The role of metamorphic fluids in the development of the Cornubian orefield: fluid inclusion evidence from south Cornwall

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Abstract

Veins developed during contact metamorphism associated with the emplacement of the Cornubian granite batholith contain both H_2O-rich and CO_2-rich fluid inclusions. Microthermometric data indicate that unmixing of a low-CO_2, low-salinity fluid occurred at 400–200 °C and 1000–500 bars to produce low-density CO_2-rich vapour and saline aqueous fluids (8–42 wt.% NaCl equivalent). Decrepitation-linked ICP analyses show that the cation composition of the brines is dominated by Na, K and Ca, but that significant amounts of Li, Sr, Ba, Fe, Mn, Zn and B are also present. Bulk volatile analyses confirm the dominance of CO_2 over N_2 and CH_4 in the vapour phase, with CO_2/N_2 molar ratios of 15.3–28.7 and CO_2/CH_4 molar ratios of 66.9–292. The relative abundance of nitrogen suggests an aureole-derived 'organic' component is present.

The source of the fluids is ambiguous as they are intermediate in composition between ideal 'magmatic' and 'metamorphic' end-members. It is proposed that this is due to mixing of the two types of fluid in the contact aureole during granite intrusion. A model is suggested in which magmatic–metamorphic circulation occurred synchronously with granite emplacement and subsequently evolved to a meteoric-dominated system with the bulk of the ore deposits forming in response to the influx of meteoric fluids.

KEYWORDS: metamorphic fluids, fluid inclusions, Cornubian orefield, Cornwall.

Introduction

As part of a detailed study of Hercynian orogenic fluid evolution in southwest England, fluids mobilized in the contact aureole of the Cornubian granite batholith have been investigated. The composition of these fluids has been established by a fluid inclusion study involving extensive microthermometric analysis and bulk volatile and decrepitate analyses. These data have allowed constraints to be placed on the source and evolution of fluids in the aureole rocks during granite emplacement, as well as providing evidence regarding the possible role of contact metamorphic fluids in the genesis of the Sn–W and polymetallic sulphide ore deposits.

Regional geology

The study area is situated on the west coast of the Lizard Peninsula in south Cornwall (Fig. 1).

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The coastline provides a well-exposed cross-section through Hercynian structures into the contact aureole of the Cornubian batholith. In Cornwall, the batholith was intruded into low-grade, dominantly pelitic metasediments of Devonian age, at shallow depths of approximately 4 km (Willis-Richards and Jackson, 1989). The currently exposed granite stocks represent apophyses of the batholith and are compositionally and texturally varied (Exley *et al.*, 1983). The Tregonning granite, in the north of the study area (Fig. 1), is a highly evolved Li- and F-rich topaz granite (Stone, 1975), which was intruded by passive stoping of the host slates at 280 ± 4 Ma (Darbyshire and Shepherd, 1987).

Contact metamorphism and deformation accompanied instrusion of the batholith, producing a zone of spotting, recumbent F_3 folds and associated S_3 crenulation cleavage (Rattey, 1980) extending up to 4 km southeast of the Tregonning granite (Fig. 1). The Tregonning granite postdates this deformation and produced its own zone of
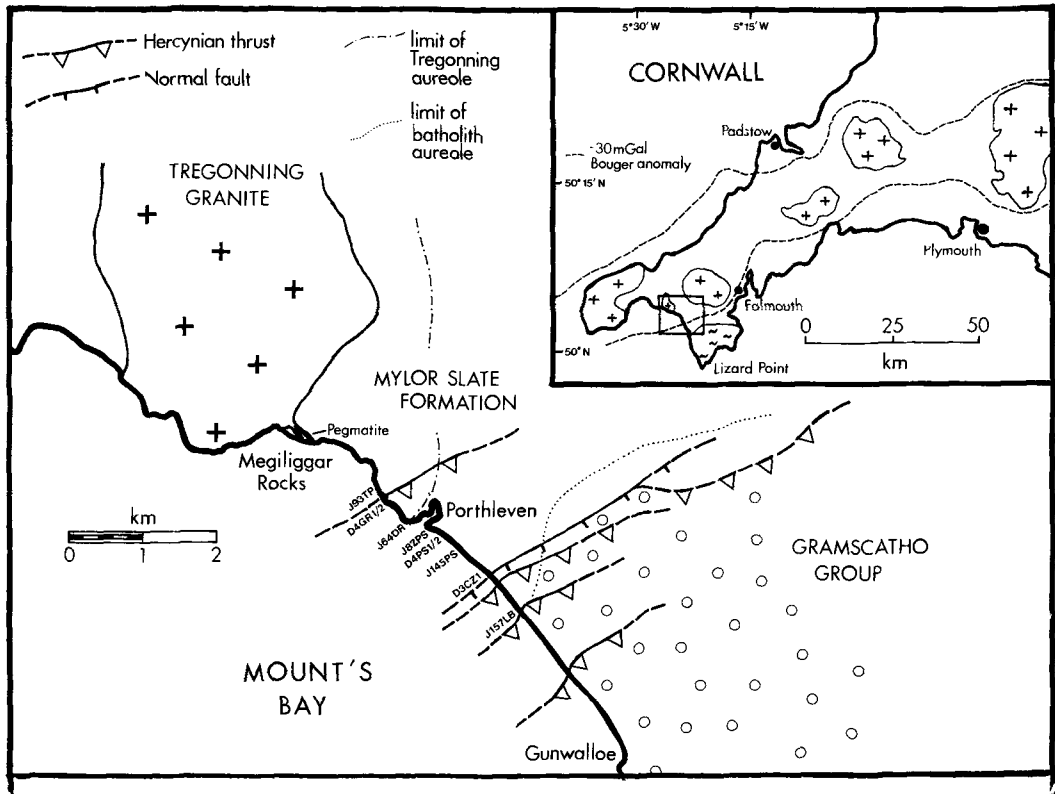
FIG. 1. Location of study area showing simplified geology and sample sites.

contact metamorphism reaching hornblende hornfels grade. Biotite, actinolite, epidote, albite, andalusite and cordierite are developed at lower grades.

Hercynian metamorphic fluids

Hercynian events in southwest England resulted in the production of metamorphic fluids (i.e. fluids evolved as a result of devolatilization reactions during prograde metamorphism) at two distinct stages: (1) During ?early–mid Carboniferous low-grade regional metamorphism (M1); (2) During late Carboniferous–early Permian contact metamorphism (M2), resulting from emplacement of the Cornubian granite batholith.

Previous studies have failed to constrain the role of such fluids in the genesis of the Cornish ore deposits. Primmer (1985) suggested that M1 fluids in North Cornwall may have been involved in post-orogenic mineralization on the basis of stable isotopic compositions comparable to those estimated for hydrothermal fluids by Sheppard (1977). However, textural evidence indicates that peak regional metamorphism in South Cornwall

was contemporaneous with the D1 deformation (Barnes and Andrews, 1981). Structural relationships (Rattey, 1980) and K–Ar dating (Dodson and Rex, 1971) both suggest that D1 significantly predated granite emplacement in this area. This evidence precludes the involvement of M1 fluids in the magmatic–hydrothermal system.

Jackson et al. (1982) considered that a metamorphic source for the fluids responsible for Sn–W and polymetallic sulphide mineralization could not be ruled out on the basis of stable isotopic data. However, they emphasized the consistency of the data with an early magmatic component and a dominantly meteoric origin for later hydrothermal fluids, in agreement with Sheppard (1977). On the basis of crush–leach studies of inclusion fluids, Bottrell and Yardley (1988) and Yardley et al. (1989) suggested that magmatic fluids may be responsible for much of the metal transport and ore deposition in the system.

The possible role of M2 fluids in the early stages of fluid circulation and mineralization has been largely ignored, or at best remained unconstrained. Simple calculations of the relative pro-

portions of 'magmatic' water (i.e. H_2O released by crystallization of a volatile-bearing melt) and contact metamorphic H_2O (produce by dehydration reactions in the aureole) indicate fluid masses of the same order of magnitude. Despite the uncertainties inherent in such calculations, the amount of M2 fluid which is likely to have been evolved is significant. Whether or not this fluid became involved in the magmatic–hydrothermal system depends on a number of factors, including the relative timing and duration of fluid release, and the direction of flow. Constraining these parameters is beyond the scope of the present paper. Here, the composition of fluids mobilized in the aureole are examined directly in order to assess the importance of different sources in their generation. This information provides some control on the role of M2 fluids in subsequent mineralization phenomena.

Field relations

A study of veins developed in the contact aureole of the Tregonning Granite in southwest Cornwall (Fig. 1) formed part of a wider investigation into Hercynian fluid evolution in the province. Field studies have revealed a series of veins developed up to 4 km from exposed granite which formed contemporaneously with granite emplacement.

The veins are composed of greyish quartz with a greasy lustre and are several centimetres to 30 cm thick, extending for up to several tens of metres in outcrop. A variety of orientations are developed. Subvertical NNW–SSE-trending veins are abundant in the outer parts of the contact aureole, whereas closer to the granite, subvertical NNW–SSE-trending and NE–SW-trending, NW- or NE-dipping veins are observed. The veins are hosted by dark grey or grey–green pelites of the Mylor Slate Formation as well as by metadolerite sills, 'greenstones', which outcrop in the vicinity of Porthleven (Fig. 1).

Thin-section examination reveals that the veins are composed of equant to elongate subhedral or anhedral quartz crystals with rare fine white mica flakes. Ore minerals (galena, arsenopyrite) are very occasionally observed in the veins. Quartz grain fabrics are generally irregular, providing little evidence of the vein growth mechanism. Alteration of the host rocks in the vein margins is not observed, implying that the vein fluids were close to equilibrium with the rock at the pressure and temperature conditions of vein formation. The observation of contact metamorphic fibrous actinolite growing into some of the greenstone-

hosted veins suggests that fluid mobilization and contact metamorphism were contemporaneous.

Although the veins themselves are essentially unmineralized, greenstone host rocks north of Porthleven do show the development of disseminated arsenopyrite, pyrite, sphalerite, chalcopyrite and galena. This mineralization may be temporally related to the mobilization of the aureole fluids and they may therefore play an important role in the generation of early ore-forming solutions.

Structural relationships indicate that the veins formed late in the intrusion history of the Cornubian batholith (290–280 Ma) since they crosscut F_3 folds and associated sub-horizontal crenulation cleavage (S_3) which formed during batholith intrusion (Rattey, 1980). The veins cannot have formed later than the emplacement of the Tregonning Granite at 280 ± 4 Ma (Darbyshire and Shepherd, 1987), which occurred post-D3.

Fluid inclusion study

A variety of complex inclusion assemblages are present in the ten samples studied. The six main inclusion types observed are described below. The subdivisions are not genetic, being based on their appearance at room temperature (e.g. Shepherd et al., 1985; Rankin and Alderton, 1985).

1. 2-phase, aqueous liquid + vapour ($F = 0.6$–0.95).
2. 2-phase, vapour + aqueous liquid ($F = 0.2$–0.5).
3. Multiphase, aqueous liquid + vapour + one or more solid phases ($F = 0.8$–0.95).
4. (Apparently) monophase, vapour ($F < 0.2$).
5. 3-phase, CO_2 vapour-rich ($F = 0.05$–0.5).
6. 2- or 3-phase, CO_2 liquid-rich ($F = 0.05$–0.2).

(Where F is the estimated volume fraction of the aqueous phase.)

Inclusions are predominantly 10–20 μm in size, although some as large as 40 μm have been recorded. Inclusions of all types occur with negative crystal, rounded or irregular morphologies except type 3 inclusions which tend to have a flattened form. All types may occur singly, in clusters, or defining annealed microfractures. The relative abundance of inclusion types varies considerably from vein to vein, as well as within individual samples. For example, in samples D4PS1 and J145PS, inclusion types 5 and 6 are far more abundant than the other types. In samples J93TP and D3CZ1, inclusion types 3 and 4 are much more abundant than in the other samples (Table 1).

Table 1   Summary of microthermometric data

Sample	Distance (km)	Host rock	Inclusion type	Vol. fraction H2O	Tm CO2	Tm Clath	Tm Ice	Th CO2	Th	Tm Solid
J93TP	1.5	Gst.	4	<0.2	-65.5				246 (V)	
			2	0.2 to 0.5	-60.1 to -59.4	9.4 to 11.6		11 to 17 (V)	363 to 422 (V)	213 to 322 (NaCl)
			3	0.8 to 0.9			-29.1 to -23.0		280 to 380 (D)	
			1	0.5 to 0.8		6.3 to 10.0	-6.1 to -5.9		282 to 441 (L)	
D4GR1	1.8	Slate	1	0.5 to 0.8	-60.3 to -59.7	1.6 to 8.4	-10.7 to -5.2	-15.7 to 6.3 (V)	330 to 418 (L)	
			2	0.2 to 0.5	-63.7 to -62.1	4.6 to 9.7		-18.4 (V)	323 to 425 (V)	
			4	<0.2	-61.2 to -59.6			-20.2 to 22.5 (V)	363 (V)	
			3	0.9 to 0.95			-43.3 to -11.8		113 to 200 (L)	70(KCl), 234(NaCl)
D4GR2	1.8	Slate	5	0.05	-58.7 to -57.8			25.8 to 27.1 (V)		
			4	<0.2	-60.9 to -58.8	8.5		8.9 (V)	251 to 409 (V)	
			3	0.9 to 0.95			-50.3 to -20.8		110 to 247 (L)	237 to 353 (NaCl)
			2	0.2 to 0.35	-59.1 to -58.9			12.5 (V)	282 to 361 (L)	
J64DR	2.3	Gst.	6	0.2 to 0.4	-58.8 to -57.0	4.4 to 8.3		19.4 to 30.4 (L)	253 to 362 (V)	
			5	0.3	-58.4			23.7 to 26.6 (V)	307 to 362 (V)	
			1	0.5 to 0.95	-58.6 to -58.0		-8.6 to -6.2		294 to 318 (L)	
			4	<0.2	-59.9 to -57.8			-7.9 to 8.6 (V)	234 to 297 (V)	
			2	0.3 to 0.5	-58.7 to -57.5				320 to 351 (V)	
J82PS	2.5	Gst.	6	0.05 to 0.2	-58.0 to -56.5			21.2 to 31.1 (L)	185 to 295 (V)	
			5	0.05 to 0.4	-57.9 to -56.8			21.8 to 30.8 (V)	251 to 310 (V)	
			1	0.6 to 0.95	-58.2		-10.4 to -5.5		159 to 248 (L)	
			4	<0.2	-58.4 to -56.8			8.8 to 10.0 (V)	197 to 313 (V)	
			2	0.2 to 0.4	-58.2 to -57.1	6.6	-5.0		270 to 278 (V)	
D4PS1	2.6	Gst.	6	0.05 to 0.2	-56.6 to -58.1	8.9 to 10.6		8.9 to 31.4 (L)	188 to 305 (V)	
			5	0.7 to 0.85				27.0 to 28.8 (V)	279 (L)	
			1	0.1 to 0.2		6.1 to 8.9				
			2	0.2					274 to 285 (V)	
D4PS2	2.6	Slate	5	0.05	-60.1 to -57.4	9.4		26.8 to 27.9 (V)		
			4	0.05 to 0.1	-60.6 to -57.5	9.0		18.4 to 20.8 (V)	248 to 254 (V)	
			1	0.85 to 0.95			-7.0 to -5.8		185 to 307 (L)	
			2	0.3 to 0.4	-60.2 to -59.2					
J145PS	2.9	Gst.	5	0.1 to 0.5	-56.9 to -56.5			23.0 to 26.9 (V)	306 to 359 (V)	
			6	0.1 to 0.4	-57.0 to -56.9			23.7 to 23.8 (L)		
			4	0.5	-57.2			20.8 (V)		
D3CZ1	3.4	Slate	1	0.8 to 0.9		-2.0 to 6.1	-10.4 to -8.1		246 to 338 (L)	
			2	0.2 to 0.5	-59.4 to -59.0	5.6 to 6.1		14.4 to 17.4 (V)	271 to 409 (V)	
			3	0.9 to 0.95			-22.8 to -19.5		228 to 250 (L)	70 (KCl), 302 (NaCl)
			4	0.1 to 0.2	-59.8 to -59.0					
			6	0.5 to 0.7	-59.5 to -59.4			20.1 to 20.4 (L)		
J157LB	4.0	Slate	1	0.5 to 0.9		6.5 to 8.0	-8.3 to -0.7		123-424 (L)	
			5	0.05 to 0.55	-60.3 to -60.0	8.5 to 9.8		21.1 to 29.5 (V)	331-382 (V)	
			2	0.2 to 0.5	-60.4 to -60.2	9.1 to 9.9		15.9 to 19.0 (V)	363-402 (V)	
			4	0.05 to 0.1	-60.3 to -59.5	9.4 to 10.2			325 to 329 (V)	
			6	0.05 to 0.1				26.5 to 29.5 (L)		

Distance = distance from exposed granite ; Gst. = greenstone ; inclusion type in order of decreasing abundance ; volume fraction H2O visually estimated at ambient T from standard charts ; (L) = homogenisation into liquid phase ; (V) = homogenisation into vapour phase ; (D) = decrepitation temperature

Textural evidence for the relative ages of the inclusion types (Roedder, 1981), where present, is generally inconsistent. For example, isolated, negative crystal type 1 inclusions may be associated with trails of type 5 inclusions defining annealed microfractures, suggesting that the type 1 fluids are earlier. However, the reverse relationship is also observed. On the basis of contradictory evidence of this nature, it is concluded that most of the inclusions were formed essentially contemporaneously, during vein formation and soon afterwards. This is consistent with observations of inclusions in other veins studied in the area which formed under a variety of orogenic conditions (author's unpublished data). These suggest that abundant microfracturing occurred during and immediately after vein formation, with microfractures sealed by fluids of the same composition as those responsible for initial quartz precipitation. Late microfractures, containing fluids of a different composition, are observed but are subordinate.

Microthermometry

Fluid inclusions in 100–200 µm thick doubly polished wafers were investigated using a Linkam THM600 heating–freezing stage and Leitz Diaplan microscope (Nikon ×40 objective). Reproducibility is of the order of ±0.2 °C between −100 and −20 °C, ±0.1 °C between −20 and +30 °C and ±1 °C between 30 and 500 °C for easily observable, non-metastable phase changes. Accuracy is calibration dependent and is estimated at ±0.5 °C between −100 and −20 °C, ±0.2 °C between −20 and +30 °C, ±1 °C between 30 and 200 °C and ±5 °C between 200 and 500 °C. Analytical errors are thus insignificant with regard to any geological interpretation.
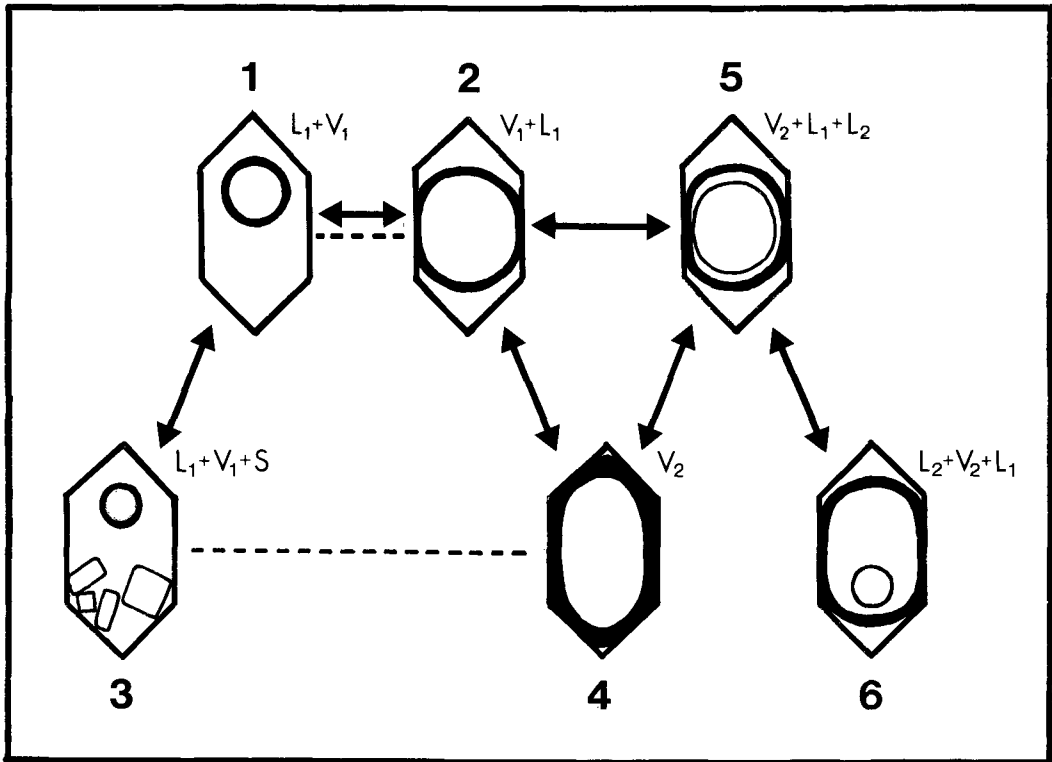
A summary of microthermometric data, in the

FIG. 2. Relationships between fluid inclusion types (see text for details). Arrows denote complete compositional gradation between inclusions; dashed lines indicate coexistence of two immiscible fluids. L_1 = aqueous liquid, V_1 = low density H_2O-rich vapour, L_2 = CO_2-rich liquid, V_2 = CO_2-rich vapour, S = solid phase(s).

form of temperature ranges for each of the major phase changes, is presented in Table 1. It is evident that the extremely variable inclusion assemblages represent a complex history of fluid evolution in both time and space. The textural evidence described above suggests that fluids trapped in different inclusions are closely related temporally and that variations in fluid composition are the result of rapid local changes in P, T and fluid chemistry. This conclusion is supported by the thermometric data which indicate that the inclusion classification is largely arbitrary, there being almost complete gradation between inclusion types. The composition of inclusion fluids thus reflects trapping in a continuously varying fluid system. Relationships between inclusion types are summarized in Fig. 2.

Inclusion types 1 and 2 almost invariably coexist with similar morphological and textural characteristics. Trapping of both types is also observed in adjacent parallel microfractures, and more rarely within the same microfracture. This evidence suggests that simultaneous trapping of two

immiscible fluids occurred. Homogenization temperature (Th) ranges overlap and estimated salinities and CO_2 contents of the two types are in agreement with experimental data for coexisting H_2O-rich liquid and CO_2-rich vapour (Gehrig, 1980; Bowers and Helgeson, 1983). These data suggest trapping between 400 and 200 °C at a fluid pressure of 1000–500 bars. Homogenization of type 2 inclusions extends to higher temperatures than for the coexisting type 1 inclusions (also observed in type 4 and 5 inclusions). This is probably the result of non-equilibrium trapping, due to preferential wetting of the growing crystal by the H_2O-rich phase (Ramboz et al., 1982). It is significant to note that these inclusions are similar to those observed in quartz veins produced by crystallization of a fluid separating from the Megiliggar pegmatite (see Badham, 1980, and Fig. 1).

Inclusion types 3 and 4 are compositionally consistent with moderate to extreme unmixing of essentially the same fluid that produced types 1 and 2. Non-mixing of two contrasting fluids may be ruled out. A Th-salinity (wt.% NaCl equiva-
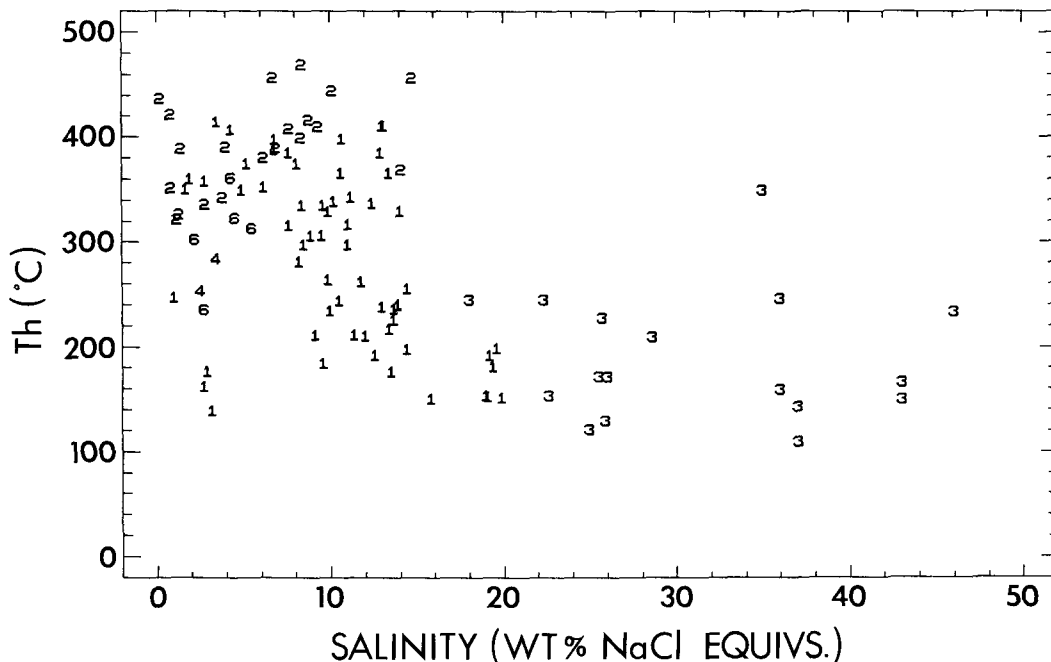
Fig. 3. Homogenization temperature (*Th*)–salinity (wt. % NaCl equivalent) plot. Numbers represent data for different inclusion types. Salinities were estimated from clathrate melting temperatures (type 5 and 6 inclusions), ice melting temperatures (type 1 and 2 inclusions), and halite dissolution temperatures (type 3 inclusions).

lent) plot (Fig. 3) illustrates the continuum between the four inclusion types. The samples tend to display a *Th* decrease away from the granite which may explain moderate unmixing to produce aqueous fluids with salinities of 10–14 wt.% NaCl equivalent. Extreme unmixing occurs locally, possibly caused by sudden depressurization during fracture propagation. However, the possibility of wallrock reactions promoting immiscibility via growth of hydrated minerals cannot be ignored.

The occurrence of samples dominated by type 6 inclusions is problematic. These fluids, with a bulk density of 0.7–0.8 g cm^{-3} and containing on average 70 mole % CO_2, cannot be accounted for by unmixing of a low-salinity, low-CO_2 fluid. The restriction of these fluids to the outer margins of the aureole (>2 km from exposed granite) is significant. It is suggested that they represent a *condensate* formed by hot, low-density, CO_2-rich vapours (represented by inclusion types 4 and 5) separating from a parent fluid and coming into contact with cooler host rocks.

Bulk solute analysis

Bulk analyses of five samples were carried out using a decrepitation-linked I.C.P. technique

(Thompson *et al.*, 1980; Alderton *et al.*, 1982). The samples were carefully selected in order to minimize interpretative problems caused by mixed inclusion populations. Since solutes dissolved in the aqueous phase are determined by this method, the analyses provide an estimate of the composition of the aqueous portion of type 1, 3 and to a lesser extent type 2 inclusions.

The data are presented in Table 2 in the form of Na/cation weight ratios. Each value given is the average of three runs on splits of the same sample. Estimates of actual fluid compositions, calculated using actual Na and in some cases K concentrations determined by microthermometry (based on the NaCl–H_2O or NaCl–KCl–H_2O systems), are shown in Table 3. These values are more dependent on the assumption of single fluid inclusion populations than the element ratios and must be treated with caution.

Major-element ratios for the fluids are plotted on a triangular Na–K–Ca diagram (Fig. 4). Shown for comparison are fields for M1 fluids (300–350 °C), retrogressive fluids (200–300 °C) (author's unpublished data), a Cornubian high-temperature magmatic fluid (Bottrell and Yardley, 1988), and a field for waters of meteoric origin (Rankama and Sahama, 1950). The aureole aqueous fluids are intermediate between 'magma-

Table 2   Bulk D-ICP data

	D3CZ1	J145PS	J82PS	J64DR	J93TP
Na/K	10.8	7.3	5.7	6.7	6.8
Na/Li	363	125	255	144	119
Na/Ca	15.4	11.5	14.3	19.0	7.9
Na/Sr	160	204	79	88	341
Na/Ba	771	1080	2810	1560	388
Na/Mn	24	1160	1140	2540	234
Na/Fe	43	287	493	442	142
Na/Zn	68	242	649	455	277
Na/B	n.d.	109	418	436	72

Na/element weight ratios in the aqueous phase ;
n.d. = not determined

tic' and 'metamorphic' end-members, suggesting a possible mixing relationship. It is re-emphasized that M1 fluids were mobilized at a much earlier stage, contemporaneous with *regional* metamorphism and the D1 deformation event. Their composition is used as an estimate of the composition of any M2 fluids evolved, assuming equilibrium with the same rocks at a similar temperature (at least for the part of the contact aureole being studied).

Although a magmatic–M2 mixture is suggested by the data, a purely magmatic origin for the fluid cannot be ruled out. This problem arises because any magmatic fluid flowing into the aureole will modify its composition through wallrock reactions (particularly due to cooling) and will tend to approach equilibrium with the host rocks. As a result, such a fluid will have a composition intermediate between a magmatic fluid and an M2 'equilibrium' fluid. Similar ambiguities arise in the interpretation of volatile compositions (see below) and stable isotopic compositions (unpublished data). The key to distinguishing between the two possibilities are the kinetics of the processes involved. Fluid mixing is rapid, at least for fluids of similar density, and quickly produces an intermediate fluid composition. In contrast, fluid re-equilibration by wallrock reaction has a strong kinetic control and some components rapidly equilibrate, whereas others (e.g. Na/K ratio) are slow to adjust (Giggenbach, 1988). Application of the relationships of Lagache and Weisbrod (1977) for a fluid in equilibrium with 2 alkali feldspars–H_2O–NaCl–KCl to the bulk ICP data yields equilibration temperatures in the range 300–385 °C. This range is comparable with the fluid trapping temperatures and suggests that the

fluids were not derived from a high-temperature (granite) source, but were generated *in situ* via devolatilization reactions.

Bulk volatile analysis

Duplicate splits of five samples were analysed by heating under vacuum from 100 to 600 °C and monitoring evolved gases by mass spectrometry. Partial pressures of H_2O, CO_2 and non-condensable gases were measured after cryogenic separation, and recalculated to mole fractions. Nitrogen and methane could also be determined from the non-condensable gas mass spectrum. The data, in the form of mole fractions of the bulk fluid, CO_2/N_2 and CO_2/CH_4 molar ratios, are presented in Table 4.

The bulk volatile analyses may be broadly correlated with the fluid inclusion populations present. The three samples with high bulk CO_2 contents are those with abundant dense CO_2-rich inclusions (type 6). The fourth sample (D3CZ1), with a relatively high CH_4 content, has a vapour component dominated by low-density type 4 inclusions. This is good evidence for preferential partitioning of methane into the vapour during phase separation. The abundance of type 1 and 2 inclusions in this sample is reflected by the high bulk H_2O content.

The data also show how CH_4 has a slightly greater effect on depression of the melting point of solid CO_2 than N_2. Samples J82PS and J64DR have similar CO_2/CH_4 ratios but display a decrease in CO_2/N_2 (an increase of 2.7 mole % N_2) accompanied by a shift of −0.5 °C in mean $TmCO_2$. Conversely, samples J64DR and D3CZ1 have similar CO_2/N_2 ratios but display a decrease
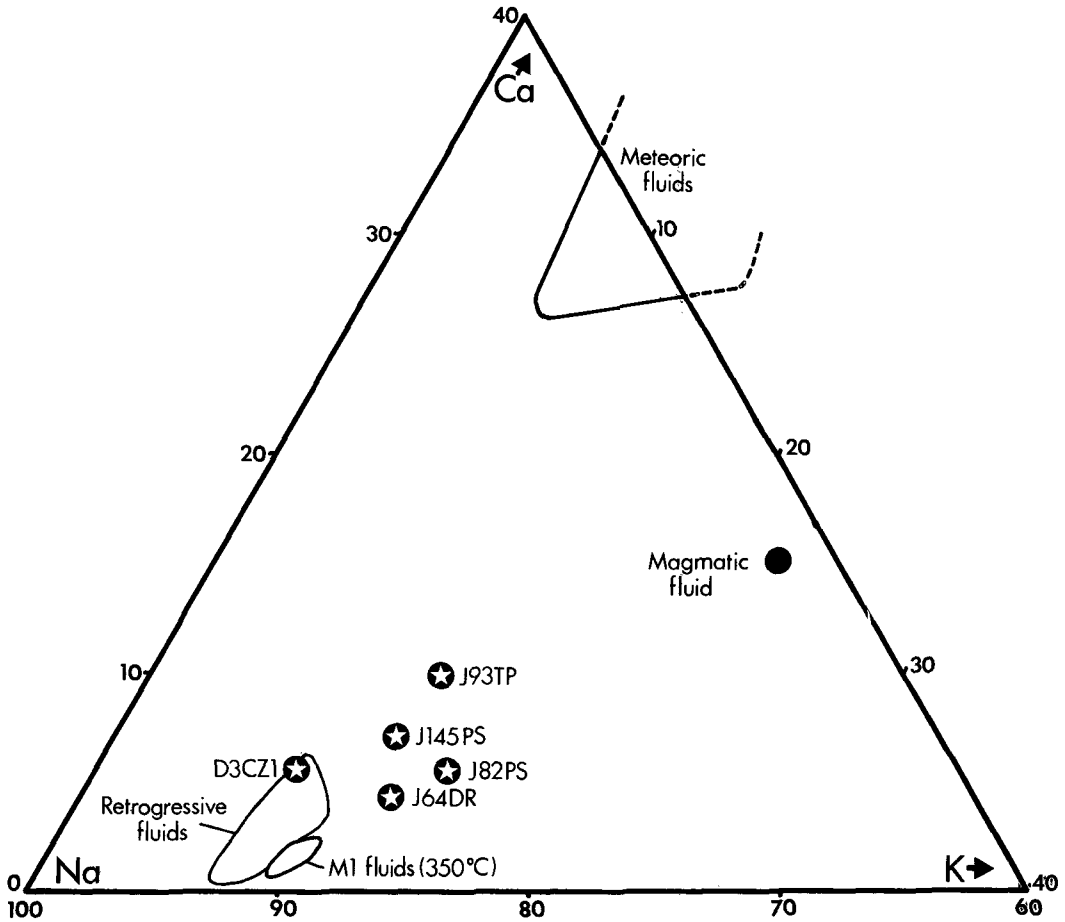
FIG. 4. Na–K–Ca major element plot (by weight) for contact aureole aqueous fluids. Regional metamorphic and retrogressive fluid fields defined by 30 ICP analyses (author's unpublished data); magmatic fluid composition from Bottrell and Yardley (1988); meteoric fluid field defined by data in Rankama and Sahama (1950).

in CO_2/CH_4 (an increase of 6.4 mole % CH_4) and show a shift of $-1.5\,°C$ in mean $TmCO_2$.

The source of the CO_2 is uncertain. Magmatic CO_2 cannot be ruled out, but it is difficult to reconcile a low-CO_2 magmatic source with the CO_2-rich fluids observed, even by boiling. The aureole host rocks contain limited carbonate, which would be an obvious source of CO_2 during metamorphic devolatilization. Greywackes of the Gramscatho Group (Fig. 1) occasionally contain abundant carbonate cement and the Mylor Slates can contain up to 5 wt. % carbonate. The metabasite sills, some of which host contact metamorphic veins, also contain variable amounts of carbonate. It is uncertain whether these rocks could have generated CO_2-rich (approx. 20 mole %) fluids during contact metamorphism. The possible role of

organic carbon and/or disordered graphite in the black slates must be considered in future studies.

Relatively low CO_2 contents (<5 mole %) recorded from aqueous fluids in zones of W-dominated mineralization (Shepherd et al., 1985) have been interpreted as being of magmatic origin on the basis of stable isotopic evidence (Miller et al., 1989). The slightly low $\delta^{13}C$ isotopic signatures (relative to average magmatic carbon) were accounted for by pelite assimilation and ultimate derivation from a pelitic source. However, the data do not preclude an aureole CO_2 source.

The presence of nitrogen in excess of methane in those samples containing dominantly type 6 inclusions is significant in that it is highly suggestive of a sedimentary source. Nitrogen is particularly abundant in organic-rich sediments and up

Table 3   Estimated fluid compositions (ppm)

	D3CZ1	J145PS	J82PS	J64DR	J93TP
Wt% NaCl	20	5	13	10	25
Na	78600	19700	51100	39300	98300
K	7650	2680	8950	5890	15800
Li	240	160	200	270	840
Ca	5180	1710	3630	2120	12400
Sr	500	96	650	450	290
Ba	110	18	19	25	190
Mn	1540	17	51	23	430
Fe	1840	69	100	96	700
Zn	1180	81	81	86	380
B	n.d.	180	120	91	1430

Table 4   Bulk volatile data

	D3CZ1	J145PS	J82PS	J64DR
X H2O	0.938	0.7825	0.7931	0.7217
X CO2	0.0535	0.2041	0.1982	0.2591
X N2	0.0035	0.0119	0.0069	0.0168
X CH4	0.0008	0.0007	0.0012	0.0013
X N.C.	0.0042	0.0008	0.0006	0.0011
CO2/N2	15.3	17.2	28.7	15.4
CO2/CH4	66.9	292	165	199

Mole fractions of volatile phases; X N.C. = mole fraction
non-condensable gases at -196°C (not including N2 or CH4)

to 1345 ppm NH_4^+ has been recorded for black shales in southwest England (Hall, 1988). In contrast, granitic rocks have low nitrogen contents, with a global average of 27 ppm NH_4^+ (Wlotzka, 1972), although Cornubian granites are slightly enriched with an average value of 36 ppm NH_4^+ (Hall, 1988). It is thus likely that an M2 fluid derived from the aureole rocks (in this case black shales) will be nitrogen bearing. However, constraining the nitrogen content of a fluid in equilibrium with a pelite containing organic nitrogen and NH_4^+ in micas is not possible in the absence of relevant thermodynamic data.

Discussion

The aqueous fluids display chemical characteristics intermediate between a primary magmatic fluid and a metamorphic fluid. These features may be produced in two ways:

(1) By equilibration of a magmatic fluid by reaction with pelitic host rocks (i.e. contact metasomatism);
(2) By mixing of a magmatic fluid with a contact metamorphic fluid (M2) derived by thermal devolatilization of the aureole rocks (i.e. contact metamorphism and mixing).

Mechanism 1 assumes that M2 fluid, which must be evolved in significant amounts in the aureole, is essentially expelled from a particular level in the system prior to the crystallizing magma reaching that level. Conversely, mechanism 2 implies that both fluids are mobilized at the same level and are able to interact.

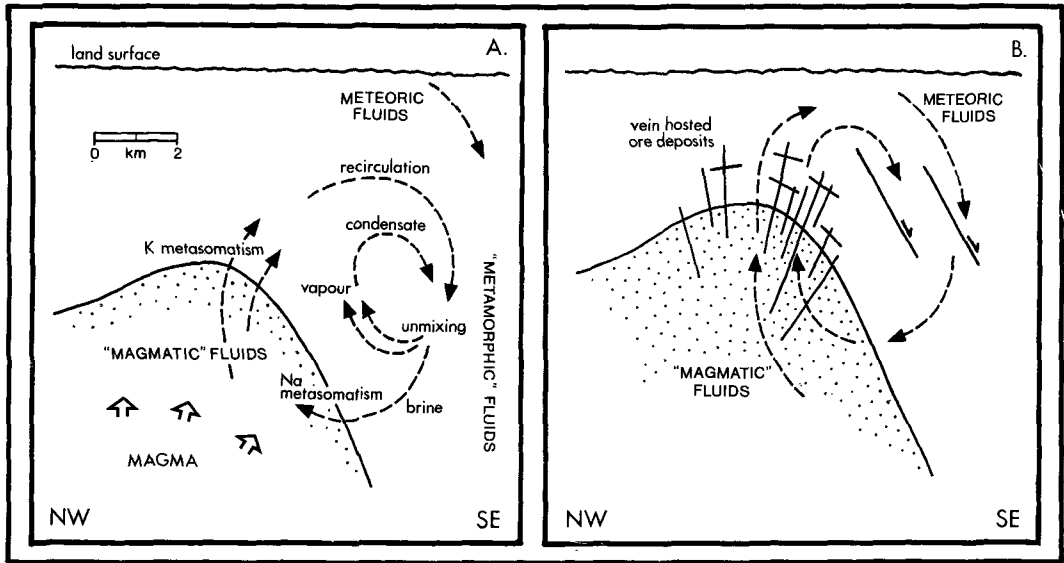Indirect evidence in support of the second

FIG. 5. Model for evolution of granite-driven hydrothermal circulation in south Cornwall. Diagrams represent simplified sections (to scale) across the southern flank of the Cornubian batholith. A. Early magmatic–metamorphic stage; B. Later meteoric(-magmatic) stage.

alternative comes from thermodynamic modelling of plutonic hydrothermal systems. Postmagmatic hydrothermal circulation in the Cornubian batholith is relatively well constrained (e.g. Fehn, 1985). Much of the mineralization is thought to have resulted from the interaction of deep convecting meteoric water with the cooling plutons (Sheppard, 1977; Jackson et al., 1982). These processes were recognized in epizonal plutons more than two decades ago (see review by Taylor, 1977) and now constitute an important part of ore deposit modelling in such systems. More recent studies (Norton and Knight, 1977; Labotka et al., 1985; Bowman, 1987; Ferry, 1989) confirm the importance of hydrothermal circulation in *plutonic* systems and provide some constraints on the nature and evolution of the convecting fluids. An important conclusion, relevant to the Cornubian batholith, is that contact metamorphic fluids are likely to be involved in syn-emplacement hydrothermal circulation.

Such a model has important implications for the evolution of the Cornubian province. It suggests that during emplacement of the batholith, volatiles evolved in the aureole were involved in a convective system and, if sufficient permeability was established in the pluton, may have circulated into the granite itself (Norton and Knight, 1977).

Simultaneous release of magmatic fluid would be dominantly upward, into the roof zone of the

batholith, resulting in contact metasomatism (e.g. Jackson et al., 1982). The magmatic fluid may also become involved in an early magmatic–metamorphic convective system. Recirculation would tend to homogenize the fluid reservoir, resulting in characteristics indicative of a mixed-fluid provenance. Different processes would occur on the flow path depending on the prevalent P, T and fluid chemistry (Fig. 5).

Phase separation in the aureole, promoted by lower temperatures and pressures, would complicate the fluid flow patterns. Low-density vapour, separating from its cogenetic liquid would be recirculated within the aureole (Fig. 5), whereas aqueous liquids, particularly the high density brines, may be preferentially circulated into the granite. Such fluids will inevitably leach metals, particularly Sn, Pb, Zn and Cu from the country rocks and transport them into the granite system. Other components which may be concentrated in the granites in this way include boron, carbon dioxide, nitrogen and methane, although as mentioned above, the volatile components are more likely to be recirculated in the aureole.

A dynamic and progressively evolving system is thus envisaged whereby magmatic–metamorphic fluids are important in the initial phase of convective circulation. There is no evidence for involvement of meteoric fluids at this early stage. However, the system did evolve to one dominated

by deeply circulating meteoric fluids concomitant with cooling, uplift, and enhanced permeability of the consolidated batholith (Sheppard, 1977; Jackson *et al.*, 1982; see Fig. 5).

Conclusions

A study of fluid inclusions in barren veins developed during contact metamorphism of pelitic sediments in south Cornwall has revealed a complex history of syn-intrusion fluid evolution. Unlike granite-hosted structures, the veins have been unaffected by later hydrothermal overprinting and retain evidence of the earliest stages of granite-related fluid flow. There is overwhelming evidence for moderate to extreme unmixing of a low-salinity, low-CO_2 fluid to produce a brine enriched in NaCl, KCl, $CaCl_2$, $FeCl_2$ and other salts and a low density CO_2-rich, N_2- and CH_4-bearing vapour. It is suggested that dense CO_2-rich liquids are produced by condensation of this vapour separating from its cogenetic liquid along a density gradient.

Both the solute and volatile components of the fluids are ambiguous with respect to the fluid source. A purely magmatic origin cannot be discounted, but a mixed magmatic–metamorphic explanation is preferred. Such an interpretation is consistent with current models for thermal evolution and fluid circulation around cooling plutons. Early attainment of significant permeability within the batholith would allow circulation of such fluids into the granites themselves. This process has important implications for the transport of trace elements such as Sn, by saline aqueous fluids, into the granite system.

Stable isotopic and thermodynamic studies, currently in progress, should provide additional constraints on the source and evolution of the aureole fluids and their importance in metallogenesis.

Acknowledgements

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