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Tin: A mantle or crustal source?

CHARLES S. HUTCHISON[1] and K.R. CHAKRABORTY[1]

Abstract: The recent theories that propose the mantle or the subducted oceanic lithosphere as the immediate source for tin are reviewed and rejected on the grounds of compelling evidence that continental crust is a necessary requirement for economic tin concentration. Continental crust becomes progressively differentiated with respect to tin by polycyclic events involving metamorphism, anatexis, and related processes. As a result the dis-distribution of tin becomes strongly irregular.

Partial melting only of the tin-enriched zones would yield tin-bearing granitic magma; the tin concentration being dependent mainly on the degree of melting, the liquid-solid partition coefficient of tin and the behaviour of tin-containing silicate and oxide phases during melting. The crystallization history of such tin-bearing magma would ultimately determine the possibility of economic tin deposits. Tectonic settings do not play any role in the generation of tin-bearing magma other than controlling the physical conditions of melting.

INTRODUCTION

Primary tin deposits, irrespective of age, are overwhelmingly associated with acid igneous or quartz-rich hydrothermal rocks. Precambrian deposits are predominantly in pegmatites, Palaeozoic and Mesozoic predominantly in the roof zones of granites, while Cenozoic deposits may occur in hydrothermal veins and breccias within volcanic rocks. Tin concentration is therefore not confined to any one tectonic level. Presently mined deposits are mostly of Mesozoic age with Palaeozoic a close second. This pattern of distribution was attributed by Schuiling (1967 a, b) to level of erosion.

Tin mineralization is widely known to be genetically related to granite. Since experimental and field studies point to anatexis of sialic crust as the origin of granitic melts, the continental crust may logically be assumed to be the immediate source of tin. Before the advent of plate tectonics, this was generally unquestioned.

In recent years, however, several suggestions regarding a non-crustal source for tin have been proposed. In particular the occurrences of Cu, Pb and Zn, currently believed to be cogenetic with subduction related magmas, led to the suggestion that other metals such as Sn might have a similar origin direct from the subducted lithosphere or from the mantle (Sillitoe, 1972; Pearce and Gale, 1977). Studies in the Andean volcano-plutonic arc have provided apparent support for this belief (Grant et. al., 1977). However, there are inherent difficulties, as will be elaborated below, in these recently proposed genetic models of tin from a noncrustal source. These models are linked to the tectonic settings and will be discussed separately.

NON-CRUSTAL GENETIC MODELS

(a) Tin in Orogenic Settings

Two models have been proposed for the introduction of tin:

(i) Sn is cogenetic with K_2O-rich magma derived from subducted oceanic lithosphere at deep levels in a Benioff Zone (Sillitoe, 1972). Diagrammatically this model is illustrated in Figure 1.

[1]Department of Geology, University of Malaya, Kuala Lumpur 22–11, Malaysia.

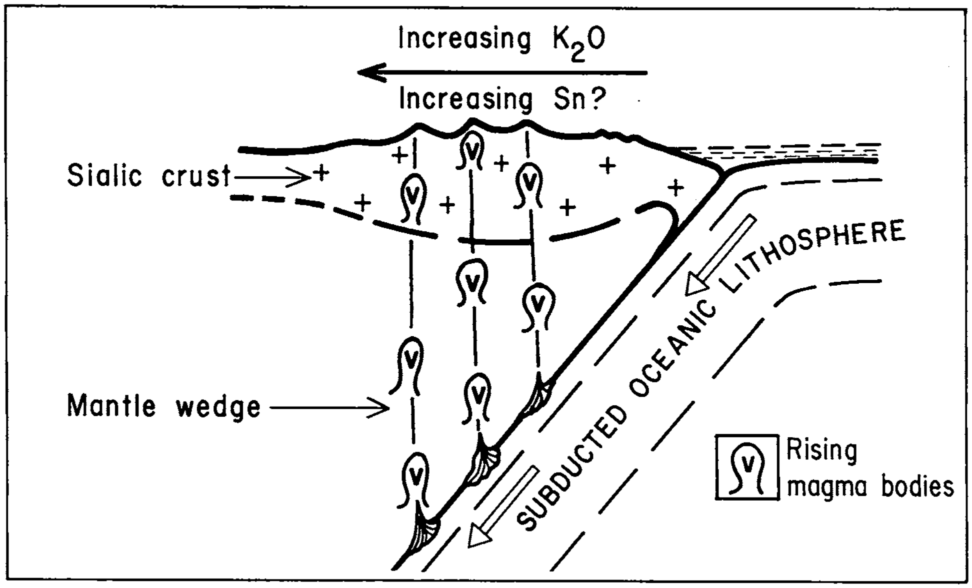

Fig. 1. Subducted lithosphere source model. Sn-bearing magma formed by partial melting of the subducted oceanic lithosphere moves upwards into the crust. Sn comes from the subducted lithosphere.

(ii) Volatiles released from the subducted lithosphere, or the magmas derived therefrom, scavenge tin together with other incompatible elements from the mantle wedge overlying the Benioff Zone as they ascend upwards to the volcano-plutonic arc (Grant et al., 1977). This model is diagrammatically illustrated in Figure 2. It has been proposed that tin-rich zones in the upper mantle or lower crust may result from this process (Pearce and Gale, 1977).

The model of Sillitoe (1972) was fundamentally based on metal zonation in the Andes. However, this zonation is not as clearly defined as the zonation of the tholeiite—calc-alkaline—high-K calc-alkaline—shoshonite series across the volcanic arc. Apparent zonations of Sn-W and Cu-Zn-Pb are on the whole not coeval (Clark et al., 1976).

If tin is cogenetic with subduction related magmas, then the potentiality of the subducted lithosphere as an immediate source of tin can be evaluated by the tin contents of orogenic rock suites. Such suites from Fiji, Saipan and Bougainville, whether tholeiitic, calc-alkaline, high-K calc-alkaline or shoshonitic, are not known to have tin contents exceeding 3 ppm. (Table 1). This low level explains the absence of tin deposits in oceanic island arcs. Higher tin contents up to 7 ppm. in pantellerites from New Zealand (Ewart et. al., 1968 a, b) probably reflect the existence of continental crust in New Zealand. Purely ensimatic island arcs are characterized by extremely low tin contents and a complete absence of economic concentrations.

The scavenging hypothesis was originally introduced to explain the increase of K, Rb and similar elements across a volcanic arc (Ninkovich and Hays, 1972; Best, 1975) and later adapted by Grant et. al (1977) for Sn. Although several objections can

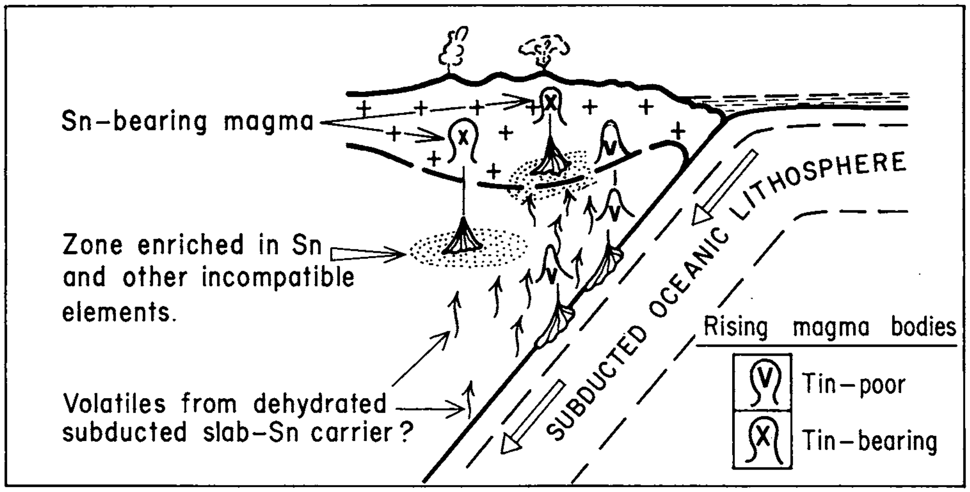

Fig. 2. The scavenging model. Rising volatiles from the dehydrated subducted slab gather Sn from the overlying mantle wedge and form tin-enriched zones either in the mantle or near the mantle-crust boundary. Melting of such tin-enriched zones produces tin-bearing magma. Also, magma derived from the subducted lithosphere can scavenge Sn from the mantle wedge.

be raised against the scavenging hypothesis (see, for example, Beswick, 1976), in its explanations of the K_2O variation it is equally applicable in all volcanic arcs whether oceanic or continental margin. But it fails for Sn in oceanic island arcs inasmuch as there is no systematic increase in Sn with K (Table 1). In Fiji, for example, the tholeiites contain up to 3 ppm, while the shoshonites contain only up to 1.6 ppm. It appears therefore that if scavenging is a viable mechanism, then the mantle wedge is an insufficient source of Sn, otherwise there would be economic tin concentrations in purely ensimatic island arcs. The tin deposits of the Japanese island arcs (Oba and Miyahisa, 1977) reflect the fact that the basement of Japan is continental and includes Precambrian rocks (Minato, 1968).

TABLE 1: TIN CONTENTS OF ISLAND ARC ROCK SUITES

Rock Suite	Sn in ppm
Island Arc Tholeiite	0.78 to 2.9
Island Arc Calcalkaline	0.29 to 0.82
High-K Calcalkaline	0.36 to 2.3
Shoshonite	0.97 to 1.97
New Zealand rhyolite-dacite-basalt	0.33 to 1.65
New Zealand pantellerites	1.35 to 7.20

Data from Gill (1970), Taylor et al (1969), Ewart et al (1968a, b), Peccerillo and Taylor (1976).

Tin is concentrated only in those volcano-plutonic arcs which have developed on continental margins or on rifted continental fragments. The absence of tin deposits from wholly ensimatic arcs makes it impossible to accept either of the subduction related processes which are proposed to generate the tin from either the subducted oceanic lithosphere or the overlying mantle. However, scavenging as a modified hypothesis may still qualify as a concentrating mechanism. But such scavenging cannot be of the mantle wedge but rather of the overlying continental crust.

(b) Tin in Anorogenic Settings

Tin deposits of Nigeria and Rhondonia in Brazil are anorogenic and are considered to be related to intra-plate magmatism. Sillitoe (1974) suggested that tin-bearing granites of Nigeria and Brazil might have been directly derived from the mantle. But Sr and Pb isotopic data strongly suggest that Nigerian tin-granites are of crustal origin (Bowden, 1970; Bowden and van Breemen, 1970). Of particular interest is Bowden's (1970) Pb isotope studies, based on which he has concluded that Jurassic granites with 'old lead ages' cannot have differentiated from the upper mantle, but have originated from fusion of mineralized crustal rocks. It should also be pointed out that Alexiev (1970) and Bowden and Turner (1974) have postulated, on the basis of rare earth characteristics and petrographic evidence, that the tin concentration in Nigerian granites is perhaps related to postmagmatic albitization. Available relevant data thus do not lend support to Sillitoe's belief.

The Pan African and other Precambrian pegmatites widely contain significant amounts of cassiterite. It is reasonable therefore to assume that mantle hot spot activity in Nigeria and Brazil, and in other comparable settings, caused melting of the pegmatitic or granitic tin-enriched crust to produce the younger tin granites.

Pearce and Gale (1977) have expressed the view that a part of the mantle becomes enriched in Sn and other incompatible elements by various mechanisms and on subsequent melting generates tin-bearing magma (Fig. 2). An alternative suggestion given by them is that Sn-bearing fluids derived from such magmas enrich the base of the sialic crust, which then undergoes partial melting. Between these two, the latter seems more acceptable as it is capable of explaining the universal occurrence of tin exclusively in acidic rocks. Their postulated models are applicable to both orogenic and nonorogenic settings.

Implicit in most of the suggested noncrustal genetic models is the assumption that tin-bearing granitic magmas are derived either by fractional crystallization of basic magmas or by direct melting of the mantle or the subducted oceanic lithosphere. On volume consideration alone, the fractional crystallization mechanism can be discounted; and melting experiments of probable mantle materials preclude any possibility of generating significant amounts of granitic liquids (Nicholls and Ringwood, 1973). In orogenic settings, although a small degree of partial melting of amphibolite or hydrous quartz eclogite (metamorphosed subducted oceanic crust) under appropriate P-T conditions, may yield acidic magma (Holloway and Burnham, 1972; Green, 1972; Green and Ringwood, 1972), it is extremely unlikely, as pointed out by Ringwood (1974), that this liquid can reach the surface through the overlying mantle wedge. It is thus difficult to understand how the noncrustal genetic models can explain the occurrence of tin deposits in acidic rocks.

SIALIC CRUST AS A TIN SOURCE AND GENERATION OF TIN-BEARING MAGMA

In the light of the above discussions, it is apparent that the suggested noncrustal genetic models for Sn are not only unsatisfactory but also cannot be reconciled with the factual data. On the other hand, the sialic crust as an immediate source for tin does not pose any serious problem. Anatexis of sialic crust is capable of yielding highly evolved SiO_2 and K_2O rich granites with which tin deposits are known to be associated. The fact that all granites of crustal origin are not tin-bearing suggests that the abundance of tin in crustal rocks is variable, due perhaps to highly irregular distribution of tin-containing silicate and oxide phases such as biotite, hornblende, sphene, magnetite and ilmenite. From the few available Sn-analyses of these minerals (Table 2),

TABLE 2

TIN CONTENTS OF BIOTITE, HORNBLENDE AND SPHENE

	Sphene	Biotite*	Hornblende*	Biotite
Sn-bearing 'granite'	120–475	4–10	trace-10	30–390
Sn-poor 'granite'	—	—	—	Trace-70

All values in ppm. *Biotite and hornblende coexist with sphene.
Data from Petrova and Legeydo (1965), Schuiling (1967b), Dodge et al (1969).

it appears that sphene is the best carrier of tin and commonly may contain up to 500 ppm. The solubility of Sn in sphene increases with temperature as it becomes isostructural with malayaite (Higgins and Ribbe, 1977). The behaviour of these phases during crustal melting, and the degree of melting coupled with the constraints imposed by the liquid-solid partition coefficient of Sn, would largely determine the tin content of the magma.

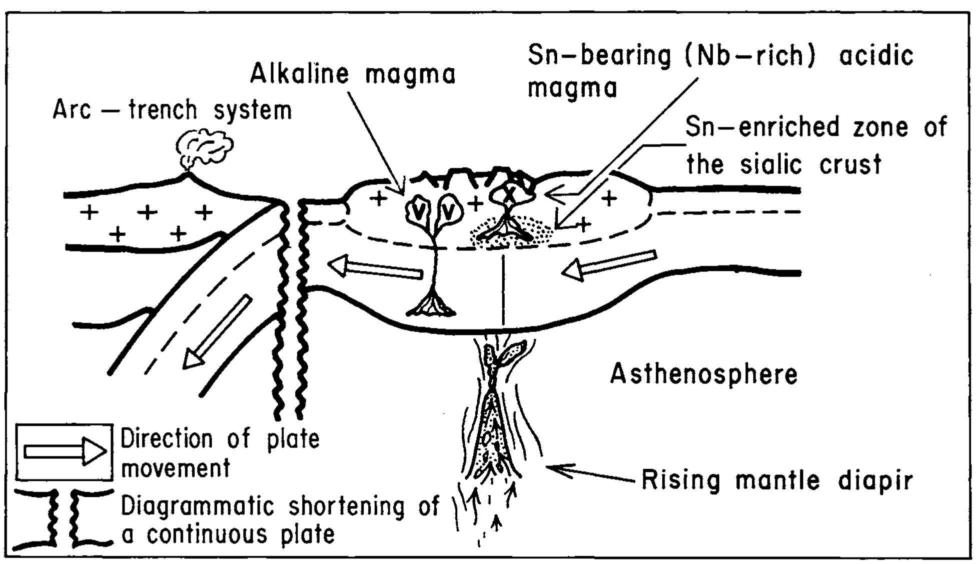

Fig. 3. Tin in non-orogenic setting. Continental crust becomes highly differentiated with respect to tin by polycyclic events and tin-enriched zones develop. Melting of such tin-enriched zones due to mantle diapirism or 'hot spot' activity produces tin-bearing granitic magma. Possible example is Nigeria.

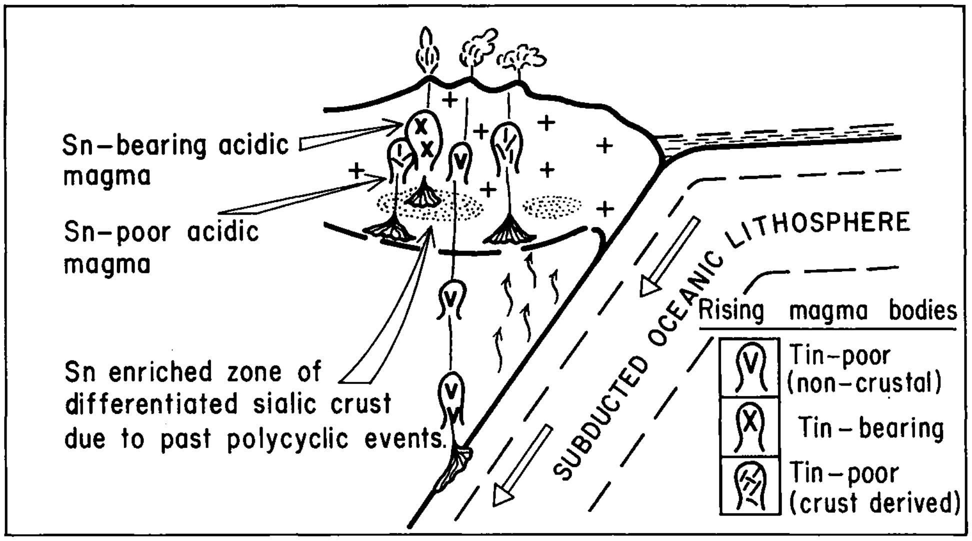

Fig. 4. Tin deposits in cordilleran-type orogenic setting. Melting of tin-enriched zone in the sialic crust, due to rising isotherms (heat transfer by volatiles) and/or depression of the solidus through hydration, produces tin-bearing granitic magma.

Tin-rich granite is likely to be the result of multi-stage processes; the final stage being the remelting or reactivation of the tin-enriched part of the sialic crust. The existence of or the gradual development of tin-enriched zones in the continental crust by polycyclic events involving such processes as metamorphism and anatexis, is, in our view, an essential prerequisite for the generation of tin-bearing granite magmas. To a certain extent, mantle contribution in the enrichment process is also quite likely. Ewart et. al. (1977) have also expressed similar views concerning the necessity of pre-concentrating tin and other elements in the crust.

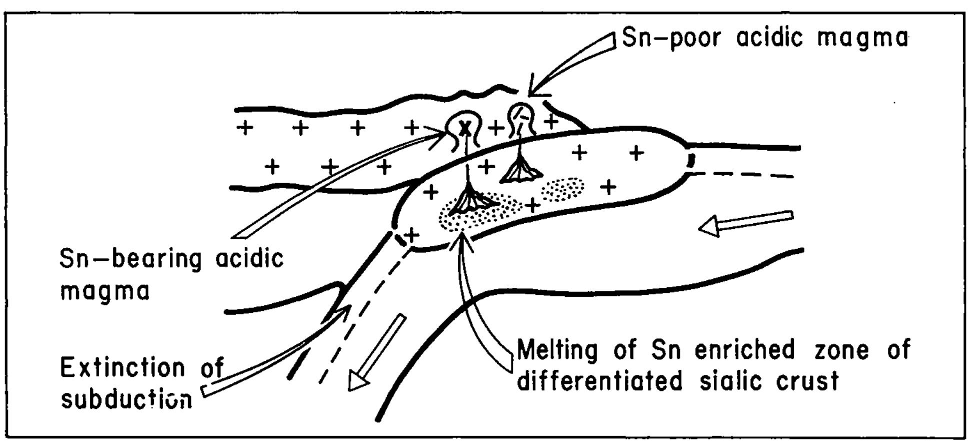

Fig. 5. Tin deposits in collision-type orogenic setting. Melting of the tin-enriched zone in the underthrust continental plate may ensue due to crustal thickening.

There is no spatial or temporal restriction on the generation of tin-bearing granitic magma. Whenever the tin-enriched crust is involved in melting, tin-bearing magma may form. Association of Sn-bearing and Sn-poor granites, both related in time and space, is thus not unlikely and is easily explicable. Tectonic settings do not have any direct bearing on the generation of tin-bearing granitic magmas. They merely control the physical conditions necessary for melting as diagrammatically shown in Fi-

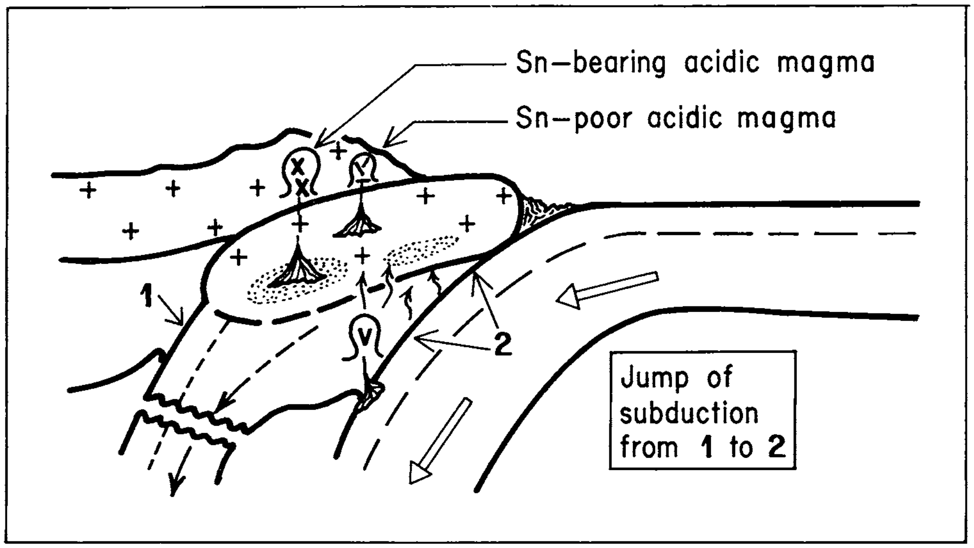

Fig. 6. Tin deposits in complex orogenic setting (combined cordilleran and collision types). Melting of the continental crust may occur due to thickening and other subduction related processes. Temporal and spatial association of tin-bearing and tin-poor granites may result through melting of contiguous tin-enriched and tin-depleted zones in the crust.

gures 3–6. Figure 3 depicts a nonorogenic situation where Sn-enriched crust melts as it passes over a 'hot spot'. Figures 4–6 represent a few possible situations in orogenic settings (cordilleran and collision types). Depending on the particular situation, a Sn-enriched zone, if involved, may melt due to a combination of several factors including crustal thickening, temperature increase, and depression of melting temperature.

CONCLUSIONS

Attention is drawn to the very low abundance of Sn in the basaltic suites as well as ensimatic island arc suites, even for the differentiated rock types. It is obvious that Sn cannot be sufficiently concentrated by simple single-stage fractional crystallization processes to economic concentrations, at least from magmas derived from oceanic lithosphere or mantle. Consequently, they cannot be responsible for the tin deposits in the continental crust. We therefore accept the view that the continental crust is the immediate source of tin, and propose the following sequential events for tin concentration.

1. Continental crust becomes progressively differentiated with respect to tin by polycyclic events and thus develops a strong irregularity in its distribution.

2. Partial melting only of the tin enriched zones yields tin-bearing granitic magma. The concentration of tin in the magma would depend primarily on (a) the degree of melting, (b) the physical conditions of melting, (c) the behaviour of tin-containing silicate and oxide phases during melting and (d) liquid-solid partition coefficient of Sn.

3. Through crystallization differentiation, tin-bearing magma produces a volatile enriched residuum that eventually forms pegmatitic or hydrothermal primary tin deposits.

4. The crystallization history of tin-bearing magma would ultimately determine the possibility of economic tin deposits. Early precipitation of a phase (or phases) having a high (>1) crystal-liquid partition coefficient would be unfavourable for economic tin deposits. The occurrence of cassiterite in ilmenite-granite (Ishihara et. al, in 1979; Hutchison and Taylor, 1978) and its absence in magnetite-sphene-granite (Ishihara et. al, in 1979) may perhaps be cited as an example. These two types possibly have different crystallization histories under different oxygen fugacity condition.

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