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The major controls of tin mineralisation in the Bushveld Igneous Complex, South Africa

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Abstract: Six tin-fields are recognised within the granitic hub of the Bushveld Igneous Complex. The cassiterite deposits occur as endogranitic pipes and primary disseminations, or as exogranitic fissure veins, fault-breccias or replacement bodies. The Bushveld granites are typically anorogenic and consist, in part, of a crudely stratiform sheet roughly 2800 m thick. Their age is approximately 1950 m.y. They display gross chemical and mineralogical homogeneity and in some localities related stocks and plugs of younger granite intrude into the stratiform phase. In each tin-field the ore is related directly or indirectly to the younger granite(s).

Within the Bushveld Igneous Complex, in particular, and in the Transvaal in general, all known deposits of fluorspar are confined within distinct regional linear zones that demonstrably reflect fundamental lithostructural and tectonic units in the underlying basement rocks, which are related directly to the tectonic framework of the Kaapvaal Craton. Six fluorine-enriched zones are recognised and it is highly significant that it is within the four of these zones which traverse across the body of the Complex that all the deposits of tin ore in the Bushveld are found. The fluorine-rich zones trend east-north-east or north-north-west. They are individually up to 650 km in length and 30 km wide.

Deposits of sedimentary fluorite in the Lower Proterozoic "Transvaal dolomite" which underlies the Complex, and the setting of the mineralized locality at the western end of a very major palaeotectonic trough which defines the axis of sedimentation of the dolomite group in the Transvaal, and which also corresponds exactly with the most prominent of the recognised zones (Murchison Zone), proves that linear zones of enrichment with fluorine of the present floor-rocks of the Complex existed in these rocks prior to the intrusion of the Bushveld Igneous Complex.

It is generally considered that the main Bushveld granites arose from the partial melting of sialic crustal rocks, that is, the basement rocks below the Complex, after depression of the floor of the Transvaal basin following the deposition of nearly 11 km of sediments. Because fluorine behaves as a flux, it is suggested that following this depression anatexis took place in and around the fluorine-enriched zones in the basement, at low temperatures, selectively, and in localised spots, relative to surrounding areas in which the strong fluxing action of fluorine was lacking. These fluxed-magmas were highly volatile and became enriched with tin and other trace metals by the process of "volatile stripping". These granites were emplaced within and near their zones of origin on the highly stable craton, and endogranitic and exogranitic tin mineralisation was a consequence of their exceptional volatility and fractionation. This hypothesis explains the undeniable geographic coincidence of the late stage "tin-granites" within the flourine-enriched linear zones and also indicates that the association is a genetic one.

Cassiterite deposits in the Bushveld Igneous Complex are therefore related to late-stage granite intrusions derived from anatexis that was brought about by the selective "fluorine-fluxing" of sialic crustal rocks in fluorine-rich loci within ancient, long-lived, linear tectonic zones in the craton. These ancestral zones are today mirrored on the surface by the linear distribution of fluorspar deposits, by the high fluorine content of groundwater, and by other, non-granitic, intrusions. The knowledge should be applied during future exploration.

INTRODUCTION

The Bushveld Igneous Complex is situated almost centrally within the Transvaal province of the Republic of South Africa and it lies wholly within the confines of the ancient anorogenic environment of the Kaapvaal Craton (fig. 1). Having an area

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of more than 67000 sq km it is by far the largest layered intrusion yet known. The Complex, excluding related satellite bodies, has a roughly cruciform outline and consists of four lobes arranged symmetrically about two axes, each 350 km long, which are aligned roughly ENE and NNW (Hunter, 1975). The Complex consists of a layered mafic and ultramafic phase which underlies and surrounds the later felsic phase. The last-mentioned comprises roughly 2800m of crudely layered granites and related rocks. The sheeted Complex was apparently emplaced beneath a roof of Lower Proterozoic sediments and felsitic volcanic rocks at least 1950 m.y. ago, and the tin mineralisation, which is related to the granitic rocks of the Complex, is of an equivalent age.

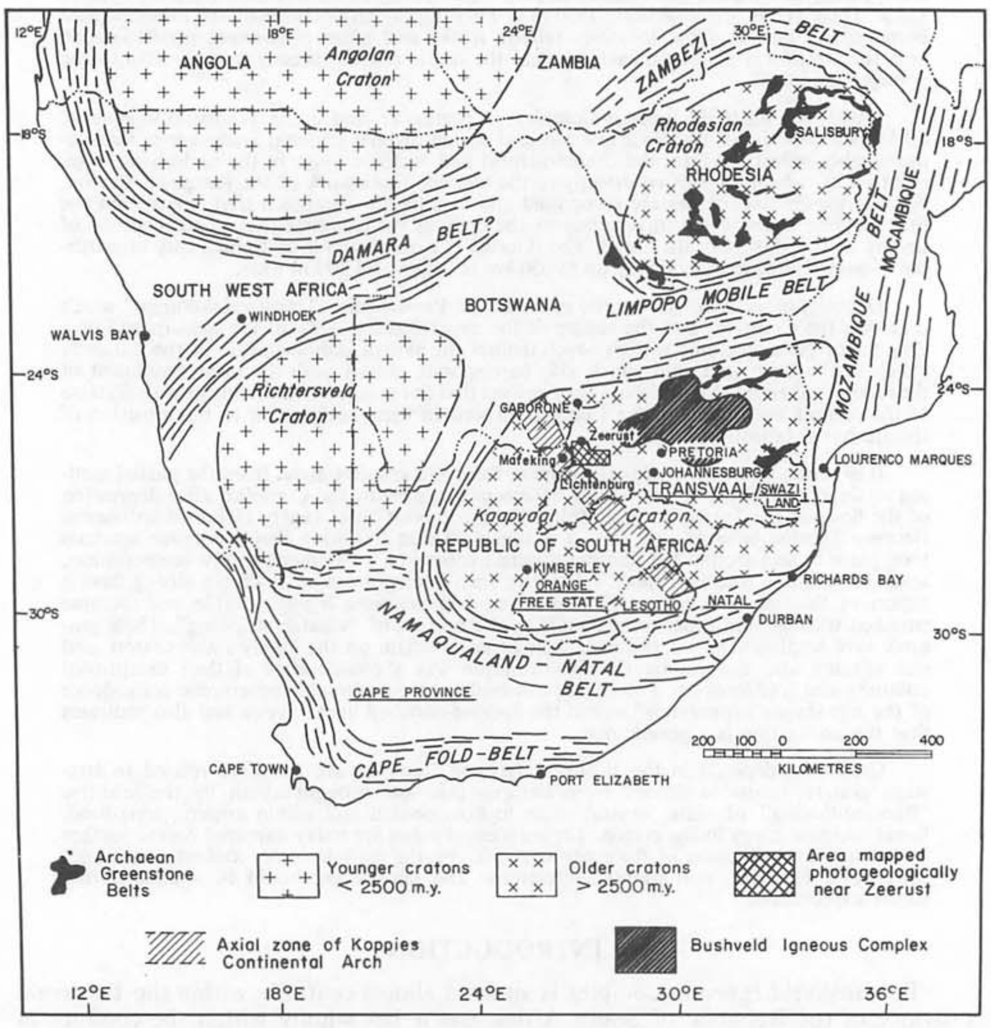

Fig. 1. Generalised geotectonic map of Southern Africa showing the approximate location of the Bushveld Igneous Complex on the Kaapvaal Craton, and the axis of the "Koppies Continental Arch". (The axial zone of the continental arch is after Pretorius, 1974, figures 1 and 4, and Hunter, 1974, figure 2).

Six tin-fields are recognised (fig. 2). Since the inception of serious mining in about 1905 the combined yield has been nearly 90000 tons of metallic tin from about 134000 tons of cassiterite concentrate (van Gruenewaldt, 1977). Three of the fields (numbered 2, 3 and 6 in fig. 2) are presently non-productive. The Nylstroom field is a minor contributor, and the active Rooiberg and Potgietersrus fields have contributed more than 85 per cent of the total production. The production of alluvial concentrate has never been of significance. No tin minerals other than cassiterite are, or have been, exploited. All of the ore is produced from underground mining.

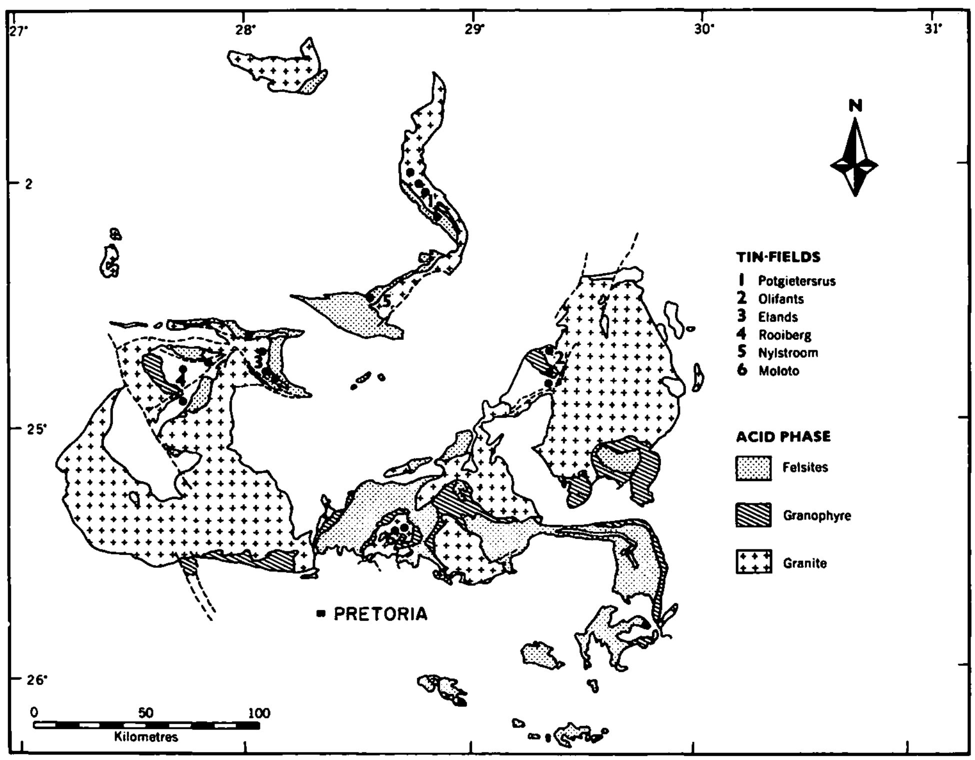

Fig. 2. Active and dormant tin-fields in the Bushveld Igneous Complex. (After Hunter, 1973, from unpublished map by D.H. Lenthall).

TIN-ORE DEPOSITS IN THE BUSHVELD

Table 1 summarises the types of cassiterite ore-deposits in each of the recognised tin-fields. The main source of the data is the 1976 edition of *Mineral Resources of the Republic of South Africa*. The mineralisation in each instance has been, and is, ascribed to the Bobbejaankop granite—a late-stage, volatile-rich and highly fractionated rock—or its equivalents. At Zaaiplaats Mine the mainstay of the important Potgietersrus tin-field, the main source of ore is the Bobbejaankop granite itself, in which cassiterite is a primary accessory mineral of the granite in the area concerned. In the three mines constituting the Rooiberg tin-field, 180 sq km in extent, epigenetic cassiterite exists in a complex series of replacement and fracture lodes related to the footwall zones of thrust faults within the shallow-dipping folded quartzitic roof-rocks of the Bushveld granite, beneath a persistent shale horizon which was impervious to the mineralising solutions. In the other active, but subordinate, tin-field (Nylstroom field) the Union Tin Mine produces very fine-grained cassiterite from replacement lodes along semi-concordant and discordant fissures in or near to the Union Tin shale formation which comprises a thin horizon of shales and argillaceous quartzites interbedded in a thick sequence of felsites. This regular suite of dense and fine grained acid lava and interbedded acid volcanic breccias is known as the Rooiberg felsites from the type locality. The Rooiberg felsites are older than the Bushveld granites and they formed the immediate roof of the composite intrusive granitic mass over large areas.

TABLE 1

IMPORTANT ORE-TYPES IN THE TRANSVAAL TIN-FIELDS

Ore-type	Tin-field					
	ROOIBERG Rooiberg A, B and C Mines	POTGIETERSRUS Zaaiplaats Mine	NYLSTROOM Union Tin Mines	ELANDS (defunct)	OLIFANTS (defunct)	MOLOTO (defunct)
1. Syngenetic deposits in younger granite						
—Cassiterite-bearing pipes		x		x	x	
—Pegmatitic bodies		x		x	x	
—Primary low grade disseminations		X				
—Greisen deposits						x
2. Epigenetic deposits in granite or roof rocks (granophyre; felsite; Transvaal Supergroup quartzites)						
—Vertical fissures and quartz veins				x	x	x
—Concordant fissures		x	X	x		
—"Pipes", breccia bodies					x	
—Stockwork replacements and fracture-lode filling	X				x	

Note: In the defunct fields no indication is given of the relative important of the ore-types. In the active field: the large symbols indicate which ore-type is of major importance at the present time.

TECTONIC CONTROLS OF INTRUSION AND MINERALISATION IN THE BUSHVELD IGNEOUS COMPLEX

General

The manner and the controls of the emplacement of the Bushveld Igneous Complex have been debated for many years. Dominant tectonic trends or lineaments have been suggested to exist, or inferred to be present, to support the various theories of numerous workers. From the time of Hall's (1932) masterly monograph on the Complex, there has been widespread belief in, and some stress on, the existence of certain preferred tectonic "lines" or "directions" in the older rocks of the craton around the Complex, and to some extent within the intrusive mass itself. The three tectonic directions that received early prominence in matters relating to the tectonic setting of the Bushveld Igneous Complex were the Murchison direction (ENE-WSW), the Franspoort direction (NNW-SSE), and the Great Dyke direction (NNE-SSW). The first-mentioned derives its name from the so-called "Murchison line" (Hall, 1932) which is the direction of alignment of the tectonic and structural fabric in the linear Archaean greenstone remnant which constitutes the Murchison mountain range in the north-eastern part of the Transvaal (fig. 3). The Franspoort direction corresponds with that

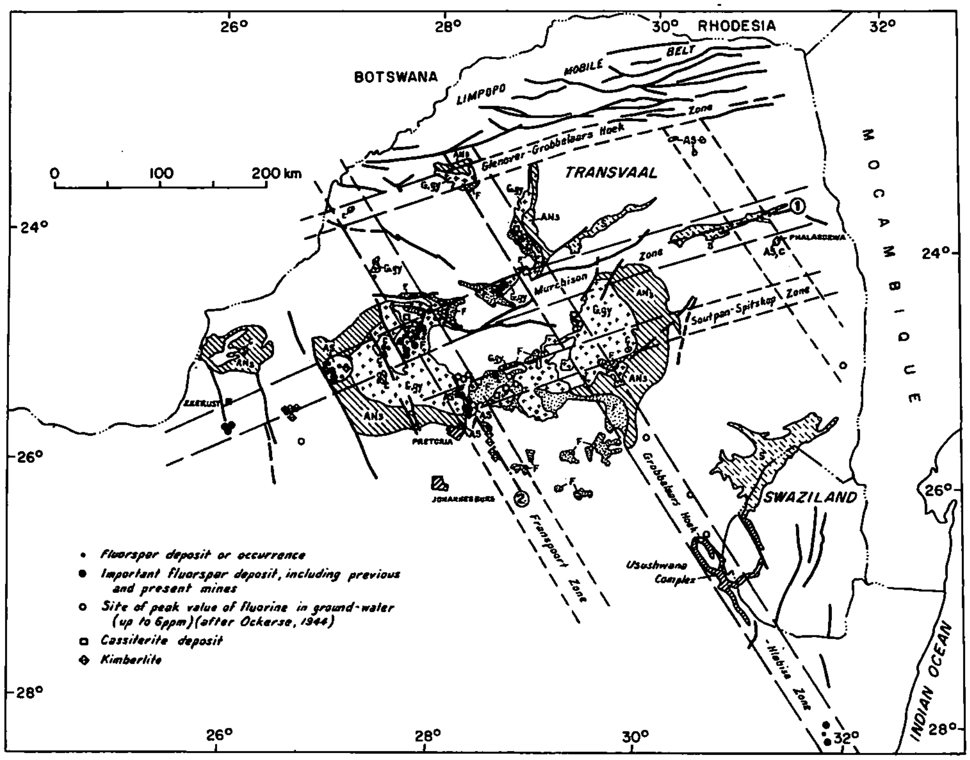

Fig. 3. The distribution of tin-deposits in the Bushveld Igneous Complex in relation to major linear zones of fluorine-enrichment on the craton. Letter-symbols are as follows: AN-3 mafic and ultramafic rocks; G, gy—granite and granophyre; F—Rooiberg felsite; AS—alkaline igneous intrusion; c—carbonitite; S—Archaean greenstone belt or schist remnant. The figures 1 and 2 in the illustration respectively indicate the Murchison and Franspoort "lines", noted by early workers.

of the so-called "Franspoort line" of alkalic intrusions (Shand, 1923) which exist within the southern part of the Complex immediately north-east of the city of Pretoria. The third of the early-acknowledged directions, which were recognised on account of supposed affiliation with important tectonic trends, corresponds with the direction of strike of the north-north-easterly-trending Great Dyke, a very major, linear, dyke-like mafic and ultramafic complex some 500 km in length which exists hundreds of kilometres to the north, in Rhodesia. (Worst, 1960).

Structural, sedimentological, geophysical and conceptual evidence of the tectonic importance of the ENE or NNW directions in the Transvaal has been noted frequently in the last twenty years or so, and increasingly in recent times; for example by Kent (1957), Vermaak (1970), Crockett (1971), Button (1973a & b), Hunter (1973a, 1974), Walraven (1974), Jansen (1975) and others. In particular Pretorius (personal communication 1974) demonstrated forcefully the dominance of ENE or NNW trends on the craton by reference to the integrated analysis and interpretation of fundamental geophysical data, including especially gravity data. Similarly, the Great Dyke trend has also been considered to be important by latter-day workers, for example Kent (1957), Cousins (1959), Verwoerd (1967), Darracott (1975), and others.

From the records it is evident that, until recently, the appraisal of the recognised tectonic trends was made in relation to the localisation and the postulated centre(s) of intrusions of the layered Bushveld Igneous Complex itself. Disregarding the pseudostratified ores of chromite, platinum and titaniferous magnetite which are indirectly related to the latter, attempts to relate important tectonic elements to either later mineralised or unmineralised intrusions, or to other primary mineral deposits within the Complex, were lacking until relatively recently. In the former sense Verwoerd (1967, Folder 19) postulated that younger carbonatitic intrusions in the Bushveld were located along an "abyssal fracture". This presumed fundamental zone of weakness in the crust had been invoked by Truter (1955) to have supposedly localised the intrusive centres from which issued the initial magmas which consolidated to form the composite intrusive complex. Later, Ferguson (1973) in discussing the "Pilanesberg alkaline province", which by definition includes the many alkalic intrusions which penetrate the mass of the Bushveld Igneous Complex, downgraded the likelihood of Verwoerd's and Truter's east-westerly trending abyssal fracture. Ferguson apparently favoured the 1400km long NNE-trending "abyssal fracture" that was discussed by Cousins (1959) (Great Dyke direction) but he recognised also a second "abyssal fracture" aligned approximately NW-SE (Ferguson, 1973, fig. 3). The latter effectively corresponds with the alignment of the axis of the Koppies continental arch (fig. 1) to which the Franspoort direction is believed by the present writer to be related (Wilson, 1977), and the observation tends to support previous emphasis regarding that tectonic direction.

Any attempt at the correlation of mineralisation in the *granitic* rocks of the Complex with recognisable discrete tectonic elements was neglected until very recently. No doubt this was partly because of the lack of unanimity which existed regarding the role of various tectonic "directions" and "abyssal fractures" that had been invoked to explain the localisation of either the Bushveld Igneous Complex itself or the alkalic intrusions within and around it.

Hunter and Lenthall (1971) actually compared the tin mineralisation in the Bushveld with the localisation in defined linear belts of the tin-ore deposits in Nigeria, Swaziland, Damaraland, and the Cape granites in the south-west part of the the Cape Province (see fig. 1). They concluded that, relative to the other areas, the tin-ores in the Bushveld Igneous Complex are "more diffusely distributed". The conclusion is interesting particularly as evidence already existed that within particular tin-fields in the Bushveld individual deposits tended to be aligned along certain fairly well defined local linear zones. For example, in the Mutue Fides-Stavoren area (area number 2 in fig. 2) the preferred alignment is NNW, (Wagner, 1921), and tin-bearing pipes at Zaaiplaats (area 1 in fig. 2) suggest a general north-westerly alignment (Sohnge, 1963). In both instances local correspondence with the regional Franspoort direction

(NNW) is sufficiently close to have warranted comment. Moreover the authors were aware of the NNW alignment of the Swaziland Tin-Belt (Hunter and Lenthall, 1971, pp. 15 and 35). Obviously, however, no specific alignments of the various tin-fields (fig. 2) were recognised at this stage, whether in relation to so-called "abyssal fractures" or to one or more of the early-recognised tectonic "directions", noted previously. Hunter and Lenthall (1971) did state, nonetheless, that a case could be made for postulating the overall localisation of the tin-fields in the Bushveld "along the flanks of the graben-like structure in which the Karroo sequence is preserved, or alternatively along north-west trending directions".

Later, Hunter (1973b) supplemented the viewpoint and drew attention to the fact that the six tin-fields in the Bushveld are located within the (general) area of intersection of what he called the "felsite belt"—an expanse of Rooiberg felsite 150km wide which trends in the NNW direction (Hunter, 1973b, fig. 6)—and the "Murchison belt", which he illustrated as a 60km-wide tract of country which is coaxial with the Murchison line, mentioned previously. The area which he defined, however, is very large, about twenty-five thousand (25,000) square kilometres, and the observation although valid in broadest tectonic terms has limited value for the explorationist. The "felsite belt" and the previously mentioned "graben-like structure" are obviously one and the same, as may be seen on reference to the current Geological map of the Republic of South Africa (Scale 1:1 000 000), so it is evident that the specific relationship which does in fact exist between individual tin-fields and discrete narrow linear zones in the Complex (see later) was not understood at that time. Nevertheless both Pretorius and Hunter shortly afterwards separately confirmed the dominance of two major tectonic trends (effectively the Murchison and Franspoort directions) when detailing, respectively, the crustal development (Hunter, 1974) and the crustal "architecture" (Pretorius, personal communication 1974) of this part of Southern Africa. The recognition of the dominance of these tectonic trends resulted from the study of the migration of sedimentary basins across the craton, as well as from analysis of regional geophysical data, noted previously. Pretorius certainly appreciated at this stage that numerous intrusions within the Bushveld Igneous Complex were localised by the ENE and NNW tectonic directions, which he re-named the "Vaal" and the "Orange" trends respectively, from rivers displaying those orientations. It is not known whether Pretorius considered the tin-fields in relation to his trends.

It appears that it was research in relation to fluorspar deposits in the Bushveld region that provided the first evidence of the existence of a very specific sympathetic pattern of distribution of tin-fields and individual narrow linear tectonic zones in the Bushveld Igneous Complex. In effect the distribution of deposits of fluorspar, and minor occurrences of fluorite in the region proved to be a criterion by which the significance of the long-recognised tectonic "directions" or trends, could be appraised, and specific elements recognised. The work was done by the writer in 1969 and 1970 and was based on the recognition of regional geological relationships by means of detailed photogeological mapping, and formed part of a major program of exploration for fluorspar-ore (Wilson, 1970). The details which follow are expanded for the present purpose only in the context of their relevance to tin-mineralisation in the Bushveld Igneous Complex. Nevertheless, they do possess other significant economic-geological implications.

Tin-fields in relation to Fluorspar Deposits

It is not commonly known that the Transvaal region in and around the Bushveld Igneous Complex probably represents the world's largest repository of fluorspar ores (see Oertel, 1966, and Gossling, 1972). Major deposits exist within the granitic rocks of the Complex; in younger alkalic intrusions within the confines of the Complex; in the Zeerust area on the south-west rim of the Complex within Lower Proterozoic "Transvaal dolomite" which underlies the intrusive mass (see fig. 1); and in the rocks which overlie the Complex, which are both younger and older than the composite intrusion. Very numerous minor fluorspar deposits and occurrences exist, and a total of more than 70 separate mineralised localities is known.

As part of the exploration program, and following a considerable amount of regional photogeological mapping by the writer, the locations of all the known fluorspar deposits (Crocker, 1972) and sites of peak-value of fluorine-in-groundwater in the Transvaal (Ockerse, 1944, Map) were plotted on a geological base. The pattern of distribution was viewed in the light of very definite ENE- and WNW-trending linear structural controls of mineralisation that had been found for the first time, by virtue of the photogeologic over-view, to exist in the lead-, zinc-, and fluorspar-bearing areas south and east of Zeerust (fig. 1), in which the correspondence between the important lineaments and the Murchison and Franspoort directions was recognised (Wilson, 1970, 1977; unpublished). It was observed that all deposits of fluorspar in the Transvaal (including those at Hlabisa in northern Zululand) are confined within long discrete linear zones that are up to 30km in width and up to 650km in length (fig. 3). These zones are aligned in *two* directions in the approximate pattern of quasi-orthogonal rectilinear sets, the respective directions of which are also ENE and NNW. More importantly it was, and is, evident that two of these fluorine-rich zones actually lie on the direct line of prolongation of the fundamental tectonic axes that are represented by the long-recognised Murchison and Franspoort Lines. The other recognised zones are parallel either to the Murchison direction or to the Franspoort direction, and in each zone the affiliation with a fundamental lithotectonic unit in the craton is manifest. For example, figure 3 shows that the Glenover-Grobbelaarshoek Zone is coincident with the zone of transcurrent faulting which defines the southern flank of the Limpopo Mobile Belt, a linear zone of continuous tectonic and thermal instability from early Precambrian until the present (Van Breemen and Dodson, 1972). The Grobbeaarshoek-Hlabisa Zone likewise corresponds with a fundamental tectonic element in the craton. This zone is coaxial with the linear Usushwana Complex of probable age 2750–3000 m.y. and Hunter (1970) has noted that the complex was emplaced in a major graben which trends north-north-west. The two remaining zones require more involved discussion to prove their validity. Such discussion would need to relate to specific photogeological studies, to the alignment of alkaline intrusions and volcanic vents, and to the existence of certain fluorine-rich loci beyond the confines of the Complex like that which is represented by the reserves of phlogopite in the carbonatitic intrusion at Phalaborwa in eastern Transvaal (fig. 3). Such detail is not warranted here, and for the present purposes it may be accepted that the postulation of the existence of each of the six linear zones shown in figure 3 is founded on geological facts, and not only on the recognised alignment of fluorspar deposits. It is relevant that many of the fluorspar deposits are related directly to some of the numerous alkaline intrusions and alkalic complexes in the Bushveld, and that these are all confined within the recognised linear zones.

Russian literature clearly conforms with the premise that fluorspar deposits constitute a specific group of ores which are controlled by zones of so-called "self-activation" and prolonged tectonism, and that they are confined most closely to zones of regional fractures and prolonged regional faulting that are particularly explicit in regions (like the Transvaal) where old crystalline rocks are exposed on the surface

(Scheglov, 1969). The hypothesis corresponds fully with the facts which are known regarding the longevity of the Murchison (tectonic) line and the similarly oriented Limpopo Mobile Belt: and also regarding the continuous tectonic imprint of the so-called "Koppies continental arch" (fig. 1) (Hunter, 1974; Pretorius, 1974) to which the Franspoort line and parallel lithostructural units like the Usushwana graben are considered to be related. (Wilson, 1977, unpublished). It has also been stated in the Russian literature that fluorite deposits are reliable indicators of tectonomagmatic activity, and that their presence in regions where no other signs of tectonomagmatic activity have been detected can be used as an indicator of its probability, and of the probable existence of deposits that are characteristic of tectonomagmatic zones (Scheglov, 1969).

The relevance and applicability of the statement to the fluorine-rich zones in the Bushveld is striking: four of the zones of fluorine enrichment traverse the body of the Bushveld Igneous Complex, and it is an inescapable fact that the six tin-fields are confined within these narrow zones.

In assigning significance to the economic and genetic implications of the last observation it is relevant that the relationship was demonstrated only incidentally, following research on fluorspar deposits, and was not influenced by preconception. It is reasonable to conclude that the tectonomagmatic affiliation of the fluorine-enriched zones, apart from the alkalic (and other mafic and ultramafic) igneous intrusions in the Bushveld, was manifested also in the form of intrusion of late-stage tin-mineralising Bobbejaankop-granite masses (and their equivalents), within the body of main Bushveld granite. Mining statistics and figure 3 show clearly that "tin-granite" in the Bushveld Igneous Complex was *emplaced only within the zones of fluorine enrichment.*

On the basis of recognition of the above relationships the writer proposed and motivated the execution of an analysis of fracture-traces within the granitic rocks of the Complex, (R.F. Loxton, Hunting and Associates, 1971, unpublished). The results have not been made available for publication. However, in a brief reference to the techniques utilised during the fracture-trace analysis, Pretorius and Partridge (1974) record that "mineralisation" was identified in the hand specimens from three of ten areas that were selected for field-investigation following the appraisal of fracture-trace "anomalies".

Implications of the Observations, and the Role of Flourine

Within the individual fluorine-enriched zones in the Bushveld the relative and absolute ages of the actual fluorspar deposits differ greatly. Taken as a whole the ages range from about 2100 m.y. to less than 125 m.y. and in some deposits fluorite is still precipitating (Crocker, 1972). Thus the time span during which every fluorspar deposit in the Transvaal has conformed with the specified ancient linear tectonic zones is very great.

The constancy of the spatial association is explained by the curious geochemical properties of fluorine. It is the most chemically reactive element and it has the property that once it is mobilised from its host-mineral or host-rock it is fixed very rapidly in its new environment (Wedepohl, 1969). Since fluorine can exist in very significant amounts in ubiquitous rock-forming minerals, particularly micas and amphiboles, the tendency towards the very rapid refixation of fluorine is accommodated by the immediate abundance of potentially favourable host-minerals. Therefore a primitive pattern in which the crustal rocks were enriched with fluorine in narrow linear (tectonic) zones could manifest itself throughout time (especially, if the processes were aided by tectonic rejuvenation and related brittle deformation), and would result in the linear distribution of deposits of fluorine-enriched minerals, including fluorspar in particular, which were of vastly different ages and which suffered various modes of formation. Owing to the very limited solubility of fluorspar, once the fluorine that was present in any area had been precipitated as CaF_2 the distribution of deposits of fluorspar would mirror the tectonic zones in which the rocks were originally enriched with fluorine.

The existence of very substantial sedimentary deposits of fluorspar in a mineralised area of nearly 300sq km near Zeerust (fig. 3) in "Transvaal dolomite" which has an age greater than 2000 m.y., and which underlies and is older than the Complex, indicates that the fluorine-enrichment of these rocks was manifest at a very early stage in the history of the craton. Note that the mineralised area coincides with the prolongation of the Murchison tectonic line which is the axis of the Murchison Zone shown in the figure. The observation is significant because it is generally agreed that the various Bushveld granites owe their origin to the partial melting of the sialic basement below the Transvaal Supergroup following the depression of the crust by the accumulation of these Transvaal sediments, which exceeded 11km in thickness (Button, 1973b). It follows from Scheglov's conclusions (see previously), and the aforegoing, that some of the rocks which suffered partial melting would have been relatively rich in flourine in places. It is in this connection that it is important to note a significant property of flourine; that is, *flourine behaves as a strong flux* (Wyllie and Tuttle, 1961, in Wedepohl, 1969). It is suggested, therefore, that those zones in the basement in which the rock contained fluorspar, or minerals which acted as hosts to fluorine, were melted preferentially during anatexis, and were rich in volatile fluorine compounds and highly mobile.

The role of volatile compounds in the transport and concentration of tin is commonly acknowledged. Generally the volatile fraction is not identified. Because of the demonstrated geographic association between the fluorine-rich zones and tin deposits, the Bushveld Igneous Complex represents one environment where it seems reasonable to predict that fluorine compounds constituted the main tin-transporting agents in the volatile rich melts. These melts represent, in fact what might be termed "fluorine-fluxed anatectic magmas". In the Complex the tin-mineralising Bobbejaankop-type granite represents this highly fractionated volatile-rich magma and it is therefore postulated by the writer that the tin-bearing granites in the Bushveld region have a dual dependence on the role of fluorine; firstly in relation to the genesis of the magma by relatively low-temperature anatexis, and secondly, in relation to the volatility and the transport and the concentration of tin. That is, the spatial relationship that exists between the deposits of fluorspar and the tin-mineralising granite in the Bushveld has a very deep, fundamental, genetic basis.

DISCUSSION AND CONCLUSION

The clue to the recognition of the major controls of the distribution of tin-ore deposits in the Bushveld Igneous Complex was provided by analysis of the distribution of fluorine and fluorspar, both in the Bushveld and in the surrounding regions of the craton. Collaboratory evidence provided by alkalic (and other) igneous intrusions and by the fundamental lithostructural elements of the region allowed acceptance of the fact that the fluorine-enriched zones, within which the tin deposits occur, coincide with ancient, long-lived, narrow linear zones of tectonism. Enrichment with flourine was an inherent attribute of the basement rocks in places within these primitive tectonic zones, and the present fluorine-rich zones largely mirror the ancestral ones because of the geochemical properties of fluorine and fluorspar. The tin-ore deposits have a fundamental genetic association *and* a direct spatial association with the flourine-enriched zones through the positive influence of fluorine on the preferential generation of highly volatile magma at relatively low temperatures during the anatexis of sialic basement rocks, to which process the tin-mineralising granite owes its origin. Future tin exploration in the Bushveld, and in similar cratonic environments elsewhere, e.g. India and Brazil, should be guided by recognised linear zones of fluorine-enriched rocks and groundwaters.

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