

ECONOMIC GEOLOGY
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ARCHAEOAN LODE GOLD DEPOSITS OF CANADA

Part I: A Synthesis of Geochemical Data from
Selected Mining Camps, with
Emphasis on Patterns of Alteration

R. KERRICH

• INFORMATION CIRCULAR No. 182

UNIVERSITY OF THE WITWATERSRAND

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ARCHAean LODE GOLD DEPOSITS OF CANADA: PART I,
A SYNTHESIS OF GEOCHEMICAL DATA FROM SELECTED MINING CAMPS,
WITH EMPHASIS ON PATTERN OF ALTERATION

by

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ABSTRACT

Lode gold deposits of Archaean greenstone belts are hosted by major fracture systems that acted as transcrustal plumbing networks. Specifically, deposits are sited at the confluence of second-order fracture arrays, at flexures, and the intersection of two fracture systems, where permeability is enhanced. In addition, deposits occur where certain lithologies such as ultramafic rocks or iron formation, which preferentially mediate fixation of hydrothermally donated S, Au, CO₂ (etc.), are traversed by tectonic structures. The major structures may have initiated as listric normal faults accommodating extension of greenstone belts, and acting as sites for the extrusion of komatiitic magmas. They also formed submarine scarps which delimit linear belts of marine clastic to volcanoclastic sediments. At this stage of greenstone belt development intense marine-water hydrothermal activity proceeded in and peripheral to fault structures, generating colinear belts of iron formation, but significant concentrations of gold were rarely generated; subsequently reverse translation occurred on the structures, accommodating shortening of a greenstone belt under compression. At this stage the tectonic zones acted as conduits for ascent of trondhjemite magmas from melting the base of the crust, alkaline magmas from the upper mantle, as well as for discharge of hydrothermal fluids from mid-crustal levels implicated in the gold deposits. Lode gold deposits do not appear to have a preferred setting in the volcanic stratigraphy; rather they are present at the basal, intermediate, and highest levels, or within intrusives, where these are transected by major structures.

Gold-bearing vein systems formed during multiple episodes of hydrofracturing, from transient, pulsed hydrothermal discharge, under conditions, where $P_{\text{fluid}} \geq \sigma_3 + T$, and P_{fluid} may have exceeded σ_1 , the maximum principal stress. Pulsed discharge generated banded veins, and was probably induced by repeated breaching of a fluid reservoir, ponded beneath an impermeable cap rock subject to a compressive horizontal crustal stress. The narrow recorded range in $\delta^{18}\text{O}$ of vein quartz at 12-15 per mil across banded veins, and of gold-bearing vein arrays within mines, independent of wall-rock type, signifies an isotopically uniform fluid reservoir, a fluid-dominated system in the hydrofracture conduits, and a relatively small temperature span over which veins precipitated. Hydrothermal solutions transporting gold were isotopically characterized by $\delta^{18}\text{O}$ 6 to 8 per mil and δD -80 to -49 per mil, consistent with a metamorphic or magmatic fluid reservoir. These fluids were at temperatures of 280 to 450°C, possessed low salinities of <2 wt. % NaCl equivalent, low pH, Na/K ~0.1, and contained significant qualities of CO₂, along with the reduced gas species CH₄, C₆H₆, H₂, N₂, and ultrafine particulate hydrocarbons. Carbon isotope values of -0.5 to -7.8 per mil in carbonate gangue indicate that the carbon may have been derived from mixtures of various possible carbon reservoirs, including marine and igneous carbonate, decarbonated marine carbonate or decarboxylation of organic hydrocarbons.

Considering the Timmins camp in Ontario, the 2000 tonnes oz of gold produced was extracted from 600km³ of source rock in 90km³ of hydrothermal fluids with gold solute concentrations of 20 ppb. Hence, large volumes of dilute hydrothermal solutions appear to have been involved rather than intrinsically auriferous fluids. Minor Cr and Pd were transported along with the gold even where immediate host rocks were not mafic or ultramafic. The fluids δD , $\delta^{18}\text{O}$, low salinity, high K/Na, high CO₂ and reduced gas species are all consistent with a metamorphic and/or magmatic fluid reservoir; whereas none of these geochemical features are typical of marine-water-derived ore-forming fluids.

Gold-bearing vein systems and their immediate wall rocks are characterized by massive additions of SiO₂ and CO₂, along with K (and the other alkali metals Rb, Li, Cs), coupled with near quantitative stripping of Na. The magnitude of sulphur introduction is highly variable. Silica precipitation appears to be a simple function of the cooling of fluids saturated with respect to quartz, with a minor component from the hydrolysis of silicates to carbonates in wall rocks. As potassium is consumed from hydrothermal fluids in the hydrolysis reaction of albite to muscovite, with concomitant Na release, the fluid K/Na may diminish, and coupled with decreasing temperature promote formation of gangue albite ± paragonite, coexisting with Fe²⁺ silicates and sulphides (reduced).

The ubiquitous gangue carbonate minerals formed via hydrolysis of Fe, Mg, Ca, Mn-silicates to Fe, Mg, Ca, Mn-carbonates in which wall rocks donate the bivalent metal cations and CO₂ is indigenous to the hydrothermal fluids. Ultramafic rocks are effective CO₂ sinks, given their inherently elevated complement of bivalent metal

cations. During wall-rock reactions, Al_2O_3 , TiO_2 , Sc, V, Zr, and Hf appear to behave essentially isochemically, enabling constraints to be placed on volume changes accompanying alteration: such changes typically vary from -40% at the periphery of alteration envelopes where leaching predominates over precipitation, to >700% gain at vein-rock contacts, the sites of gangue mineral additions. The rare-earth elements (REE) appear to behave isochemically at the lowest states of alteration, but significant mobility of the heavy REE occurs at the highest intensities of alteration. The abundant CO_2 introduced into vein systems may have been generated at source by decarbonation reactions accompanying dehydration during prograde metamorphism, and also by the hydrolysis of hydrocarbons in interflow sedimentary rocks, and reactions in which oxidation of hydrocarbons is linked to reduction of Fe^{2+} .

Wall rocks to veins are intensely reduced ($\text{Fe}^{2+}/\Sigma\text{Fe} \sim 0.9$) relative to back ground ($\text{Fe}^{2+}/\Sigma\text{Fe} \sim 0.7$), and this is also reflected in positive anomalies of Eu^{2+} . The reductant involved was probably H_2 , a product of the dissociation of H_2O under high T and P conditions in source rocks, where $P_{\text{H}_2} \gg P_{\text{O}_2}$, an account of reactions such as $\text{Fe}^{2+}\text{-silicate} + \text{H}_2\text{O} \rightarrow \text{Fe}_{3+} + \text{O}_4 + \text{silicate} + \text{H}_2$. All such vein-related alteration is typically superimposed on a prior spilitic alteration induced by incursion of marine water into cooling greenstone-belt rock sequences at the time of their extrusion, or deposition, in a submarine environment.

Deposits are characteristically enriched in a certain suite of large ion lithophile elements including K, Rb, Li, Ba, Pb, Cs, B, as well as CO_2 , in addition to the prominent rare elements Au, Ag, As, Sb, Se, Te, Bi, and W. Other lithophile elements such as Be, U, Th, F, REE, Zr, and P, do not appear to have been significantly concentrated by the ore-forming system.

It is suggested that rift environments, with high heat fluxes, are appropriate for efficient gold concentration. Here, listric normal faults initially control extension along with ultramafic volcanism, provide pathways for mafic and felsic magmas, are responsible for scarp-dominated sedimentary rocks, and act as conduits from hydrothermal discharge. At late stages of greenstone belt development, reverse motion on the faults accommodates crustal compression, along with continued hydrothermal discharge. Thus the Archaean lode gold deposits formed late in the development of greenstone belts, during major episodes of brittle-ductile deformation, and constitute an integral part of the thermal-mechanical energy of the volcanic-plutonic ensemble.

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I. INTRODUCTION

During the last decade an increasing body of geochemical and isotopic data has been obtained on Archaean lode gold deposits of Canada, principally those of the Superior Province. However, most of the studies are restricted in scope, and there are few comprehensive quantitative treatments of major deposits. This paper attempts to present a concise synthesis of the salient geochemical features of Archaean lode gold systems, with reference to a few examples of the better studied deposits selected to encompass the principal lithological and tectonic environments. A summary of data is first reported on gold deposits of the Yellowknife greenstone belts, Slave Province. For the Abitibi belt - Superior Province, (the most productive lode gold camp globally), the Dome, Hollinger, Macassa, Kerr Addison, and Lamaque mines are each discussed in turn. In each case, the geological setting and essential mineralogical characteristics are briefly summarized to provide a geological context for the chemical data.

The salient question addressed here is the nature of the hydrothermal and hydraulic regimes of ore-forming geothermal systems responsible for the Archaean lode deposits. Emphasis is placed on the geochemical patterns of alteration in contiguous rocks to the various deposits, employing rigorous two-way calculations of chemical mass balance. Specifically, the source of volatiles, of carbon, and sulphur in the ore bodies is explored using information from light stable isotopes. Evidence from alteration mineral assemblages plus fluid inclusions are used to place constraints on intensive chemical variables of the hydrothermal fluids such as Eh, pH, Na/K, X_{CO_2} , salinity, and gas species.

In a companion paper (Part II, Kerrich (1986),) the diverse lines of geochemical and geological evidence reported in this paper (Part I) are drawn together in an attempt to synthesize the data into a coherent scheme for Archaean gold concentrating systems. The source of hydrothermal solutes, in particular incompatible elements (Rb, Pb) and possibly of gold itself, is considered by means of radio-isotope tracers. The second paper concludes with a critical discussion of the various models proposed for Archaean gold deposits. This article draws on a previous review paper which describes the analytical techniques employed (Kerrich, 1983), and incorporates entirely new information.

II. ALTERATION REGIMES: CALCULATIONS OF CHEMICAL MASS BALANCE

One of the areas of geochemistry that has conventionally been most susceptible to errors of interpretation is that of hydrothermal alteration. In its most simple form, this involves comparison of the chemical composition of a parent rock to that of an altered counterpart. However, simple inspection of tables of analyses is not satisfactory for deducing chemical changes. Because the component oxides are constrained to a constant sum (100%), no single component is independent of the others, and an infinite number of solutions exist for transfers of chemical components. Gresens (1967) has pointed out that in many instances comparisons of bulk composition are made on a quantitative basis with the tacit assumption of constant volume, but this assumption is untenable if alteration is accompanied by deformation and/or changes of volatile content. For instance, apparent gains or losses of immobile elements during metasomatism, arising from volume decrease and increase, respectively, could be incorrectly deduced if the volume relations were not known.

Gresens (1967) suggested incorporating specific-gravity data into two-way mass-balance calculations, such that fixing either volume change or the behaviour of one component during a reaction provides a unique solution. For any transformation of parent rock to altered product, volume factors (fv) may be computed which correspond to the isochemical behaviour of individual components. Clustering of the fv 's of several components which are empirically known to be relatively immobile (e.g. TiO_2 , Al_2O_3 , Sc, Hf, Zr) then provides a rational basis for estimating the volume change of the reaction as a whole. In the notation used by Gresens (1967), $fv = 1$ signifies constant-volume metasomatic alteration of reactants to products; $fv = 0.8$ and $fv = 2.0$, for example, correspond to 20% volume reduction and 100% volume increase, respectively. Furthermore, rigorous calculations of chemical mass balance require that the series of altered rocks along with the unaltered parent all belonged to an initially chemically uniform population.

Most of the published alteration studies of base metal massive sulphide deposits have failed to (i) demonstrate that the series of least to most altered rocks belonged to an initially chemically uniform population or (ii) identify the volume changes accompanying alteration (Roberts and Reardon, 1978; Mattagami; Riverin and Hodgson, 1980, Millenchach; Franklin *et al.*, 1975, Mattabi).

Failure to take these two basic requirements into account is also evident in most existing studies of alteration associated with lode gold deposits (Boyle, 1961; MacGeehan and Hodgson, 1982; MacGeehan *et al.*, 1982; Guha *et al.*, 1982).

The frequently made assumption of isovolumetric hydrothermal alteration is contra-indicated by rigorous studies of chemical mass balance employing Gresens' method (cf. Costa, 1980; Costa *et al.*, 1983, alteration of footwall rhyolites at the Mattagami Lake Cu-Zn massive sulphide deposit); and by noting that a linear error of $\pm 15\%$ in measurement of a petrographic feature on which the assumption of constant volume is based may lead to a volumetric error of $\pm 50\%$. For example, Ludden *et al.* (1984) have deduced gains or losses of chemical components accompanying alteration in the Sigma gold deposit, Val d'Or, Quebec, based on the non-unique assumption of constant volume alteration. Spilitization of ultramafic rocks is a prime example of hydrothermal alteration involving volume changes of $\sim 40\%$.

In any given suite of rocks representing various stages of alteration, the absolute abundances of elements may change by real gains or losses if mobile. For the case of elements characterized by isochemical behaviour, measured contents may change by dilution resulting from additions of other components, or concentration via leaching of soluble components. A corollary to this is that immobile elements maintain constant ratios to one another at all stages of alteration, irrespective of changes in absolute abundance. The question of mobility or otherwise of elements during hydrothermal alteration is a hotly debated one (cf. Finlow Bates and Stumpf, 1981; Hynes, 1980; Ludden *et al.*, 1984). No element or group of elements provides a panacea for defining isochemical behaviour, or for constraining volume factors, inasmuch as the extent of mobility is dependent on temperature, redox, halogen, and CO₂ contents of fluids, stable minerals. However, if a group of elements such as Ti, Al, Hf, Zr, and Sc, maintain approximately constant ratios to one another in a set of rocks recording variable intensities of alteration, then the set probably belongs to a common parental rock type; furthermore, these elements can be considered to have behaved isochemically. The alternative, that these geochemically diverse elements have all been added or subtracted in the same proportion, requires a contrived explanation.

It is important to emphasize that chemical mass balance reveals only the finite chemical transfers between a starting parental rock and its metasomatic product: the infinitesimal incremental steps involved in arriving at the finite state cannot be quantitatively deduced with any certainty. For instance, a felsic igneous rock may initially gain sodium during spilitization involving the reaction of plagioclase to albite, subsequently losing Na and gaining Fe+Mg as the albite converts to chlorite.

In this paper patterns of alteration are defined on the basis of rigorous two-way calculations of mass balance, employing Gresens' procedure.

III. VEIN DEPOSITS IN SHEAR ZONES AT YELLOWKNIFE

A. Geological Setting

Au-bearing vein deposits are located within major ductile shear zones at Yellowknife, in the Slave Province (Figs. 1, 2). The largest shear zones, the Con, Campbell, and Giant, are 10-150m wide, extending to depths in excess of 1-2km. Shear zones transect metabasic volcanic rocks and interflow metasediments at angles of 20-70° in the vertical plane. In detail, the major structures consist of an anastomosing network of second-order shear zones which envelop lens-shaped domains of isotropic rock. The tectonic schistosity describes a sigmoidal form between shear-zone boundaries, and contains a subvertically dipping lineation. These geometrical relations indicate that the shear zones conform to the simple shear model of Ramsay and Graham (1970).

After initial development of the shear zones, these structures subsequently acted as permeable conduits for discharge of hydrothermal fluids which precipitated the Au-bearing quartz-carbonate veins. Such veins are typically located within the confluence of second-order shear zones, at the apices of the intervening domains of undeformed rock. The structures and orebodies contained in them have been described by Boyle (1961), Henderson and Brown (1966) and Breakey (1975). From considerations of the ambient stress regime for fluid flow along shear zones, Kerrich *et al.* (1977a) and Kerrich and Allison (1978) interpreted the gold bearing vein deposits to have been formed from discharge of high-pressure hydrothermal fluids during successive episodes of hydraulic fracturing (see below).

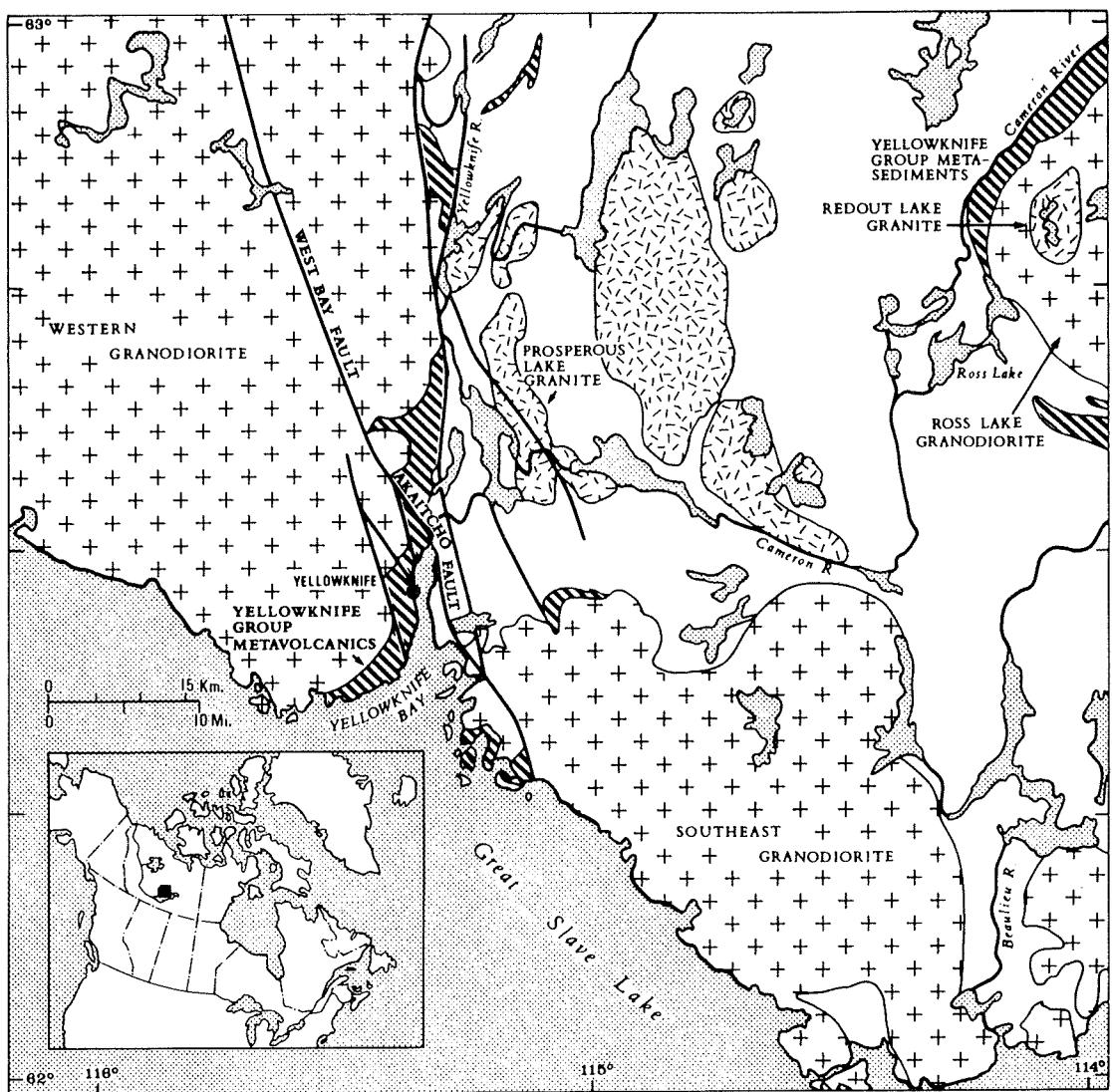


Figure 1 : Generalized geological map of the Yellowknife area, Slave Province, illustrating the configuration of major structures.

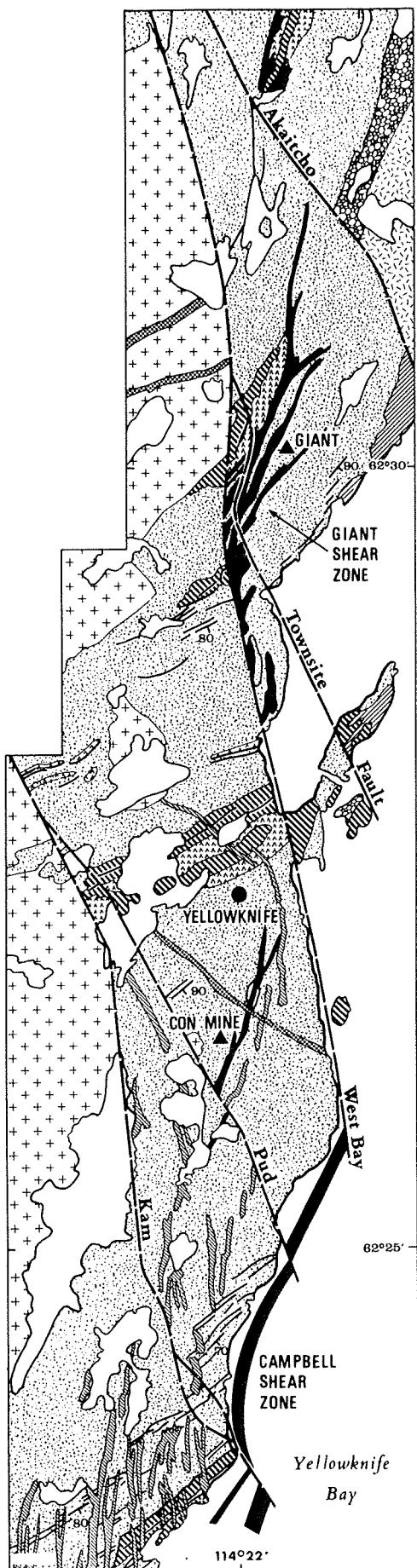
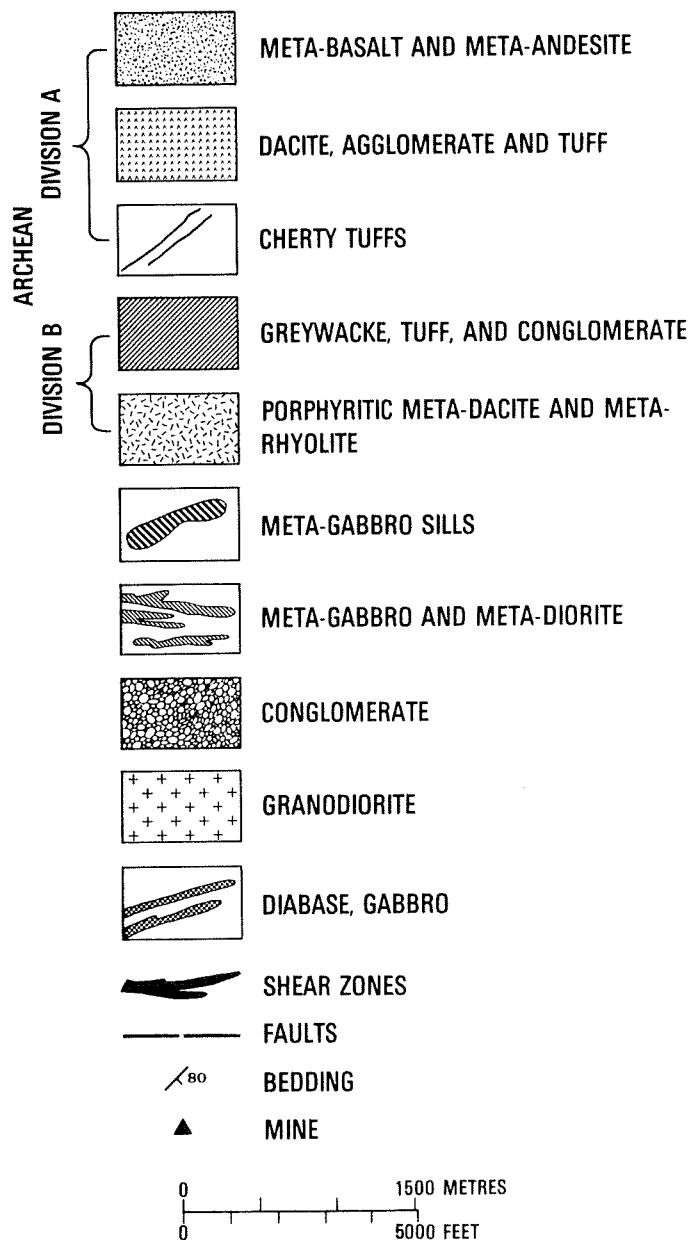


Figure 2 : Simplified geological map of the Yellowknife greenstone belt, portraying the disposition of major shear zones and faults (modified after Henderson and Brown, 1966).

B. Chemical Relations in the Shear Zones

Vein systems at Yellowknife traverse a relatively uniform series of metabasalts, but evaluation of alteration patterns is not a readily tractable problem due to a complex history of chemical alteration prior to vein emplacement. External to vein systems, basalt flows have erratic abundances of the alkali- and alkaline-earth metals, coupled with whole-rock $\delta^{18}\text{O}$ values averaging 7 (compared to primary δ -values of 5.7 ± 0.3 per mil). These data are interpreted by Kerrich and Fyfe (1981) to signify spilitization reactions in the presence of seawater at low temperatures, during and shortly after extrusion. Gold abundances of basalts remote from the shear zones are uniformly in the low ppb range, signifying that little or no gold enrichment occurred during this seawater-hydrothermal stage.

A second stage of chemical transfer occurred during early propagation of the shear zones into which auriferous veins were later emplaced. Deformation of epidote-amphibolite-facies metabasalts to chlorite schists in the shear zone, initially by brittle transgranular fracturing and subsequently by means of pressure solution, involved loss of SiO_2 plus Na_2O with concomitant gains of $\text{H}_2\text{O} + \text{CO}_2$. Neither of these episodes of seawater-hydrothermal or deformation-induced alteration appears to have involved significant changes in abundance of the relatively immobile elements such as Al, Ti, Zr, and Sc. Hence, deformed chlorite schists within unmineralized domains of the shear zones are probably the most reasonable parent rocks to select for comparison with mineralized counterparts.

C. Hydrothermal Alteration

Gains and losses of major-element oxides involved in hydrothermal alteration accompanying precipitation of the gold-bearing veins are tabulated by Kerrich and Fyfe (1981), and illustrated in Figs. 3 and 4. Volume factors range from 0.8 at the periphery of alteration domains to >7 at vein margins where there is a significant admixture of gangue minerals as vein arrays to the metabasic schists. The salient chemical mass transfers accompanying hydrothermal alteration are as follows. Additions of SiO_2 and volatiles occur in the majority of transformations considered; the former which is consistent with precipitation of quartz from cooling solution, and the latter with hydration and fixation of CO_2 in carbonates. According to Boyle (1961), CO_2 increases from ~1% in unmineralized basalts in the epidote-amphibolite facies, to ~8% in sericite-carbonate schists adjacent to veins. CaO , MnO , are depleted at volume factors of 1.3 or less reflecting the hydrolysis of chlorite + epidote to muscovite, but are added at $f_v > 1.3$ where the bivalent metal cations are incorporated into ferroan dolomite. Na_2O is depleted and K_2O fixed over the entire range of volume factors. Small positive and negative variations of total Fe occur at $f_v < 1.7$, with addition to $f_v > 1.7$. Al_2O_3 , Sc, and Zr are conserved at all states of hydrothermal alteration.

Precious metals, together with Cr, Ni, Cu, Zn, Pb, Rb, Cd, and Ba, have been added from hydrothermal solutions to the veins and altered wall rocks; V and Nb do not exhibit any large departures from background abundances. Rb and Sr behave sympathetically with K and Ca, respectively (Figs. 3, 4).

The simplest interpretation of these results is that the hydrothermal fluids contributed SiO_2 , $\text{H}_2\text{O} + \text{CO}_2$, precious metals, and K_2O to the wall rocks, which is reflected in the presence of vein quartz, elevated precious-metal abundances, hydration and carbonation of wall rocks, together with pervasive development of sericite. Such additions to the chlorite schist precursor require volume factors $>> 1$.

At increasing distances from veins, in the order of 2-15m, additions become progressively smaller as fluid penetration into wall rocks diminished, and volume factors correspondingly approach unity. In the peripheral regions of alteration envelopes, depletions of CaO and MgO exceed additions of SiO_2 , K_2O , volatiles, etc., such that volume factors are less than unity - i.e. leaching predominates over precipitation.

It is suggested that some Ca, Mn, and Mg (also possibly some Fe) are taken into solution in the peripheral alteration regions where $f_v < 1$, and combine with CO_2 contributed by the hydrothermal fluids to yield carbonate minerals in regions of alteration where $f_v > 1$, and in veins (Figs. 3, 4). Cr, Ni, Sr, and sulphur may behave in the same manner to some extent, signifying some local redistribution, as well as absolute additions. Inferred chemical changes are essentially the same for the Con, Campbell, and Giant shear zones, at equivalent estimated volume factors, attesting to the overall coherence of alteration style.

REE patterns for unmineralized metabasalts are comparable to those of relatively fresh Archaean tholeiitic basalts in general (Condie, 1981), excepting a slight monotonic decrease in abundance toward the heavy REE (Fig.

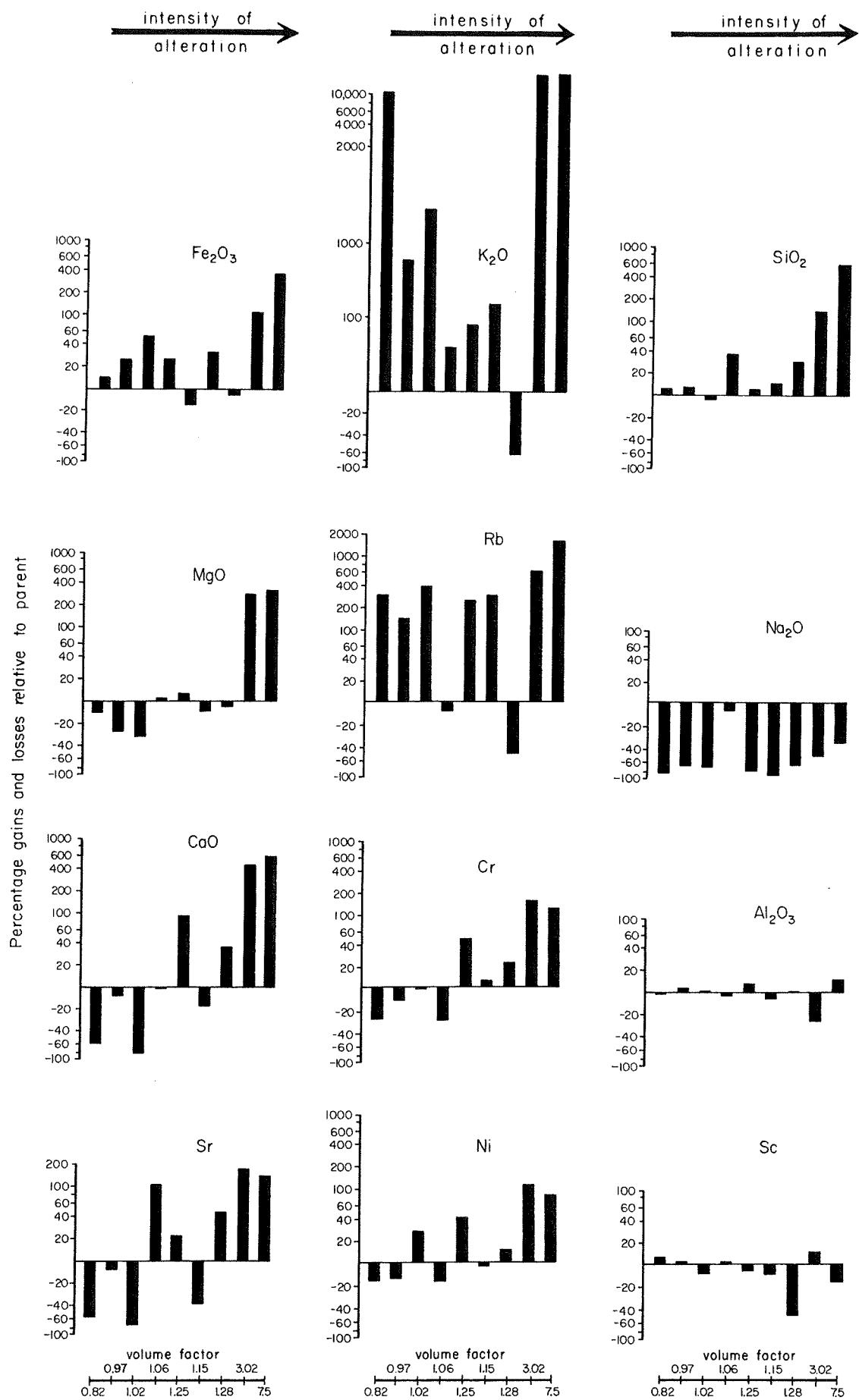


Figure 3 : Gains or losses of major element oxides and selected trace elements in hydrothermally altered rocks of primary basaltic composition, Campbell and Con shear zones, Yellowknife. Gains and losses expressed as percentage changes relative to abundances in the unaltered parent rock, and ordered according to increasing volume factor (after Kerrich and Fyfe, 1981).

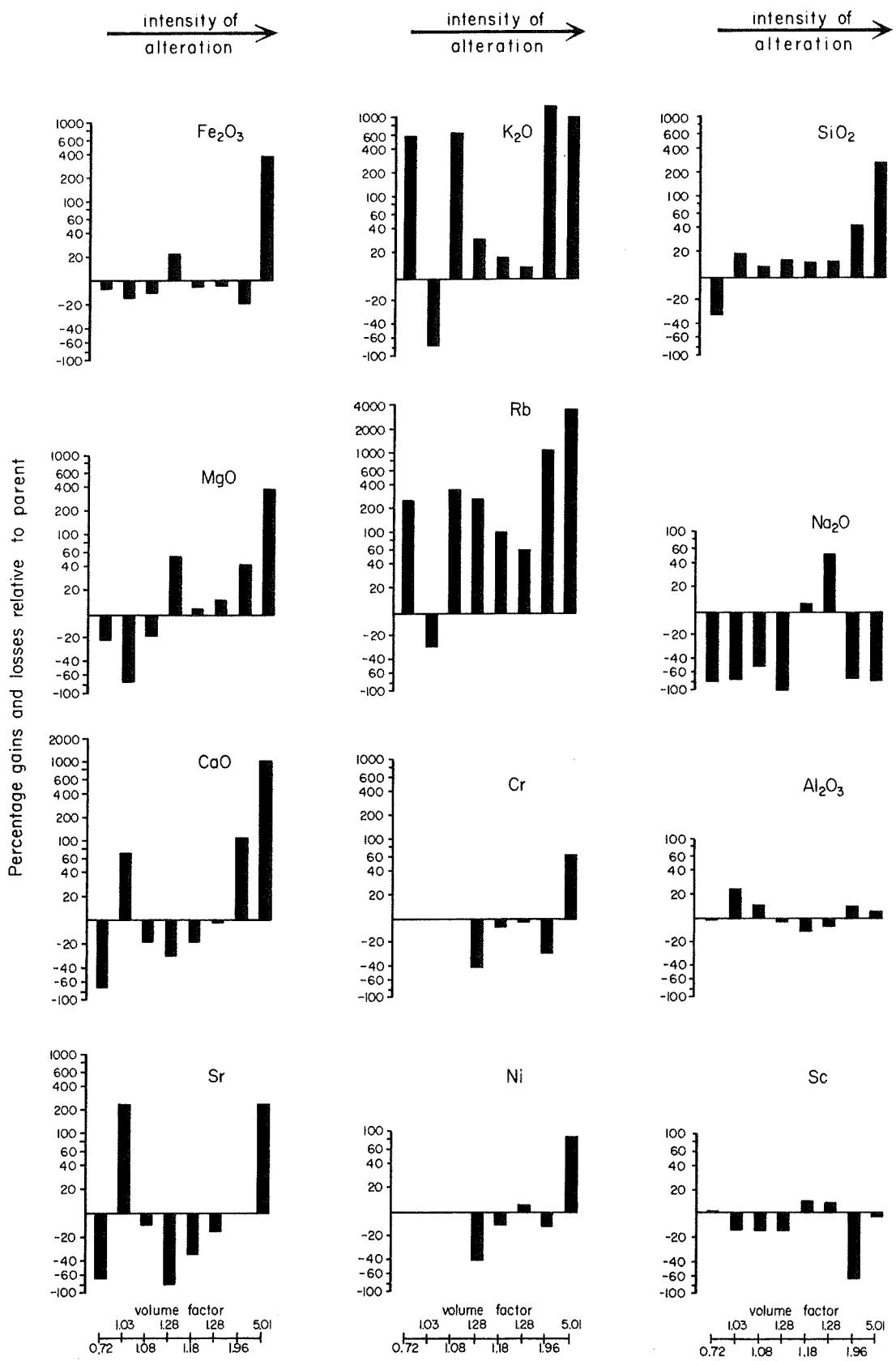


Figure 4 : Gains or losses of major element oxides and selected trace elements in hydrothermally altered rocks of primary basaltic composition, Con shear zone, Yellowknife. Gains and losses expressed as percentage changes relative to abundances in the unaltered parent rock, and ordered according to increasing volume factor (after Kerrich and Fyfe, 1981).

5). These results signify that the REE were largely unmodified by low-temperature seawater alteration, or possibly underwent only minor enrichments of the light REE. In deformed and mineralized counterparts at progressively higher states of hydrothermal alteration (3, 4 intermediate; 5, 6 intense veining, Fig. 5), the REE are shifted to lower absolute abundances with the original profiles essentially retained, except for higher scatter and a positive europium anomaly in some samples; the downward shift is attributable largely to dilution of the chlorite schist host by introduction of quartz veins possessing negligible REE contents.

In order to further test this interpretation of coherent downward shift in REE abundances by dilution, abundances of La and Yb in the unmineralized metabasalts have been multiplied by the mean dilution factors of Al, Ti, Zr, and Sc in mineralized equivalents, and are represented as bars on diagrams of the latter: a clear correspondence is evident, corroborating the original interpretation of diminished abundance via dilution (see Fig. 5). One sample (D120), however, which has undergone extensive hydrothermal leaching as evidenced by the apparent coherent increase in abundance of Al, Ti, Zr, and Sc, also displays absolute depletions of the REE. These data confirm mobility of the REE during intense leaching as independently deduced from results obtained on hydrothermally leached samples of the Dome Mine (Fig. 11: Kerrich and Fryer, 1979).

In proximity to veins, the whole-rock $\delta^{18}\text{O}$ and $\text{Fe}^{2+}/\Sigma\text{Fe}$ ratios exhibit a major perturbation from background values of +7 and 0,7, respectively (Au < 4 ppb) to +9 to +10 per mil and an average $\text{Fe}^{2+}/\Sigma\text{Fe}$ of 0,92 in carbonate-muscovite schists enveloping Au-bearing quartz veins (Au 1-40 ppm). The $\delta^{18}\text{O}$ of vein quartz at 12-13 is equal to that of quartz extracted from the carbonated mafic schists, to within the limits of analytical precision, implying oxygen isotope equilibrium between hydrothermal fluids and altered wall rocks over a few meters (Tabel I; Kerrich and Fyfe, 1981). At greater distances from the veins, in isotropic metabasalts external to the shear zone boundaries, $\delta^{18}\text{O}$ quartz and the redox state diminish to background values.

Low redox states in mineralized wall rocks, indicated by the predominance of Fe^{2+} , is considered to result from the reduction of Fe^{3+} in silicates and metal oxides by hydrogen, during chemical exchange with a large flux of H_2 -bearing aqueous solutions ascending along a T-P gradient through conduits in the shear zones, and precipitating gold, quartz, etc. (fig. 6). Hydrogen is the most powerful reductant in natural systems, and its generation in hydrothermal reservoirs is discussed in a later section. Boyle (1977) has argued that the observed reduction in veins at Yellowknife is due to the 'lateral diffusion' of components into the shear zones, including arsenic, which may act as a reducing agent. The hypothesis of lateral diffusion as an ore-forming process can probably be ruled out on the basis of several lines of chemical evidence, specifically oxygen isotopes (see later section); and, in addition, it is important to note that wall rocks to auriferous veins are extensively reduced, even when the arsenic abundance is low (Table II).

The oxygen isotope composition of vein quartz falls in a narrow range of 11 to 13 per mil for the Con, Campbell, and Giant vein systems, and quartz-muscovite and quartz-chlorite fractionations are relatively uniform at 3,8 to 3,4 per mil and 5,8 to 6,2 per mil, respectively (Table I). From these data, the ambient temperature of mineralization can be estimated at 350-400°C, and the $\delta^{18}\text{O}$ of fluids from which the veins were precipitated was $+7,5 \pm 0,5$ - within the range of metamorphic fluids. Ferroan dolomite and calcite constituting the ubiquitous carbonate gangue has a uniform carbon isotope composition where $\delta^{13}\text{C} = -5$ to -2: however, $\delta^{18}\text{O}$ is scattered between 8 and 16. These results are considered, collectively with carbonate data for all deposits discussed here, in Part II (Kerrich, 1986).

Provisional results for primary liquid inclusions in vein quartz associated with precipitation of gold indicates fluids of low salinity (<2 wt. % NaCl equivalent), with liquid CO_2 present. Halite daughter crystals are present in liquid inclusions of late-stage barren vein quartz.

D. Hydraulic Conditions During Vein Propagation

One of the fundamental questions pertaining to Archaean lode gold deposits is the hydraulic regime of the ore-forming system. Are the geothermal fluids undergoing thermally driven convective circulation under approximately hydrostatic conditions and in equilibrium with surface waters or, alternatively, do the extensive vein stockworks form by hydraulic fracturing in the presence of geopressurized aqueous reservoirs? This question has been addressed by Kerrich and Allison (1978) with reference to Yellowknife, and Robert and Brown (1984) for the Sigma Mine, Val d'Or, where orientations of the principal stresses and ambient fluid pressures during vein propagation may be deduced given the well-constrained geometry of shear zones and the vein arrays they host.

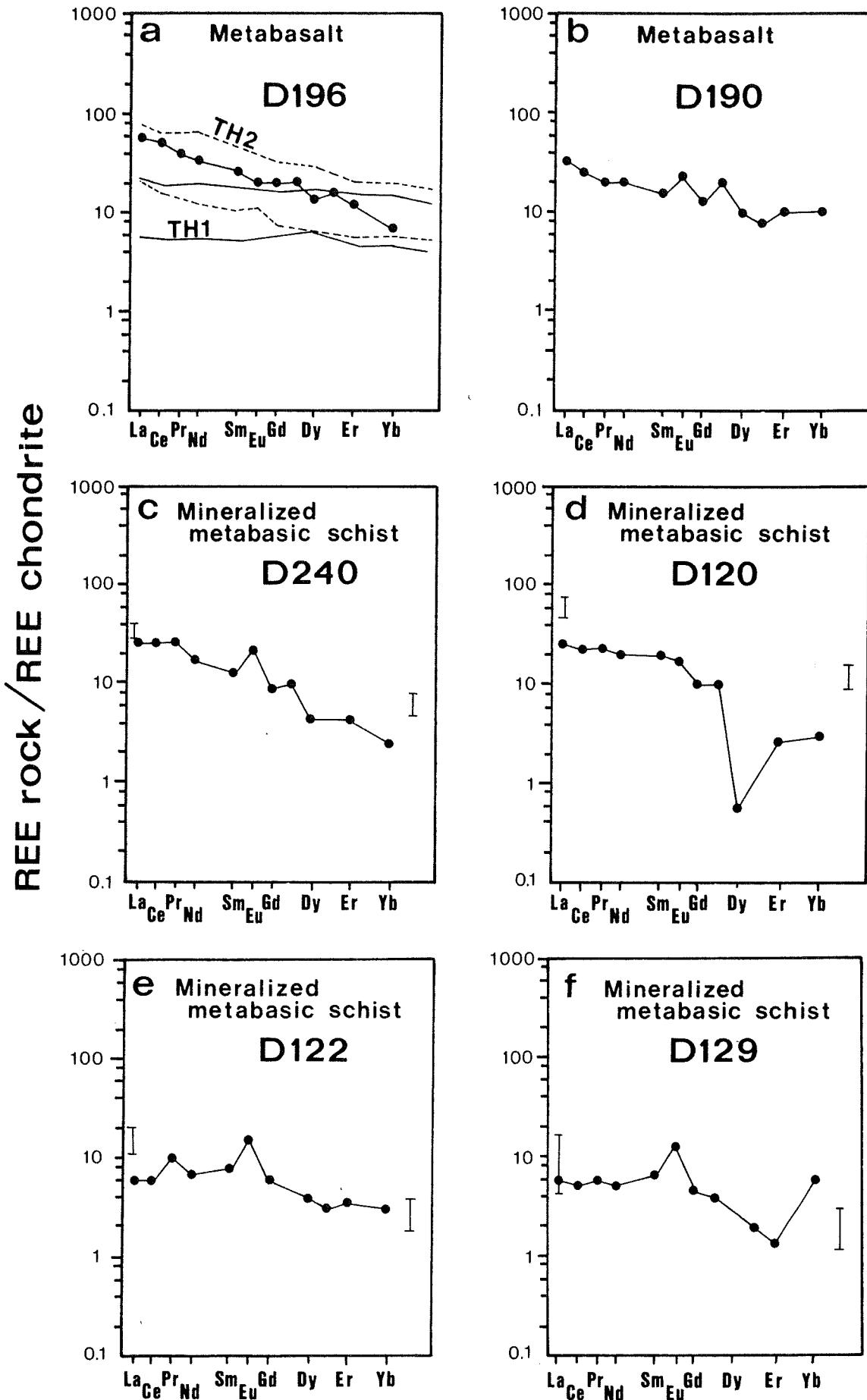


Figure 5 : REE distributions in unaltered (1, 2) slightly mineralized (3, 4) and intensely mineralized (5, 6) basalts, Con Mine, Yellowknife, The vertical bars signify the extent to which La and Yb would be shifted by experiencing the same coherent dilution from the unaltered state (1, 2) as is evident for Al, Zr, and Sc, due to additions of vein material relative to abundances in samples 1 and 2 (unaltered). Superimposed on the REE envelopes for enriched (TH2) and depleted (TH1) Archaean tholeiites (after Condie, 1981).

TABLE I

Oxygen Isotope Composition of Minerals Separated from Gold-bearing Veins and their Host Rocks in the Yellowknife, Timmins and Val d'Or Districts, Together with Calculated Isotopic Temperatures and $\delta^{18}\text{O}$ fluid

		$\delta^{18}\text{O}$ vein quartz	$\delta^{18}\text{O}$ mineral	$\delta^{18}\text{O}$ host quartz	quartz-mineral	temperature $^{\circ}\text{C}$	$\delta^{18}\text{O}$ fluid
YELLOKNIFE DISTRICT	gold-bearing quartz-carbonate veins, 2300 m in sericite-chlorite schist	12,48 12,53 11,50 11,59 4900 5100	6,58 c 5,97 c 7,03 m	12,6	5,95 5,53 4,56	440 480 320	8,2 7,9 7,5
Campbell shear	gold-bearing quartz-carbonate veins, 250 m in sericite-chlorite schist	11,43 10,80		11,29			
Con shear	gold-bearing quartz-carbonate veins, 1550 m in sericite-chlorite schist	12,25 11,50 12,06	5,97 c	12,13	5,53	480	7,9
Giant shear- east zone H.G. zone open pit	gold-bearing quartz-carbonate veins in sericite chlorite schist	12,28 12,77 12,01		12,57			
Western gran- odiorite	gold-bearing quartz veins emplaced into shear zone within graniorite	13,03		13,70			
Ptarmigan	gold-bearing quartz veins in metagreywacke	12,60 13,16	6,67 c	13,91	5,93	440	8,2
Surface	gold-bearing quartz-carbonate veins in metabasalts	13,51 13,56	6,70 c 7,45 c		6,81 6,11	370 420	7,6 8,9
DOME MINE TIMMINS	banded quartz-muscovite veins in ultramafic schist	14,74 14,41 14,37 14,52 14,63	10,98 m 11,28 m 10,78 m 10,54 m	14,66	3,76 3,13 3,59 3,98	430 380	9,8 8,8
	banded quartz-tourmaline veins	15,07 15,24					
	veins in quartz-feldspar porphyry	14,97 13,93 14,19		15,31 13,87 14,26	6,14	420	9,6
	quartz-tourmaline veins in dacite	15,09 15,17	9,21 c 9,38 c		5,88 5,79	440 450	10,8 11,1
	quartz veins in Timiskaming slates	14,65 14,52 14,76		14,10 15,77	3,50	440	10,5
	quartz-carbonate veins in metabasic schists	14,53 15,20	8,99 c	14,84	5,54	480	10,9
	quartz-carbonate veins parallel to auriferous stratiform carbonate	14,87	9,31 c	15,32	5,56	480	11,6
AUNOR MINE TIMMINS	quartz veins parallel to auriferous stratiform carbonate	14,65 15,01					
MACINTYRE MINE	quartz-carbonate veins 1526 stope	15,02 14,96	10,62 m	14,86	4,40	340	8,2
	quartz-carbonate veins, 4675-5 vein	14,81 14,74	10,80 m	14,90	4,01	380	9,2
PAYMASTER	quartz-carbonate-chlorite veins. Mine dump	14,87 14,89	9,17 c		5,70	460	10,9
	silicified Au-bearing porphyry	14,80 14,62					
HOLLINGER	quartz-carbonate veins in altered ultramafic tuffs	13,5	7,7 c		5,8	440	9,1

		$\delta^{18}\text{O}$ vein quartz	$\delta^{18}\text{O}$ mineral	$\delta^{18}\text{O}$ host quartz	quartz-mineral	temperature $^{\circ}\text{C}$	$\delta^{18}\text{O}$ fluid
CHADBOURNE	quartz-albite-carbonate veins in fractured basalt and andesite	12,0 to 13,5	6,1 to 6,9 c	5,9 6,8	3,6 to 4,0	380 to 450	8,1
KERR ADDISON MINE	quartz-muscovite-carbonate veins in carbonate sediment	14,48	10,54 m		3,94	390	9,0
	"flow ore" - albitic-pyrite tuffs and flows	14,4	12,0 ab 6,9 c		4,2	350	8
	"flow ore" - muscovite pyrite tuffs and flows	14,2	10,1 m				
LAMAQUE	quartz-tourmaline - carbonate veins. Main granodiorite	12,84 12,71 12,79	6,54 c		6,30	410	7,8
PASCALES	quartz-tourmaline - carbonate veins	11,86 11,58	5,71 c		6,15	420	8,1
BRAS D'OR	quartz-tourmaline - carbonate veins	11,61 12,70	5,61 c		6,00	430	8,2
EAST MALARTIC	albite-orthoclase-quartz-tuffaceous chert	13,4 to 21,7	10,4 to 12,3 (ab)			200	0,1
			14,1 to 16,7 (or)			150	0,1

c = chlorite; m = muscovite; ab = albite; or = orthoclase.

A three stage sequence of veining has been recognized (Kerrich and Allison, 1978) as follows:

1. the formation of the major shear zones, with concomitant development of the early en-echelon barren veins,
2. development of the massive to banded gold-quartz veins approximately parallel to the schistosity, in the shear zones, and
3. formation of late "ladder" vein systems, which are also locally auriferous, at high angles to the schistosity within the shear zones.

This sequence is illustrated in Fig. 6b. The origin of each vein system will now be considered in turn.

The veins at Yellowknife formed by the infilling of tensile fractures. Close to the earth's surface tensile fractures may form, but at depth the increase of confining pressure (σ_3) includes propagation of shear fracture. However, under conditions of high fluid pressure (Pf) tensile failure by hydraulic fracturing may occur at depths in the crust, in excess of 30km. The principles involved are discussed by Fyfe *et al.* (1979). The stress conditions under which hydraulic fracturing can occur may be represented by:

1. $\sigma_3 - Pf \leq T$
2. $\sigma_1 - \sigma_3 \leq -4T$

where σ_1 and σ_3 are the maximum and minimum principal stresses respectively, and T is the tensile strength of the rock. The first inequality represents the condition where the fluid pressure exceeds the confining pressure by an amount equal to or greater than the tensile strength of the rock. The second inequality is the condition for suppression of the shear failure mode. These stress conditions may be portrayed on a Mohr diagram (Fig. 7a).

The shear zones are characterized by an intense schistosity, the mechanical properties of which are highly anisotropic. In particular, its tensile strength in a direction normal to the schistosity (T_I) will be low compared to that parallel to the schistosity (T_{II}). On a Mohr diagram the envelope for failure parallel to the schistosity will occur at lower stresses than the envelope for failure normal to the schistosity (Fig. 7b). However, as the pore fluid pressure increases and the effective stresses are reduced until σ_3 intersects the Mohr envelope, failure will occur only if the schistosity is oriented normal to the direction of σ_3 (Fig. 7c). If the schistosity is oriented orthogonal to the σ_1 direction then failure along the schistosity will occur when the value of σ_1 intersects the Mohr envelope, as long as σ_3 is less than the tensile strength of the rock normal to the schistosity (Fig. 7d). It is thus possible to achieve hydraulic fracturing within the shear zone parallel to the schistosity with the same external stress regime that caused the initial development of the shear zones. The switch in orientation of stresses postulated by Kerrich and Allison (1978), and illustrated in Fig. 6b, is plausible, but not necessary. The stress conditions which must be satisfied for these veins to develop are:

1. $\sigma_3 - Pf \leq T_{II}$
2. $\sigma_1 - \sigma_3 < -(T - T_{II})$
3. $\sigma_1 - \sigma_3 \leq -4T_{II}$

The latest system of fractures occurs as an array of "ladder" veins oriented approximately normal to the schistosity and dipping at shallow angles towards the east. These veins cross-cut those of stage two which now have a pinch and swell structure as a result of progressive incremental deformation in the shear zones. The stress conditions for this late stage of hydraulic fracturing may be formulated as:

1. $\sigma_3 - Pf \leq T$
2. $\sigma_3 - \sigma_1 < -4T$
3. $\sigma_1 - \sigma_3 < -(T - T_{II})$

and are portrayed on a Mohr diagram (Fig. 7e).

The geometry of the early veins and the schistosity within the shear zones accords well with the concept of shear zone development in rocks showing material behaviour transitional between brittle and ductile.

The geochemical evidence indicates local redistribution of material via migration in a fluid phase, and the absence of any significant gold mineralization during the initial development of the ductile shear zone structures. The second stage veins have a conspicuous banding and often contain slivers of schist oriented parallel to the vein margins. Later intracrystalline deformation has obliterated the original quartz microstructure, but the banded nature and the volumes of hydrothermal fluids involved suggest that the veins were formed by repeated hydraulic fracturing and infilling by quartz precipitated from the hydrothermal fluids. One may envisage a repeated cycle of build up of a fluid reservoir accompanied by elevation of fluid pressure to a point sufficient to induce hydraulic fracture, leading to discharge of the geopressurized reservoir and with resultant volume increase and a consequent reduction of fluid pressure in the source region. Repeated episodes of hydraulic fracturing under conditions of

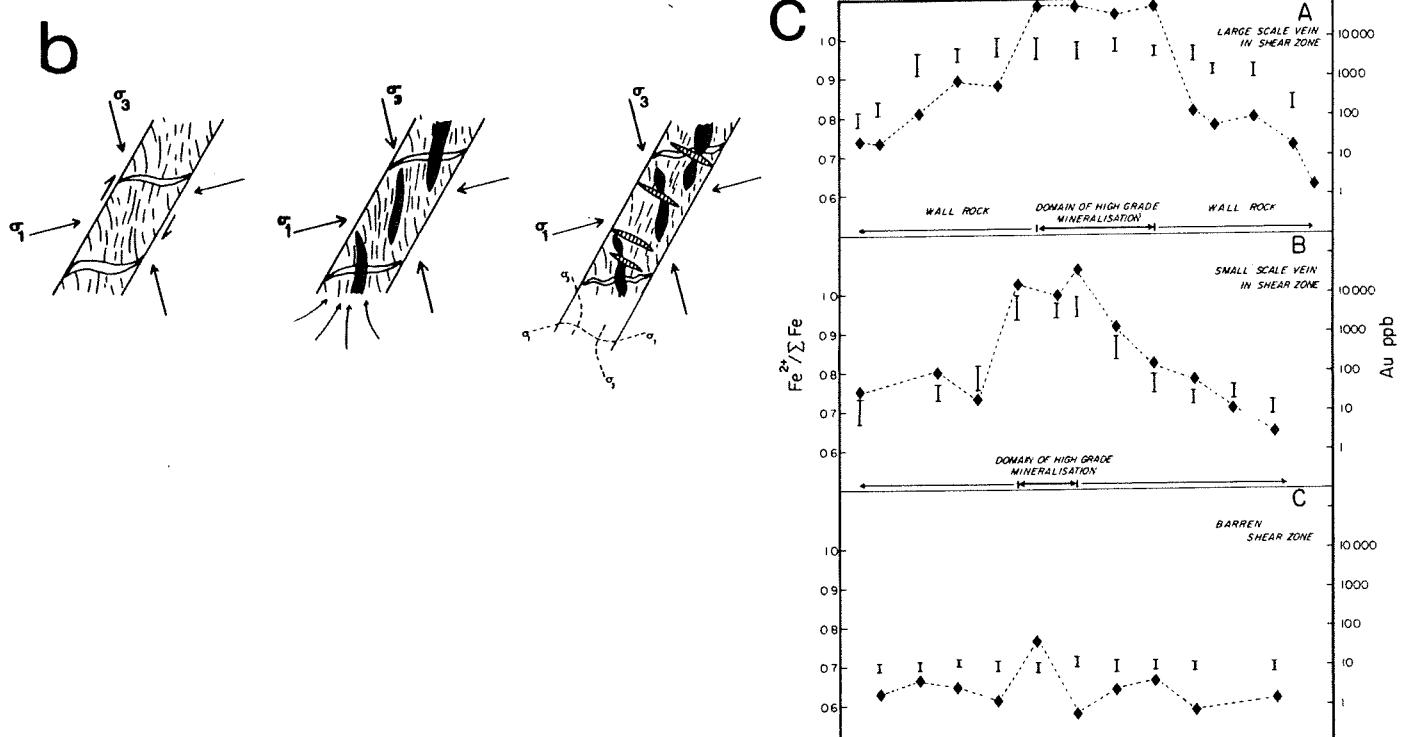
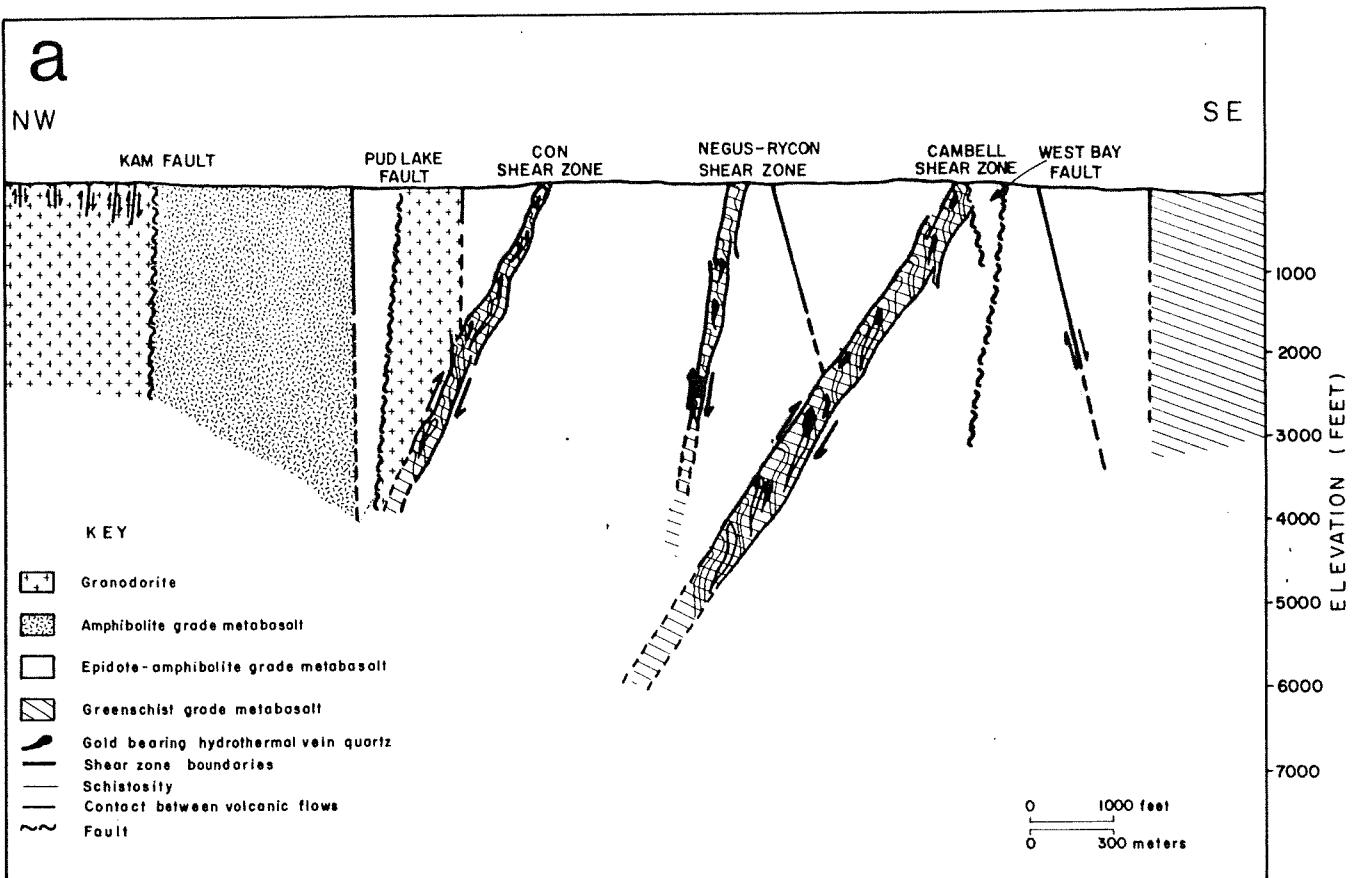


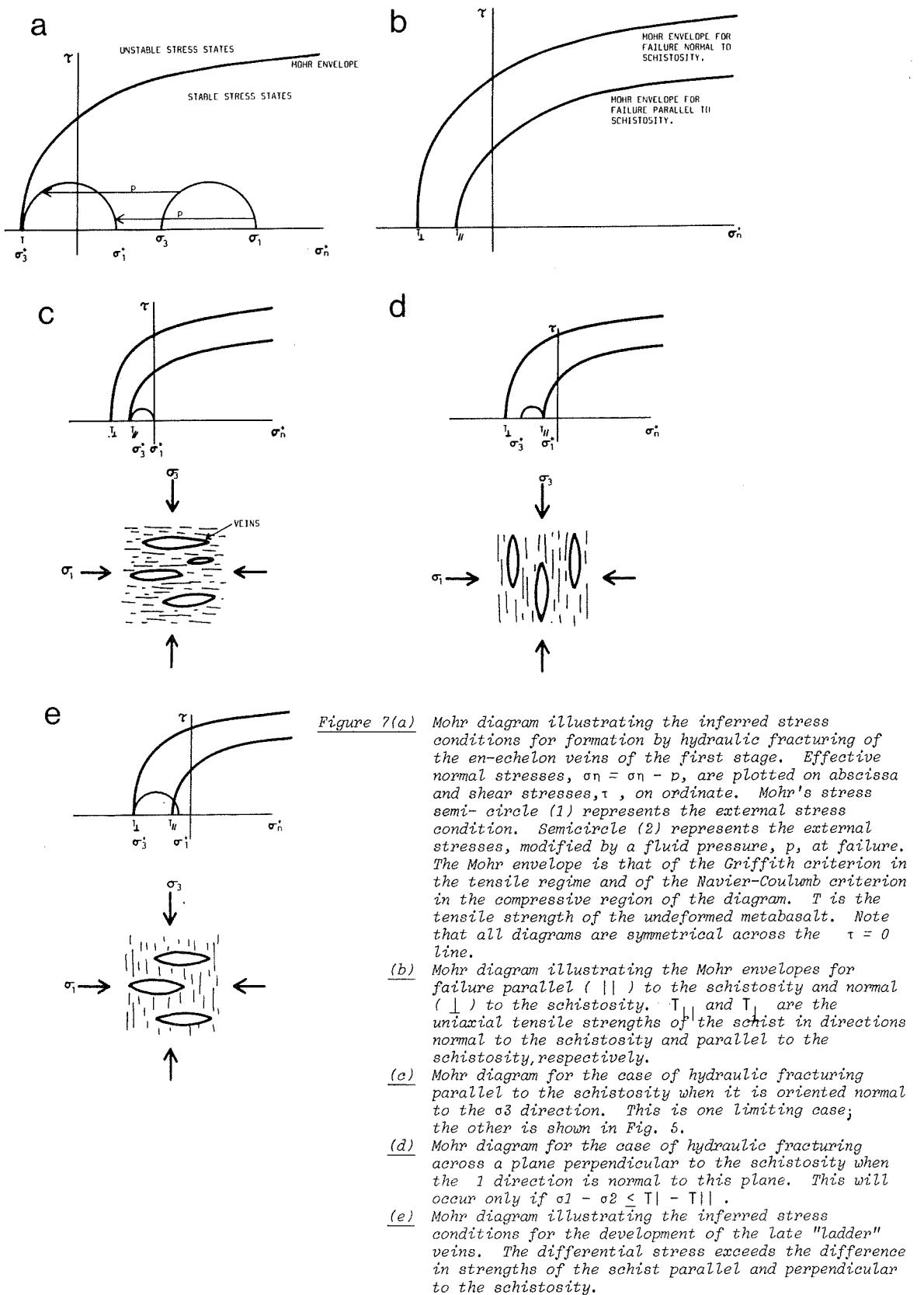
Figure 6 : (a) Schematic geological cross-section of the Yellowknife greenstone belt, illustrating the disposition of the principal rock types, and geometry of the brittle-ductile shear zones. (b) Possible switching of stress regimes accompanying generation of the three sets of vein arrays. (c) Variations in redox state and gold abundance across mineralized and barren shear zones. Gold - bars, redox state - diamonds.

TABLE II

Summary of Data for the Oxidation State of Iron in Background and Au-mineralized Rocks

Mine	Rock description	Fe	Fe ²⁺	Fe ²⁺ / Fe	Statistical functions *	Mean Au ppm
CON and GIANT MINES - YELLOW-KNIFE	Epidote - amphibolite metabasalt - unmineralized Chlorite schist - unmineralized	8,23 (1,168) 8,76 (1,496)	6,28 (0,950) 6,88 (1,257)	0,76 0,78	0,028 0,056	0,002 0,012
DOME and AUNOR MINES-TIMMINS	Epidote-amphibolite metabasalt- unmineralized Chlorite-schist-unmineralized Mineralized sericite-chlorite-quartz-pyrite schist Epidote-amphibolite metabasalt- unmineralized	8,43 (0,707) 8,99 (2,065) 5,94 (2,492) 7,82 (0,521)	6,36 (1,045) 7,22 (2,025) 5,62 (2,378) 6,39 (0,611)	0,75 0,80 0,95 0,81	0,076 0,058 ₁₀ 0,041 ₂₄ 0,061 ₉	0,001 0,027 30
DICKENSEN MINE - RED LAKE	Mafic to intermediate flows- unmineralized Weakly mineralized mafic flows Mineralized metabasic tuff Mineralized metabasic tuffs enveloping Au-bearing carbonate chemical sediments Mineralized Timiskaming slate Mineralized ultrabasic schist (H/A zone)	9,45 (0,783) 9,32 (1,471) 8,16 (0,084) 8,42 (3,071) 5,27 (0,864) 6,53 (1,872)	6,89 (0,465) 7,66 (1,516) 7,43 (4,698) 7,46 (2,914) 3,97 (0,798) 6,04 (1,699)	0,73 0,82 0,91 0,88 0,75 0,92	0,026 ₃ 0,085 ₅ 0,013 ₄ 0,064 ₈ 0,080 ₃ 0,957 ₄	0,003 0,028 2,1 4,0 7,0 0,8
E. MALARTIC MINE-VAL D'OR	Mineralized metabasic flows enveloping Au-bearing tuffaceous chemical sediments Metabasic tuffs-unmineralized Weakly mineralized quartz-feldspar porphyry Mineralized felsic cherty-tuffs Weakly mineralized greywacke Weakly mineralized metabasic tuffs	5,27 (0,467) 7,34 (4,052) 2,37 (1,016) 2,32 (1,608) 3,33 (0,644) 6,59 (3,381)	7,36 (0,172) 4,79 (2,008) 1,11 (0,306) 1,36-(0,406) 1,73 (0,462) 3,84 (2,336)	0,72 0,70 0,51 0,41 0,53 0,58	0,120 ₄ 0,114 ₄ 0,147 ₄ 0,138 ₉ 0,068 ₇ 0,130 ₄	0,13 0,25 8 1,7 4,3

* Standard deviation and number of determinations



high P_f have cycled the effective confining stress ($\sigma_3 - P_f$) such that the rocks have in turn cycled through the brittle ($\sigma_3 - P_f$, low) to ductile ($\sigma_3 - P_f$, high) transition.

Mechanical anisotropy of schists within the shear zones will cause refraction of the stress, and hydraulic fracturing will tend, therefore, to form parallel or normal to the fabric as in the second and third stages of vein development (Figs. 6b, c, 7).

Development of the second stage veins requires fluid pressure to exceed the maximum principal stress by an amount equal to the tensile strength. This will occur if the fluid pressure has a value close to the geostatic pressure for a given depth. Hydraulic fracturing will permit upward movement of this fluid the pressure of which is equivalent to the geostatic pressure at greater depth and which, it is suggested, is capable of exceeding the maximum principal stress at higher levels. The hydraulic fractures will, therefore, propagate from towards the surface.

These structural considerations apply equally to many other of the vein gold deposits discussed below, which appear also to have formed under conditions of hydraulic fracturing induced by geopressurized hydrothermal reservoirs.

E. Summary and Discussion

In summary, the gold vein deposits at Yellowknife were emplaced into shear zones during episodes of hydrofracturing, from a hydrothermal reservoir at 400-450°C, at elevated pressure, characterized by moderate CO_2 content, low redox state and salinity, with $\delta^{18}O$ in the range of metamorphic fluids. Hydrothermal alteration of basaltic wall rocks was characterized by hydrolysis of Fe, Mg, Ca, Mn-silicates to Fe, Mg, Ca, Mn-carbonates, with the wall rocks donating the bivalent metal cations and fluids introducing CO_2 . Hydrolysis of albite to muscovite accompanying alteration proceeded via massive additions of potassium from fluids to the wall rock, with concomitant loss of sodium to the fluid.

Important early studies of the geochemistry of altered rocks adjacent to Au-bearing veins at Yellowknife were conducted by Boyle (1961) who suggested the Sb, As, Au, silica, the transition metals, and other elements were liberated during carbonate replacement alteration of rocks, and that this process is an important factor in the contribution of components to certain Au-bearing lodes. This premise is based on simple comparison of element abundances in carbonated rocks and their precursors, taking into account changes of specific gravity (Boyle, 1961, Table 7, and p. 23), but not possible large changes of volume.

Under the conditions of large volume increase required for carbonation and veining, involving additions of H_2O , CO_2 and SiO_2 , together with decrease of specific gravity, all relatively immobile elements of the parent rocks will appear to undergo a similar proportional decrease in abundance by dilution - e.g., Al_2O_3 , Sc, Zr (see Fig. 8). The analytically measured abundances of Cr, Ni, and other elements may decrease from country rocks to carbonated alteration rocks (cf. Boyle, 1961, pp. 61, 66; Boyle, 1976, Table 7), but if, as demonstrated above, volume factors accompanying carbonate alteration may exceed 7 then introduction of these elements into the system is required (Figs. 3, 4). However, the apparent decrease of Al_2O_3 , Cr, Ni, in carbonated alteration zones to veins is treated as an absolute reduction in abundance by Boyle (1961; 1976, Table 7). Use of these inferred chemical gradients, without consideration of volume changes, to deduce the direction or magnitude of chemical fluxes from wall rocks into veins during mineralization is invalid.

IV. DOME AND HOLLINGER MINES - TIMMINS DISTRICT

Cumulative gold production from greenstone belt deposits of the Superior Province to date exceeds 5287 tonnes (>170 M oz) (Bertoni, 1983; Colvine *et al.*, 1984). Two of the largest deposits, the Dome (311 tonnes Au) and Hollinger (602 tonnes Au) are located in the Timmins District of the Abitibi greenstone belt, and some of their essential geochemical characteristics are described below (Fig. 9). Recent overviews of the geology and structures of the Timmins District are reported by Roberts (1980) and Hodgson (1983).

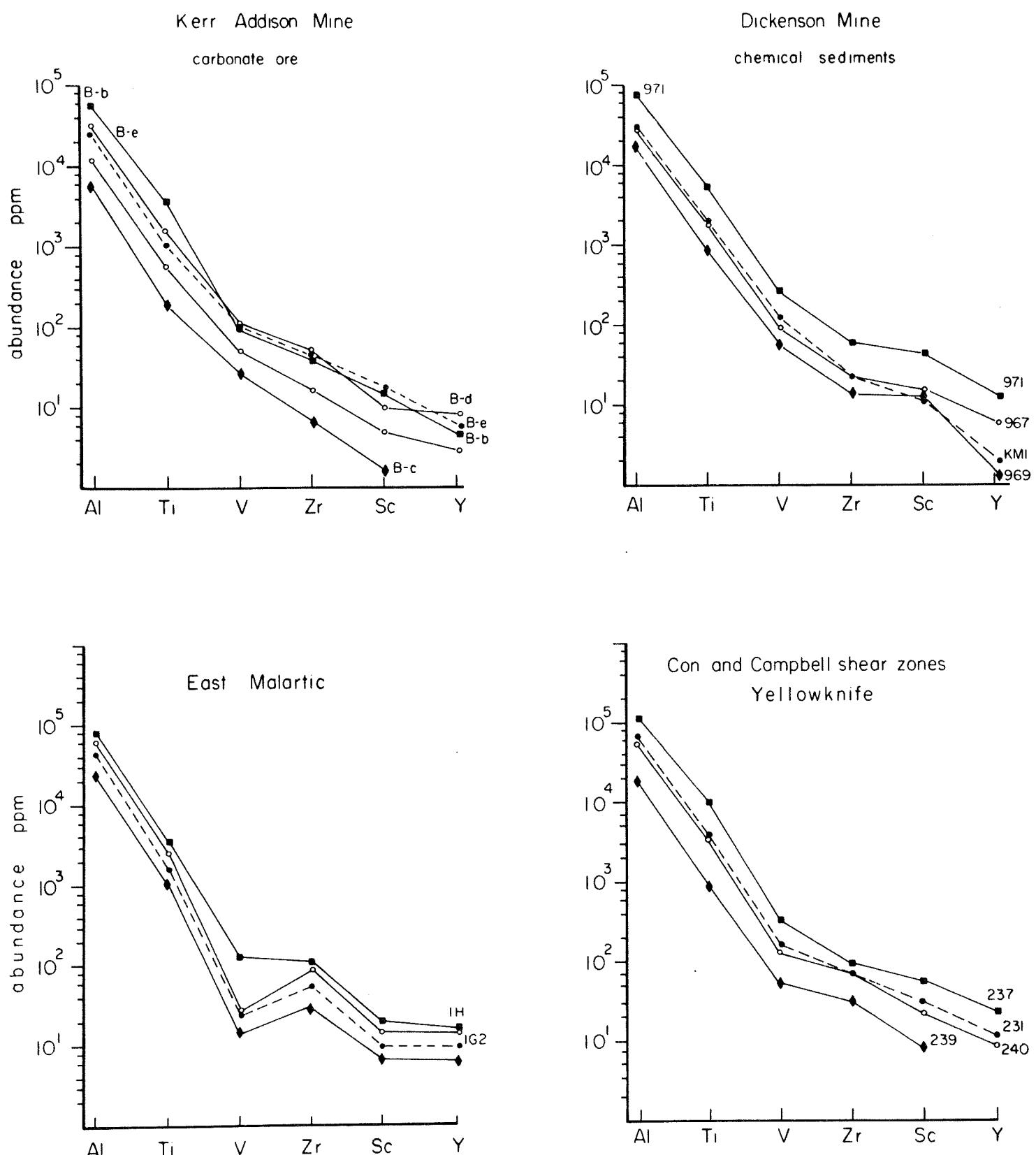


Figure 8 : Absolute abundances of Al, Ti, V, Zr, Sc and Y, in chemical sedimentary and vein gold deposits. The overall coherent dilution of these elements corresponds to increasing additions of a hydrothermal precipitant containing no Al, Ti, V, Zr, Sc or Y to a wall-rock component to which these elements are exclusively indigenous, for the case of vein deposits (after Kerrich, 1983).

A. Dome Mine: Auriferous Ferroan Dolomite Chemical Sediments

1. Geological Setting

Fourteen gold-bearing sedimentary units are disposed as interflow horizons in basaltic flows at the Dome Mine. These basalts lie between the south-facing South Greenstones and the turbidites of the Timiskaming metasediments, which are situated on the south limb of the Porcupine Syncline (Roberts, 1980; Roberts and Reading, 1981). Pillowed, variolitic, and massive varieties of basaltic flow are present, along with associated mafic tuffs and hyaloclastite.

The sedimentary rocks are composed principally of laminated ferroan dolomite and microcrystalline quartz, with interposed laminae of tuffaceous material. Native gold and hydrocarbons are ubiquitous, together with muscovite and the Mg-tourmaline dravite in the 10 m size range: up to 3% pyrite and pyrrhotite are present (Holmes, 1968; Fryer *et al.*, 1979). Veins with both conformable and cross-cutting relationships are present in the carbonate units and their enveloping basaltic rocks: the veins are composed of coarse-grained (mm size range) quartz, albite, pyrrhotite, ferroan dolomite, muscovite, and dravite, and this assemblage of coarse-grained minerals is pronounced at the boundaries of carbonate units. These relationships of the carbonate sediments, veins, and bounding volcanics are also present in the Aunor Mine (Van Hees, 1979).

Chemical analyses of the principal rock types and their mineralized equivalents for the Timmins area in general and in the Dome Mine have been reported by Pyke (1980), Fryer *et al.*, (1979), and Roberts and Reading (1981). Based on the absolute TiO₂, Zr, Cr, and Ni abundances, coupled with lower than chondritic Al₂O₃/TiO₂ (Fryer *et al.*, 1979), it is probable that the mafic flows which host the carbonate sedimentary units were originally Fe-tholeiitic basalts in composition (cf. Nesbitt and Sun, 1976).

Samples of the flows, which appear least altered in hand specimen, have albite, quartz, chlorite, epidote, and calcite as the principal mineral constituents - the typical assemblage of ocean-floor spilites. They possess low gold contents in general, and are characterized by relatively uniform abundances of the less mobile major and trace elements, whereas there are significant variations in K₂O, Na₂O, MgO, and CaO. The basalts have $\delta^{18}\text{O}$ whole-rock values of 8 to 10, and average δ -quartz = 12 (Kerrich and Fryer, 1979). Taylor (1968) has shown that fresh, unaltered submarine basalts have whole-rock δ -values of +5,7 ± 0,3 per mil. The ^{18}O enrichment recorded for the Dome basaltic flows relative to primary ocean-floor basalts is attributed to oxygen isotope exchange with seawater at low temperature (<300°C), during fluid transport through the cooling submarine volcanic sequence. This interpretation is compatible with the observed variation in abundance of the alkali- and alkaline-earth metals, which are characteristic of spilitization reactions in ocean-floor basalts (cf. Fyfe and Lonsdale, 1981).

Basalt flows which immediately bound the carbonate sedimentary units are bleached, and transected by quartz-ferroan dolomite-tourmaline veins. The chemical compositions of the flows are correspondingly erratic owing, in part, to the variable amounts of vein material contained within them. In particular, SiO₂ is strongly dependent on the extent and type of veining, showing a range from 33 to 71 wt. % in rocks of similar primary chemistry, as signified by relatively constant ratios of Ti/Zr and Al₂O₃/TiO₂, which match those in the less-mineralized equivalents discussed above. Other elements that may have absolute abundances influenced by mixing are CaO, MgO, and Fe₂O₃, inasmuch as they are major components of carbonate minerals comprising veins and the carbonate sediments.

Despite these large-scale changes in the chemical composition of the basalt flows, certain elements have probably been conserved. For instance, Al₂O₃, TiO₂ and Zr maintain relatively constant ratios to one another over a factor of three in absolute abundance. This provides a basis for conducting calculation of chemical mass balance, which are illustrated in Fig. 10. The salient results are loss of MgO, CaO, Na₂O, Fe₂O₃, and SiO₂ at volume factors less than unity, indicative of extensive hydrothermal leaching, resulting in highly elevated absolute Al, Ti, and Zr abundances. At volume factors in excess of unity, signifying additions of hydrothermal precipitates, SiO₂, MnO, Fe₂O₃, and volatiles are added, corresponding to the introduction of quartz-ferroan dolomite veins. Massive fixation of K₂O, with concomitant stripping of Na₂O, MgO, CaO, and Sr, occur at all observed finite states of alteration.

These bleached and altered basalt flows have a $\delta^{18}\text{O}$ whole rock or 11 to 14, or 1 to 6 per mil heavier than the less-mineralized counterparts: $\delta^{18}\text{O}$ quartz of 15,3 to 16 is closely comparable to that of quartz in veins transecting the basalts and interflow sediments, signifying attainment of isotopic equilibrium between fluids

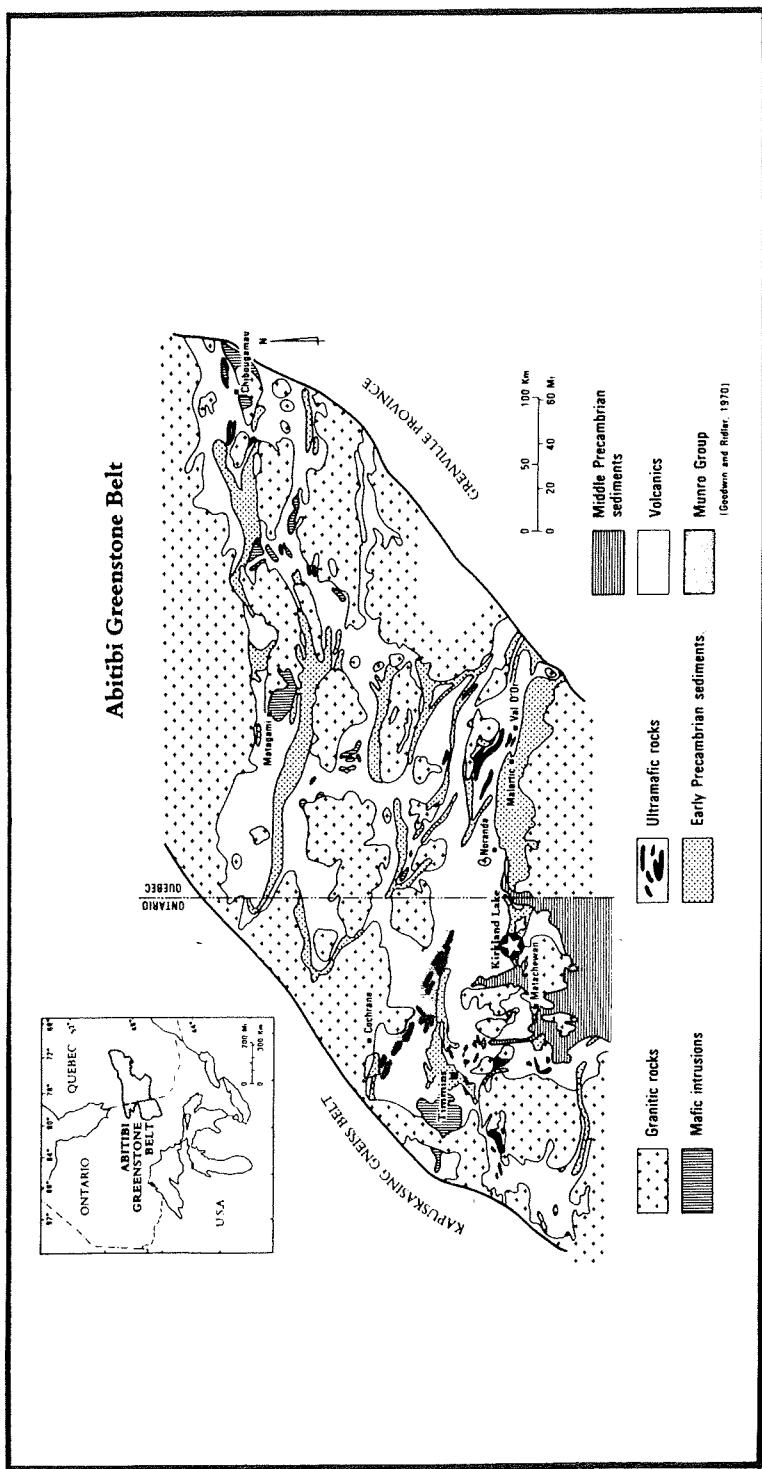


Figure 9 : Schematic geology of the Abitibi belt, modified after Goodwin and Ridder (1970). Of the Archaean lode gold deposits described in this paper, the Dome and Hollinger Mines are located in the Timmins District, the Macassa Mine is in Kirkland Lake, the East Malartic Mine in the Malartic District, and Lamaque Mine at Val d'Or.

coursing through the veins and their immediate wall rocks. Temperatures of veining and attendant alteration of the basalts are estimated at 350-400°C, from quartz-chlorite oxygen isotope fractionations and fluid-inclusion filling temperatures (Table I; Kerrich and Fryer, 1979).

Basaltic flows which host the carbonate sediments, but are not mineralized, have the unfractionated REE patterns typical of Archaean tholeiitic basalts (Roberts and Reading, 1981, see Fig. 11). However, all studied samples of their bleached equivalents that immediately envelop the carbonate ore horizons have anomalous REE distributions: light REE abundances are relatively unfractionated, but REE heavier than Sm exhibit progressive depletion with respect to increasing atomic number, and for most samples a slight depletion in Eu ($\text{Eu/Eu}^* = 0.89$). One of the rocks which has undergone intense hydrothermal leaching shows a pronounced enrichment of the heaviest REE superimposed on the previously described patterns; this is interpreted as the result of the precipitated of the heaviest REE (previously leached from the volcanic sequence, Fig. 11), during the waning stages of hydrothermal activity.

Fyon and Crocket (1982) considered that the low-temperature palagonite, zeolite, clay, calcite, high- ^{18}O style of alteration, and the subsequent carbonate alteration (both ore and non-ore associated) of basalts in the Timmins District are an integral part of early seafloor and subseafloor hydrothermal alteration of the volcanic pile of seawater. This conclusion is based partly on reported increases of B, Li, K, ^{18}O and volatiles in the low-temperature altered basalts (as is observed for marine water alteration of modern ocean-floor basalts), coupled with still greater concentrations of these components in ore-related carbonated tholeiitic basalts.

However, as described by Fryer *et al.* (1979), and in this paper, some of the carbonation initially involved Mg and Na stripping of basalts (see Fig. 10), in contrast to seawater alteration in which magnesium and sodium are transferred from the marine reservoir to rocks. Furthermore, carbonate-altered rocks associated with ore possess significantly heavier whole-rock $\delta^{18}\text{O}$ than their low-temperature marine-water-altered counterparts. This high- ^{18}O signature of carbonated rocks cannot be accounted for by higher fluid fluxes relative to the low-temperature alteration regime as suggested by Fyon and Crocket (1982, p. 122), or to higher temperatures during carbonate production, as both of these factors would drive the whole rock to lower $\delta^{18}\text{O}$. As suggested by Kerrich and Fryer (1979), the high- ^{18}O character of carbonate rocks associated with ore can be attributed to an independent high- ^{18}O , CO_2 -rich, low-salinity hydrothermal reservoir.

Finally, it is worth noting that whereas both Archaean and modern oceanic basalts subjected to alteration by marine water have common mineralogical, redox, and isotopic characteristics, modern examples possess neither the pervasive carbonate alteration, major quartz veins, nor lode gold deposits of their Archaean counterparts.

Extremely aluminous rocks (up to 27% Al_2O_3 in a rock of primary Fe-tholeiitic basalt composition) are interpreted to be the product of near seafloor hydrothermal leaching in the presence of an acid vapour phase and CO_2 , evolved from boiling and CO_2 immiscibility of a CO_2 -rich hydrothermal fluid. Boiling would signify relatively shallow water depths, corroborated by the presence of columnar joints in the basalt flows, by tuffaceous horizons indicative of explosive volcanism, and by fragments of volcanic ejecta in the interflow chemical sediments (cf. Van Hees, 1979).

The auriferous carbonate chemical sediments are characterized by relatively simple chemistry, reflecting varying proportions of ferroan dolomite, chert, and mafic tuff, with superimposed dilutions of these components by subsequent additions of quartz-carbonate-tourmaline veins. As for the chemical sediments at Red Lake (Kerrich *et al.*, 1981), the mafic tuffs appear to have donated Al, Ti, Zr, Cr, and Ni, whereas the Si, Fe, Mn, S, C, Mg, Ca, Cu, and Zn reflect hydrothermal precipitation of ferroan dolomite, chert, and sulphides on the seafloor. Manganese is present at highly anomalous levels, in the divalent state, substituting in the ferroan dolomite structure (see Kerrich, 1983). Gold contents are erratic, varying from 1 to 26 ppm, Ag ranges from 1 to 16 ppm, and Au/Ag from 0.6 to 10. Up to 260 ppm Pd has been recorded in these sediments (Fryer *et al.*, 1979). Copper and zinc abundances are highly variable, but average <100 ppm each.

Chert in the carbonate sediments has a $\delta^{18}\text{O}$ quartz of 17, significantly higher than that of quartz in veins and their immediate host rocks. As for the auriferous sediments at Red Lake ($\delta^{18}\text{O} = 18$, Kerrich *et al.*, 1981), this isotopically heavy value may signify coprecipitation of gold, chert, and carbonates at ambient ocean-floor temperatures of 90-150°C. REE distributions of the sediments have a pronounced positive Eu peak, characteristic of most Archaean chemical sedimentary rocks (Fig. 11; Fryer, 1977).

ALTERATION OF BASALTIC AND ULTRAMAFIC ROCKS DOME MINE

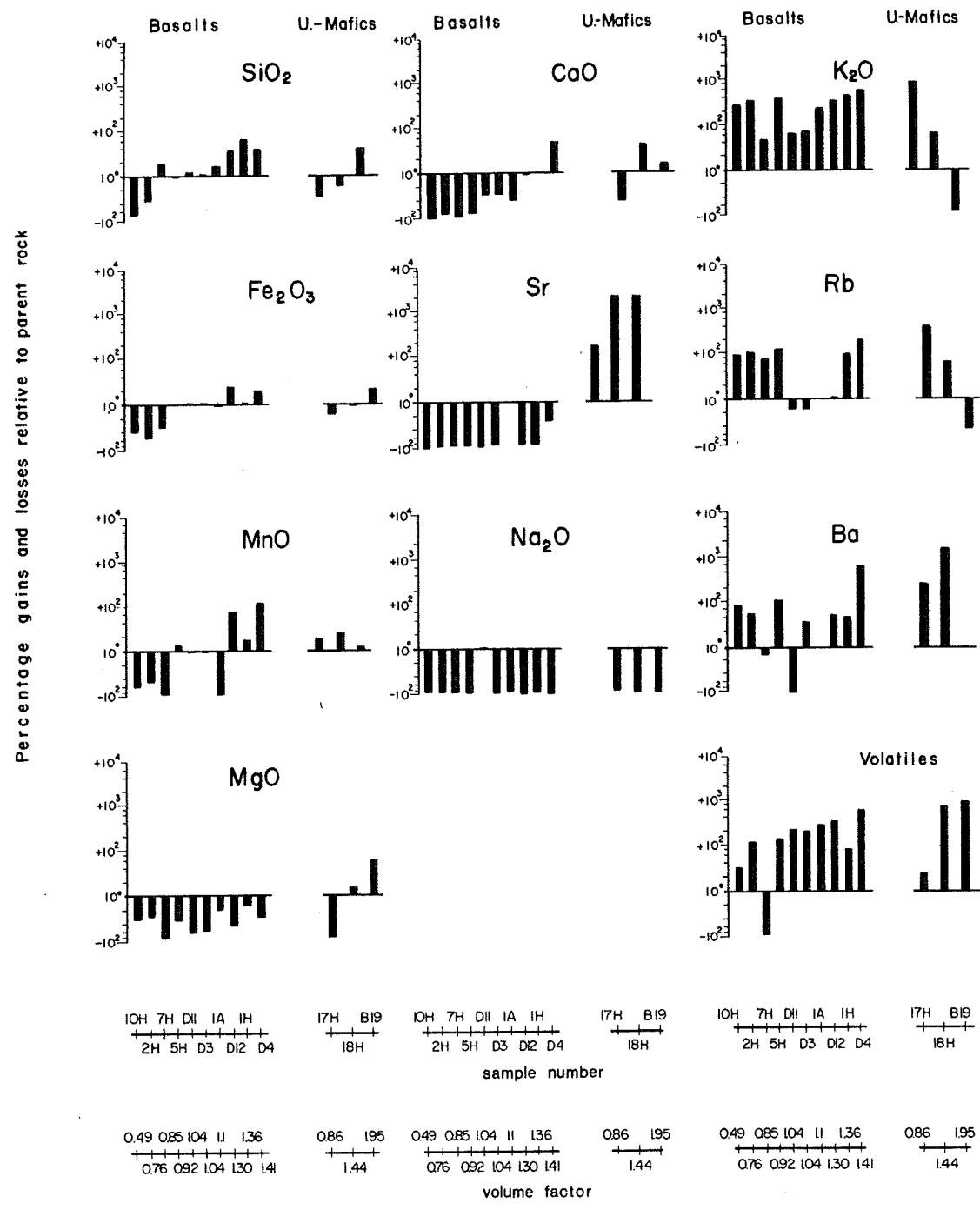


Figure 10 : Gains or losses of major oxides and selected trace elements in hydrothermally altered rocks of primary Fe-tholeiitic basalt composition enveloping auriferous ferroan dolomite sediments, and of primary ultramafic composition hosting banded veins, Dome Mine. Gains and losses expressed as percentages relative to abundances in the unaltered parent rock, and ordered according to increasing volume factor (after Kerrich, 1983).

DOME MINE REE

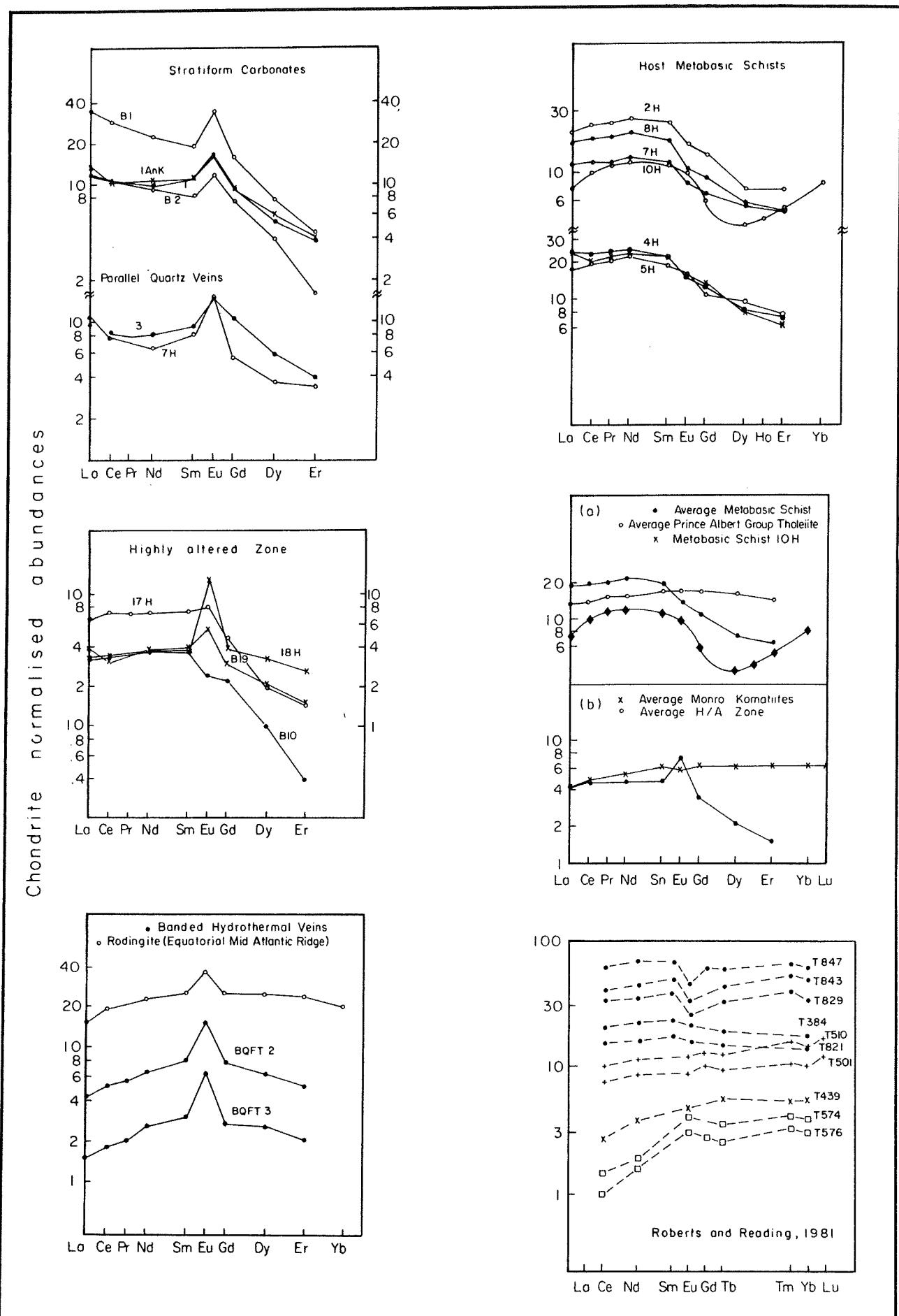


Figure 11 : Distributions of the REE in various rock types at the Dome Mine (after Kerrich, 1983).

Carbonate compositions of the interflow chemical sediments are uniformly in the range of ferroan dolomite, with a significant manganese content (2 wt % MnCO₃): the dolomite is laminated, fine grained, and contains abundant disseminated carbonaceous and sulphide inclusions. Vein carbonates are, in general, distinctly more Fe- and Mn-rich, coarser grained, and clear of inclusions, signifying that they were not simply derived from local recrystallization of the sedimentary carbonates. Siderite is present as a minor phase in some vein selvages. These observations corroborate the separate origin of the sediments and veins, also implied by their differences in δ¹⁸O and REE distributions, thus endorsing multistage gold enrichment. Manganiferous siderite has also been reported for the auriferous pyrite, siderite, and siderite iron-formations at the Agnico Eagle Mine (Barnett *et al.*, 1982).

2. Environments of Gold Enrichment

In summary, the sequence of basaltic flows within which the auriferous interflow chemical sediments occur appear to have undergone oxidative spilitization reactions in the presence of seawater with δ¹⁸O ~ 0, and low CO₂ content, at temperatures of <300°C during and shortly after extrusion. This stage involved little or no gold enrichment of the flows, but probably involved fixation of marine carbonate as calcite, and marine sodium as albite, in the normal manner of spilitization reactions, as seawater heated on penetrating the cooling volcanic sequence.

Meanwhile, reducing, low-salinity, high-¹⁸O and CO₂-rich hydrothermal fluids were escaping from deeper levels of the volcanic sequence, to debouche onto the seafloor, mixing with ambient marine water, to precipitate gold-bearing ferroan dolomite sediments. Such fluids may have been derived by metamorphic outgassing. This first stage of possible gold enrichment in sediments occurred during periods of relative quiescence, marked only by intermittent input of mafic volcaniclastic material or tuff. As suggested above, the CO₂-rich fluids were probably derived from deeper levels of the volcanic sequence (in contrast to the shallow circulating seawater involved in the initial spilitization reactions). During venting at the ocean floor under conditions of low P_{CO₂}, the fluids carbonated previously spilitized basalts via the hydrolysis of Fe, Mg, Ca-silicates to Fe, Mg, Ca-carbonates, producing volume increase. This process is clearly illustrated in Fig. 9, and in the metasomatic variation diagram of Roberts and Reading (1981) for less altered rocks in which progressive addition of CO₂ to the mafic flows occurs at essentially constant Fe, Mg, and Ca, signifying local transfer of the bivalent metal cations from a silicate to a carbonate reservoir.

In the final stage of mineralization, the carbonate interflow sediments appear to have acted as a permeability barrier to further outgassing of CO₂-rich fluids, so that fluid ponding and/or streaming along the sediment boundaries may have occurred. Periodic breaching of the barrier by hydrofracturing led to the ubiquitous 'ladder' veining with attendant second stage gold enrichment, and bleaching of basalt flows bounding the interflow carbonates.

B. Dome Mine - Massive Quartz Veins in Altered Ultramafic Rocks

Two massive veins of banded quartz-tourmaline and banded quartz-Cr muscovite (formerly termed fuchsite), respectively, are associated with the E-W trending zone of 'highly altered' carbonate rock at the Dome Mine (so-called H/A zone). The veins are subvertically oriented, with dimensions of metre width and a maximum horizontal and vertical extent of ~300m (see Roberts, 1980): exceptionally rich concentrations of gold are present in these veins. Banding has been interpreted to represent incremental dilation during successive episodes of hydraulic fracture accompanying fluid discharge (Kerrich and Fryer, 1979).

The banded veins are predominantly quartz, with variable amounts of albite, chlorite, dravite, carbonates, sulphides, and Cr-rich mica. Analyses of muscovite separates show them to be highly enriched in Cr (2370-8460 ppm), but with only low to moderate content of Ni (160-2500 ppm). Whole-rock analyses of the vein material show comparable Ni and Cr abundances, implying that Ni must also be contained in phases other than muscovite. Assuming that the Cr-muscovite compositions of the veins are similar to those of the H/A zone, this would imply a similar relationship of Ni in the H/A zone (Fryer, *et al.*, 1979).

The zone of highly altered rocks (H/A zone) is made up of variable proportions of wall rocks and quartz-carbonate vein material. Unlike the chemical composition of the stratiform carbonate layers within the mafic schists, however, the calculated carbonate composition of the H/A zone are more Mg-rich. The elevated Mg contents of certain samples reflect the high proportion of magnesite and Mg-chlorite. Base metals are sporadically

distributed, but overall are present at lower than crustal background abundance, except for lead at ~330 ppm in the quartz-muscovite vein.

Primary fluid inclusions are rarely preserved; preliminary evidence reveals the presence of liquid CO₂ immiscibility, and fluids of <1.5 wt % NaCl equivalent. Electron-microprobe analyses of carbonates show coexisting iron-rich magnesite and ferroan dolomite (Fryer *et al.*, 1979; Kerrich, 1983), and chlorites may contain up to 1.35 % Cr. High levels of Cr and Ni in the H/A zone are most distinctive. This may be a primary feature of the host schists, as their chondritic Ti/Zr and Al₂O₃ ratios and REE data (Kerrich and Fryer, 1979; Fig. 11) suggest that they could have been ultramafic.

The banded hydrothermal veins analyzed from the Dome Mine contain fundamentally different REE abundances than the other rocks present (Fig. 11). They are characterized by gently convex upward REE patterns with strong enrichment in Eu, and do not show the depletion in the heavier REE characteristic of the metabasic schists or their wall rocks, the H/A zone (Fig. 11). These data and other geological and geochemical evidence discussed earlier suggest that the fluids that deposited these REE were of high temperature and would have been in equilibrium with the mafic and ultramafic rocks found stratigraphically below the veins. The REE characteristics of the veins are what would be predicted from the available experimental work (Cullers *et al.*, 1973) on rockwater equilibrium at high temperature, given the extremely reducing nature of the fluids as indicated by the highly reduced state of the iron in the wall rocks (Table II).

The similar heavy REE depletions observed in the metabasic and ultramafic schists adjacent to veins imply a similar origin (Fig. 11). Most studies on REE mobility have suggested that the light REE are much more mobile than the heavy REE (cf. Frey *et al.*, 1976; Wood *et al.*, 1976), but the opposite appears to be the case for the rocks analyzed from the Dome and Con mines (Figs. 5, sample D120, Fig. 11). The distributions are distinct from hydrothermally altered ocean-floor basalts which typically exhibit enrichments of the light REE (Frey *et al.*, 1976). The most probable complexing agent for the REE is CO²⁻ (cf. Hermann, 1972; Kosterin, 1959), which would account for the greater mobility of the HREE.

For the purpose of chemical mass balance, an average of analyses for relatively fresh komatiites has been utilized as a plausible hypothetical parent rock to the H/A zone, based on the same lines of reasoning as employed for deducing parental compositions of altered ultramafic rocks at Hollinger (see below). Many rocks have undergone substantial volume losses during alteration from depletions of SiO₂, CaO, Fe₂O₃, Na₂O, and MgO in excess of the absolute gains in volatiles and K₂O. By analogy with alteration of ultramafic rocks at Hollinger, this may indicate multistage hydrothermal events. At volume factors of <1.5, alteration is characterized by near quantitative loss of Na₂O, minor gains of MnO, small depletions of SiO₂ and Fe₂O₃, and variable gains or losses of CaO + MgO, in conjunction with massive introduction of K₂O, Rb, Ba, and volatiles (Fig. 10). At volume factors in excess of 1.5, absolute abundances of elements are diluted by the addition of vein quartz, but except for Sr addition, patterns of alteration are essentially as above. As for the patterns of chemical change at Yellowknife, depletion of CaO and MgO at low fv's is balanced by gains of these oxides at higher fv's. These relations probably signify Ca, Mg transfer from a silicate reservoir in wall rocks to a carbonate reservoir in vein selvages, accompanying the hydrolysis of Ca, Mg-silicates to Ca, Mg-carbonates during CO₂ fixation from hydrothermal fluids. In many respects, these alteration patterns are similar to those observed at the Hollinger Mine.

In summary, the banded hydrothermal veins at the Dome Mine were precipitated from solutions at 380-480°C, possessing significant CO₂ coupled with low salinities and redox state, with δ¹⁸O fluid 8 ± 1 - probably of metamorphic derivation (Table I). These fluids discharged in pulses inducing hydrofracturing, and precipitated veins with abundant silica and low sulphur, high gold with low base metal contents, and transported HREE. The H/A zone ultramafic rocks may have undergone an early stage of intense hydrolysis in the seafloor environment, coevally with extrusion, leading to stripping of soluble components. Subsequently, fluids streaming through vein conduits imposed an alteration pattern characterized by massive additions of SiO₂, K₂O, Rb, Ba, and volatiles.

For the Timmins camp in general, Fyon *et al.*, (1982a,b) have shown that the δ¹³C (-4.5 to 0) and δ¹⁸O (+9 to +13) of vein and replacement carbonate minerals at any given site are essentially independent of the magnitude of gold production, with the exception of Hollinger. However, the δ¹⁸O of carbonate minerals and of vein quartz (+10 to +15 per mil) correlates with stratigraphic position, such that the isotopically heaviest samples are highest in the section. This covariance could reflect (1) an upward decreasing temperature of vein precipitation, (2) a progressive increase in bulk rock ¹⁸O up section, with which the fluids equilibrate at source, or (3) generation of fluids at lower temperatures and therefore higher ¹⁸O at higher stratigraphic levels. Beaty (1980) and Beaty and

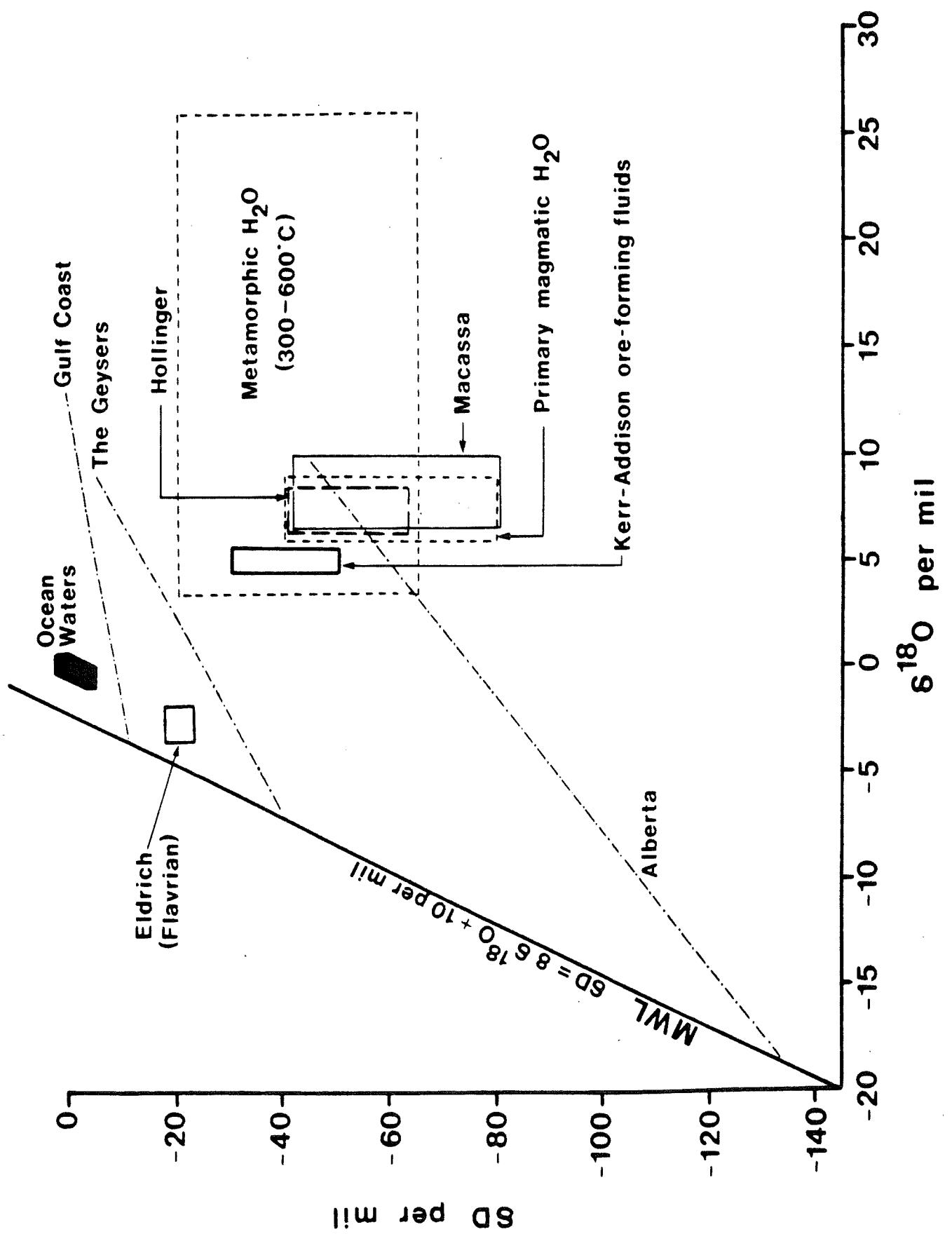


Figure 12 : Fields of δD , $\delta^{18}O$, for mineralized structures in the Abitibi greenstone belt (after Kerrich and Watson, 1984), other sources and new data (this paper).

Taylor (1980) reported a gross trend toward heavier whole-rock $\delta^{18}\text{O}$ values up section in the Abitibi greenstone belt, lending support to the second alternative.

Hydrogen isotope compositions of water in liquid inclusions range from -50 to +5 per mil (Fyon *et al.*, 1982a,b), and δD muscovite = -60 ± 10 [this paper], Fig. 12. This large observed spread of δD H_2O cannot be attributed to mixing of light ($\delta\text{D} = -50$) and heavier ($\delta\text{D} = 0$) fluid reservoirs, because any such mixing would be reflected in shifts of both $\delta^{18}\text{O}$ and δD fluid. Rather, the observed range in δD may be due to the presence of H_2 and/or CH_4 in the aqueous fluids, coupled with immiscibility of the reduced gas species (Fyon *et al.*, 1982a,b; Higgins and Kerrich, 1982; Ohmoto and Rye, 1979).

Both the $\delta^{18}\text{O}$ and δD of the fluids from which the auriferous veins were precipitated are close to or within the range of fluids implicated in metamorphic dehydration reactions and magmas (cf. Taylor, 1974; Fig. 12). A summary diagram for all Archaean lode gold deposited is presented in Part II.

C. Hollinger Mine Number 12 Vein: Patterns of Alteration

The Number 12 vein of the Hollinger Mine traverses a variety of different rock types where it outcrops in open pits at surface. Host rocks of original trondhjemitic, basaltic, and ultramafic parentage can be identified on the basis of ratios of the less mobile major and trace elements, with values of Ti/Zr and Zr/Y falling into three populations: 20 ± 1.1 (Ti/Zr); 6.7 ± 2.1 (Zr/Y), characteristic of trondhjemites; 52 ± 2.3 ; 2.7 ± 0.5 , characteristic of basalts; and 108 ± 10 ; 1.6 ± 0.3 , characteristic of ultramafic rocks (Fig. 13). The third group possesses only 6 to 16 wt % MgO , endorsing the observation that conventional discrimination diagrams for igneous rocks, which employ mobile elements such as magnesium and/or iron, are not useful for deducing original rock types where these have undergone alteration: rather it is necessary to have recourse to analysis of the less mobile trace elements (Figs. 8, 13).

All of the rocks in the vicinity of the Number 12 vein (a massive quartz-tourmaline-muscovite vein), contain abundant carbonate, along with variable proportions of pyrite, so that it is difficult to select an example of least altered rock or identify the precise chemical composition of the original rocks, for the purposes of chemical mass balance. Both the mafic and ultramafic rocks possess fine banding, with interspersed carbopnate laminae and abundant carbonaceous material: these features probably signal codeposition of tuffs and chemical sediments in a reducing basin, raising the possibility of multistage alteration - a problem addressed below. Chemical transfers in the rocks of probable ultramafic, basaltic, and trondhjemitic origin are dealt with here in turn.

1. Alteration of Ultramafic Rocks

An average of the analyses for three komatiite flows from Munro Township (Nesbit and Sun, 1976, Table I, 8-11) is utilized here as a hypothetical parental rock, based on compliance of Ti/Zr , Zr/Y , $\text{Al}_2\text{O}_3/\text{TiO}_2$, and Ni between this population of fresh rocks and the Hollinger altered counterparts. Given the values of the above inter-element ratios, coupled with the positive correlation of MgO to Ni , and an inverse relationship of MgO to TiO_2 in fresh komatiites, the Hollinger ultramafic rocks probably had primary MgO contents in the range of 22-26 wt %.

It is not possible with the present sampling to establish the extent of chemical modification to the ultramafic rocks arising from possible hydrothermal alteration shortly after extrusion, and/or the chemical effects of deformation, prior to later hydrothermal alteration associated with the auriferous veins, as can be done at Yellowknife (see above); and this uncertainty extends to all rock types present. However, a significant component of early alteration related to chemical exchange with a fluid carrying CO_2 , and possibly to seawater incursion in addition, is considered likely. This is based on the observed extensive leaching of Mg , Ca , and Fe , and differences in carbonate mineral chemistry of primary laminated to secondary vein carbonates, coupled with high $\delta^{18}\text{O}$ values for silicate minerals which signify equilibrium at temperatures of $<200^\circ\text{C}$ ($\delta^{18}\text{O}$ chlorite + 16 per mil - compared to data for basalts at Red Lake). During near-surface alteration (either by seawater which contains low CO_2 contents, or CO_2 -rich metamorphic fluids), P_{CO_2} is low such that hydrolysis of Mg , Fe , Ca -silicates typically results in removal of the metal cations in solution, or their incorporation into low-temperature hydrous silicates, rather than fixation of Fe , into carbonate minerals. The leached bivalent metal cations may subsequently precipitate as a chemical sediment.

Carbonate minerals interlaminated with ultramafic tuff, and of possible sedimentary origin, are cloudy, fine grained, anhedral, and in the compositional range of high-Mg dolomite, with no significant Mn substitution

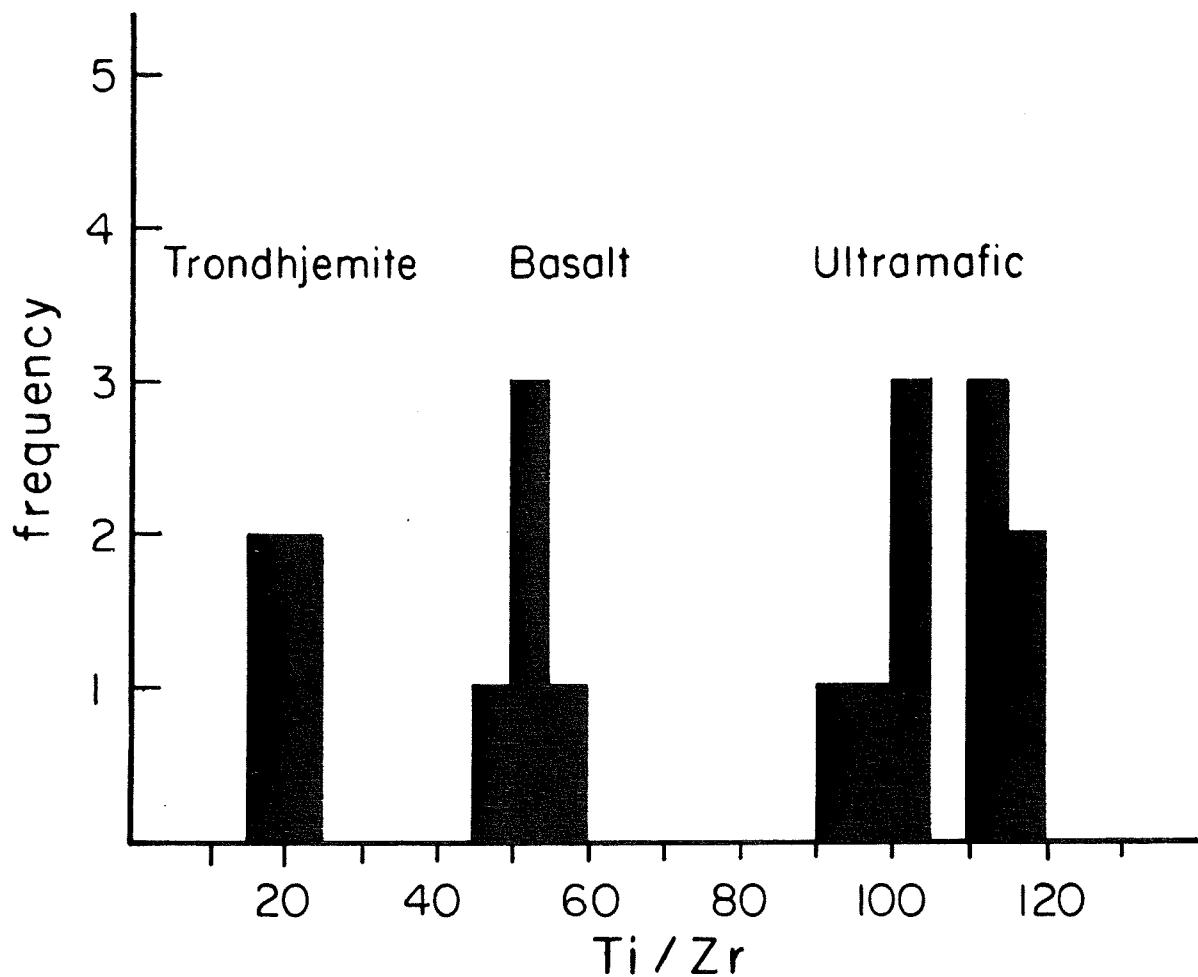


Figure 13 : Histograms of Ti/Zr for altered rocks at the Hollinger Mine, number 12 vein, open pit, illustrating the presence of precursors of trondhjemitic, basaltic and ultramafic primary compositions to the altered products (after Kerrich, 1983).

(Kerrich, 1983, Fig. 22). Where recrystallized at vein margins, the carbonates are compositionally ferroan-dolomite. Secondary carbonates, texturally associated with quartz-chlorite-muscovite-gold veins, are clear, coarse grained, anhedral and within the magnesite-siderite solid-solution series. In general, the ultramafic rocks have undergone a massive loss of iron relative to their precursors: the observed trend of iron enrichment in secondary carbonates could partly be accounted for by transfer to Fe from a silicate reservoir to a carbonate reservoir accompanying the hydrolysis of chlorite to muscovite in vein wall rocks. However, the abundance of carbonate minerals requires, in addition, an absolute introduction of iron during deposition of vein minerals.

Both vein-related muscovite and chlorite possess $\sim 1\%$ Cr_2O_3 reflecting the elevated chromium content of the ultramafic host rock. Muscovites do not contain significant barium, nor do chlorites contain appreciable manganese - features typical of these minerals in base metal massive sulphide deposits (Kerrich, 1983, Table 15; Costa *et al.*, 1983).

Geochemical results for altered ultramafic rocks at Hollinger form two data arrays: a low- and high- K_2O series, respectively. The former are remote from veins, have been leached to low volume factors (0.8 - 0.9), reflecting the extensive removal of oxides, and possess low K_2O , Au, Rb, Ba, As, and Sb; whereas the latter group are adjacent to veins and characterized by massive additions of these elements. Taking the geological, textural, mineral, chemical, isotopic, and geochemical lines of evidence collectively, it is suggested that the ultramafic rocks at Hollinger underwent an early stage of seawater and/or metamorphic fluid-induced alteration under conditions of low T and P_{CO_2} . This stage involved loss of Si, Fe, Mn, Mg, Na, and K, with gains of Sr plus volatiles, reflected in early laminated carbonates, during hydrolysis of primary silicate minerals to zeolites and clays. Subsequently, under ambient conditions of higher T and P_{CO_2} , during vein emplacement, the rocks experienced massive gains of Au, CO_2 , K, Rb, and Ba, and minor fixation of Fe, Ca, and Mn, reflected in the conversion of clays and zeolites, or their greenschist facies products, to secondary Fe, Mg-carbonates, muscovite, and chlorite (Fig. 14A). Additional sodium may have been lost during hydrothermal alteration associated with vein emplacement, to give the low observed content of Na_2O .

REE patterns for the low- and high- K_2O series, respectively, have flat configurations characteristic of most Archaean komatiites, but the high K_2O mineralized rocks have systematically higher abundances by a factor of 1.5 to 2 (Fig. 15a,b). This cannot be fully accounted for by enrichment during volume loss, thus signifying some absolute REE enrichment accompanying hydrothermal alteration (see also Kerrich and Fryer, 1979; Ludden *et al.*, 1984).

Many rocks have experienced volume losses of $\sim 50\%$ during the successive episodes of hydrothermal alteration, with absolute cumulative depletions of SiO_2 , Fe_2O_3 , CaO , MgO , and Na_2O in excess of the total gains of volatiles and K_2O . These over-all losses of chemical components have left the rocks relatively aluminous: the origin of altered rocks possessing elevated Al_2O_3 contents is considered in Part II.

Copper, zinc, and lead are erratically distributed, with both small gains or losses during the various stages of alteration. Average abundances of Cu 45 ($\pm 43\ \text{\AA}$), Zn 76 (± 33) and Pb 13 (± 5) ppm correspond to over-all enrichments of about 4, 1.5, and 10, respectively, relative to background contents in rocks of ultramafic composition.

Fluids which induced the K-Si-CO₂ alteration in proximity to veins, and from which the auriferous veins were precipitated, were at temperatures of $\sim 400^\circ\text{C}$, with fluid $\delta^{18}\text{O} = 9 \pm 1$ per mil (Table I), and at low redox potential: the latter property is indicated by the absence of Fe^{3+} silicates or oxides in the alteration mineral assemblage. Studies of primary liquid inclusions in vein quartz yield filling temperatures of 360°C (filling temperatures are a minimum estimate of the real temperature of hydrothermal mineral growth) and salinities of < 1.5 wt % NaCl equivalent, and reveal the presence of significant liquid CO₂. Pressures are estimated at 2-3- kb.

2. Alteration of Mafic and Trondhjemite Rocks

Chemical transfers accompanying alteration of tuffs and flows possessing original primary basaltic compositions are illustrated in Fig. 14b. Given the finely laminated nature of some units and the abundance of carbonaceous material, along with unusually high whole-rock δ -values for samples relatively low in gold and remote from major veins ($\delta^{18}\text{O} = 14-17$), it is likely that these mafic rocks underwent extensive alteration prior to vein emplacement, as is also indicated for their ultramafic neighbours.

ALTERATION OF ULTRAMAFIC ROCKS

HOLLINGER MINE

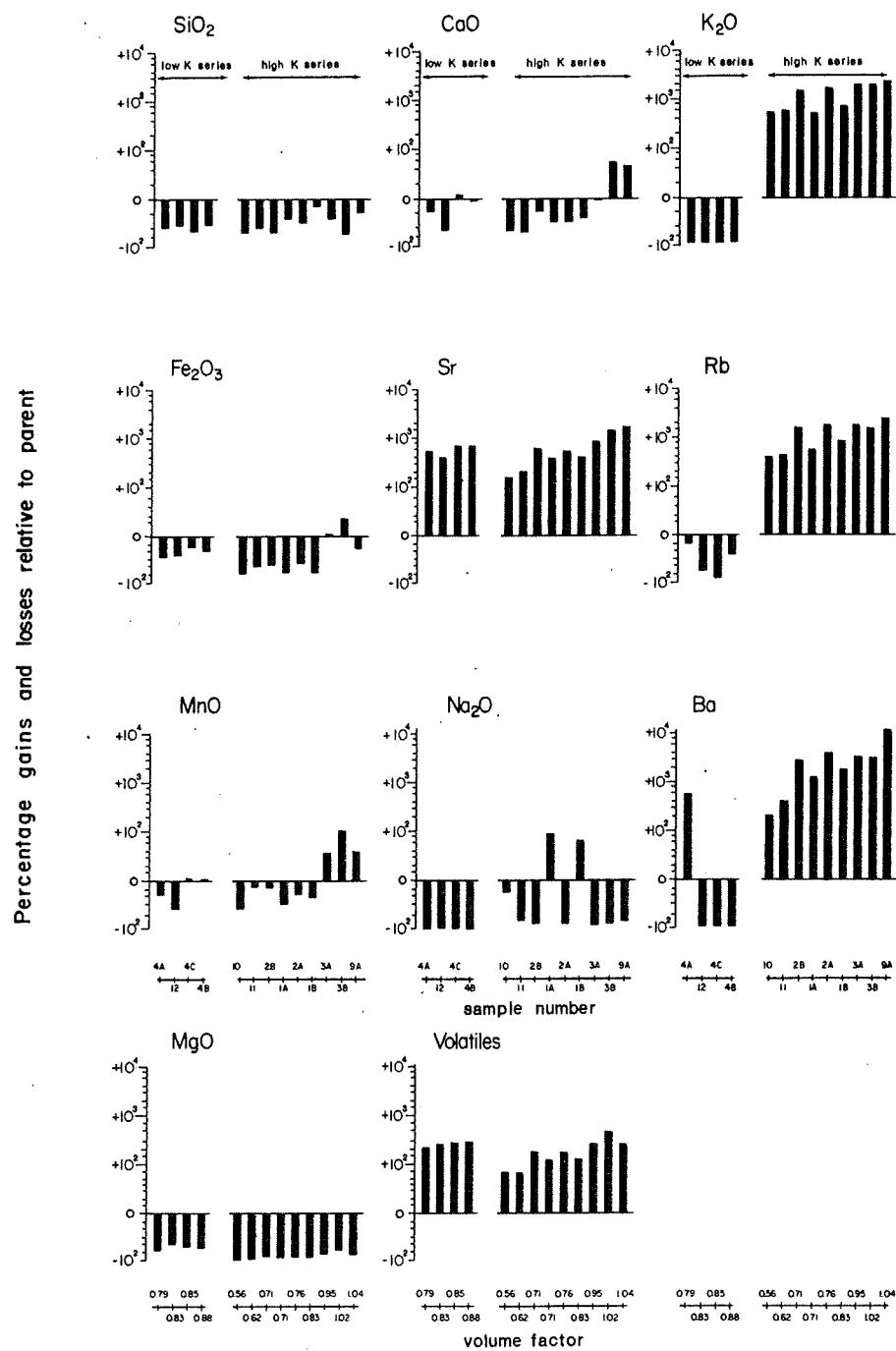


Figure 14a: Gains or losses of major element oxides and selected trace elements hydrothermally altered in rocks of primary ultramafic compositions (peridotitic komatiites), Hollinger Mine, number 12 vein, open pit. Gains and losses expressed as percentage changes relative to abundances in the unaltered parent rock, and ordered according to increasing volume factor (after Kerrich, 1983).

ALTERATION OF BASALTS AND TRONDHJEMITE HOLLINGER MINE

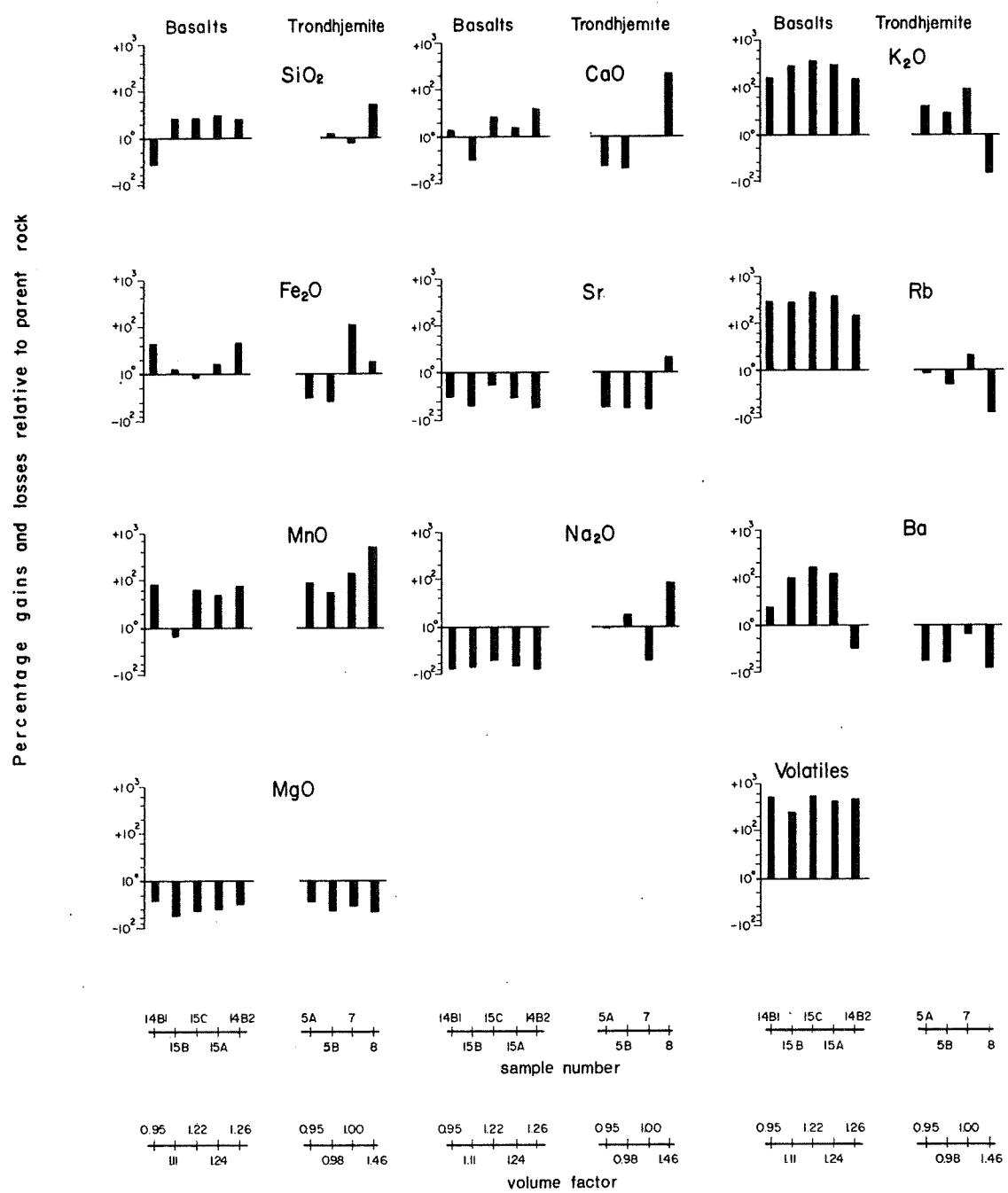


Figure 14b: Gains or losses of major element oxides and selected trace elements in hydrothermally altered rocks of primary basaltic and trondhjemitic composition, Hollinger Mine, number 12 vein, open pit. Gains and losses expressed as percentage changes relative to abundances in the unaltered parent rock, and ordered according to increasing volume factor (after Kerrich, 1983).

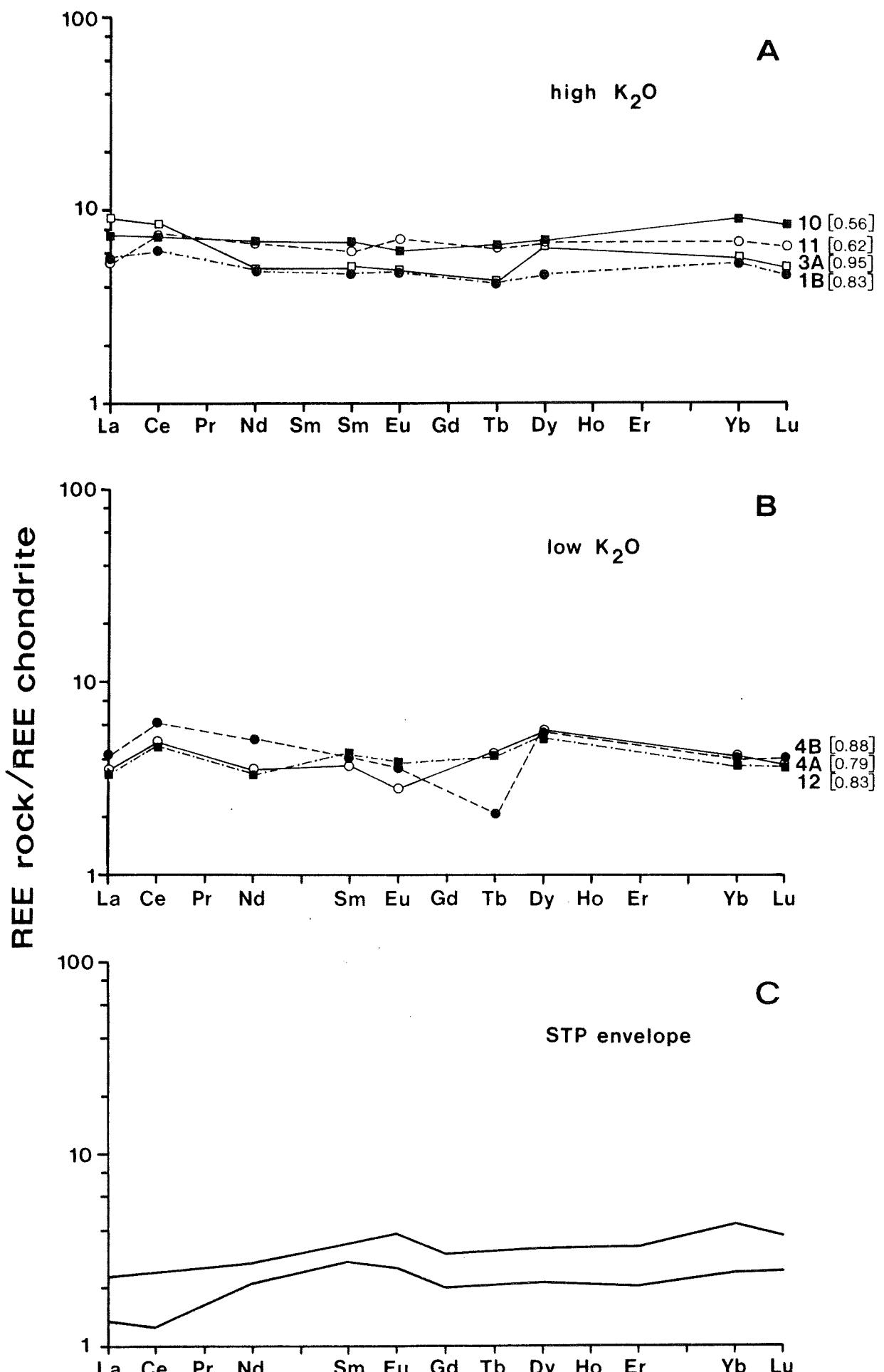


Figure 15 : (a) Chondrite normalized rare earth element distributions for mineralized rocks of original ultramafic composition, number 12 vein, Hollinger Mine. Bold figures are sample numbers, the figures in square brackets correspond to deduced volume factors of alteration. (b) REE patterns for unmineralized counterparts, contiguous with those in (a) above. (c) REE envelope for relatively fresh komatiites - formerly termed peridotitic komatiites and sometimes designated STP for spinifex textured peridotites (cf. Sun and Nesbitt, 1976)

Over the deduced range of volume factors (0.95 to 1.26), the salient feature of alteration are as follows: massive fixation of K₂O (plus the related alkali metals Rb plus Ba), MnO and volatiles; minor gains of SiO₂, CaO, Fe₂O₃, coupled with major depletions of MgO, and near quantitative loss of Na₂O.

Minor anomalies of B ($46 \pm 39 \text{ } \sigma$), As (152 ± 98), Sb (0.9 ± 0.3) and W (7 ± 4) are present in the altered mafic rocks, as is the case for the adjacent ultramafic units. Copper, lead and zinc average $65 \pm 12 \text{ } \sigma$, 55 ± 24 and 11 ± 5 ppm respectively, corresponding to enrichment factors of 0.7, 0.5 and 2 times the background abundance of these elements in primary rocks of basaltic composition.

Patterns of alteration in the quartz-feldspar porphyries of primary trondhjemite origin are illustrated in Figure 14b.

3. Summary

Mafic and ultramafic rocks enveloping the Number 12 vein at Hollinger appear to have undergone multistage alteration. The first stage involved codeposition of tuffs, carbonaceous material and Mg-rich dolomite, with pervasive hydrothermal leaching of the tuffs by CO₂-bearing fluids of probable metamorphic origin and/or seawater at low temperature. Massive stripping of magnesium is a salient feature of the alteration. Gold contents of all rocks which retain evidence of this alteration regime are in the low-ppb range, signalling that it did not involve significant introduction of gold. No anomalies of Mn and Ba are present either in the bulk rock or in individual mineral species.

Deposition of major gold-bearing quartz-carbonate veins was accompanied by massive fixation of K₂O in their wall rocks, from a hydrothermal reservoir at $\sim 400^\circ\text{C}$, containing variable proportions of CO₂, of low salinity and redox potential, and of probable metamorphic origin. It is interesting to note that all these chemical features were imposed by solutions streaming through veins or their wall rocks, irrespective of whether the wall rocks were of primary ultramafic, mafic or trondhjemite composition: this signifies a fluid-dominated system and contraindicates local remobilization of a putative coextensive, syngenetic gold-enriched chemical sediment. It is possible that gold was introduced during the first alteration stage, and subsequently quantitatively mobilized into the veins. However, given the textural, mineral, chemical, isotopic, thermal and bulk chemical disequilibrium between veins and background rocks retaining evidence of stage one alteration, this is not considered likely. Furthermore, background rocks do not possess anomalies of Mn and Ba, characteristic of major chemical sedimentary gold deposits.

V. THE MACASSA MINE - KIRKLAND LAKE

The Kirkland Lake mining district is located along a major structural discontinuity, locally termed the Larder Lake break, in the south-central region of the Abitibi greenstone belt (Fig. 9). Cumulative production of gold from all mines in this camp since 1913 is in excess of 710 tonnes (Lovell and Ploeger, 1980), second only to the Timmins District. To date, production of gold from the Macassa mine is ~ 93 tonnes. The geology of the area has been discussed most recently by Jensen (1976, 1978a,b, 1980) and Jensen and Langford (1983); and the mines are described by numerous earlier workers referred to in a recent review by Watson and Kerrich (1983). The following account of the Macassa Mine is condensed from Kerrich and Watson (1984).

A. Regional Geological Setting

In the Kirkland Lake district, the volcanic, sedimentary and associated intrusive rocks, form part of an elongate, east-plunging synclinorium located between the Lake Abitibi and Round Lake batholiths. Two cycles of volcanism with associated sedimentary and intrusive rocks occur in the area. Each is composed of komatiitic rocks at the base, overlain in turn by tholeiitic and calc-alkalic rocks, and capped by an upper alkaline sequence. The two volcanic cycles are separated from each other by sedimentary rocks comprising conglomerate, argillite, chert and iron-formation (Jensen and Langford, 1983).

The gold mines of Kirkland Lake are within the upper alkaline part of the second cycle, termed the Timiskaming Group. The Timiskaming Group includes both sedimentary and volcanic rocks, notably conglomerate, sandstone, siltstone, argillite, chert, iron-formation, flows, agglomerate and tuff (Hyde, 1980). Volcanic rocks are dominated by trachytes and phonolites. The Timiskaming Group unconformably overlies the Kinojevis, Blake River and Larder Lake Groups, and have been intruded by a composite syenite stock.

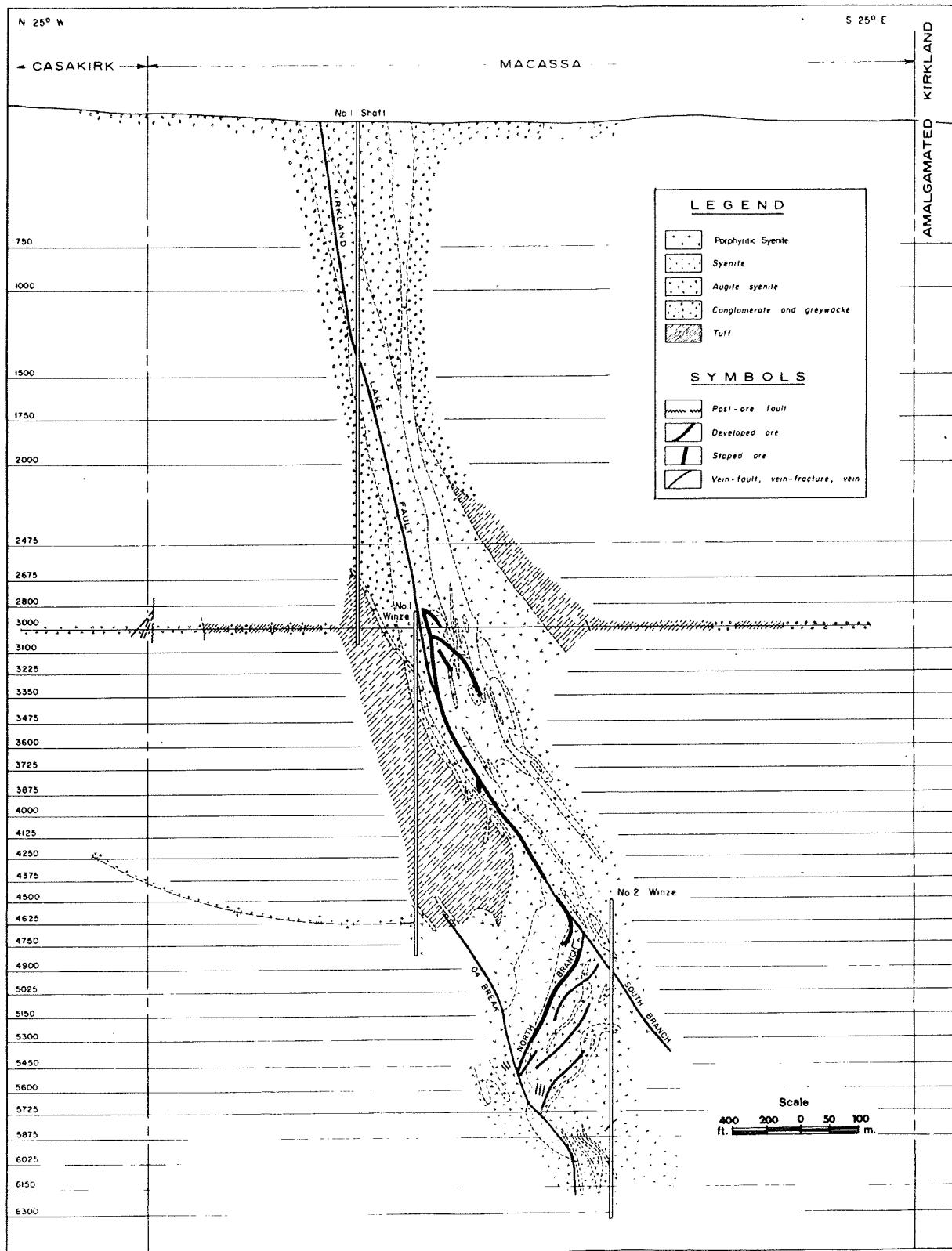


Figure 16 : Macassa Mine, geological section through No. 1 shaft (looking 65°) (after Charlewood, 1964).

The main structural elements of the district are two steeply inclined, east-trending tectonic discontinuities: the Destor-Porcupine Break in the north and the Larder Lake Break in the south. The Larder Lake Break has been variously described as 1) a major thrust fault with attendant hydrothermal carbonation (Thomson, 1948); 2) a sedimentary horizon of carbonate exhalite iron-formation (Ridler, 1969, 1975); and 3) a zone of ultramafic flows (Jensen, 1976).

In structural terms, the gold hosting Timiskaming Group is an east-trending, continuous belt 0.5 to 5km wide northeast of the Round Lake batholith. It is a south-facing homoclinal sequence striking 065° and dipping 60 to 75° south, cut by strike faults, cross-faults and oblique faults.

B. Mine Geology

The Timiskaming Group is represented by pebble and boulder conglomerates and volcanic rocks in the Macassa Mine workings. Hyde (1980) has interpreted the sedimentary rocks as representing a resedimented marine facies. Greywackes and tuffs are common on the north and south margins of the composite syenite stock in the east and central part of the mine.

The main intrusive rock types occur in the Macassa Mine: augite syenite, felsic syenite and porphyritic syenite. The long axes of all the surface exposures of intrusive rocks strike 060-080° and are generally parallel to the strike of the sedimentary and volcanic rocks of the Timiskaming Group.

Augite syenite is the oldest and most widespread of the intrusive rocks (Ward and Thomson, 1950). The fresh rock is dark green to black colored, commonly with a coarse almost granitoid texture. The essential ferromagnesian mineral is augite, although this is generally pseudomorphed by chlorite, Fe-Mg-carbonate, magnetite and actinolite. The feldspar is generally about Ab₉₀An₁₀, but is commonly replaced by fine mosaic orthoclase. Accessory minerals are magnetite, apatite and minor titanite.

The felsic syenite occurs primarily as a westerly pitching pipe-like mass. The rock has a granitic texture and is comprised mostly of orthoclase with 10% intergrown oligoclase. Felsic syenite may be transitional into augite syenite with increasing augite content, or alternatively may have a sharp, well-defined intrusive contact.

In the Macassa Mine, porphyritic syenite occurs as dykes and small irregularly shaped sills which transect both syenite and augite syenite with well-defined intrusive contacts. The porphyritic syenite is therefore the youngest phase of the intrusive complex. Sodic plagioclase (Ab₈₀-Ab₉₅) is the dominant phenocrysts, and rare phenocrysts of orthoclase (Hawley, 1950). Biotite, hornblende and chlorite are the common ferromagnesian minerals.

C. Fault and Fracture Systems

The principal gold-producing mines of Kirkland Lake are disposed along one of several fault systems known as the Kirkland Lake Fault or the Main Break. The strike is about 067°, approximately parallel to the long dimension of the composite intrusive stock and the regional trend of the Timiskaming Group. North and south of the Main Break there are other more or less parallel faults. Of these, the Narrows Break to the north and the Amalgamated Kirkland Break to the south are most prominent. There are two groups of faults and fractures: pre-ore and post-ore. Detailed analysis of the various forms and patterns of faulting and fracturing within the Kirkland Lake camp is reported in Thomson *et al.* (1950) and Charlewood (1964). The following synopsis for the Macassa Mine is taken largely from Nemcsok (1980) and Watson and Kerrich (1983).

The Kirkland Lake Fault, or Main Break, traverses the entire 3.2km length of the Macassa property. It is generally a zone of cataclastic and some times brecciated wallrock, chloritic schist or fault gouge, in which deformation was accommodated principally by transgranular fracturing. There is a vertical displacement across the Main Break of approximately 1,500' (450m) in the west end of the Macassa Mine (Thomson *et al.*, 1950) with the south (hanging wall) side up in relation to the north (footwall).

The strike of the Main Break averages 065° and dips 80° south to above the 3457' level where it gradually rotates, flattening a dip to about 50° (see Fig. 3, Watson and Kerrich, 1983). The deeper levels of the mine have a branching fault system.

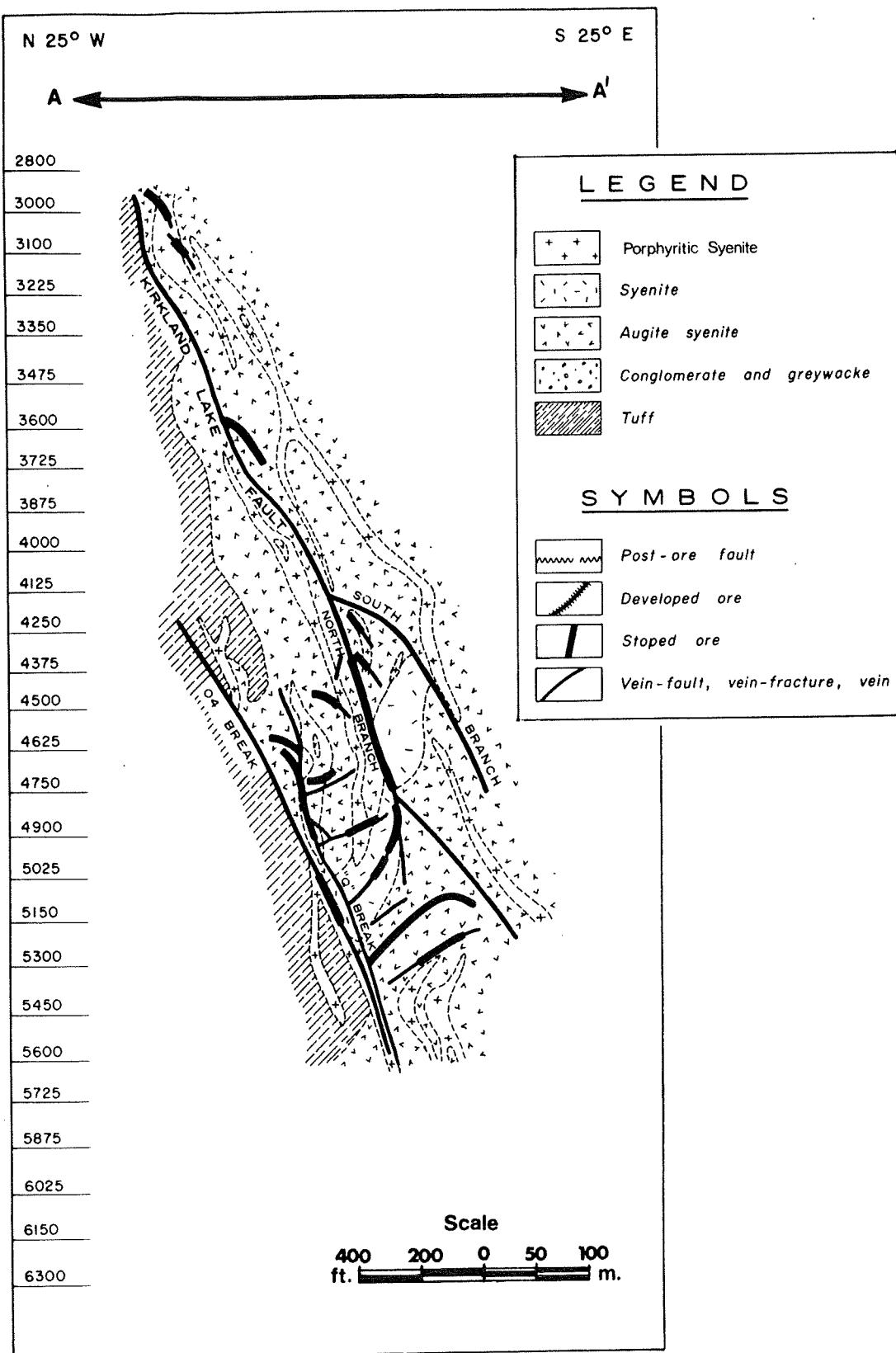


Figure 17 : Macassa Mine, geological section along A-A' (Figure 4) illustrating fracture pattern between the Main Break and '04 Break (after Charlewood, 1964).

Another fault of major importance, known as the '04 Break, is oriented subparallel to the Main Break. The '04 is connected to the north branch of the Main Break via the S and R-2 Breaks (see Fig. 4, Watson and Kerrich, 1983).

Pre-ore fracturing is related to the major faults. On the upper levels, subsidiary fractures branch off the Main Break both vertically and horizontally. Hanging wall subsidiary fractures generally parallel the strike and have dips 10-20° flatter than the main fault going up dip. Other more steep dipping hanging wall fractures make contact down dip with the fault plane. On lower levels, in the east part of the mine, a widespread zone of fracturing occurs between the '04 and Main Breaks. Here these fractures typically extend between the major faults with relatively shallow dips to the north.

Major north striking faults which displace both sedimentary and volcanic units, along with the pre-ore structures are present in the Kirkland Lake region. Three major post-ore faults of the Macassa Mine are the Boundary Fault, the Tegren Crossfault system and the Amikougami Crossfault: the structural features and displacement of these faults are further described by Watson and Kerrich (1983).

D. Varieties of Gold Ore

Three types of gold occurrences have been proposed for the Macassa Mine (Watson and Kerrich, 1983): 1) Break ore, which is native Au in chloritic fault gouge or quartz lenses within sections of the major fault system i.e. the Main Break and '04 Break; 2) Vein ore, which is gold-bearing quartz veins in both the hanging and footwalls of this fault system; and 3) Breccia ore, which is relatively wide (up to 15m) zones in the deep western areas of the mine of highly fractured, bleached rock containing lenses and pods of quartz with native Au and tellurides. Details of the mineralogy, structural disposition of the gold ore varieties, and their associated alteration, along with geological cross-sections, are reported in Watson and Kerrich (1983).

E. Chemical Composition of the Syenites

Analyses of syenites and trachytic tuffs, along with their altered counterparts adjacent to ore, are reported in Kerrich and Watson (1984). As for syenite-ferrosyenite rocks in general, the Macassa examples are characterized by high absolute K₂O, coupled with SiO₂ in the range 48-56 weight percent. Relatively abundant augite and/or hornblende is reflected in elevated TiO₂, Fe₂O₃, MnO, CaO and MgO contents, along with high concentrations of mafic-affiliated elements such as V, Cr, Co, Ni and Sc.

Nevertheless, the Kirkland Lake syenitic suite differs in several important respects from the composition of typical syenitic rocks (cf. Sorenson, 1974; Gerasimovsky, 1974; Turekian and Wedepohl, 1961).

Rare earth element patterns for unaltered examples of the felsic-, augite-, and porphyritic-syenites are remarkably uniform, defining a coherent data array with La 100 to 200 times chondritic, and the HREE about 10 times chondrite abundances (see Part II9: this feature may imply a common magma parentage. Relative to Archaean syenites in general, for which the REE envelopes is depicted in Fig. 12a, Part II, Kirkland Lake alkalic rocks have lower chondrite normalized ratios of the light to intermediate REE, but higher ratios for the HREE (see Condie, 1981; Taylor, 1979). This discrepancy is in accord with the observations outlined above that the Kirkland Lake alkalic rocks differ compositionally in several important respects from conventional syenites.

Trachytic tuffs are enriched in incompatible elements, including Ti, P, U, Th, Rb, Sr, Y, Zr, Nb and Ba, compared to the augite and porphyritic syenite members. Specifically, the tuffs possess higher Ti and significantly greater Zr, resulting in lower Ti/Zr ratios. A prominent aspect of their chemistry is the extremely high U (up to 15 ppm) and Th (26-54 ppm) abundances, commensurate with their overall relative enrichment in incompatible elements. Thorium and uranium covary, giving uniform Th/U ratios of 2.0 to 3.5 throughout the entire compositional spectrum. These ratios are within the magmatic Th/U range (cf. Maynard, 1983), signifying that the elevated absolute abundances are inherently a primary feature of the magmas.

Such trends in large ion lithophile (LIL), or incompatible elements, in volcanic rocks are common in alkaline plutonic-extrusive complexes, probably due to the preferential concentration of the incompatible elements plus volatiles into the explosive extrusive phase (cf. Taylor, 1979). Overall, the REE are displaced to higher absolute abundances in the trachytic tuffs, but La_N/Yb_N is about 25, indicating some systematic fractionation of the REE between intrusive and extrusive phases.

In summary, it appears that the various members of the alkalic igneous suite at Kirkland Lake may have a common magma parentage, but that compositional differences are the result of a complex interplay of several underlined processes.

Alkalic igneous rocks at Kirkland Lake resemble in some respects the major element compositions of ferroaugite syenites from the Coldwell Complex, Ontario, as reported by Mitchell and Platt (1978), although the former have K_2O/Na_2O ratios 2 to 5 times greater than the latter. Augite syenites specifically, as well as the other varieties, closely resemble alkalic basalts in terms of major and trace element abundances, interelement ratios, and REE patterns (Fig. 4). Alkalic basalts are generally considered to have been derived from partial melting of an enriched upper mantle, or by mantle metasomatism involving the introduction of incompatible elements (cf. Van Kooten, 1980; Saunders, 1984; Cullers and Graf, 1984). Hence the Kirkland Lake igneous rock are perhaps members of an alkalic basalt-gabbro series, and should be termed accordingly; although the name syenite is generally retained to maintain consistency with previous descriptive terminology of rock units.

Given that some of the syenites possess primary igneous whole rock oxygen isotope compositions, along with near-magmatic feldspar-augite and feldspar-hornblende fractionations, these unusual compositional features are interpreted to be intrinsically magmatic (Kerrich and Watson, 1984).

F. Metal Distribution of the Ores

In addition to elevated gold contents, the most significant features of the Macassa vein ores are the low overall S, together with sporadic high values of tellurium. Gold/silver ratios average about 5. Of the base metals, Cu (22 ppm \pm 12 σ) and Zn (79 ppm \pm 37) have been leached during mineralization, whereas Pb (67 ppm \pm 35) has been introduced along with tellurium to form the lead telluride, altaite. Arsenic (5,7 ppm \pm 3,2) and Sb (4,2 ppm \pm 2,6) are present at low levels, but W at 29 ppm \pm 25 ppm is significantly enriched over background levels which average ~3 ppm in the syenites (Table III) and 0,4 ppm in basalts (Helson *et al.*, 1978). Transition metals, including V, Sc, Cr, Co and Ni are present at levels which broadly reflect the amount of wall rock incorporated into ore. Altered rocks adjacent to Break ores have similar distributions of the precious-, semi-, base- and transition-metals as vein ore, but possess significantly lower S content (Table V).

In summary, the Macassa gold ores have the same overall metal distribution as Archaean lode gold deposits in general, with large to moderate enrichments of rare elements including Au, Ag, As, Sb, W, Se, Te, Bi, coupled with low to negative enrichments of the abundant base metals Cu, Pb, and Zn (for a review see Kerrich, 1983).

G. Patterns of Alteration

Transfers of chemical components during hydrothermal alteration of the felsic syenite traversed by the 26A vein (Group I samples) and of augite syenite adjacent to the 58E vein (Group II samples) are illustrated in Fig. 18. The felsic syenite and augite syenite have been altered over recorded ranges in volume factor of 1,2 to 1,5 and 1,2 to 2,1 respectively, representing volume increases of 20-50% in the former host rock and 20-110% in the latter.

Massive gains of gold and sulphur, reflected in the presence of native gold and pyrite, are the salient feature of alteration in both of the host rock types. Additions of iron and minor compared to sulphur, signifying that much of the iron present in pyrite is derived from hydrolysis of Fe-Mg silicates indigenous to parental syenites, whereas 98% of the sulphur has been added from solution. Small net gains of SiO_2 correspond to the presence of vein quartz, and gains of Fe_2O_3 , MnO, MgO plus CaO reflect the precipitation of Fe, Mn, Mg, Ca-carbonates plus calcite.

Sodium and potassium have experienced variable minor gains or losses, expressed in the relative proportions of albite and muscovite respectively: Rb and Ba covary broadly with K_2O . Of the transition and base metals, Cr plus Ni have been added overall, residing in chlorite and muscovite, whereas a massive introduction of tungsten is evident, W being present in ubiquitous scheelite. Copper, Zn and Pb have all been added to a variable extent, whereas As and Sb display erratic minor excursions about zero gain/loss.

Altered syenites adjacent to these veins are neither extensively hydrated nor have significant fixation of CO_2 - commensurate with the low observed proportions of hydroxy or carbonate minerals.

Vein Ore Alteration

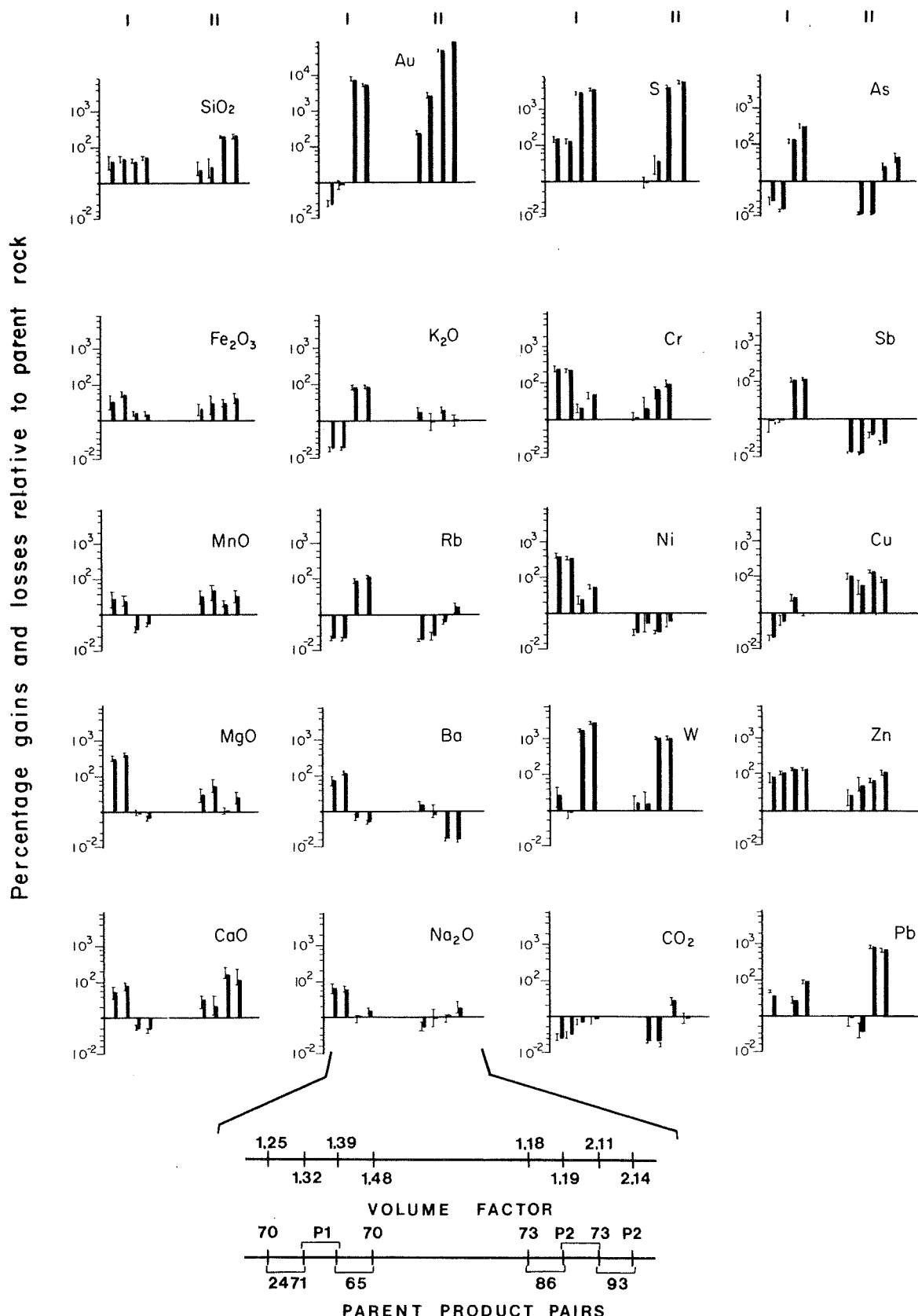


Figure 18 : Gains and losses of chemical components during hydrothermal alteration associated with tuff breccia (group III) and augite syenite breccia (group IV) ore (expressed as percentage changes relative to abundance in average parent rock and selected individual parent rocks). Altered products are arranged in order of increasing volume factor. Small bars indicate variations in gain or loss about the solid bars arising from 1 of the mean volume factor (after Kerrich and Watson, 1984).

Breccia Ore Alteration

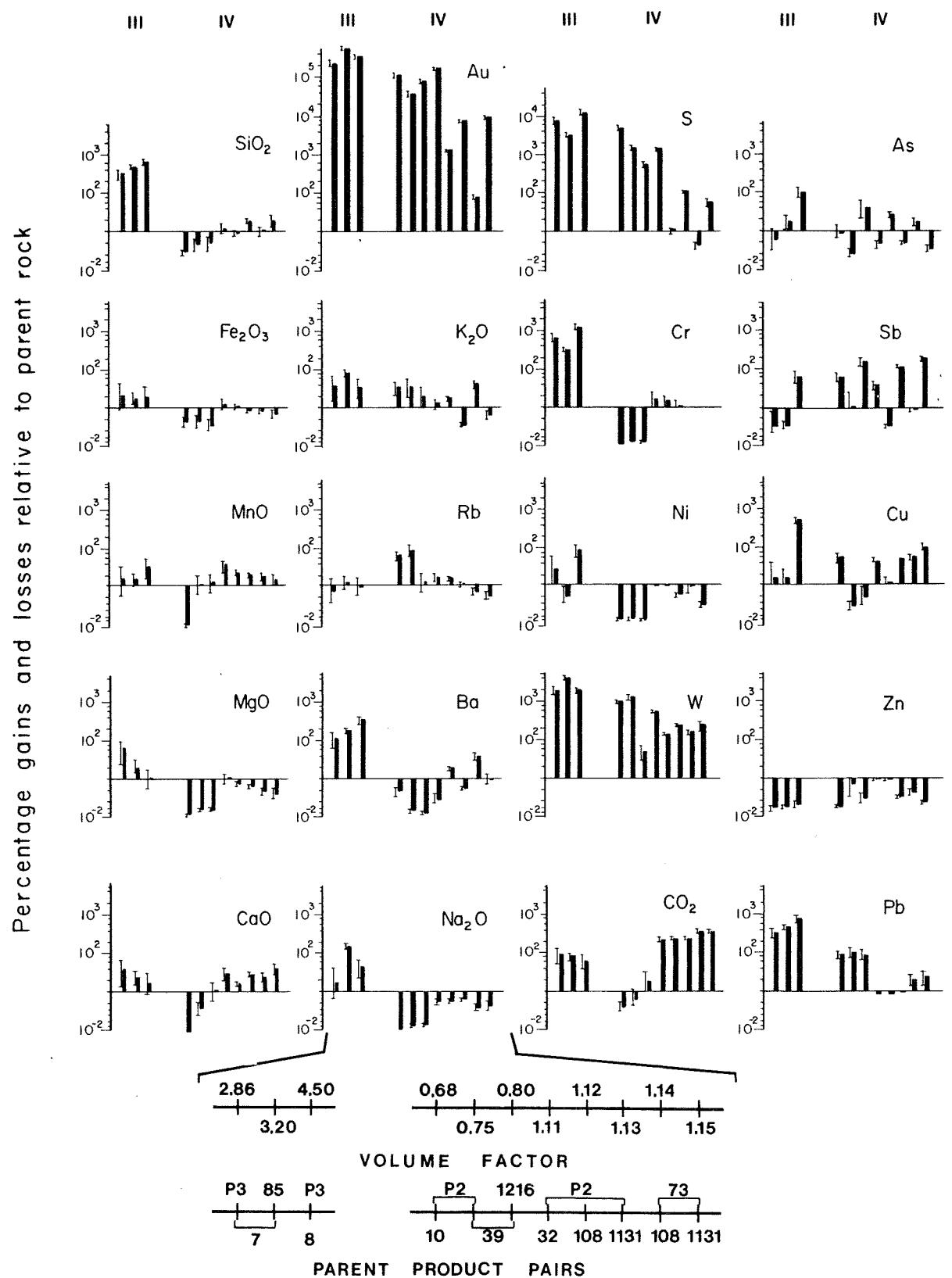


Figure 19: Gains and losses of chemical components during hydrothermal alteration associated with 26A vein (group I) and 58E vein (group II) ore (expressed as percentage changes relative to abundance in average parent rock and selected individual parent rocks). Altered products are arranged in order of increasing volume factor. Small bars indicate variations in gain or loss about the solid bars, arising from 1 of the mean volume factor (after Kerrich and Watson, 1984).

Introduction of gold and sulphur on a massive scale are the most pronounced chemical transfers involved in the hydrothermal alteration accompanying breccia formation within the augite syenite and tuff (Fig. 19). Iron and S behave in a manner comparable to that for vein-related alteration.

Fixation of SiO₂ is more pronounced in the tuff breccia ore than in the augite syenite breccia ore, commensurate with a higher proportion of vein quartz in the former. Small gains or losses of Fe₂O₃, MnO, MgO, and CaO reflect variability in the relative abundance of Fe, Mn, Mg, Ca-carbonate plus calcite. Potassium and Rb have experienced comparable minor overall gains, but whereas Ba covaries with K₂O in the tuff breccia ore, it behaves erratically in the augite syenite. Given that K₂O is predominantly in feldspars and biotite in parental rocks, but is incorporated into muscovite in altered equivalents, and further that for the ore, Ba plus Rb do not reside in phases other than muscovite, these relations collectively suggest that the micas are not unusually Rb or Ba rich, a conjecture confirmed by electron microprobe analyses.

Chromium and Ni have been added in minor proportions to the tuff breccia ore, where they substitute in chlorite and muscovite: however these elements are leached from augite syenite hosted breccia ore. As for the vein related counterparts, massive introduction of tungsten is represented by the presence of scheelite. Arsenic and Sb are distributed essentially as for the vein ores.

H. Summary and Discussion of Geochemical Data

Break ore, vein ore, and breccia ores were all precipitated from hydrothermal solution δ¹⁸O +7 to +9,6 per mil, δD -35 to -85 per mil, over the temperature interval 380 to 490°C (Fig. 20). These fluids were probably evolved by dehydration reactions during accumulation and burial of the volcanic and sedimentary rocks, and released via hydrofracturing through permeable conduits provided by the faults: a magmatic origin, or mixtures of magmatic and metamorphic fluids are possible alternatives based on the isotope data. The δ¹⁸O quartz, temperatures and fluid isotopic composition of Macassa gold veins are generally similar to other vein dominated gold deposits (for a review see Kerrich, 1983).

For all ore types, quartz in veins and bounding wall rocks is close to isotopic equilibrium, but heavy compared to the whole rock δ¹⁸O of fresh syenite hosting the veins, or δ-values appropriate for their constituent feldspars. Hence lateral secretion of silica from wall rocks into veins is not commensurate with the isotopic data.

Rocks contained within the break locally record both isotopic and mineralogical disequilibrium. Isotopic relations are tentatively interpreted in terms of an early episode of discharge of high δ¹⁸O fluids of probable metamorphic origin implicated in precipitation of quartz, gold, magnetite and chlorite. This was followed by incursion of oxidising, sulphate-bearing fluids, δ¹⁸O 0 to +2,2 per mil, δD -20 to -70 per mil, of probable marine and/or evolved meteoric water origin, initially at temperatures of ≤ 200°C, waning to 50°C or less: downward fluid penetration is likely in view of the negative temperature dependence of solubility for sulphate species.

The early fluid regime is interpreted to reflect crustal compression, with hydrothermal discharge during episodes of hydrofracturing under conditions of anomalously high hydraulic pressure, whereas the later fluid regime is considered to reflect fluid input at hydrostatic pressure during relaxation of crustal compression, with attendant dilation of both large and small scale structures creating permeability.

Arrays of quartz-magnetite stringer veins were precipitated over the temperature interval 130 to 220°C from hydrothermal fluids of meteoric origin (δ¹⁸O = -2 per mil). This in turn requires the existence of land above sea level, with downward penetration of groundwaters into fractured rock media. The timing of this meteoric water dominated fluid regime cannot be assessed with certainty in the absence of independent age determinations. However, inasmuch as the estimated temperatures of vein formation are close to ⁴⁰K-⁴⁰Ar blocking temperatures for muscovite of ~300°C, and given ages of ~2,5 Ga for Abitibi belt rocks dated by this decay scheme (Purdy and York, 1968), it is not unlikely that the meteoric water incursion was of Archaean age.

For the Noranda District, Kennedy and Kerrich (1982) discuss the transition from marine water to meteoric water cooling of the Flavrian pluton, accompanying its emergence above sea level. Isotopic evidence for such emergence is commensurate with the presence of fluvialite sedimentary rocks high in the stratigraphic sequence. Hence emergence of land above sea level, with attendant meteoric water incursion, may not be uncommon for the late stages in development of the Abitibi greenstone belt.

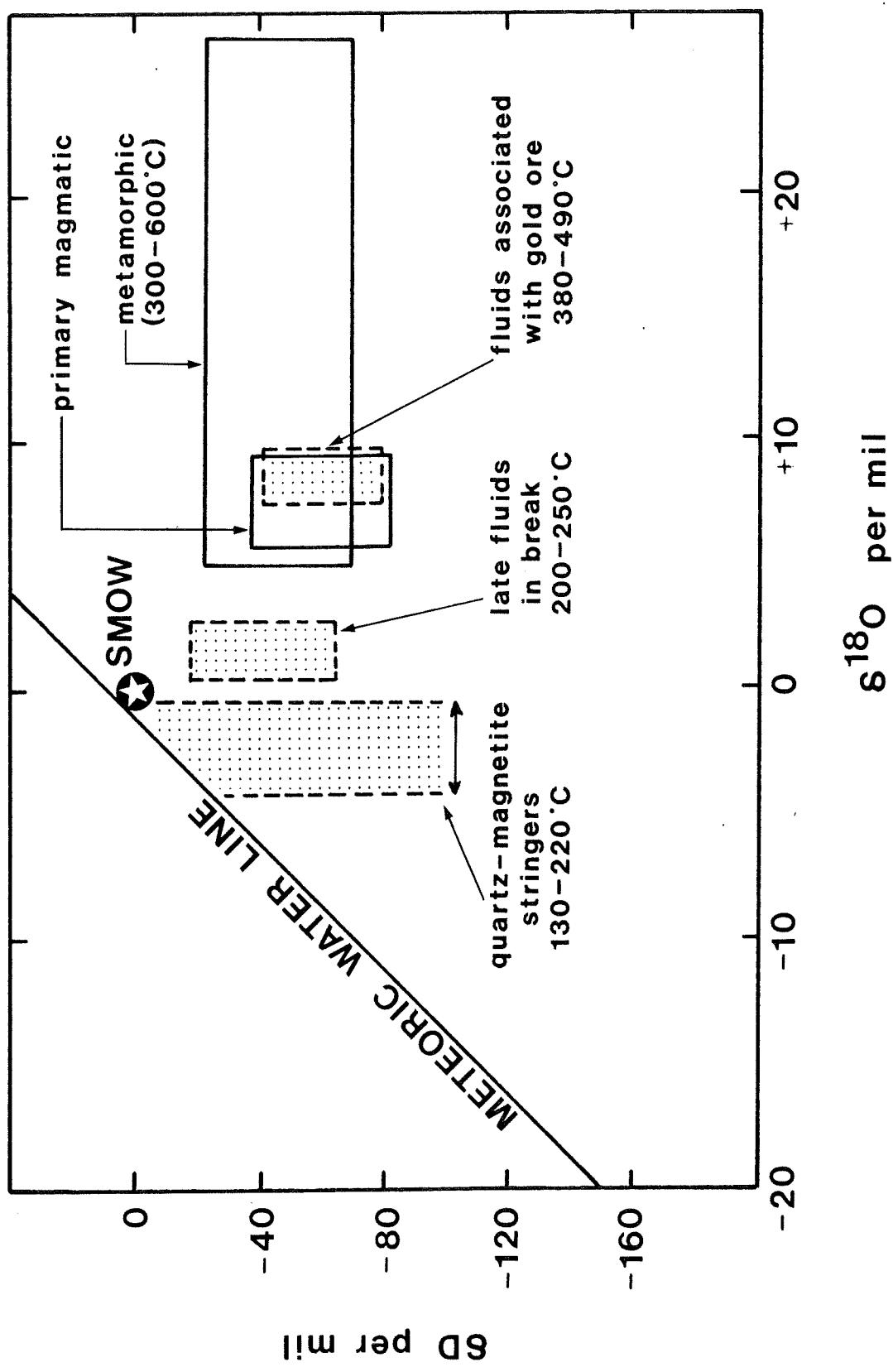


Figure 20 : Isotopic composition of natural terrestrial fluid reservoirs in δD , $\delta^{18}O$ co-ordinate space modified from Taylor (1974). Superimposed are calculated fields for 3 vein stages at Macassa (after Kerrich and Watson, 1984), and Hollinger (this paper). The dashed envelope is for H_2O decrepitated from quartz veins of the Hollinger Mine (after Fyon et al., 1983).

Patterns of alteration for Macassa ores are similar to those present in most vein type Archaean gold deposits (for a review see Kerrich, 1983). Additions of SiO₂, S, and K₂O with concomitant depletions of Na₂O correspond to the characteristic quartz, pyrite, muscovite assemblage with plagioclase feldspar hydrolysis. The ubiquitous carbonate gangue minerals do not appear to form by precipitation from solution, but rather are dominantly products of fluid-wall rock reactions, in which Fe, Mg, Ca, Mn-silicates are carbonated to Fe, Mg, Ca, Mn-carbonates, such that wall rocks donate the bivalent metal cations and fluids contribute CO₂. Similarly, the bulk of iron present in pyrite appears to have been indigenous to wall rock silicates, whereas fluids introduced the S.

An interesting feature of the Macassa gold ores is the sporadic abundance of magnetite. In most Archaean lode gold deposits studied to date (cf. Kerrich, 1983) hydrothermal alteration involves reduction of Fe³⁺ silicates and oxides to Fe²⁺ bearing silicate or carbonate phases. Moreover, the local prevalence of K feldspar over muscovite is in contrast to the muscovite-dominated alteration of many vein settings in Archaean vein deposits studied to date. The simplest interpretations of these observations is that hydrothermal fluids at Macassa were relatively less reducing and less acidic.

VI. KERR ADDISON MINE: ULTRAMAFIC VOLCANIC ENVIRONMENT

A. Geological Setting

The geology of the Kirkland Lake - Larder Lake region has been described most recently by Jensen (1980), and the setting of the Kerr Addison Mine at Virginiatown by Downes (1980), Thompson (1980), and Jensen and Trowell (1981). Ore deposits at Kerr Addison lie within mixed ultramafic-mafic extrusive volcanic rocks, along with their volcaniclastic counterparts and clastic sediments, as well as minor chemical sedimentary rocks, collectively assigned to the Larder Lake Group (Fig. 21). At Kerr Addison, the 'Main Break', or Kirkland Lake - Larder Lake fault zone, has tectonically juxtaposed rocks of the Kinojevis Group, with those of the Larder Lake Group. Ore bodies are disposed between the 'Main Break' and Kerr Fault (Fig. 21), the latter structure possibly being a splay of the 'Main Break'.

Two principal types of ore occur at the Kerr Addison Mine, the so-called "carbonate" and "flow" ores, both of which exhibit stratabound and structural controls. According to Downes (1980), the former consists of green Cr-muscovite-bearing dolomitized ultramafic volcanic rocks, with intense quartz-carbonate-muscovite veining. Gold occurs principally in quartz veins, but is not significantly enriched in green carbonate. Most rocks have undergone intense alteration, but Downes (1980) has noted that the original nature of rock types can sometimes be deduced on the basis of remnant textural features (cf. spinifex). Flow ore is comprised of three units which, from stratigraphic footwall to hanging wall, are (i) a pyritic graphite unit, (ii) a Cr-muscovite dolomitic unit disrupted by a massive to pillowd tholeiitic lava flow, and (iii) a pyritic laminated chert. The ore is bounded by polymict mass-flow conglomerates (Jensen and Trowell, 1981). A comprehensive account of the mineral paragenesis of all lithological types along with their altered counterparts has recently been reported by Kishida (1984).

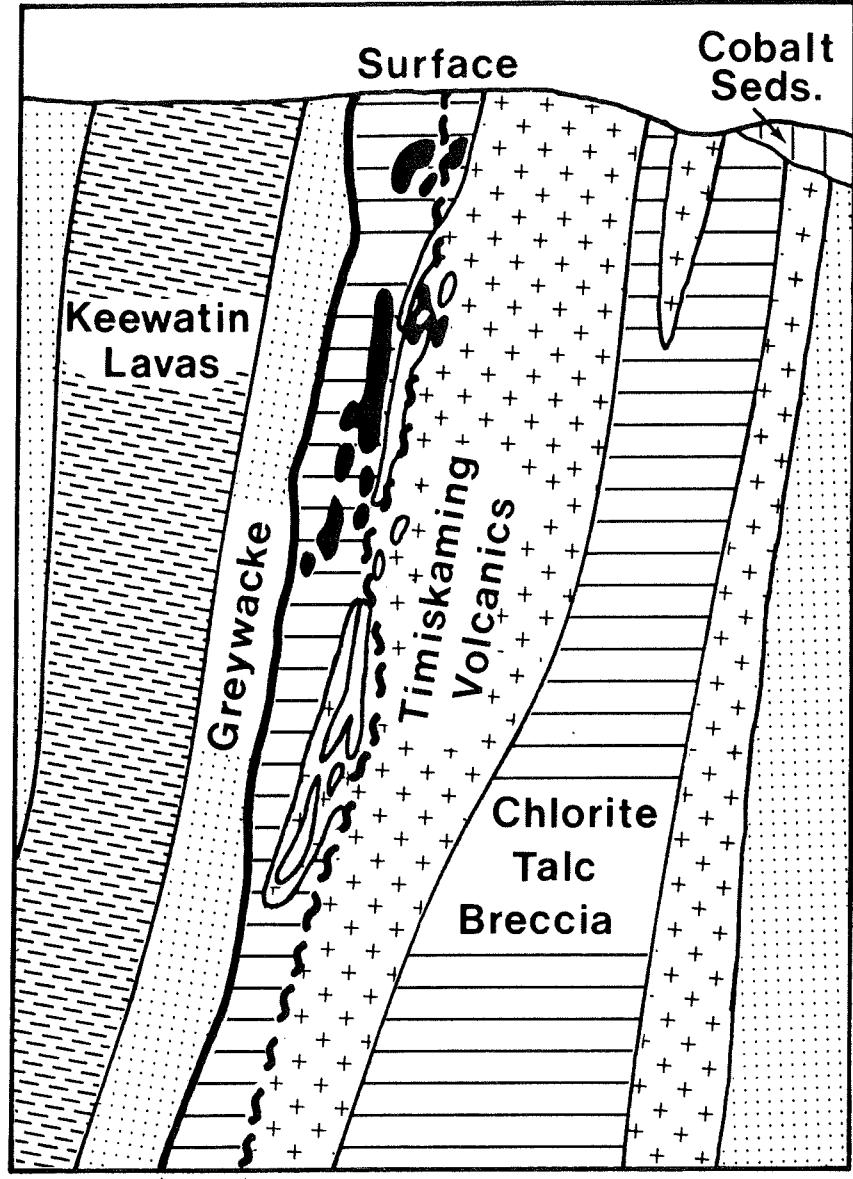
B. Chemistry of the Carbonate Ore

Carbonate ore consists of carbonate-altered volcanic flows and tuff, with minor interflow laminated magnesite, ferroan dolomite and chert, collectively traversed by major arrays of quartz-carbonate-muscovite veins. Chemical analyses of ore samples collected from stopes on the 3200 level are reported by Kerrich (1983) and Kishida (1984). Absolute abundances of the major-element oxides and trace elements are highly erratic, owing both to the local variable dilution of flows by sediments, and of all rocks by veins. However, inspection of the ratios of the less mobile elements reveals two populations of data: (i) Ti/Zr 40-60, relatively higher Zr/Y and lower Cr plus Ni, corresponding to precursors of basaltic composition; and (ii) Ti/Zr 97 (\pm 30 σ), relatively lower Zr/Y, along with elevated Cr (1200) and Ni (800) ppm, representing ultramafic precursors (see Kerrich, 1983). The essentially isochemical behaviour of these less mobile elements, indigenous to the ultramafic precursors, is indicated by their overall coherent decrease in abundance during progressive dilution by the introduction of veins. A small degree of scatter of the inter-element ratios, together with variations in absolute abundance of Cr and Ni signify some minor local mobility of these elements, especially of the latter two, which are incorporated into vein muscovite and chlorite.

In the suite of carbonate ore samples collected, the rocks of ultramafic parentage record alteration at volume factors of 1.6 to 2.2, signifying volume changes of plus 60 per cent to over 100 per cent. Altered rocks exhibit major gains of K₂O and volatiles, along with additions of SiO₂, Fe₂O₃, MgO, CaO and Mn, corresponding to the

**Kerr-Addison
CROSS SECTION 56E**

← N45°W



Kinojevis Group ← → **Larder Lake Group**

LEGEND

- Carbonate Ore
- Flow Ore

SCALE

0 1000
feet

Figure 21 : Schematic cross section of the Kerr-Addison Mine, modified after Lowrie and Witon (1980). The stratigraphic scheme according to Downes (1980) is printed below the section.

introduction of vein muscovite, quartz and carbonate (Fig. 22a). Rubidium and barium covary with potassium; strontium covaries with calcium. Of the abundant silica present in quartz veins, some is probably a product of the hydrolysis of Fe, Ca, Mg-silicates to Fe, Mg, Ca-carbonates accompanying CO₂ fixation, whereas the majority was introduced from hydrothermal solution. Small gains or losses of Na₂O are evident reflecting the sporadic distribution of albite. There are only minor excursions of Al₂O₃, TiO₂ and Zr from zero gain/loss signifying the overall conservation of these elements during alteration (Fig. 22a).

Rocks of basaltic precursors which have been analyzed were altered at high volume factors (fv = 1,5, to 11,5) representing intense veining. Patterns of alteration are essentially similar to those described for the ultramafic rocks, with massive additions of SiO₂, K₂O, Rb, Ba, CaO, MgO volatiles and Sr, representing the production of secondary vein quartz, muscovite and carbonate respectively. Both basaltic rocks record a major addition of Na₂O reflected in the presence of vein albite (Fig. 22a).

Although carbonate-altered ultramafic rocks devoid of veins do not make ore grade as such, they possess gold at levels significantly above background (314 ppb \pm 610 1 σ). Along with enrichment of gold are erratic high concentrations of As (940 ppm \pm 470 1 σ), Sb (18 \pm 9) and B (880 \pm 1400), as well as minor anomalies of W (9 \pm 2,4). Distributions of the transition metals, including Cr, Co, Ni and V, are erratic, but broadly reflect the nature of the original flow composition, ultramafic or mafic. Of the base metals, Cu (<1 to 99 ppm) and Pb (<1 to 5 ppm) show variable gains and losses during the alteration, whereas over-all Zn, with an average abundance of 41 ppm (\pm 15), is introduced.

It is difficult at present to establish whether early carbonate alteration of the flows and the later quartz-carbonate veining were (i) separate alteration events, (ii) occurred coevally or (iii) reflect sequential stages in evolution of a given fluid reservoir. From oxygen isotope and fluid inclusion studies of the veins, the mineralizing fluids were at temperatures of 300-350°C, had $\delta^{18}\text{O}$ fluid 6-7 and possessed significant CO₂ (Table 2; Kishida, 1984).

C. Chemistry of the Flow Ore

Analyses of major-element oxides and selected trace elements for samples of "flow" ore collected from the footwall to the hanging wall of the 3821 - 50 1/2 stope are reported by Kerrich and Hodder (1982) and Kerrich (1983). Inspection of ratios among the less mobile major and trace elements reveals three populations (i) Ti/Zr = 20-39, Al₂O₃/TiO₂ = 17, Sc = 15-22, Nb = 31-42, (ii) Ti/Zr = 40-60, Al₂O₃/TiO₂ = 7-9, Cr = 30-100, Ni = 40-80, and (iii) Ti/Zr = 36-58, Al₂O₃/TiO₂ = 16-20, Sc = 21-40, Cr = 1750-2870, Ni = 800-1280. These three groups are equated with volcanic rocks of primary trondhjemitic or dacitic, Fe-tholeiitic basalt and ultramafic compositions respectively, with some rocks probably reflecting contamination and/or tectonic mixtures. The third group possesses low Ti/Zr and high Zr/Y for ultramafic rocks, signifying possible minor mobility of these elements, contamination, mixing, or an unusual initial composition. Based on absolute titania and Ni contents along with Ti/Sc ratios, the third group may have been komatiites with a primary MgO content of 24 wt % (cf. Arndt and Nesbitt, 1984; see section above on Hollinger veins).

Three distinctive patterns of alteration are evident in flow ore rocks, (i) reductive-iron-magnesium, (ii) reductive-sodic-CO₂ enrichment and (iii) reductive-potassic-CO₂. Rocks with type (i) alteration are composed of chlorite, quartz, pyrite and Fe-talc, type (ii) of albite, quartz, pyrite, and Fe, Mg-carbonates; and type (iii) of muscovite, quartz, Fe, Mg-carbonates and pyrite. Enrichments of sodium and CO₂ are essentially confined to rocks of trondhjemitic and basaltic parentage, whereas the potassic CO₂ type is best developed in rocks of initial ultramafic composition. The second type, with up to 7,9 wt % Na₂O and 0,18 wt % K₂O, possess about ten times the sodium and one tenth the potassium of the potassic CO₂ suite (Hodder and Kerrich, 1982).

Rocks with a precursor of basaltic composition also exemplify the reductive sodic alteration (Fig. 22b). Alteration has proceeded at volume factors of 0,9 to 1,8 (10% volume loss to 80% volume gain), involving massive fixation of Na₂O, sulphur and volatiles (principally CO₂), corresponding to the production of abundant albite, pyrite, Fe-talc and carbonates. Carbonate minerals are either ferroan dolomites or members of the magnesite-siderite solid-solution series, all of which contain only a minor manganese component (Kerrich, 1983). There is an overall gain of SiO₂, most pronounced at higher volume factors, reflecting progressive introduction of vein quartz. Potassium and the related alkali metals Rb and Ba, along with MgO, undergo extensive leaching; and Fe₂O₃, CaO, Sr and Mn exhibit variable gains or losses.

ALTERATION OF CARBONATE ORE ROCKS KERR ADDISON MINE

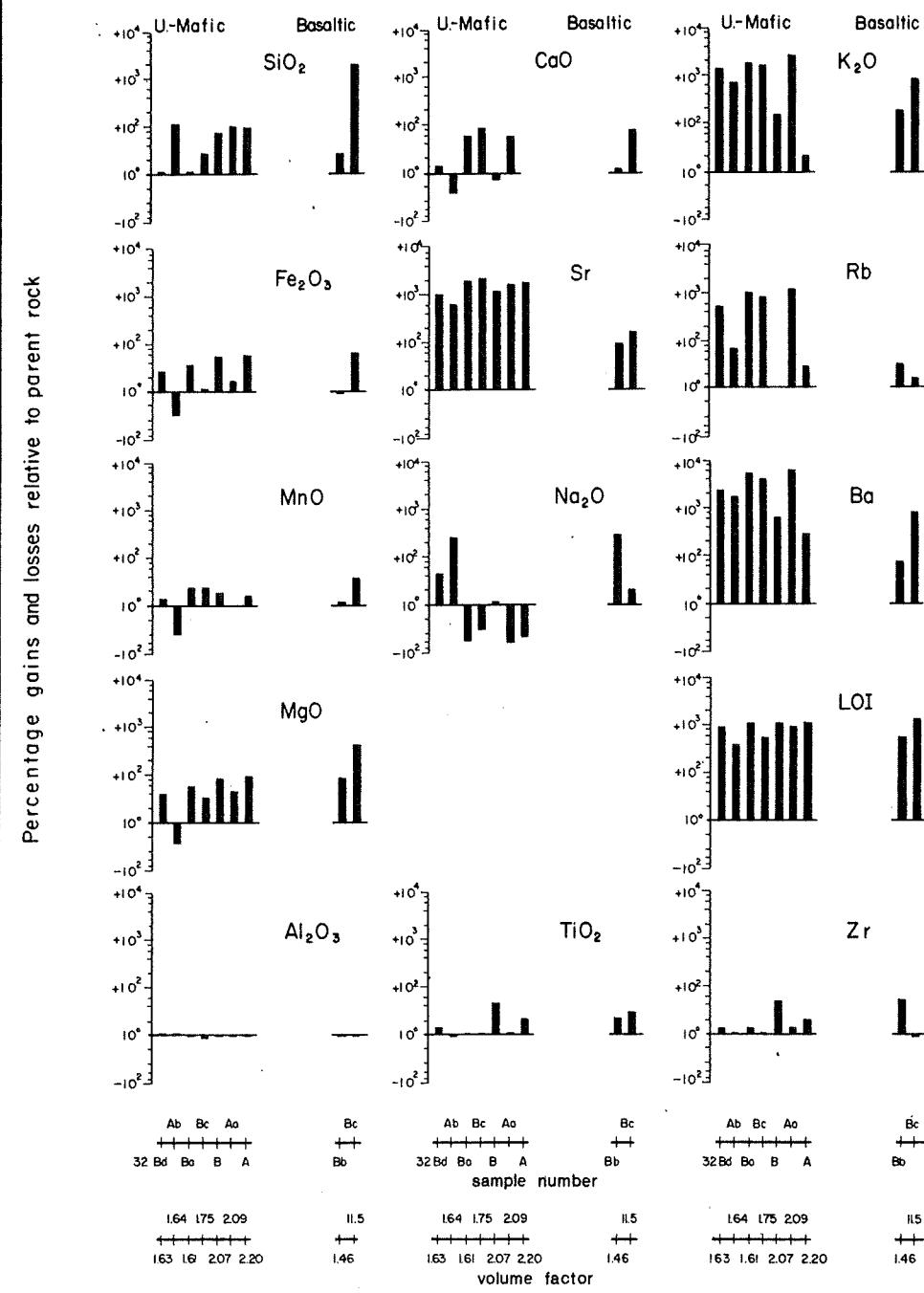


Figure 22a: Gains or losses of major element oxides and selected trace elements in hydrothermally altered rocks of primary ultramafic and basaltic composition, carbonate ore, Kerr Addison Mine. Gains and losses expressed as percentage changes relative to abundances in the unaltered parent rock, and ordered according to increasing volume factor.

ALTERATION OF FLOW ORE ROCKS KERR ADDISON MINE

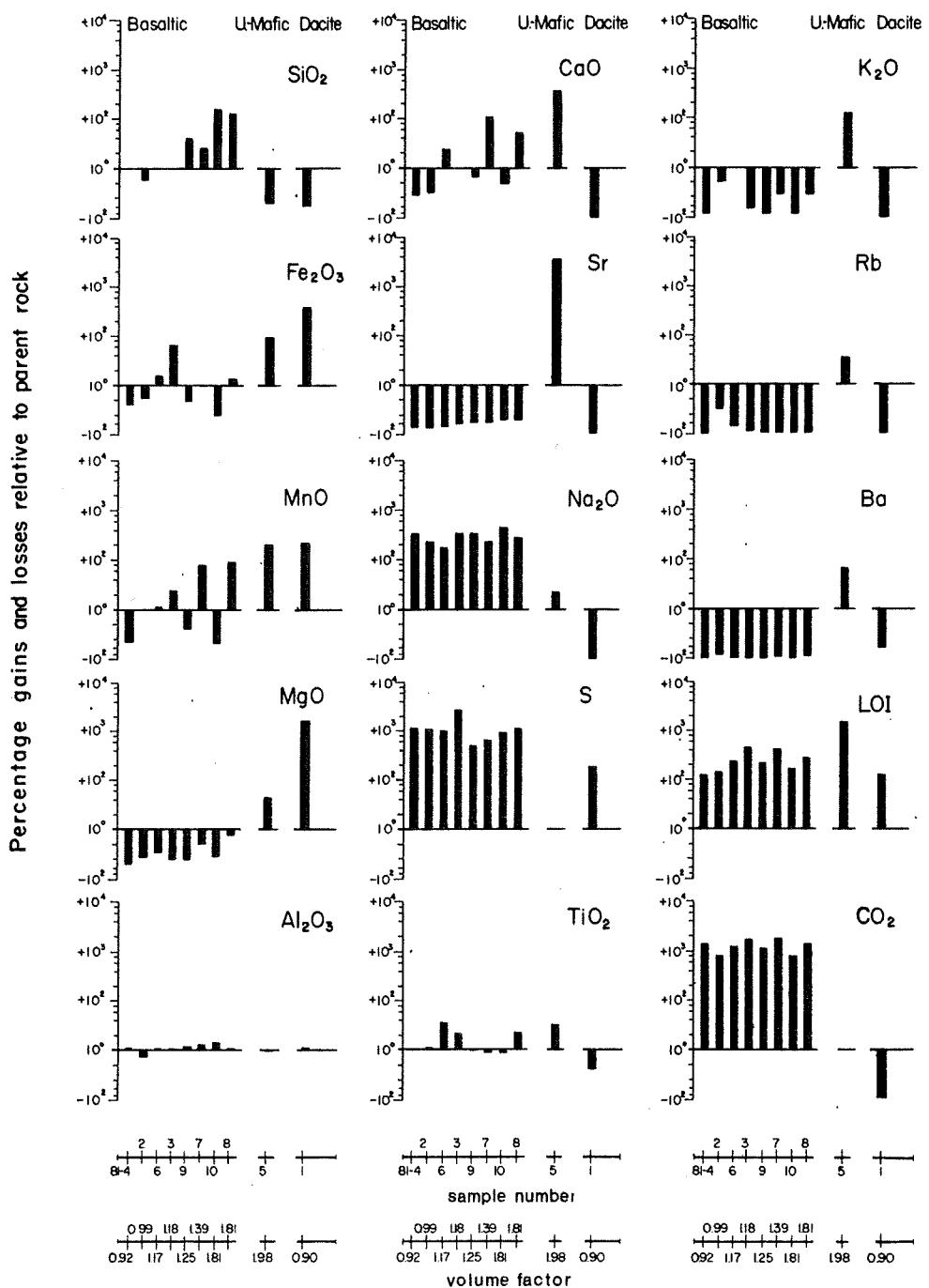


Figure 22b: Gains or losses of major element oxides and selected trace elements in hydrothermally altered rocks of primary basaltic, ultramafic and dacitic composition, 'flow ore', Kerr Addison Mine. Gains and losses expressed as percentage changes relative to abundances in the unaltered parent rock, and ordered according to increasing volume factor.

During alteration, hydrolysis of Fe, Mg, Ca-silicates coupled with the introduction of S and CO₂ appears to have involved transfer of iron from a silicate to a sulphide and carbonate reservoir, and transfer of Fe₂O₃, MgO plus CaO from a silicate to a carbonate reservoir, with some absolute removal of MgO.

The single example of a rock with ultramafic parentage analyzed from this section of the flow ore exhibits reductive potassio-CO₂ alteration, at a volume factor of about two. Pronounced additions of K₂O (+ Rb, Ba), Fe₂O₃, MnO, MgO, CaO (Sr) and volatiles reflect the introduction of secondary muscovite and Fe, Mg, Mn-carbonates. Minor losses of SiO₂ are evident (Fig. 22b).

An entirely different pattern of alteration (type (i)) to those described above for the Kerr Addison Mine is present in one sample of probable trondhjemite parentage located at the immediate footwall to the flow ore. Massive gains of Fe₂O₃, MnO, MgO, S and volatiles correspond to the production of secondary chlorite, pyrite and Fe-talc (Fig. 22b). Silica, along with the alkali and alkali earth metals, are stripped, and a notable feature is the virtual absence of carbonate minerals. These chemical and mineralogical features of alteration are in many respects similar to those characteristic of footwall alteration in base metal massive sulphide deposits (cf. Franklin *et al.*, 1981; Costa *et al.*, 1983).

The Cr contents of muscovite and Fe, Mg, Ca-contents of carbonates are related to the abundance of these elements in the parental rock.

Variable enrichments of As (300-1800 ppm) and Sb (14-15 ppm) are associated with gold in the flow ore, the higher contents being present in the potassio-CO₂ alteration type. Base metals are erratically distributed in both sodic and potassio ore, with mean abundances of Cu at 280 ppm ± 250 (1σ), Zn (36 ± 20) and Pb <5.

D. Discussion

Downes (1980) and Thomson (1980) have clearly demonstrated a late stage of K-Si-CO₂ metasomatism involving gold enrichment which cross-cuts structures that in turn displace the volcanic stratigraphy. Kishida (1984) has demonstrated that the potassio alteration is coeval with development of carbonate. Potassium distribution in the Kerr Addison Mine has been mapped by Thomson (1980) utilizing the X-ray intensity of ⁴⁰K, separated from the minor contributions from relatively low and uniform background abundances of Th and U.

An essential problem to the resolved is the juxtaposition of rocks characterized by reductive-sodic-CO₂ and reductive-potassio-CO₂ patterns of alteration, both of which contain significant gold enrichments. A possibility raised by Kerrich and Hodder (1982) is mixing of two fluid reservoirs in permeable volcanic aquifers in the subseafloor environment. One fluid was auriferous, relatively hot (350-450°C), reduced and of probable metamorphic origin, possessing elevated CO₂ to stabilize the carbonate and Na/K ≤ 10 such that muscovite was stable. The second reservoir was cool (<250°C), oxidized and of probable marine origin, possessing low CO₂ and a Na/K ratio of ~27 (seawater ratio) such that albite formed from the hydrolysis of igneous plagioclase.

Munha *et al.* (1980) have shown that incorporation of sodium into subvolcanic to extrusive Archaean "QFPs" during seawater-induced spilitization typically occurs under low-temperature oxidative conditions, with minor CO₂ fixation as calcite and SO₄²⁻ fixation as anhydrite, coupled with stripping of transition metals. If this type of process was active during extrusion of the volcanic flows, then the high-Na and Eh seawater-derived fluid would have had to evolve to a reduced state, possibly by mixing with the postulated first reservoir of low redox potential, to be consistent with the observed reduced state of the sodic flow ore rocks.

An alternative explanation is that a reducing CO₂-rich fluid reservoir with relatively high K/Na developed to conditions of lower K/Na, so that albite was stabilized over muscovite. The second interpretation is favoured here, on the basis of low redox state in the sodic-dominated flow ore, signified by abundant pyrite plus hydrocarbons; and inasmuch as quartz plus muscovite from the potassio and quartz plus albite from the sodic alteration types are isotopically concordant, indicating equilibrium with a common fluid reservoir of δ¹⁸O 8 per mil at 350°C (δ¹⁸O quartz = 14,4, albite = 12,0, chlorite = 6,9 sodic type; δ¹⁸O quartz = 14,2, muscovite = 10,1 potassio type - see Table 3).

It is interesting to note that one sample (KA 81-1 Kerrich, 1983), dominated by Fe, Mn, Mg additions exemplifying a marine water style of alteration, retains a record of this event in the isotopic composition of less exchangeable quartz (8,9 per mil). However, chlorite, which more readily re-equilibrates, has been isotopically

overprinted, probably by the fluid reservoir involved in flow ore Au mineralization, such that the $\delta^{18}\text{O}$ of chlorite (6,8) is now concordant with chlorite in the flow ore.

Jensen (1980) suggested that an early stage of gold enrichment may have involved emanation of hydrothermal brines along newly developed fractures, with gold precipitating in nearby reducing acid sedimentary traps. He also proposed that gold deposition at an early stage may have involved transport of gold in solution and particulate form by ocean currents moving outward from the core of an older volcanic pile, with precipitation in acid reducing ocean-floor environments.

In summary, several distinct hydrothermal regimes and stages of gold enrichment can be discerned in the Kerr Addison Mine. An early episode in carbonate and chert chemical sedimentary rocks, marked by intermittent ashfall, possibly involved emanation of CO_2 -rich auriferous fluids of possible metamorphic origin onto the seafloor, coupled with pervasive leaching of the volcanic sequence. According to Jensen (1980), gold may have been transported into the basin by ocean currents at this stage. Coevally, chlorite-pyrite alteration was forming locally by massive introduction of Fe_2O_3 , MgO , MnO and S (but not Au), probably as a result of thermally driven convection of seawater ($\delta^{18}\text{O} \sim 0$ per mil) through the cooling volcanic sequence. However, this alteration type experienced partial isotopic overprinting by high- ^{18}O fluids, during a later stage of gold enrichment in quartz-carbonate-muscovite veins with attendant reductive- $\text{K}_2\text{O}-\text{SiO}_2-\text{CO}_2$ hydrothermal metasomatism, localized by stratabound and structurally controlled permeability. Where the reservoir evolved to lower K/Na and/or lower temperature, reductive- $\text{Na}_2\text{O}-\text{SiO}_2-\text{CO}_2$ alteration was dominant.

By analogy with alteration patterns of the Dome Mine, the multiple episodes of gold enrichment may represent semi-continuous discharge of a single auriferous- CO_2 -rich fluid reservoir, but with early unfocussed venting into the hydrosphere at low pressure such that CO_2 was incorporated into sedimentary carbonates, followed by later discharge through hydrofractures at higher pressures, after slumping and deformation of the volcanic-sedimentary sequence, with CO_2 fixation via hydrolysis of silicate minerals.

VII. QUARTZ-TOURMALINE VEIN ARRAYS - LAMAQUE MINE, VAL D'OR

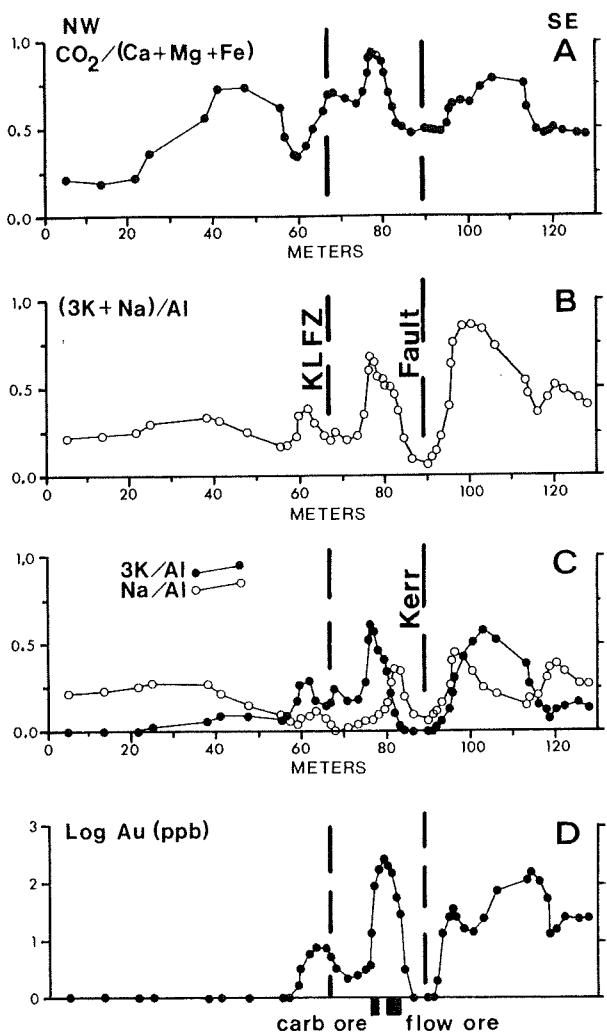
Gold is mined from major arrays of quartz-tourmaline veins at the Lamaque Mine, Val d'Or. The veins are laterally extensive, transecting several different rock types, and dip at angles of 25 to 75 degrees. Data reported in this section pertain to that part of the mine where veins cross-cut the 'Main Plug', a vertically extensive, subcylindrical composite stock, with a core composed of granodiorite (Bedard and Imbeau, 1980).

The principal vein gangue minerals are quartz, tourmaline and carbonates ranging in composition from ankerite and dolomite to calcite. Subordinate quantities of pyrite, pyrrhotite, chalcopyrite, scheelite, Cr-muscovite, gold and tellurides are present. A zone of hydrothermal occurs adjacent to most of the veins, extending a distance of a few cm to one metre into the wall rock. Alteration is marked by pronounced bleaching due to the conversion of igneous Fe, Mg-silicates, Fe-oxides and plagioclase to quartz, carbonate, albite and pyrite. Bedard (1980) reports that the highest intensities of alteration are always indicated by the presence of brilliant emerald green coloured chromian muscovite, which also coincides with high grades of gold.

Chemical analyses for samples of unaltered granodiorite and bleached counterparts adjacent to veins are reported in Kerrich (1983, Table 16) and illustrated here in Fig. 24. The salient chemical transfers accompanying hydrothermal alteration are as follows. Minor losses of SiO_2 are evident in bleached rocks characterized by $\text{fv} < 1$ and the absence of quartz stringers: this loss reflects hydrolysis of primary plagioclase and Fe, Mg-silicates to carbonate minerals, which involved local transfer of the metal cations from a silicate to a carbonate reservoir, accompanied by release of Si as H_2SiO_4 aqueous, and its transport out of the rock in solution. Losses of silica are replaced by gains at $\text{fv} > 1$, due to additions of vein quartz (Fig. 24).

Depletions of magnesium (minor) and sodium (major) are observed at all stages of alteration, the latter representing destruction of Na-bearing igneous plagioclase. However, Na_2O is not quantitatively lost, as is the case at Yellowknife for instance, but is incorporated into both hydrothermal albite and tourmaline.

Significant additions of K_2O and volatiles occur at all intensities of alteration, the former along with the related trace elements Ba and Rb being incorporated into muscovite, and the latter fixed in carbonate minerals. Minor over-all gains of calcium are present, but Sr behaves antipathetically to Ca, being stripped by the hydrothermal solutions.



INIT	Ctd	INIT	AD	INIT	AD	INIT
				C-M C-a	C-a C-M	

Figure 23 : A, B, C. Variations of alteration stages across the 3850' level of the Kerr-Addison Mine, relative to saturation indices of CO_2 and alkali-metals. Initial stage of alteration (IN) is characterized by low $\text{CO}_2/(\text{Ca}+\text{Mg}+\text{Fe})$ and $(\text{3K}+\text{Na})/\text{Al}$ indices. Advanced stage of alteration (AD) corresponds to areas of high $\text{CO}_2/(\text{Ca}+\text{Mg}+\text{Fe})$ and $(\text{3K}+\text{Na})/\text{Al}$ indices. The broad $\text{CO}_2/(\text{Ca}+\text{Mg}+\text{Fe})$ peak north of the KLFZ has no associated $(\text{3K}+\text{Na})/\text{Al}$ maxima, corresponding to an area of chloritoid alteration (chltd.). Areas of the advanced stage of alteration (AD) can be subdivided into zones of carbonate-muscovite type (cb-mu) and carbonate-albite type (cb-alb) on the basis of high $3\text{K}/\text{Al}$ or Na/Al , respectively. Note the symmetrical distribution of different saturation indices relative to the Kerr-fault. All points correspond to moving averages of 5 samples, projected on a N30W vertical plane (see Appendix 1). D. Distribution of moving averages of Au across the 3850' level of the Kerr-Addison Mine, compared to the saturation indices of CO_2 and alkali-metals. Concentrations of Au are generally high south of the KLFZ. Note that the gold maxima are slightly displaced relative to the maxima of the saturation indices. Peaks of Au correspond to points where $3\text{K}/\text{Al}$ and Na/Al indices display similar values, and are therefore in the transition zone between carbonate-muscovite and carbonate-albite alteration types.

ALTERATION OF GRANODIORITE LAMAQUE MINE

Percentage gains and losses relative to unaltered granodiorite

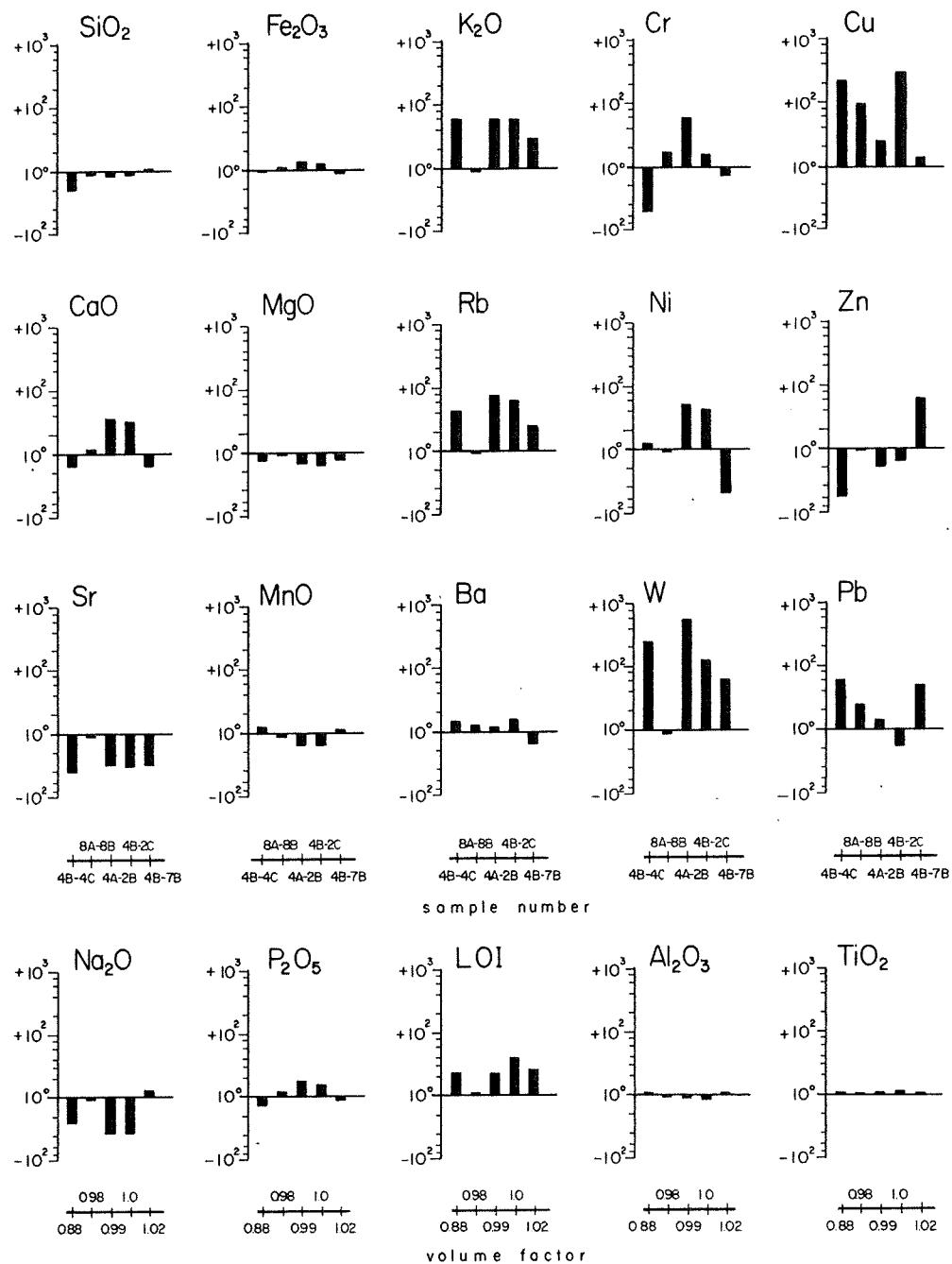


Figure 24 : Gains or losses of major element oxides and selected trace elements accompanying hydrothermal alteration of wall rocks to veins, granodiorite, Lamaque Mine. Gains and losses expressed as percentage changes relative to abundances in unaltered granodiorite, and ordered according to increasing volume factor.

Iron, manganese and phosphorous exhibit minor variable gains or losses, but over-all these elements are conserved. Formation of pyrite at essentially constant total iron reflects simple transfer of iron from primary silicate and oxide minerals to a sulphide reservoir, accompanying introduction of S from the hydrothermal source; however, products are always reduced relative to reactants. Chlorite is quite rare either in veins or their bleached wall rocks: this may indicate that K_{aq} competed most effectively for the available aluminum (made available in hydrolysis of igneous aluminosilicates) in forming muscovite. Alternatively, aqueous S and CO_2 competed most effectively for the available iron (made available by destruction of igneous Fe oxides and silicates) in forming pyrite and Fe-carbonates respectively, so that there was insufficient Fe + Mg to nucleate chlorite.

Of the transition metals, Cr and Ni show variable gains or losses, but over-all have been introduced to altered rocks from hydrothermal solution, with local incorporation of Cr into muscovite. Minor quantities of Pb and Cu were added during alteration, but zinc was stripped. Significant gains of W are evident in all altered rocks, although visible scheelite is erratically distributed.

Fluids from which the veins were precipitated and which induced the attendant alteration were at temperatures of $400^\circ C$, at high fluid pressure required for hydrofracturing and flow along shallow-dipping veins, and were characterized by elevated CO_2 , $K > Na$, low redox potential, $\delta^{18}O$ fluid 7 ± 1 per mil and salinities of 1,5 wt % NaCl equivalent.

For the adjacent Sigma Mine, which has many features in common with Lamaque, Robert and Brown (1982) described synchronous incremental dilation of mutually orthogonal banded vein systems, which requires that $P_{fluid} \geq P_{lithostatic} + T$; these relations signify pulsed discharge of a fluid reservoir at approximately lithostatic pressure (see also section on Yellowknife, Figs. 6, 7; Kerrich and Allison, 1978; Hodgson and MacGeehan, 1982, Fig. 7b).

VIII. GOLD-QUARTZ VEINS IN HIGH-LEVEL FELSIC PLUTONS LOW- ^{18}O ARCHAEN METEORIC WATER

Arrays of gold-bearing quartz-carbonate veins are present in fractures traversing central batholiths to volcanic complexes in the Abitibi greenstone belt, such as the Flavrian pluton, Noranda. These plutons are generally considered to represent subvolcanic magma chambers intruding their volcanic carapace. Kennedy and Kerrich (1982) have identified a component of meteoric water in the Elder and Eldrich vein deposits, Noranda District. Vein quartz $\delta^{18}O$ ranges from +9,4 to +11,4 per mil and quartz-chlorite from +9,2 to +10,3 per mil, signifying fluids of -0,7 to -2 per mil at temperatures of 220 to $250^\circ C$. The fluids implicated in mineralization may have become depleted in ^{18}O by CO_2 immiscibility (cf. Higgins and Kerrich, 1982), but the presence of low- ^{18}O albite (+6,2 to +4,5 per mil) in the host granite requires isotope exchange with low- ^{18}O fluids. The only fluid reservoir with negative $\delta^{18}O$ values is meteoric water, indicating that the Flavrian pluton was locally above sea level at the time of vein formation.

Some of the gold-bearing quartz veins in high-level plutons of greenstone belts may be analogous to precious-metal vein deposits associated with epizonal felsic stocks of the Western U.S.A., for which a significant component of meteoric water is implicated in the mineralizing fluids (cf. Taylor, 1974). Such fluids possess calculated δD , $\delta^{18}O$ compositions distinct from those implicated in the majority of gold-bearing quartz-carbonate vein deposits discussed above (Fig. 20).

IX. CONCLUSIONS

The principal conclusions from geochemical and structural data reported in this paper are as follows:

1. Most of the Archaean lode gold deposits are hosted by major tectonic structures. Specifically, deposits are sited at the confluence of second-order fracture arrays or splays of the main structures, at flexures, and intersections of two fracture systems, where permeability is enhanced. In addition, deposits occur where certain lithologies such as ultramafic rocks or iron formation, which preferentially mediate fixation of hydrothermally donated S, Au, CO_2 (etc.), are traversed by tectonic structures.
2. The major structures may have initiated as listric normal faults accommodating extension of greenstone belts, and acting as sites for the extrusion of komatiitic magmas. They also formed submarine scarps which delimit linear belts of marine clastic to volcaniclastic sediments. At this stage of greenstone belt development intense marine-water hydrothermal activity proceeded in the peripheral to fault structures, generating colinear belts of chemical sedimentary rock, predominantly iron formation, but with rare concentrations of gold.

3. Subsequently reverse motion occurred on the structures, accommodating shortening of a greenstone belt under compression. At this stage the tectonic zones acted as conduits for the ascent of trondhjemitic and alkaline magmas, as well as for discharge of hydrothermal fluids implicated in the gold deposits. If alkaline magmas are the product of low degrees of partial melting of the mantle, then the structures were likely transcrustal, penetrating into the upper mantle.
4. Lode gold deposits do not appear to have a preferred setting in the volcanic stratigraphy of greenstone belts. Rather, they are present in the basal, intermediate and highest stratigraphic levels of volcanic cycles, as well as within or marginal to intrusives, where these are transected by large scale structures.
5. Alteration in rocks hosting the gold deposits is the product of complex incremental steps. Initially volcanic rocks underwent silitization reactions due to the infiltration of marine water during thermally driven convective cooling in the submarine environment. This induced minor excursions of the alkalic, alkaline earth and related mobile elements, in conjunction with variable degrees of $\delta^{18}\text{O}$ enrichment, but little or no concentration of gold. Second, deformation of rocks in the structures by transgranular fracturing, pressure solution, and interacrystalline creep typically produced retrograde mineral assemblages, hydration and minor internal redistribution of SiO_2 , Na_2O , $\text{CO}_2 + \text{H}_2\text{O}$. Hydrothermal alteration associated with the gold deposits is superimposed on the combined metasomatic signatures of the previous two incremental stages.
6. Generally gold introduction was coeval with or postdated peak metamorphism. Specifically, mineral assemblages of hydrothermally altered rocks are out of mineralogical, redox and isotopic equilibrium with unmineralized counterparts in contiguous rocks.
7. Gold-bearing vein systems formed during multiple episodes of hydrofracturing, from transient, pulsed hydrothermal discharge, under conditions where $P_{\text{fluid}} \geq \sigma_3 + T$, and P_{fluid} may have exceeded σ_1 , the maximum principal stress. Pulsed discharge generated banded veins, and was probably induced by repeated breaching of a fluid reservoir, ponded beneath an impermeable cap rock subject to a compressive horizontal crustal stress.
8. The narrow recorded range in $\delta^{18}\text{O}$ of vein quartz at 12-15 per mil across banded veins, and of gold-bearing vein arrays within mines, independent of wall-rock type, signifies an isotopically uniform fluid reservoir, a fluid-dominated system in the hydrofracture conduits and a relatively small temperature span over which veins precipitated. Hydrothermal solutions transporting gold were isotopically characterized by $\delta^{18}\text{O}$ 6 to 8 per mil and δD -80 to -40 per mil, consistent with a metamorphic or magmatic fluid reservoir.
9. These fluids were at temperatures of 280 to 450°C, possessed low salinities of ≤ 2 wt % NaCl equivalent, low pH, Na/K 0,1, and contained significant quantities of CO_2 , along with the reduced gas species CH_4 , CO , H_2 , N_2 and ultrafine particulate hydrocarbons.
10. Carbon isotope values of -0,5 to -3,8 per mil in carbonate gangue indicate that the carbon may have been derived from mixtures of various possible carbon reservoirs, including marine and igneous carbonate, decarbonated marine carbonate or decarboxylation of organic hydrocarbons.
11. Considering the Timmins camp, the ~2000 tonnes of gold produced was extracted from ~600 km³ of source rock in 90 km³ of hydrothermal fluids with gold solute concentrations of ~20 ppb. Hence, large volumes of dilute hydrothermal solutions appear to have been involved rather than intrinsically auriferous fluids. Minor Cr and Pd were transported along with the gold even where immediate host rocks were not mafic or ultramafic.
12. The fluid δD , $\delta^{18}\text{O}$, low salinity, high K/Na, high CO_2 and reduced gas species are all consistent with a metamorphic fluid reservoir or possibly magmatic; whereas none of these geochemical features are typical of marine-water-derived ore-forming fluids.
13. Gold-bearing vein systems and their immediate wall rocks are characterized by massive additions of SiO_2 and CO_2 , along with K (and the other alkali metals Rb, Li, Cs), coupled with near quantitative stripping of Na. The magnitude of sulphur introduction is highly variable. Silica precipitation appears to be a simple function of the cooling of fluids saturated with respect to quartz, with a minor component from the hydrolysis of silicates to carbonates in wall rocks. As potassium is consumed from hydrothermal fluids in the hydrolysis reaction of albite to muscovite, with concomitant Na release, the fluid K/Na may diminish, and coupled with decreasing temperature promote formation of gangue albite + paragonite, coexisting with Fe^{2+} -silicates and sulphides (reduced).
14. The ubiquitous gangue carbonate minerals formed via hydrolysis of Fe, Mg, Ca, Mn-silicates to Fe, Mg, Ca, Mn-carbonates in which wall rocks donate the bivalent metal cations and CO_2 is indigenous to the hydrothermal fluids. Ultramafic rocks are effective CO_2 sinks, given their inherently elevated complement of bivalent metal cations. Such carbonate- and/or sulphide-forming reactions may mediate gold precipitation, raising the possibility that gold is transported as a carbonyl (CO) COS , or related complex.
15. During wall-rock reactions, Al_2O_3 , TiO_2 , Sc. V. Zr and Hf appear to behave essentially isochemically, enabling constraints to be placed on volume changes accompanying alteration : such changes typically vary from -40% at the periphery of alteration envelopes where leaching predominates over precipitation,

- to >700% gain at vein-rock contacts, the sites of gangue mineral additions.
16. The rare-earth elements (REE) appear to behave isochemically at the lowest states of alteration, but significant mobility of the heavy REE occurs at the highest intensities of alteration. The abundant CO₂ introduced into vein systems may have been generated at source by decarbonation reactions accompanying dehydration during prograde metamorphism, and also by the hydrolysis of hydrocarbons in interflow sedimentary rocks, and reactions in which oxidation of hydrocarbons is linked to reduction of Fe³⁺.
 17. Wall rocks to veins are intensely reduced ($\text{Fe}^{2+}/\Sigma\text{Fe} \sim 0,9$) relative to background ($\text{Fe}^{2+}/\Sigma\text{Fe} \sim 0,7$), and this is also reflected in positive anomalies of Eu²⁺. The reductant involved was probably H₂, a product of the dissociation of H₂O under high T and P conditions in source rocks, where $P_{\text{H}_2} >> P_{\text{O}_2}$, an account of reactions such as Fe²⁺-silicate + H₂O, - Fe₃₊ + O₂ + silicate + H₂. At the Macassa and some other deposits, more oxidizing conditions prevailed, signified by the presence of Fe³⁺ oxides. All such vein-related alteration is typically superimposed on a prior spilitic alteration induced by incursion of marine water into cooling greenstone-belt rock sequences at the time of their extrusion, or deposition, in a submarine environment.
 18. Deposits are characteristically enriched in a suite of certain large ion lithophile elements including K, Rb, Li, Ba, Pb, Cs, B (etc.), as well as CO₂, in addition to the prominent rare element Au, Ag, As, Sb, Se, Te, Bi, and W. Other lithophile elements such as Be, U, Th, F, REE, Zr and P do not appear to have been significantly concentrated by the ore-forming systems.
 19. The Archaean lode gold deposits appear to have formed late in the development of greenstone belts, during major episodes of brittle-ductile deformation, and constitute an integral part of the thermal-mechanical energy of the volcanic-plutonic ensemble.

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