

LITHOPROBE: Faults and Fluids

W. S. Fyfe, R. Kerrich, S. R. Hicock and F. C. Colloza

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[See table of contents](#)

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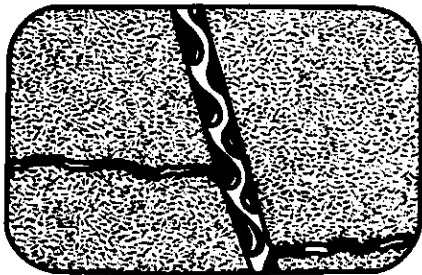
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Article abstract

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Articles



LITHOPROBE: Faults and Fluids

W.S. Fyfe, R. Kerrich¹, S.R. Hicock and F.C. Colloza
 Department of Geology
 University of Western Ontario
 London, Ontario N6A 5B7

Present address:

¹ Department of Geological Sciences
 University of Saskatchewan
 Saskatoon, Saskatchewan S7N 0W0

Abstract

Data are reported on fluid activity along two major structures covered by LITHOPROBE seismic reflection traverses — Vancouver Island and Kapuskasing. Major faults on Vancouver Island are characterized by sporadic Mn-oxides (≤ 17 weight percent (wt.%) or carbonate-hydrocarbon mineralization. Mn-oxides have infiltrated disturbed glaciogenic sediments (≤ 30 ka) interpreted as projections of bedrock faults into Quaternary cover. Fault carbonates are characterized by a distinctive trace element composition including enhanced abundances of V (40-146 ppm), Co (11-31 ppm), Ni (32-70 ppm) and Zn (39-86 ppm); and the hydrocarbons possess elevated V (146-603 ppm), Ni (60-210 ppm) and Zn (26-80 ppm). Carbonate $\delta^{13}\text{C}$ spans -14 to 0 per mil (‰), implying some reduced C in the source region. Fault mineralization is interpreted as the product of the distillation of volatiles and solutes off the Juan de Fuca plate during subduction. Such fluid refluxing in continental margin faults may account for

This paper was invited as a report of progress on specific geological studies associated with the LITHOPROBE program.

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Introduction and Scope of Study

The transport rate of H₂O from the hydrosphere into subduction zones is estimated at $9.7 \pm 3.4 \times 10^{14}$ g \cdot yr⁻¹ (Fyfe, 1978; Ito *et al.*, 1983). This estimate takes into account H₂O as a structural component of hydroxy-silicates in altered oceanic crust and its sedimentary cover, but not the pore water content of such rocks which may be large. Fyfe (1978) and Ito *et al.*, (1983) have noted that the reflux of subducted H₂O to surface reservoirs cannot be accounted for by a combination of arc, spreading centre, and hot-spot magmatism, giving an apparent disparity in the global transport budget of H₂O equivalent to a net flux of $1.2\text{-}11 \times 10^{14}$ g \cdot yr⁻¹ into the mantle. In the light of these boundary conditions for the global H₂O budget, this study was designed to explore the possibility that continental margin faults act as conduits for the reflux of H₂O generated by dewatering of pore fluids and devolatilization of oceanic lithosphere and its sedimentary cover, using Vancouver Island, above the Juan de Fuca plate as an active experimental test. We report, in addition, preliminary observations on the nature of fluid and melt activity in the thrust belt of the Kapuskasing Structural Zone.

Faults — Vancouver Island

Vancouver Island is located in a seismically active area, sited above the eastwardly subducting Juan de Fuca oceanic plate. The island, which has been accreted onto the North American continent, is transected by numerous large-scale faults, many of which have recorded significant displacements as recently as the Eocene (Clowes and Brandon, 1985).

The disposition of major faults on Vancouver Island is portrayed in Figure 1, together with simplified lithological contacts, and sampling localities. Material was obtained principally from faults in the bedrock; but also where

possible from tectonically disturbed glaciogenic sediments on strike with bedrock faults, and interpreted as their projection into the unconsolidated Pleistocene cover.

Examination of the faults revealed intense metasomatic activity along significant sectors of their strike length. Two specific varieties were observed; carbonate-hydrocarbon vein stockworks in fault breccia, and pervasive manganese impregnation of faults. These types are described in turn below.

Faulting — Sproat Lake. Carbonate-hydrocarbon metasomatism is pronounced along the Taylor River fault, the trace of which runs parallel to the north shore of Sproat Lake (Figure 1). This fault transects tholeiitic volcanic rocks of the Karmutsen Formation, which are at prehnite-pumpellyite facies of regional metamorphism, and are the predominant lithological type on Vancouver Island (Muller and Carson, 1969; Muller, 1977, 1980, 1981).

Carbonate-hydrocarbon veining appears to be the latest stage of fault infilling, occurring as multiple generations of tensile fractures (Figures 2 and 3). Hydrocarbons are present as interstitial fragments in carbonate aggregates: they are characterized by hard, vitreous properties, and are opaque. Earlier generations of veins responded to successive episodes of fracturing by the recrystallization, bend gliding and transgranular fracturing of carbonates, and microfracturing of the hydrocarbons (Figure 3).

Representative multi-element analyses of hand-picked carbonates and hydrocarbons from the veins illustrated in Figure 3 are reported in Table 1. Vein carbonates are typically ferroan dolomite in composition, with MnO restricted within the range of 0.31 to 0.35 wt.%. Carbonates are characterized by a distinctive trace element inventory including enhanced levels of V (40-146 ppm), Co (11-31 ppm), Ni (32-70 ppm), and Zn (39-86 ppm), compared with the abundances of these elements in most hydrothermal carbonate minerals. Hand-picked carbonates were digested in dilute HCl prior to analysis, and hence the distinctive trace-element pattern is regarded as being indigenous to the carbonates, rather than due to a contribution from solid inclusions.

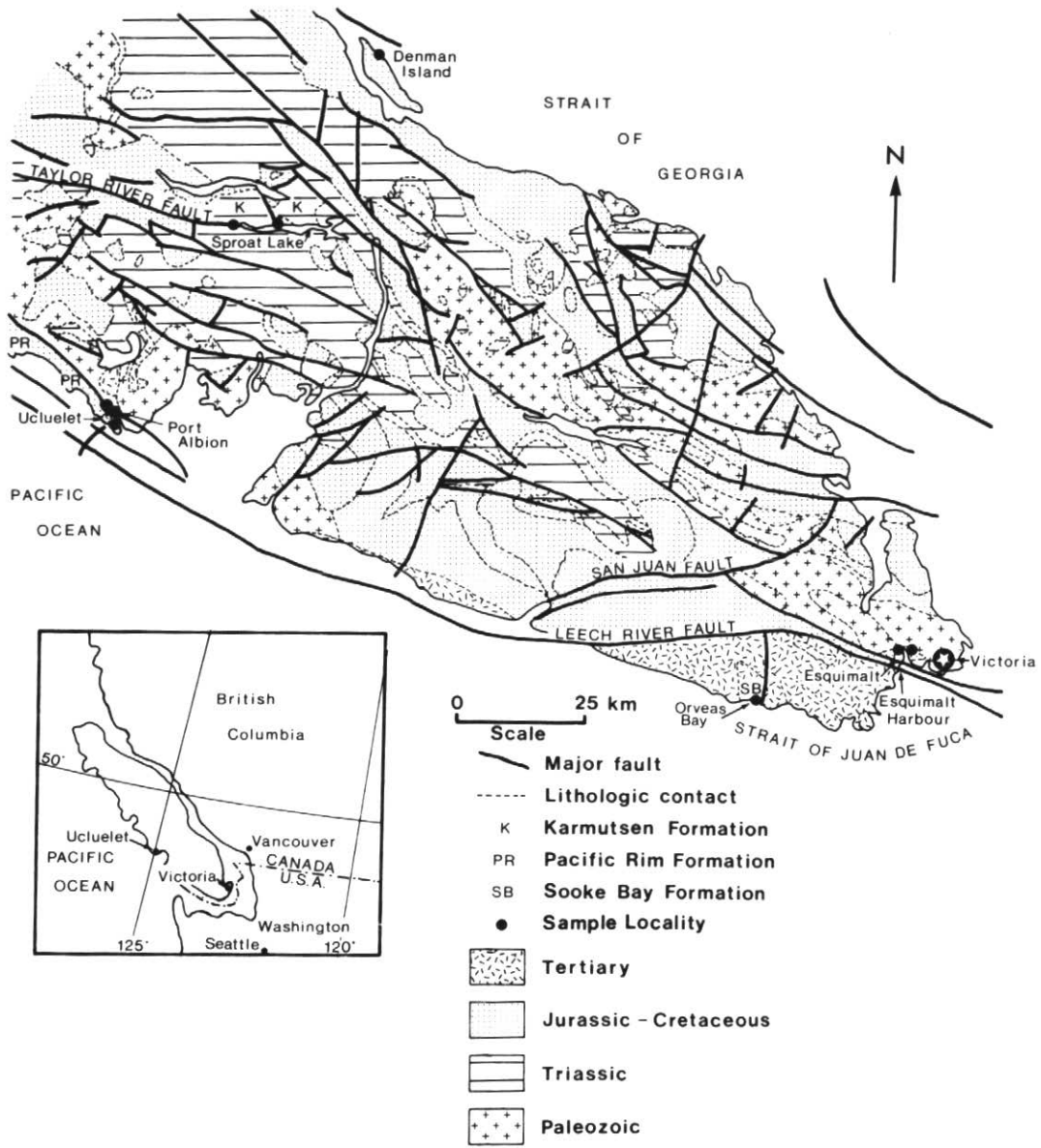
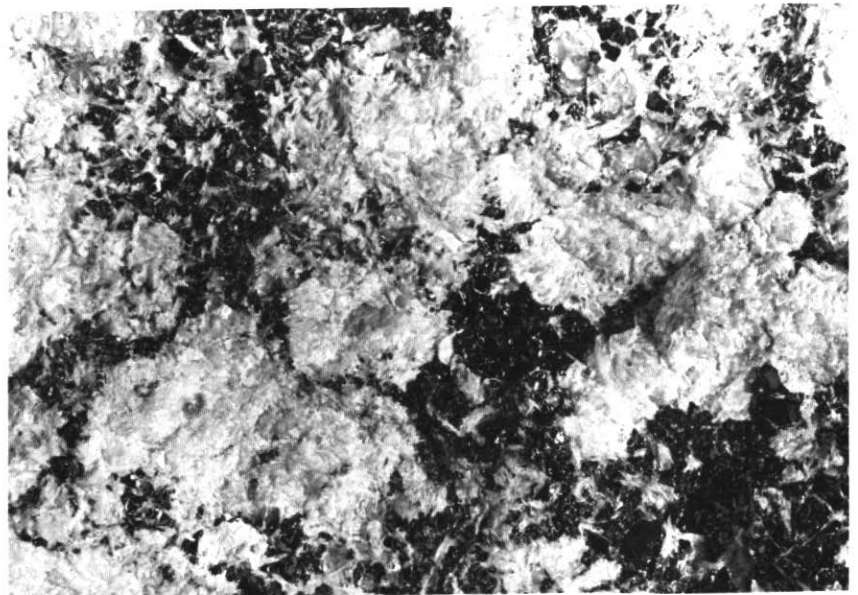


Figure 1 Simplified geological map of southern Vancouver Island (modified after Roddick et al., 1976), illustrating the disposition of major faults, and sampling localities.

Figure 2 Fresh surface of ferroan dolomite-hydrocarbon aggregate within Taylor River fault zone, from the north shore of Sproat Lake. Horizontal field of view = 60 mm.



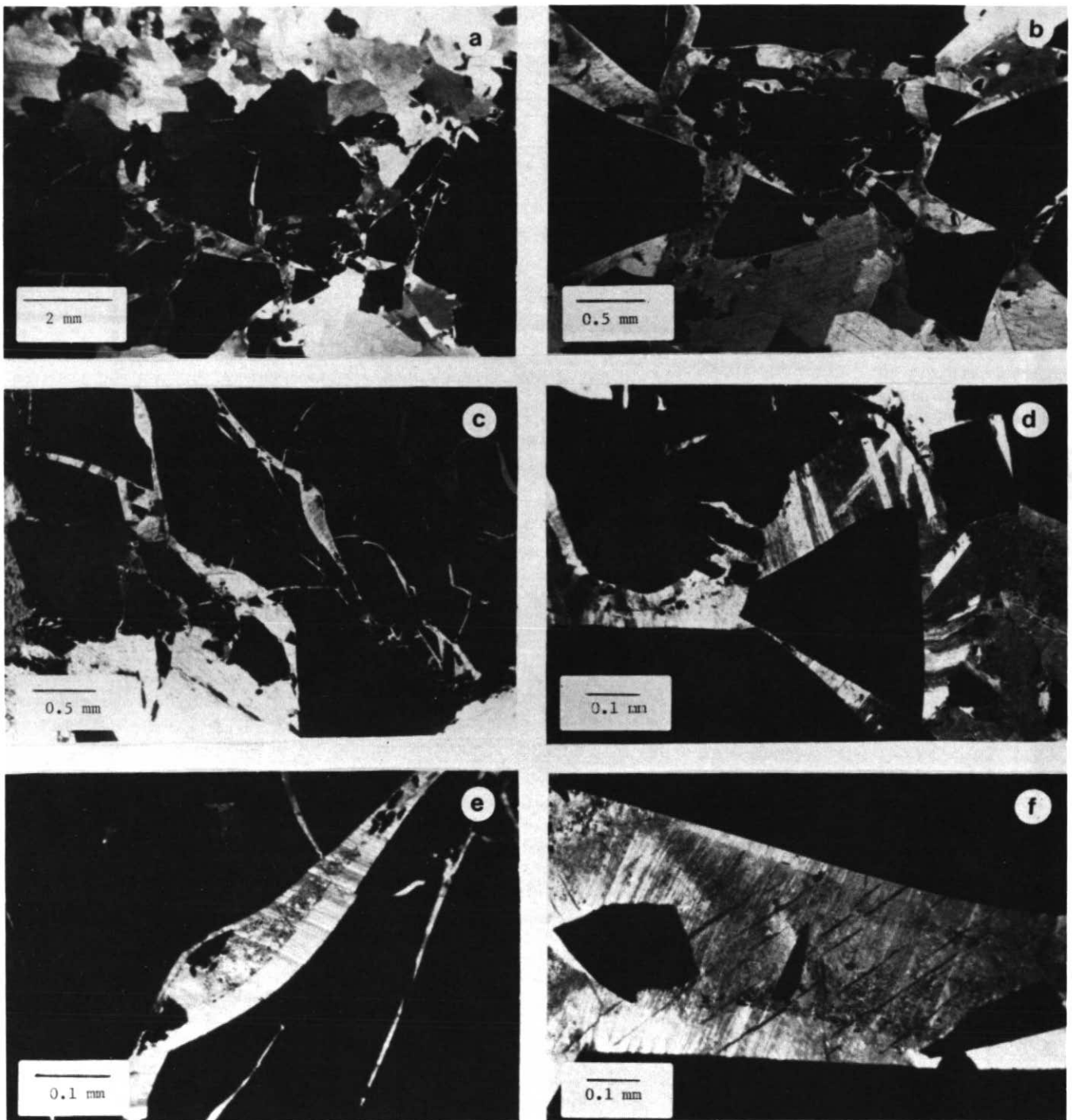


Figure 3 Photomicrographs (crossed polars) of the carbonate-hydrocarbon fault metasomatism.

A, B General views of fractured ferroan dolomite and opaque hydrocarbons.

C, D Close up of microfractures in hydrocarbons, with successive generations of carbonate-hydrocarbon infilling. Note bend gliding deformation in Fe-dolomite (**D**).

E, F Multiple generations of microfractures. Early carbonates (cloudy) and hydrocarbons in median position, with later epitaxial precipitation of clear carbonates.

Hydrocarbons lack the X-ray spectra of graphite: they contain negligible levels of all major element oxides, and minor Ca, Mg and Fe which are likely due to the presence of trace carbonate inclusions (see Figure 3c-f). Systematically elevated abundances of V (146-603 ppm), Ni (60-210 ppm) and Zn (26-80 ppm) are present in the hydrocarbons (Table 1).

Faulting at Port Albion and Ucluelet. Manganiferous fault gouge occurs in argillite, chert, and greywackes of the Pacific Rim Formation, on the peninsula south of Ucluelet (Figure 1). This formation represents intensely faulted and deformed tectonic mélange (Muller, 1977, 1981). The fault gouge is composed of a friable aggregate of Mn- and Fe-oxides and hydroxides, which appear to have infiltrated the fault and impregnated the bounding wall rock.

Representative multi-element analyses of wall rocks and their mineralized counterparts are reported in Table 2. Wall rocks (Table 2, PA-3, PA-4) are compositionally similar to high-Ti tholeiites in terms of major and trace

element contents. Mineralized fault gouge contains up to 16.8 wt.% MnO together with sporadically elevated Fe₂O₃ (Table 2, PA-1, PA-2). Relative to less deformed and mineralized wall rocks, the fault contains enhanced abundances of K₂O (0.87-1.0 wt.%), P₂O₅ (0.21-0.49 wt.%), Sr (582-705 ppm), Ag (3.6-3.8 ppm), Ba (1270-2220 ppm), Th (28-42 ppm), and Co (45-208 ppm). Across the inlet at Port Albion, and on strike with the fault zone, Pleistocene glaciogenic sediments exposed in a roadcut are disturbed and contain Fe- and Mn-oxides (Table 2, PA-7).

Leech River fault. The Leech River fault transects meta-amphibolite and diabase at Esquimalt, west of Victoria. Fault breccias contain sporadically elevated Fe₂O₃ (23.9 wt.%), K₂O (\leq 2.4 wt.%) and MnO (0.44 wt.%), along with ubiquitous carbonate vein stockworks.

A single sample of fault breccia from Orveas Bay is enriched in MnO (2.02 wt.%), Co (346 ppm), Ni (327 ppm), Cu (148 ppm) and Zn (230 ppm).

All fault breccias are characterized by multiple generations of carbonate-filled fractures, the latest of which appears as dilational open-space fillings.

C and O isotopic composition of fault carbonates. Hydrothermal carbonates in fault breccias from the various localities sampled, generally plot in distinct fields in $\delta^{13}\text{C}$ versus $\delta^{18}\text{O}$ co-ordinates (Figure 4). At Port Albion, disseminated carbonates associated with the manganese oxides occupy a relatively restricted interval of $\delta^{13}\text{C}$ at -7.5 to -14‰, whereas $\delta^{18}\text{O}$ values span 2 to 20‰. Ferroan dolomite vein stockworks in the Taylor River fault at Sproat Lake are systematically enriched with respect to carbon isotope composition ($\delta^{13}\text{C} = -7$ to 0‰) and extend to more positive values of $\delta^{18}\text{O}$ (Figure 4).

Ohmoto and Rye (1979) have shown that the $\delta^{13}\text{C}$ of hydrothermal carbonates is mediated by the $\delta^{13}\text{C}$ of the fluid, and the ambient conditions of T, Eh, and pH at the site of deposition. In general, organic hydrocarbons are systematically more negative than other carbon reservoirs, but the average $\delta^{13}\text{C}$ of

Table 1 Representative major and trace element analyses of hydrocarbons and carbonates from the Taylor River fault, Sproat Lake

	Hydrocarbons				Carbonates		
	S2	2A1	2A2	2A3	2B2	2B3	2B4
TiO ₂	0.1	< 0.01	0.01	0.01	< 0.01	< 0.01	< 0.01
Al ₂ O ₃	0.22	0.58	0.09	0.19	< 0.01	0.58	0.08
Fe ₂ O ₃	1.23	0.82	0.95	0.55	13.2	5.76	13.6
MnO	0.11	0.04	0.02	0.04	0.35	0.31	0.34
MgO	0.81	0.58	0.40	0.96	12.5	5.2	12.7
CaO	7.70	3.53	1.30	3.32	32.5	44.2	31.2
K ₂ O	< 0.03	0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01
Na ₂ O	0.04	0.18	0.3	1.7	< 0.01	< 0.01	< 0.01
P ₂ O ₅	0.03	0.01	< 0.01	< 0.01	0.03	0.03	0.04
Be ppm	< 0.1	< 0.05	< 0.4	< 0.4	< 0.01	0.60	0.08
V	603	554	146	438	49	40	146
Cr	8	4	< 8	14	10	7	10
Co	< 10	< 5	< 5	< 5	31	11	20
Ni	210	192	60	190	62	32	70
Cu	10	2.6	< 5	10	6	5	60
Zn	30	26	80	120	86	39	80
Pb	< 5	< 5	< 5	< 5	< 5	< 5	< 5
Ag	< 1	< 0.5	< 0.5	< 0.5	< 0.5	< 0.5	< 0.5
Mo	< 50	< 20	< 20	< 20	< 20	< 20	< 20
Sr	23	11	5	28	115	64	99
Th	20	< 5	< 5	< 5	< 5	< 5	< 5
Zr	30	6	< 5	< 5	26	19	10
Cd	< 3	< 1	< 1	< 1	< 1	< 1	< 1

Analysis by inductively coupled plasma emission spectroscopy.

igneous, metamorphic and sedimentary reservoirs is approximately -5‰ (Ohmoto and Rye, 1979).

Carbon isotope compositions of the fault carbonate breccias are difficult to interpret in the absence of information on the temperature, pH and redox state of the hydrothermal fluids. It is possible that the most depleted values at Port Albion ($\delta^{13}\text{C} = -12$ to -14‰) represent CO_2 derived from a low ^{13}C organic precursor. The $\delta^{13}\text{C}$ of CO_2 derived from organic material depends critically on the process of its modification, namely by sulphate reduction ($\delta^{13}\text{C} = -25\text{‰}$), fermentation (-15‰) and thermally induced decarboxylation (-20‰) relative to PDB (Irwin *et al.*, 1977).

The oxygen isotope composition of fluids from which the carbonates were precipitated cannot readily be estimated, given the absence of temperature data, in conjunction

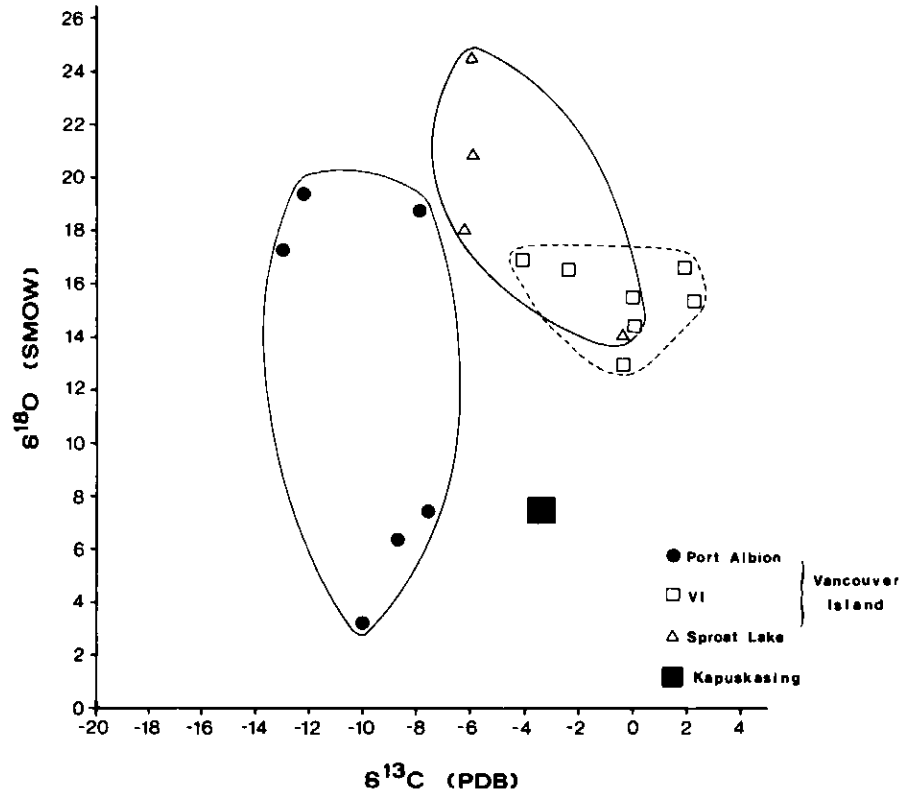


Figure 4 The oxygen and carbon isotopic composition of fault-related carbonates, from specified localities, southern Vancouver Island, and from lamprophyres in the Kapuskasing Structural Zone. $\delta^{13}\text{C}$ referenced to PDB, $\delta^{18}\text{O}$ relative to SMOW.

Table 2 Representative major and trace element analyses of metasomatized fault breccias at specified locations on Vancouver Island

	EH-1	EH-3	EH-8	OB-1	PA-3	PA-4	PA-1	PA-2	PA-7
SiO ₂	55.8	50.9	54.4	57.8	51.9	51.0	46.2	35.3	60.6
TiO ₂	0.94	0.76	0.50	0.83	1.71	1.77	0.44	0.37	0.76
Al ₂ O ₃	19.4	17.3	8.27	16.7	15.1	15.5	11.3	9.40	17.4
Fe ₂ O ₃	7.48	9.53	23.9	6.89	11.3	11.8	7.10	19.3	7.93
MnO	0.08	0.12	0.44	2.02	0.15	0.18	16.6	16.8	0.72
MgO	2.58	2.51	3.73	3.09	5.05	5.47	1.91	1.68	2.44
CaO	0.54	2.34	0.46	3.07	5.62	6.96	4.33	3.40	0.14
K ₂ O	2.19	2.37	< 0.01	1.23	0.51	0.52	1.00	0.87	2.59
Na ₂ O	1.82	1.86	0.07	2.62	2.55	2.60	3.30	2.32	1.80
P ₂ O ₅	0.14	0.11	0.24	0.13	0.13	0.12	0.21	0.49	0.14
LOI	10.5	13.9	7.80	5.64	5.35	5.17	8.19	10.4	6.45
Total	101.5	101.7	100.8	100.0	99.4	101.1	100.6	100.3	101.0
Be ppm	0.9	0.8	< 0.05	1.6	0.07	0.24	1.61	0.71	1.1
V	195	179	509	156	300	309	17	7	158
Cr	100	84	209	117	168	166	54	40	64
Co	< 5	< 5	< 5	346	< 5	< 5	45	< 5	208
Ni	43	53	173	327	62	67	20	20	25
Cu	70	119	259	148	144	162	46	47	65
Zn	112	102	310	230	90	98	43	43	98
Pb	< 5	30	< 5	5	< 5	< 5	< 5	< 5	< 5
Ag	< 0.5	< 0.5	< 0.5	< 0.5	< 0.5	< 0.5	3.6	3.8	< 0.5
Mo	< 20	< 20	< 20	< 20	< 20	< 20	< 20	90	< 20
Sr	115	87	21	270	230	215	705	582	42
Th	20	16	28	14	8	< 5	28	42	15
Zr	88	76	55	33	89	96	< 5	< 5	44
Cd	< 1	< 1	< 1	< 1	< 1	< 1	< 1	< 1	< 1
Ba	700	697	55	531	179	151	1270	2220	850

EH - Esquimalt Harbour; OB - Orveas Bay; PA - Port Albion

with the susceptibility of carbonates to undergo retrograde oxygen isotope exchange. Assuming temperatures of $\leq 200^{\circ}\text{C}$, then carbonates would have been in equilibrium with fluids of approximately -10 to $+4\%$. Based on this and other considerations, we interpret the data to signify the presence of a deep-seated fluid source characterized by positive $\delta^{18}\text{O}$, mixing with low ^{18}O fluids of meteoric origin in a near surface environment; or alternatively, carbonates subsequently undergoing variable degrees of exchange with low ^{18}O fluids.

Discussion

Two key problems in regard to fault-related mineralization on Vancouver Island are (1) the source(s) of volatiles and solutes, and (2) the timing of the fluid flux.

For the volatiles and solutes, we consider three possible sources: (1) Quaternary glaciogenic sediments, (2) the accreted metamorphic terrane, and (3) subducted oceanic lithosphere of the Juan de Fuca plate.

There is a general consensus that for organic-rich rocks, decarboxylation reactions representing the thermal maturation of hydrocarbons such as kerogen, proceed to completion at temperatures of $200\text{--}250^{\circ}\text{C}$. Accordingly, hydrocarbon compounds do not survive in rocks which have attained prehnite-pumpellyite or higher grades of metamorphism, and carbon is the sole product of hydrocarbon reactants.

Given this constraint, it is unlikely that the fault-related hydrocarbons were remobilized from organic precursors during or after metamorphism of the basement. On the other hand, it is probable that temperatures of fluid migration through the Quaternary glaciogenic sediments were too low for extensive mobilization of organic material. This leaves the organic rich sediments on the Juan de Fuca plate as the most plausible source of the fault-hydrocarbons. Similarly, manganese-rich fault gouge at Port Albion and other localities may reasonably be derived from Mn, Fe hydrothermal sediments on the Juan de Fuca plate, rather than from the Quaternary sediments or basement, especially when the associated trace metal distribution of Ni, Co, etc. is taken into account.

At present, there is no firm evidence on the timing of fault-related fluid flow. It is noted, however, that hydrocarbon introduction must postdate metamorphism of the bedrock, and that local manganese impregnation of Quaternary glaciogenic sediments constrains the metasomatism to ≤ 30 ka (Hicock, 1980, 1984). Further, the low-temperature mineralogy of the Mn-oxyhydroxides, coupled with the open-space geometry of carbonate vein stockworks, collectively point toward a recent, low-temperature, and high-level mineralization. In summary, we interpret the fault-related metasomatism on Vancouver Island as the product of low-temperature distillation of organic and Mn-Fe rich sediments of the Juan de Fuca plate.

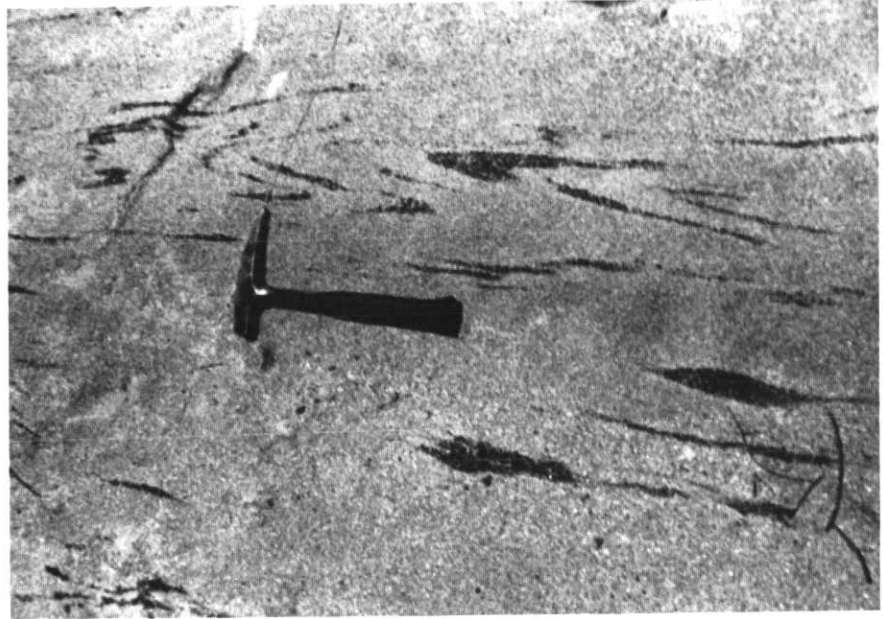


Figure 5 Highly deformed anorthosite close to a zone of slight deformation. Such rocks contain pervasive microfractures with development of zoisite, carbonate and micas.

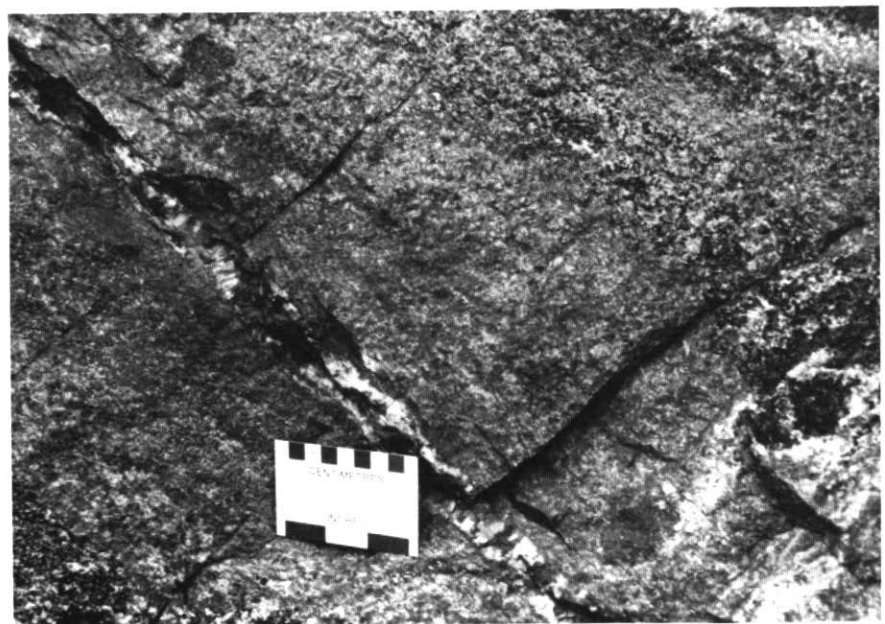


Figure 6 Typical carbonate alteration zone in gneissic amphibolite. The dominant alteration comprises Ca-Fe carbonates. A small amount of quartz is present in the central fracture.

The disparity in the global transport rate of H_2O to surface reservoirs by magmatism, compared with the subduction rate of H_2O , is $1.2 \cdot 10^{14} \text{ g} \cdot \text{yr}^{-1}$. Considering the subduction of sediments with ~30% porosity at a rate of up to $3.5 \cdot 10^{15} \text{ g} \cdot \text{yr}^{-1}$, an additional $\sim 10^{15} \text{ g}$ pore fluids are carried down to significant levels in subduction zones on an annual basis.

During the subduction of oceanic lithosphere and its sedimentary cover, the principal changes that take place to depths of 15-18 km are dewatering and diagenesis of the sediments. Expelled water may percolate along faults and fractures in the accreting wedge and thereby return to the surface. Clay minerals would dehydrate at 20-50 km, depending on the thermal structure (Ito *et al.*, 1983).

The transport rate of thermal waters of marine origin through the mid-ocean ridge system is estimated at $0.5\text{-}1.0 \cdot 10^{17} \text{ g} \cdot \text{yr}^{-1}$ (Wolery and Sleep, 1976). Fluid refluxing up subduction zones involves $1\text{-}2 \cdot 10^{15} \text{ g} \cdot \text{yr}^{-1}$, but fluids are likely modified by reactions under conditions of low water/rock ratio. Such fluid refluxing may approximately balance the discrepancy between the net transport rate of H_2O to surface reservoirs in magmas and the rate of subduction of H_2O for an approximately steady state ocean mass; however, the balance between reflux of water and its incorporation into the upper mantle over a long time constant remain unanswered and are likely to vary through time.

The Kapuskasing Structural Zone. Preliminary LITHOPROBE data on the Kapuskasing structure (Cook, 1985) has confirmed the Percival and Card (1983) model. It appears that Archean basement rocks may indeed be thrust over the Abitibi belt. During such thrusting (see Fyfe and Kerrich, 1985) degassing of the underthrust greenschist facies rocks of the Abitibi subprovince and retrograde metamorphism of the overthrust basement is anticipated.

We have made some preliminary observations on the search for such fluid transport phenomena as influenced by thrust processes. What is perhaps most spectacular is the broad zone of intense deformation and metasomatism in rocks to the west of the main thrust boundary. In particular, the deformation in the anorthosites is spectacular (Figure 5).

Vein systems are ubiquitous throughout the allochthonous overthrust block. The most common types observed at this time are associated with intense CO_2 addition as might be expected if typical Abitibi rocks were prograded (Figure 6). During prograding, the reaction between ubiquitous spilitic carbonate and silicates generates CO_2 as does the hydrolysis or oxidation of carbonaceous material present in interflow sediments. Pseudotachylite veins are also common signifying transient conditions of fast displacement rates combined with high effective confining stress. Carbonates, which formed along with zoisite, epidote and chlorite, are compositionally dominated by calcite, but

some carbonates contain up to 6% FeO and 5% MgO as revealed by microprobe analysis. Carbonate alteration is in accord with the data of Rudnick *et al.* (1984) who found CO_2 -rich fluid inclusions.

In some sheared anorthosites, plagioclase is replaced by carbonate and zoisite. The formation of almost monomineralic zoisite from plagioclase in shear domains suggests a reaction: $6NaAlSi_3O_8 + 4CaCO_3 + H_2O \rightarrow 2Ca_2Al_3Si_3O_{12}OH + 3Na_2CO_3 + 12SiO_2 + CO_2$ which should liberate silica. Silica is not obvious in the veins and this indicates that the thermal gradient may well be inverted during fluid penetration.

At one locality close to the Kapuskasing zone boundary thrust, immediately west of Foleyet, we have found a large retrograde shear zone (chlorite-quartz-sulphides-carbonates) which on preliminary analysis of a composite sample shows gold in the range 100-300 ppb. This anomaly indicates that gold may well be mobilized from the underlying rocks undergoing prograde metamorphism.

Carbonates associated with the lamprophyres and domains of carbonate alteration are isotopically uniform, where $\delta^{13}C = -4$ to -5% , and $\delta^{18}O = 7.2$ to 8.0% (Figure 4). The average $\delta^{13}C$ of igneous, metamorphic and sedimentary rock is approximately -5% (Ohmoto and Rye, 1979), such that the carbon isotope composition of Kapuskasing carbonates is not alone diagnostic of the source of CO_2 . However, the tight clustering of $\delta^{13}C$ and $\delta^{18}O$ values, taken along with the geological boundary conditions, are consistent with a magmatic or uniform deep crustal reservoir as the CO_2 donor.

We have also noticed the frequent occurrence of generally undeformed granitic segregations in the overthrust high grade basement. It is possible that hot basement rocks unloaded after thrusting, have responded by a small degree of melting.

All such observations are preliminary but it appears that there are numerous phenomena which would fit the current models.

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