when outcropping deposits are located or sub-outcropping ones are delineated by geochemical means, they should be further investigated by pitting, trenching and drilling, whichever seems to be the most appropriate method or group of methods should be employed. In certain instances these investigations would need to be followed by underground methods, involving shaft-sinking, driving, cross-cutting, etc., in order to further delineate the deposit and to determine the grade and tonnage of such ore as may be present.

The more detailed the knowledge concerning the distribution of tungsten in the area to be prospected the less the stages of exploration which have to be carried out before the point is reached when a tungsten deposit is sampled directly. Should the exploration be confined to an abandoned underground mine filled with water, then, following library research and the drawing if possible, of Conolly and other contour sections in order to establish the possible presence of ore shoots beyond the immediate mine excavations, a geochemical survey involving the analysis of soils for tungsten and associated elements is often in order in an endeavour to trace extensions of known lodes and to locate any sub-outcropping neighbouring lodes. Diamond drilling to test the initial results and conclusions would follow, and if the results of drilling were encouraging the mine would be unwatered, rehabilitated, and its potential further established by underground investigations.

The search for further tungsten deposits in reopened and operating mines is, of course, based on knowledge of the local mineralisation obtained from study of geologic and other data from more mature neighbouring mines and on structural and mineralogic data and the spatial characteristics of the ore shoots obtained from appropriate plans, reports, etc., of the mine itself. The actual search will involve such operations as cross-cutting, sinking, raising, sampling and drilling.

In many tungsten-bearing lodes and veins the wolframite and/or scheelite are often erratically disposed and this often leads to evaluation problems. Because of this Solomon and Brooks (1966) have used point counting as a method of assaying wolframite at Story's Creek Mine, Tasmania, the preliminary tests having shown "that the wolframite follows a distribution that allows application of point counting formulae from which the precision of the estimate of the percentage of wolframite can be gauged." At Carris Mine, Portugal, near-vertical swarms of veins, some of which contained wolframite, scheelite, casiterite, etc., which were exposed in development ends, were collectively evaluated simply by determining the total width of the mineralised members. (Hosking. Unpublished Studies.)

Tungsten veins of the type mentioned above may also be associated with others which are, economically speaking, barren of tungsten. Hence during the examination of diamond drill cores obtained from such an environment visual inspection may not enable one to differentiate between a barren portion of a productive vein and a portion of a barren vein. This was a problem which faced the writer at Panasqueira (Portugal). He thought that perhaps the trace element content of the quartz from the barren veins might be significantly different from that of tungsten-rich ones and so during a preliminary study to test this hypothesis he determined the W, Sn, As and Cu contents of a number of quartz samples from a barren and a productive lode. Each sample was taken across the full width of the deposit. The results suggest that the tungsten content of the quartz from the productive lodes might well be significantly higher than that of similar samples from barren ones, and they certainly justified a further study so designed that the results would be statistically acceptable (fig. 17). For various reasons the writer was unable to do this. The initial study also indicated that the concentrations of the other elements which were determined were of no help in differentiating between the two types of veins. (Hosking. Unpublished studies.) This study prompted the writer to set up a similar investigation at Geevor Mine (Cornwall) in order to see if a study of the metal content of the numerous veins intersected in a cross-out would enable differentiation to be made between those which elsewhere were known to contain economic concentrations of cassiterite and those which lacked such concentrations. The study established that only those veins which were tin-rich elsewhere possessed anomalously high trace concentrations of copper where they were intersected by the cross-cut (see Garnett, 1967). This study is included because elsewhere tungsten-rich lodes may be indicated in a similar manner. At South Crofty Mine (Cornwall) examination of drill core indicated that as wolfram-bearing, etc., lodes were approached the density of mineralised fractures (which did not generally contain recognizable wolframite, cassiterite, etc.) per unit length tended to increase as did the trace tungsten and tin content, albeit in an erratic way (Hosking and Burn. Unpublished studies). Rapid geochemical methods of analysis also proved suitable at South Crofty Mine for establishing the tungsten, tin, arsenic and copper content of samples of sludge obtained during a long-hole ring drilling programme aimed at testing the potential of a block of ground containing numerous arsenopyrite and wolframite-bearing veins and others consisting essentially of cassiterite, chlorite, fluorite and quartz. The analytical results allowed "contour" diagrams of the elements under examination to be prepared (fig. 18). (Hosking and Burn. Unpublished studies.)

CONCLUSION

In this paper the writer has endeavoured to bring together a variety of data and views which might facilitate the search fortungsten deposits of economic importance. As far as possible he has drawn on his own experience because, by so doing, he is adding something to the corpus of knowledge relevant to this subject which is already in the literature, albeit in a somewhat scattered array.

The preparation of this paper has been of benefit to the writer in that it has served to high-light for him the many gaps in the tungsten "story" which need to be filled. In

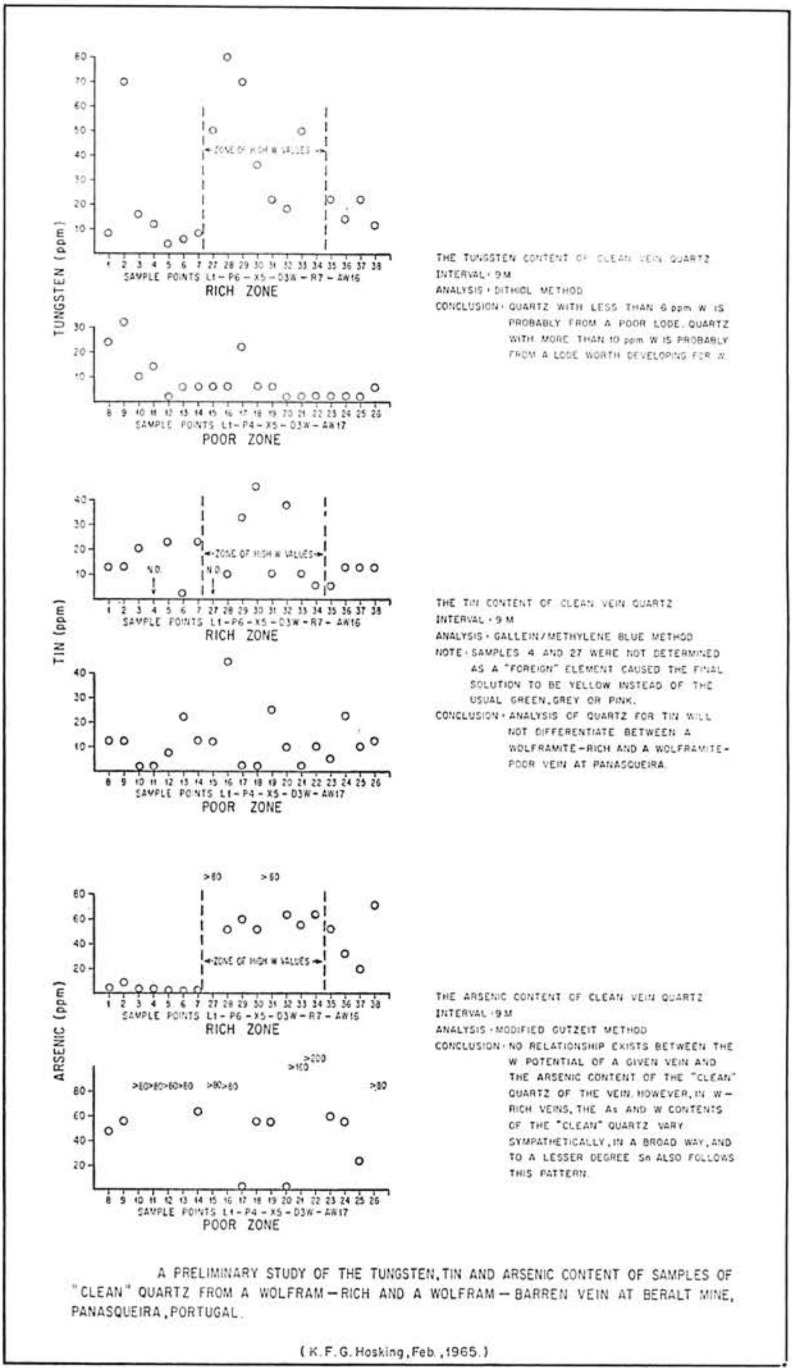
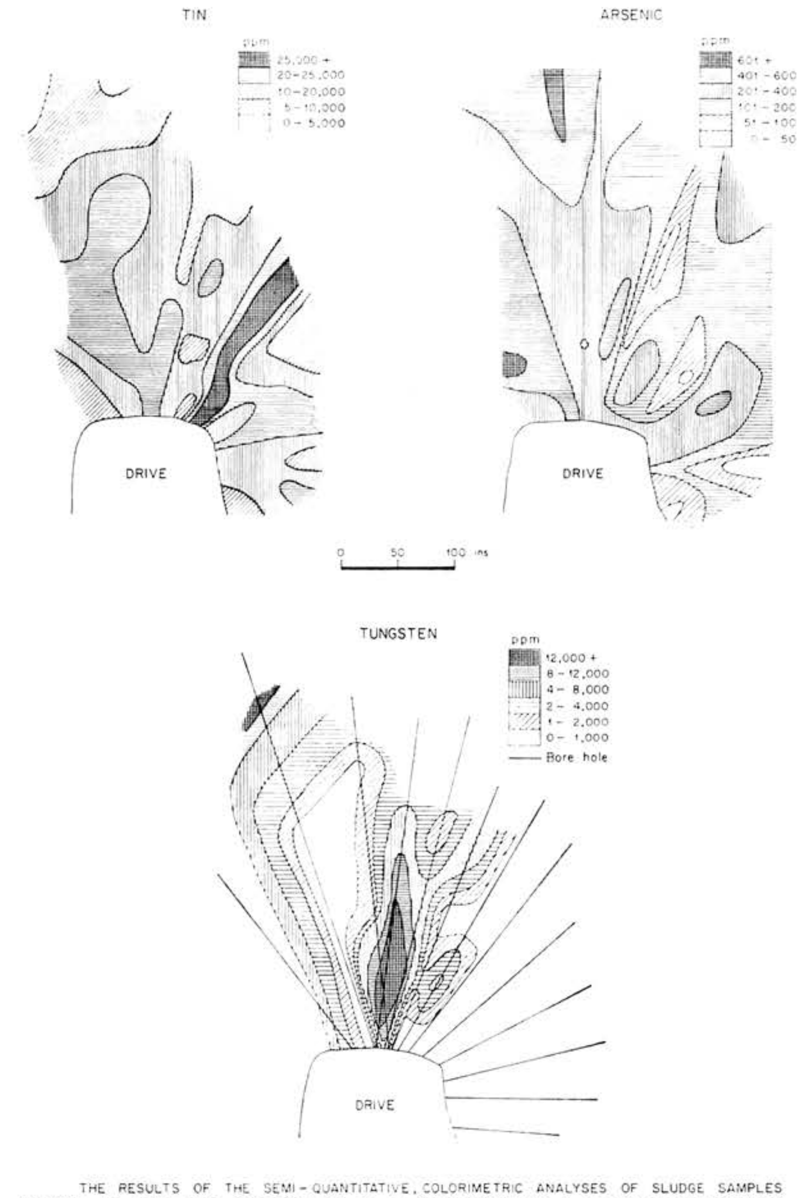

TUNGSTEN (ppm)
ZONE OF HIGH W VALUES
SAMPLE POINTS L1 - P6 - X5 - D3W - R7 - AW16
RICH ZONE
SAMPLE POINTS L1 - P4 - X5 - D3W - AW17
POOR ZONE
THE TUNGSTEN CONTENT OF CLEAN VEIN QUARTZ
INTERVAL : 9 M
ANALYSIS : DITHIOL METHOD
CONCLUSION : QUARTZ WITH LESS THAN 6 ppm W IS PROBABLY FROM A POOR LODE. QUARTZ WITH MORE THAN 10 ppm W IS PROBABLY FROM A LODE WORTH DEVELOPING FOR W.
TIN (ppm)
N.D.
ZONE OF HIGH W VALUES
SAMPLE POINTS L1 - P6 - X5 - D3W - R7 - AW16
RICH ZONE
SAMPLE POINTS L1 - P4 - X5 - D3W - AW17
POOR ZONE
THE TIN CONTENT OF CLEAN VEIN QUARTZ
INTERVAL : 9 M
ANALYSIS : GALLEIN/METHYLENE BLUE METHOD
NOTE : SAMPLES 4 AND 27 WERE NOT DETERMINED AS A "FOREIGN" ELEMENT CAUSED THE FINAL SOLUTION TO BE YELLOW INSTEAD OF THE USUAL GREEN, GREY OR PINK.
CONCLUSION : ANALYSIS OF QUARTZ FOR TIN WILL NOT DIFFERENTIATE BETWEEN A WOLFRAMITE-RICH AND A WOLFRAMITE-POOR VEIN AT PANASQUEIRA.
ARSENIC (ppm)
ZONE OF HIGH W VALUES
SAMPLE POINTS L1 - P6 - X5 - D3W - R7 - AW16
RICH ZONE
SAMPLE POINTS L1 - P4 - X5 - D3W - AW17
POOR ZONE
THE ARSENIC CONTENT OF CLEAN VEIN QUARTZ
INTERVAL : 9 M
ANALYSIS : MODIFIED GUTZEIT METHOD
CONCLUSION : NO RELATIONSHIP EXISTS BETWEEN THE W POTENTIAL OF A GIVEN VEIN AND THE ARSENIC CONTENT OF THE "CLEAN" QUARTZ OF THE VEIN. HOWEVER, IN W-RICH VEINS, THE As AND W CONTENTS OF THE "CLEAN" QUARTZ VARY SYMPATHETICALLY, IN A BROAD WAY, AND TO A LESSER DEGREE Sn ALSO FOLLOWS THIS PATTERN.
A PRELIMINARY STUDY OF THE TUNGSTEN, TIN AND ARSENIC CONTENT OF SAMPLES OF "CLEAN" QUARTZ FROM A WOLFRAM-RICH AND A WOLFRAM-BARREN VEIN AT BERALT MINE, PANASQUEIRA, PORTUGAL.
(K. F. G. Hosking, Feb., 1965.)

Fig. 17



THE RESULTS OF THE SEMI-QUANTITATIVE, COLORIMETRIC ANALYSES OF SLUDGE SAMPLES OBTAINED BY LONG-HOLE RING DRILLING IN AN AREA CONTAINING A PLEXUS OF WOLFRAMITE/ARSENOPYRITE VEINS AND CASSITERITE VEINS, SOUTH CROFTY MINE, CORNWALL

(Hosking, K.F.G. and Burn, R. unpublished studies, 1962.)

Fig. 18

particular, the tungsten productive/tungsten barren granite problem needs further study, as does the behaviour of tungsten minerals in the superficial environment.

Finally, in his various discussions regarding the various aspects of prospecting for tungsten deposits the writer has not considered the rôles played by the "not so technical' human beings. Perhaps this was a mistake, particularly as the three most exciting tungsten discoveries which have been made in recent years in South-east Asia (at Weng Papas and near Nakhan Sithammarat, in Thailand, and a little to the west of Gambang, in West Malaysia) have been made, not by professional geologists and others employing sophisticated techniques, but by villagers and local, untrained miners capable of much walking, good observation, and the employment of the simplest confirmatory tests, who were motivated by the wish to make money much more quickly than their normal and legal occupations would permit them to do.

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