Ore Controls for the Salau Scheelite Deposit (Ariege, France): Evolution of Ideas and Present State of Knowledge

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Abstract

In the Salau skarn-type scheelite deposit, ore controls are of three kinds: lithologic, structural and mineralogical. Lithologic controls include the proximity of a granodioritic narrow apex, and a special banded formation called 'barrégiennes', composed of thin alternating beds of limestone and shales or sandstone. Structural controls include the folding pattern of barrégiennes, early blastomylonite and two types of faults: f1, the drainage channel of fluids responsible for the main stage of mineralization; f2, a series of reverse faults with individual displacements of 100-m magnitude which delimit the main orebodies. The general pattern of the deposit as a whole is an aureole of orebodies in barrégiennes in or near an f1 fault, around an apophysis of the granite. In the conclusion of this chapter, the predicted (already partly confirmed by drilling) location of new orebodies is deduced.

From a mineralogical standpoint, the Salau skarns can be described as having been developed in a two-stage process: the first stage produced clearly zoned skarn with grossularite and hedenbergite (always on the marble side) and low-grade scheelite; the second stage was cross-cutting in relation to f1 fractures, with almandine-spessartite rich garnet often in direct contact with the marble, and (somewhat later) an abundance of pyrrhotite and high-grade scheelite. The fluids of the first stage come from granite, whereas almandine-spessartite rich garnet is an indicator of the action of a fluid in equilibrium with country rocks (including limestone), and is the best mineralogical guide to high-grade scheelite ore in the Salau mine. The mechanism of precipitation of rich ore is inferred to be an inter-reaction in the later stage of two fluids of contrasting origins (one originating in the granite, the other one circulating in the country rocks). It is shown that the various types of chemical changes observed in rocks (through exchange or precipitation) can be explained by this model.

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In the Appendix an outline of the case history is given, and explained by the successive development of new ideas induced both by the development of ore extraction and by the progress of the scientific analysis of structural setting, mineralogy and petrology.

1 Introduction

The basic method of mining geology is still that of reasoning by analogy and extrapolation, traditionally known as the method of ore controls. Even when geophysical and geochemical methods for prospecting and test drilling are used systematically and extensively, this cannot be done efficiently without some previous idea of the favourable areas, nor can they be interpreted without some basic ideas on the geology. Sufficient knowledge and understanding of the controls can save much time and money. Faulty knowledge may lead to abandonment of deposits because their extensions could not be found in the form of non-outcropping orebodies separated from previously known bodies. It can be assumed that this was the case for a fair number of mines until the 1950s. When metal prices are low, it may be wise to look for extensions of high-grade deposits, which represent large savings on investments and hold promise of finding ore of the same quality as in the bodies first discovered, rather than prospecting other occurrences. However, present methods are based on the recognition of types, although effective, they are not sufficiently fine and selective to guarantee that the potential deposits found will be of an economic grade under present conditions.

Naturally, the method of ore controls no longer amounts to simple reasoning by analogy. There is a fast-growing body of ideas and methods for analyzing geological reality in order to understand how the ore has been deposited, deformed, displaced, etc. Actually, these new methods only serve to provide new ore controls which are more subtle and more precise, but which still hardly ever have an absolute value. However proud we may be of progress in this field, it must be recognized that these methods do not, in general, enable us to definitely determine where we shall find ore, or of what grade it will be. There are at least three reasons for this:

1. Our knowledge of the processes is usually incomplete and our methods of analysis imperfect. Thus, the validity of our extrapolations beyond the ranges observed is not guaranteed.
2. Some processes are of a random nature, for example fracturing phenomena whose frequency is known but only in a statistical sense, arrangement into channels on a more or less horizontal surface (peneplain, delta), etc.
3. Geological phenomena of the most varied kind may be superimposed and occur locally, upsetting a 'law' which was of necessity derived from a limited subset of these phenomena.

As a mine develops, mineralization controls become more accurate. We come to know the limits of their validity, which may be of two kinds:

1. The discovery of other orebodies may often show that a law which appeared general, is not, and that there are other orebodies which are differently located or organized which thus enables other laws to be established (other controls independent of those already known which may be applied in parallel).
2. The systematic study of orebodies located or arranged according to a particular control often produces conditions limiting or specifying their range of application, sometimes throwing the initial formulation into doubt and enabling another to be proposed.

The aim of this chapter is to show how the available ore controls have evolved over time as a mine developed, using as an example the scheelite skarn deposit at Salau (Ariège). This case is interesting for various reasons: firstly, because some of us were able to follow the evolution of ideas over more than 20 years since the discovery of the deposit; and secondly, because this was a difficult case, with rich ore but without continuity or consistent grades; and finally, because in the present state of knowledge, the mine reserves are limited. Under such conditions, it was advisable for us to combine all our ideas on the structure of the deposit and methods of finding extensions. Thus, certain characteristics of the structure, which had not been clear at previous stages, seemed important enough to justify new research in the mine. Actually, it has led to the discovery of a new body of high-grade ore, the dimension of which is still unknown because the mine was closed just at that time due to the present very low price of tungsten and other financial problems. However, it will probably reopen in the future as it is clearly one of the highest grade tungsten deposits known at present and the ore reserves might in fact still be large. We believe that the understanding so acquired of a rich, but very complex, scheelite skarn deposit could also be useful for guiding research on several analogous occurrences presently being studied in France and elsewhere in western Europe.

2 Geological Controls: Exploration for Extensions of the Deposit

2.1 Scheelite Mineralizations

The first scheelite mineralizations of any magnitude found in the Pyrenees were at Costabonne. The grades and reserves of this deposit finally proved to be inadequate after fairly detailed investigation, but attempts were made to use the experience gained to look for other scheelite deposits. Controls were defined by analogy with Costabonne. A search was made for skarn-type deposits developed in Pre-Hercynian limestone or dolomite strata in the neighbourhood of the Hercynian granitic intrusions.

Investigations were made near, but not necessarily at, the contact, since the southern skarn at Costabonne developed on a schist-dolomite contact, while the northern skarn developed on a granite-dolomite contact (Dubru et al., this Vol.)

The Salau deposit was discovered by BRGM (Bureau de Recherhes Géologiques et Minières) in 1960 during these prospections.

NB. *Salau ores are classified hereafter into four types (0, 1, 2, 3), according to their relative size or economic importance. Thus, type 3 ore is the most important, whereas type 0 is very subordinate.*

2.2 Lithological and Petrological Controls: Type 3 Ore

Following the discovery of the mineralizations in the Bois d'Anglade at Salau (Fig. 1), and the first gallery works carried out by BRGM at level 1430 as well as the systematic prospecting of the la Fourque granite contacts, which were carried out simultaneously, it was determined (Autran et al. 1980) that:

1. The first major orebodies (*type 3 ore*) were developed in banded iron-rich skarns derived by metasomatosis of Devonian limestones (known locally as barrégiennes), which are characterized by alternations every 1–10 cm corresponding to varying proportions of sandstone- or shale-type materials and limestone.
2. In these barrégiennes, the skarns were developed at the granite contact. Embayments are structures favouring this development, and in general, contacts where the granite actually cuts across strata were more favourable than subparallel contacts. In particular, these resulted in the development of much thicker skarns (normal contact thickness multiplied by a factor of about 10).

The pure or graphitic limestones overlaying the barrégiennes in the Devonian series at Salau were considered unfavourable, as the skarns developing at contacts between granite and limestones of this type or in veins in it are generally very thin (10 cm to 1 m maximum thickness). Contacts of granite and Devonian limestones are very complex in the upper part of the Ravin de la Fourque (Fig. 5), with apophyses, embayments, etc. These structures are generally considered to favour skarn-type mineralizations. However, at Salau such mineralizations are of secondary or very limited importance. The main explanation for this, following the line of argument developed above, was found in the fact that a fair proportion of these limestones are pure limestones and not barrégiennes.

Another peculiarity of the Salau deposit, as far as it was known at this stage, was the systematic association, without exception, of economic grade scheelite with pyrrhotite. The highest grades often appeared in the limestone contact zone (marble line). Dispersed low-grade scheelite was observed in skarns which had not been invaded by pyrrhotite, but WO_3 contents were not above 0.3–0.4%. The grades associated with pyrrhotite were always from 1% to several percent (type 3 ore), even though massive pyrrhotite could also be barren. All efforts to distinguish barren pyrrhotite from pyrrhotite associated with scheelite, using mineralogical or chemical data or considering the silicate gangue, were in vain. All indications are that the pyrrhotite involved is the same, formed at the same stage of mineralization. The Costabonne occurrence, in which there is no pyrrhotite (and very little pyrite) was, on the whole, poor compared with the Salau deposit, with grades of 0.3–0.4%.

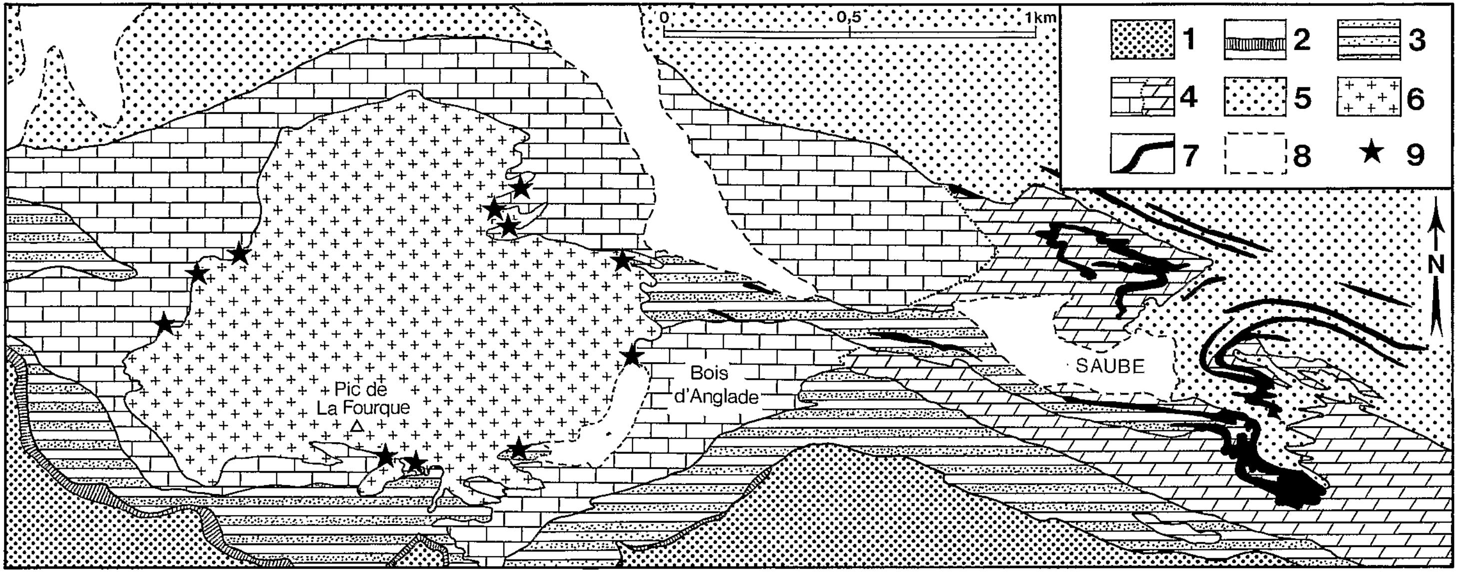

Fig. 1. Geological surroundings and distribution of scheelite occurrences around the la Fourque granitic apex (Derré 1983 and Nansot, unpublished SMA documents). *1* Shale-sandstone series (Ordovician). Salau series (Devonian): *2* crinoidal limestone; *3* Barrégiennes; *4* Salau limestone and dolomite; *5* bluish shale; *6* la Fourque granodioritic apex; *7* microgranite or microgranodiorite sills; *8* quaternary cover; *9* Scheelite occurrences

This gave rise to the idea that the presence of pyrrhotite was an essential factor influencing the value of scheelite skarns in the Pyrenees.

2.3 Controls by the Fold Structure

Since at this stage of investigations, most of the ore and, presumably, the reserves were contained in the barrégiennes, the thickness of which is limited, the fold structure of these and their intersections with the granitic apophyses appeared to be the chief controls for mineralizations in their initial state before they were disturbed by faulting. The broad lines of the fold structure were hard to decipher in the sector where the mine is located. This was due to (1) invasion by the granite; (2) disturbances induced by the mineralization itself and by faulting which was intense at the southern edge of the granite; and (3) the fact that the observable outcrops were limited and barely accessible. The structural study was thus carried out on the eastern side of the valley facing the mine, away from the granite. Kaelin (1982) recognized three main phases of folding, of which the first two are responsible for the overall structural pattern and are more or less coaxial (horizontal E–W), although of contrasting styles: horizontal recumbent folds for phase 1, tight upright folds for phase 2. Phase 3 has a different orientation and plays only a subsidiary role.

The structures unraveled by Kaelin are in the axial extension of those in the mine, of which they provide an understanding. A large antiform of phase 2 or 1 + 2 (Fig. 2) thus explains the overall arrangement of the marbles, barrégiennes and shales as mapped, for example in detail by Derré (1983). The mineralizations are largely distributed in the embayments of barrégiennes in the granite which were folded in stage 2. These embayments are open to the east and west. Their bottom is defined by the intersection of this large, practically cylindrical, horizontal struc-

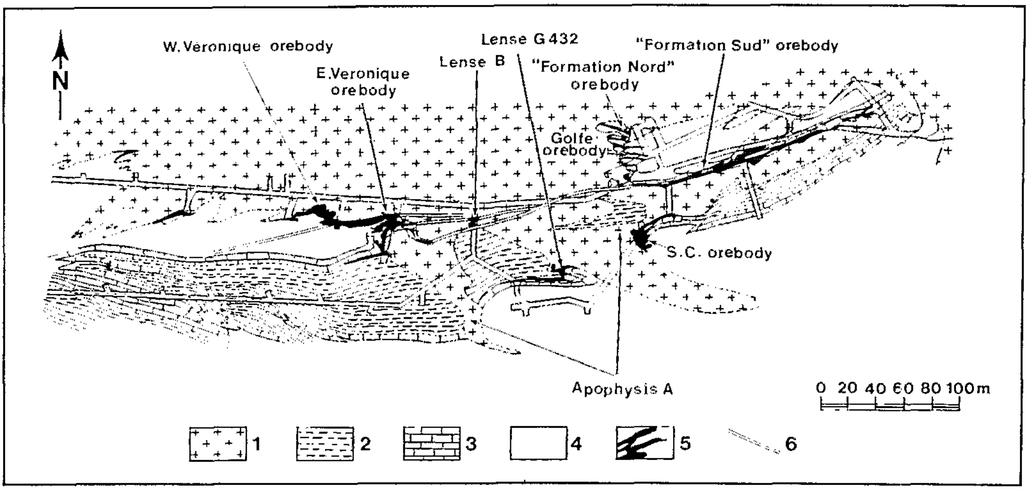

Fig. 2. Plan of anticlinal structure at level 1430 (according to Derré, 1983). *1* Granite; *2* metashales; *3* marble and limestone; *4* calcic hornfels (Barrégiennes); *5* skarns and mineral bodies; *6* main faults

ture with a major granite apophysis oriented to the southeast, apophysis A. Part of this cylindrical structure, which opens towards the east, corresponds to the Bois d'Anglade embayment and to the Quer de l'Aigle occurrences. The part opening towards the west makes up the NW part of the 'Véronique' orebody.

Here, a feature observed long ago should be pointed out: the parallel arrangement of the granite and subhorizontal ridges at the bottom of the Bois d'Anglade, clearly visible on the block diagram shown in Soler (1977).

Small-scale boundary shapes with a horizontal axis have been found above 1486, where they form the upward closure of the Véronique orebody, and at around 1150 (according to borehole surveys) where they presently participate in the downward closure of the Véronique orebody which has already been prospected. The sections drawn up by Nansot for this part of the deposit, all based on borehole surveys (Fig. 3), show that the ore-bearing limestone layer is delimited by two roughly parallel, cylindrical, horizontal axis surfaces, the one forming the roof consisting of shales, the other, which forms the floor, consisting of granite. All these observations appear to show that locally the granite-limestone boundary is inherited from a pregranitic shale-limestone boundary. This granite structure, which forms a horizontal roof or arch above Véronique, inherited from the pre-existing shale structure, probably explains, through its action of blocking the fluids in their upward movement, the rich mineralization of the upper part of Véronique.

2.4 Controls by Faulting[1]: Type 1 and 2 Ores

The existence of many silicified crush zones oriented EW in the granite and their importance in the morphology of the exposed granite have long been known. Recognition of the role of these faults in the delimitation of the orebody may be attributed to Soler (1977), who showed that a major fault of this family separates the NW and SE parts of the Véronique orebody which was discovered shortly before. He showed, step by step, that the 'Formation Sud' which forms the southern edge of the Bois d'Anglade embayment (the first orebody discovered at Salau), could also be regarded as a fault linked to the Véronique fault, but with a different filling.

Kaelin (1982) made a systematic distinction. He identified two principal stages of fracturing which he called faults f1 and f2.

2.4.1 Faults f1

The faults f1 have a strike of 80 to 90 and a northerly dip of 70° to 80°. However, they appear as faults only in silicate rocks, granites and shales. In the limestone they disappear as the limestone flows and adapts to the movements of the blocks of

[1] Note that Ledru and Autran (1987) have a completely different kinematic and dynamic conception of the development of the Salau structure from ours. It did not appear fruitful to discuss this approach in this chapter, since Ledru's work, which appeared recently, did not play any part in the history of the identification of controls actually used in developing the deposit. The interested reader should refer to the original article.

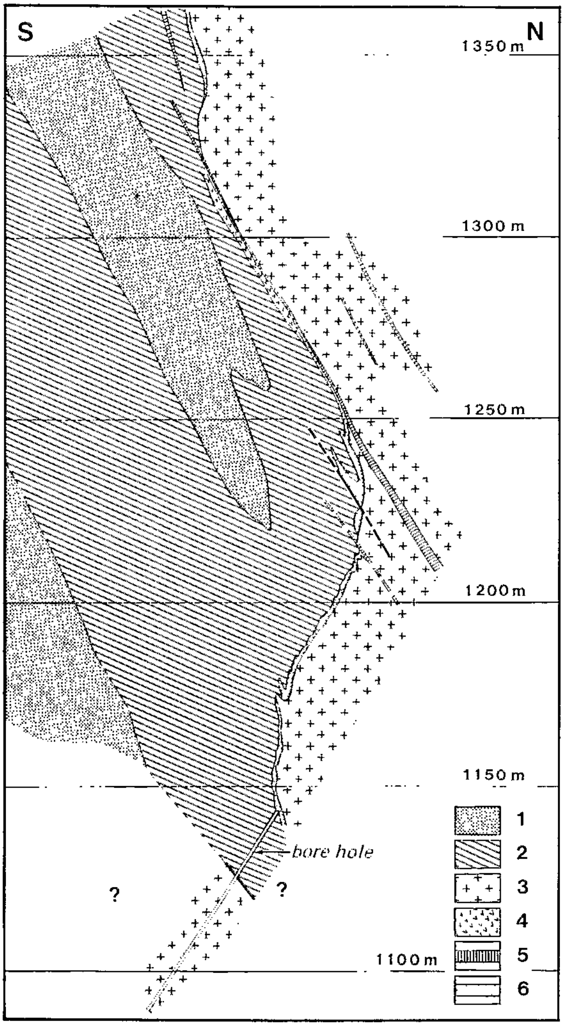

Fig. 3. N–S section at Véronique (Nansot, unpublished SMA documents). *1* Metashales; *2* marble; *3* granite; *4* breccia, including ore, granite and marble; *5* faults f2; *6* skarns and mineralized pyrrhotite

silicate rock with complex disharmonic folds which are emphasized by the graphitic banding.

The high-grade association of pyrrhotite and richly mineralized scheelite has mostly developed in the skarns along this type of fault, usually removing all apparent traces of crushing or deformation at a sample scale. Among the characteristics of this formation, the presence of approximately 1-cm spots of quartz or quartz + clinopyroxene or amphibole and of lenses of graphitic limestone some tens of centimetres in size, contorted and disrupted in a complicated way, should be noted. These spots and lenses are surrounded by massive pyrrhotite (±scheelite).

This type of 'filling' of the f1 faults is identical with the mineralization in the Formation Sud of the Bois d'Anglade embayment, which also has approximately the same strike. This is what we call *type 2 ore*.

The two known occurrences of wolframite in the quartz, where the Bois d'Anglade Formation Sud pinches out in the granite (Fonteilles and Machairas 1968; Soler 1977), could be part of this mineralization in the fault f1 developed under intragranitic conditions without influence from the calcic environment.

2.4.2 Faults f2

The faults f2 have a strike angle of 80 to 140 (mean about 120) and a northerly dip of 40° to 80°. They are filled with quartz accompanied by scheelite in large crystals, which are infrequent throughout and are of no economic interest. Unlike f1 they often develop remarkable slickensides. They clearly intersect with the f1 faults, at the same time limiting the workable, mineralized panels. In fact, these are not single faults but a series of regularly spaced parallel faults whose displacements are all of the same type. According to Kaelin (1982), the movement of these faults is reverse and senestral (although the extent of this movement had in no case been determined at the time he was studying them).

With the exploitation of the Véronique orebody, a new type of ore was distinguished, consisting of crushed quartz, sometimes presenting a mottled appearance, rich in scheelite (with associated arsenopyrite and pyrrhotite) distributed along a subvertical, nearly 5-m-thick mylonitic zone f0, striking 120 (Fig. 4). This mylonitic zone is interrupted to the north by an f2 fault. Although of economic grade (0.7–2.5% WO_3, average 1%), this type of ore is still small in volume at the present state of knowledge of the deposit. This zone, whose horizontal extension is small (less than 50 m) becomes poorer to the east and has not been followed at all levels. It disappears locally into the massive pyrrhotite (+scheelite), which fills the faults f1, in particular at levels 1470 and 1486. This ore thus appears to be the oldest of economic significance developed in the deposit. In support of the notion that this ore was developed in a comparatively early stage, it should be noted that this mineralized mylonite is folded by the third stage of folding defined by Kaelin (1982). This ore is designated *type 1*.

2.5 Type 2 Ore in 'Véronique Southeast' and Estimation of Displacements Along Faults f2

The upper part of the 'Véronique Southeast' orebody is extremely dislocated by faulting, and thus far its characteristics are not well understood up to the present stage of development. At the deeper levels, which have now been reached with boreholes and galleries, it has escaped the action of the late faults f2 and its characteristics are clearly apparent. Between levels 1150 and 1250 it appears as a several metres thick orebody with a fairly constant horizontal extension of about 50 m in an easterly direction, along the contact between the granite and the graphitic limestone. The ore is of type 2 and is very characteristic, with contorted decimetric lenses of graphitic limestone surrounded by massive pyrrhotite containing scheelite. WO_3 contents are fairly constant, of the order of 1.5 to 2.0%. At its extremity, very

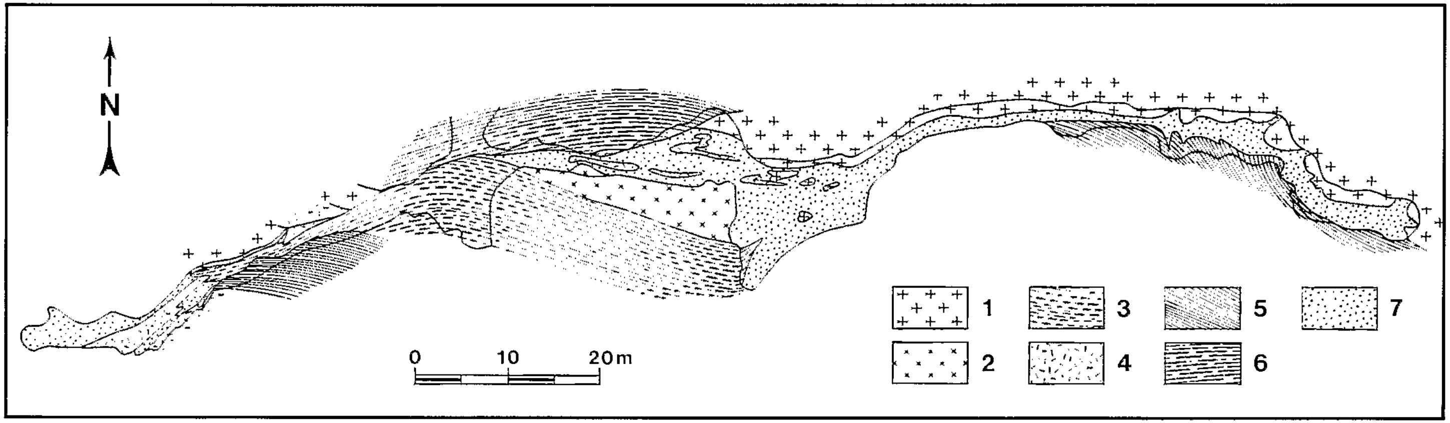

Fig. 4. Location of type 1 ore (site plan DV 1470, Kaelin, 1982). *1* Granite; *2* albitized granite; *3* silicified and mineralized mylonites (f0 and type 1 ore); *4* marble; *5* calcic hornfels; *6* skarns developed at the expense of calcic hornfels; *7* massive pyrrhotite (partly mineralized)

locally, skarn residues are observed in the pyrrhotite mass, then the orebody pinches out in apophysis A. To the west it is disrupted and loses continuity, and contents often fall below the cut-off grade.

Further up, boreholes show that grades are low and mineralization is thin between levels 1250 and 1350. Nansot's sections (Fig. 3) show that this drop in grade is a result of shearing and drawing-out of the orebody along the largest f2 fault known in the mine. Observations in galleries show that it is in fact a type 2 ore, completely dislocated in lenses and overturned blocks.

Above level 1350, the Véronique Southeast orebody again develops in the same way with virtually the same grades as below 1250, and this can be followed upwards continuously to about 1480, despite a fairly dislocated character, in detail. The shift between 1250 and 1350 gives the extent of the translation movement associated with the main plane f2. This is indeed a reverse fault with a throw of about 100 m, but with negligible horizontal displacement, which contradicts the initial impression derived from the striations.

This conclusion is very important as the results available at present from boreholes show that the 'Véronique West' column stops suddenly at about 1150, where the marbles disappear between granite at the footwall and to the north, and shales to the south. Comparisons between the various N–S sections drawn up from the borehole results suggest that the northern boundary of the shales is aligned in an approximately EW plane, which can be interpreted as an f2 plane. It may be expected that movement along this plane is of the same type as that along the main fault f2, with an amplitude of the same order. This shows us where to drill to find the extension of Véronique Southeast. This drilling was recently completed before the mine was closed, and *new high-grade ore was in fact found in this way.*

To summarize, the Véronique Southeast mineralized column is now known to be over more than 300 m in height without major variations in horizontal dimension or grades. A considerable extension downwards may be anticipated, with grades and dimensions of the same order. This column is not vertical; its projection on a vertical east-west plane has a westward pitch of about 70°, with the granite apophysis A forming its eastward boundary. The column is also not flat and, irrespective of the throws of the reverse faults f2, it is located on a cylindrical surface with a rather variable SSW dip, which is greater in the upper part than in the lower part, where it is ca. 45°. The axis of this cylindrical surface, like that of the folds of the shaley roof and in the limestone, dips to the east at about 15° to 20°.

2.6 Overall Layout of Known Orebodies Around Apophysis A. Role and Significance of Faults f1 and f2 and Type 2 Ore

With the possible exception of zones V and VI, which are minor orebodies located in the upper part of the deposit (around 1620 and 1750 respectively, Fig. 5), on a projection on an E–W vertical plane, all the known orebodies at Salau are situated in an aureole around a parabolically-shaped barren area formed by apophysis A.

Broadly speaking, the orebodies appear to be distributed in space over a cylindrical surface with the axis striking 80 and dipping 15° to the east, close to the

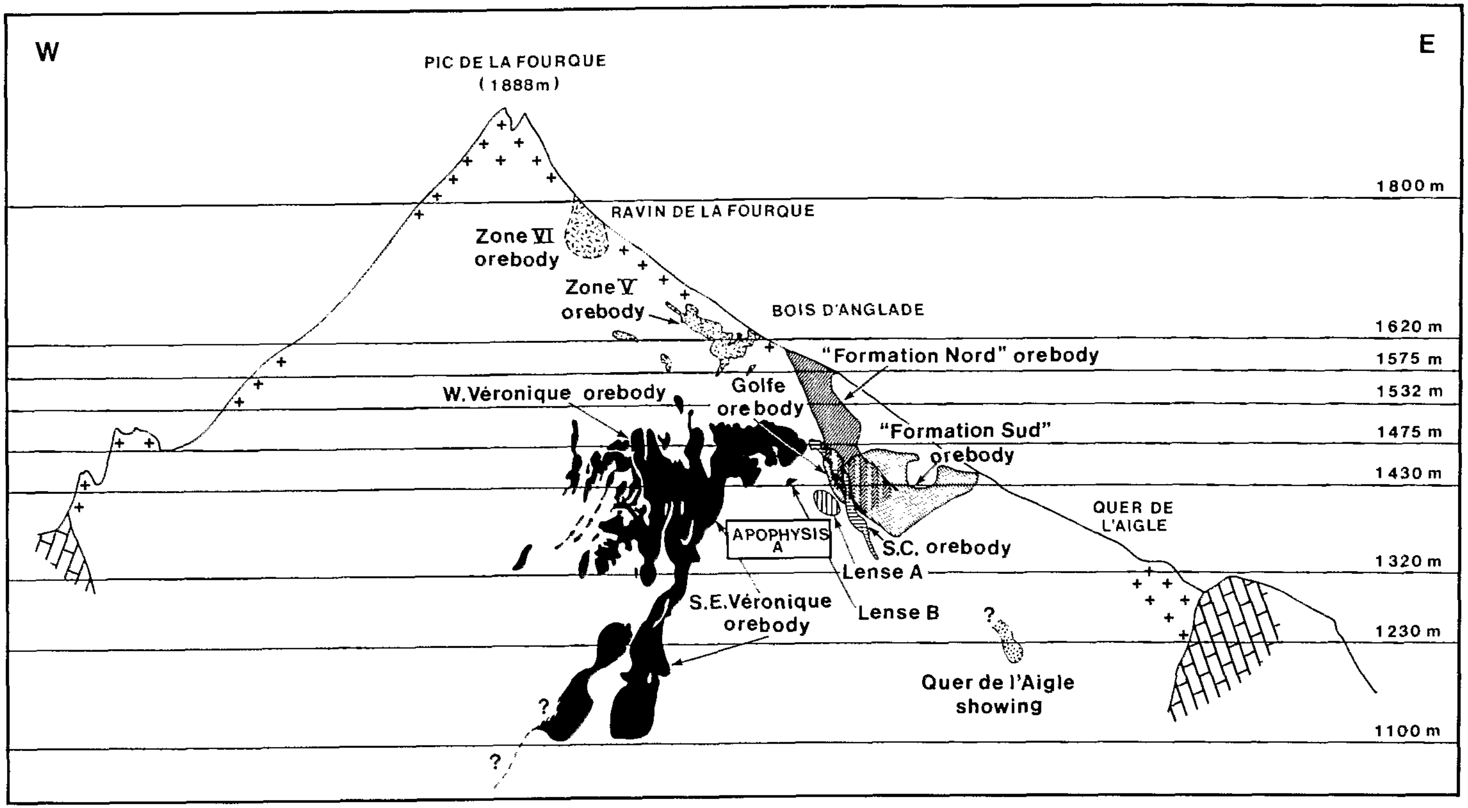

Fig. 5. Overall distribution of orebodies around granitic apophysis A (projection on an EW vertical plane, Nansot, unpublished SMA documents)

intersection of this surface and the granite apophysis A. More precisely, this surface and this intersection are outlined by the type 2 orebodies Véronique Southeast and Formation Sud in the Bois d'Anglade. Therefore, we interpret this distribution as being linked to a fault f1 intersecting with the granite apophysis A. This fault dies away in the limestones which flow long the granite blocks.

Type 2 ore has thus only developed in the immediate neighbourhood of the points where this fault emerges from the granite, i.e. in an aureole around apophysis A. According to Kaelin (1982), fault f1 was thus the channel through which the fluids responsible for the mineralization arrived. The observed granite only played a passive role and remained mostly barren. The source was lower along f1.

In view of this, the type 2 ore developed in the skarns (always very limited in extent) formed at the contact between the granite and the graphitic limestone. This small volume of skarn (porous medium) was the route which the solutions had to take, and is a 'throttling' [Pélissonier (1965) used the word '*étranglement*'], which explains the richness of this mineralization and the almost complete transformation of these skarns into massive pyrrhotite and scheelite ore. Thus type 3 ore appears to be the result of an 'oil-stain' extension of the mineralization where the fluid was able to reach and penetrate the Barrégiennes, which are clearly much more favourable to transformation and circulation. This oil-stain development, by percolation, explains the ragged aureole formed by the type 3 orebodies around the most proximal and regular type 2 orebodies. Zones V and VI could be slightly more remote extensions of these type 3, discontinuous mineralizations.

The Formation Sud of the Bois d'Anglade embayment is interrupted downwards by f2. The throw of this main f2 being of the order of 100 m, the extension of the Formation Sud, if any, should be found about 100 m below the bottom of the embayment. In view of the folding axes observed in the lower part of Véronique, such mineralizations could be the continuous westward extension of the known Quer de l'Aigle occurrences and would represent the equivalent offset downwards by a fault f2 of the zone where the Bois d'Anglade embayment opens towards the east, becoming progressively poorer in grade. The Quer de l'Aigle and its westward extension would thus complete the circular arrangement of mineralized formations around the apophysis A of the granite.

2.7 Probability of Extension

Fault 1, the channel for the mineralizing fluids, with its strike of 80°, diverges progressively from the la Fourque granite towards the west. This may explain why no new economic orebody was found on the extending gallery 1430 westwards and, if our line of reasoning is correct, leaves little chance of finding any in the southwestern part of the granite contacts at any level.

On the other hand, the two known groups of occurrences to the northeast and northwest on either side of the granite (Fig. 1) could correspond to the intersection of another f1 plane with the edges of the granite. If this is so, investigations should be carried out to determine whether this other f1 plane develops orebodies analogous to Véronique Southeast and the Formation Sud in the Bois d'Anglade, at greater depth.

3 Mineralogical Controls (Pyrrhotite, Garnet II): Their Application to the Assessment of Occurrences of Scheelite Skarns

The skarns and mineralization developed during a whole series of hydrothermal events: additions and renewals by successive solutions with different characteristics. Each of these episodes is characterized by the development of a particular, more or less specific mineralogy.

If there is a distinctive mineralogy associated with the stage at which the economic mineralization is developed, the idea naturally arises to consider the presence of this mineralogy as a favourable sign and to systematically examine whether it appears in the scheelite occurrences whose value is to be determined. In some cases these mineralogical properties have even been taken as a condition sine qua non for the presence of economic ore.

This proposal was made for the pyrrhotite which so clearly accompanies most of the scheelite at Salau. In our opinion, this concept is erroneous and the application of such a criterion could well result in some of the richest deposits being abandoned. As an example we could mention the large scheelite skarn deposit at Shizuyan (China), where pyrrhotite is either absent or present in very minor quantities.

In fact, a comparative study to determine whether the supposed mineralogical criterion occurred with sufficient frequency in the known deposits throughout the world had been omitted.

3.1 Controls in the "Golfe" Ore Body

In the initial history of the Salau mine, the skarns discovered were mainly exoskarns, differing principally in the nature of the substrate rock. On pure limestone (whether or not graphitic), in contact with granite or in veins, skarns are characterized by three monomineral zones: an internal grossular garnet zone, a hedenbergite zone (by far the largest) and an external zone of white calcite separating the silicate skarn from the graphitic marble. A small proportion of the garnet probably developed in an endoskarn. The development of a plagioclase-clinopyroxene $\pm$ quartz paragenesis on the external edge of the granite in contact with the skarns may also be linked with endoskarn development.

On the barrégiennes, the development of two transformation zones yielding banded skarns may be observed. The light-coloured external zone is characterized, among other features, by a salite-type pyroxene, the darker internal zone by hedenbergite. The other minerals are grossular, etc. The modifications of the granite are apparently the same as those in the former case. WO_3 contents in the unmodified skarns are of the order of 0.3–0.4%.

After the development of the skarns proper, two successive episodes are noted:

1. A stage in which the garnet and the adjacent granite are epidotized with transformation of clinopyroxene into hornblende $\pm$ calcite $\pm$ quartz. This stage corresponds to a transformation of the skarns without any marked additions (except perhaps for iron in certain cases);
2. A stage in which a paragenesis of the 'propylitic' type is usually developed. We have called the resulting rock RHO (Rock of Hydrothermal Origin, as opposed to skarns as such) which, depending on the substrate rock, consists of:
   a) On the granite: albite (transparent), chlorite, sometimes biotite, muscovite, quartz $\pm$ epidote (type 0 ore).
   b) On the skarns: actinolite, epidote, calcite, quartz (type 2 and 3 ores).

The presence of chalcopyrite, bismuth, often massive magnesian tourmaline (dravite) and sometimes apatite implies metasomatic additions. The scheelite content is extremely variable and often high. This episode is the one at which mineable ore is developed.

3.2 Garnet II Stage in "Véronique"

This simple model was greatly complicated after the discovery of the Véronique orebody. A new stage of development of typical skarns characterized in particular by garnet II rich in almandine-spessartine components appears in this orebody after the epidote stage and before the RHO stage. Among the minerals associated with the garnet, a blue-green hornblende and, rather unusually, a scapolite may be observed. This garnet is also accompanied by masses of black quartz.

The main characteristics of this garnet stage are the following:

1. These skarns have always developed on silicate rocks, either granite or epidotized granite, or else first-stage (exo)skarns. At this stage there is no development of skarns at the expense of the carbonated country rock;
2. They may consist of veins intersecting the primary hedenbergite, but these veins grade into indistinct recrystallization veins in the calcite where they emerge from the primary skarn;
3. Regardless of the type of involved silicate rock (granite or hedenbergite skarn, for example), the garnet tends to develop at the contact with the pre-existing silicate rock and the limestone (always on the silicate rock side) and not as an internal zone which is the usual position of skarn garnets.

The residual skarns observed in the type 2 ore masses generally display very well this stage of garnet II.

3.3 Direction of Fluid Movement

The first-stage skarns developed mostly as exoskarns. The fluids were in equilibrium with the minerals present in the granite, and were very aggressive towards the carbonate environment (destruction of graphite by oxidation, conversion of carbonate into ferrous or aluminous silicates).

The epidote stage, in view of its oxidizing nature (which is thus foreign to graphitic marble) could be the lower temperature outcome of this episode, the source of the fluid being essentially the same.

For the second-stage skarns, the RHO and the associated ore, the reverse is true, the fluid was in equilibrium with the external carbonate medium and reacted with the primary silicates; note in particular the high CO_2 fugacity (development of carbonates and scapolites) and the reducing character of this fluid, which transforms more or less pistacite-rich epidote into grossular-almandine garnet.

We conclude that the fluid responsible for the formation of the initial stages of the skarns (and perhaps for the epidotization) came from the granite, whereas the fluid responsible for garnet I and the RHO came from the limestone country rock. The isotope data (C, O, H) available at present (Guy 1979; Toulhoat 1978) agree with this interpretation. In both cases it is a question of the immediate origin of the fluid and not its ultimate origin.

3.4 Economic Significance of the Stages

This is an important result, because the scheelite contents associated with the first-stage skarn are still low (0.3 - 0.4%, not recoverable at present) and the mineable ore is linked with late transformations associated with fluids 'originating' in the country rock. Note that this has no implications with regards to the quantities of tungsten added at this stage. It is even possible that the recoverable mineralizations could result from simple, late reconcentration phenomena. At all events, it seems that the appearance of such solutions was indispensable for the skarns to be of an economic grade. The pyrrhotite, which was from the start regarded as a mineralogical control, is indeed deposited by these solutions. But it is an unreliable indicator in other areas. The presence of pyrrhotite is related to other factors, in particular sulphur fugacity, which appear to be independent from those which favour transport and deposition of tungsten.

On the other hand, type II garnet, rich in almandine-spessartine, may be a good indicator that a solution of the type which interests us here was present.

The idea of assigning an important role to garnet II as an indicator of the proximity of rich mineralizations is the result of repeated observation (Shimazaki 1977; Brown et al. 1985) of the occurrence of this mineral in economic deposits. Investigation of the presence or absence of this type of garnet in known deposits should be systematized.

4 Speculation on the Part Played by Granite and on the Origin of the Fluids (based on the consideration of the controls discussed above)

It is perhaps surprising not to find the composition of the granite among the ore controls proposed here. This is because we do not know whether the granite observed in the outcrop and in the mine played any part in the process other than a purely passive one.

It should be recalled that this granite may be classified in the common calc-alkaline Pyrenean categories of granite, but is more basic (granodiorite) than average, with many even more basic xenoliths (diorite). It is distinguished from the normal trend by a slightly higher iron content at the same stage of evolution (Soler 1977); and it shares this characteristic with the Batère granite which appears to be associated with a small, richly mineralized skarn at Roc Jalère (Salemink and De Jong, this Vol.). Note that granites, as little evolved as those of Salau, are not, in general, very favourable to the development of tungsten mineralizations, a fact which may be correlated with the low tungsten content of magmas at this stage of evolution, which in turn probably results in low W contents in fluids issuing from these magmas. However, the Costabonne granite does not show this relatively high iron content. It is also more evolved and accompanied at its margins by small bodies of white granite (Le Guyader 1982; Dubru et al., this Vol.). The notion that granite is the source of the fluids responsible for the mineralization is a classic one. At Salau, with regards to the rich mineralization associated with massive pyrrhotite (RHO stage), the presence of abundant tourmaline and occasional pockets of apatite may be considered as an indication in favour of this idea, the more so since irregular occurrences of fibrous tourmaline (dravite) have developed locally in the granite, together with small, blind, greisenized veins close to the mineralized zones. Note also that two occurrences of wolframite have been described, occurring as residues in the scheelite (Fonteilles and Machairas 1968; Soler 1977). All these observations suggest that the mineralization is related to granites which are more evolved than those observed in the mine. Moreover, the relationship which has recently been shown between rich mineralization and a subvertical f1 fault, together with the lack of change with increasing depth in the type 2 ore down the 350 m of the Véronique Southeast column, does not speak in favour of a nearby source of tungsten. At all events, the source is not the adjacent granite. Note that these observations give rise to hopes that the economic mineralizations may extend downwards. The fluid was channelled by fault f1. We should note that such channelling of the fluid, which for the most part explains the distribution of the ore, is only conceivable if the source is very localized, which contradicts the hypothesis which is sometimes advanced that common fluids circulate in the country rock.

It is not impossible that a very evolved, light-coloured granite comparable to the Costabonne granite was active at depth and fed fault f1 with mineralizing fluids. The apparent evolution of the fluids in the light of the above discussion may be summarized as follows:

At the early stage, the fact that the skarns are chiefly exoskarns and the evidence of important additions (Fe, Si, W, etc.) imply a source irrelevant to the country rock, possibly a granitic one.

The garnet II stage is clearly related to a fluid originating in the country rock, in equilibrium with the marble and graphite. There is nothing to suggest that any tungsten was added at this stage. The RHO may be related, as the early stage, to a fluid derived from a deep granitic source.

Two difficulties remain with regard to such a representation:

1. For the garnet II stage, a fairly massive fringe of black quartz often developed at the edge of this garnet on the marble side.
2. For the RHO stage, there was progressive but intense enrichment in scheelite on the edges of the 'skarns' (in a broad sense) up to the contact with marble, where the grade drops sharply to zero ('marble line'), a phenomenon which is present in most scheelite skarn deposits. Contradicting the proposed representation, this phenomenon could suggest that the tungsten-bearing fluid was very low in silica which circulated in the marble and that the scheelite was precipitated by a reaction with the silica in the skarns or the granite. Such silica-poor fluids could transport aluminium (Pascal 1984) and could thus be responsible for the formation of garnet II by replacement of hedenbergite on the edge of the skarns. However, this contradicts the successive nature of the development of the garnet II and the RHO.

One way of resolving these contradictions would be to assume that the precipitation of the scheelite arises from the meeting of two fluids with different sources and compositions, one in equilibrium with the carbonate environment, the other with the granitic silicate environment (the latter being able to transport tungsten). The garnet II stage would only represent a negative fluctuation in the supply of granitic fluid, during which the external fluid temporarily penetrated the silicate environment near its edges. The black quartz deposit would then represent a positive fluctuation, when the fluid originating from the granitic medium again tended to penetrate the marble. Knowledge of the isotope composition of the oxygen and the hydrogen in the fluid inclusions in this black quartz and in the quartz associated with the RHO seems essential at this stage.

The marble line could be explained by a very large scheelite precipitation where the two fluids came into contact. The random distribution of the tungsten contents at a metric scale and in samples would then be explained by fluctuations in the path and derivation of these two flows of fluids.

Appendix

We have collated in three stables the successive geological controls used for the ore at Salau. In the second and third tables (position with respect to the granite and structural controls), the comments will, we hope, make possible a better understanding of how the ideas evolved and how the emphasis placed on certain controls changed as knowledge of the deposit increased.

A. Type of control: lithology (*nature of substrate*)		Underlying ideas and comments
General		
1st idea	Marble or dolomite	
At Salau		
2nd idea (1965)	Main part played by barrégiennes (banded limestone with narrow layers of shale or sandstone)	Type 3 ore ('Golfe', 'S.C', 'Véronique NW' orebodies)

3rd idea (1976)	Undetermined nature of the Formation Sud and Véronique SE substrate (massive pyrrhotite with contorted lenses of graphic limestone)	Type 2 ore
4th idea (1980)	Mineralized mylonite south of Véronique	Type 1 ore
5th idea (1984)	Development of rich ore at the expense of more or less skarnified granite (first discovered in the upper part of Véronique NW); sometimes biotitization	Type 0 ore
6th idea (1986)	Development of type 2 ore, at the expense of the pure ± graphitic limestones, by superimposition on previous skarnification	Type 2 ore is associated with and equivalent to type 0 ore on a different substrate rock

B. Second type of control: position with respect to the granite		Underlying ideas and comments
General		
1st idea	Granite-limestone contact	1st interpretation: the granite immediately in contact is the source of fluids
at Costabonne		
2nd idea	This is not the only interesting contact; there are also skarn veins, and above all skarn bodies, in other contacts between marble and silicate rocks other than granite, for example shale strata	2nd interpretation: the source is not the adjacent granite but a deeper part of the granite intrusion (interpretation 1 is false) 3rd interpretation: the limestone silicate rock contacts are the main sites of fluid circulations
at Salau		
3rd idea (1965)	The skarns and the mineralization (at the granite contact) were mostly developed in the barrégiennes (type 3 ore) but to a very limited extent in the pure ± graphitic marble	Interpretation 3: the fluid is mostly guided by the pelitic beds in the marble
4th idea	There are mineralized mylonites of recoverable grades over 50 m horizontally southwards from the mineralized body	
5th idea (1979)	The rich (pyrrhotite) ore developed where a particular family of faults (f1) cut across the barrégiennes	5th interpretation: circulation of fluids along the veins; the barrégiennes as traps; abandonment of interpretation 3
6th idea (1986)	A rather special type of rich pyrrhotite ore (type 2) may develop on the pure ± graphitic previously skarnified limestones (the 3rd idea above again loses importance)	

7th idea	This type 2 ore is arranged in a narrow aureole around granite apohysis A on a surface f1; type 3 ore in a ragged aureole round the former	Type 3 ore is explained by 'leakage anomalies', which explain its random nature; the channel through which the solutions arrived is a single, well-defined fault f1; they have a deep origin

C. Third type of control: structural control		Underlying ideas and comments
General		
1st idea	Granitic apices of very small dimensions are the most favourable; diameter of la Fourque granite, 1.2 km	1. Essentially subvertical, monoclinal structure of the series
2nd idea (1965)	Major part played by semi-enclosed structures (embayments, roof pendants, etc.)	2. Faults play only a very subsidiary role
	The Bois d'Anglade embayment and the 'S.C': two embayment structures (open towards the east)	
(1977)	Véronique Northwest: an embayment open to the west; the main orebodies are blow 1500 m, where the granite forms the roof of the limestone	3. Granite as caprock
3rd idea (1977)	The large fault in Véronique: a fault delimiting a northern and a southern compartment, the relationship between which is not known	4. Abandoning 2; abandoning 3 except around the 1486 m level The deposit is divided into panels by the fault
	The large Véronique fault continues eastwards through the Formation Sud of the Bois d'Anglade embayment	5. What is the continuation of the Véronique North and Bois d'Anglade embayment on the other side of the fault? Perhaps Véronique South and 'S.C' respectively
4th idea (1979)	Part played by fold structures; importance of early folds with EW subhorizontal axis and vertical plane; existence of a large limestone anticline with a shale core south of Véronique The deposit developed in the embayments was created at the intersection of apophysis A with this anticline; the structure discovered towards the east (Saubé area) is a good model of the folded structure around the mine	Abandoning 1
	The large Véronique fault is a reverse fault and the position of the granite forming the roof of the ore in Véronique is to a large extent due to the displacement of this fault, regularly spaced	Hypothesis 5 is false; how to determine the throw of f2?
5th idea (1978–80)	Discovery of the mylonitic zone f0, an early structure with scheelite mineralization but poor in pyrrhotite	

6th idea	Recognition in Véronique of an f1 fault invaded and cemented by mineralization rich in scheelite and pyrrhotite	
	This f1 fault in the silicate rocks degenerates into a flow zone in the marble; it predates f2, which interrupts and displaces the orebodies associated with f1	
7th idea	The ore SE of the la Fourque granite has developed mainly where an f1 fault with strike 80 emerges from the granite apophysis A and disappears in the limestone	This explains the absence of ore SW of the granite
	The ore is arranged in two columns, one west of apophysis A (Véronique SE), the other to the east (Formation Sud of Bois d'Anglade); the displacement caused by the reverse fault f2 may be assessed at about 100 m following the line of greatest slope, from examination of the Véronique	The solution formation is not the extension of the large f2 fault in Véronique but of f1 displaced and deformed by f2
	SE orebody between 1350, 1250; the downward closure of the deposit at level 1150, shown in borehole surveys is due to displacement of the Véronique SE orebody by a replica of f2	The slightly mineralized body at the Quer de l'Aigle may represent an extension of the Bois d'Anglade embayment south of the main f2 fault

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