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PRECAMBRIAN GOLD: PERSPECTIVES FROM THE TOP AND BOTTOM OF SHEAR ZONES*

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ABSTRACT

Studies of the Kirkland Lake gold camp, along a narrow, brittle shear in the upper crust, and the Bamble belt, Norway, a broad shear zone from the lower crust, test a hypothesis that deep shear-zones were a source for gold. At Kirkland Lake, long-term displacement along a major strike-slip fault resulted in localized extension and thinning of the crust. This produced extensional basins at the surface, a broad deformation zone at depth, and upwelling of mantle. Partial melting and decarbonation of the upwelling mantle were represented at Kirkland Lake by alkaline magmatism and a long period of carbonatization. When extension ceased, there was uplift, during which overpressured, CO_2-bearing fluids, which carried gold from depth, were focused into the narrow, upper part of the shear zone. The Bamble shear belt is a lower crustal analogue of this extensional terrane, characterized by a counterclockwise P – T – t metamorphic path. During extension, mafic magma carried CO_2 into the shear belt; the CO_2 may have been a cause for oxidation of its rocks during prograde metamorphism. There was a long period of isobaric cooling, when fluid movement was inhibited, because inclusions formed during peak metamorphism were underpressured. During this period, internal buffering by the mineral assemblage caused oxidation of pyrrhotite to pyrite. Pyrrhotite is a principal host of gold in mafic lower crust; its transformation to pyrite made the gold accessible to later fluids. Isobaric cooling was followed by rapid, isothermal uplift. Fluid inclusions, containing CO_2, now became overpressured, causing their release. It was during this period that gold was likely extracted from the deep shear belt, the rocks of which now contain only 0.06 of the crustal abundance of this element.

Keywords: Kirkland Lake, Ontario, Bamble belt, Norway, gold, extensional tectonics, metamorphism, alkaline magmatism, mantle, oxidation, isobaric cooling, uplift.

SOMMAIRE

Les études des gîtes aurifères du camp minier de Kirkland Lake, en Ontario, situés le long d'une étroite zone cisaillée cassante dans la croûte supérieure, ainsi que des roches de la ceinture de Bamble, en Norvège, une zone cisaillée plus diffuse typique de la croûte inférieure, permettent de vérifier l'hypothèse que les zones cisaillées profondes sont la source de l'or. A Kirkland Lake, les déplacements horizontaux soutenus le long d'une faille majeure ont provoqué une extension localisée et un amincissement de la croûte. Il en résulta des bassins extensionnels à la surface, une zone de déformation diffuse en profondeur, et un bombement du manteau. La fusion partielle et la perte de gaz carbonique libéré du manteau ainsi soulevé sont à l'origine du magmatisme alcalin et d'une période soutenue de carbonatisation à Kirkland Lake. Une fois la période d'extension terminée, une phase fluide surcomprimée, riche en CO_2, a transporté l'or des niveaux profonds lors d'un soulèvement régional, pour ensuite l'acheminer vers la partie étroite supérieure de la zone cisaillée. La ceinture de Bamble sert d'exemple du niveau inférieur de cette zone d'extension. Elle démontre un tracé P – T – t de l'évolution métamorphique contraire au sens de l'horloge. Pendant l'extension, des magmas mafiques ont introduit le CO_2 dans la zone cisaillée, ce qui pourrait bien expliquer l'oxydation des roches durant le métamorphisme prograde. Au cours d'une longue période de refroidissement isobare, le déplacement de la phase fluide était limité, parce que les inclusions fluides formées sous conditions de métamorphisme maximales sont sous-comprimées. Pendant cette période, un tampon interne des assemblages a mené à l'oxydation de la pyrrhotite en pyrite. Comme la pyrrhotite est l'hôte principal de l'or dans la croûte inférieure mafique, sa transformation en pyrite rendit l'or accessible aux fluides tardifs. Le refroidissement isobare fût suivi par un soulèvement isotherme rapide. Les inclusions fluides, contenant du gaz carbonique, devinrent surcomprimées, et furent détruites. C'est durant cette période de dégazage que l'or aurait probablement été extrait de cette zone cisaillée profonde, dont les échantillons ne rendent plus compte que de 6% de l'or dans la croûte terrestre.

(Traduit par la Rédaction)

Mots-clés: Kirkland Lake, Ontario, ceinture de Bamble, Norvège, or, tectonique d'extension, métamorphisme, magmatisme alcalin, manteau, oxydation, refroidissement isobare, soulèvement.

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INTRODUCTION

Large Precambrian gold deposits are invariably associated with major linear faults or shear zones. The relationship is so apparent that understanding the genesis of these deposits must depend on knowledge of the processes, such as localized metamorphism and magmatism, that occur along these structures. Shear zones serve as an important conduit for material transfer within the lithosphere, for both fluids and melts; younger fault zones of similar regional extent have been shown to cut the lithosphere from mantle to surface. The presence of rocks of mantle origin along these fault zones in close spatial association with some gold deposits suggests that the entire lithosphere may be involved in the genesis of deposits (Libby *et al.* 1990). Yet veins appear to postdate peak metamorphism and magmatism. Possible explanations for this enigma are not readily apparent at the level of exposure of the gold veins. This paper examines some of the deeper processes that may be relevant.

The Kirkland Lake camp, in the southern Abitibi greenstone belt, is used as a model for the "top" of a gold-productive shear-zone. At Kirkland Lake, virtually all of the features that are associated with shear-zone-related gold are well exposed. The selected area for the "bottom" of the shear zone is the Proterozoic Bamble shear belt, Norway. Major transcurrent shear-zones broaden with depth below the brittle – ductile transition to as much as 40 km wide in the lower crust (Bak *et al.* 1975, Hanmer 1988). Such is their volume, allied with strain-induced permeability, that they provide a potential source for gold (Cameron 1989a, b). The Bamble shear belt, 30 km wide, was tectonically active during metamorphism at granulite and upper amphibolite grade, when the presently exposed area was at a depth of about 25 km (Lamb *et al.* 1986). Initial studies of the Bamble rocks (Cameron 1989a, c) showed them to be strongly depleted in gold and in other chalcophile elements enriched in gold deposits.

PART I: TOP OF THE SHEAR ZONE

The 2.7 Ga Abitibi belt has produced more gold than any other Archean greenstone belt. Much of this has come from mines on and near two major east – west linear faults, the Porcupine – Destor and the Larder Lake – Cadillac (LLC) (Fig. 1). Large deposits, with production plus reserves in excess of 50 t Au, are not evenly distributed along these faults, but show a strong clustering near the western ends of the main zones of deformation, at Timmins and at Kirkland Lake.

GEOLOGY OF KIRKLAND LAKE

Much of the geological knowledge of Kirkland Lake derives from the classic reports of Thomson (1950) and Thomson *et al.* (1950), which are the source of much of the description below. The principal feature of the district is the Kirkland Lake – Larder Lake Fault zone (KLF), a branch of the LLC fault (Fig. 2). Mines within the KLF, mainly at Kirkland Lake and Larder Lake, have produced 1110 t Au. The KLF is 50 km long and up to 5 km wide and cuts a basaltic (greenstone) basement. It forms a "basin" containing interbedded sedimentary and alkaline volcanic rocks of the Timiskaming Group, which lie unconformably on the older basaltic rocks. This basin can be subdivided into three segments (Fig. 3). In the west, the Kirkland basin trends ~067°; in the east, the Larder basin has a variable strike, which in the vicinity of the Kerr Addison mine is 060° to 070°. These are linked by the Dobie basin, which trends 106°.

Rocks of the Timiskaming Group, up to 3500 m thick, form a south-dipping homocline. The southern margin is a fault contact against uplifted basaltic basement, whereas the northern margin is, in part, an unconformity of Timiskaming rocks on basement, and elsewhere a fault. Hyde (1980) identified a non-marine

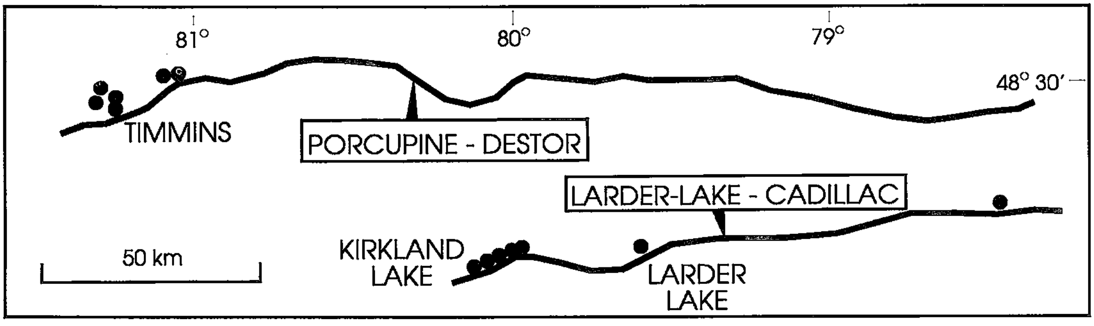


FIG. 1. Location of major gold deposits (production plus reserves greater than 50 t Au) in the region of the Abitibi belt containing the Porcupine – Destor and Larder Lake – Cadillac faults.

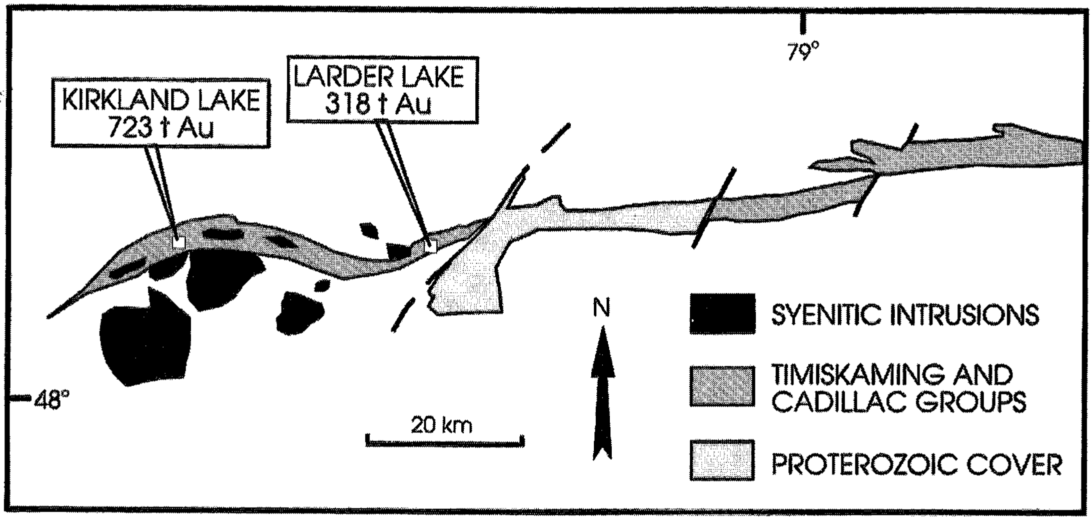


FIG. 2. Geology of the Larder Lake – Cadillac fault.

series of conglomerate and sandstone from a braided river environment, thin to medium-bedded sandstone, siltstone, and argillite, deposited in a flood plain, and thick-bedded sandstone, which may represent eolian dunes. There is also a resedimented series: principally 1800 m of proximal turbidites with conglomerate, probably formed in a submarine fan. There are calc-alkaline to alkaline flows and pyroclastic rocks, the alkaline rocks including alkali olivine basalt, trachybasalt, tristianite, hawaiite and mugearite (Basu *et al.*

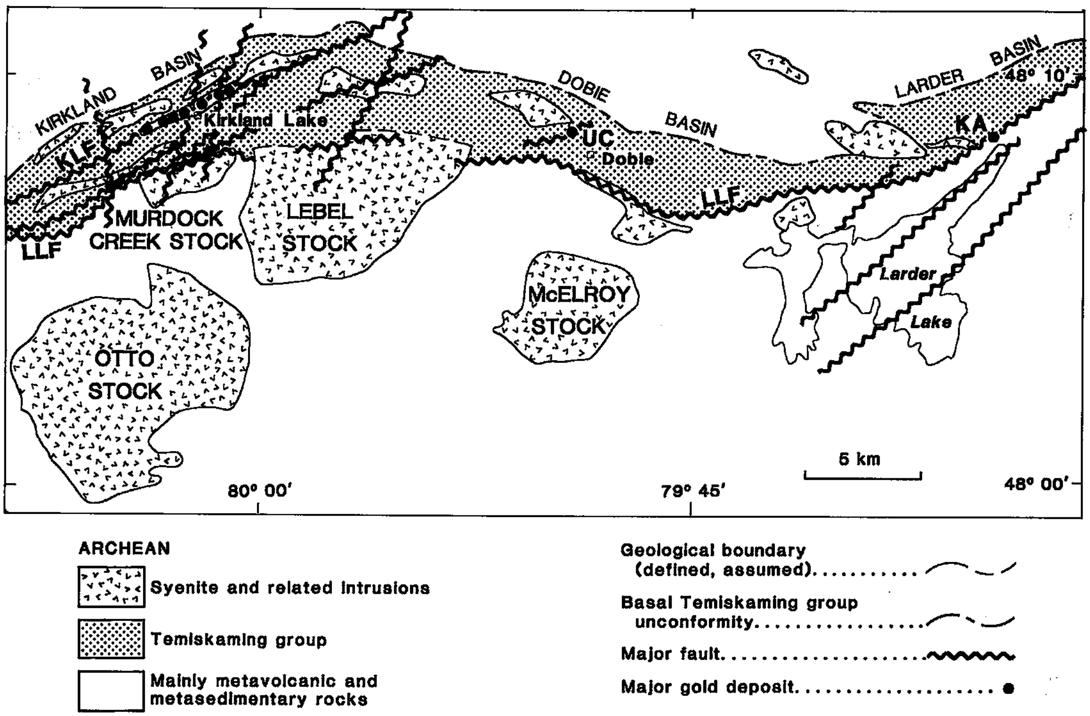


FIG. 3. Geology of Kirkland Lake – Larder Lake fault zone (KLF). LLF: Larder Lake fault; KLF: Kirkland Lake fault; UC: Upper Canada mine; KA: Kerr Addison mine. Modified from Thomson (1950).

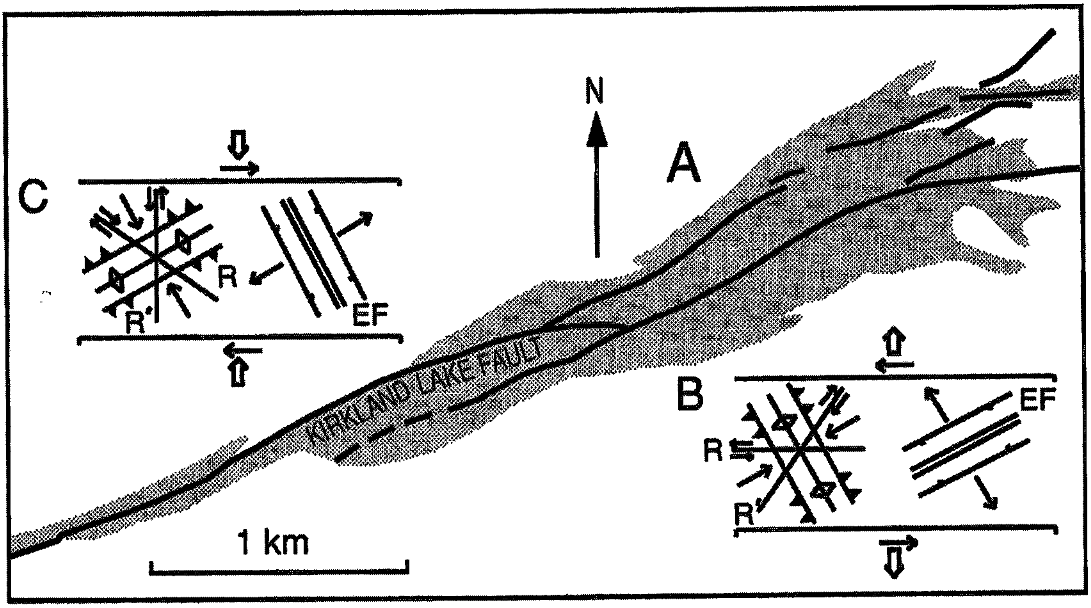


FIG. 4. A. Surface plan of composite syenitic intrusion that hosts most of the gold ore at Kirkland Lake (from Thomson *et al.* 1950). B. and C. Orientation of structures formed by sinistral transtension and by dextral transpression; EF: extensional fracture (from Sanderson & Marchini 1984).

1984).

The district is notable for LILE-enriched syenitic intrusions, which represent one of the earliest major occurrences of alkaline magmatism. These form a cluster of round plutons south of the KLF, but within the KLF they are strongly elongate, parallel to the margins of the basin (Figs. 3, 4). Intrusions are mafic to felsic in composition. For the Murdock Creek stock, Rowins *et al.* (1991) found alkali-feldspar syenite to be the dominant rock-type, with melasyenite, melamonzodiorite, meladiorite, hornblendite, and clinopyroxenite also represented. Lamprophyre dykes cut Timiskaming rocks and the alkaline intrusions.

Greenstones underlying the Timiskaming Group were regionally metamorphosed at prehnite – pumpellyite to greenschist grade (Jolly 1978). Timiskaming rocks show only diagenetic assemblages, with clay minerals and white mica being the only secondary minerals. Clasts within the Timiskaming conglomerates contain a prehnite – pumpellyite assemblage (Jolly 1978), implying that metamorphism of the greenstones preceded deposition of the Timiskaming.

All important gold deposits occur along steeply dipping faults, classified by Thomson (1950) as "strike faults", that parallel the trend of the Kirkland and Larder basins. Seven mines, with a total production of 723 t Au, are spaced along a four-km length of the Kirkland Lake fault (Fig. 3). This fault strikes 067°, dips steeply south, and has a reverse component, with the south side moved upward as much as 460 m. Strike faults created a series of parallel blocks, each of which rose relative to the block to the north, with the major displacements preceding the formation of gold-bearing veins. At Kirkland Lake, deposits are hosted by an elongate, steeply south-dipping intrusion of mafic to felsic syenite cut by the Kirkland Lake fault. The long axis of the intrusion has the same orientation as the strike of this fault (Fig. 4A) and as the axis of the Kirkland basin. Deposits in the other basins lie on steeply dipping faults subparallel to the Kirkland Lake fault. The Kerr Addison deposit (318 t Au) in the Larder basin is located along the Larder Lake fault, which trends 060° – 070°. The only important deposit in the Dobie basin, the Upper Canada mine (43 t Au), is associated with faults trending 073° to 080°. Other sets of fault in the KLF trend north (cross faults), or northeasterly (diagonal faults), the former being mainly post-ore.

There was extensive carbonatization within the KLF, structurally controlled along strike and diagonal faults. All rocks, and particularly the basic units, were altered into siliceous carbonate rock containing iron-rich dolomite, calcite, and green mica. Syenite intrusions are affected, but also, in places, cut carbonatized zones (Thomson 1950). This observation, together with Hewitt's (1963) finding of pebbles of carbonatized rock in upper beds of the Timiskaming, suggest a long period of CO_2 fluxing. In ore-bearing rocks, carbonatization was sequentially followed by pyritization of wallrocks, precipitation of quartz, introduction of

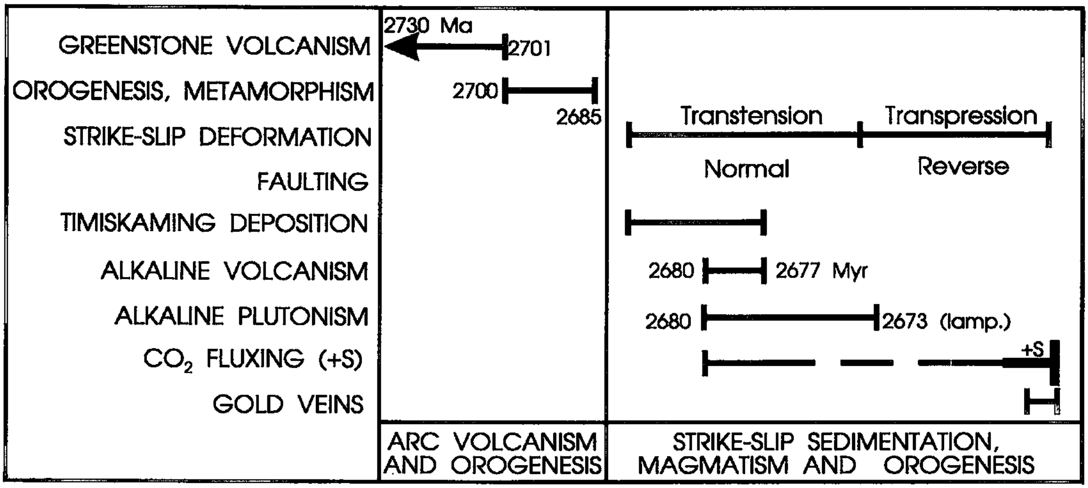


FIG. 5. Sequence of geological events, Kirkland Lake – Larder Lake area. See text for sources of geochronological data.

calcite and, finally, deposition of sulfides, tellurides and gold. Values of $\delta^{13}C$ in carbonates from Kirkland Lake vary from –2.5 to –4.4 ‰ (Kerrich *et al.* 1987), a range consistent with CO_2 of juvenile or mantle origin (Taylor 1986).

Relevant temporal relationships are summarized in Figure 5. These are constrained by high-precision U–Pb dates on zircon and titanite. Corfu & Noble (1992) estimated that volcanism in the Abitibi greenstone belt occurred between 2730 and 2700 Ma ago, and orogenesis, comprising folding, thrusting, deposition of turbidites and calc-alkaline plutonism, at about 2700 to 2685 Ma. The latter period is taken here to be coincident with regional metamorphism. Subsequent to these regional events were localized sedimentation, magmatism and orogenesis along the KLF. Timiskaming sedimentation was coincident with magmatism within the KLF, which spans the interval 2680 – 2677 Ma (Corfu *et al.* 1991), whereas alkaline magmatism outside the KLF, represented by the Otto stock, was of a similar age at 2680 ± 1 Ma (Corfu *et al.* 1989). Corfu *et al.* (1991) emphasized the close temporal relationship between Timiskaming sedimentation and alkaline magmatism, although Timiskaming sedimentation may have started as early as 2685 Ma (Corfu *et al.* 1991). In the discussion below, sedimentation and magmatism within the KLF are related to localized extension (transtension) along the KLF. A lamprophyre dyke that cross-cuts syenite, and that accompanied later folding and thrusting of the Timiskaming rocks (Corfu *et al.* 1989), has been estimated at 2674 ± 2 Ma by U–Pb dating of titanite (Wyman & Kerrich 1989).

Attempts to directly date minerals from gold-bearing veins elsewhere in the Abitibi belt, including muscovite, rutile and scheelite, have given dates that are substantially younger, by 50 Ma or more, than the youngest intrusions (*e.g.*, Bell *et al.* 1989). However, there is no consensus on whether these dates represent the time of introduction of gold. At Val d'Or, at the eastern end of the LLC fault, Wong *et al.* (1991) used Pb–U dating of rutile to estimate an age of 2599 ± 7 Ma for alteration around gold-bearing veins, whereas regional greenschist metamorphism occurred at 2684 ± 7 Ma. But Claoué-Long *et al.* (1990) estimated gold-bearing veins from the same area at 2680 Ma, based on hydrothermal zircon. In the Yilgarn Block, Australia, Clark *et al.* (1988) estimated from U–Pb in rutile that veins in the Victory mine were formed 30 Ma later than the peak of metamorphism and the youngest felsic plutons. No precise date is available for the formation of gold-bearing veins at Kirkland Lake. However, two different types of evidence suggest that a substantial interval of time elapsed between emplacement of the host syenite and the veins. The first is described in the succeeding sections, where the syenite is shown to have been intruded during a phase of crustal extension and basin formation, whereas the veins were emplaced during a later phase of compression and uplift. Second, Hattori (1993) found altaite intimately associated with gold in the Kirkland Lake veins to have a radiogenic Pb isotopic composition. The data are consistent with formation of the veins after the U-rich host syenite had generated significant radiogenic Pb, which was extracted by the hydrothermal fluids.

Relation of Localized Sedimentation and Magmatism to Strike-Slip Faulting

Strike-slip movements, where the velocity is sufficiently high and long-lived, may cause uplift or subsidence along faults. These effects occur where the faults cross the horizontal trace of plate movement, or at oversteps, or at fault terminations. Narrow orogenic belts may be produced by a phase of transtension, leading to basin formation and sedimentation, followed by transpression causing basins to be uplifted and folded (Reading 1980). Extensional (strike-slip or pull-apart) basins along major strike-slip faults are small but deep. Subsidence is rapid. The dynamic environment is reflected in the sediment fill, with rapid change in facies as a principal characteristic. Basins above sea level are typically bordered by alluvial fans that pass rapidly through fluvial deposits into lacustrine sediments. Marine basins are filled by subaqueous mass-gravity transport of coarse clastic material, deposited, in part, on submarine fans. During subsidence, normal faulting dominates, whereas during transpression, reverse and thrust faults are developed. In strike-slip orogenic belts, magmatic activity is almost entirely confined to the transtensional phase, and metamorphism of the basinal sediments is feeble.

Volcanic rocks are found in a minority of strike-slip basins. Where present, they are commonly of alkaline composition, such as in the Erzincan basin along the North Anatolian fault in Turkey (Hempton & Dunne 1984) and the submarine Pantelleria Trough, between Sicily and North Africa (Ben-Avraham *et al.* 1987). The sparing occurrence of volcanic rocks in strike-slip basins, their restriction to the transtensive phase, and their tendency to alkaline compositions, are consistent with the model of McKenzie & Bickle (1988) for generation of basaltic magma by extension of the lithosphere. Extension causes upwelling of mantle; solidus boundaries may be crossed, causing partial melting. Where there is major extension, as at plate margins, upwelling is greatest, and large volumes of tholeiitic basalt are generated by extensive melting at shallow levels. Where extension is less, upwelling is more modest, and partial melting, if it occurs, leads to a small fraction of melt, of alkaline composition, at greater depth. The degree of extension (β), defined as the ratio of final to initial surface-area, required to generate melt depends on several conditions, including the potential temperature (T_p) of the mantle. For a T_p of 1480°C, melting, to produce alkali basalt, occurs only where β reaches 1.5 to 2.0. Strike-slip movements usually cause only moderate extension. For basins along the boundary between the North America and Pacific plates, with a high transform-velocity of 4 – 6 cm/yr, J.A. Andrews & M.S. Steckler (in Pitman & Andrews 1985) found β to range up to about 1.6. This is near the lower bound required for melting. Thus most strike-slip basins will form in crust where extension is less than that required for partial melting; these basins will not contain volcanic rocks.

The southern part of the Archean Superior Province is composed of east-trending, elongate belts (subprovinces) of metavolcanic and granitic rocks (greenstone belts) that alternate with metasedimentary belts. Major, linear faults or "breaks", such as the LLC, which also approximate an easterly trend, cross subprovinces or form their boundaries. In part, these features are now related to terrane accretion, thrusting and strike-slip movement during oblique convergence (*e.g.*, Percival & Williams 1989). In the Yilgarn Block, Australia, gold deposits are associated with faults that extend for hundreds of kilometers, some of which may be terrane boundaries, and which were the locus for intrusions of lamprophyre and felsic porphyry (Libby *et al.* 1990).

The Timiskaming Group at Kirkland Lake is interpreted to have been deposited within deep, narrow basins formed during strike-slip extension. Its features show close correspondence with those of younger strike-slip mobile belts (Table 1). Alkaline magmatism is most reasonably interpreted to be the product of partial melting during the mantle upwelling that accompanied thinning of the lithosphere. The Timiskaming is cut by elongate intrusions, such as the syenitic intrusion hosting the ore at Kirkland Lake (Fig. 4A); elongation is parallel to the basin axes. The plutons are interpreted to have been passively emplaced into extensional fractures after the Timiskaming had been tilted to the south, but while the fault zone was still undergoing extension. The approximately 067° orientation for the Kirkland and Larder basins and for the plutons passively intruded into extensional fractures suggested to Cameron (1990) that these events were a consequence of sinistral transtension along the east – west-trending LLC fault (Fig. 4B). Many of the structural features that might have been associated with sinistral transtension have been obscured by later deformation. However, based on the geometry of internal magmatic foliation, distribution of igneous phases, and pluton shape, Cruden (1992) has shown that the Murdock Creek syenitic stock (Fig. 3) was emplaced into a dilational zone during sinistral deformation. In contrast, the round, alkaline intrusions south of the KLF were forcefully emplaced. An analogous contrast between elongate and round alkaline and calc-alkaline granites occurs along the Ajjaj shear zone, Saudi Arabia (Davies 1982).

Extension may be interpreted to have occurred in the south quadrant at the west termination of a fault undergoing sinistral displacement (Cameron 1990). Extension in this quadrant accounts for the major concentration of alkaline plutons south of the fault zone. If the proposal of Leclair *et al.* (1993) is correct, that the LLC fault continues west of Kirkland Lake, but changes strike to west–southwest, then the Kirkland and Larder basins are releasing bends along the LLC, where this fault crossed the direction of plate motion. The two explanations are not necessarily incompatible; a major part of strike-slip displacement along the eastern part of the LLC fault could have been taken up by extension around Kirkland Lake, with a lesser

TABLE 1. COMPARISON OF CHARACTERISTICS OF STRIKE-SLIP MOBILE BELTS[a] WITH TIMISKAMING GROUP, KIRKLAND LAKE - LARDER LAKE FAULT ZONE.

	CHARACTERISTICS OF STRIKE-SLIP MOBILE BELTS	TIMISKAMING GROUP, KIRKLAND LAKE - LARDER LAKE FAULT ZONE
Terrestrial sedimentation:	Alluvial fans, fluvial and lacustrine deposits; often thick conglomerates.	Braided river, floodplain, and eolian deposits; conglomerate units to 1300 m.
Marine Sedimentation:	Mass-gravity transport of coarse clastics to submarine fans, basin plains, slope aprons.	Thick proximal turbidite, conglomerates; probably deposited in a submarine fan.
Facies Change:	Extreme lateral facies change.	Rapid local facies change; e.g., alluvial fan/fluvial sediments to turbidites, all in less than 25 km.
Stratigraphic Thickness:	Great, relative to basin size.	3.5 km thickness in basin of 5 km width.
Metamorphism:	Little or none.	Less than sub-greenschist.
Volcanism:	Mostly absent; where present, often alkaline.	Alkaline flows and pyroclastic deposits.
Faulting During Transtension:	Normal faults and extensional fractures.	Normal faults?; alkaline intrusions in extensional fractures.
Faulting During Transpression:	Reverse, thrust.	Reverse faults. Thrusts?

(a) Mainly after Reading (1980)

amount expressed as displacement along a fault to the west of Kirkland Lake.

Strike faults within the KLF, such as the Kirkland Lake fault, are reverse faults. With an orientation that is the same as the basin and the principal axis of the elongate syenite intrusions, these are interpreted to have resulted from reactivation during compression of normal faults that formed during the earlier extensional phase.

Thus there is evidence for two distinct phases of deformation: first extension, as indicated by basin formation, sedimentation, and injection of alkaline magma, and then compression, with reactivation of earlier normal faults as reverse faults and the introduction of gold-bearing fluids along these faults. Shortening of the area also is reflected in differences in petrography for the alkaline and calc-alkaline igneous rocks near Kirkland Lake. Lévesque *et al.* (1991) have shown that the round intrusions south of the KLF crystallized at depth: they are plutonic. By contrast, intrusions within the KLF, and scarce intrusions north of the fault zone, are hypabyssal and occur in association with similar rocks of extrusive origin. This implies relative uplift of the southern block subsequent to the extension-related magmatic activity, compatible with the hypothesis of reverse faulting noted above.

The orientation of the reverse faults that guided the ore fluids is consistent with reactivation under dextral transpression (Fig. 4C), although this need not be a unique solution. Previous studies along the ~200 km length of the LLC fault provide evidence for both sinistral and dextral movement. At Rouyn-Noranda, east of Kirkland Lake, Hubert *et al.* (1984) identified two important deformations. They related the first, represented by west–northwest folds, to sinistral movement along the Porcupine – Destor and LLC faults. This was followed by folding along east–west axes caused by compression normal to these faults. Along the eastern portion of the LLC fault, Robert (1989) found evidence for dextral transpression, coincident with the formation of important gold-bearing veins.

Colvine *et al.* (1988) suggested that Timiskaming sediments at Timmins may have been deposited in a pull-apart basin. Extensive carbonatization in this camp suggests extension-related uplift of mantle, with degassing. But the absence of significant volumes of alkaline rock at Timmins may indicate a lower degree of lithospheric extension or a stalling of melts at the base of the crust. Mueller *et al.* (1991) considered that sediments deposited within the Duparquet basin, Quebec, may have formed at a releasing bend during dextral strike-slip along the Porcupine – Destor fault. Toogood & Hodgson (1985) suggested that the Dobie basin (Fig. 3) formed as a pull-apart during dextral transpression while sedimentation and volcanism were taking place within other parts of the KLF. Their scenario of 1) dextral transpression, accompanied by sedimentation and volcanism and 2) a compressive phase, with beds becoming vertical before syenitic magma was intruded, differs from the interpretation given here.

A younger example that replicates several features of the KLF is the 500-km long, 20-km wide North Pyrenean transform zone (Vielzeuf & Kornprobst 1984, Golberg & Leyreloup 1990). Along this fault zone, there was an initial phase of extensional transcurrent deformation during Upper Cretaceous time. Pull-apart basins developed, with alkaline magmatism and metamorphism localized within the fault zone. This was followed by a phase of compression. Uplift of mantle along the fault zone is most insistently shown by the emplacement of lherzolites, which Vielzeuf & Kornprobst (1984) attributed to the combined effects of extension and compression. Extension caused mantle to rise; during compression, slices of mantle were thrust upward.

Part II: The Mantle Below Kirkland Lake

In this account, two principal features of the Kirkland Lake camp derive from the mantle: alkaline

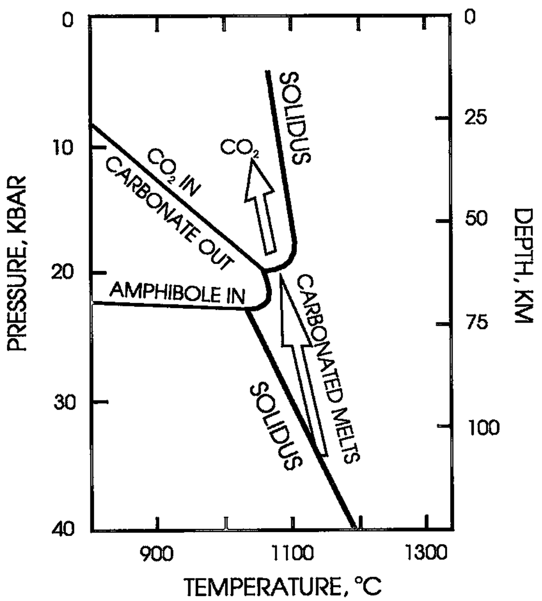


FIG. 6. Solidus curve for CO_2 – H_2O-bearing or carbonated peridotite. After Meen (1987).

magmas and CO_2 fluxing. Both can be related to upwelling of the mantle that resulted from localized lithospheric extension and thinning along the LLC fault. For volatile-bearing (CO_2 and H_2O) or carbonated peridotite, carbonate is stable on the solidus at pressures greater than 17 kbar. Partial melts of carbonated peridotite, released at depth during moderate extension, will rise to intersect a solidus ledge near 17 kbar (Fig. 6). There, following Meen (1987) and others, melts will react to produce carbonate-free peridotite or pyroxenite and CO_2-rich fluid. Repeated impingement of melts at the solidus ledge enriches peridotite in incompatible elements, creating a metasomatized zone, which can melt to an alkaline basalt magma rich in these elements. These melts may carry CO_2 to the crust.

The alkaline magmas were strongly enriched in large-ion lithophile elements (LILE) (Fig. 7) and depleted in Nd. Ben Othman *et al.* (1990) estimated a ϵ_{Nd} of 2.5 for the Timiskaming volcanic suite. Hattori & Hart (1990), who analyzed samples of clinopyroxene that are unaffected by hydrothermal fluids, found no difference in Sr and Nd isotope ratios for syenite and lamprophyre, indicating a common source for these rock types. The $(^{87}Sr/^{86}Sr)_i$ values are low, 0.7009 to 0.7016, and ϵ_{Nd} is high, 0.8 to 3.0. Positive ϵ_{Nd} values indicate previous depletion by the extraction of melts. Enrichment of the previously depleted mantle in LILE occurred too close in time to the extraction of the alkaline melts to allow for generation of radiogenic isotope components. There are two possibilities to explain the relative lack of radiogenic isotopes. The first, outlined in the previous paragraph, is that localized lithospheric extension along a major fault caused mantle upwelling. This triggered LILE- and volatile-rich melts to rise within the mantle and create a metasomatized zone, which then became the source of the alkaline melts. The source of the LILE- and volatile-rich melts may have been undepleted mantle, with possible addition of material from a slab. In this model, metasomatism and partial melting are parts of a single process that extended over only a few Ma. The second model, favored by Hattori & Hart (1990), is that LILE enrichment took place by material directly introduced from a subducting slab. This requires a cycle from generation of the slab rocks, through subduction, metasomatism and partial melting that is rapid, *i.e.*, less than 20 Ma.

A feature that attracted Hattori & Hart to a fast recycling model is that the LILE-enriched alkaline magmas were not similarly enriched in high-field-strength elements (HFSE), a feature that is widely taken to be characteristic of arc volcanism related to subducted slabs. Spidergram plots (Fig. 7) of rock units comprising the Murdock Creek stock (Fig. 3) show troughs for the HFSE, particularly Nb. The reasons why this may be related to processes other than subduction have been addressed by Rowins *et al.*

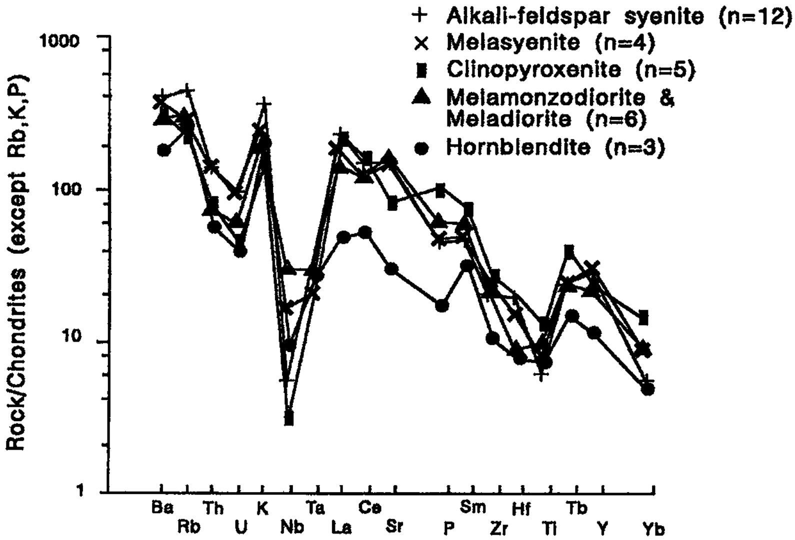


FIG. 7. Chondrite-normalized incompatible element patterns (spidergram) for rock units of the Murdock Creek pluton (from Rowins *et al.* 1993). Rb, K, and P are normalized to terrestrial abundances; "n" is number of samples averaged.

(1993). HFSE troughs are found in continental ultrapotassic rocks distant from subduction zones. Samples from the Murdock Creek stock are classified within group-II ultrapotassic mafic rocks of Foley *et al.* (1987), which are characteristic of continental rift zones, such as the East African rift. Depletion in HFSE (Ti-group) requires a Ti-rich residual phase; Rowins *et al.* (1993) favored titanite, in part because of the intrinsically oxidized nature of the Murdock Creek magmas.

Oxidation provides a link between the mantle source-region of the alkaline magmas and the gold-bearing veins. Cameron & Hattori (1987) noted several characteristics of the veins at Kirkland Lake that indicate their deposition from oxidized fluids, which contrasted with the otherwise reduced nature of the Archean crust. This included the presence of sulfate minerals, hematite in altered wallrocks, and strong ^{34}S depletion of pyrite intimately associated with the gold, indicative of isotopic fractionation between sulfide and sulfate. Rowins *et al.* (1991) found that the Murdock Creek stock formed from an inherently oxidized magma, that was derived from oxidized mantle. This is shown by clinopyroxene and biotite, which retain a consistently low Fe/(Fe + Mg) and high $Fe^{3+}/(Fe^{2+} + Fe^{3+})$ ratios throughout the pluton's evolution, and by abundant, early-formed magnetite and titanite. The link between oxidized ore-forming fluids and oxidized magma caused Cameron & Hattori (1987) to suggest that the fluids were derived from the magma. Data showing that introduction of gold substantially postdated magmatism indicate that this interpretation is incorrect; any link was indirect. The late arrival of gold also makes it difficult to invoke a scenario for the extraction of gold from the mantle, or its magmatic products, since the principal processes affecting the mantle, *i.e.*, metasomatism, melt extraction, and devolatilization, were concurrent with magmatism. Rowins *et al.* (1993) reported an average of 2 ppb Au for 13 rock samples from the Murdock Creek stock that are unaffected by alteration. Wyman & Kerrich (1989) reported an average of 3.9 ppb Au for fresh shoshonitic lamprophyres from the Canadian Shield that are associated with structures that host gold. Both sets of data indicate neither enrichment nor depletion of gold in magmatic products of the late Archean mantle below major gold deposits.

McInnes *et al.* (in prep.) and McInnes & Cameron (1994) reported on mantle xenocrysts and xenoliths in basanites and alkali olivine basalts from the Tabar – Lihir – Tanga – Feni (TLTF) ensimatic island arc off Papua New Guinea. The arc contains one of the world's major gold deposits in the Luise caldera on Lihir island. The nodules contain alkali-rich aluminosilicate glass, which represent a melt that reacted with the host xenocrysts and xenoliths. The glass contains daughter minerals: anhydrite, calcite, sodalite and fluorapatite. Analyses indicate that the melt contained substantial dissolved H_2O, CO_3^{2+}, SO_4^{2-}, and had a high $f(O_2)$. Such a melt will tend to dissolve sulfides and the gold that is contained within the sulfides when reacting with mantle material. If gold was extracted during mantle metasomatism and partial melting, then carried in a volatile phase to the surface, its deposition in the upper crust would be early and coincident with volcanism, as it is on Lihir. The late arrival of gold at Kirkland Lake and many other major Archean deposits presents a puzzle, as does the relatively high state of oxidation of mantle-generated magma and ore fluids at Kirkland Lake. A possible explanation lies in the understanding of processes operating within the deep shear-zone that lies between the mantle and the deposits, as considered in Part III.

Part III: A Deep Shear-Zone, the Bamble Shear Belt

The deep portion of the shear zone below Kirkland Lake is inaccessible. In searching for an analogue exposed elsewhere, there are two important features to seek. The first is evidence for the passage of CO_2. At Kirkland Lake, there was a long period of CO_2 fluxing. Given its apparent origin in the mantle, the CO_2 must have passed through the deep portion of the shear zone. The second feature is evidence for oxidative metamorphism. If gold at Kirkland Lake was derived from the deep shear-zone, the oxidized nature of the ore fluids may denote a similarly oxidized source.

Geology of the Bamble Shear Belt

The 30-km-wide Bamble shear belt of southern Norway (Fig. 8) formed as a result of transcurrent motion between two major crustal blocks (Falkum & Petersen 1980). Metamorphism at upper amphibolite and granulite grades was concurrent with ductile deformation; strong deformation is reflected in tight folding with steeply dipping foliation (Falkum & Petersen 1980). Touret (1971) found abundant CO_2-rich fluid inclusions in the granulite-facies rocks. Lamb *et al.* (1986) estimated granulite metamorphism

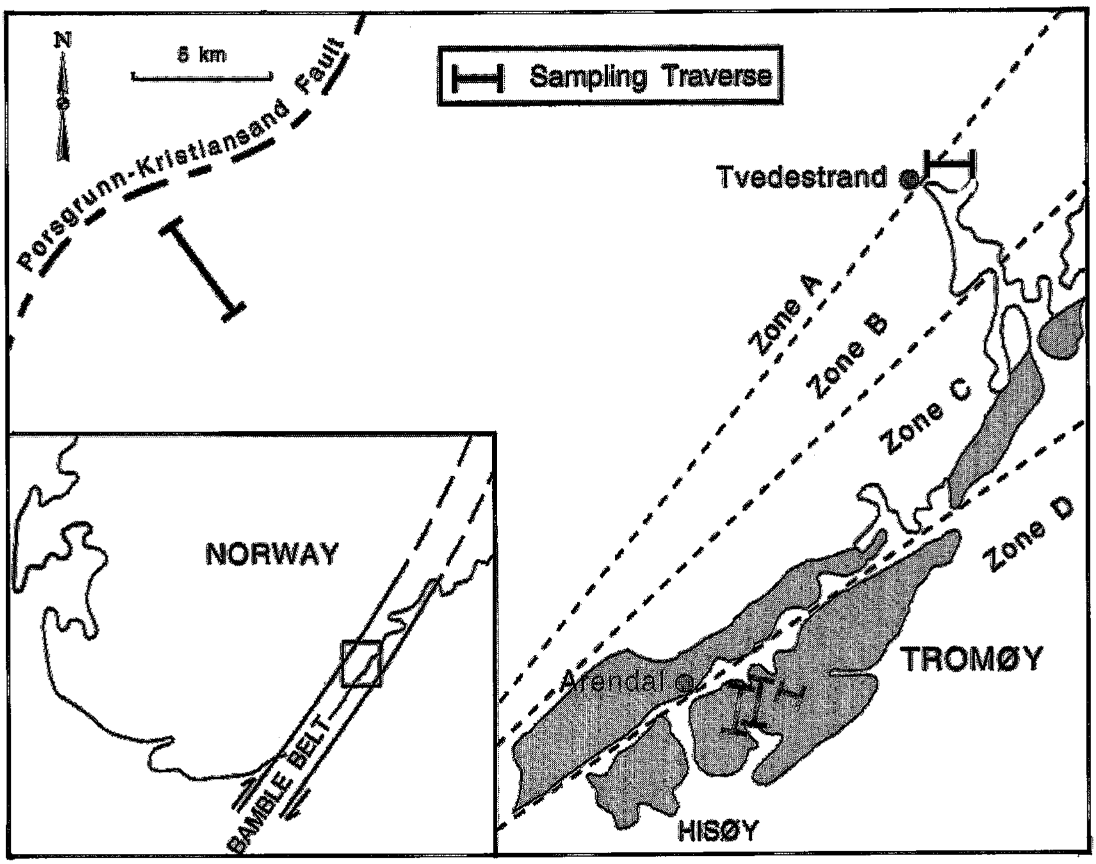


FIG. 8. Bamble shear belt. Metamorphic zones, after Field *et al.* (1980): A is upper amphibolite, B is a transitional facies with orthopyroxene in a minority of metabasite intrusions, C is granulite, D is granulite with less hornblende and biotite than zone C, and orthogneiss depleted in LILE. Shaded area contains enderbitic and charnockitic rocks.

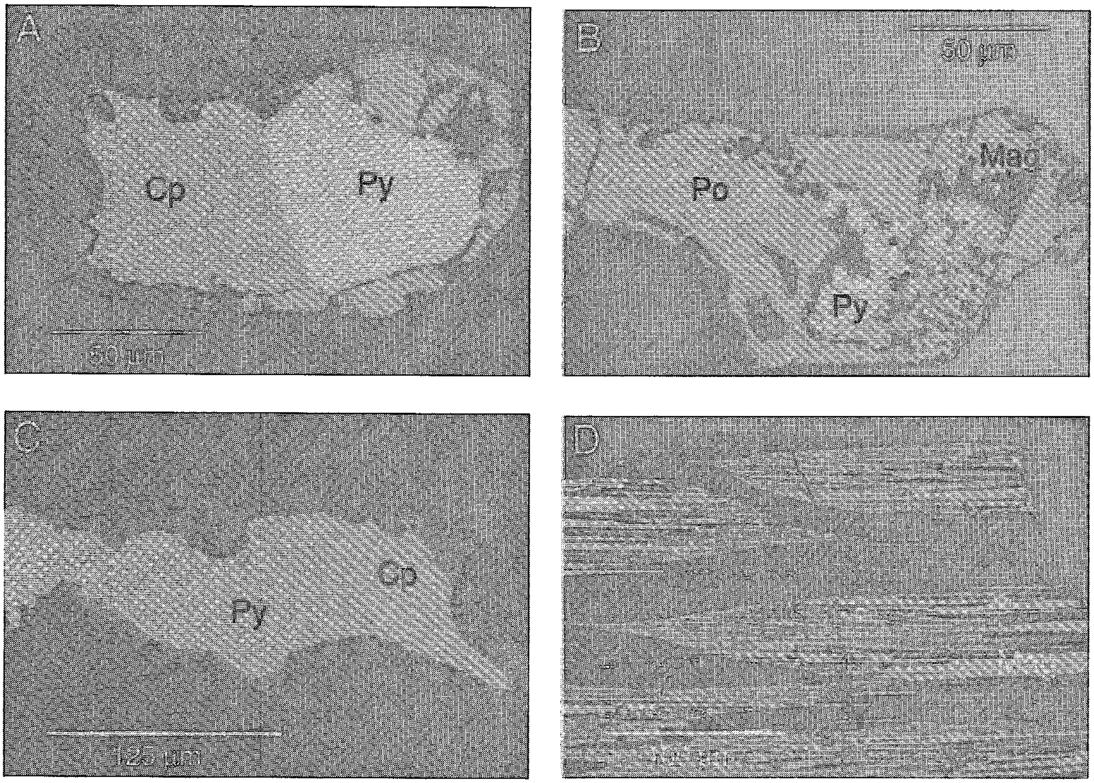


FIG. 9. Photomicrographs of: (A) composite grain of pyrite and chalcopyrite, both with rim of magnetite, upper-amphibolite-grade metabasite, Tvedestrand, Norway. (B) Grain of pyrrhotite partially oxidized at right to a mixture of pyrite and magnetite, coronitic gabbro interior of hyperite dyke, Tvedestrand. (C) Composite grain of pyrite and chalcopyrite, both with rim of magnetite, retrograded granulite, Canisp shear zone, Scotland. (D) Back-scattered electron image of ilmenite grain from upper-amphibolite-grade metabasite, Tvedestrand, Norway. Broad lamellae of ilmenite (dark grey) and hematite (light grey), with fine secondary lamellae of these minerals. Thin white lamellae of magnetite lie mainly within broad lamellae of hematite.

to have occurred at 800 ± 60 °C and 7.3 ± 0.5 kbar. These conditions differ little from T and P estimates obtained from fluid inclusions in upper-amphibolite-facies rocks (Touret & Dietvorst 1983), which suggests that the change from upper amphibolite to granulite occurred at constant T and P, the result of fluid composition changing from H_2O-rich to CO_2-rich (Touret 1971). The presence of Mg-rich pyroxene and hematite-rich ilmenite indicates prograde metamorphism at high $f(O_2)$ (Cameron 1989c, Harlov 1992).

The earliest rocks in the Bamble belt are sediments, overlain by a mixed volcanic – sedimentary sequence. Mafic dykes and sheets (metabasites) of tholeiitic composition are abundant. Tonalitic – trondhjemitic magma (tonalite gneiss) was intruded in the coastal belt of highest grade around the island of Tromøy. Metamorphism of all these rocks spanned the interval 1152–1095 Ma (Kullerud & Dahlgren 1991). Anatectic granitic rocks are present in the upper amphibolite zone. Granulites on Tromøy are depleted in LILE (Field & Clough 1976, Cooper & Field 1977, Clough & Field 1980). Mafic dykes and sheets (hyperites) were intruded in several stages subsequent to the main metamorphic event; they were modified to coronitic gabbros and then locally amphibolitized. Subsequently, medium-grained granite was intruded, and there was localized retrogression of granulites at greenschist grade at about 1060 Ma (Field *et al.* 1985). During retrogression, Au, As, Sb, Cu, sulfide and LILE were re-introduced into the previously depleted granulites (Cameron 1993).

GOLD IN THE BAMBLE SHEAR BELT

Sampling of rocks of varying lithology from across the width of the shear belt showed them to be substantially depleted in gold relative to its crustal abundance, both in the granulite and upper amphibolite facies (Cameron 1989a, c). For example, metabasite intru-

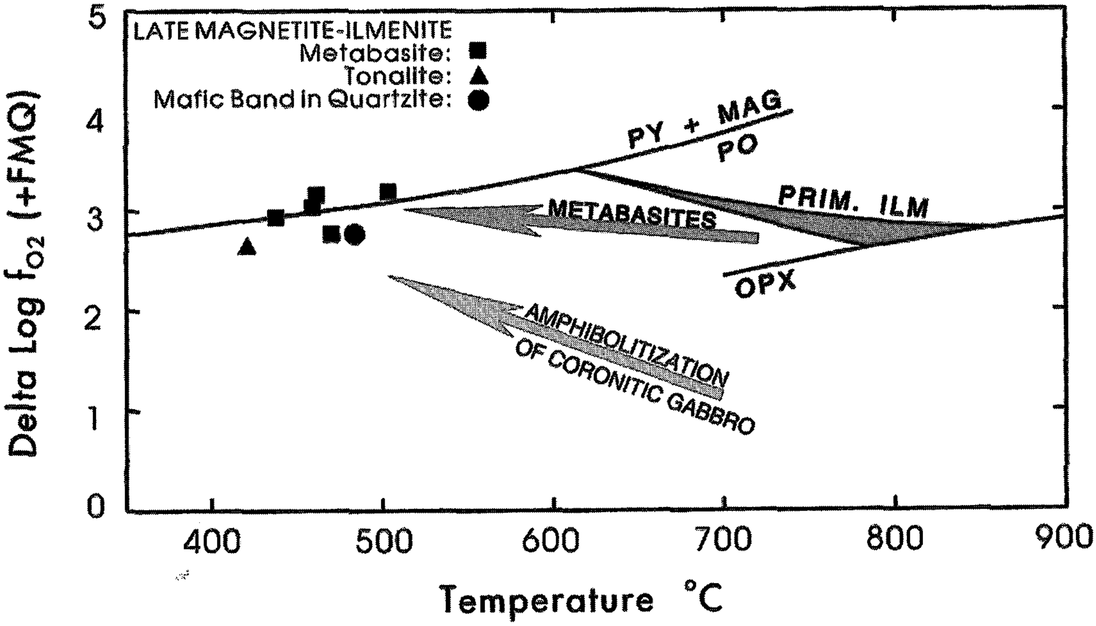


FIG. 10. Upper arrow is estimate of path of metamorphic cooling for Bamble metabasites in $f(O_2)$ – T space. Conditions at the peak of metamorphism are derived from the intersection of an isopleth band for primary ilmenite with an isopleth for orthopyroxene. Ilmenite isopleths were derived from the data for four metabasite samples (two granulite facies, two upper amphibolite facies) computed by a program of M.S. Ghiorso (see Ghiorso & Sack 1991). The orthopyroxene data, representing the mean of six samples, were applied to the empirical formulation of Fonarev & Grafchikov (1984). The cooling path is located along the pyrrhotite – pyrite – magnetite (PPM) buffer by point estimates for samples of metabasite (two from granulite facies, two from upper amphibolite), a tonalite (granulite) and a mafic band in metaquartzite (granulite). The point estimates were obtained from the composition of lamellae of magnetite and ilmenite in ilmenite grains. [Note that using program QUILF (Andersen *et al.* 1993), the estimated temperature at which the metabasite samples intersected the PPM buffer is significantly higher, averaging 560°C]. The lower arrow is an estimate of the path taken during amphibolitization of coronitic gabbro, obtained from a hyperite dyke near Tvedestrand (see Cameron *et al.* 1993 for details). The PPM buffer is from Kishima (1989), the FMQ buffer, from Myers & Eugster (1983).

sions contain only 0.04 of the usual abundance of gold in mafic rocks, *i.e.*, a mean of 0.17 ppb Au *versus* 4.1 ppb (Cameron 1989c). Other chalcophile elements commonly associated with gold in veins, such as Sb and As, also are depleted. Granulite samples from Tromøy are depleted in Cu, S and Rb, but these are present at near-normal levels in samples from the upper amphibolite zone.

During crystallization of mafic rocks, gold mainly enters the sulfide phase; the partition factor, sulfide melt/silicate melt, has been estimated to be in the range 1,000 (Stone *et al.* 1990) to 10,000 (Barnes 1993). Release of gold during metamorphism of mafic rocks requires modification of this phase. Pyrrhotite is the principal sulfide mineral in unmetamorphosed mafic rocks. In the Bamble metabasites, both from the granulite and upper amphibolite zones, pyrite is the dominant sulfide mineral, accompanied by chalcopyrite; grains of both minerals have invariably been replaced around their margins (mantled) by magnetite (Fig. 9A). Pyrrhotite is virtually absent in these rocks, but must have been present during peak metamorphism at ~800 °C, given that pyrite is not stable above about 740°C (Kullerud & Yoder 1959). As will be discussed below, transformation of pyrrhotite to pyrite provided an opportunity for the release of gold.

High-grade metamorphism in the Bamble shear belt resulted in an unusually oxidized assemblage of minerals, with hematite-rich ilmenite and Mg-rich ferromagnesian silicates. A typical grain of ilmenite from metabasite is shown in Figure 9D. At peak metamorphism, this was a homogeneous grain of hematite-rich ilmenite. During cooling, the ilmenite – hematite solvus was intersected, causing phase separation into broad lamellae of ilmenite and hematite. Further cooling resulted in the exsolution of successive generations of fine lamellae of ilmenite in hematite and of hematite in ilmenite. Finally, there was reduction of some hematite to magnetite, with magnetite lamellae occurring preferentially within broad lamellae of hematite (Fig. 9D). Other granulites that contain hematite-rich ilmenite include those of Proterozoic age from Lofoten – Vestralen, Norway (Schlinger 1985), a lower crustal shear-zone of Archean age from Labwor Hills, Uganda (Nixon *et al.* 1973, Sandiford *et al.* 1987), and granulites retrograded to amphibolite uplifted along the Red Sea Rift (Seyler & Bonatti 1988)

It is possible to reconstruct the path taken in $f(O_2)$ – T space during cooling from the peak of metamorphism (Cameron *et al.* 1993). The composition of primary ilmenite was obtained by re-integrating the exsolved ilmenite, hematite and magnetite components using image analysis to estimate their proportions and results of electron-microprobe analyses of the three phases. In Figure 10, an isopleth band representing the reconstructed compositions of primary ilmenite in metabasite samples is shown intersecting an isopleth for orthopyroxene [note that this figure and others show $\Delta f(O_2)$ values, which is $f(O_2)$ relative to the FMQ buffer]. The ilmenite isopleth band is derived from two samples of metabasite from the granulite facies and two from the upper amphibolite facies. Five orthopyroxene compositions are from the granulite facies, the other from the upper amphibolite facies, but the results from both facies are similar. The intersection of the isopleths defines the $f(O_2)$ – T where oxides and ferromagnesian silicates equilibrated during peak metamorphism. This intersection brackets 800°C, in agreement with the independent estimates cited above for the temperature of peak metamorphism.

During cooling from peak metamorphism, the ilmenite – hematite solvus was intersected at approximately 740°C (Cameron *et al.* 1993). In grains of ilmenite, this resulted in the exsolution of broad lamellae of ilmenite and hematite, as described above. During continued cooling down the solvus, further generations of these minerals were exsolved as fine lamellae. The formation of magnetite lamellae in ilmenite grains by reduction of hematite occurred later. Compositions of these magnetite lamellae and adjoining ilmenite provide estimates of the $f(O_2)$ and T at which the phases reached equilibrium. These values cluster along the pyrrhotite – pyrite – magnetite (PPM) buffer (Fig. 10). Thus the cooling path was subparallel to the FMQ buffer and intersected the PPM buffer at a temperature below 600°C. Magnetite – ilmenite pairs in ilmenite grains from a sample of tonalite gneiss and

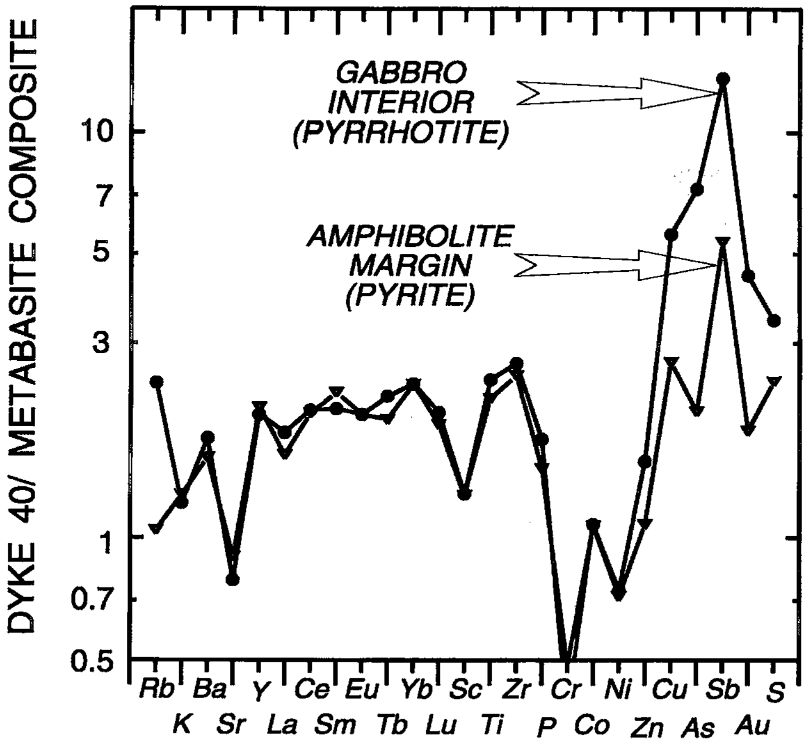
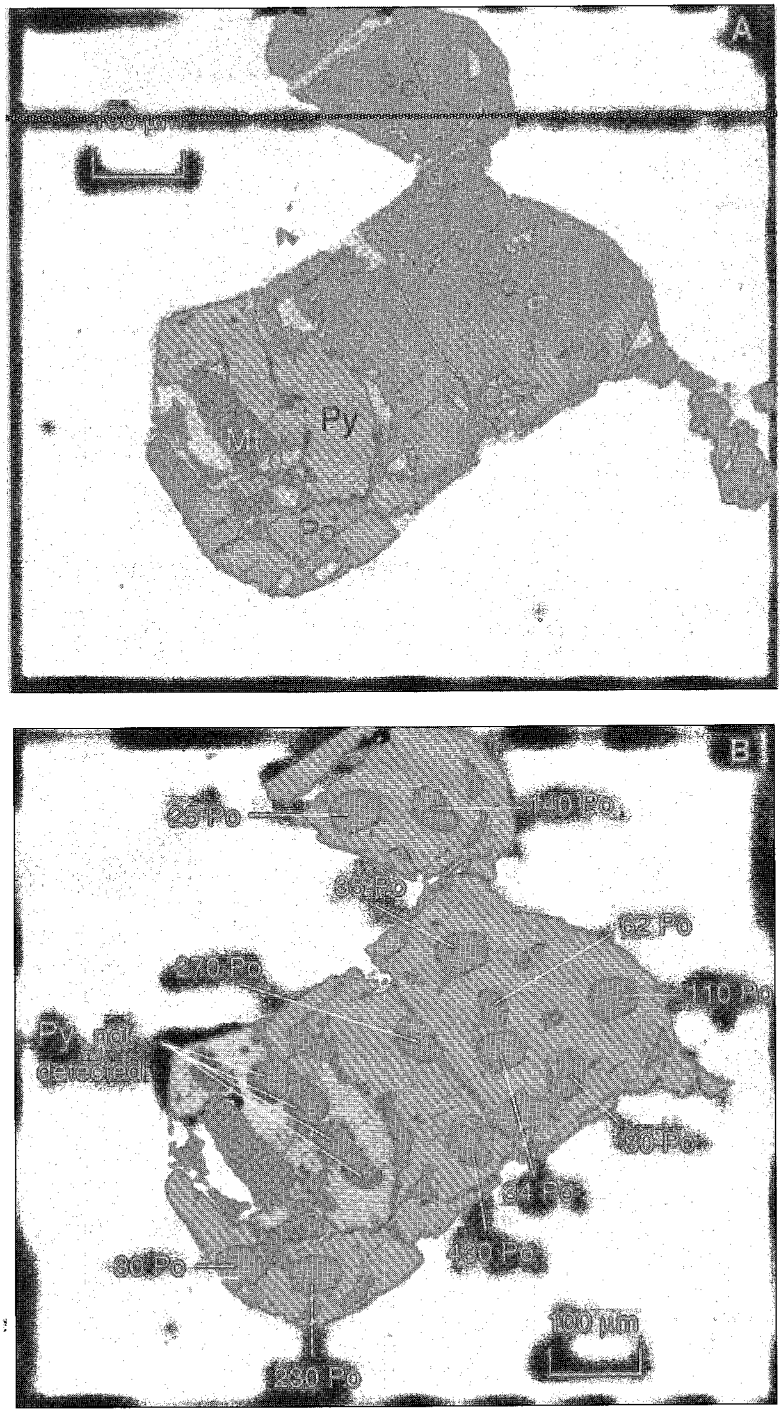


FIG. 11. Spidergram plot for elements in the amphibolite marginal zone (pyrite-dominant) and in the coronitic gabbro inte zone (pyrrhotite-dominant) of hyperite dyke 40 from near Tvedestrand. Data represent the mean of two samples for zone, normalized to the mean composition of sixteen metabasite samples from Tromøy. The metabasites represent sar that are strongly depleted in chalcophile elements and LILE from the high-grade metamorphic event.



from a thin mafic band in quartzite, both from the granulite facies, also plot close to the PPM buffer (Fig. 10). Clustering of these points around the PPM buffer can be accounted for if the conversion of pyrrhotite to pyrite was a closed-system oxidation reaction, where the complementary reduction of hematite to magnetite

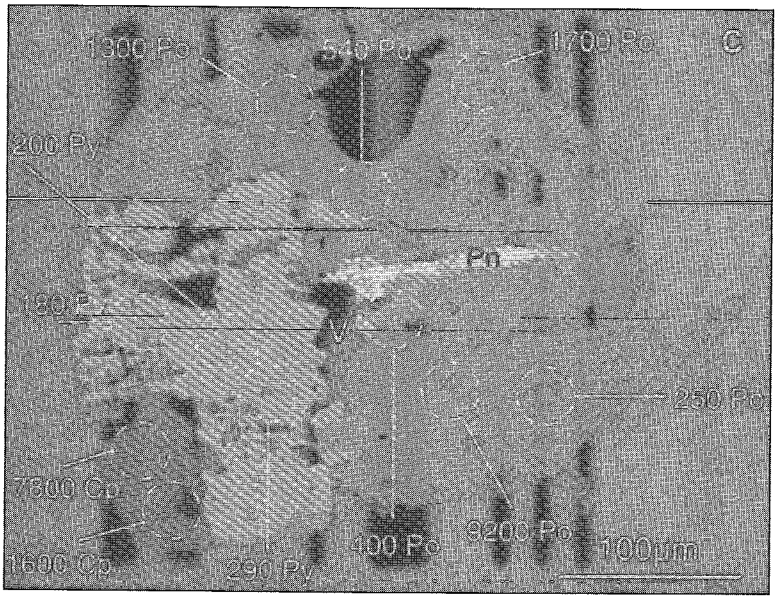


FIG. 12. A. Grain of pyrrhotite (Po) partially transformed to pyrite (Py) and magnetite (Mt). From sample 4008, coronitic gabbro interior of hyperite dyke 40, Bamble shear belt. B. Same grain as in A after spot analyses by ion microprobe; results of analyses are shown in ppb gold. C. Grain of pyrrhotite (Po) containing inclusions of chalcopyrite (Cp) and pentlandite (Pn); Lewisian granulite sample 1604, Kylestrome. The pyrrhotite was partly converted to pyrite (Py) with void space (V), the latter now filled by chlorite and calcite. Circles indicate the position of spots analyzed for gold by ion microprobe. Data shown in parts per billion Au.

served as the O_2 donor:

$$6\,FeS + 12\,Fe_2O_3 \rightarrow 3\,FeS_2 + 9\,Fe_3O_4.$$

The cooling path from 800°C, being subparallel to the FMQ buffer, is also indicative of a closed system, with the path determined by the oxidation state of the minerals formed during prograde metamorphism. Given the lower blocking temperature of oxide minerals relative to silicates (Frost 1991), the cooling path was mainly determined by the composition of the oxides (Frost *et al.* 1988, Frost 1991). Thus the hematite-rich nature of the primary ilmenite was important in determining the cooling path (Cameron *et al.* 1993); the hematite-rich ilmenite was a product of prograde metamorphism under oxidizing conditions. The reason why prograde metamorphism was oxidizing in nature, an observation confirmed by Harlov (1992), is not clear. One possibility is that pervasive CO_2-bearing fluids acted as an oxidant. However, the petrological studies required to find the causes of oxidative metamorphism in the Bamble belt and similar terranes, such as Labwor and Lofoten – Vestralen, have yet to be attempted.

Rocks of the Bamble belt metamorphosed at a high grade represent the end stage of processes that resulted in severe depletion of gold, to below its average crustal abundance. The nature and timing of these processed can only be surmised. However, the cooling path shown in Figure 10 provides a realistic mechanism, with the transformation of pyrrhotite to pyrite making gold accessible to later fluids. Transformation could only have taken place a substantial time after peak metamorphism, when the belt had cooled from 800°C to below 600°C. After pyrite was formed, there was partial dissolution of pyrite and chalcopyrite, which are mantled by magnetite (Fig. 9A). This provides a mechanism for the removal of Au^+ in a metamorphic fluid, complexed by dissolved sulfide (Cameron 1989a, c).

EVIDENCE FROM HYPERITES

Whereas intermediate stages in the process for the extraction of gold are not found in the high-grade rocks, evidence is preserved in the hyperites, which were intruded after peak metamorphism, then modified to coronitic gabbros and partially amphibolitized. One dyke of hyperite examined shows a transition from coronitic gabbro in the interior to foliated amphibolite at the margin. Samples taken from the interior zone, through an intermediate zone, to the amphibolite margin show a progressive decline in contents of gold and related chalcophile elements, whereas other ele-

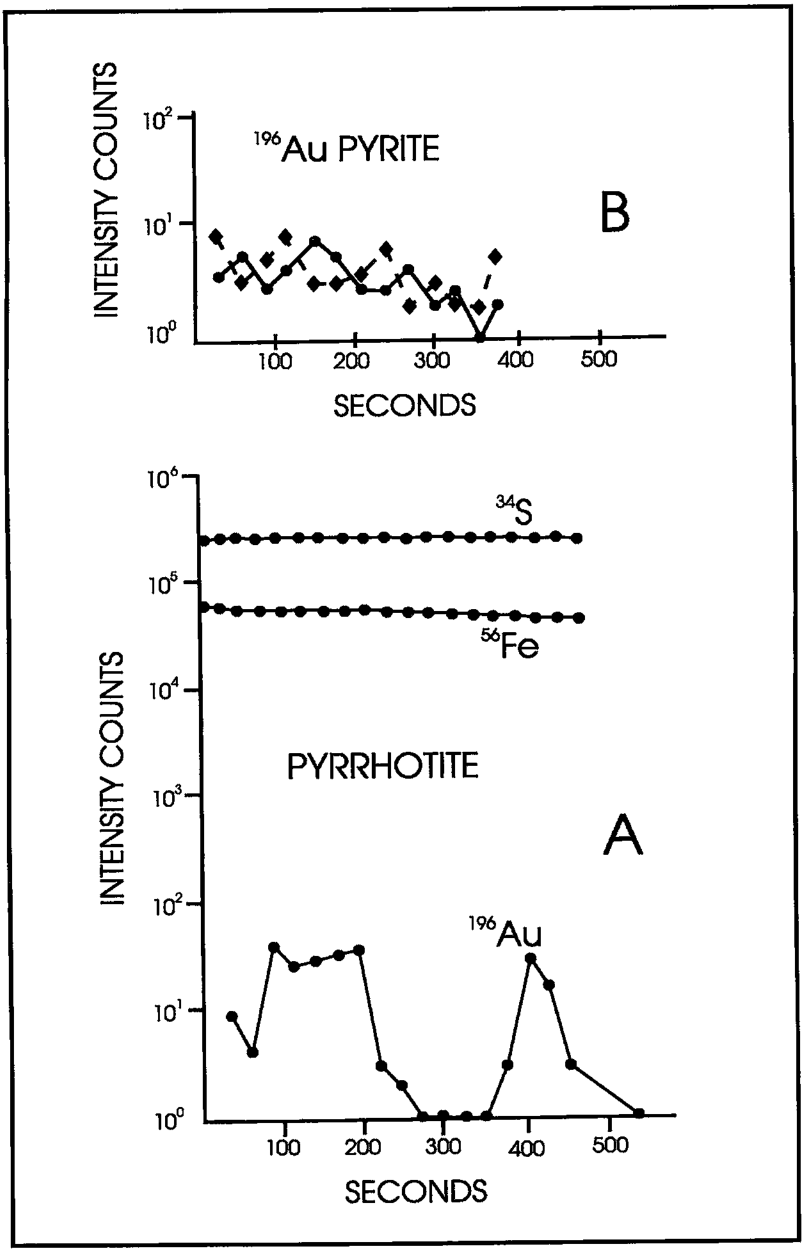


FIG. 13. A. Ion beam in-depth profile of concentrations through pyrrhotite from sample 4008. This profile averages 330 ppb Au. B. Comparative profiles showing similar (background) values for ELBA pyrite (5 ppb Au) and the pyrite reaction product shown in Figure 12.

ments remain relatively constant (Fig. 11). Corresponding to these chemical changes is the replacement of a pyrrhotite-dominant sulfide assemblage in the gabbroic interior by a pyrite-dominant assemblage in the marginal amphibolite. Some grains of pyrite in the latter are mantled by magnetite, replicating the grains found ubiquitously in lithologies that experienced peak metamorphism.

To substantiate the role of the pyrrhotite → pyrite + magnetite transformation in the loss of gold, Cameron

& Chryssoulis (submitted) have measured the gold content of the three phases using an ion microprobe. Figure 12A shows a grain of pyrrhotite that is partly transformed to pyrite and magnetite, from sample 4008 in the interior of hyperite dyke 40. Figure 12B shows the same grain after analysis by the ion microprobe. The circular pits represent material eroded by the ion beam during the analysis of individual spots across the grain surface. At each spot, the ion beam provides an in-depth profile of concentrations as material is eroded. A typical profile for pyrrhotite (Fig. 13A), with broad and narrow "spikes", shows that gold is not uniformly distributed as a solid-solution impurity, but is present as colloidal-size particles of gold or gold-rich material. For all spot analyses, profiles from the surface to a depth of 1.3 μm (~500 seconds) were taken, and the results averaged. The presence of particulate gold effectively increases the analytical sensitivity, since a narrow spike will be averaged over the whole profile. For example, a single-point spike to 100 ppb Au, which can readily be detected, amounts to 7 ppb Au if averaged over 15 points. The inhomogeneous distribution of the gold also is shown by the variation in the results of spot analyses across the pyrrhotite grain (Fig. 12B); eleven analyses gave from 25 to 430 ppb Au, with a mean of 142 ppb. In total, forty-four spot analyses of pyrrhotite from the interior of the dyke averaged 136 ppb Au, and eleven analyses of chalcopyrite averaged 125 ppb. These values compare well with 111 ppb Au reported by Boyd *et al.* (1988) for a bulk sample of pyrrhotite, chalcopyrite, pyrite and pentlandite from the Ertelien deposit, one of several deposits of Fe–Ni–Cu sulfides segregated from hyperite magmas in southern Norway. Bulk analyses of sample 4008 gave, on average, 0.8 ppb Au, which likely represents a decrease from the primary content, given the partial transformation of pyrrhotite to pyrite. Sample 4001 from the margin of the amphibolite dyke contains 0.3 ppb Au, compared to an average of 0.16 ppb for 16 samples from nearby metabasite dykes at Tvedestrand.

Six analyses were made of the pyrite portion of the grain shown in Figure 12B, none of which detected gold. Unlike pyrrhotite, there is a weak molecular background for pyrite (FeS_2) from CsS_2^-, with the same mass as gold (Cs is from the primary ion beam). Background was established by analyses of ELBA pyrite, containing 5.2 ppb Au. In-depth profiles of

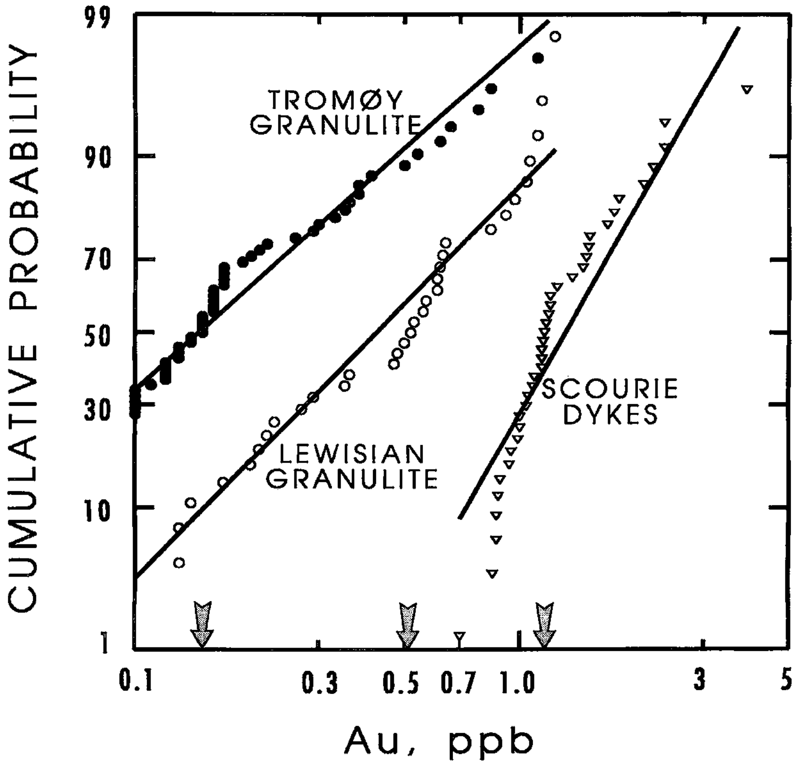


FIG. 14. Curves showing cumulative frequency distribution curves of Au (ppb) for Tromøy granulite (n = 67), Lewisian granulite (n = 33) and Scourie dykes (n = 39). Median for each distribution shown by arrow.

concentration for all analytical spots on pyrite are background values similar to those in ELBA (Fig. 13B); what is most significant is that profiles lack the spikes that reveal particulate gold in the adjacent pyrrhotite. The results indicate that essentially all gold is lost when pyrrhotite changes to pyrite. No gold (<10 ppb) was detected by subsequent analyses of the magnetite reaction-product shown on Figure 12.

The path taken in $f(O_2)$ – T space by the hyperite dyke to reach the PPM buffer is difficult to define, because magnetite, that might be used with ilmenite to estimate this path, continued to re-equilibrate to low temperatures. However, reconstructed primary compositions of ilmenite (Cameron *et al.* 1993) indicate that the coronitic gabbro crystallized close to the FMQ buffer. Pyrite formed in the margin of the dyke under amphibolite-facies conditions. The approximate path constrained by these observations is shown in Figure 10. It implies an increase in $f(O_2)$ relative to the FMQ buffer, different from that of the metabasites, which cooled subparallel to the FMQ buffer. Whereas the cooling path for the metabasites was internally buffered by the assemblage of oxidized minerals formed during peak metamorphism, the increase in $\Delta f(O_2)$ during amphibolitization of the margin of the hyperite dyke may have been externally buffered by the fluid that caused amphibolitization. In effect, the fluid would have equalized $f(O_2)$ conditions between the dyke margin and the host rocks previously metamorphosed at high grade under oxidizing conditions.

Comparison with the Lewisian Complex

The Lewisian granulite complex in northwestern Scotland is one of the world's most strongly LILE-depleted exposures of lower crust. Lewisian granulites, which are orthogneiss, subhorizontally banded into mafic material of tholeiitic affinity and felsic bands of tonalitic and trondjhemitic composition, have only 0.04 of the crustal abundance for U and 0.07 for Th (Weaver & Tarney 1984). Peak metamorphism for the Lewisian occurred at 2.66 Ga (Pidgeon & Bowes 1972), 940–990°C and 11 kbar (Cartwright & Barnicoat 1987). From about 2.6 to 2.3 Ga, there was the Inverian period of deformation and retrogression by fluids introduced under amphibolite-facies conditions, which was most severe along several shear-belts. This was followed at 2.4 and 2.0 Ga by major injection of the Scourie mafic dykes.

Figure 14 shows comparative data on gold concentrations in granulite-facies rocks from Tromøy in the Bamble belt, for Lewisian granulite from the Drumbeg – Kylestrome area, and for the Scourie dykes near Kylestrome. The Tromøy suite consists of 16 samples of metabasite and 51 of tonalite gneiss; the Lewisian granulites are represented by 33 samples of banded orthogneiss, and the Scourie dykes, by 39 samples of quartz dolerite. Lewisian granulite is depleted in gold relative to its crustal abundance of about 4 ppb (Anderson 1983), but not as severely as the Tromøy samples. Like the Bamble rocks, the sulfides present in the Lewisian granulites are mainly pyrite with some chalcopyrite; both minerals commonly have a thin or partial mantle of magnetite. Peak temperatures of metamorphism above 900°C for the Lewisian granulites were well above the stability limit of pyrite. Although obvious zones of retrogression were avoided during sampling, most Lewisian samples show some effects. Oxide minerals were particularly sensitive to the effects of retrogression; ilmenite was changed to fine-grained mixtures of magnetite and titanite or rutile. Changes affecting the oxide and sulfide minerals are most severe within the shear zones. Figure 9C shows a composite grain of pyrite and chalcopyrite from the Canisp shear-zone with a well-developed rim of magnetite, similar to those of the Bamble rocks.

Pyrrhotite also is present in the Lewisian granulites, but only in a few thin sections that lack all evidence of retrogression, further suggesting that the formation of pyrite was the result of the fluids that caused Inverian retrogression. These fluids were oxidizing in nature (Beach & Fyfe 1972, Beach & Tarney 1978, Sills 1983). The Scourie dykes, which were emplaced after Inverian retrogression, but while the terrane was still deep in the crust, retain a pyrrhotite-dominant sulfide mineralogy, and a gold content that is significantly higher (average 1.5 ppb Au) than the pyrite-dominant Tromøy granulite (mean 0.22 ppb Au) and Lewisian granulite (mean 0.54 ppb Au).

Figure 12C shows a grain of pyrrhotite from Kylestrome with inclusions of chalcopyrite and pentlandite. The pyrrhotite has, in part, altered to pyrite. Ion-microprobe analyses (Cameron & Chryssoulis 1993) of six spots in pyrrhotite range from 400 to 9,200 ppb Au, averaging 2,200 ppb Au, substantially higher than the pyrrhotite from the Bamble hyperite dyke. Intensity profiles show that, like the Bamble pyrrhotite, gold is present as fine, irregularly distributed particles. Two analyses of a chalcopyrite inclusion gave an average of 1,200 ppb Au; gold also is present in this mineral as fine particles. In contrast to the sharp peaks in the intensity profiles for pyrrhotite, indicative of particulate gold, profiles from pyrite are relatively flat. Analyses of pyrite gave, on average, 220 ppb Au, an order of magnitude less than in pyrrhotite.

Discussion

At Kirkland Lake, the formation of large deposits of gold was not the product of regional metamorphism or magmatism, but the result of localized crustal extension, then uplift, along a major fault-zone. The same broad tectonic pattern of extension followed by uplift can be recognized at a deeper level within the Bamble shear belt. Metamorphism in an extensional

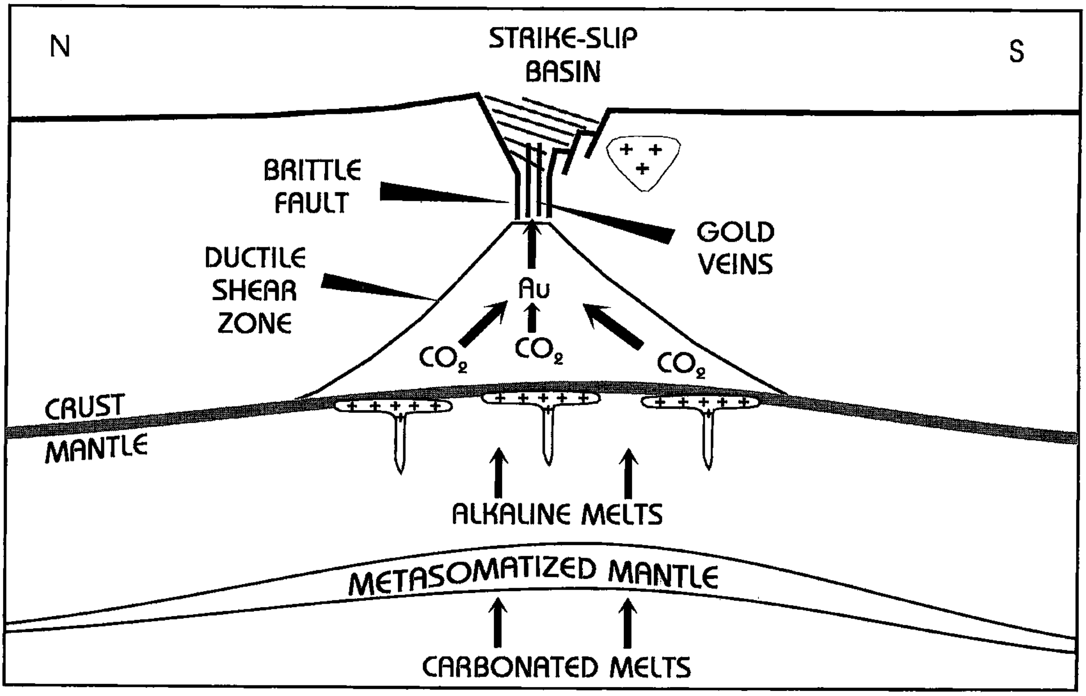


FIG. 15. Conceptual model for north–south section of lithosphere at Kirkland Lake.

setting occurs at high T and low P, and is termed "diastathermal" by Robinson & Bevins (1989). High temperature derives from uprise of mantle and injection of mafic melts into the base of the crust. Modeling indicates an counterclockwise P – T – t path (Robinson & Bevins 1989), a consequence of heating before loading, rather than the clockwise path of regional burial metamorphism, which results from loading before heating (Bohlen 1987). After extension stops, there is a substantial period of isobaric cooling (Sandiford & Powell 1986). The Bamble belt conforms to this model; Kihle (1989) has established a counterclockwise P – T – t path, with isobaric cooling at about 8 kbar from 800 to about 540°C, followed by isothermal uplift. Major injection of mafic magmas (now represented by metabasites and hyperites) occurred before, during and after peak metamorphism. These magmas were of mainly tholeiitic nature, suggesting that extension was greater at Bamble than at Kirkland Lake, where magmatism was mainly alkaline. At Kirkland Lake, the subgreenschist grade of metamorphism of the Timiskaming sequence is consonant with that for diastathermal metamorphism of an extensional basin fill (Robinson & Bevins 1989). The Labwor Hills shear belt, Uganda, is an Archean analogue of the Bamble belt. Metamorphism appears to have been more strongly oxidizing, near the hematite – magnetite buffer, with hematite dominant over ilmenite in intergrowths of these minerals (Sandiford *et al.* 1987). Peak metamorphism occurred at a high temperature, 850–1000°C, which Sandiford *et al.* (1987) attributed to heat from the mantle during crustal extension and thinning. This was followed by isobaric cooling at 7–9 kbar.

An idealized lithospheric cross-section through Kirkland Lake (Fig. 15) shows a broad shear-zone at depth, perhaps analogous to that of the Bamble shear belt. Broad zones of deformation may be associated with both vertical (strike-slip) and low-angle (thrust or detachment) faults. Knowledge of the processes of deformation along strike-slip faults has come from field observations, such as those of Bak *et al.* (1975) and Hanmer (1988), and from models based on rheological properties of rocks, such as those of Yuen *et al.* (1978), Turcotte *et al.* (1980) and Lockett & Kusznir (1982). Initially, movement along a major fault is confined to a narrow zone. Within this zone, frictional heating increases temperature over ambient conditions, reducing the viscosity of the rocks and facilitating ductile deformation. With time, frictional heat spreads out, lowering the viscosity within a broader zone. This broadening increases with depth as the ambient temperature increases. Since the velocity of fault movement determines the frictional heat gener-

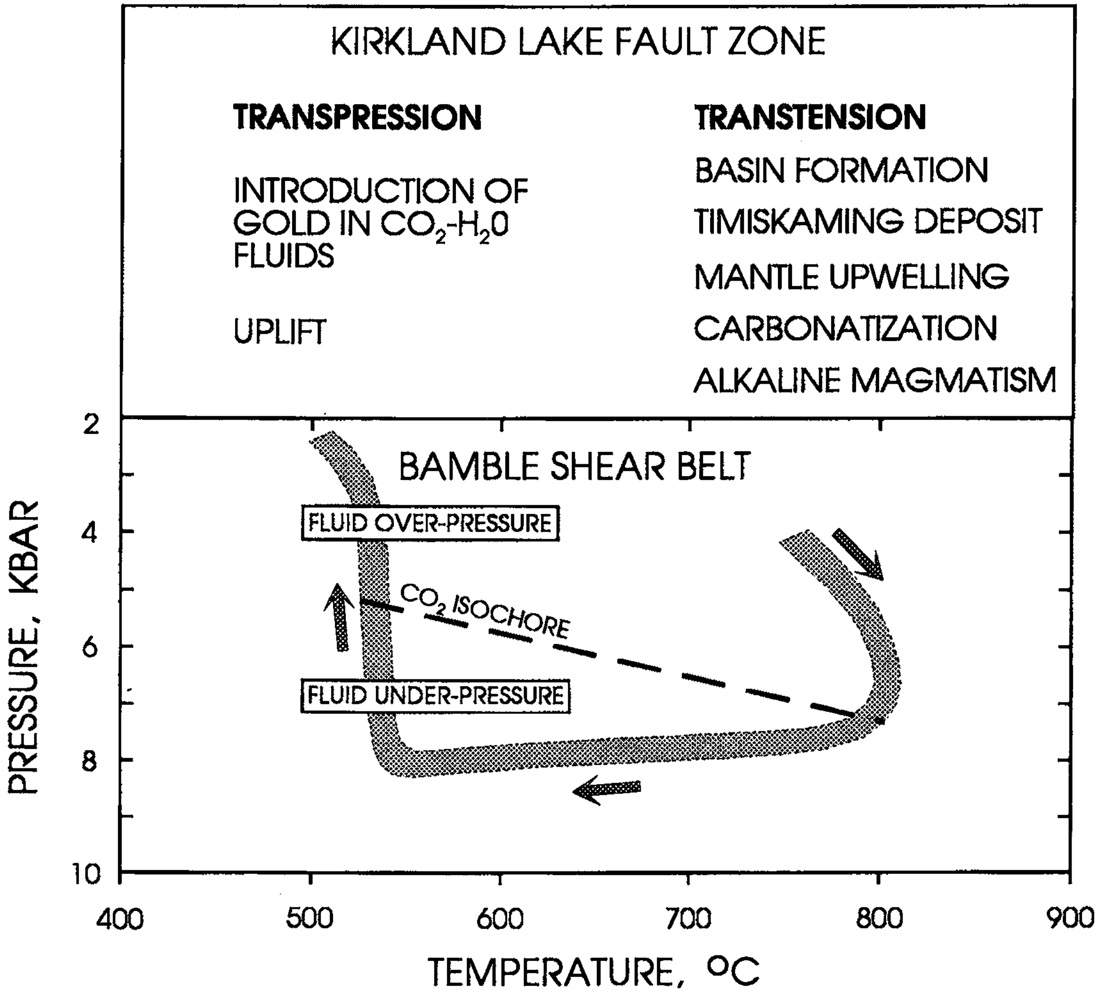


FIG. 16. Pressure – temperature – time (P – T – t) path of Bamble shear belt (Kihle 1989) that is characteristic of a deep crustal response to extensional tectonics. Superimposed is isochore for CO_2 inclusions formed during peak metamorphism. Inclusions will be at less than lithostatic pressure during isobaric cooling, but will become overpressured during uplift, causing the release of CO_2. The diagram is plotted with pressure increasing downward, opposite to the usual practice; thus the P – T – t path appears as clockwise. The top part of the diagram shows comparative events at Kirkland Lake that are related to an upper crustal response to extensional tectonics.

ated, the rate of broadening is greatest for high velocities of displacement. Broadening is facilitated by the heating generated by uplift of mantle in an extensional terrane.

Rutter & Brodie (1985) observed that under conditions of medium- to high-grade static metamorphism, permeability is low, sufficient to permit a fluid phase to permeate only a few meters per Ma. Increased permeability during ductile deformation is caused by dilatancy related to intense intergranular and transgranular microcracking. Dilatant flow occurs under high differential stress. Dilation is also favored by high fluid pressure, notably at negative effective pressure. Experiments by Spiers & Peach (1989) on deformation of rock salt in the dilatant field showed an increase in permeability of 5 orders of magnitude over a range of strain from 0 to 5%.

CO_2-rich high-density inclusions of peak metamorphic origin in Bamble rocks (Touret 1971) are overwhelmingly predominant in the granulite terrane of

Tromøy (Touret 1986). In the transition zone between the granulite and amphibolite facies, H_2O-rich inclusions are common, but CO_2-rich inclusions are present in the amphibolite facies near mafic intrusive rocks. Touret (1986) suggested that mafic magma was a vector for introduction of CO_2 of mantle origin. CO_2-rich inclusions are common in many granulite terranes and are not necessarily derived from the mantle, but may simply be the residue from dehydration by partial melting (Fyfe 1973). An important topic for research is to determine whether CO_2 fluids played a part in the transformation of Bamble rocks into a relatively oxidized assemblage during prograde metamorphism, which, in turn, determined the closed-system cooling path that crossed the pyrrhotite – pyrite phase boundary. This is of consequence in the Kirkland Lake area, where a long period of CO_2-fluxing in the KLF has been alluded to in an earlier section. Rowins *et al.* (1991) found that the magma for the Murdock Creek stock was "dry", consistent with dehydration by the evolution of a CO_2 – H_2O phase during ascent. A CO_2-rich silicate melt will tend to evolve a CO_2 – H_2O phase on rising because of the limited solubility of CO_2 and its pressure dependence (Holloway 1976).

In Figure 16, events in the Bamble shear belt relevant to the loss of gold are related to the metamorphic P – T – t path of Kihle (1989). Based on the cited fluid-inclusion data, CO_2 fluids were present at the peak metamorphic conditions. During isobaric cooling from 800°C to about 540°C, conditions were unfavorable for fluid migration. Fluids trapped as inclusions during peak metamorphism would likely have been preserved, since lithostatic pressure during isobaric cooling was greater than the internal pressure of the inclusions (Touret 1992). Lack of fluid during this phase is supported by the cooling path in $f(O_2)$ – T space (Fig. 10) that was internally buffered by the mineral assemblage. On crossing the PPM buffer, at a temperature of 600°C or below, oxidation of pyrrhotite to pyrite also took place in a closed system, with the reaction being balanced by reduction of hematite within ilmenite grains. The transformation of primary pyrrhotite made gold available to extraction by a later fluid phase.

The following phase of isothermal uplift provided conditions conducive to the out-migration of fluids. Inclusions preserved through isobaric cooling would have been released when their internal pressure

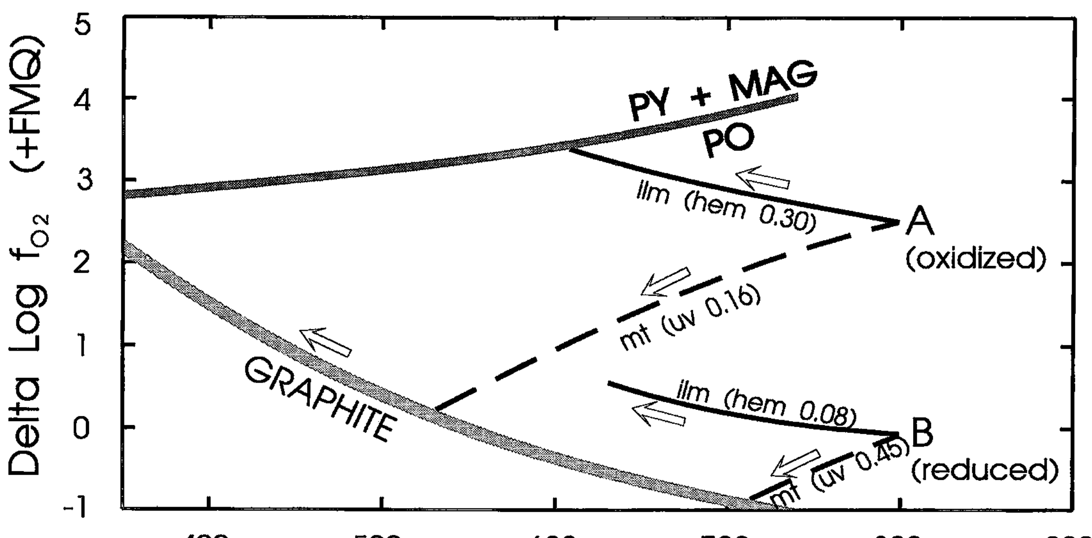


FIG. 17. Diagram showing paths taken in $f(O_2)$ – T space during cooling from metamorphic peak where the rocks are buffered by oxide – oxide re-equilibration. "A" is an oxidized assemblage, similar to that of the Bamble or Labwor shear belts. Where ilmenite is the only oxide, cooling will be along the isopleth for hematite in ilmenite. For a magnetite-only assemblage, cooling will be along the ulvöspinel in magnetite isopleth. Mixtures of ilmenite and magnetite result in an intermediate path. However, ilmenite is well buffered with 0.30 mole fraction hematite, relative to 0.16 mole fraction ulvöspinel in magnetite. Thus, except in rocks with magnetite in large excess over ilmenite, the cooling path is likely to cross into the field of stability of pyrite. The reduced assemblage "B" is poorly buffered with respect to hematite and is unlikely to cool into the pyrite field. Based on Frost *et al.* (1988) and Frost (1991). The graphite buffer at 3 kbar is from Frost & Chacko (1989); the pyrrhotite – pyrite – magnetite buffer is from Kishima (1989). Oxide isopleths were computed by a program of M.S. Ghiorso (see Ghiorso & Sack 1991), the FMQ buffer, from Myers & Eugster (1983).

exceeded the decreasing lithostatic pressure. Whereas the change from pyrrhotite to pyrite during isobaric cooling did not require a fluid oxidant, the subsequent partial replacement of pyrite and chalcopyrite by magnetite required both an oxidant and a fluid to remove the sulfide released by the reaction. Although there is no direct evidence as to when gold was removed from the Bamble belt, this fluid seems the most probable agent, with the sulfide acting as a ligand to complex Au^+. The same fluid may have been responsible for the partial amphibolitization of the hyperites. Finally, there was variable retrogression of the uplifted granulite terrane under greenschist-facies conditions, with re-introduction of gold into previously depleted granulite (Cameron 1993). The time from peak metamorphism until the start of uplift and possible loss of gold can be approximated. Geochronological data cited earlier for the termination of peak metamorphism (~800°C) at 1095 Ma and for retrogression of granulites under greenschist conditions (~350°C) at 1060 Ma give an approximate cooling rate of 8 Ma per 100°C, or 21 Ma to cool from 800 to 540°C.

Rapid uplift results in the compression of isotherms; as a result, the brittle – ductile transition may rise to within 6 to 8 km of the surface (Holm *et al.* 1989). Thermal gradients are highest near the surface. Koons (1987) estimated that rock uplifted from 25 km would have a 10°C/km gradient during the first 10 km of uplift, 20°C/km for the next 10 km, and 70°C/km for the final 5 km. The high thermal gradient in the upper crust favors convective flow of fluid (Koons & Craw 1991). Norris & Henley (1976) showed that in metamorphic belts with a thermal gradient greater than 12°C/km, uplift will result in the expansion of metamorphic water, with resulting hydraulic fracturing. This gives rise to overpressured fluids at depth migrating upward to mix with convecting fluids above the brittle – ductile transition. Sibson *et al.* (1988) suggested that high-angle reverse faults acted as valves to release overpressured (supralithostatic) fluids from below into a hydrostatic regime, where gold was deposited. The ore at Kirkland Lake was largely deposited along a high-angle reverse fault during a major phase of uplift. At Kirkland Lake, fluids that scoured gold from the lower crust were focused into the narrow, upper part of the shear zone.

An important conclusion of previous sections is that conditions of deep crustal metamorphism should be conducive to the modification of sulfide minerals that are the principal host of gold. In mafic rocks, which are an important component of the lower crust, the sulfide fraction amounts to about 0.25 wt.%, of which pyrrhotite is the most important mineral. In both the Lewisian granulites and the Bamble shear belt, it is pyrite, not pyrrhotite, that is now the dominant sulfide mineral. Ion-microprobe analyses of samples from both areas show that the metamorphic transformation of pyrrhotite to pyrite resulted in a loss of gold by a factor of 10. This occurred well after peak metamorphism, when the rocks had cooled below 600°C. In the Bamble belt, the silicate minerals that formed during peak metamorphism were retained in unmodified form during cooling, whereas oxide and sulfide minerals continued to re-equilibrate long after the peak.

Modification of the minor sulfide fraction, without involvement of silicate phases, required less fluid than otherwise and avoided dissolution of major components within the rock. The oxide minerals influenced the modification of the sulfide fraction. Frost *et al.* (1988) and Frost (1991) suggested that the $f(O_2)$ – T path taken after peak metamorphism is largely determined by the nature and composition of the oxides. For rocks where ilmenite is the only oxide, the path of cooling will follow the isopleth for ilmenite, which can result in a moderate increase in $\Delta f(O_2)$ (Fig. 17). Where magnetite is the only oxide, the path will follow the appropriate isopleth for ulvöspinel in magnetite, which results in a decrease in $\Delta f(O_2)$ (Fig. 17). For mixtures of magnetite and ilmenite, an intermediate path is obtained. Along this intermediate path, the hematite content of ilmenite and the ulvöspinel content of magnetite both decrease, reflecting the balanced redox reaction and the exchange of components between the two oxide minerals:

$$Fe_2TiO_4 + Fe_2O_3 = FeTiO_3 + Fe_3O_4.$$

The Bamble metabasites contain an oxide assemblage that is particularly favorable to a cooling path that crosses the pyrrhotite – pyrite phase boundary. In these rocks, ilmenite is the dominant oxide phase (Cameron *et al.* 1993); ilmenite formed during peak metamorphism was well buffered with respect to hematite, with 0.30 mole fraction of the latter. The reduced assemblage "B" (Fig. 17) is poorly buffered with respect to hematite and is unlikely to enter the field of stability of pyrite. It appears that many granulite terranes took a path that decreased in $\Delta f(O_2)$, to intersect the graphite saturation surface (Frost & Chacko 1989). Sedimentary sequences containing graphite also will buffer the rocks to low $f(O_2)$. This may bear on the preferential concentration of major Archean gold deposits in metavolcanic rather than metasedimentary belts.

For the Lewisian granulites, conversion of primary pyrrhotite to pyrite and the associated loss of gold involved the introduction of oxidized fluids during retrogression. The fluids not only modified the sulfide fraction, but caused change in the oxide and silicate minerals. The effects of the fluids were more pronounced along shear zones.

Ages for gold veins in the Yilgarn Block, Australia, fall within a tight interval of 2660 to 2630 Ma (Groves *et al.* 1990), which is similar to the ages cited above for veins in the Abitibi belt. The association of deposits with major faults, which, in some cases, have been shown to be terrane boundaries, suggests that gold was related to a worldwide episode of terrane assembly at the end of Archean time. The major strike-slip movements required for terrane assembly produced broad zones of ductile deformation in the lower crust, to serve as the large-volume, permeable source-regions for gold. The observation of Libby *et al.* (1990), of lamprophyre and porphyry intrusions along the major faults in the Yilgarn Block, suggests that localized extension, with upwelling and melting of mantle, was widespread during terrane assembly. When assembly was completed, the extended areas were uplifted. Permeability was then high, as fluids became overpressured.

Conclusions

For a mafic lower crust, a precondition for extraction of gold is modification of the sulfide fraction, the principal host for gold. Pyrrhotite is the main primary sulfide mineral and the stable form of iron sulfide during high-grade metamorphism. The phase change of pyrrhotite to pyrite, which occurs during metamorphic cooling, and which requires a relatively high $f(O_2)$, is required for the extraction of gold. Both for the Bamble shear belt and Lewisian granulite, ion-microprobe analysis has shown a factor of ten loss in gold during the metamorphic transformation of pyrrhotite to pyrite.

Prograde metamorphism of the Bamble shear belt under conditions of the upper amphibolite and granulite facies produced a mineral assemblage that was relatively oxidized. During cooling from the metamorphic peak, buffering by this assemblage, notably by hematite-rich ilmenite, took the rock into the stability field of pyrite. Silicate minerals retained their peak metamorphic composition, contrasting with sulfide and oxide minerals, which continued to be reactive to below 600°C. Since the latter are only small fractions of the total rock, gold was, in effect, selectively extracted from a large volume of mainly unreactive rock, requiring lesser amounts of fluid.

The Bamble shear belt is perhaps analogous to the lower crust below the Kirkland Lake gold camp. Both at Bamble and Kirkland Lake, extensional tectonics appeared to play a key role in the mobilization and transfer of gold. Rocks metamorphosed at high grade in an extensional terrane typically follow a counter-clockwise P – T – t path. Isobaric cooling is followed by near-isothermal uplift. Fluids present as inclusions during peak metamorphism will tend to be retained by high lithostatic pressure during isobaric cooling. But with uplift, and after phase change in the sulfide minerals, the fluids become overpressured and are released. This is the probable time when gold was extracted, carried upward, and focused at the brittle – ductile transition. Fluids present, then expelled, from the deep crust were usually CO_2-rich, but the CO_2 may be of diverse origin: CO_2 derived from magma of mantle origin, and CO_2 of crustal origin that accumulated as a consequence of dehydration reactions.

Kirkland Lake displays features of extensional tectonics at a higher level. Here, extension was a consequence of motion along a major, long-lived, linear fault, interpreted to be strike-slip. Extension caused formation of basins, in which Timiskaming sediments were deposited, and upwelling of mantle, accompanied by CO_2-degassing and melting to LILE-enriched alkaline compositions. High heat flow, together with the long-lived nature of displacement along the fault, would have favored the formation of a broad, ductile shear-zone in the lower crust that served as a source for gold. Localized magmatism and metamorphism along the fault zone occurred during extension. It was later, during uplift, that gold was deposited along high-angle reverse faults. The late arrival of gold in the upper part of the shear zone is in conformity with the evidence from the Bamble shear belt suggesting that gold was extracted during rapid uplift following isobaric cooling.

The Bamble scenario, for metamorphic oxidation of a large volume of lower crust, is most favorable for extraction of gold. If the primary composition of the Bamble rocks was close to the crustal average of 4 ppb Au (Anderson 1983), a 10-km-long segment of the deep shear belt, 5 km deep and 30 km wide, could have released and focused 15,000 t Au into the upper, narrow portion of the shear zone. This compares with the 723 t Au produced from Kirkland Lake. Widespread metamorphic oxidation in the Bamble deep shear zone may relate to the finding (Cameron & Hattori 1987, Mikucki & Groves 1990) that several of the largest Archean gold deposits, including those from Kirkland Lake, were formed from oxidized fluids. The demonstrated high mobility of gold in the deep crust suggests that a variety of tectonic conditions (and thus genetic models) may be able to exploit its mobility.

Both in Australia and Canada, the formation of gold deposits in late Archean time occurred during a period of terrane accretion that formed the cratons existing today. The major strike-slip movements implicit in terrane accretion produced the conditions required for the generation of gold deposits described here. These are broad zones of deformation in the lower crust; localized extension gave rise to mantle upwelling with magmatism, CO_2-degassing and heating of the lower crust, followed by rapid uplift, with release of stored fluids and the extraction and concentration of gold.

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