

# Post-magmatic processes in south-west England and Brittany

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Several types of deuteritic alteration (mainly greisenisation, tourmalinisation and kaolinisation) developed in several occurrences in Cornwall and Brittany are described and compared: petrological implications and chemical evolutions are summarized and discussed using a statistical approach. Physico-chemical characteristics of the hydrothermal solutions responsible for these modifications are emphasised: P.T. conditions, salinity and acidity are estimated. The conclusions presented are applicable to the examples studied and in fact cannot be generalized to give a more evolved genetic model.

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## Introduction

It is universally admitted that stannic-wolframiferous mineralization is spatially associated with granitic magmatism (references in Taylor 1979). Mineralization appears to be genetically related to the late and post-magmatic evolution developed in the intrusive bodies. Microclinisation, albitisation, greisenisation, tourmalinisation, topazification, fluoritisation, etc., are the most frequently encountered phenomena associated with Sn and W (Scherba 1970; Stemprok 1971). Cornwall with its abundance and diversity of these deuteritic occurrences appears to be an exemplary place for their qualitative and quantitative study.

Several late and post-magmatic alteration types have been studied in apparently exemplary localities in Cornwall and some of them compared with previous results from Brittany. This study forms the subject of a thesis-memoir prepared in Nancy University (Charoy 1979). In this paper, the greisenisation phenomena will be described and evaluated.

## The greisenisation process

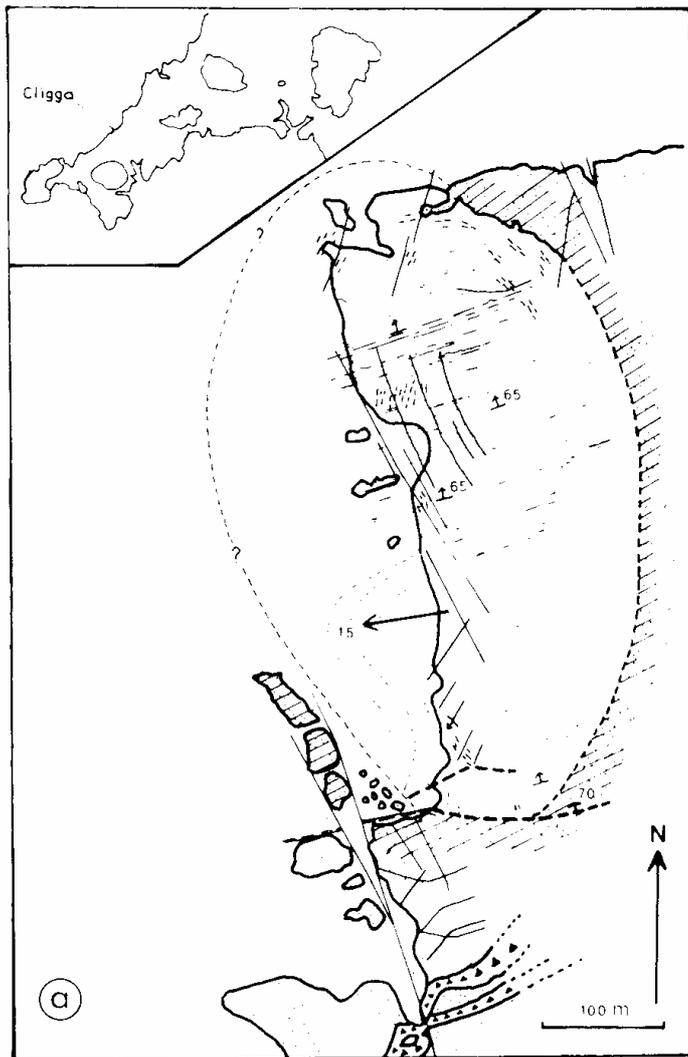
The example selected is that of Cligga Head near Perranporth on the north coast of Cornwall. The Cligga Head stock is a very well known example of a small cupola protruding from the surface of the Cornubian batholith and is considered to be related in depth with the ENE-trending St Agnes-Cligga ridge. The cliffs and mining works offer a very good three-dimensional view of the internal organization of a mineralized quartz-rich stockwork (Dines 1956) (Fig. 1). The granite intrusion is

of the porphyry type considered by Hall (1971) to be a textural differentiation of the main Cornubian coarse-grained granite. The whole stock appears to be homogeneous and the contacts with the surrounding killas are sharp except at the faulted south boundary.

The celebrity of Cligga comes principally from its shape, which is that of a dissymmetrical arch formed by the mineralized quartz veins. These veins are recognized as filling early joints (called curved primary flat lying joints by Moore and Jackson 1977). This curious geometry has been interpreted in several different ways:

(a) deformation of a laccolithic structure (granite-tongue) overthrust to the south (Scrivenor 1903), (b) partial collapse or slumping of the chilled hood of the cupola by withdrawal of the underlying magma, followed by a strong inverse shearing to the south (Cox 1961), (c) joint arch produced by internal contractional stresses disturbed on the south side around an active reverse fault (Moore and Jackson 1977).

Stockwork mineralized bodies occur in other small granite porphyry stocks such as St Michael's Mount and Hemerdon Ball, but the sheeted vein system is never regularly curved as at Cligga. Moore (1977) explains this as being due to different levels of erosion; only the upper part can present this regular shape, in relation to the behaviour of an hypothetical fluid pressure cell in the underlying cupola (Moore and Jackson 1977). Thus this very unusual shape of the vein complex at Cligga is thought to be only the expression of a local disturbance of the regional stress field.



-  Killas
-  Elvan dyke
-  wall rock greisen  
Sn,W,Cu veins
-  Phenocryst alignment

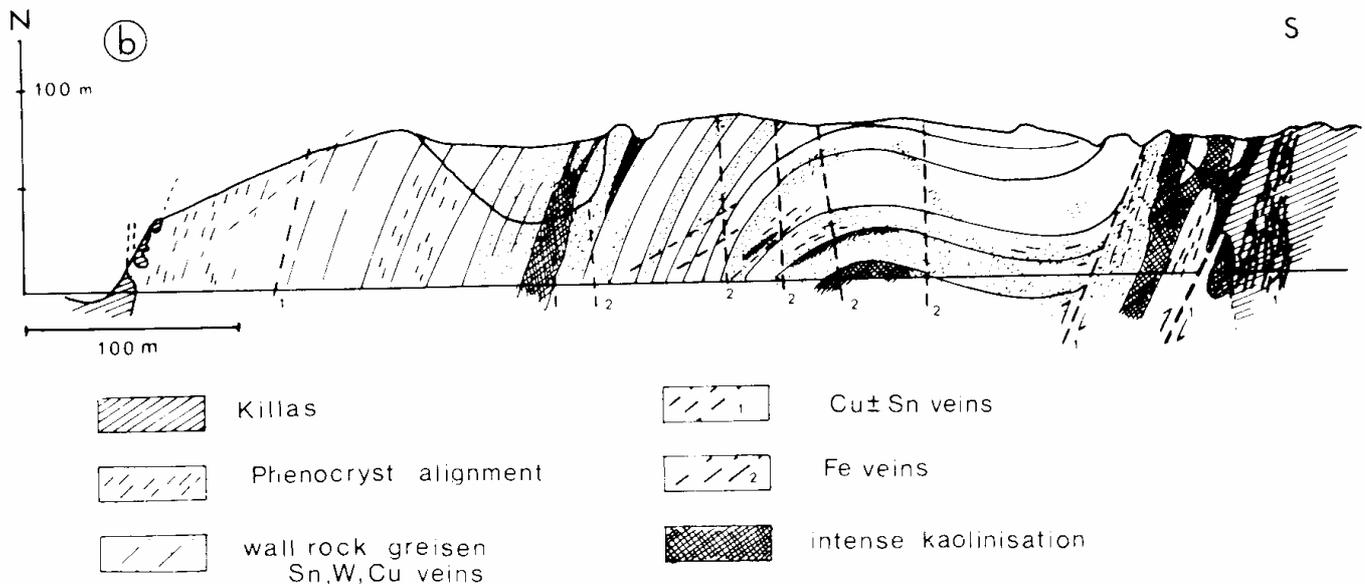


Figure 1. General map and cross-section of the Cligga Head stock (in Moore and Jackson 1977).

According to Exley and Stone (1964), the granite porphyry belongs to the lithionite type; however, petrographic observations and petrological characterization show that the earlier paragenesis has been dramatically altered by hydrothermal solutions throughout the stock, even in parts where kaolinisation appears to be less strongly developed (the contrast between the hard grey greisen bordering quartz veins and the white and soft kaolinised granite is one of the more strange and interesting characteristics of the stock). Oligoclase is altered to albite; primary biotite remains only as relicts in late protolithionite which is erroneously considered by Hall (1971) as the first phyllic constituent; muscovite is always secondarily superimposed around lithic micas and replaces feldspar (for some complete descriptions, see Hall 1971 and Charoy 1979). Tourmaline is typically zoned brown to blue. Globular quartz and feldspar phenocrysts and often early brown tourmaline show a zonal ordering of acicular minerals analysed as sillimanite. This is interpreted as proving the very early character of these host minerals including tourmaline, which must be considered as a primary magmatic phase. Andalusite is not frequent and cordierite is always altered to gigantolite, an association of white mica and chlorite. Nevertheless; a special non-porphyrific facies very close to the southern contact is composed of a fine-grained granite with dark interlayers strongly enriched in aluminium silicates such as andalusite, sillimanite and pseudomorphosed cordierite (Charoy 1979). Andalusite as pink prisms is also encountered in slates constituting a small breccia structure to the south which was interpreted by Moore and Jackson (1977) as a stoping relict. Topaz is only present in the south part of the stock.

Greisenisation is developed in the wall rocks adjacent to quartz veins (Hall 1971); a phyllic alteration is also widespread throughout the stock, the fine-grained matrix of the granite porphyry being more strongly affected.

Wall-rock greisen is confined to the margins of the quartz veins, the width being statistically proportional to that of the central quartz infill. Greisen is essentially composed of quartz and micas (muscovite and more or less beached relict protolithionite: composition in Hall 1971) zoned tourmaline and variable amounts of fluorapatite. Cassiterite and some sulphides occur as accessories. Petrographical comparison between more and less greisenised material shows that microcline is the first feldspar to be hydrolysed and that albite is only leached out in the more strongly altered samples (more details in Hall 1971; Charoy 1979).

If on the whole, the spatial relationship between greisen and quartz vein is very marked, both are subsequently affected by important superimposed fracturing events related to conformable or crosscutting quartz and/or tourmaline veinlets, some of them with a bordering greisen alteration (Dines 1956; Moore and Jackson

1977). Later sulphide mineralization may crosscut or follow the earlier joints.

A chronological evolution with five main episodes is proposed:

1. beginning of greisenisation along the primary joints,
2. filling with the main mineralization (wolframite and cassiterite with quartz),
3. refracturing and deposition of blue ferrous acicular tourmaline, perhaps with some wolframite,
4. repeated refracturing and precipitation of sulphides: arsenopyrite, chalcopyrite, pyrite, some stannite, sphalerite and molybdenite with muscovite, sericite, chlorite, fluorite and quartz as the main gangue minerals; some secondary cassiterite may be related to this phase,
5. development of north-south crosscutting fractures with iron oxide, kaolinite and vughy quartz, responsible for the morphology and colour of the cliffs.

This paragenetic succession is really schematic but renders an account Of the dramatic complexity encountered in some of the mineralised quartz veins.

Muscovite or sericite and quartz are the only stable phases throughout the hydrothermal sequence. The greisenised wall rocks must thus result from the superposition of several successive hydrothermal phases over a large period of time and must not be considered as only one paragenetic stage. Thus in spite of the apparent geometrical regularity of the phenomena, the Cligga example does not lend itself to a study of a quantified chemical balance for the greisenisation: this will be affected in a variable amount by the later hydrothermal processes (chlorite, fluorite precipitation...)

Chemically, the hydrolysis of the feldspars is expressed by a differential leaching of alkalis: total for sodium, partial for potassium which is largely fixed in the new micaceous phases. Silica released during the hydrolysis is also partly leached. The mesonormative composition of some progressively more greisenised samples can be compared (from analyses of Hall 1971; Charoy 1979) in Table I.

Hall (1971), from the Cligga example, tries to draw a global chemical balance for the greisenisation process (see also Moore 1977) He concludes that "there is no single geochemical pattern which characterises greisenisation apart from the depletion in sodium; each greisen has its own special characteristics..."The variations presented by the mineral content in apparently similar samples induce some reflections:

- a question of nomenclature: a sample termed as greisenised granite often does not appear equivalent in fact. This disharmony will be greater in a statistical study of analyses taken from the literature.
- even in one studied deposit, variations inside a, petrographically defined term may be large on account of later modifications in greater or lesser proportions.

	1	2	3	4	5	6	7	8	9	10	11	12	13
Q	33.9	32.0	33.2	32.5	34.8	34.0	36.5	37.5	58.0	52.4	56.2	53.2	54.8
Or	17.6	21.7	21.0	22.2	20.2	27.1	21.3	18.0	3.9	7.9	6.4	5.5	6.5
Ab	29.8	27.9	31.1	28.5	25.3	23.0	22.9	18.5	0	2.1	0.9	0	0
Bi	1.4	2.3	1.1	1.4	2.5	0.8	2.1	2.7	1.7	1.8	1.8	2.1	1.5
Musc	14.2	13.6	10.3	12.1	13.9	9.0	13.5	20.2	27.2	31.7	30.1	31.6	30.2
Tne	3.0	2.5	3.3	3.1	3.3	6.5	3.7	3.1	9.2	4.0	4.6	7.5	7.0

	CIH50	CIH51	CIH59	CIH60	CIH62	St Michael's Mount
Q	35.5	33.7	33.7	53.3	57.5	51.6
Or	18.3	17.6	17.8	21.7	9.4	0
Ab	26.0	31.7	30.6	0.7	0	0.4
Bi	2.3	2.2	2.3	0	0	5.4
						Chlorite
Musc	17.9	14.9	15.6	19.5	27.7	39.1
Tne	nd	nd	nd	4.8	5.4	3.4

Hall 1971	1, 2	unaltered granite greisenised granite greisen
	3, 4, 5, 6, 7, 8	
	9, 10, 11, 12, 13	
Charoy 1979	C1H 50, 51, 59	unaltered granite greisenised granite greisen
	C1H 60,	
	C1H 62	
Exley and Stone 1964	St Michael's Mount	greisen

Table 1. Normative compositions of granite, greisenised granite and greisen samples.

The attempt made by Hall (1971) to investigate the gradational nature of the granite-greisen transition in one sample is interesting because it shows that the chemical variations cannot be strictly superimposed on the mineralogical transformation. In spite of the apparently abrupt contact between the enclosing granite and the greisen, the chemical change does not reflect this abrupt transition.

All the greisen rocks described in the literature show a very large scope of mineral association in which only quartz and/or micas are the main phases, thus it is consistent with a broad geochemical variation (see Hall 1971 and Charoy 1979 for comparison with other greisen localities).

In a statistical form, the chemical evolution during greisening can be drawn with the help of several constructions:

- triangular mesonormative composition with Q, feldspars and muscovite (Fig. 2)

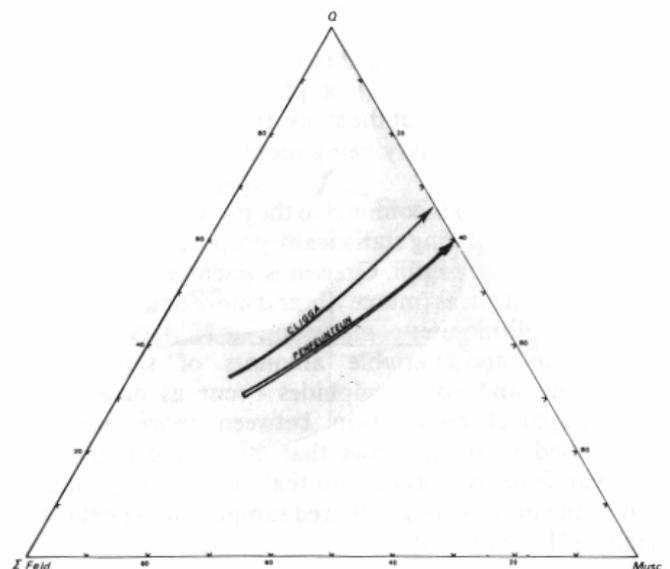


Figure 2. Chemical trend drawn by the greisening process in the normative triangle Q-Σ feld-Musc. Comparison between Cligga Head and Penfeunteun occurrences. The analytical evolution between granite and greisen from the literature is represented by the dotted area

- chemico-mineralogical diagrams. In these, millication parameters are used in an attempt to separate the mineral phases of the successive parageneses.

For example, the rectangular diagram Q-F (La Roche 1964) with respectively

$$Q = Si_3 - (K + Na + 2Ca/3) \simeq (\text{free silica quartz amount})$$

$$F = K - (Na + Ca) (\text{the feldspathic range})$$

shows the chemical trend defined in the Cligga fissure-style greisen (Fig. 3). This may be compared with that drawn for Penfeunteun (Brittany) where local but pervasive greisenisation is developed (Charoy 1975). Also represented is the statistical distribution of greisenised granites and greisens from the literature. The general trend is not strictly defined, because of the sharp geochemical hiatus between the samples and the lack of analyses of the intermediate phases. Nevertheless, one can assume from the comparative analysis that the discontinuity with the increasing alteration may be

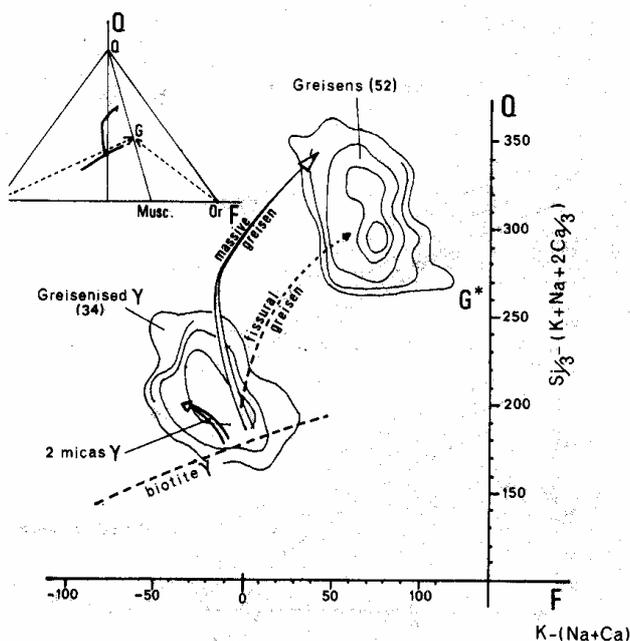
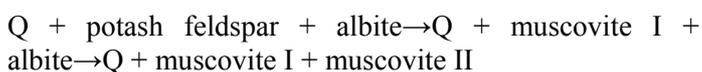


Figure 3: Statistical distribution of greisenised granites and greisens in the chemico-mineralogical diagram Q [ $Si_3 - (K + Na + 2Ca)$ ] - F [ $K - (Na + Ca)$ ] and comparison with the chemical trend<sup>3</sup> in Cligga Head and Penfeunteun examples, G = muscovite + Q (association resulting from the hydrolysis of the feldspathic phases).

related to the successive equilibria:



as petrographically displayed.

The fissure-style greisens (as at Cligga) appear to be less siliceous than the diffuse-style ones (as at Penfeunteun); this can be explained by the precipitation of a part of the leached silica directly in the adjacent fractures. On the contrary, in the diffuse type, silica leached out during the hydrolysis precipitates directly in the greisen; and thus the porosity of the enclosing rock decreases, circulation of the hydrothermal solutions is strongly reduced and the process ends (see Groves and Taylor 1973). This may explain why diffuse greisens without any relation with joints are rarely perfectly and widely developed. Greisenisation of a rock will be complete only if the channelways remain open for the circulation of the hydrothermal solutions over a long period of time.

Other parameters especially designated for two mica granites and their altered equivalents are available and may be used with the same statistical method (La Roche 1978a, 1978b, 1979).

In order to estimate the thermobarometric conditions during alteration and to characterize the composition of the hydrothermal solutions responsible for greisenisation, fluid inclusions in the globular quartz from the unaltered granite and greisen, in quartz from mineralised and barren veins and in primary cassiterite were studied. Unfortunately, the large superposition of the alteration parageneses is also expressed by a dramatic mixing in the same quartz grains of the successive generations of fluids. This is especially marked in the veins which served as channelways for the reactive solutions during the whole complex hydrothermal evolution. This is also true in the quartz phenocrysts from the wall rocks (granite and greisen) but with a decreased effect laterally.

All the inclusions have two phases, with a liquid/total volume ratio of 0.85 to 0.95. Homogenization always occurs in the liquid phase. Daughter minerals are never encountered but some phyllite flakes and tourmaline-like needles may be recognized as captive phases. One phase gaseous inclusions are rare and possibly secondary artefacts. In spite of the numerous samples studied in polished section, it was impossible to determine a clear chronology between the different generations of inclusions: none of them can be described as primary. Thus microthermometric results from freezing and heating runs are presented together according to their spatial location (Fig. 4 and 5). Fluid inclusion characteristics are very similar in mineralized and barren veins. Very often, metastable monophasic liquid inclusions are recognized, especially in the latest and coldest veins associated with argillisation. Evidence of  $CO_2$  is found only by the presence of hydrate crystals at low temperature and it is probably contemporaneous with the precipitation of some sulphides.  $CO_2$  however does not play an important role during the bulk of the mineralization. The histograms of Figure 5 can be

compared with those constructed by Jackson and others (1977) on the same deposit (Fig. 6). Both are in relatively good agreement. Several assumptions must be made in order to interpret logically the results presented. Several maxima in homogenization temperatures can be defined and may be related to major geological events. These maxima represent thermometric ranges and largely overlap. Thus the phenomena in question are not strictly isothermal. Also, secondary modification of the physical characteristics of the inclusions such as necking-down which appears to be very common and perhaps leakage may have modified the microthermometric parameters of the trapped solutions. Some mixing of non-contemporaneous fluids would also be possible in an environment characterized by repeated fracturing. Nevertheless, the thermometric maxima are well established and the salinity variations within each postulated event small enough to be realistic for major hydrothermal stages.

These maxima occur simultaneously in veins and wall-rock greisens. Fluids encountered in the unaltered enclosing granite (but in fact the granite is never devoid of some phyllic alteration) (see Table 1) homogenize at lower temperature as do those related to sulphide deposition.

It can be assumed that the successive phases of fracturing never strongly affect the characteristics of the hydrothermal solutions. The whole hydrothermal evolution may be considered as continuous in time with both salinity and temperature decreasing in a classical manner; no boiling of the fluids occurred even during the fracturing events. On the other hand, Jackson and others (1977) admit that the pressure is low enough to allow some boiling to occur (monophased gaseous and halite-bearing inclusions).

These authors recognize three main phases of hydrothermal activity (alteration and mineralisation);

- Q-main mineralization: 250 to 380°C; salinity of 3-12 eq. wt% NaCl
- Q-sulphides: 210 to 340°C; salinity of 3-11.5 eq. wt% NaCl
- Q with collomorphic iron and kaolinite: 70 to 150°C

with metasomatic quartz (greisen) overlapping between the first two phases of metallic infill: 270 to 420°C with the same range of salinity.

Fluid inclusions in St Michael's Mount and Hemerdon Ball areas which have very similar geological setting and alteration paragenesis have also been studied by Jackson and Rankin and may be compared (Fig. 7). They conclude from fluid inclusion results that the hydrothermal history is slightly different from St Michael's Mount and Cligga at Hemerdon Ball: higher temperatures recorded and evidence for some sporadic and secondary boiling.

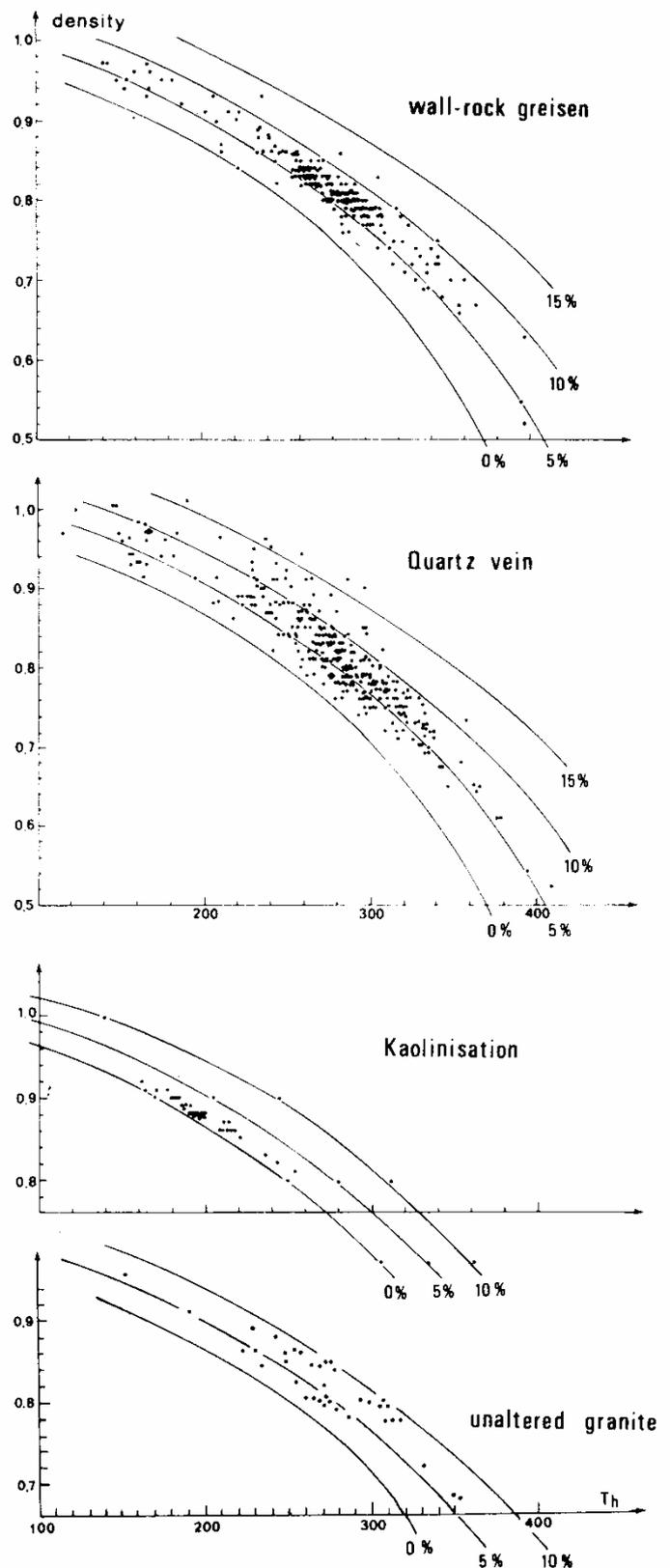


Figure 4. Density - salinity - homogenization temperature diagram.

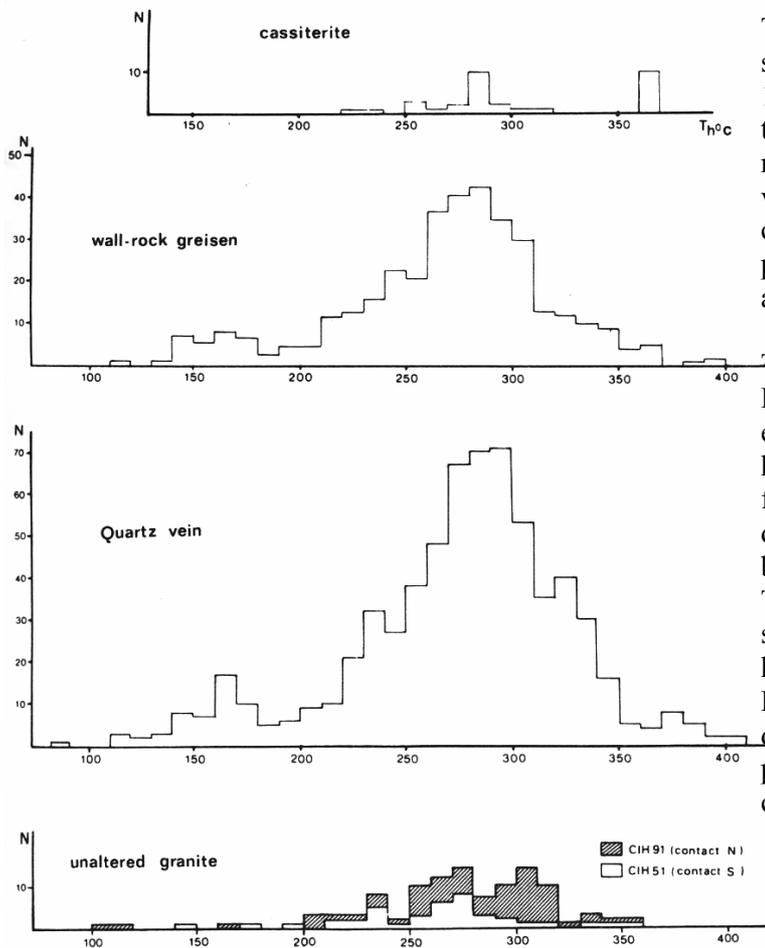


Figure 5. Global distribution of the homogenization temperature in the liquid.

The characteristics of the early fluids at Cligga are very similar in veins and wall rock greisen: salinity around 8-10 eq. wt% NaCl and main temperature range from 350 to 390°C, up to 420°C. This confirms the close genetic relationship between the two phenomena: filling of the vein and surrounding alteration which must be considered as two complementary expressions of the same process, a proposition which confirms the chemical assumption.

The characteristics of these fluids may be shown in a P.V.T. diagram where two main isochores for 5 and 10 eq. wt% NaCl are constructed (Fig. 8). The homogenization temperature are subject to a correction for the effects of pressure. At the time of trapping, the depth of emplacement of the Cornubian batholith has been estimated by British authors to be about 2 to 4km. The minimum pressure required to prevent boiling of the solutions is about 200 bars, equivalent to 3 kms under hydrostatic pressure or 770 metres in a lithostatic regime. Figure 8 shows the possible trapping temperatures for depths of 2 and 4km both hydrostatic and lithostatic pressures. Table 2 summarizes the temperature correction for both cases.

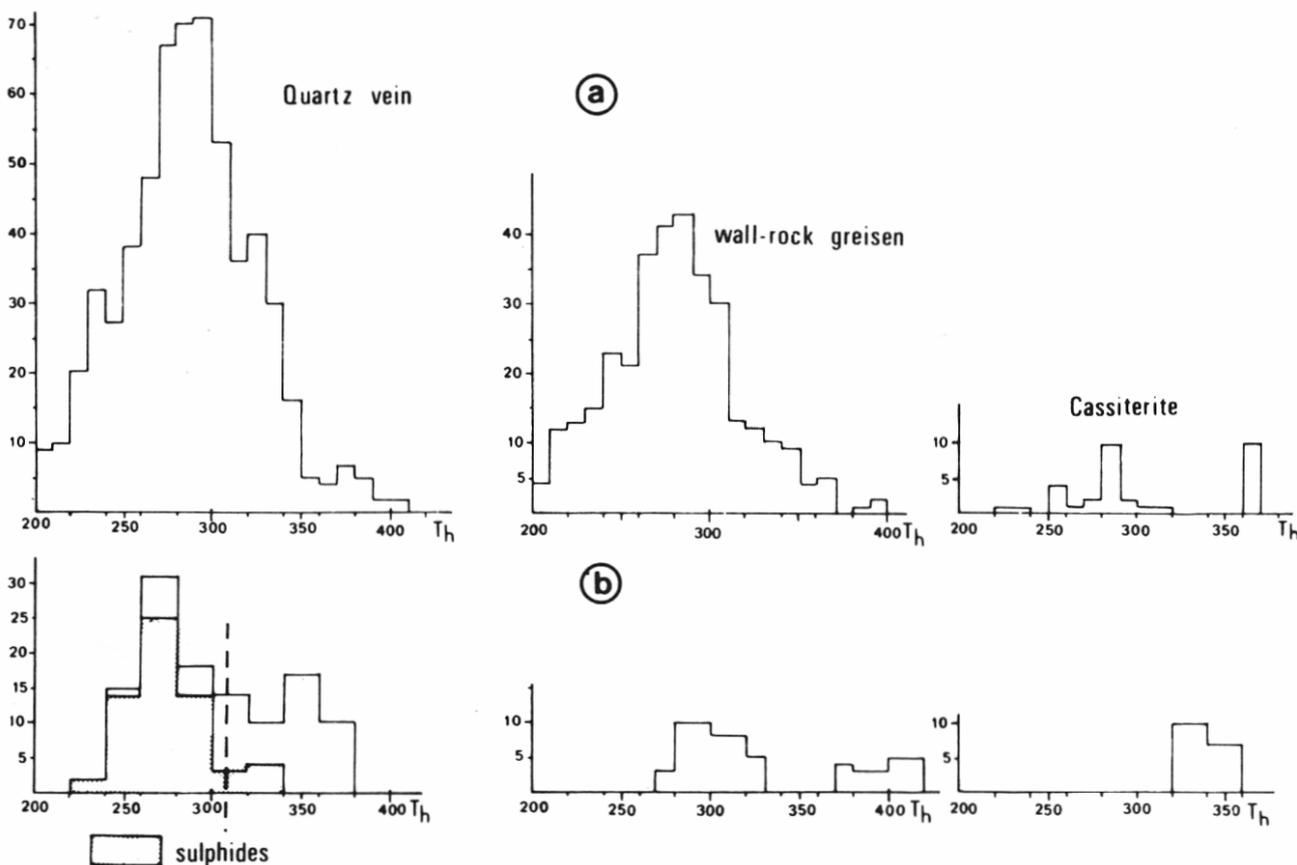


Figure 6. Comparison between the frequency histograms of homogenization temperatures a) Charoy 1979, b) Jackson and others 1977.

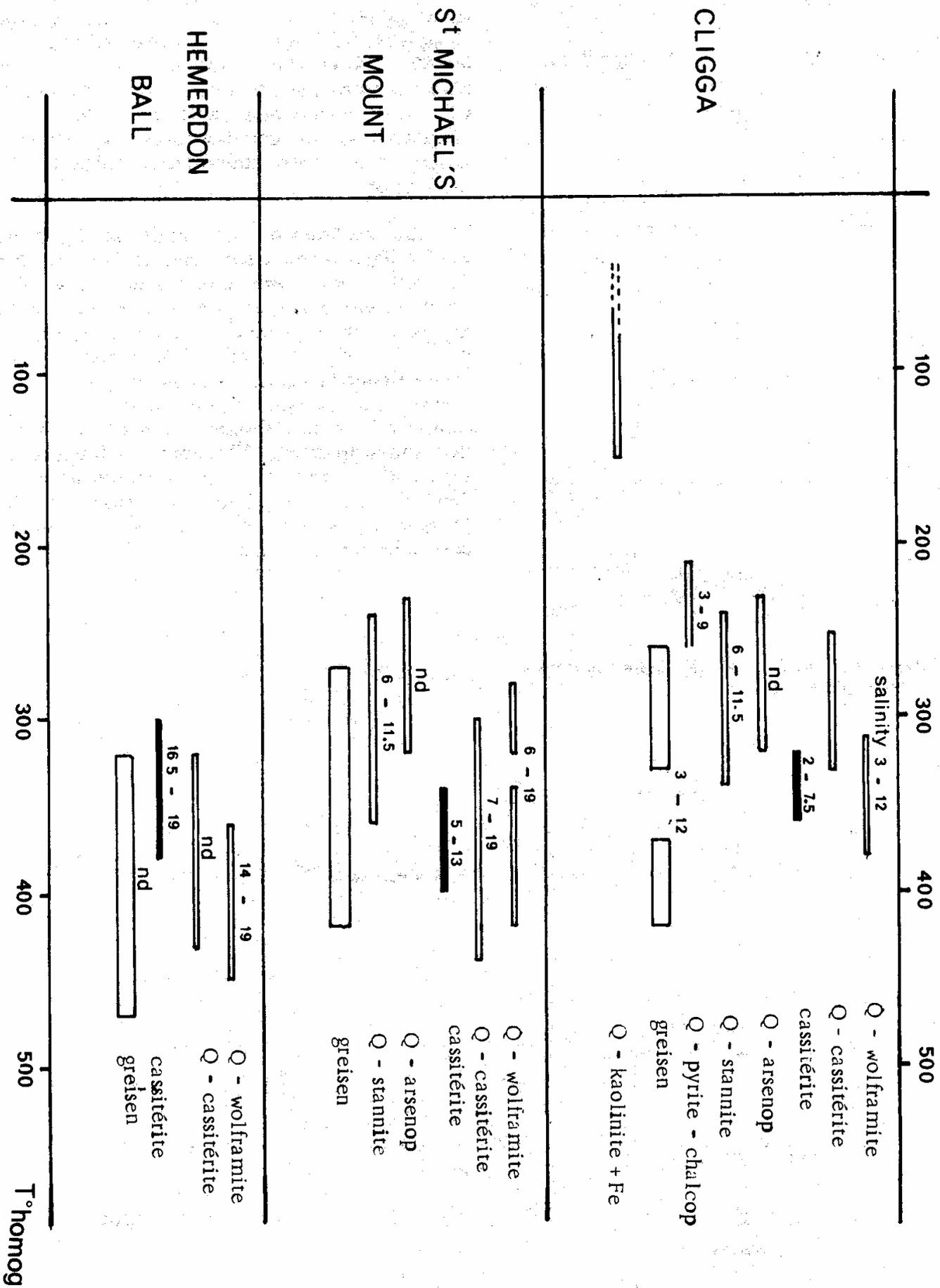


Figure 7. Schematic distribution of the main range of homogenization temperatures in St Michael's Mount, Cligga Head and Hemerdon Ball (from Jackson and Rankin data).

Isochore	P at the time of trapping for 2 and 4km	Temperature Correction	necessary P to prevent boiling
T. homog = 380°C Salinity = 10 eq. wt% NaCl Density = 0.7	130b. hydrost.	boiling	3000m in hydrost. pressure
	260b. hydrost.	6°C	
	500b. lithost.	40°C	770m in lithost. pressure
	1000b. lithost.	106°C	
T. homog = 285°C Salinity = 5 eq. wt% NaCl Density = 0.8	150b. hydrost.	10°C	800m in hydrost. pressure
	300b. hydrost.	25°C	
	500b. lithost.	45°C	230m in lithost. pressure
	1000b. lithost.	73°C	

Table 2. Hypothetical corrections for the homogenization temperatures for 2 main isochores at depths of 2 and 4km. (Charoy 1979)

Sawkins (1966) postulates that the maximum correction is unlikely to exceed 40°C. The phenomenon of greisenisation requires an abundance of hydrogen ions and thus needs a large volume of solution percolating through the joints to bring hydrogen and leach alkalis (essentially sodium) and some silica out of the alteration zone. Thus the granite-solution system is necessarily open and this suggests that the surrounding pressure is not truly lithostatic. From Fig. 8; the pressure correction varies from a few to one hundred degrees. A depth of 4km must be too high because of the very high level setting of the whole Cornubian intrusion and the sub-volcanic

character of the Cligga stock over the batholith ridge; also because of the meteoric composition of even the primary hydrothermal solutions as demonstrated by their stable isotope composition (Sheppard 1977).

Bulk crushing and leaching of quartz samples from several examples of quartz veins were made and K/Na atomic ratio determined. In spite of the important mixing of solutions, the atomic ratios can be statistically averaged into three ranges. They are representative only of the most abundant generations of inclusions in the samples (Table 3).

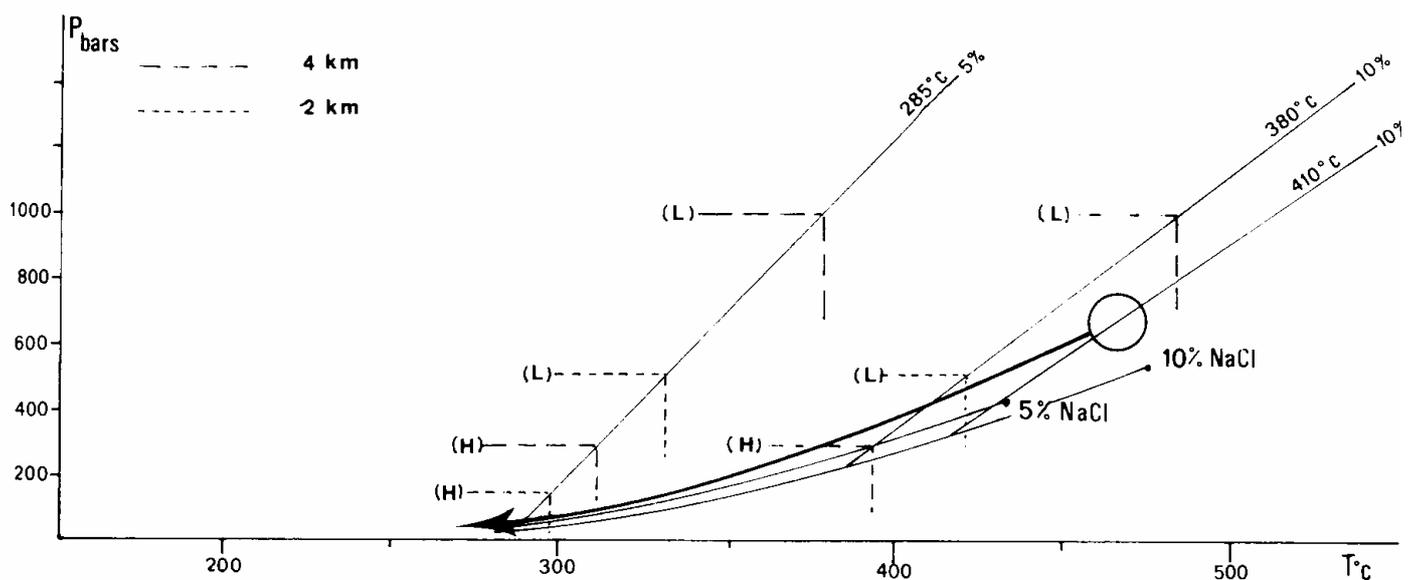


Figure 8. Hypothetical corrections for the effects of pressure (in hydrostatic and lithostatic regimes) for an overlapping of 2 and 4km. The hypothetical path of the hydrothermal fluids evolution during alteration and mineralization is shown by the arrow.

Occurrences	K/Na atomic ratio	equivalent temperature (equilibrium with 2 feldspars)
Cassiterite vein	0.063 to 0.091	285°C
Wolframite * (20)	** 0.077	
Wolframite vein	0.105 to 0.147	365°C
Sulphides * (20)	** 0.118	
Kaolinite vein * (11)	0.191 to 0.310 ** 0.248	600°C

Table 3. Average K<sub>2</sub>O/Na<sub>2</sub>O atomic ratio in the lixiviat of crushed quartz samples and their equivalent temperature at equilibrium with two feldspars (from Lagache and Weisbrod 1977) in Charoy 1979.

\*number of analyses  
\*\* average

These solutions were aggressive with the feldspathic association of the enclosing granite. Lagache and Weisbrod (1977) have demonstrated that the K/Na atomic ratio of a hydrothermal solution buffered by 2 feldspars depends only on temperature. In fact, equilibrium temperatures corresponding to the K/Na ratios (Table 3) form a sequence opposite to that logically expected and suggest constant disequilibrium between solutions and granite. This requires that the successive fracturing events maintain an essentially open system during the whole alteration process. These abnormal ratios can also be looked at in relation to the paragenesis: - The first ratio (0.077) is too low and only the K feldspar will be hydrolysed. This earlier fluid is never equilibrated with the mineral association of the granite and may not have a magmatic origin; it may be derived from the surrounding low grade metamorphic killas,  
- the second ratio (0.118) must give a good representation

of the greisenising fluids, so the feldspars were both leached out. This agrees very well with the characteristics of the fluid phase associated with some tin deposits in Brittany (Charoy and Weisbrod 1975),  
- the third range (average 0.248) is too high and must be explained by the preferential leaching of plagioclase during kaolinisation as shown by Exley (1976). This agrees with the ratio found in quartz samples from the Ploemeur kaolin deposit in Brittany (Charoy 1975). This high ratio may also be partly explained by some contamination during the crushing and leaching process with illitic material intergrown with kaolinite.

The acidity of the solutions may be approximated from solution-alteration mineral equilibrium diagrams (Montoya and Hemley 1975). Ph values are reported in Table 4. These values move from 3.2 up to 4.9 and increase with decreasing temperature.

T.°C	Salinity eq.wt% NaCl	K/Na at	Molality		log aK <sup>+</sup> /aH <sup>+</sup>	log a Na <sup>+</sup> /aH <sup>+</sup>	pH aH <sup>+</sup>	paragenesis
			NaCl	KCl				
450	9	0.080	1.570	0.125	2.3		3.2	muscovite
					3.5		4.4	
300	8	0.130	1.320	0.172		4	3.8	muscovite Ab equilibrium
					2.5		3.3	
					4		4.8	
						3.75	3.6	muscovite
200	3	0.250	0.423	0.106			4.6	
					3		4	muscovite
						4.5	4.9	kaolinite equilibrium

Table 4. Chemical characteristics and estimated acidity of three main stages of hydrothermal alteration.

In conclusion, it can be established that:

1. In spite of the ideal appearance of the greisen, the Cligga Head area does not represent such a good example for the comprehension of the whole phenomenon and for its physico-chemical quantification because of the important disturbance and overprinting by later hydrothermal stages.

2. Chemically, greisenisation appears to be characterized by a variable leaching of some major elements from the granite: total for sodium, partial for silica and potassium; these last may precipitate directly from the solutions into the bordering fractures. The width of the greisen wall-rock will depend on the porosity of the host rock and on the relative amount of unbuffered solution percolating through these pores and fractures.

3. The main greisenisation occurs over a wide range of decreasing temperature, from 420°C (or more) to about 300°C. The solutions have a relatively low salinity, are strongly acid and are responsible for the hydrolysis of the feldspathic association in the enclosing granite. K feldspar is more unstable and becomes unstable earlier than albite. This can be considered as the first stage of mineralization of the "depart acide, type and is followed by the precipitation of the bulk of the sulphides and some cassiterite with muscovite, chlorite and fluorite, a very similar association to the whole paragenesis of the lodes (respectively Q-cassiterite-greisen and Q-cassiterite-sulphide types in the Russian literature).

4. The evolution of the hydrothermal system is thought to be more or less continuous in time with regularly decreasing pressure, temperature and salinity of the solution. This certainly must be regarded as an excessive simplification if one considers the large multiplicity of hydrothermal events in the Cornubian Province as indicated by geochronological data (Halliday 1980). Also the whole sequence of mineralized solutions may not be encountered in the Cligga area; for example, the low temperature brines described by Alderton (1975, 1978) in the cross-course strike lead-zinc ores never occur in the greisenised sheet vein mineralization associated with the Cligga Head granite-porphry stock.

5. The assumption that tin and tungsten are preferentially carried in hydrothermal solutions by fluorine complexes (Barsukov and Kuril' Chikova, 1966; Tischendorf 1973) appears to be in part unrealistic. However, according to the successive gangue mineral associations, several complexes including borate then fluorine complexes may be responsible for carrying the metals in solution.

There remains the problem of the time interval between the crystallization of the rock, its fracturing and the beginning of convective circulation and the related alteration. One may assume a solidus temperature lower than 700°C at low total pressure because of the effect of boron, fluorine and lithium on the solidus curve. The start of the greisenisation process takes place at about 450°C. The batholith was emplaced at its high level around 295 Ma (up to 300-310 Ma for Hawkes, personal

communication and this volume) and some phyllic assemblages of greisen bodies have given an age around 280-285 Ma (Halliday 1980). Is this temperature lowering of about 250°C compatible with a hiatus of 10-15Ma or more?. According to Norton (1979), the life span of a hydrothermal convection cell created by an intrusion will be only of the maximum order of 105 years and will be essentially a function of the flow rate of the solutions. This temporal incompatibility may suggest that:

- either the age of the phyllic alteration is too young,
- or the age of small stocks protruding from the main batholith (such as Cligga) is younger than that of the main granite body,
- or the hydrothermal convection system developed on the flanks of the major ridge plutons (Jackson 1979) and especially in and around the Cligga stock are not directly genetically related to the crystallization of the granite magma itself but must be connected with a later widespread magmatic event, perhaps of the elvan type, as suggested by Hawkes (1974) and Hawkes and Dangerfield (1978).

## The tourmalinisation process

Tourmalinisation is the second phenomenon studied in Cornwall. This province must be chemically characterized by a huge anomaly in boron (associated with lithium and fluorine). As some conclusions have already been presented during the MAWAM Meeting in Exeter (Charoy 1980) and must be published soon, they will be only summarized here.

Tourmaline is a mineral which occurs throughout the alteration processes and the successive generations present sharp important chemical variations. Beside true tourmalinisation examples (Lister 1978), one can affirm that in some cases, tourmaline is a true magmatic phase as at Cligga Head. Although quartz-tourmaline associations are often recognized as a metasomatic alteration, some of them must be considered as the consequence of the unmixing of a particularly boron and alkalis rich phase escaping from a crystallizing magma as thus primary in origin. As at Cape Cornwall, this phase can generate only spots and patches in a pegmatitic structure or a tourmaline granite (tourmaline as the single coloured phase). Locally the phenomenon must be complicated by a more complete unmixing of the components to form a true quartz-tourmaline rock associated with a strong metasomatism. Sodium is preferentially partitioned into a brine contemporaneous with this unmixing. This process is summarized in Fig. 9. This model is well supported by the experimental work of Pichavant (1979) on the system granite-B<sub>2</sub>O<sub>3</sub>-H<sub>2</sub>O.

Roche Rock on the north side of the St Austell pluton would have a similar origin (Badham 1980); potash metasomatism would be expressed by the surrounding microclinized slates in association with some brecciation

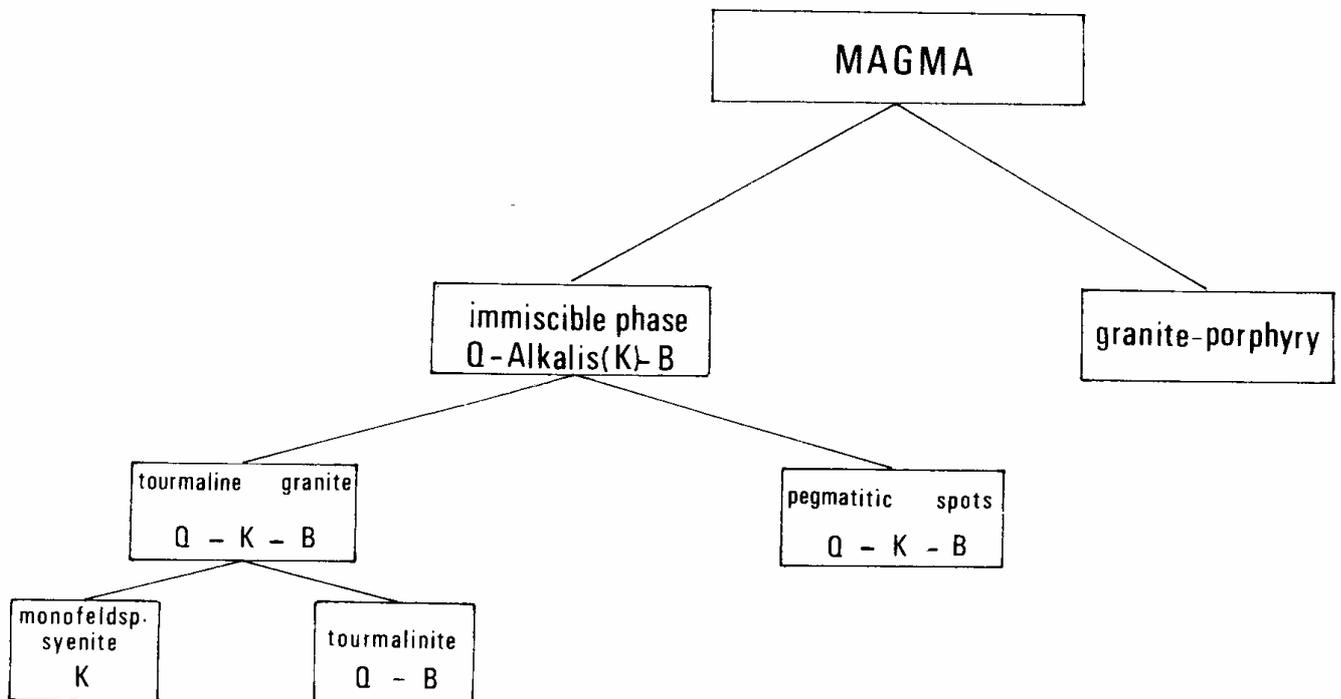
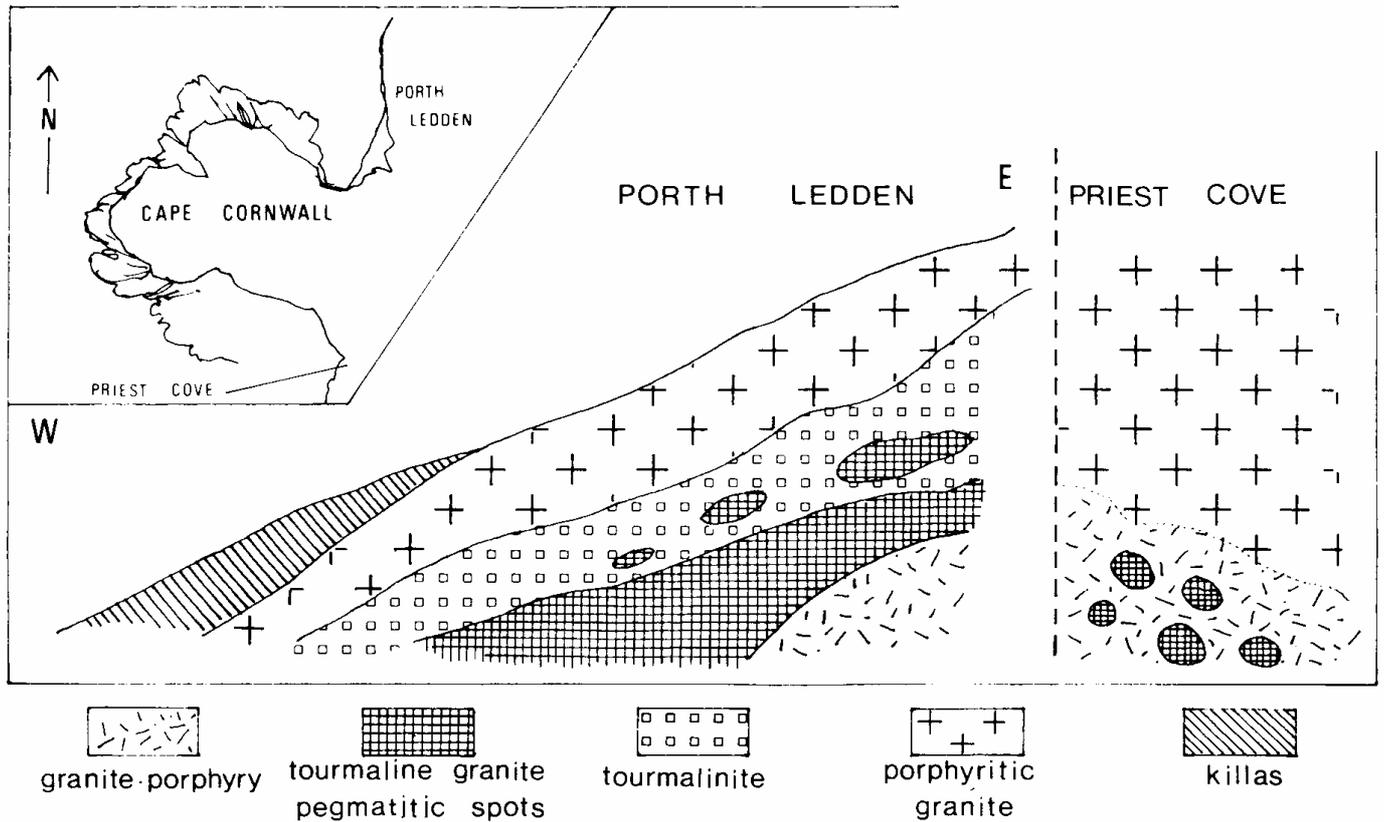


Figure 9. Successive unmixing episodes and their expressions in Cape Cornwall. (Priest's Cove and Porth Ledden).

(Goode and Taylor 1980) and/or by a pegmatite body of alkali feldspar with lesser quartz and tourmaline as described by Edmonds and others (1969).

During this unmixing the fluid pressure can exceed the lithostatic head and thus generate intrusive or pneumatolytic breccia structure as described by Goode and Taylor (1980). The Wheal Remfry breccia in the western part of the St Austell mass appears to be very early (crosscut by aplite vein and elvan dyke) and would be explained by this genetic model (Halls and others 1977; Badham 1980).

## The kaolinisation process

China clay deposits of considerable economic significance (2.5 millions tonnes of kaolin per annum) are one of the characteristic features of south-west England. The St Austell pluton contains most of the large china clay open pits and kaolin exploitation has in large part changed the flat morphology of the country.

There is considerable debate amongst geologists about the origin of the kaolin, whether by tropical weathering or hydrothermal alteration.

In Cornwall and Devon especially, arguments are conflicting and several lines of evidence have been put forward; these have been summarised by Bristow (1977):

- late supergene origin:
  - evidence of Tertiary lateritic weathering;
  - low density and high porosity of china clay matrix and large well preserved morphology of kaolinite stacks;
  - oxygen/hydrogen isotope studies indicating a late low temperature supergene environment.
- hydrothermal alteration:
  - great depth and funnel morphology of the deposits;
  - close association with true hydrothermal events.

Experimental investigations on kaolinite show that synthesis conditions are very variable and the controlling parameters are numerous: pressure, temperature, Si/Al ratio, acidity, other cations in solution... (Charoy, 1979).

The increasing kaolinisation of a granite body, as with the greisenisation process, appears to be differential for the feldspathic phases with a double correlation between the respective amounts of K feldspar - illite and albite (montmorillonite) + kaolinite (Exley 1959, 1976). The incongruent dissolution of albite is twice as fast as that for K feldspar (Lagache 1976).

Chemically, global analyses recalculated to take into account the strong decrease of bulk density show that the kaolinisation process is characterized by an incomplete leaching of alkalis (some potassium will be fixed in a

illitic phase) and a partial leaching of silica. Alumina appears to be strictly constant which seems to confirm its insolubility. In spite of this assumption, Al must be present in significant amounts in solution to precipitate clay minerals directly, such as those encountered in vughy quartz (Charoy 1975-1979). A microthermometric investigation of the fluids contemporaneous with kaolinite has been made on some clay deposits in Brittany and Cornwall (Charoy 1975, 1979). Results (see also Figs. 4 and 5) show that the argillisation process must begin around 200°C. The solutions have a very low salinity (1 to 3 eq. wt% NaCl) are very poor in sulphate anions, and are acid (pH around 4.5).

The very close spatial relation between kaolinised occurrences and undoubtedly higher temperature hydrothermal events such as greisenisation and tourmaline veins must be considered as the logical prolongation of the previous hydrothermal activity. According to Bristow (1977) the hydrothermalized metastable matrix will be much more susceptible to later supergene kaolinisation. Charoy (1975) suggested that the fracture system in an already hydrolysed granite body would facilitate the percolation of a larger volume of water; thus the granite would be more intensively affected by a later weathering process.

## Conclusion

The phenomena studied have been presented out of their regional, magmatic, tectonic and metallogenic context. In spite of the statistical approach used, the results and the conclusions concern only the studied examples. It would be presumptuous, dangerous and even wrong to draw more general conclusions. Furthermore, these are only some examples of the more complicated magmatic, late magmatic and hydrothermal history of the polyphased Cornubian batholith where successive but often superimposed differentiation, unmixing, metasomatism and alteration have taken place. So, what is really the part played by such or such process (Badham 1980)? Do these always have the same expression and a definite chronology? How are these important in the origin, the transport and precipitation of the ore minerals? Must they be considered as purely granitic fluids enriched in volatile components or a greater or lesser mixing of external solutions from the low grade metamorphosed killas? What is the real role played by late magmatic events, is the strict parallelism between the strike of lodes and elvans more than the consequence of the infill of fractures grown in a single stress regime? May these same fluids be responsible for numerous alteration or differentiation types according to the structural level, the porosity and the fracturing of the enclosing rocks?

The history of the Cornubian batholith is complex and more studies are still needed to help answer these questions before a clear and logical understanding of all these phenomena and their mutual relationships is found.

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## Discussion

*Dr D.A.C. Manning* asked whether the granite solidus temperature (700°C) given by Dr Charoy had taken account of the presence of volatile elements such as boron and fluorine. The presence of either boron or fluorine may reduce the solidus to 600°C or less at 1kb and so greatly reduce the temperature interval between magmatic and hydrothermal processes.

*Author's reply:* The influence of fluorine or boron (or both) on the lowering of the granite solidus temperature in experiments carried out by Dr Manning in Manchester and Dr Pichavant in Nancy is now well understood, and it is certain that the given 700°C estimation at 1kb is too high, particularly in the boron-rich environment of Cape Cornwall. Moreover, with this assumption, the isochore of the primary saturated brines postulated in equilibrium with the silica-boron rich phase will crosscut the lowered solidus at lower pressures (around 3kb) than those graphically drawn in my thesis.