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Symposium Held at the University of Waterloo March 7, 1980

edited by
E.G. Pye and R.G. Roberts

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Genesis of Archean, Volcanic-Hosted Gold Deposits Symposium Held at the University of Waterloo March 7, 1980

Edited by E.G. Pye[1] and R.G. Roberts[2]

Introduction

This volume consists of the eleven papers that were presented at a symposium on Archean, volcanic-hosted gold deposits, held at the University of Waterloo, 7th March 1980. The papers describe field and laboratory studies of deposits in the Timmins, Kirkland Lake, Red Lake, Yellowknife, and Val d'Or-Malartic areas.

The recognition of gold-bearing chemical sedimentary rocks probably provides the most convincing evidence that volcanic processes played a part in the formation of these deposits. Furthermore, in several mines, there is a spatial relationship between these sedimentary rocks and gold-bearing quartz veins. Consequently the ultimate objective of geologists studying these deposits is to describe and understand the volcanic and tectonic processes involved in their genesis, and the relationships between these processes.

Compared to volcanogenic massive sulphide deposits, the alteration of volcanic rocks hosting lode gold deposits is not well described or understood. Apart from the fact that they have received less attention, this is probably because the morphology of their alteration zones has proved to be difficult to define, and their mineral assemblages are more varied than in the massive sulphide counterparts. Several of the papers in this volume describe the progress being made in understanding these synvolcanic processes. The description, by J.A. Fyon and J.H. Crocket, of the morphology and mineral zoning of carbonate alteration in flows in the Timmins area, and its interpretation as a surface and near-surface process under marine conditions, is a significant contribution. W.O. Karvinen, with a regional approach to the Timmins area, identifies vent (hydrothermal discharge?) zones of intense carbonatization, and discusses their significance as the loci of syngenetic and metamorphogenic orebodies. McGeehan and Hodgson have identified synvolcanic alteration that affected mafic volcanic rocks in the Red Lake area, stripping them of gold, iron, and magnesium. Such zones of depletion are obviously important in the development of a genetic model; however, they have not yet been recognized in the Timmins or Kirkland Lake areas.'

J. Pirie, D.R. Pyke, and L.S. Jensen describe the regional settings of the deposits of the Red Lake, Timmins, and Kirkland Lake areas, respectively. From this perspective, Pyke and Jensen consider the major faults (Destor-Porcupine and the Larder Lake systems) to be of critical significance in the location of the deposits. Careful work in the Kirkland Lake area by M.J. Downes provides field evidence for a spatial relationship of the de-

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posits and carbonate alteration to the Larder Lake 'Break'. He also describes field evidence from which he concludes that the carbonatization process postdates the principal period of faulting.

W.O. Karvinen, R.G. Roberts, and A.J. Fyon and J.H. Crocket, from their studies in Timmins, are in general agreement that the spatial relationships of the tectonic (metamorphogenic) quartz veins to carbonatized volcanic rocks, indicate their derivation from the altered rocks. However, D.M. Rigg and H. Helmstaedt suggest that, in the Red Lake area, the veins do not have the same precise spatial relationship to carbonatized flow rocks, but rather that the veins are the location of conduits for hydrothermal solutions. They conclude that "gold deposition commenced after through-going fissures had opened along structurally formed anisotropies bringing the rocks in contact with large amounts of gold-bearing fluids derived from elsewhere."

The paper by R. Kerrich includes geochemical and isotopic data from deposits in the Timmins, Red Lake, Yellowknife, and Val d'Or - Malartic areas. Kerrich describes the fundamental geochemical differences between lode gold deposits and massive sulphide deposits, which must reflect differences between the hydrothermal systems of the two types. He concludes that the hydrothermal solutions of the lode gold deposits originate as metamorphic fluids, formed at the transition between greenschist and amphibolite facies conditions.

Although there are many differences among the three areas, and even among deposits within an area, nevertheless there are common factors relating the deposits. Eventually these factors will be evaluated and formulated into a genetic model based on chemical-physical principles. However, it is a reflection of our understanding of the volcanic and tectonic processes involved in the formation of these deposits that the majority of the authors have not attempted to produce such a general model.

Several authors of this volume were financed through the Ontario Geoscience Research Grants Program, or are geologists currently or very recently working for the Ontario Geological Survey. The symposium was sponsored by the Ontario Geological Survey, the Mineral Deposits Division of the Geological Association of Canada, and the University of Waterloo. Many of the diagrams in this volume were draughted by Ms. Maureen Maziarz in the Earth Science Department of the University of Waterloo.

Relationship of Gold Mineralization to Stratigraphy and Structure in Timmins and Surrounding Area

D.R. Pyke[1]

Abstract

The volcanic Archean rocks of the Timmins area are divided into two groups: the older Deloro Group and the overlying Tisdale Group. Each group is divided into three volcanic formations. The Deloro Group is largely a calc-alkaline sequence. The composition of the volcanic rocks of the Tisdale Group ranges from komatiitic in the lower formation, through a thick succession of tholeiitic rocks to the upper formation of calc-alkalic rocks. The sedimentary rocks[2] of the Porcupine Group are equivalent in time to the volcanic rocks of the upper part of the Deloro Group and the Tisdale Group. When viewed in the context of the Timmins-Matachewan-Kirkland Lake region, the groups defined in the Timmins area are in reality supergroups, and the formations should be raised to the status of groups.

When the gold deposits are viewed on a regional scale, the significant relationships are as follows:

1)The majority of the deposits are spacially associated with the Destor-Porcupine Fault and the Larder Lake Fault.
2)Extensive carbonatization occurs along the faults.
3)The faults coincide with the komatiitic rocks of the basal group of the Upper Supergroup.
4)Sedimentary rocks are relatively more abundant in the gold-producing areas.
5)Stocks of quartz-feldspar porphyry are common within or near the komatiitic rocks. It is proposed that the ultramafic komatiitic rocks formed the principal source bed and that the gold was released by carbonatization and concentrated in dilatant zones.

Introduction

Some factors are common to the genesis of most or all Archean volcanic-hosted gold deposits, and by considering only a limited number of deposits or a restricted setting, these factors could easily be overlooked. That is not to say that the regional approach is all-encompassing, rather it is to emphasize that some important aspects of the localization of mineralization may only become apparent from a regional overview. Therefore, the summary of the general geology, stratigraphy, and geochemistry of the Timmins area presented here is followed by an interpretation of the stratigraphy of the Timmins-Kirkland Lake region and some common factors related to gold mineralization.

The Timmins Area

General Geology

With the exception of a few diabase dikes and minor Middle Precambrian sedimentary rocks, all the bedrock in the area is of Early Precambrian (Archean) age (Figure 1-1). The volcanic rocks are conveniently divided into two groups (Figure 1-2), the older Deloro Group and the overlying Tisdale Group (Dunbar 1948; Hogg 1950). In addition, each group is divided into three volcanic formations, which from older to younger are herein numbered I to III in the Deloro Group, and IV to VI in the Tisdale Group. The Deloro Group is largely a calc-alkaline sequence, approximately 4500-5000 m (15,000 feet) thick, and is composed mainly of flows of andesite and basalt in the lower part and dacite flows and dacitic and rhyolitic pyroclastic rocks toward the top. Iron formation is common at or near the top of the group. Most of the Deloro Group is confined to a large domal structure (Shaw Dome) in the east-central part of the area. A major change in volcanism marks the beginning of the Tisdale Group. The lower formation is largely a komatiitic sequence. This in turn is overlain by a thick succession of tholeiitic basalt. The uppermost formation is largely volcaniclastic and of a calc-alkaline to dacitic composition. Total thickness of the Tisdale Group is about 5000 m (15,000 feet).

Metasediments of the Porcupine Group, consisting mainly of interlayered greywacke and siltstone with lesser conglomerate, form part of what is for the most part a turbidite sequence. The rocks of the Porcupine Group are time equivalent to the upper part of the Deloro Group and the whole of the Tisdale Group. Maximum thickness of the group is approximately 3000 m (10,000 feet).

Large, generally sill-like bodies of dunite and lherzolite were emplaced almost entirely within the Deloro

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[1] Ontario Geological Survey

[2] All rocks in the area have been metamorphosed. Therefore the prefix "meta" will not be used.

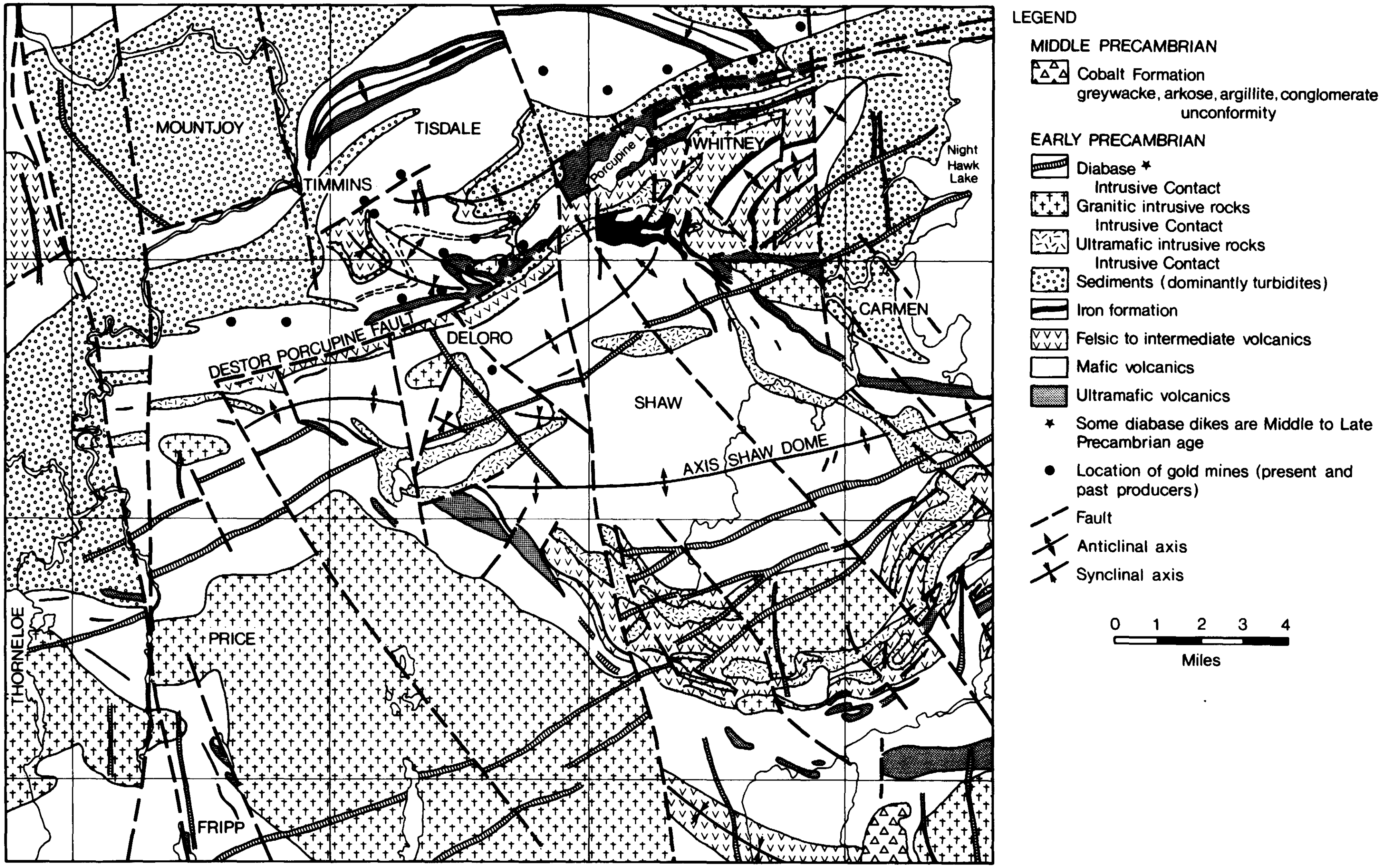

Figure 1-1—Geological sketch map of the Timmins area.

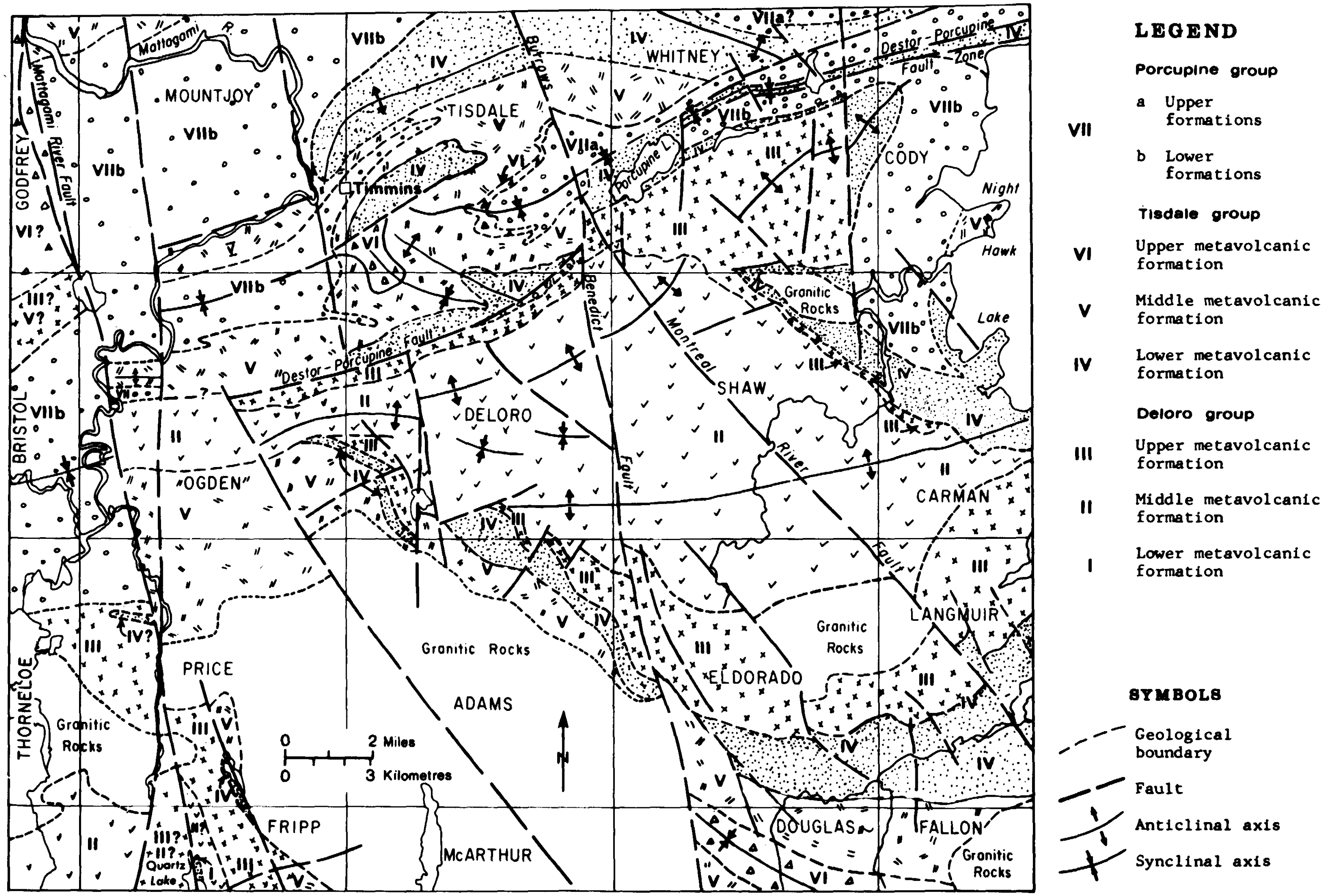

Figure 1-2—Distribution of stratigraphic units in the Timmins area.

Group volcanic rocks. Conceivably some of the sills may have acted as magma reservoirs, thereby providing a source for some of the overlying komatiitic flows of the Tisdale Group.

Minor subvolcanic quartz-feldspar porphyry "intrusions" occur within a restrictive stratigraphic interval, suggesting that they in part may represent extrusive rhyolitic domes.

A major structural break, the Destor-Porcupine Fault, separates the Timmins area into two main structural domains: (1) the area north of the fault, which encompasses the main gold mining camp and (2) the area south of the fault. Even though only a small segment of the Destor-Porcupine Fault traverses the area it is the writer's opinion that this represents a fundamental fracture in the Early Precambrian crust. The fault extends at least as far west as the Kukatush area (Milne 1972) and probably as far as the Kapuskasing structure. The fault has been traced to the east as far as the Noranda area (Wilson 1962: Dimroth *et al.* 1973; Gelinas *et al.* 1977) where it merges with the Cadillac Break, which is the eastward extension of the Larder Lake Break (Thomson 1948) in the Kirkland Lake area. The Cadillac Break extends eastward to the Grenville Front, approximately 40 miles east of Val d'Or. The Destor-Porcupine Fault is therefore part of a major east-west fracture zone probably extending from the Kapuskasing structure to the Grenville Front, a distance of approximately 275 miles. Conceivably the fault was of much greater extent in the Early Precambrian as it is terminated at either end by younger fault systems.

North of the fault in the Timmins area two periods of folding can be discerned; an original north-trending series of overturned folds were subsequently refolded about an east-northeast axis (Pyke 1976). Interpretation of the overall fold pattern, however, is particularly hampered where extensive faulting has occurred, as in north Whitney Township. Nevertheless, the main axis of the second period of deformation is delineated by the Porcupine Syncline (Ferguson *et al.* 1968).

South of the Destor-Porcupine Fault, the Shaw Dome forms the main structural feature; the axis trends approximately east-west across the southern part of Shaw Township.

Volcanic Rocks

The volcanic rock classification used here (Figure 1-3) follows that of L.S. Jensen (1976a).

Deloro Group

I Lower Volcanic Formation: This formation is proposed on the basis of the mapping in the Peterlong Lake area (Pyke 1978a) which adjoins the southern boundary of the Timmins area. Here, minor ultramafic volcanic rocks, maximum thickness 300 m, are engulfed in a massive to weakly foliated diorite which forms the marginal phase of a large batholithic complex. The northern extremity of these ultramafic rocks extends into the southwestern part of the Timmins area. The presence of ultramafic volcanic rocks at this stratigraphic level suggests that komatiitic-rocks may have been more extensive and underlain much of the Deloro Group in this area.

II Middle Volcanic Formation: This formation forms the bulk of the Deloro Group and is best exposed in the central part of the Shaw Dome. The base of the formation is not exposed. The upper boundary is, in general, ill-defined as a result of lack of outcrop, but is placed at the base of the first recognizable and persistent units of dacitic volcanic rocks, most of which are pyroclastic.

The formation is composed almost entirely of flows of calc-alkaline basalt and andesite (Figure 1-4) and it is only near the upper part of the formation that pyroclastic rocks dominate. Most of the intrusive ultramafic rocks are confined to this formation. The most continuously exposed section is in northwest Deloro Township, where the maximum thickness is in the order of 3000 m.

III Upper Volcanic Formation: This formation is characterized by an abundance of iron formation of oxide and sulphide facies. Calc-alkalic rhyolite and dacitic tuff, and lapilli-tuff form the bulk of the formation (Figure 1-5). The felsic pyroclasitc rocks are preferentially developed along the north and south sides of the Shaw Dome. In south Whitney Township the maximum thickness is estimated to be approximately 1500 m. Near the southern margin of the dome the thickness appears to be a maximum of approximately 2000 to 2500 m. Elsewhere as in Shaw, Carmen, and southern Deloro Townships the formation is delineated largely by a few tens of metres of iron formation and minor intercalated tuffs.

Tisdale Group

IV Lower Volcanic Formation: Formation IV forms the base of the Tisdale Group. It consists largely of peridotitic and basaltic komatiites at the base, and interlayered basaltic komatiites, magnesium tholeiitic basalts, and lesser iron tholeiitic basalts in the upper part (Figure 1-6). The base of the formation is exposed near the north boundary of Shaw Township. Here, serpentinized ultramafic flows conformably overlie sulphide facies iron formation. In this part of the area, the formation has a maximum thickness of approximately 300 m. In north-central Carmen and southern Langmuir Townships thicknesses may be up to 3000 m.

North of the Destor-Porcupine Fault the best exposed sections are in northern Tisdale and Whitney Townships. The maximun thickness of Formation IV is approximately 3000 m and is exposed in northeast Whitney Township. The exposure extends from the anticlinal axis in north Whitney Township to a massive iron tholeiitic basalt underlying a variolitic sequence, in the southwestern part of Whitney Township, defining the base of the overlying formation. In general, Formation IV north of the Destor-Porcupine Fault consists of 25 percent komatiites, 65 percent magnesium tholeiitic basalt, and 15 percent iron tholeiitic basalt. Virtually all the iron tholeiitic basalt flows are towards the top of the formation where they are intercalated with magnesium tholeiitic basalt. The majority of the flows with compositions that plot in the tholeiitic field in Figure 1-6, are relatively enriched in magnesium.

V Middle Volcanic Formation: Formation V is composed dominantly of iron-rich tholeiitic basalt (Figure 1-7). North

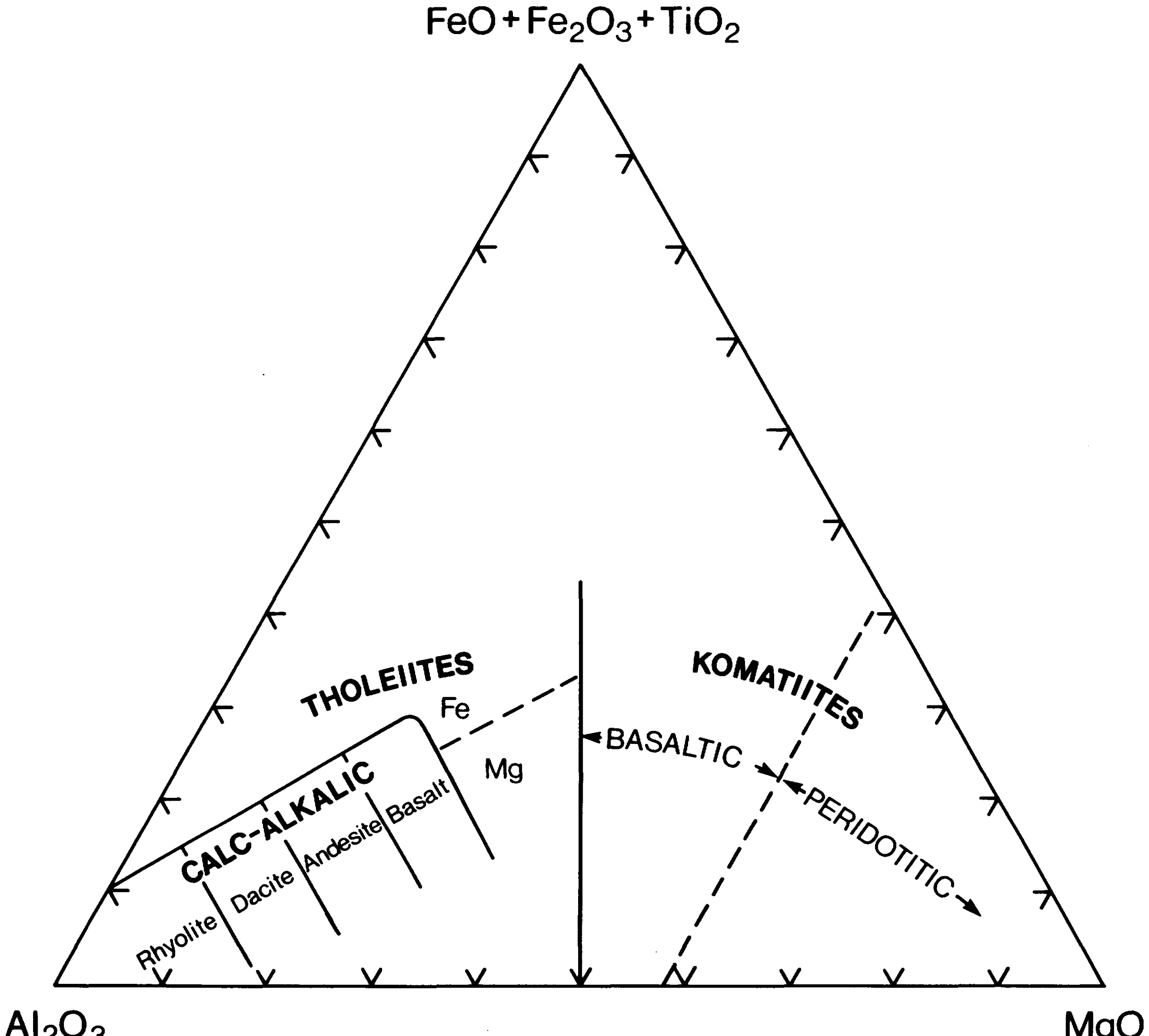

Figure 1-3—Al_2O_3 - (Fe?O?$_3$ + TiO_2)-MgO cation plot (after Jensen 1976a).

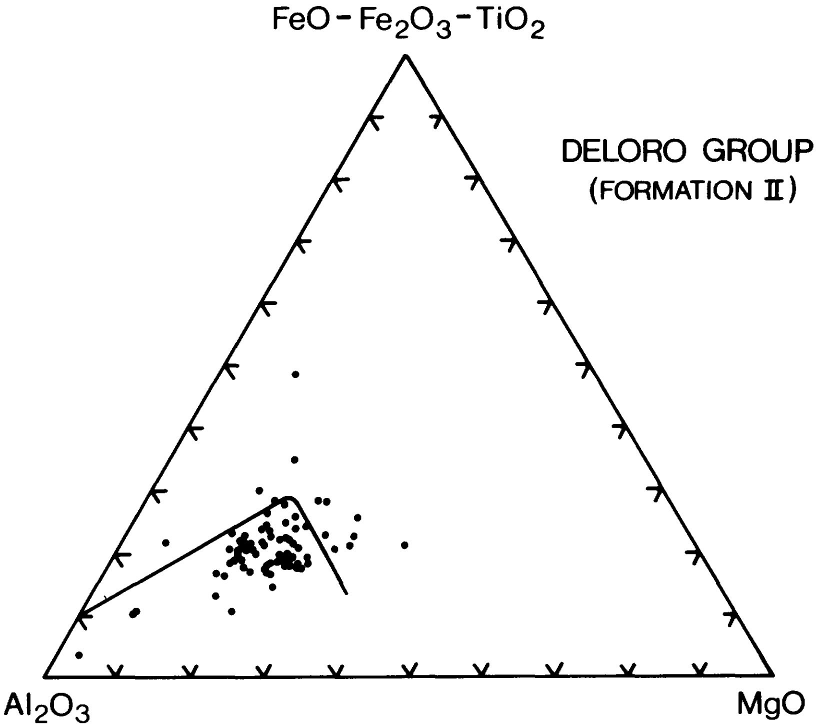

Figure 1-4—Plot of volcanic rocks from the Deloro Group, Formation II.

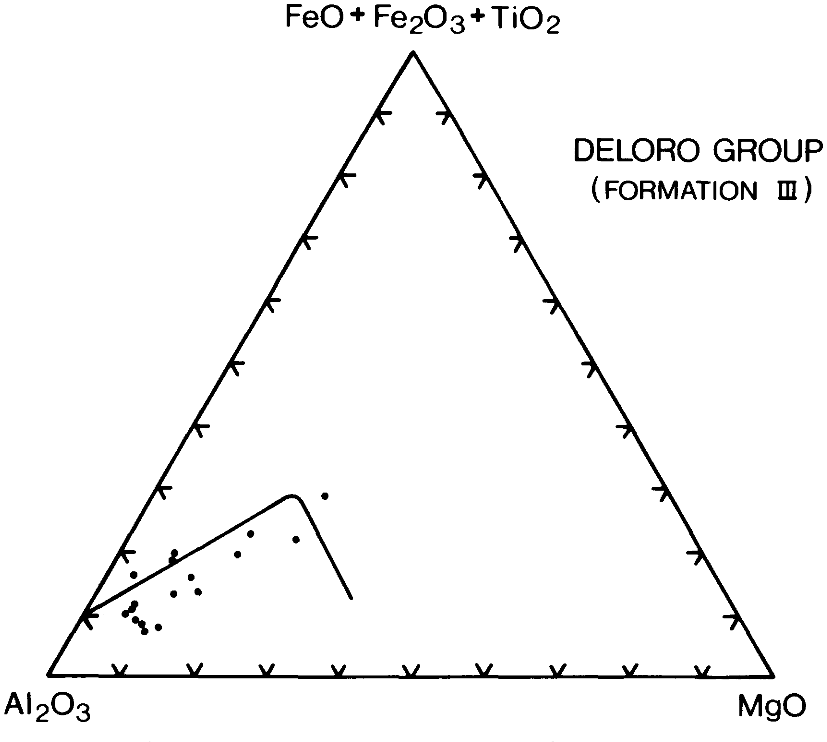

Figure 1-5—Plot of volcanic rocks from the Deloro Group, Formation III.

of the Destor-Porcupine Fault, the "99 flow" (Ferguson *et al.* 1968; Graton *et al.* 1933) is taken as the base of the formation as it is the first easily recognized iron tholeiite in the lower part of the Tisdale Group, and in many parts of the area directly underlies the distinctive "V8" variolitic basalt (Ferguson *et al.* 1968). The formation corresponds approximately to the Vipond Subgroup of previous workers (Ferguson *et al.* 1968). The maximum thickness varies from 300 to 1000 m, and the best exposed section is in south Tisdale Township in the area between the Dome and Paymaster mines. Variolitic basalt forms a prominent part of the formation, notably the "V8" and "V10 flows" (Ferguson *et al.* 1968). The top of the formation is marked by the abrupt termination of tholeiitic volcanism and the commencement of felsic, calc-alkalic volcanism of the Upper Volcanic Formation.

South of the Destor-Porcupine Fault the formation is not as well defined because the exposure is extremely poor. Nevertheless, a few good isolated outcrop areas are available for examination, confirming the presence of an iron-rich tholeiitic sequence overlying the komatiites. In contrast to the iron tholeiitc sequence north of the Destor-Porcupine Fault, variolitic basalt is virtually absent.

VI Upper Volcanic Formation: Formation VI, the uppermost volcanic formation, consists dominantly of felsic calc-alkaline pyroclastic rocks (Figure 1-8). The formation is best developed in Tisdale Township where it is referred to as the Krist fragmental (Ferguson *et al.* 1968) and has a maximum thickness of 350 m. Underlying the Krist fragmental and forming the base of the formation is a thin (zero to 100 m) unit of carbonaceous argillite exposed in drill holes and underground workings.

South of the Destor-Porcupine Fault in Douglas Township, calc-alkalic crystal and lapilli-tuff, ranging in composition from andesite to rhyolite, forms the uppermost volcanic sequence overlying the iron tholeiitic basalts. Rare intercalated ultramafic tuff and lean cherty sulphide iron formation are also present. The occurrence of ultramafic tuff high in the stratigraphic sequence is not unique to this formation, since komatiitic tuff is known to occur in the upper formations of the Porcupine Group.

Summmary

The chemical data for samples from Formation II to Formation V inclusive are plotted in Figure 1-9, and the boundaries of the majority of the compositions within the formations are shown in Figure 1-10. The plots illustrate the compositional trends for the komatiitic, tholeiitic, and calc-alkalic suites. The overlap of compositions of the various formations serves to illustrate that a few samples from an area of overlap would not be sufficient to define the chemical affinity of a formation.

Sedimentary Rocks

In parts of the area, sedimentation was continuous with the emplacement of the volcanic rocks of the Tisdale Group. In Price, Thornloe, and Fripp Townships the lowermost sedimentary rocks are interlayered with volcanic rocks of Formation III of the Deloro Group. Although exposure is extremely poor in the Thornloe-Bristol area (Ferguson 1957), volcanic rocks of the Tisdale Group appear to be absent, and the area was thus one of continuous sedimentation during the period of volcanic activity that spanned the upper part of the Deloro Group, and the whole of the Tisdale Group. Similarly the sedimentary rocks in Mountjoy Township and northwest Tisdale Township are interpreted to be largely equivalent to the Tisdale Group volcanic rocks, but again exposure is poor and hence reliable stratigraphic data are lacking. In Whitney Township, the Whitney Formation directly overlies the Deloro Group and in Cody Township the Whitney Formation is interlayered with the (basal) Formation IV of the Tisdale Group.

The Dome and Beatty Formations in Tisdale and Whitney Townships (Figure 1-11) are in part time equivalent to the volcanic rocks of the Tisdale Group. For example, the Dome Formation near the Dome mine merges into and is intercalated with the pyroclastic breccia of Formation VI (Krist fragmental). Furthermore, this implies that the Beatty Formation which underlies the Dome Formation is at least in part equivalent to Formation V. Indeed, sedimentary rocks interpreted to be part of the Beatty Formation in southeast Tisdale Township, east of the Preston mine, are intercalated with the volcanic rocks of Formation V.

Figure 1-12 shows a number of composite stratigraphic columns traversing the area in a general east-west arrangement. These illustrate the time equivalence of sedimentation and volcanism. This is also diagrammatically depicted in Figure 1-13.

Timmins-Kirkland Lake Area Volcanic Stratigraphy

Introduction

When the region is viewed in a larger perspective than that of the Timmins area, it is seen that the groups of the Timmins area are in reality supergroups (given that the correlations presented here are correct), and in turn the formations would necessarily be raised to group status. This concept is incorporated in Figure 1-14, whereby the Deloro Group within the Shaw Dome is shown as forming part of the Lower Supergroup (in a regional context). The Tisdale Group on the other hand corresponds to the Upper Supergroup. This division of the volcanic rocks into two supergroups follows the subdivision previously presented by D.R. Pyke and L.S. Jensen (1976). The geology of the Timmins-Matachewan area, is taken largely from Pyke (1978b) and that of the Lake Abitibi-Kirkland Lake area from Jensen (1979).

The division between the Lower and Upper Supergroups marks a major change in volcanism, and is the single most important stratigraphic marker in the area. Felsic, calc-alkaline, largely pyroclastic volcanism, with abundant associated iron formation forms the upper part of the Lower Supergroup throughout a large part of the area. The base of the overlying supergroup is marked by

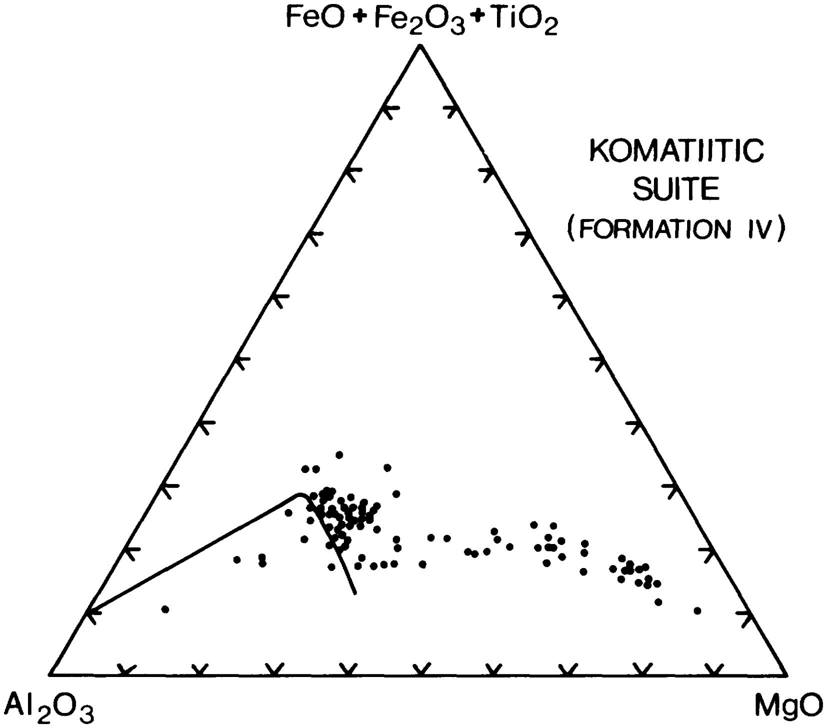

Figure 1-6—Plot of volcanic rocks from the Tisdale Group. Formation IV.

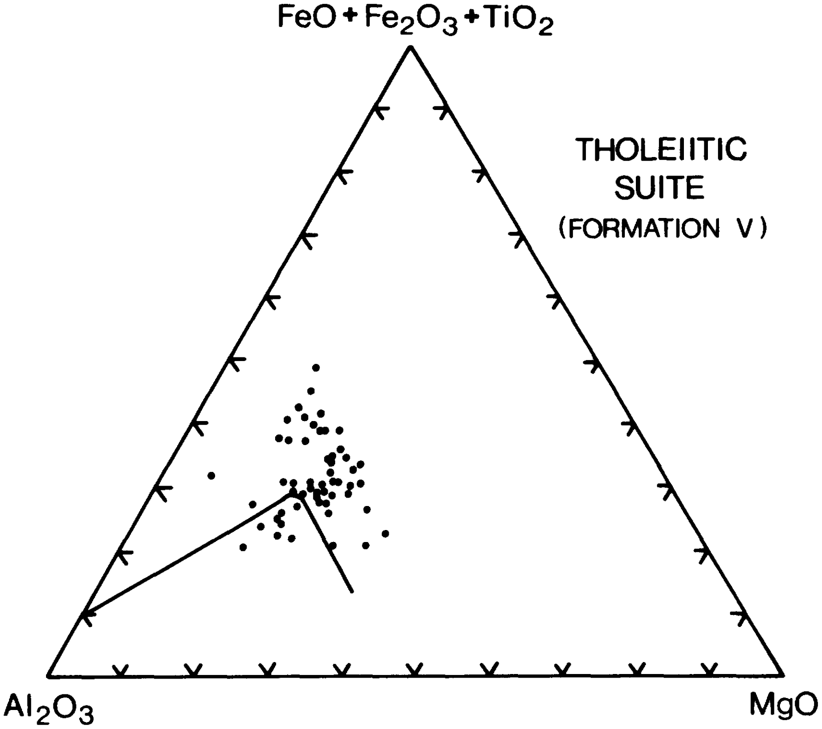

Figure 1-7—Plot of volcanic rocks from the Tisdale Group, Formation V.

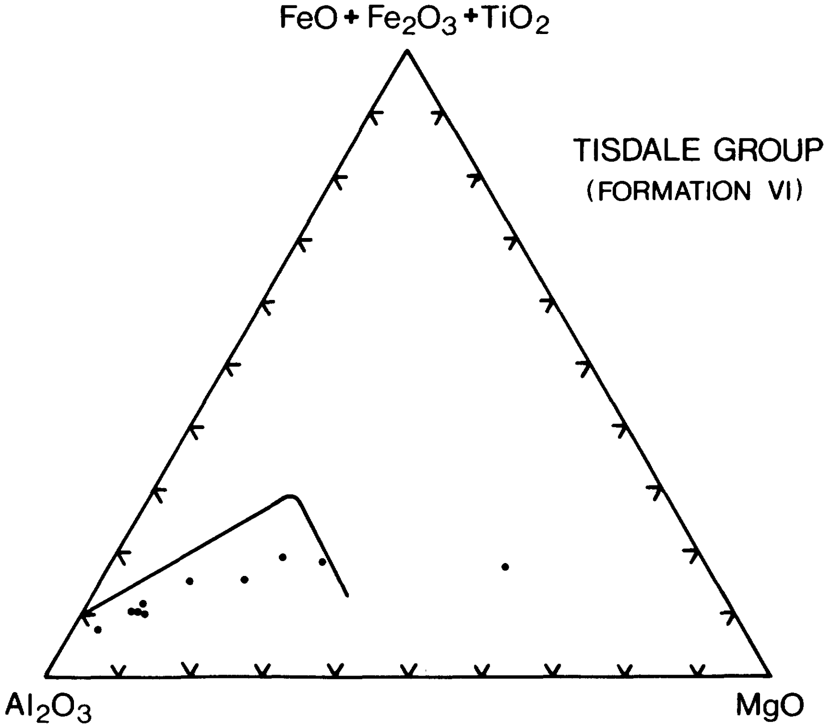

Figure 1-8—Plot of volcanic rocks from the Tisdale Group, Formation VI.

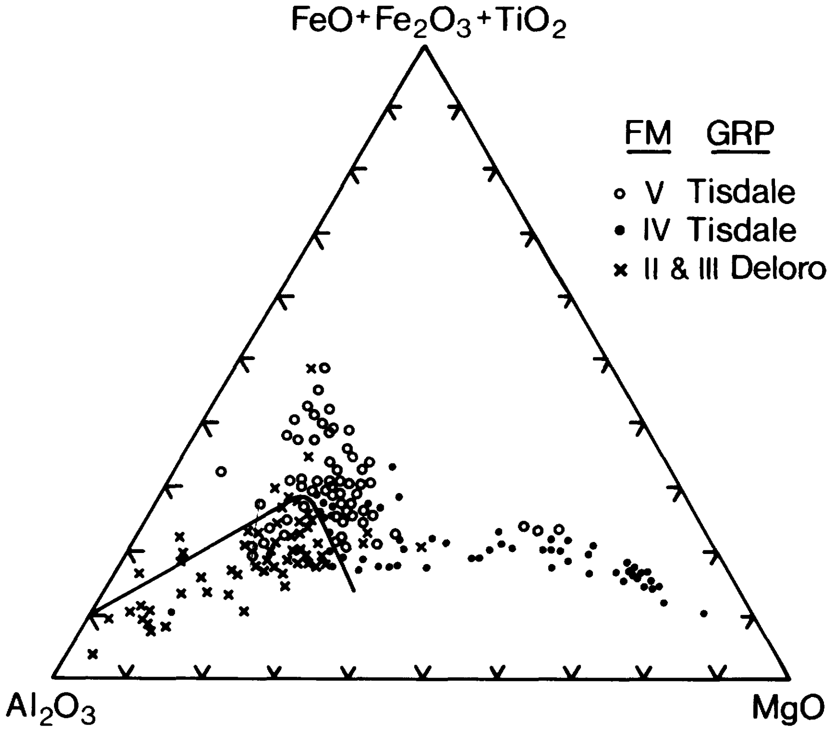

Figure 1-9—Plot of chemical analyses in Formations II to V inclusive.

komatiitic volcanism, which is for the most part ultramafic. At the contact, volcanic rocks of komatiitic and calc-alkaline compositions may be interlayered, and volcanic rocks are interlayered with turbidites, marking the first major incursion of sediments into the area.

The onset of komatiitic volcanism is taken to represent a common litho-stratigraphic horizon throughout the area shown in Figure 1-14, and is the basic assumption on which much of the stratigraphic interpretation hinges. If incorrect then changes will be required. For example, ultramafic volcanic rocks are known to occur at the base of the Deloro Group adjacent to the Kenogamissi Batholith (Pyke 1978a) as well as in the Wabewawa Group in the Kirkland Lake area and therefore can obviously occur at more than one stratigraphic level. Nevertheless, the correlation of the particular komatiitic volcanic rocks in the Timmins area (Figure 1-14) does provide a meaningful starting point for a stratigraphic framework.

Lower Supergroup

The Lower Supergroup is largely a calc-alkaline sequence; tholeiites are prominent only towards the bottom of the supergroup in the Peterlong Lake area (Pyke 1978a) and in the Catherine volcanic rocks in the Kirkland Lake area (Jensen 1978a). Iron formation is common at or near the top of the supergroup and forms a persistent stratigraphic marker throughout much of the area south of the Destor-Porcupine Fault. In fact, the abundance of iron formation is perhaps one of the most obvious differences between the two supergroups. By comparison iron formation is virtually absent from the Upper Supergroup. Furthermore, dunitic intrusions also are confined almost solely to the Lower Supergroup.

The Lower Supergroup is confined to domal-type structures such as the Shaw Dome and Pamour Dome (?) or to the margins of granitic plutons (e.g. Kenogamissi, Round Lake, and Lake Abitibi Batholiths) that have pushed up (domed) the surrounding supracrustal rocks.

Upper Supergroup

The Upper Supergroup is divided into three groups, each characterized by a distinct chemical composition. This subdivision is essentially an extension of the manner in which the Tisdale Group was partitioned in the Timmins area. The chemo-stratigraphic breakdown as shown on Figure 1-14 is largely based on a number of unpublished analyses (Pyke, in preparation and Jensen, in preparation).

The base of the Upper Supergroup is composed mainly of basaltic and peridotitic komatiites and magnesium-rich tholeiitic basalts; the komatiitic rocks are most common near the base of the Lower Group. The overlying group is dominantly an iron-rich tholeiitic sequence. The Upper Group is composed almost entirely of volcanic rocks of calc-alkaline chemical affinity.

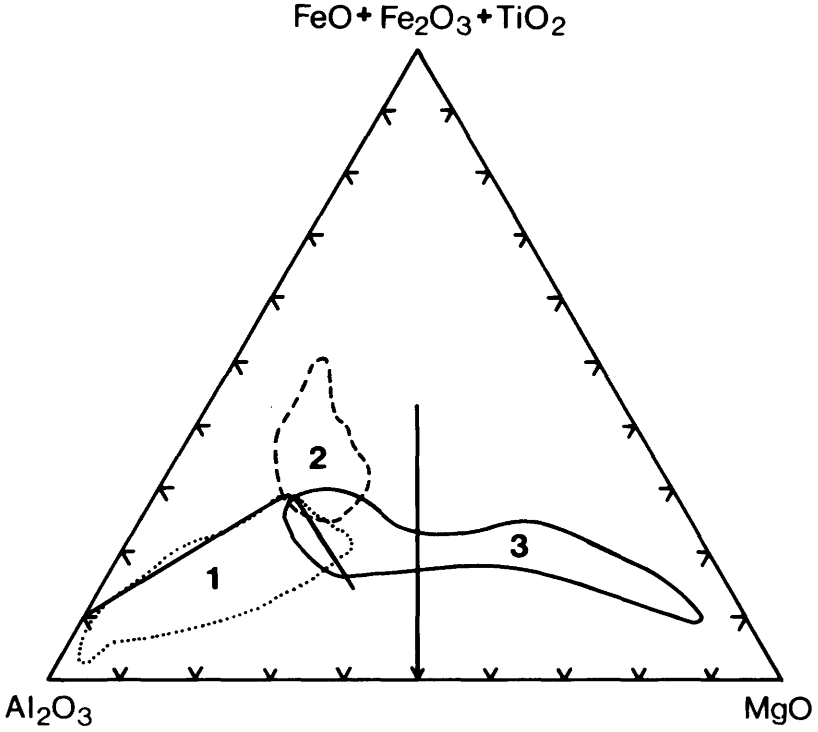

Figure 1-10—Plot shows fields of calc-alkalic (1), tholeiitic (2), and komatiitic suites (3) as taken from Figure 9.

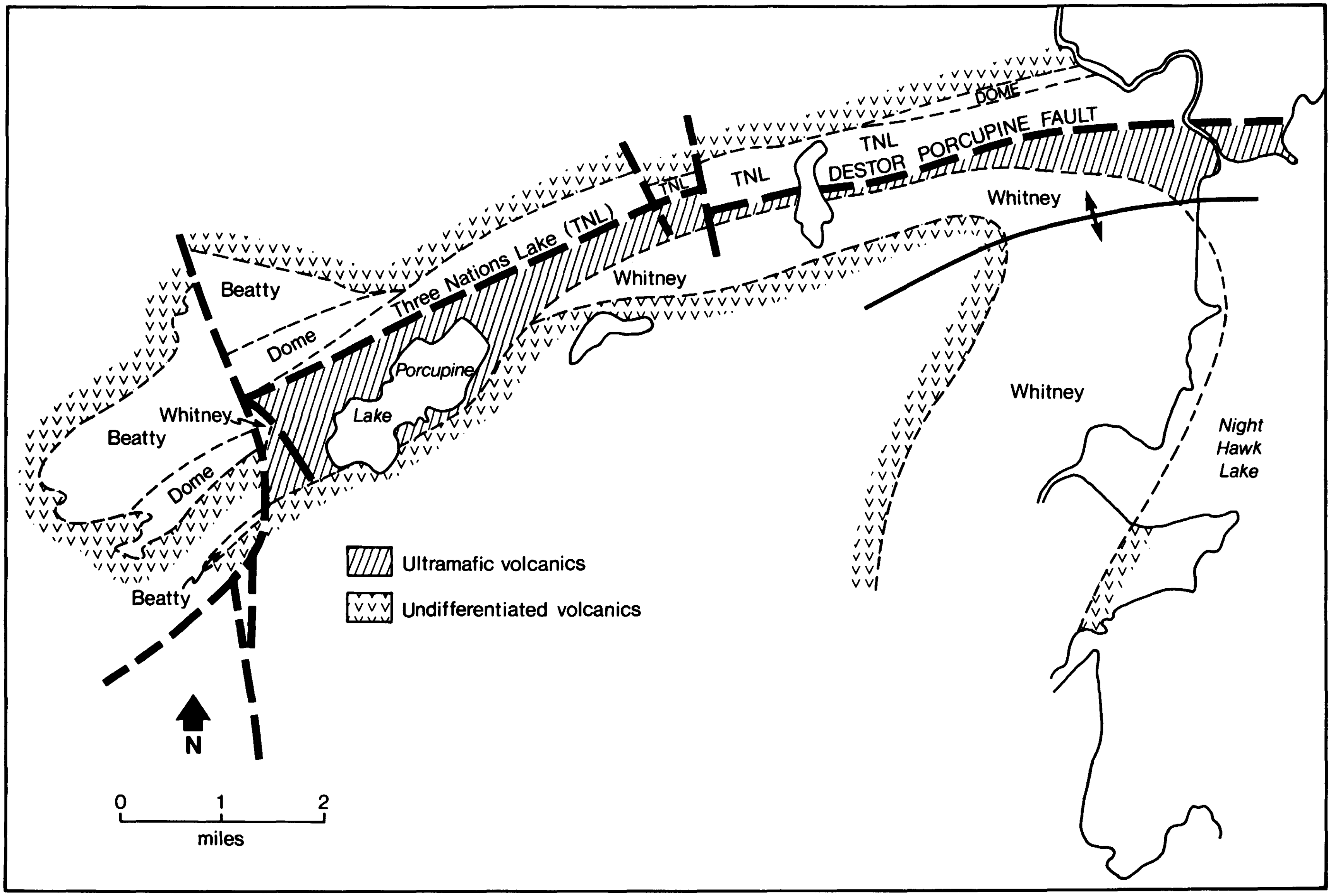

Figure 1-11—Map showing the distribution of the formations (Whitney, Beatty, Dome, Three Nations Lake) of the Porcupine Group in part of the Timmins area (largely from Lorsong 1975).

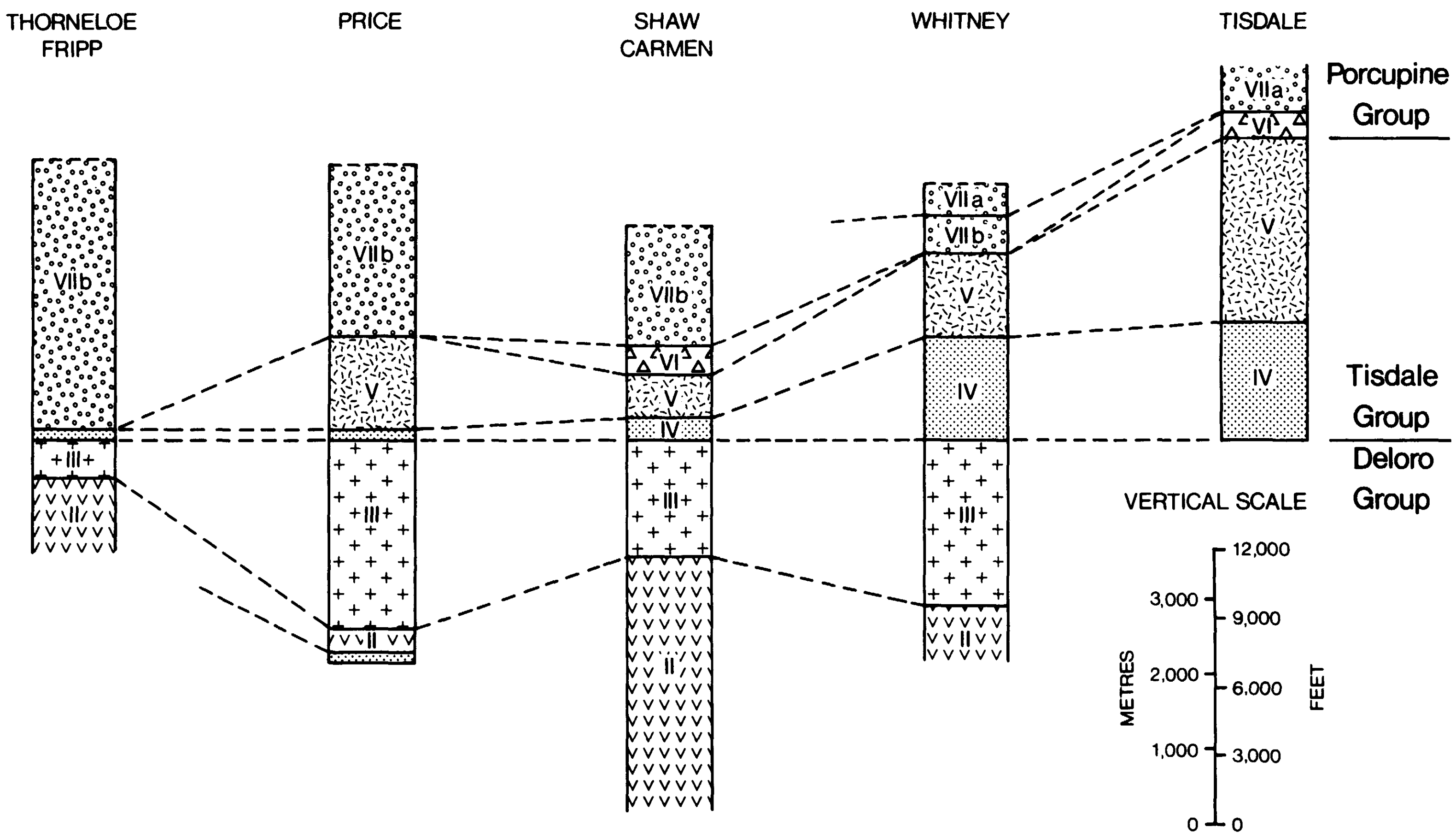

Figure 1-12—Stratigraphic columns of the Timmins area illustrating the generalized correlations of the various stratigraphic units.

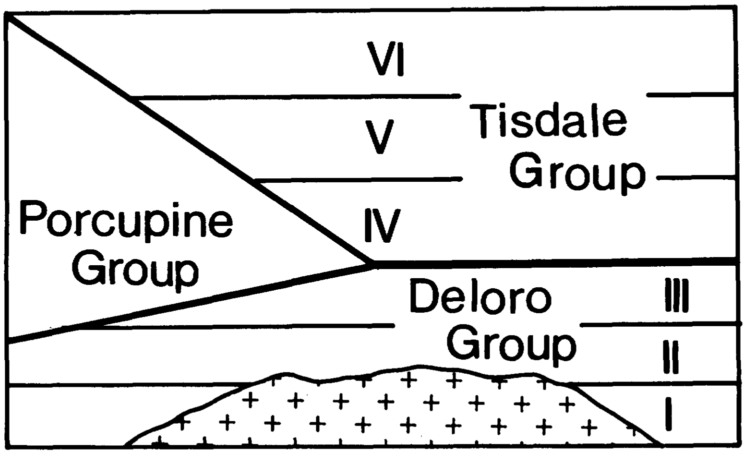

Figure 1-13—Diagrammatic illustration of the time equivalence of sedimentation (Porcupine Group) and volcanism (Deloro and Tisdale Groups) in the Timmins area.

Given that the above correlations are correct, then there is considerable thinning of the Upper Supergroup from east to west. The maximum thickness is approximately 30000 m near the Ontario-Quebec provincial boundary (Jensen 1979), and approximately 12000 m in the Timmins-Matachewan area. Near the Ontario-Quebec boundary the principal structure within the Upper Supergroup is an east-plunging synclinorium (Baragar 1968; Goodwin 1965; Jensen 1979). The volcanic rocks of the Timmins-Matachewan area are interpreted to be at the closure of this synclinorium. The volcanic strata not only thin to the west, but they are highly disrupted by batholithic intrusions, resulting in bifurcations of the main synclinal axis. The emplacement of the Kenogamissi Batholith and the resulting updoming of the adjacent volcanic rocks of the Lower Supergroup marks the westward termination of the Upper Supergroup and associated synclinorium.

Gold Mineralization - Some Regional Implications

A number of features of the gold mineralization in the Timmins-Kirkland Lake area become evident on a regional scale. Some of the more obvious relationships are:

1)Virtually all the past-producing and producing gold mines are in proximity to the major east-west trending fault zones, i.e. the Destor-Porcupine and Larder Lake Faults.

2)Along and near the fault zones there has been extensive carbonatization.

3)The faults coincide approximatley with the basal group of the Upper Supergroup, that is the komatiitic sequence.

4)Sedimentary rocks are relatively more abundant in the gold-producing areas than elsewhere.

5)Small stocks of quartz-feldspar porphyry or syenite are common within or near the komatiitic sequence.

It is the writer's opinion that the above factors provide the main building blocks for all the gold deposits in the area. Notwithstanding the variations between ore zones, whether they be quartz-carbonate veins in a variety of host rocks, carbonate or siliceous exhalative layers, or pyritized zones, a common mode of origin is suggested. Of the factors controlling ore deposition, three are of critical importance: faulting, carbonatization, and the presence of carbonate-bearing sedimentary rocks.

1)The fault zones are important for ground preparation or "plumbing". This is particularly obvious in that numerous localities throughout the Timmins-Kirkland Lake area exhibit factors 2 to 5 given above, yet have no important producers. One is therefore forced to recognize the importance of the Destor-Porcupine and Larder Lake Faults in the localization of the ore zones. This has been recognized by prospectors and explorationists for years as pointed out by A.B. Burrows (1924), P.E. Hopkins (1924), M.E. Hurst (1942), and J.E. Thomson (1948).

2)The carbonatization process is important as a means of releasing gold contained in rocks (Keays 1975; Viljoen *et al.* 1969). In this regard, komatiites are particularly significant as they are more susceptible to carbonatization than other rock types (Pyke 1976) thereby making their contained gold readily available for transportation and concentration.

3)The sedimentary rocks are believed to be important as a source of CO_2. This was probably present in the original sediments as calcium carbonate cement, but also in pore fluids prior to lithification.

Briefly then the prototype model envisaged for the gold deposits is as follows:

1)The Destor-Porcupine Fault and Larder Lake Fault are believed to be very primitive fractures developed in the Early Archean crust.

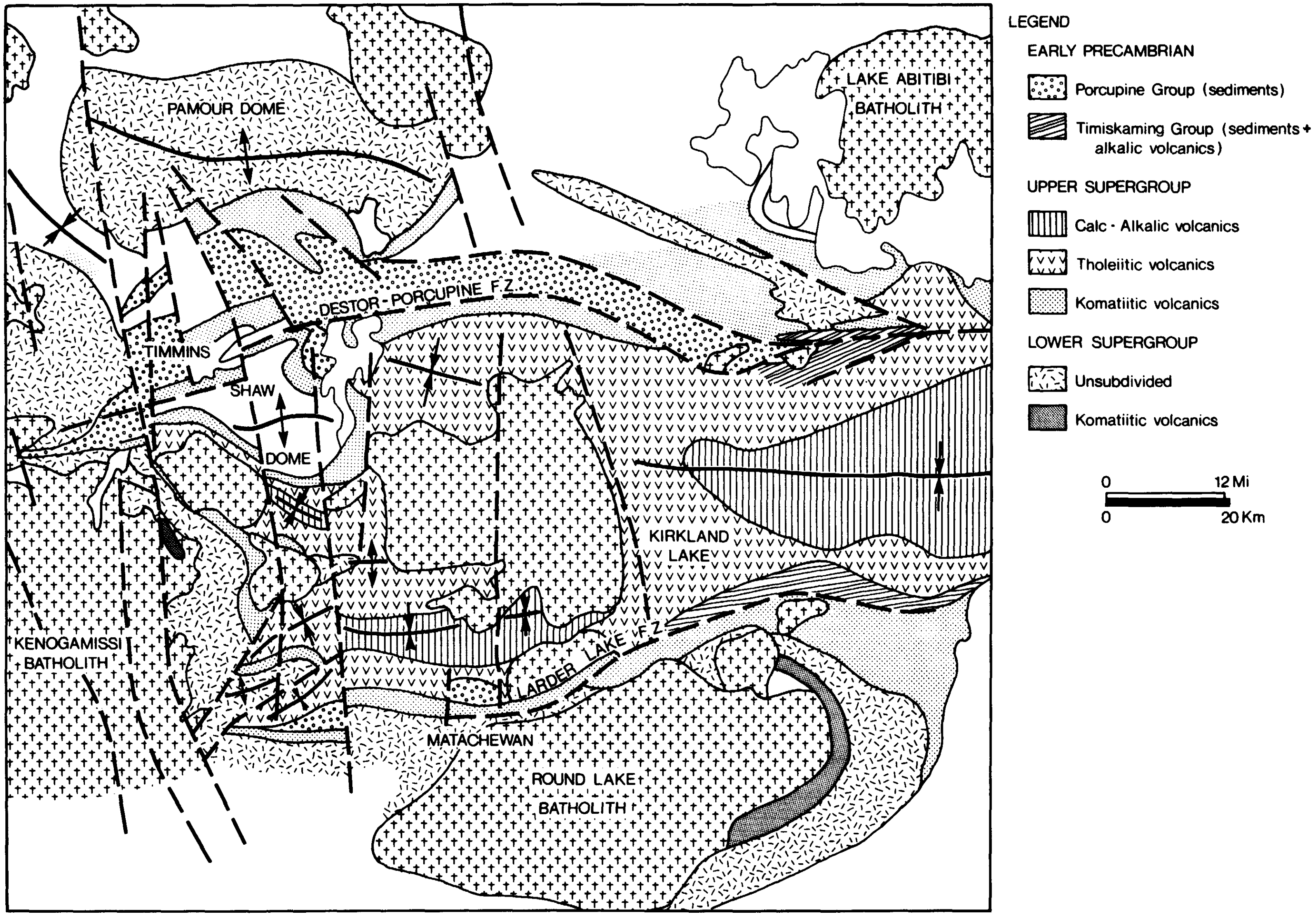

Figure 1-14—Stratigraphy of the Timmins-Kirkland Lake area (after Pyke 1978b and Jensen 1979).

2)Continued movement along these fault zones led to extensive fracturing and formation of dilatant zones.

3)Fluids from the surrounding rocks migrated to the fractured fault zones during dynamothermal metamorphism. It is suggested that most of these fluids were derived from the sedimentary rocks as they initially had a higher porosity than other rock types. A small amount of CO_2 in the nearby sedimentary rocks would probably be sufficient to produce extensive carbonatization if concentrated along the fault zones.

4)Extensive carbonatization of the rocks in and adjacent to the fault zones led to the release of large quantities of gold. Most of this gold was probably derived from the komatiites because of their higher susceptibility to carbonatization as compared to other rock types.

5)Part of the released gold was concentrated by a variety of mechanisms into quartz-carbonate veins filling dilatant zones, pyritized zones, or stratiform exhalative deposits.

6)The effect of the intrusion of later quartz porphyry or syenite into the earlier concentrations was to remobilize and further concentrate the gold.

Although a variety of mechanisms may be invoked for the ultimate concentration of gold into an ore deposit, the presence of faults, carbonatization, and proximity to sedimentary rocks are, from the regional perspective, characteristics common to all deposits in the area.

The Volcanic-Tectonic Setting of Gold Deposits in the Timmins Area, Ontario

R.G. Roberts[1]

Abstract

In the Timmins area, the structural architecture is controlled to a large degree by volcanic linear domes and troughs. The Porcupine Syncline is at the position of a former volcanic trough that received turbidite-type sediments. The trough was bounded on the north and southwest by linear domes, the positions of which are now occupied by the Central Tisdale Anticline and the South Tisdale Anticline.

The trends of the two domes converged at an angle of approximately 60 degrees. The trend of the Central Tisdale dome is parallel to the present regional trend, and it appears to have had a comparatively simple volcanic history. The complexities of the South Tisdale dome are due to a series of movements, leading ultimately to its collapse, on axes of rotation parallel to the regional trend. These axes transect the earlier trend of the dome. These later volcanic movements are reflected in the Timiskaming-Keewatin unconformity. The first tectonic deformation D_1 was imprinted on these volcanic, D_0, structures.

Each gold-bearing unit consists of two components: carbonate-rich unit, which may be a sedimentary rock or an altered volcanic rock; and a quartz vein system which has a direct spatial association with the carbonate-rich unit. The formation of the altered volcanic units predates D_1. The association of altered (carbonatized) volcanic units with carbonate-rich sedimentary rocks suggests that the carbonatization was a volcanic (near-surface) process. The quartz veins postdate the emplacement of the carbonate-rich units.

Introduction

This paper describes the volcanic-tectonic history of part of the Timmins area, and shows the relationship of these events to the formation of the gold deposits. The lithologies of units have not been described except where such descriptions are directly relevant to the formation of the gold-bearing units. For descriptions of the lithologies, the reader is referred to S.A. Ferguson *et al.* (1968), D.R. Pyke (1975), J.F. Davies (1977), and B.J. Fryer *et al.* (1979).

Terms such as Keewatin and Timiskaming are used for convenience, to identify well established sedimentary rock units[2].

Structures of the Timmins Area

Major Structures

The major structures of the Timmins area are illustrated in Figure 2-1. The dominant structure is the Porcupine Syncline which closes in the southwest and plunges to the northeast. It is flanked on the northwest by the Central Tisdale Anticline and on the southwest by the South Tisdale Anticline. The trends of the axes of these two anticlines converge at 60 degrees.

The Burrows-Benedict Fault is the most prominent of a number of late faults, all of which strike northwest. They transect the fold structures and are consequently the least controversial faults of the area. The Burrows-Benedict Fault is vertical, and the probable movement was east block down.

The Destor-Porcupine Fault lies within a zone of sedimentary rocks and serpentinized ultramafic rocks. The fault separates volcanic rocks of the Tisdale Group and sedimentary rocks of the Porcupine Group, from rocks of The Deloro Group to the south. The proposed fault is parallel to the strike of the rock units, and consequently, its precise location is the subject of debate.

The Hollinger Fault occurs at about the position of the axial surface of the Central Tisdale Anticline.

Other faults have been proposed (Davies 1977; Ferguson *et al.* 1968), but will not be described here.

Minor Structures

Minor or mesoscopic structures (structures on the scale of a hand specimen and up to an outcrop) may be

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[2] All rocks in the area have been metamorphosed, therefore the prefix 'meta' is not used.

ascribed to specific periods of deformation, and their crosscutting relationships serve to establish the chronology of the periods of deformation. They are described below in chronological order.

D_0 Deformation

The earliest minor structures are prelithification or slump folds in bedded greywacke-argillite units. The F_0 folds occur typically as isolated fold structures confined between apparently nonfolded beds. They may be associated with locally brecciated beds and with discontinuities that have the appearance of unconformities but are probably the result of sliding during the D_0 deformation. The folds do not have an associated fabric. Younger foliations may transect the F_0 folds or be deflected by them.

D_1 Deformation

A well developed, penetrative, planar and linear fabric was imprinted on the rocks during this deformation. S_1 is defined by the preferred orientation of chlorite and sericite. It is axial planar to mesoscopic F_1 folds (Figure 2-2). The lineation L_1 is defined by the plunge of F_1 fold axes, the intersection of bedding and S_1, and the elongation of pillows, variolites, clasts, and aggregates of mechanically resistant grains. In any one domain, the various linear structures have the same attitude and lie in the plane of S_1 (Figure 2-1).

D_2 Deformation

The principal mesoscopic structure of this deformation is a crenulation-fracture cleavage, S_2. The cleavage strikes northeast and dips steeply, predominantly to the northwest (Figure 2-3). The attitude of S_2 is reasonably constant throughout the area. Mesoscopic F_2 folds include crenulations, kinks, and flexural folds (Figure 2-4). Folds plunge to the north at steep to moderately steep angles. Both bedding and S_1 are folded.

D_3 Deformation

Subhorizontal kink planes with associated fracture cleavage are associated with the D_3 deformation. The structures are unevenly developed throughout the area. They are best developed in units with well developed S_1 foliation, such as the feldspar porphyry units and the argillites.

Relationship of Major Structures to Minor Structures

The mesoscopic planar and linear structures of the D_1 deformation are found in all rock units except the diabase dikes. Thus the Keewatin-Timiskaming unconformity predates the D_1 deformation.

The attitudes of S_1 and L_1 are shown in Figure 2-1. The regional strike of the foliation is approximately northeast (040 to 070 degrees), and is invariably steeply dipping. In the Timmins area the attitude of the foliation changes such that it is approximately parallel to the trend of the South Tisdale Anticline; transects the trace of the axial surface of the Porcupine Syncline at approximately 35 degrees; and transects the trace of the Central Tisdale Anticline at approximately 20 degrees. This suggests that these structures have a history of deformation that, in part at least, predates the S_1 foliation.

The north-trending S_2 fracture cleavage is not geometrically related to the major structures since it transects the trends of the folds at high angles. The D_2 deformation produced mesoscopic flexural folds, particularly in rocks with strong S_1 foliation, but the variable attitude of S_1 throughout the area (Figure 2-1) cannot be ascribed to regional scale F_2 folds. It is, therefore, concluded that the D_2 deformation did not produce major fold structures.

The Porcupine Syncline

General Statement

One of the more puzzling aspects of the structural geology of the Timmins area relates to the dominantly eastward plunge of the structures. This includes the mesoscopic L_1 structures, the axis of the Porcupine Syncline, the plunge of the porphyry units, and the unconformable relationships on the south limb of the Porcupine Syncline exposed at the Dome mine. The closure of the South Tisdale Anticline to the west is difficult to reconcile with the generally east-plunging structures. This is further complicated by the eastward plunge of primary structures at the Edwards shaft (Ferguson *et al.* 1968, Section 10), which is located approximately at the core of the South Tisdale Anticline (Figure 2-5).

Outcrop Pattern

In plan view (Figure 2-5) the Porcupine Syncline as defined by the Krist Formation has a hook-shaped pattern in which the long limb of the hook is the north limb of the syncline. This pattern is repeated by the conglomerate unit at the base of the Timiskaming sedimentary rocks, and by the porphyry that conformably underlies the South Greenstones unit. Consequently, in a section across the Porcupine Syncline 2 km east of the Dome mine (just west of the Burrows-Benedict Fault), the rock units exposed at surface are south-facing.

Contact Relationships Exposed at the Dome Mine

The relationships between the volcanic flow-units and sedimentary units in the Dome mine are illustrated in the geological map of the twelfth level (Figure 2-6). The more important structural relationships among the rock units are summarized below.

1) The Krist Formation is overlain and underlain by thin

units of carbonaceous shale. Within the mine, the Krist Formation grades to the east from a felsic unit containing breccia fragments to a unit of fine-grained tuff and lapilli-sized fragments which contains approximately 15 percent carbonaceous material. Further east, the Krist wedges out and the underlying and overlying carbonaceous units form a high unit.

2) There is no detectable unconformable relationship between the carbonaceous shale overlying the Krist Formation and the Timiskaming conglomerate.

3) The carbonaceous shale underlying the Krist Formation, and conformable with the Krist, is in faulted contact with the Timiskaming sedimentary rocks to the south. These sedimentary rocks consist of beds of carbonaceous argillite and greywacke-argillite couplets. The sedimentary rocks are folded but carefully mapped sections through them, from the Krist to the carbonate-rich units to the south, show that they are south-facing. T.G. Holmes (1968) arrived at the same conclusion.

4) The mafic flows interfinger with units of massive tuff, laminated cherty and sericitic units (tuff), and units of conglomerate. These relationships are illustrated in Figure 2-7. The contact between the flows and the conglomerate is therefore not an unconformity but one that may be expected at the termination of a sequence of flows.

5) The ankerite units which occur within interflow tuff extend into the sequence of conglomerate and tuff.

6) The mafic flows, laminated tuff, conglomerate, and massive tuff described above dip to the northeast. To the east, these units are overlain by the south-facing Timiskaming sedimentary rocks (Figure 2-6).

7) A zone of carbonate-rich rocks and porphyries overlies Timiskaming greywacke-argillite, separating the sedimentary rocks from the south-facing mafic flows of the South Greenstones unit (Figure 2-6). The carbonate-rich rocks consist of two mappable units: "carbonate rock" and "Highly Altered" (Holmes 1968). The field evidence indicates that the two units are the result of alteration processes, but their precise origin is in doubt (Fryer *et al.* 1979). Holmes (1968) and Davies (1977) suggest that the carbonate-rich rocks and porphyries of this zone define a fault separating the south-facing Timiskaming sedimentary rocks from the south-facing South Greenstones unit. Faults occur within the units but is is difficult to demonstrate that they involve major displacements. The continuous nature of the sequence is suggested by the fact that sedimentary rocks occur within the zone of carbonate-rich rocks, and "carbonate rock" and Highly Altered" may occur within and towards the top of the Timiskaming sedimentary sequence.

Volcanic-Tectonic History of the Porcupine Syncline

In the following, the events that led to the development of the Porcupine Syncline are described. In the reconstruction, emphasis is placed on the structural events and the relationship of these structural events to the history of sedimentation. This leads to the conclusion that significant deformation occurred during volcanism. The Porcupine Syncline developed as a trough receiving turbidite sediments. The trough was flanked by a linear dome to the north (the Central Tisdale Anticline, trending N60E) and a linear dome to the south (the South Tisdale Anticline).

Figure 2-11 is a right section across the Porcupine Syncline looking to the southwest. The information projected onto the section is obtained from the surface geological map (Ferguson *et al.* 1968) and the geological map of the twelfth level of the Dome mine (Figure 2-6). Figures 2-8 to 2-10 depict various stages of volcanic deformation in the development of the structure.

Stage I

At the south limb of the Porcupine Syncline, exposed at the Dome mine, the mafic flows terminate and interfinger with volcanic conglomerate tuff, carbonate-rich chemical sedimentary rocks (ankerite units), and cherty laminated units. The Krist Formation, which throughout the area is underlain and overlain by carbonaceous shale, at the Dome mine thins and passes through a carbonaceous unit with tuff and lapilli-size felsic fragments, to a carbonaceous shale. The coincidence of the facies change involving the Krist Formation with the termination of the underlying flows, suggests that the South Tisdale linear dome controlled the topography of the turbidite basin (Figure 2-8).

Stage II

In order to explain the Timiskaming-Keewatin contact, which varies from conformable to strongly unconformable, it is necessary to postulate a turbidite basin that was subject to subsidence and deformation concomitant with sedimentation.

At Stage II (Figure 2-8), in the central part of the township, the form of the basin was controlled by the South Tisdale dome and the Central Tisdale dome. The trend of the South Tisdale dome converged on the North Tisdale dome at an angle of 60 degrees. The axis of subsidence between these two domes forms the axis of the Porcupine Syncline. The turbidites and Krist Formation of the basin wedge and thin on to the south limb of the basin (syncline) where they are represented by carbonaceous and pyritic, shale, and cherty sedimentary rocks.

East of the Burrows-Benedict Fault and in the northeast corner of the township, the volcanic units face south, and strike approximately parallel to the trend of the South Tisdale dome. It is assumed that this reflects the trend of the axis of a dome, which is northeast of the map-area.

Stage III

This stage (Figure 2-9) was characterized by volcanic movements about axes trending N60E. This direction, which is parallel to the trend of the Destor-Porcupine Fault, cuts across the trends of the South Tisdale Anticline (dome), the Porcupine Syncline (basin), and the dome referred to above, which is northeast of the map-area. Rotation about the N60E trend followed by subsidence resulted in the erosion of volcanic and sedimentary units and the subsequent deposition of sediments to produce the unconformable Keewatin-Timiskaming relationships.

On the south limb of the Porcupine basin at the Dome mine, rotation about the N60E trend resulted in erosion of sedimentary rocks in the immediate vicinity of the South Tisdale dome. This was followed by deposition of the Timiskaming conglomerate. The conglomerate was emplaced by mass transport of clasts suspended in a finer grained matrix, into an environment of quiet sedimentation. Beds of sorted, clast-supported conglomerate occur in the unit. These were probably formed by redeposition of matrix-supported conglomerate. Beds of matrix-free conglomerate, so formed, were later cemented by ferroan calcite precipitated from thermal waters.

Stage IV

Rotation of the north limb of the South Tisdale dome (south limb of the Porcupine Syncline) about the N60E trend is required to form the syncline outlined by the Timiskaming conglomerate unit (Figure 2-10). Since the syncline does not apparently affect the overlying units, its initial development, at least, is associated with volcanic-sedimentary events. The trend of the axial surface of this syncline transects that of the main Porcupine Syncline.

Stage V

The stage depicted in Figure 2-11, is a section across the Porcupine Syncline in its present form. The structural interpretation is constrained by the south-facing Timiskaming sedimentary rocks and South Greenstones unit, and by the structural continuity from the sedimentary rocks to the South Greenstones unit, through the carbonatized ultramafic rocks and porphyry units. These carbonatized volcanic units host the "tourmaline vein" and "fuchsite vein" at the Dome mine.

The events that led up to the emplacement of the South Greenstones unit must have involved the development of a trough with a N60E trend across the southern part of the South Tisdale Anticline or dome.

Summary

In volcanic terranes, a structural model based on folded "layer cake" stratigraphy may not be appropriate. In the Timmins area the structural architecture is controlled to a large degree by volcanic domes and troughs. The history of these domes, as with the South Tisdale dome, may be complex. The Central Tisdale dome appears to have had a more simple volcanic history. The complexities of the South Tisdale dome appear to be due to a series of movements, leading ultimately to its collapse, on axes of rotation parallel to the regional trend. These axes transect the earlier trend of the dome.

The first "tectonic" deformation (D_1) was imprinted on the volcanic structures. The trend of the S_1 and L_1 structures is largely controlled by the two earlier dome structures.

The gold-bearing carbonate-rich units have a direct spatial relationship to the dome structures.

Gold-Bearing Units at the Dome Mine

The gold-bearing units examined by the author consist of two components: a carbonate-rich unit which may be a sedimentary rock or an altered volcanic rock, and a quartz vein system which has a direct spatial association with the carbonate-rich unit. The carbonate-rich components of the various gold-bearing units are described briefly below. The *en echelon* vein systems in the most northern flows exposed in the Dome mine (Figure 2-6) were not examined by the author and are not included in the discussion.

Ankerite Units

The author agrees with the conclusions of Fryer *et al.* (1979) that the ankerite units are chemically precipitated sedimentary rocks with associated fine-grained clastic material. The units typically occur in association with tuff and hyaloclastite beds at flow contacts, and may extend beyond the flows to be interbedded with the volcanic conglomerate and tuffaceous rocks at the "Greenstone Nose". They also occur in association with fine-grained, cherty sedimentary rocks interbedded with the volcanic conglomerate directly overlying the Paymaster Porphyry (the "Trough" of Holmes 1968). Their coincidence with flow contacts is illustrated in Figure 2-7. The apparent crosscutting relationships are simply the consequence of localized interruption of sedimentation by impersistent volcanic units.

The mafic flows associated with the ankerite units are strongly cabonatized and may contain in excess of 20 percent ferroan dolomite, by volume.

Calcite-Cement Conglomerate

The Timiskaming conglomerate contains beds, up to 1 m thick, of clast-supported conglomerate in which the clasts are cemented by ferroan calcite (up to 85 percent), quartz, and minor ferroan dolomite (Figures 2-12 and 2-13). The beds are impersistent along strike (maximum of 10 m), have well defined upper contacts, but may have irregular lower surfaces (Figure 2-14). The host of the calcite-cement conglomerate is matrix-supported conglomerate in which the matrix consists of silt to gravel-sized fragments.

A maximum value of 80 ppb gold was obtained from the carbonate matrix. The ore consists of the calcite-cement conglomerate units, with associated quartz veins (Figures 2-12 and 2-14).

"Highly Altered" and "Carbonate Rock" Units

These units are shown as "carbonate-rich" (altered) rocks in Figure 2-6. These units are the hosts to two quartz vein systems referred to in the mine as the tourmaline vein and the fuchsite vein. Both lithologies have similar mineralogies: ferroan dolomite, minor magnesite, quartz, and chlorite. The "Highly Altered" unit is characterized by chrome-bearing mica giving it a typical greenish cast. The boundaries between the two rock types are gradational, and the buff coloured "carbonate rock" may grade with increasing chlorite to carbonate-rich mafic flows of the South Greenstones unit. A clastic structure was observed in sections of the "Highly Altered". The field evidence indicates that the two rock types of the carbonate-rich unit are the result of alteration processes. On the basis of the high chrome and nickel contents, Fryer *et al.* (1979) have suggested that the "Highly Altered" could be a carbonatized ultramafic rock. This gains more credence by the fact that the unit is at the same stratigraphic position as undoubted carbonatized ultramafic rocks exposed at surface (Figure 2-5).

Time of Formation of the Carbonate-Rich Units

The significant observations are as follows:

1) The carbonate-rich units formed by the alteration of volcanic rocks were affected by the D_1 deformation and contain S_1 and L_1 structures (mesoscopic mineral foliation and lineations).

2) There is a spatial relationship between carbonatized mafic volcanic flows and associated interflow sedimentary rocks that contain beds and laminations of ferroan dolomite (ankerite units).

3) The beds of clast-supported conglomerate in the Timiskaming conglomerate are cemented by ferroan, gold-bearing calcite.

4) The clasts of the Timiskaming conglomerate include carbonatized mafic volcanic rock.

The close spatial relationship of carbonate-bearing sedimentary rocks and carbonatized flows is good evidence that they were formed by the same process. The most reasonable explanation is that the thermal waters that passed through the flows and carbonatized the flows, also caused deposition of carbonate sediments at discharge sites on the seafloor. These or related solutions probably precipitated carbonates in the permeable conglomerate beds.

Development of Vein Structures

The following observations are significant to any model for the genesis of the quartz veins.

1) The veins have a close spatial relationship to carbonate-rich units. This is particularly obvious in the ankerite units where "ladder veins" have very precise restriction to the most carbonate-rich layers of the units.

2) Tabular, continuous veins are generally at the margins of a carbonate-rich unit.

3) The large continuous veins are generally layered, and may have host rock material between layers. Extremely irregular veins surround the large continuous veins. These veins may pass into the larger structure to form a discrete layer to the major vein (Figure 2-15). This structure is very complex in the vicinity of the tourmaline and fuchsite veins, but is relatively simple at the ankerite units. Here they form "gash veins" that pass into the tabular veins within the ankerite units. These "gash veins" are particularly abundant where the ankerite units extend into the conglomerate at the "Greenstone Nose" (Figure 2-7).

4) The "gash veins" or complex veins that pass into the tabular veins are folded by the D_1 deformation. This is shown by their relationship to S_1 (Figure 2-16). In thin section the quartz grains may have sutured grain boundaries, undulose extinction, and subgrain development. At fold closures, quartz grains are lenticular, and lie in the plane of S_1 (Figure 2-17). In hand specimen this is expressed as a fracture cleavage. The large tabular veins may locally show fracture cleavage.

The ladder veins in ankerite units (and also in the fuchsite and tourmaline veins) postdate the tabular veins and associated structures. They do not show the effects of deformation by D_1. They were probably developed by boudinage-type effects during D_1.

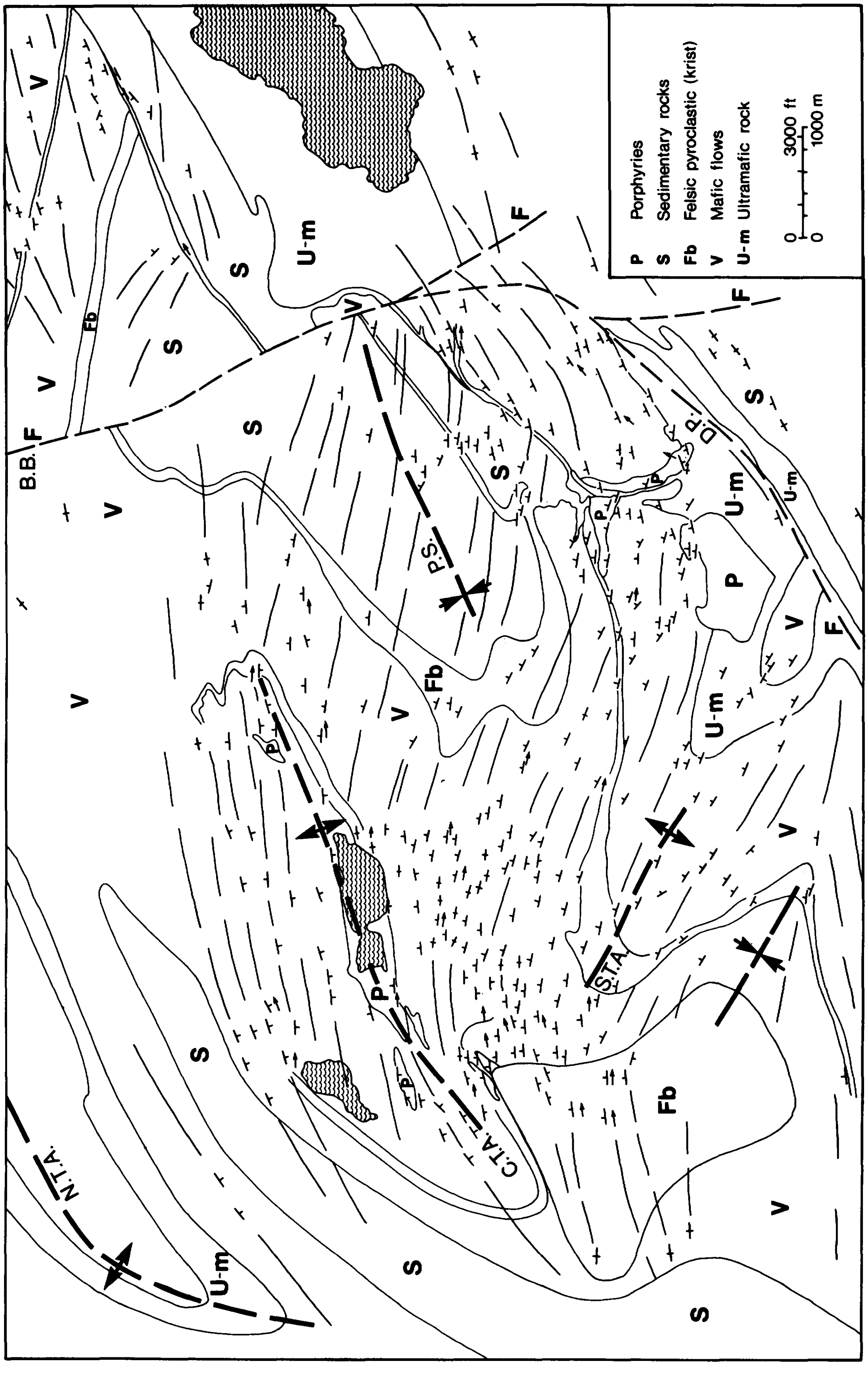

Figure 2-1—Major structures and attitudes of S_1 and L_1 in the Timmins area. ***NTA***–*North Tisdale Anticline;* ***C.T.A.***–*Central Tisdale Anticline;* ***P.S.***–*Porcupine Syncline;* ***S.T.A.***–*South Tisdale Anticline;* ***D.P.***–*Destor-Porcupine Fault;* ***B.B.***–*Burrows-Benedict Fault.*

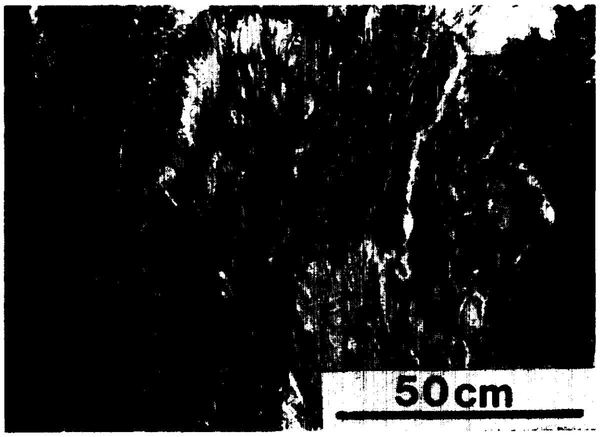

Figure 2-2—F_1 fold in bed of greywacke and shale. Note the axial planar foliation, S_1.

Figure 2-3—Stereographic plot of poles to 270 S_2 cleavage planes from the Timmins area (contours at O, 14, 28 percent per 1 percent area).

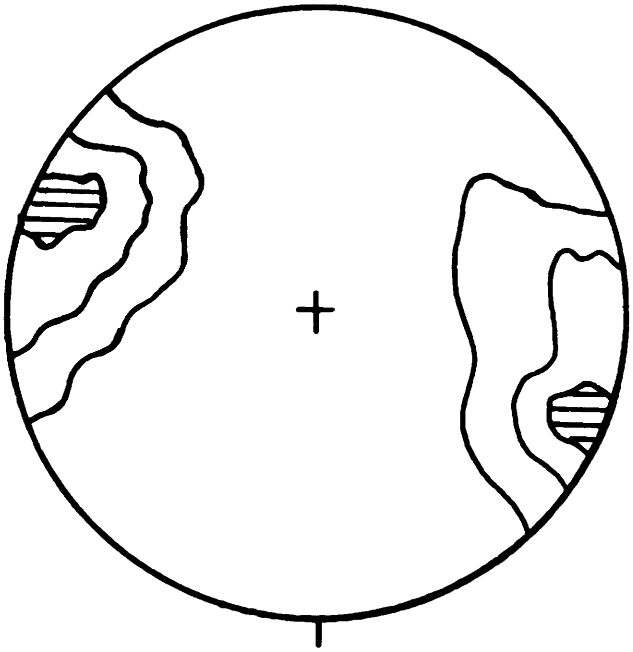

Figure 2-4—F_2 fold in mafic flows. S_1 is folded.

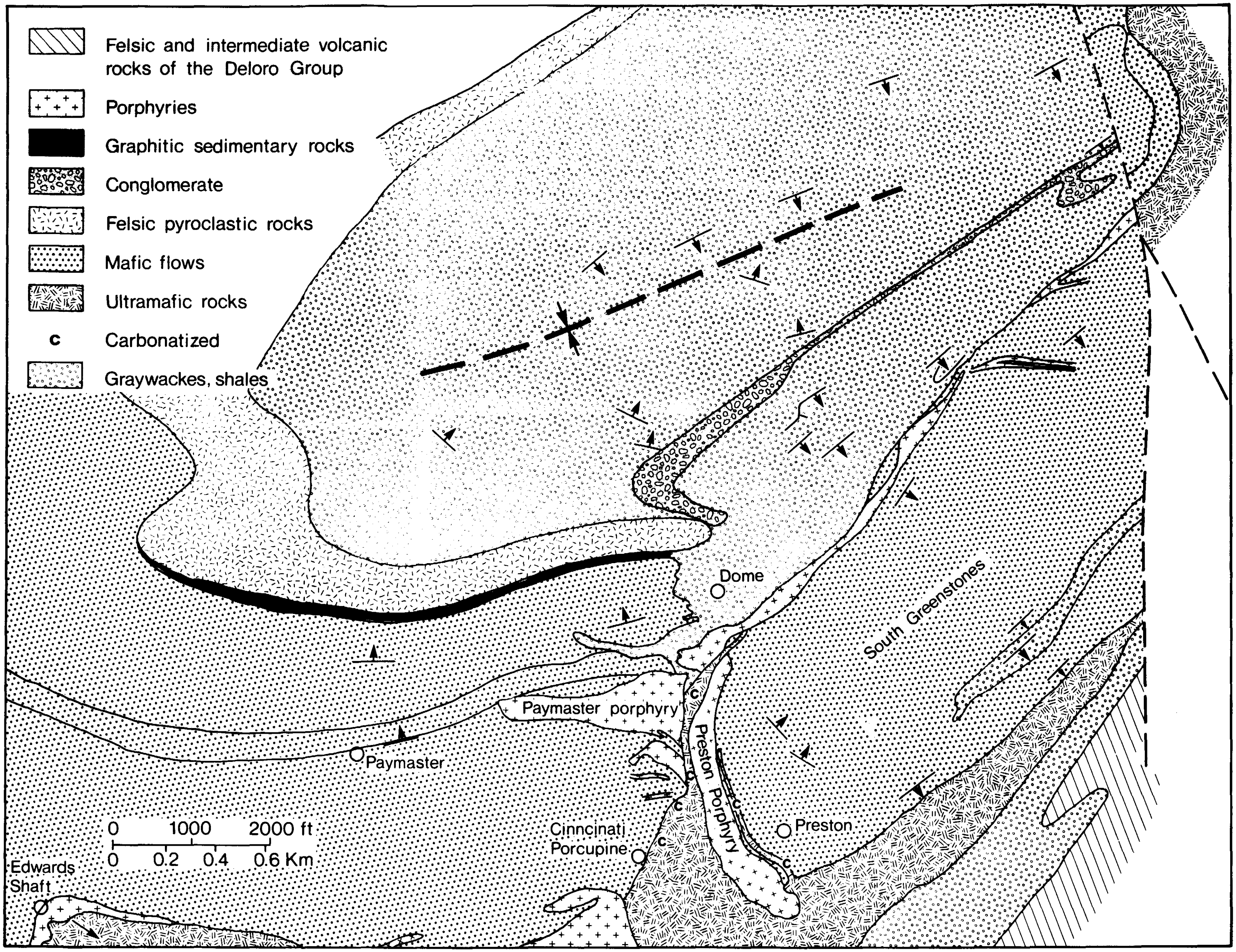

Figure 2-5—The Porcupine Syncline.

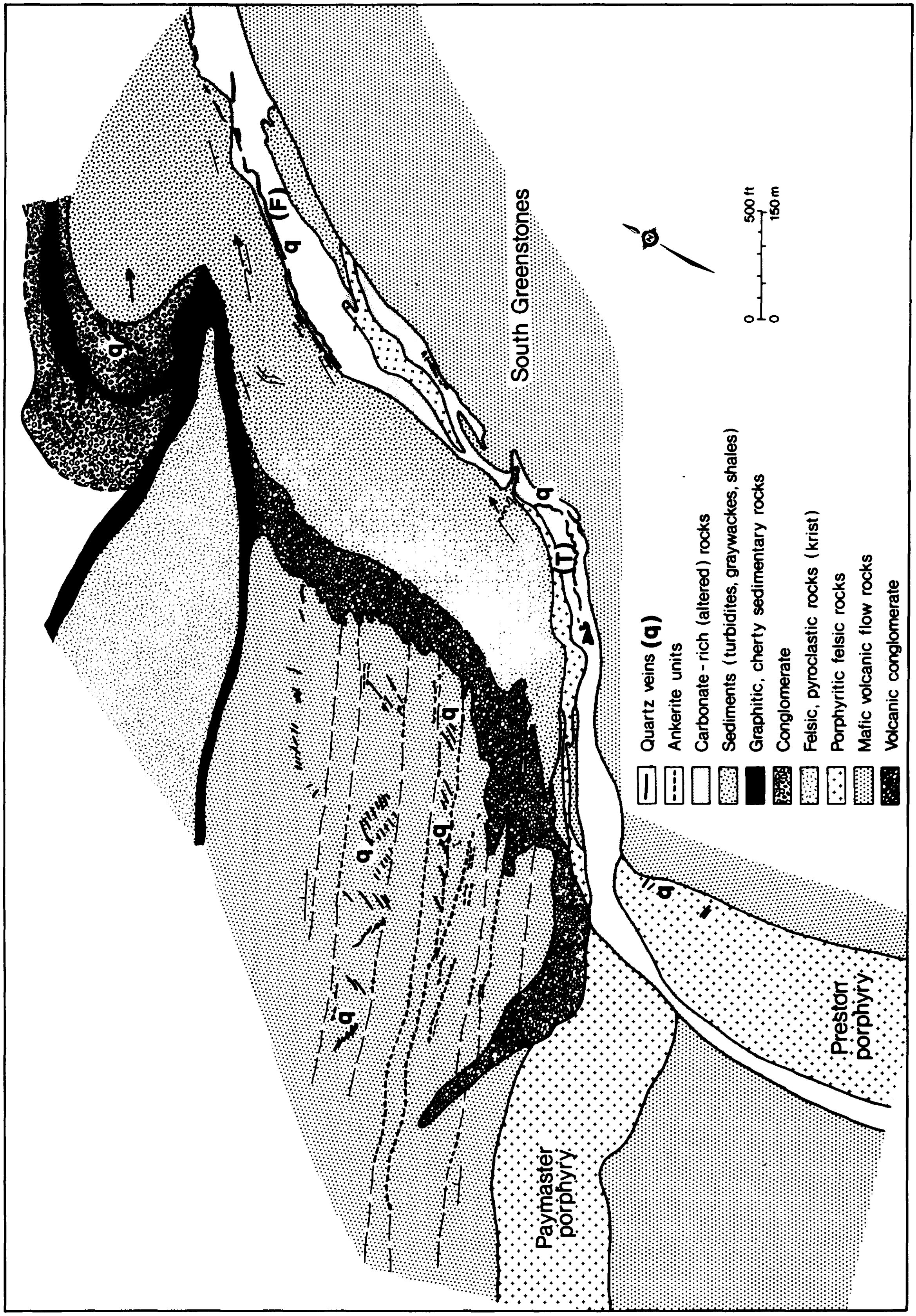

Figure 2-6—Dome mine; map of the 12th level. ***F***–*Fuchsite-quartz vein;* ***T***–*Tourmaline-quartz vein.*

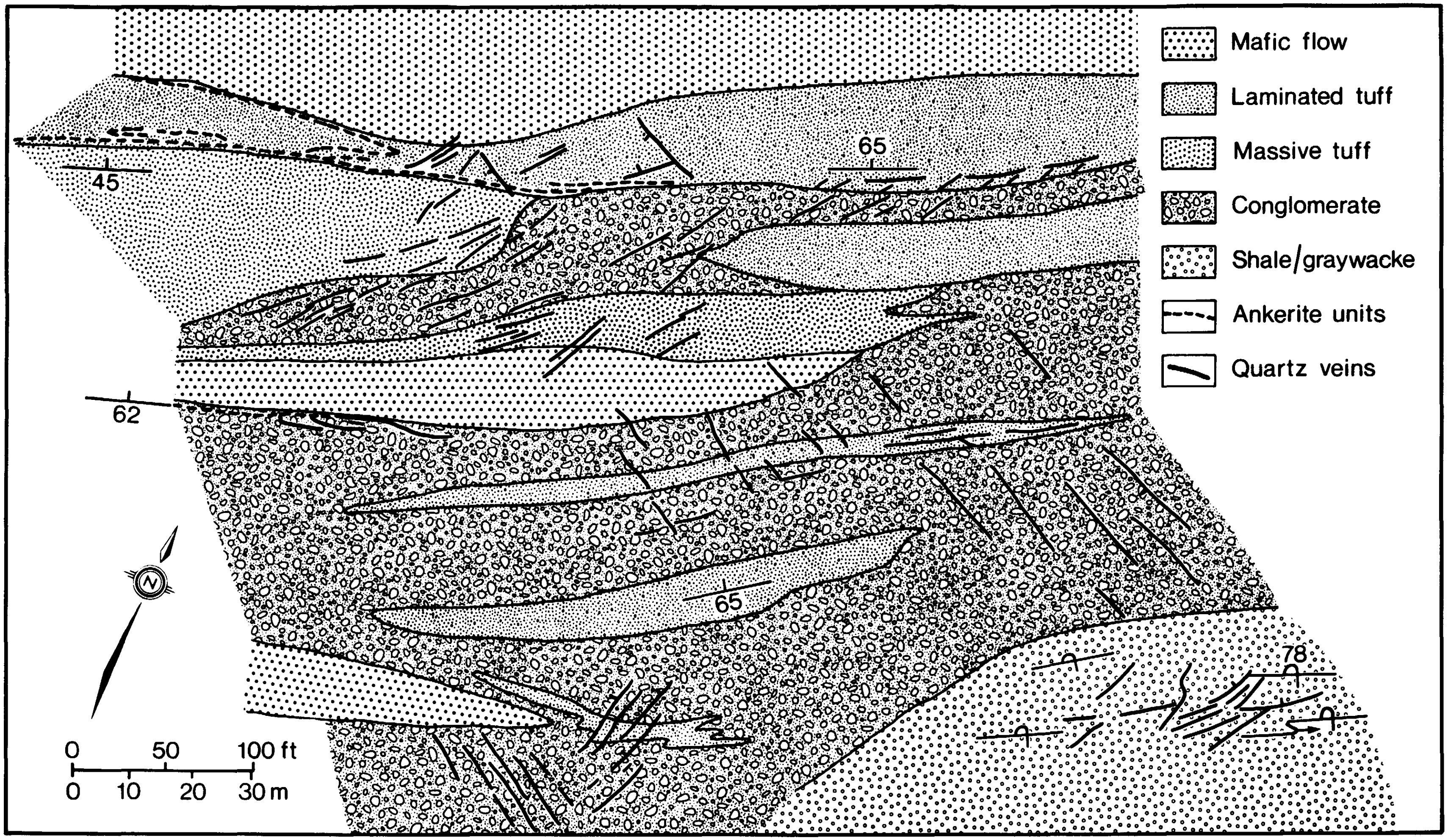

Figure 2-7—Dome mine; map of the 1372-88 stope. The map shows the relationships between flows, volcanic conglomerates, tuff, and ankerite units.

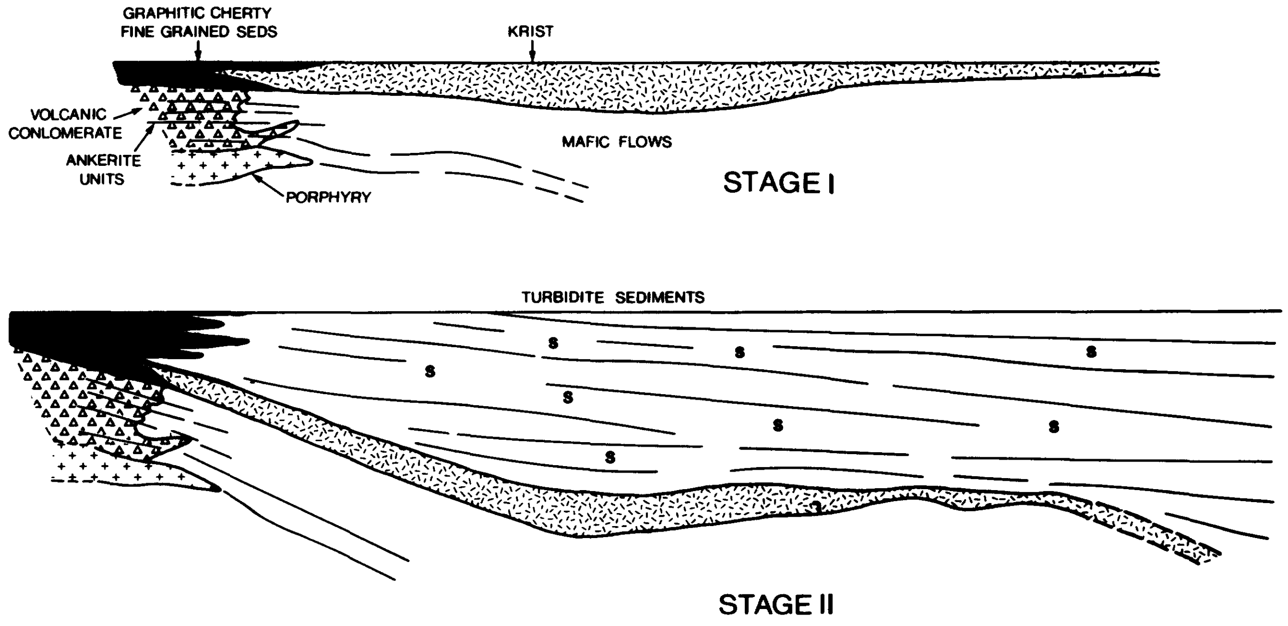

Figure 2-8—Development of the Porcupine Syncline. Stages I and II looking southwest.

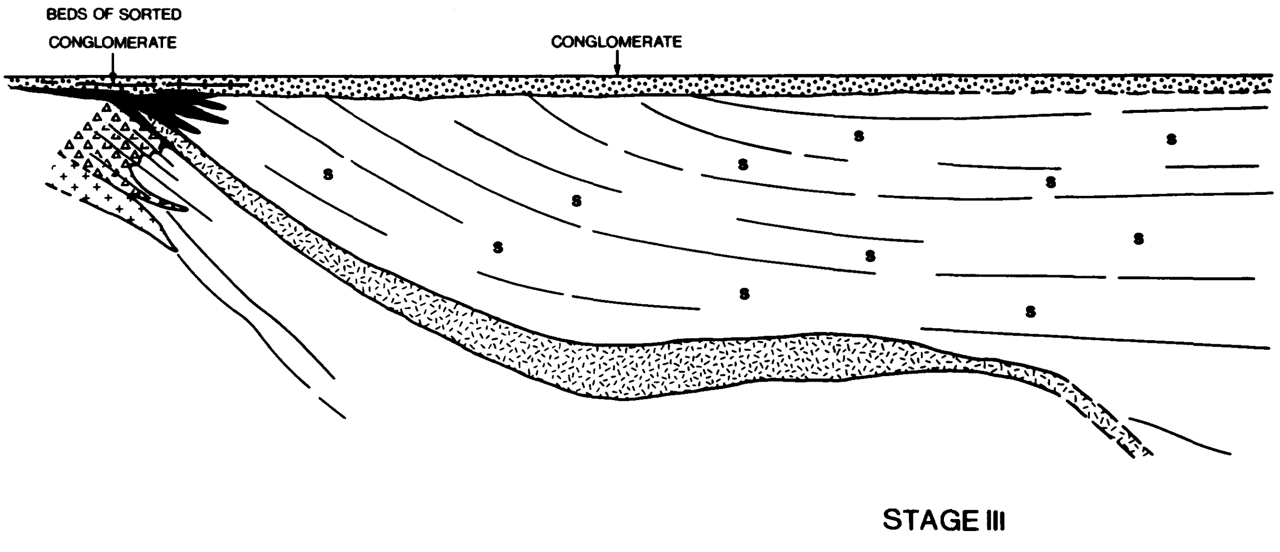

Figure 2-9—Development of the Porcupine Syncline. Stage III.

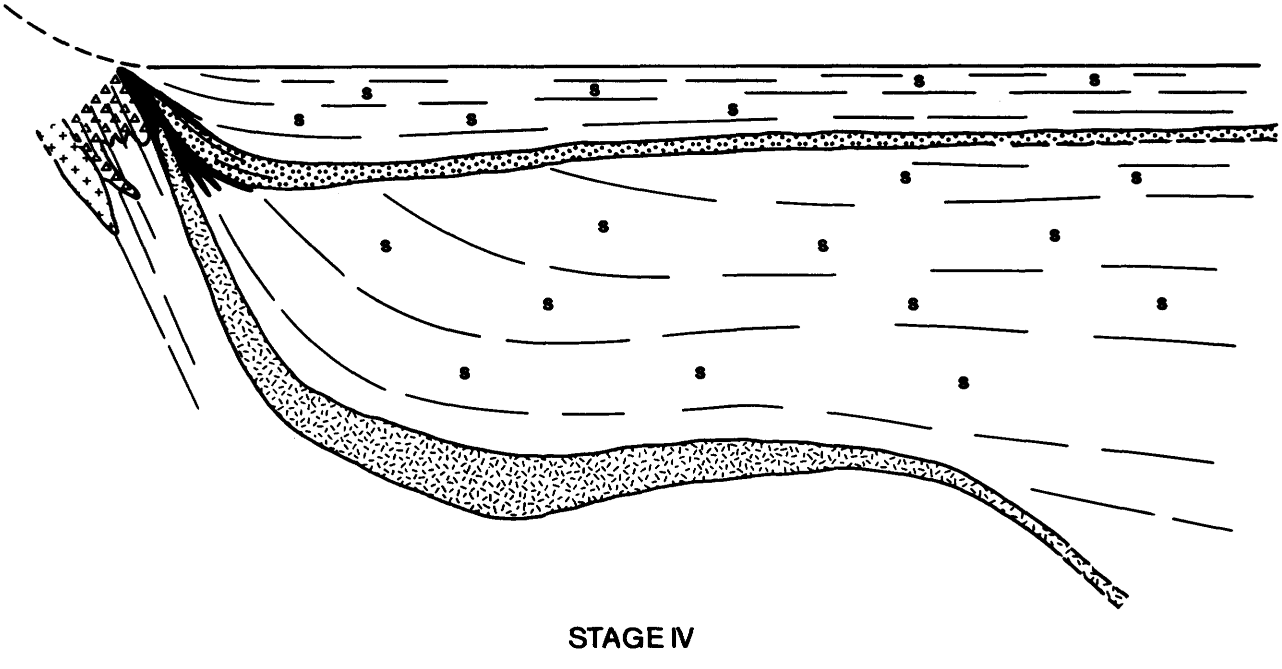

Figure 2-10—Development of the Porcupine Syncline. Stage IV.

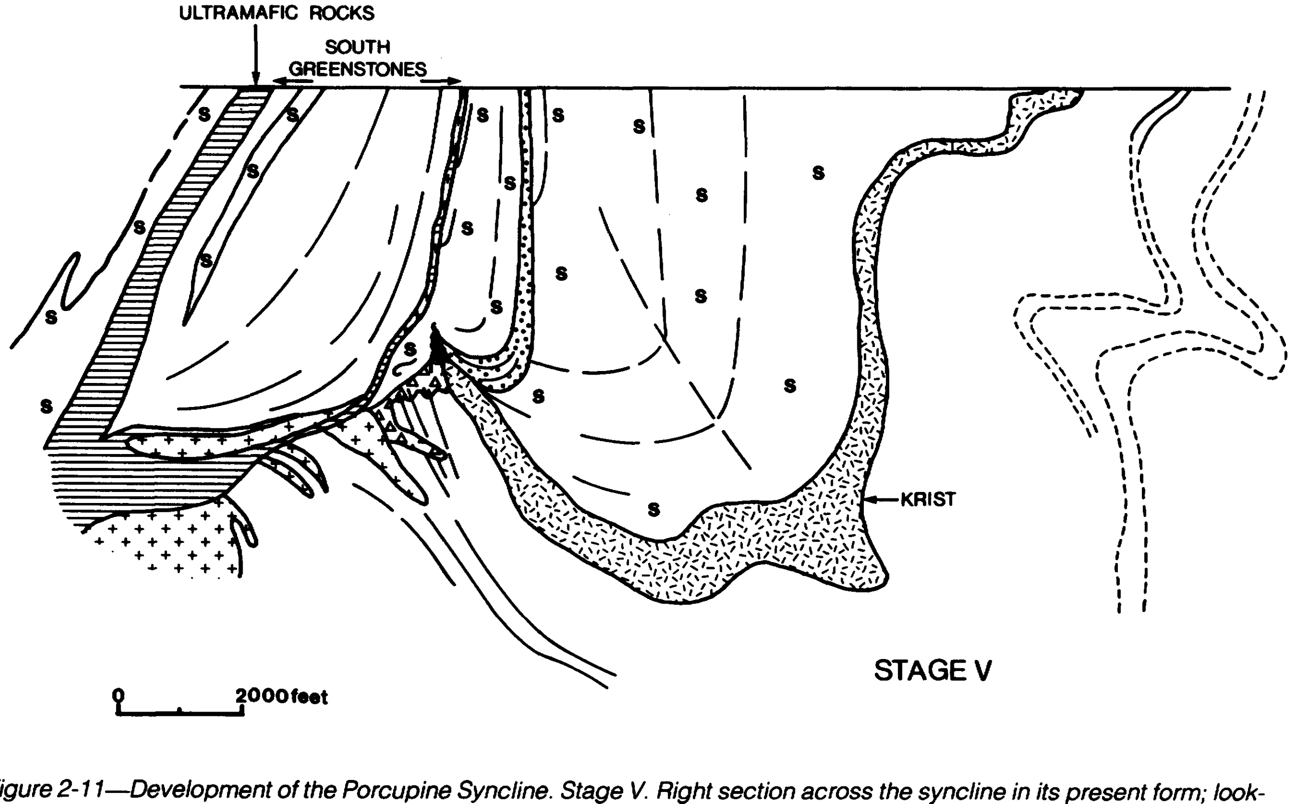

Figure 2-11—Development of the Porcupine Syncline. Stage V. Right section across the syncline in its present form; looking southwest. S—metasediments; ultramafic units shown by horizontal pattern.

Figure 2-12—Beds of clast-supported (sorted) conglomerate with calcite cement, separated by beds of matrix-supported conglomerate. The conglomerate is cut by later gold-bearing quartz veins.

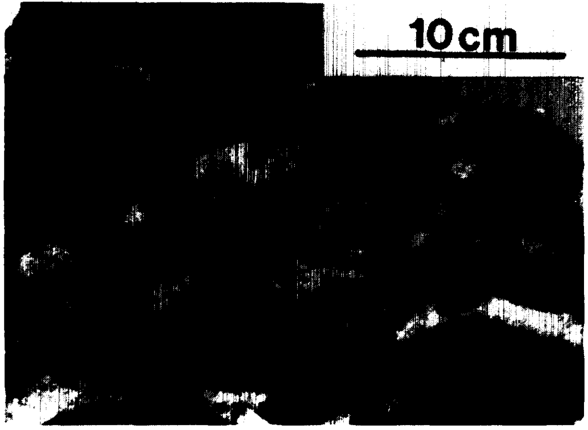

Figure 2-13—Cut block of calcite-cement conglomerate.

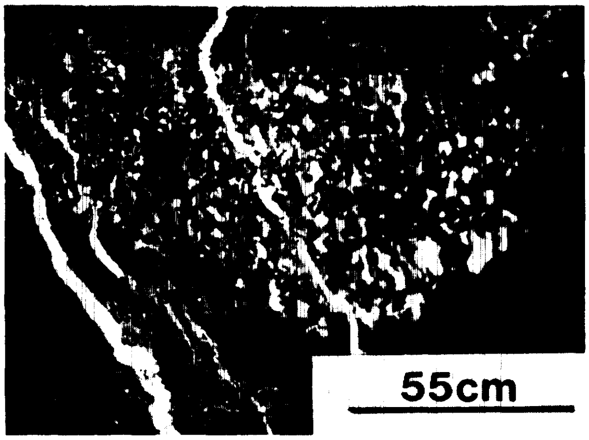

Figure 2-14—Bed of calcite-cement conglomerate with regular upper contact and irregular lower contact. The bed is cut by later gold-bearing veins.

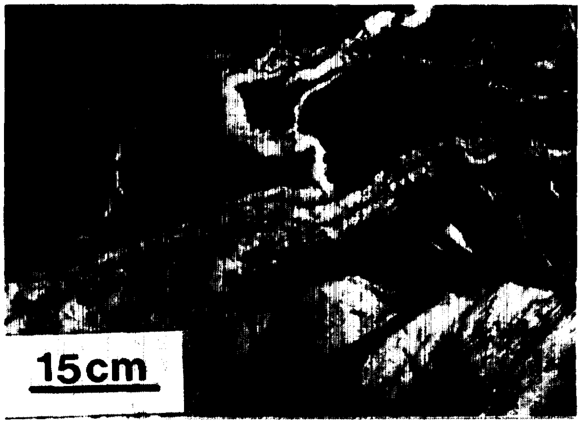

Figure 2-15—Complex, irregular veins pass into and form a layer in a larger tabular vein (Dome mine, 12th Level).

Figure 2-16—Folded "gash vein". The S_1 foliation in the volcanic host is deflected by the more competent vein.

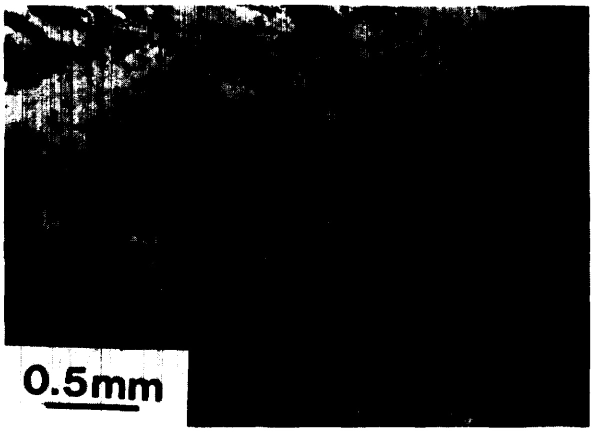

Figure 2-17—Photomicrograph of a vein at closure of a fold. Note the lenticular form of the quartz grains and undulose extinction (crossed nicols).

Geology and Evolution of Gold Deposits, Timmins Area, Ontario

W.O. Karvinen[1]

Abstract

In the Timmins area there is a close spatial and chronological association of the gold deposits with two major stratabound carbonate-rich members and related quartz-feldspar porphyries. The two principle types of mineralization are synvolcanic and metamorphogenic. Synvolcanic ores include the stratiform quartz-ankerite "veins", pyritic carbonates and chert-carbonate-tuff sedimentary rocks[2], and epigenetic vent-related breccia and stringer zones. Metamorphogenic ores consist of quartz-carbonate fracture-fillings in dilatant zones developed during various phases of regional deformation and metamorphism. They are classically epigenetic in character.

The evidence suggests a primary syngenetic enrichment of gold on the seafloor and in vent areas during submarine felsic volcanism and related exhalative-hydrothermal activity, followed by further enrichment into quartz-carbonate stockworks during regional deformation and greenschist facies, metamorphism.

Although normally thin (a few hundred metres) carbonate members in Archean volcanic terrain represent intense hydrothermal activity which could have transported gold and formed localized conentrations. Such "leads" should be used to locate fossil vents and structurally favourable zones where economic mineralization may be found.

Introduction

History of Mining

The Timmins area has been a major producer of gold for the past 70 years. During this time over 50 million ounces (1.4×10^9 grams) of gold have been mined from over two dozen different deposits, making it the largest gold-producing camp in Canada. After the increase in the price of gold in 1934, maximum production was achieved in the early 1940s when eighteen properties were being mined. Since then production has steadily decreased and today gold is mined underground at only four mines (Dome, Pamour No.1, Pamour No. 3, and Schumacher) and at one open pit (formerly the Hollinger mine). The dramatic increase in the price of gold in the early 1970s and the impressive surge in the last two years have revived exploration interest in the area and provided much needed assistance to existing operations.

Most of the past and present producing mines in the area were found and developed during the period 1909 to 1940. No significant new deposits have been found in the past 35 to 40 years and as a result it is generally felt that the camp has been well explored and is nearing exhaustion. It is interesting to note, however, that most of the geological research and related exploration in the area were done during the 1930s and 1940s and that exploration in the area, as well as research interest in gold genesis in general, declined dramatically from the mid-1940s to the late 1960s. It is only in the last decade that researchers and explorationists have "rediscovered" gold and have begun to reevaluate genetic models and exploration techniques. It is the author's contention that in the light of past genetic models (mainly epigenetic), the Timmins area has been well explored, but as will be shown in this paper, a syngenetic model for the origin of the deposits offers several important gold exploration parameters and a new optimistic outlook on the potential of the area.

Development of Models of Ore Genesis

In the past, epigenetic models for the deposits in the Timmins area and elsewhere were advocated, emphasizing the intrusion of granitic rocks (e.g. Pearl Lake Porphyry) into a passive mafic volcanic sequence as the primary source of mineralizing solutions, and major fractures or faults (e.g. Porcupine-Destor Fault) as plumbing systems along which such solutions emanated from unknown sources at depth. Although many local features could be explained by these models, serious problems still remained even within the limits of one camp (e.g. the absence of porphyries in and near the deposits of Whitney Township).

During the past decade, syngenetic models for gold have become popular for several Archean gold areas (Fripp 1976; Ridler 1976; Barnett *et al.* 1978; Fryer *et al.* 1979). At Timmins, D.R. Pyke (1975) pointed out the close spatial relationship between komatiitic ultramafic flows

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[1] Consulting Geologist, Sudbury, Ontario

[2] All rocks in the area have been metamorphosed, therefore the prefix 'meta' is not used.

and major gold deposits and suggested that gold was derived from these rocks during carbonatization. W.O. Karvinen (1977, 1978) presented preliminary results of detailed mapping of carbonate rocks in the Timmins area and suggested that they were mainly stratabound, and reflected major submarine hydrothermal events which initially enriched gold on the seafloor during Archean volcanism. Subsequent deformation and metamorphism of these rocks resulted in a further concentration of gold in veins. Field and laboratory investigations at McMaster University (Fyon, Crocket and Karvinen 1979; Fyon and Crocket 1979; Crocket, Schwartz and Fyon 1979) have supported a synvolcanic model although the simple stratabound model has been greatly modified. Other studies, mainly isotopic and geochemical, have been carried out by R. Kerrich (1979); B.J. Fryer *et al.* (1979), and J.F. Davies, *et al.* (1979). In 1976 the writer began a detailed mapping program to (1) establish the spatial distribution of carbonate-rich rocks and their relationship to gold deposits, and (2) to determine if such rocks are crosscutting, as the epigenetic models imply, or concordant with the enclosing country rock. Results of the mapping project are summarized in this report.

General Geology

For a description of the volcanic stratigraphy and general geology of the area, the reader is referred to Pyke (1975, and this volume). Although little factual data are available, the writer agrees with Pyke's (1975) interpretation that the Vipond Anticline (Pyke's South Tisdale Anticline) and the North Tisdale Anticline are of the same generation of folding (F_1) and predate the Porcupine Syncline (F_2). Other F_1 folds include the Northern Anticline, the Hollinger Anticline (Coniaurum Anticline), and the Kayorum Syncline. The McIntyre Syncline is thought to be related to the Porcupine Syncline (F_2).

The major phases of folding are also reflected by a variety of vein configurations varying from those which are straight and undeformed to those which are tightly folded or completely broken by intensive deformation.

Geological Controls to Gold Mineralization

Introduction

In the Timmins area there is a close spatial and chronological association of the gold deposits with two major stratabound carbonate-rich members, and related quartz-feldspar porphyries (Figure 3-1). Both major carbonate members can be followed along strike for over 20 km, and may be distinguished on the basis of their mineralogy. Most of the quartz-feldspar porphyry in the area occurs along or near one of the carbonate-rich members. Vent areas are characterized by crosscutting relationship of the carbonate member and breccia structures. At vent areas, the quartz-feldspar porphyries cross the primary structures.

Carbonate-rich Rocks

Geological investigations have noted the presence of regional alteration in the area of the deposits (Burrows 1924; Hurst 1936). At the McIntyre Mine, G.B. Langford (1939 p.9) recognized a pre-vein alteration in the rocks and states: "This [profound alteration] has taken place on a regional scale and is not to be confused with alteration by the vein-forming solutions". He described carbonatization as the major alteration, but also stated that in decreasing order of intensity, chloritization, sericitization, silicification, and steatitization had also occurred.

The stratabound nature of the carbonate-rich rock was recognized and used successfully in exploration and mine planning in the Aunor-Delnite area. At the Delnite, G.L. Holbrooke (1940, p.13) stated that "most of the known major ore bodies of Keewatin type are found in one broad geologic horizon in the lavas. This ore horizon consists of a series of heavily carbonated "lenticular lava flows". B.S.W. Buffam (1948b, p.509) described the Aunor ore zone as occurring "in pillowed, fine-grained andesite, irregular bands of medium, even-grained, carbonatized andesite, diorite and irregular bodies of quartz-feldspar porphyry bounded on both the north and south by dark, bluish-gray, talc-chlorite schist." He believed the ore zone to be "essentially parallel and probably conformable" with the volcanic flows.

Stratigraphic control of the ore deposits has been referred to by several workers. S.A. Ferguson *et al.* (1968 p.59) observed "that certain stratigraphic units occur in the central parts of many of the anticlines and the veins also occur in a similar position." W.R. Dunbar (1948 p.453) noted that "the ore favours the upper part of the Tisdale group, which has a fragmental character. No. 95 flow or equivalent horizons appear to be the most extensive and most important. The orebodies so far found in the Temiskaming series appear to occur in the general vicinity of the original position of No. 95 flow before it was eroded and sediments deposited unconformably on its eroded surface".

Although not specifically described in the literature, it is evident from mine plans of the Broulan Reef mine (west), the Buffalo-Ankerite mine, and upper levels of the Coniaurum mine that they represent excellent examples of stratabound ore-bearing carbonate zones.

The study carried out by the author has shown that over a stratigraphic thickness of approximately 800 to 900 m within the upper part of the Goose Lake Formation and the Schumacher Formation (Formations IV and V of Pyke 1975 and this volume), a variety of stratabound and crosscutting carbonate zones occur in and near major exhalative vents, but away from these centres, two stratabound carbonate members persists. These two units, here called the Lower Carbonate Member and the Upper Carbonate Member, are distinct mappable rock-types that can be traced along strike for over 20 km (Figures 3-1 and 3-2).

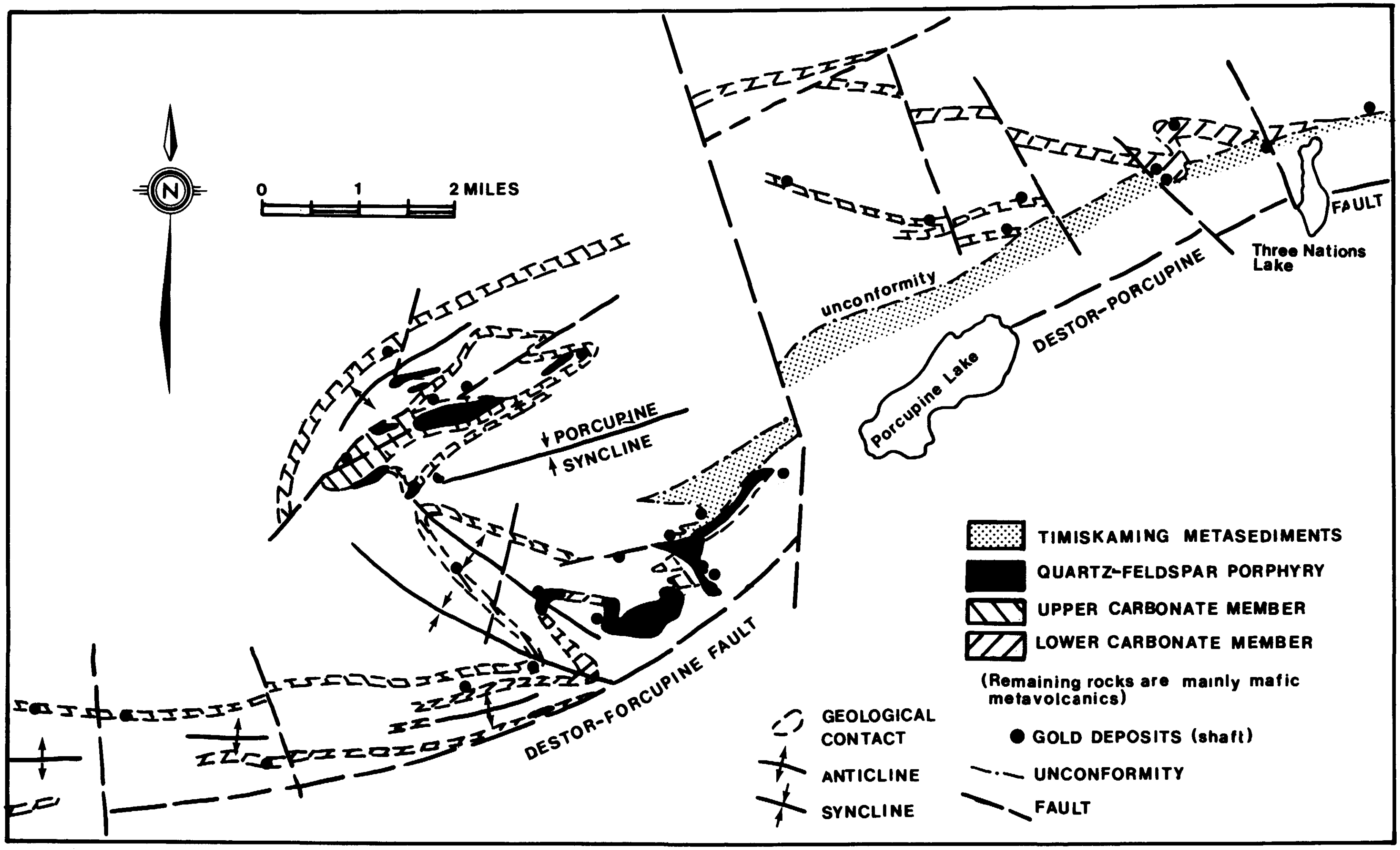

Figure 3-1—Distribution of carbonate-rich rocks, porphyries, and gold deposits, Timmins area.

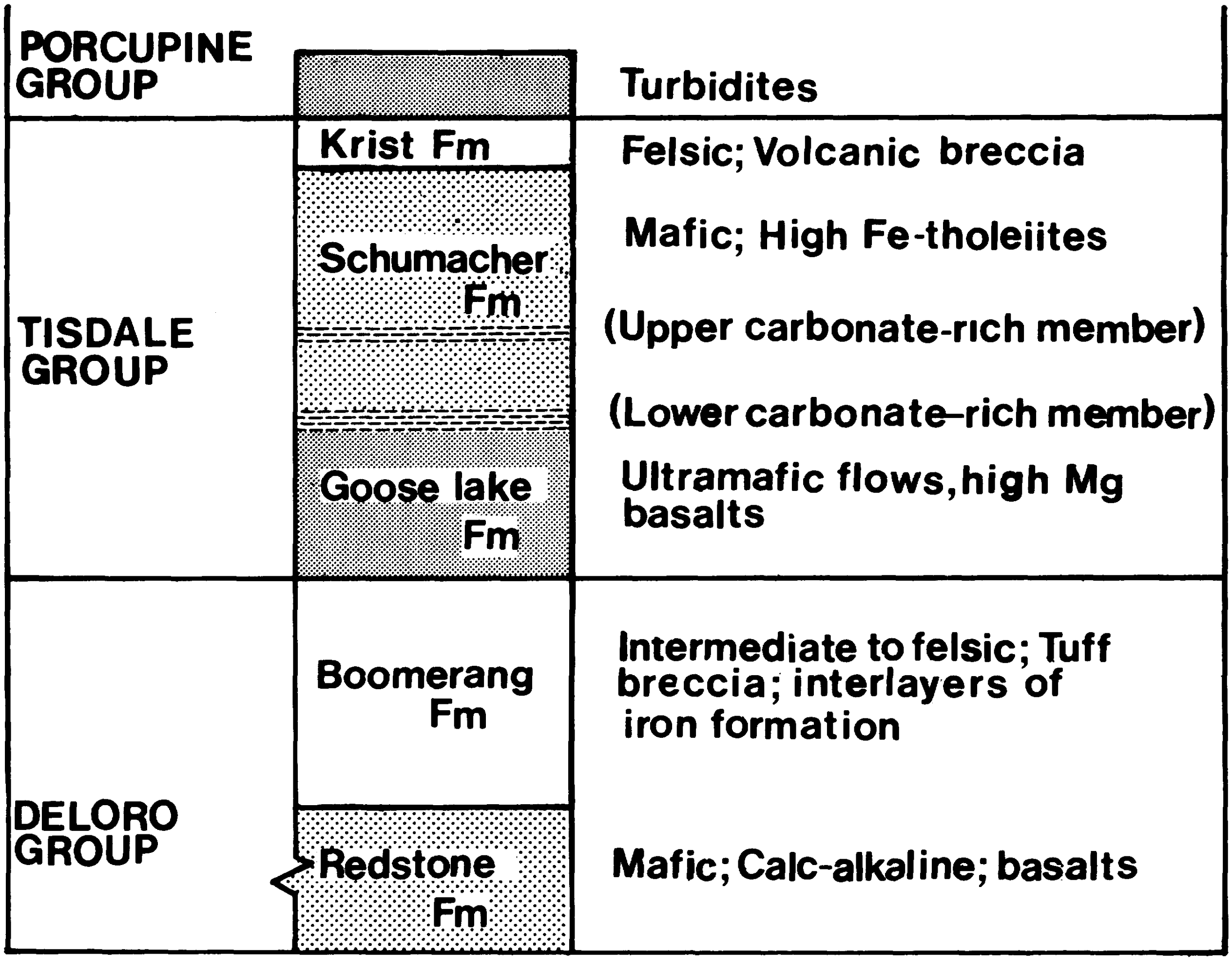

Figure 3-2—Stratigraphic column showing positions of Lower and Upper Carbonate Members.

Lower Carbonate Member

The Lower Carbonate Member is associated with the komatiitic ultramafic flows and tuff of the upper part of the Goose Lake Formation. It is the thicker of the two major units (average thickness 70 m), and consists predominantly of carbonatized ultramafic flows and tuff and some layered, massive carbonate of sedimentary origin. It is characterized by the predominance of magnesite (70 to 90 percent) with lesser amounts of talc, ankerite, sericite, chlorite, quartz, fuchsite (chrome muscovite), and pyrite. Relict textures, such as polysuturing and spinifex (Fig. 3-3), can be found in completely carbonatized flows and in places bombs and pyroclastic fragments are present in carbonatized ultramafic tuff. Deposits on or near the Lower Carbonate Member are: DeSantis, Kenilworth (Naybob), Delnite, Aunor, Buffalo Ankerite, Edwards, Dome, Hollinger, McIntyre, Beaumont, Hallnor, Broulan Reef (east), Pamour and Hoyle (see Fyon and Crocket, this volume Figure 4-1).

Upper Carbonate Member

The Upper Carbonate Member occurs approximately 670 m, stratigraphically above the Lower Member, in the tholeiitic volcanic rocks of the Schumacher Formation. In Tisdale Township it closely follows the "99 flow" but to the east it is a few hundred metres below this flow. The average thickness of the unit is 30 m.

The Upper Member is characterized by the abundance of ankerite (40 to 80 percent) and the absence of chrome muscovite (fuchsite). In addition to ankerite, other minerals include chlorite, relict plagioclase, sericite, quartz, and pyrite. Unlike the Lower Member, which is normally massive and medium to coarse grained, the Upper Member is very fine grained and is commonly well foliated. Because of the good foliation it has frequently

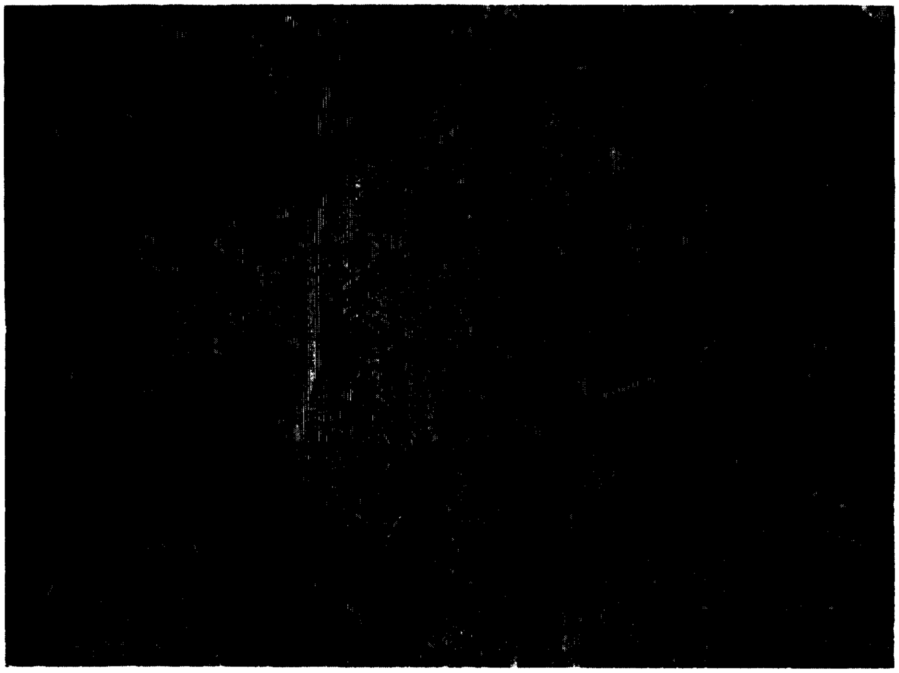

Figure 3-3—Carbonatized spinifex-bearing ultramafic flow, Hallnor mine, Whitney Township.

been interpreted as a shear zone. Discontinuous lenses of massive ankerite interlayered with silicate-rich lenses are a common feature. Relict textures and structures suggest that much of the Upper Member represents either a carbonatized tuff or a mixture of sedimentary carbonate and tuff. Towards the west in Ogden Township in the vicinity of the McEnaney deposit, the Upper Member grades laterally to a carbonaceous phyllite interbedded with chert and carbonate (Figure 3-4). In northeastern Tisdale Township in the vicinity of the Davidson Tisdale Mining Limited property, parts of the Upper Member are represented by carbonatized massive and pillowed basalt. In Whitney Township near the Canusa it splits into three thin members. Deposits on or near the Upper Member are: McEnaney, Gold Top, Paymaster, Dome, Moneta, Hollinger, Schumacher (McIntyre), Coniaurum, Consolidated Gillies, Davidson Tisdale, Canusa, and Broulan Reef (west) (see Fyon and Crocket, this volume, Figure 4-1).

Other Carbonate Units

In addition to the main carbonate members, several thin (less than 5 m) stratabound ankeritic carbonate horizons as well as irregular, crosscutting, dolomitic carbonate zones are found in and near major vent areas. They occur through the section from the Lower Carbonate Member to well above the Upper Carbonate Member. Although many are host to some mineralization, (e.g. Hughes Prospect, Whitney Township), only in one horizon has there been any production (Vipond and North Thompson deposits). Thin, concordant carbonates are found in Whitney Township, west of the Buffalo Ankerite, and the Delnite area.

Crosscutting carbonate alteration with mineral assemblages similar to those found in the main carbonate members but containing predominantly dolomite instead of ankerite, are common in fossil vent areas. Because this alteration does not give a rusty weathered surface, it is difficult to detect in outcrop, however, a recrystallized, buff to grey fresh surface is characteristic. Crosscutting alteration is common at Skynner Lake west of Delnite, at Buffalo Ankerite, Dome, and Pearl Lake.

Identification of Carbonates

Because iron-magnesium carbonates have a brown weathered surface, they are easily recognized in outcrop and thus readily distinguished from the noncarbonatized mafic volcanic rocks which are greenish black to black in surface exposures. However, underground or in drill core the carbonate-rich rocks, particularly the Upper Member, are easily missed and at many of the mines in Timmins they have been mapped as dacite, andesite, bleached volcanic rocks, etc. A simple staining technique can be used to determine the presence of both ankerite and magnesite (Karvinen 1978).

Quartz-Feldspar Porphyry Units

Irregular bodies of quartz-feldspar porphyry are in intimate association with the Lower Carbonate Member and occur at several stratigraphic levels up to the Upper Car-

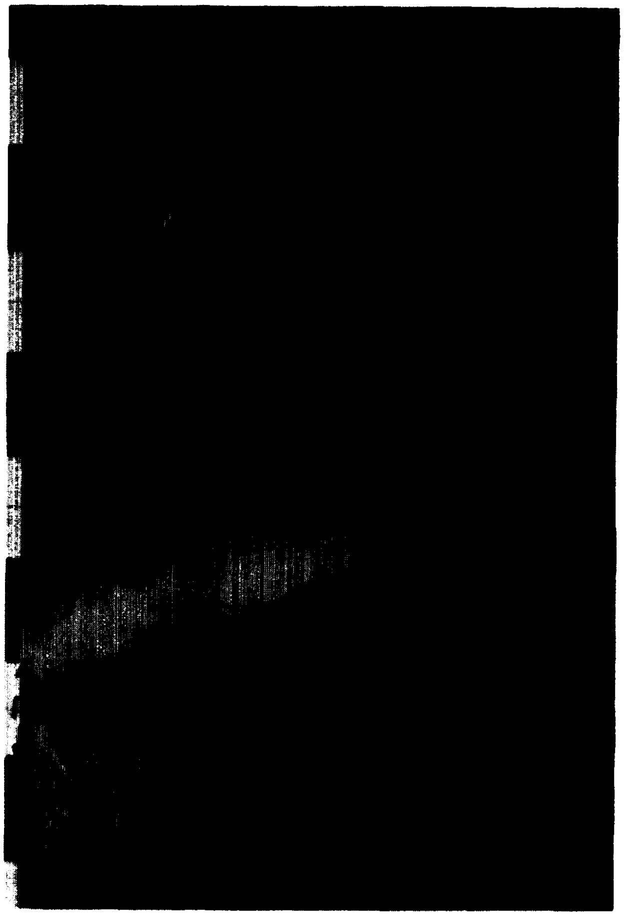

Figure 3-4—Gold-bearing chert-carbonate-tuff beds, McEnaney deposit, Ogden Township.

bonate Member at fossil vent areas. Only the bigger bodies such as the Pearl Lake and Preston-Paymaster Porphyries are shown in Figure 3-1. In detail, however, numerous thin lenses of porphyry, ranging from a metre to several tens of metres in thickness are commonly found in and near the Lower Member. In general, the porphyries consist of quartz, sodic plagioclase, and sericite with small amounts of pyrite. Textures vary from massive to porphyritic and normally "quartz eyes" are common in most varieties. They are generally well foliated and in many places are best described as sericite schist. Fragments, reminiscent of extrusive felsic volcanic material, can be found locally, particularly in the smaller bodies. Compositional layering indicative of an extrusive origin is common. The porphyries contain varying amounts of ankerite and calcite, especially near the contacts, and at the McIntyre mine a variety of alteration assemblages related to the Au-Cu mineralization have been identified (Luhta 1974).

Albitite dikes occur in and near the Pearl Lake Porphyry at the Hollinger and McIntyre mines between the 2750- and 3500-foot levels (Ferguson *et al.* 1968). They form an east-west vertical zone and may be traced along strike for up to 600 m. The thicknesses of the dikes vary from less than 1 m up to 5 m. Although the dikes are intrusive into the porphyry, where the writer has observed them they are deformed and contain the same structural fabric of the enclosing rocks. The dikes consist of inclusions of granitic rock fragments of sodic plagioclase, microperthite, subordinate microcline, and quartz, in a matrix of sodic plagioclase and quartz. Some important mineralization has been found in and near these dikes in the Pearl Lake area.

The Gold Deposits

Gold occurs as the native metal or in sulphides, mainly in systems of quartz-ankerite veins but also in auriferous, pyrite-rich carbonatized rocks that contain no veins (e.g. Buffalo Ankerite and McIntyre mines). The principal accessory minerals include tourmaline, scheelite, arsenopyrite, albite, pyrrhotite, chalcopyrite, galena, sphalerite, fuchsite, and gold-silver tellurides. Silver occurs predominantly as a natural alloy with gold. The ratio of gold to silver in the area varies from 5:1 near major porphyries to 14:1 in deposits away from porphyries (Buller 1971).

Based on stratigraphic and structural relationships, two principal types of gold deposits are recognized. These are synvolcanic ores and metamorphogenic ores.

Synvolcanic Ores

Synvolcanic ores are those which formed during the main exhalative phases of submarine volcanism. These ores are stratabound and in many places can be shown to be stratiform. Sedimentary features are common and are interbedded with volcaniclastic and chemogenic sedimentary rocks. They have been affected by all phases of structural deformation. Such ores are intimately associated in time and space with stratabound and crosscutting carbonate-rich rocks.

Three types of synvolcanic ores are recognized.

1)Continuous, stratabound bodies of quartz, ankerite, and tourmaline which pinch and swell and are characterized by crosscutting "ladder veins" (Figures 3-5 and 3-7).

2)Massive siliceous carbonate rock containing 5 to 20 percent pyrite in which only minor quartz-carbonate stringers are found (Figures 3-6 and 3-8).

3)Breccia bodies within fossil vents where mineralization occurs as disseminated pyrite in matrix material or as pyritic quartz-carbonate stringer-vein systems (Figure 3-9).

Type 1 quartz ankerite "veins" are recorded in the literature from the Dome and Paymaster mines, but they are also major contributors to ore at the McIntrye, Coniaurum, Hollinger, Aunor, and Delnite and possibly the Pam-

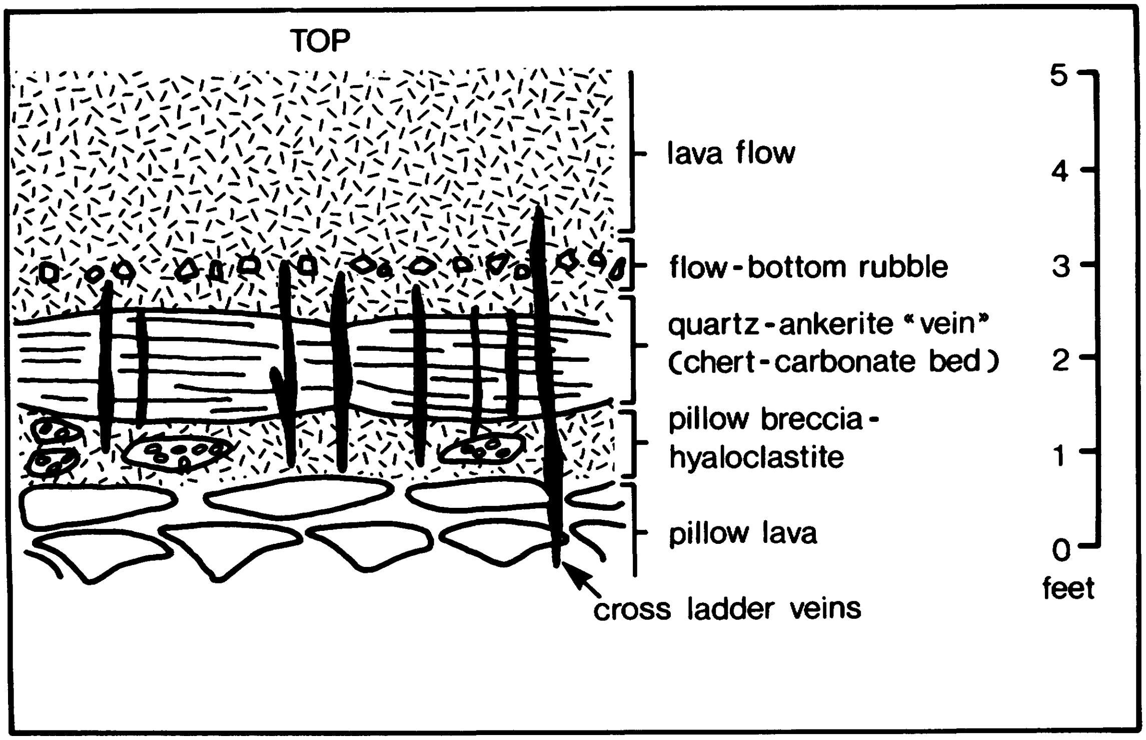

Figure 3-5—Synvolcanic ore: stratiform quartz-ankerite "vein" (chert-carbonate bed) with metamorphogenic cross ladder veins, 1000-foot level, Aunor mine.

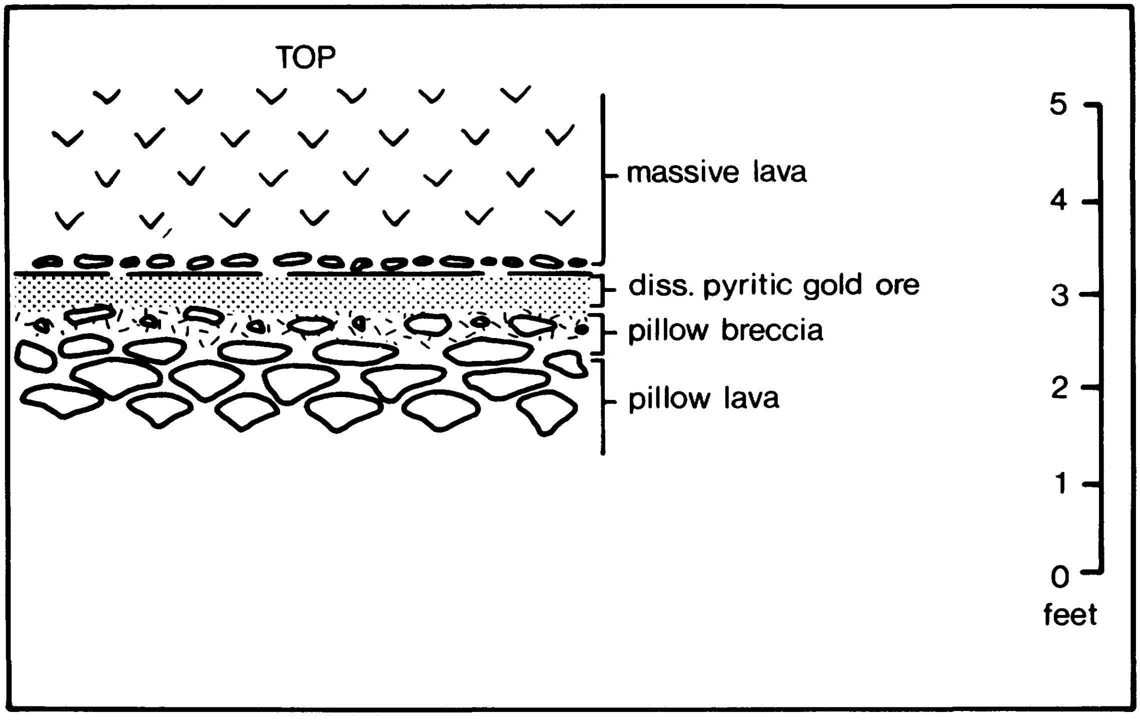

Figure 3-6—Synvolcanic ore: stratiform pyritic gold ore in massive carbonaceous and/or carbonate-rich interflow sedimentary rocks (e.g. Moneta orebody; McIntyre dacite ore.)

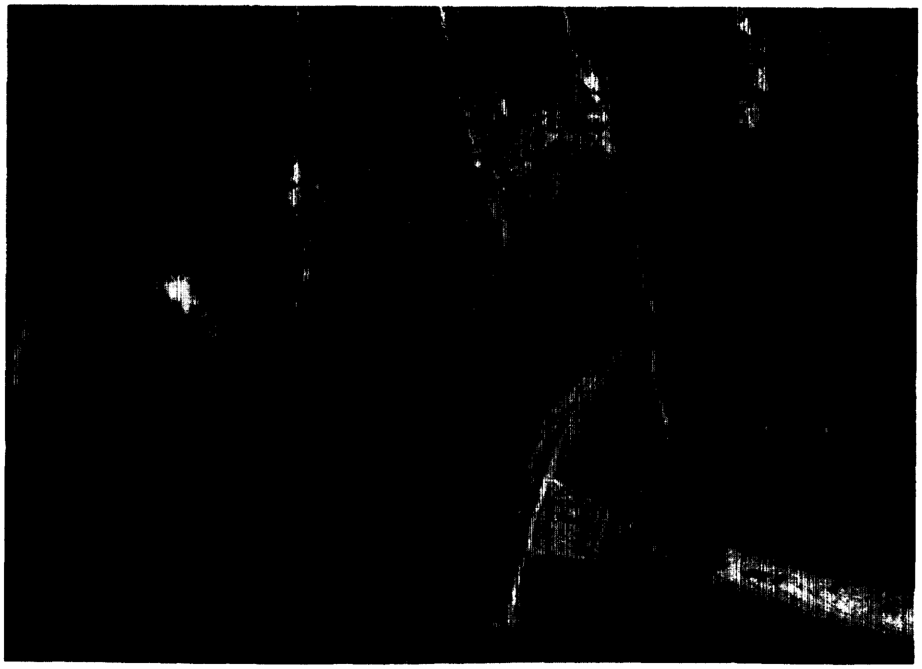

Figure 3-7—Typical quartz-ankerite "veins" with crosscutting ladder veins, Aunor mine, Deloro Township.

our No. 1 mines. At the Dome they occur as interflow units with strike-lengths of up to 300 m (Holmes 1968). These "veins" at the Dome have been recently interpreted as sedimentary carbonate deposits (Fryer *et al.* 1979). At other mines, where they have been examined by the writer, they have all the characteristics of chemical sedimentary rocks (Figure 3-7): they are conformable with the enclosing strata and are commonly layered; they frequently show an asymmetrical distribution of minerals and in some places crude "graded bedding" is apparent. At the Pamour and Aunor mines ankerite-quartz units are intercalated with massive green carbonates or carbonatized, pillowed magnesium-rich basalt of the Lower Carbonate Member, whereas at the Dome and Pearl Lake areas they are found throughout the succession from the Lower Carbonate Member to above the Upper Carbonate Member.

The type 1 veins generally make good ore, but may be barren. Where ladder veins are well developed, the units are generally enriched in gold. The ladder veins are interpreted as being the consequence of superimposed deformation which resulted in the remobilization of quartz, ankerite, and pyrite and further enrichment of gold. In the Aunor and Delnite mines, the ladder veins are parallel to foliation planes related to early isoclinal folds, F_1, which were rotated and became dilatant during subsequent folding, F_2 (Holbrooke 1940). The ladder veins are classed below as metamorphogenic ore.

Type 2 ore consists of stratabound, siliceous, carbonate-rich rock, commonly massive but also layered, in which the gold occurs in association with disseminated pyrite or pyrrhotite. The host rock may be a carbonatized mafic volcanic or a sequence of chert, carbonate, and tuff. In the Pearl Lake area examples of this ore are found at the McIntyre (McIntrye flow and No. 6 dacite), the Hollinger (No. 55 vein), and the Moneta mines. These ore bodies occur mainly within the Upper Carbonate Member where they are closely associated with carbonaceous tuff and interflow sedimentary rocks that apparently overlie them. The carbonaceous tuff contains important metamorphogenic veins (e.g. 91 and 95 veins at Hollinger; No. 3 vein at McIntyre). At the Dome mine the ore is known as "mineralized rock" (Holmes 1968). The orebodies consist of disseminated pyrite with little or no vein material, generally in altered sedimentary rocks. Similar ore occurs in the dacite units of the mine. The No. 36 ore zone at the Paymaster is an example of the sulphide type. According to C.S. Longley (1964, p. 103) the ore zone "lies in lava just north of the talc-chlorite-carbonate fault zone, . . . There is one narrow quartz-carbonate vein in this 25-feet wide ore zone and only a few stringers. The sulfide content is as high as 10 percent of pyrrhotite, pyrite and locally chalcopyrite . . . The values are concentrated near the fault contact but the well mineralized lava is usually ore". The "replacement-type lenses" in the Preston Porphyry at the Preston East Dome mine also fall into this category (Butterfield 1941).

Sulphide orebodies generally have greater dimensions and more consistent grades than vein-type ore zones. The No. 55 vein at the Hollinger mine, where mined on the surface by Pamour Porcupine Mines Limit-

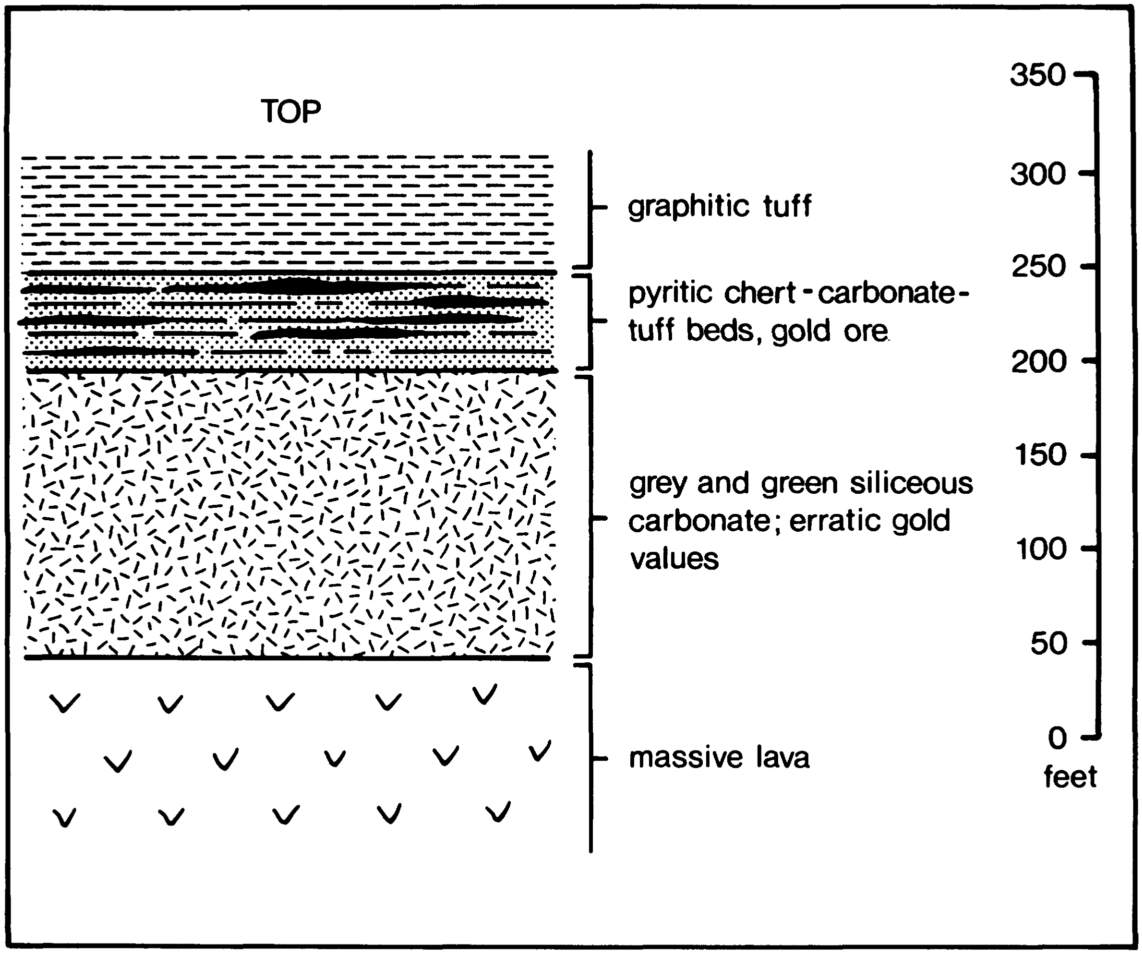

Figure 3-8—Synvolcanic ore: stratiform pyritic gold in well-layered chert-carbonate tuff beds (e.g. 80-88 zone, Porcupine Peninsular mine).

ed, averaged 0.10 oz. Au/ton across 12 m and along a strike-length of over 30 m. In the McIntyre flow near veins 3, 5, 7 and 10, massive, green-grey to brownish grey rock contained 15 percent pyrite and averaged 0.50 oz. Au/ton across widths of up to 30 m (Langford 1938). At the Moneta mine, the ore zone consisted of carbonatized pillowed and massive flows containing 15 to 20 percent pyrite (Figure 3-10). The orebody had a maximum width of 12 m, a strike-length of nearly 200 m, and was mined to a depth of 160 m. Average grades ranged from 0.3 to 0.6 oz. Au/ton (Buffam 1948a).

Type 2 deposits have the best potential for large tonnage, low-grade open pit or mechanized underground mining. Being pyritic they may also be detected by conventional geophysical techniques.

Type 3 synvolcanic ore is the least known ore type of the area. It occurs in major fossil vents, which are identified by breccia, agglomerate, crosscutting alteration zones, and pyrite-quartz stringers. The ores are vein-type or sulphide ores that can be shown to possess synvolcanic epigenetic features. The best example known to the writer is at the No. 6 shaft area of the McIntyre mine where breccia bodies of angular fragments of altered mafic flow rock, ranging in size from 2 cm to more than 1 m, are cemented by gold-bearing, quartz-pyrite veins (Figure 3-11). Other examples of this ore type include: pyritic agglomerate at the Buffalo Ankerite (Figure 3-12), originally mapped as conglomerate (Kinkel 1948); and possibly that part of the McIntyre "flow" and Buffalo Ankerite "dacite" ore that is characterized by veinlets may be of this type. The gold-copper ore associated with the Pearl Lake Porphyry at the McIntyre mine is considered to be Type 3 ore. The series of alteration envelopes and metal zones delineated in the ore zone (Luhta 1974; Davies and Luhta 1979) is believed to represent synvolcanic mineralization within the Pearl Lake vent zone.

The vent-related orebodies, although epigenetic in relation to their host rocks, are chronologically and spa-

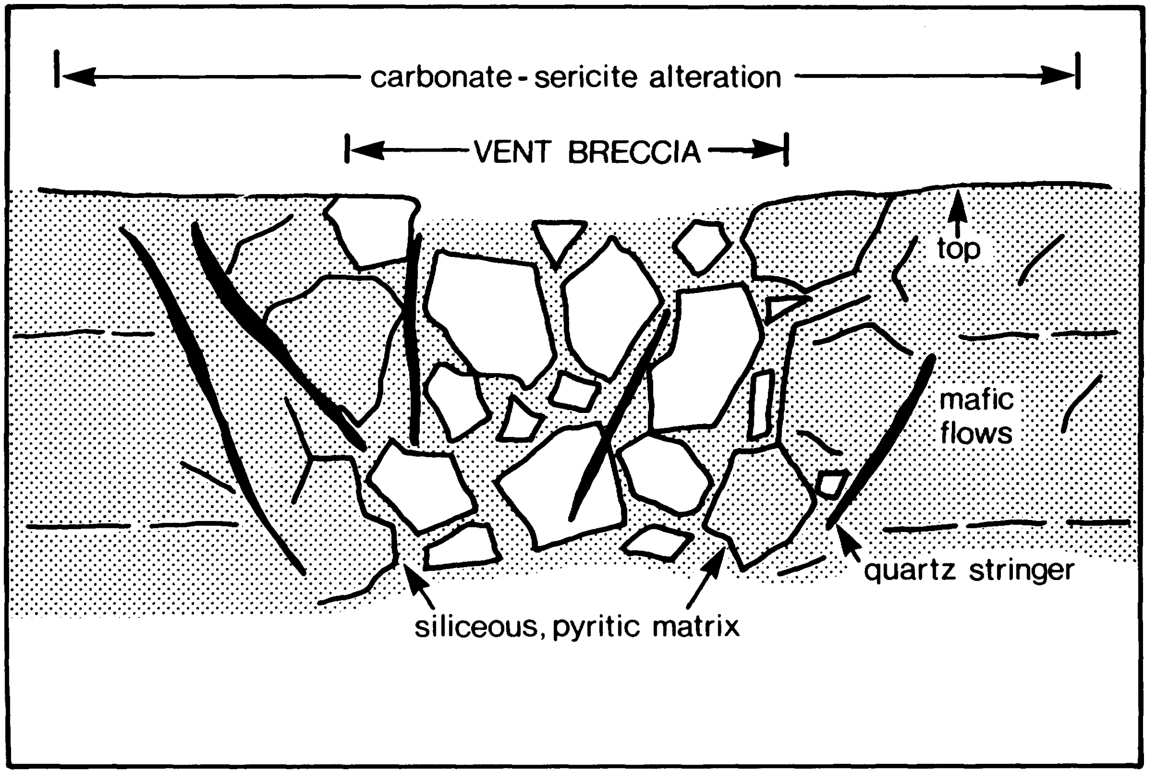

Figure 3-9—Synvolcanic "epigenetic" ore: mineralized exhalative vent with disseminated pyritic gold ore and auriferous pyritic quartz stringers.

tially related to other types of synvolcanic ores that are normally stratiform. They are all the result of the same volcanic exhalative processes, but their relative positions in the volcanic complex were determined by different physical and chemical conditions.

Metamorphogenic Ores

Metamorphogenic ores consist of gold-bearing quartz veins with minor amounts of carbonate. They may be up to 30 m thick but average approximately 3 m, and are several hundred metres long. The veins transgress primary volcanic structures locally and occur in a variety of rock types, but on the regional scale they follow the main carbonate members. Vein systems are complex and the individual veins may be discontinuous, lenticular, and sinuous. They may also occur in well-defined fractures which may be more or less parallel, but which branch out and join other networks of veins. Slab-like inclusions of wall-rock may occur within the veins, both the veins show no evidence of bedding or sedimentation, and some veins have a symmetry typical of fracture-filling. They are also characterized by wall-rock alteration. The fracture systems of the veins are believed to be foliations and joints created during the two major periods of deformation. The spatial association of the vein systems with the main carbonate members suggests that the carbonates were the source rocks for the gold.

Examples of metamorphogenic mineralization occur in most of the major deposits. Such veins at the Hollinger, according to W.A. Jones (1948, p. 114) "form *en echelon* lodes [of] white . . . quartz. Ankerite may occur as a narrow selvage along the sharply defined contact with the wallrock but may also be distributed in small patches throughout the quartz. Irregular pyritized fragments of wallrock in which tourmaline is developed are not uncommon . . . Veins of this type, which are of ore grade, contain rather conspicuous amounts of visible gold".

At the McIntyre mine the major period of mineralization described by Langford (1938) is metamorphogenic. According to Langford (1938, p. 18), this period of mineralization "formed in reopened early veins as well as in other fractures. Fragments of the quartz tourmaline veins [early] are found in many of the veins". A good example of a metamorphogenic orebody at the McIntyre mine is the 25 Vein which produced over 1.4 million ounces of gold. This particular vein parallels the F_2 foliation direction and has been traced for over 1000 m down dip.

Ore-bearing vein systems in sedimentary rocks (Timiskaming), such as at the Dome, Hallnor, Broulan Reef (east), Pamour No. 1, and Hoyle mines, are all considered to be metamorphogenic. At all these deposits synvolcanic carbonate rocks are found in the underlying volcanic rock and could have been the source of the mineralization. If the sedimentary rocks are a facies equivalent of the volcanic rocks, as suggested by some (Pyke 1975; Roberts *et al.* 1978) the sedimentary rocks themselves may have been the source of the mineralization.

Ladder veins are commonly associated with synvolcanic quartz-ankerite units. These veins generally fill prominent dilatant fractures related to regional folding (Holbrooke 1940). They are good examples of gold remobilized and enriched from the source bed (quartz-ankerite unit) during regional metamorphism and deformation. Thus they also are classed as metamorphogenic.

The Upper Carbonate Member and nearby strata commonly host metamorphogenic-type veins, particularly in structurally complex areas away from vent zones. A good example occurs in the upper levels of the Coniaurum mine where discontinuous, irregular, quartz veins carrying very erratic, but nevertheless ore-grade gold, follow the Upper Member around the nose of the Hollinger Anticline. Other similar examples are found at the Davidson Tisdale, the Broulan Reef (west) mines, and at the Thompson and Vipond area.

Environments of Gold Deposition

Economic concentrations of gold appear to be localized in three principal geological environments: 1)major exhalative vent areas; 2)structurally deformed zones of the carbonate members; 3)at contacts of carbonatized volcanic rocks and clastic sedimentary rocks.

Vent Areas

M.E. Hurst (1936) suggested that the porphyry bodies and their volcanic equivalents (Krist Formation) indicate proximity to volcanic vents. Evidence from the present study indicates three major and several minor vents in the Timmins area. The locations of the major vents are: Pearl Lake, the Dome mine, and at depth at the Buffalo Ankerite mine. A possible fourth major vent may occur at the Skynner Lake area, west of the Delnite mine.

The evidence for the recognition of a fossil vent area is as follows:

1)The consanguinity of the lenses of porphyry (felsic crystal tuff) and the major porphyry bodies (Preston and Pearl Lake Porphyries) suggests that the latter represent the build-up of felsic material at a vent.

2)Mineral and trace element zoning associated with the Pearl Lake Porphyry is indicative of a discharge zone of hydrothermal solutions. Zoning of anhydrite, ankerite, and calcite and trace amounts of gold and copper about the Pearl Lake Porphyry is described by M.R. Keyes (1940), and alteration envelopes about the gold-copper ore zone on the north contact of the porphyry are described by J.F. Davies and J.E. Luhta (1979).

3)Suspected volcanic centres are characterized by crosscutting zones of carbonate alteration. This type of alteration is best exposed on surface along the west contact of the Paymaster Porphyry, north of Simpson Lake. Other surface exposures include the altered pillow lavas north of No. 11 shaft of the McIntyre mine and the altered volcanic rocks above the Upper Carbonate Member in the Vipond-North Thompson area and the Skynner Lake area.

4)Numerous, thin, stratabound, ankeritic carbonate units throughout the stratigraphic section from the Lower Carbonate Member to well above the Upper Carbonate Member indicate a location proximal to a vent area. In such a position, hydrothermal activity would be more continuous and intense than at more distal locations.

5)The presence of breccia bodies and agglomerate indicates near-vent conditions.

6)The physical continuity of the Krist Formation with the Crown Porphyry at the Vipond mine suggests that the porphyry represents high-level intrusion within a vent complex and therefore may be the intrusive equivalent of extrusive volcanic clastic rocks as suggested by Hurst (1936).

Pearl Lake Vent: The bulk of the production in the Pearl Lake vent area has been from the Hollinger, McIntyre, and Coniaurum mines with smaller contributions from the Moneta, Consolidated Gillies Lake, Vipond, Crown, and North Thompson deposits. The major ore zones are located in and near the margins of the east-plunging Pearl Lake Porphyry and within carbonatized rocks of the two main members as well as in crosscutting vent alteration zones. The complex structural and volcanic history in the area makes stratigraphic interpretations difficult, but it appears that older rocks of the lower Schumacher Formation (Figure 3-2) are exposed in the core of the Hollinger Anticline. Green carbonate similar to that of the Lower Carbonate Member occurs on surface at the Hollinger mine site west of the old glory hole. Similar carbonatized ultramafic rock, now mainly talc-chlorite, has been identified in the No. 16 vein area of the McIntyre from the 2000-foot level to the bottom of the mine. Langford's (1938) description of steatitization at the McIntyre mine may also refer to the Lower Carbonate Member.

The Upper Carbonate Member, which follows the "99 flow" (Ferguson *et al.* 1968), is well exposed and is an important host for ore in the Pearl Lake area. In addition, a thin stratabound carbonate unit and crosscutting carbonate zones of alteration are hosts for ore at the Vipond and North Thompson Mines, located a few hundred metres stratigraphically above the Upper Carbonate Member.

Dome Vent: The Dome Mine has been the biggest producer in the Dome vent area, followed by the Paymaster and Preston mines. Much of the complexity in this area is due to major structural events related to volcanism as suggested recently by R.G. Roberts (1979) and possibly due to explosive vent activity as well. It appears that the Dome vent may have been dormant or relatively inactive at the time of the exhalative, hydrothermal activities which produced the Lower Carbonate Member, but subsequently became more active as a hydrothermal and ex-

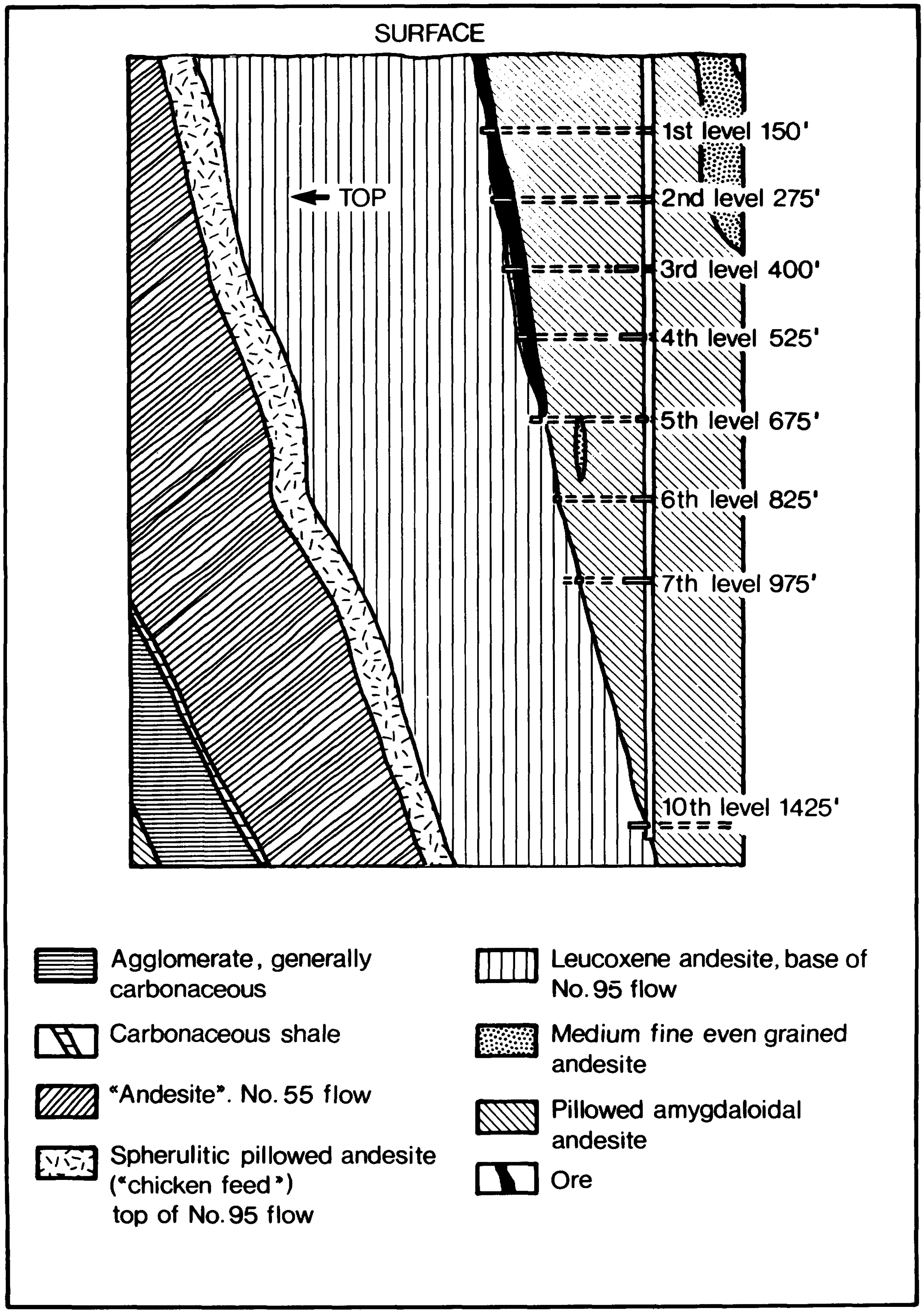

Figure 3-10—Vertical cross section looking northeast, Moneta mine (after Buffam 1948a).

Figure 3-11—Vent breccia with auriferous pyritic matrix, No. 6 Shaft area, McIntyre mine.

halative centre with the intrusion and possibly partial extrusion of the Preston-Paymaster porphyry. During this activity the "Replacement ores" in the porphyry and possibly some of the quartz-ankerite veins were formed. The quartz-ankerite units formed at this time correlate stratigraphically with the gold-bearing Upper Carbonate Member elsewhere in the area. It is possible that violent explosive volcanic activity removed part of the porphyry and the earlier formed Lower Carbonate Member creating a deep trough extending to the east in which the Timiskaming Group turbidites were deposited. Continued exhalative activity resulted in gold deposition of the "replacement" type in the Timiskaming sedimentary rocks and the dacite flows at the Dome Mine.

Buffalo Ankerite Vent: Because of the lack of detailed underground mapping and surface exposures, the sequence of events at the Buffalo Ankerite vent are obscure. However, a major porphyry body in the mine 900 m below surface, thin stratabound carbonate units above the main carbonate, and agglomerate sulphide "replacement ores" indicate a vent zone.

Deformed Zones of Carbonate Units

There is little doubt that the proliferation of metamorphogenic veins in the Pearl Lake area is partly due to the structural events which produced a multitude of dilatant fractures into which remobilized gold, quartz, and carbonate were deposited. Along the flanks of folds where little deformation has occurred (the "dead areas" of Holbrooke 1940), veining is considerably less abundant.

The effect of structural deformation is well demonstrated by the Upper Carbonate Member, which has economic mineralization only where it is folded. Examples are the upper levels of the Coniaurum mine (e.g. Hook vein) and the west part (Porcupine Reef) of the Broulan Reef mine.

Contact of Carbonatized Volcanic Rocks with Sedimentary Rocks.

Metamorphogenic veins occur at the contact of carbonatized volcanic rocks and sedimentary rocks at the Dome, Broulan Reef (east), Hallnor, Pamour No. 1, and Hoyle mines. In an earlier interpretation, assuming the contact to be an unconformity, the writer (Karvinen 1978) explained the deposits as the result of the formation of dilatant zones along the contact into which mineralization from the "source-bed" carbonate rocks was remobilized. This argument is still sound in as much as veins of the deposits at the contact and in the sedimentary rocks are metamorphogenic. However, this interpretation may be modified in the light of the recent suggestion that the sedimentary rocks may be facies equivalents of the volcanic rocks and, therefore, of the carbonate rocks as well. It may be significant that elsewhere in the Abitibi Belt (e.g. Matachewan Consolidated mine) and at Red Lake (Campbell and Dickenson mines, Hodgson *et al.* 1979), major gold deposits are located in areas of facies change between volcanic rocks and sedimentary rocks.

Figure 3-12—Gold-bearing pyritic agglomerate with carbonate fragments, Buffalo Ankerite mine, Deloro Township.

Formation of the Gold Deposits

Significant Factors

A discussion of the formation of gold deposits in the Timmins area must take into consideration the following:

1)The area is characterized by zones of carbonatization of volcanic rocks which may be stratabound or crosscut the primary volcanic structure.

2)There is a spatial relationship between the quartz-feldspar porphyry bodies and the carbonatized units.

3)Ore deposits may be characterized as synvolcanic and metamorphogenic.

4)There is a close spatial relationship between metamorphogenic veins and the carbonate-rich units.

5)The deposits are concentrated at vent areas.

6)Clasts of porphyry and of carbonate rock occur in the Krist Formation.

7)The carbonate members, vent-related structures, and porphyries have been affected by two, and possibly three, periods of folding.

8)Trace elements enriched in the deposits and host rocks include those which normally have affinities with mafic and ultramafic rocks (e.g. nickel, chromium, palladium), those which are enriched in felsic rocks (boron, tungsten, molybdenum, tellurium, lead antimony), and the metals, copper, zinc, and silver.

Sequence of Events

The volcanic and tectonic events that led to the formation of the gold deposits are summarized below.

1)The concordant and discordant carbonate-rich rocks formed during a period of submarine exhalative-hydrothermal activity centred at several major vents in the area (Figure 3-13). The stratabound carbonate members are the result of alteration of a variety of rock types on the seafloor, whereas crosscutting carbonate alteration formed along fractures and breccia zones in and near the vents at greater depths.

The circulating waters in each system provided the mechanism whereby gold and other trace elements were transferred from within the volcanic pile to the seafloor or close to the seafloor to form synvolcanic orebodies. Precipitation of the transported elements occurred at positions of low Eh and high sulphur activity.

The Lower Carbonate Member was formed during the earliest phase of hydrothermal activity and was accompanied by extrusion and high-level intrusion of the porphyries. Most of the large deposits of the area are associated with this phase of hydrothermal activity which suggests that it was probably the most intense.

2)Exhalative activity then waned and the build-up of the submarine flows of the Schumacher Formation continued, probably from a vent outside the area. Hydrothermal processes nevertheless were not totally dormant but were sufficiently active over the main vent areas to form the synvolcanic quartz-ankerite units.

3)The formation of the Upper Carbonate Member sig-

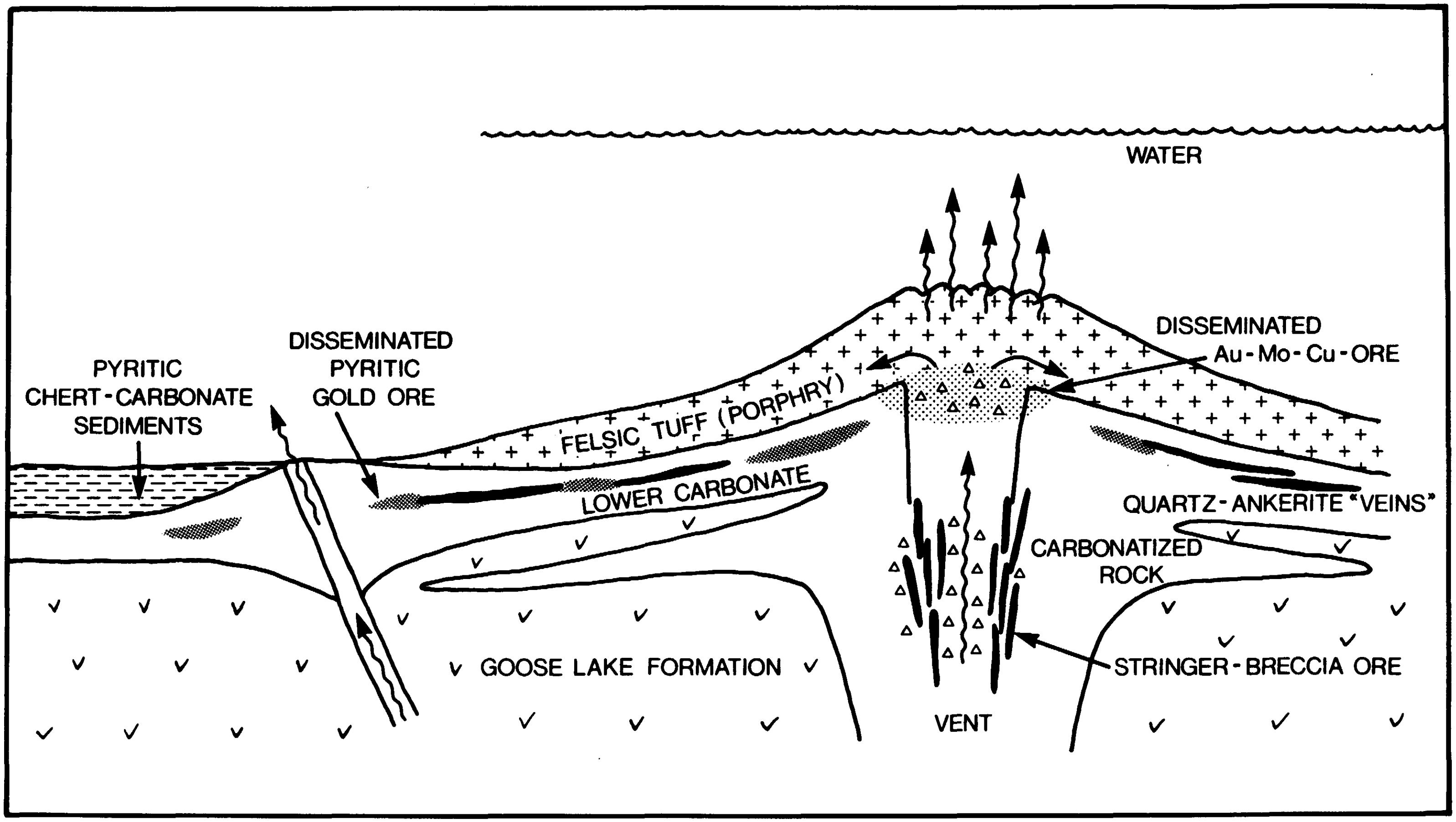

Figure 3-13—Environments of primary gold deposition.

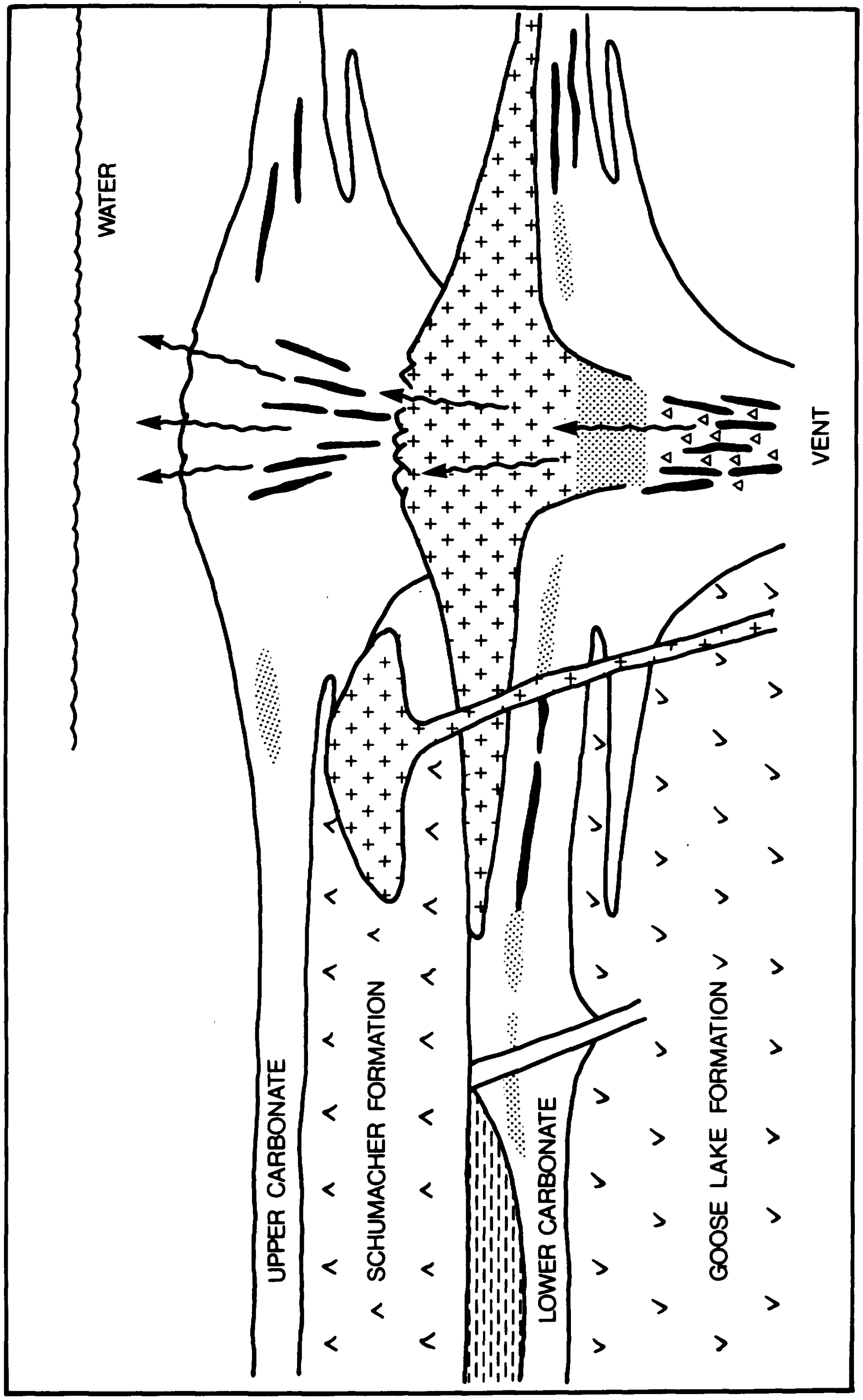

Figure 3-14—Continued exhalative activity at major vent.

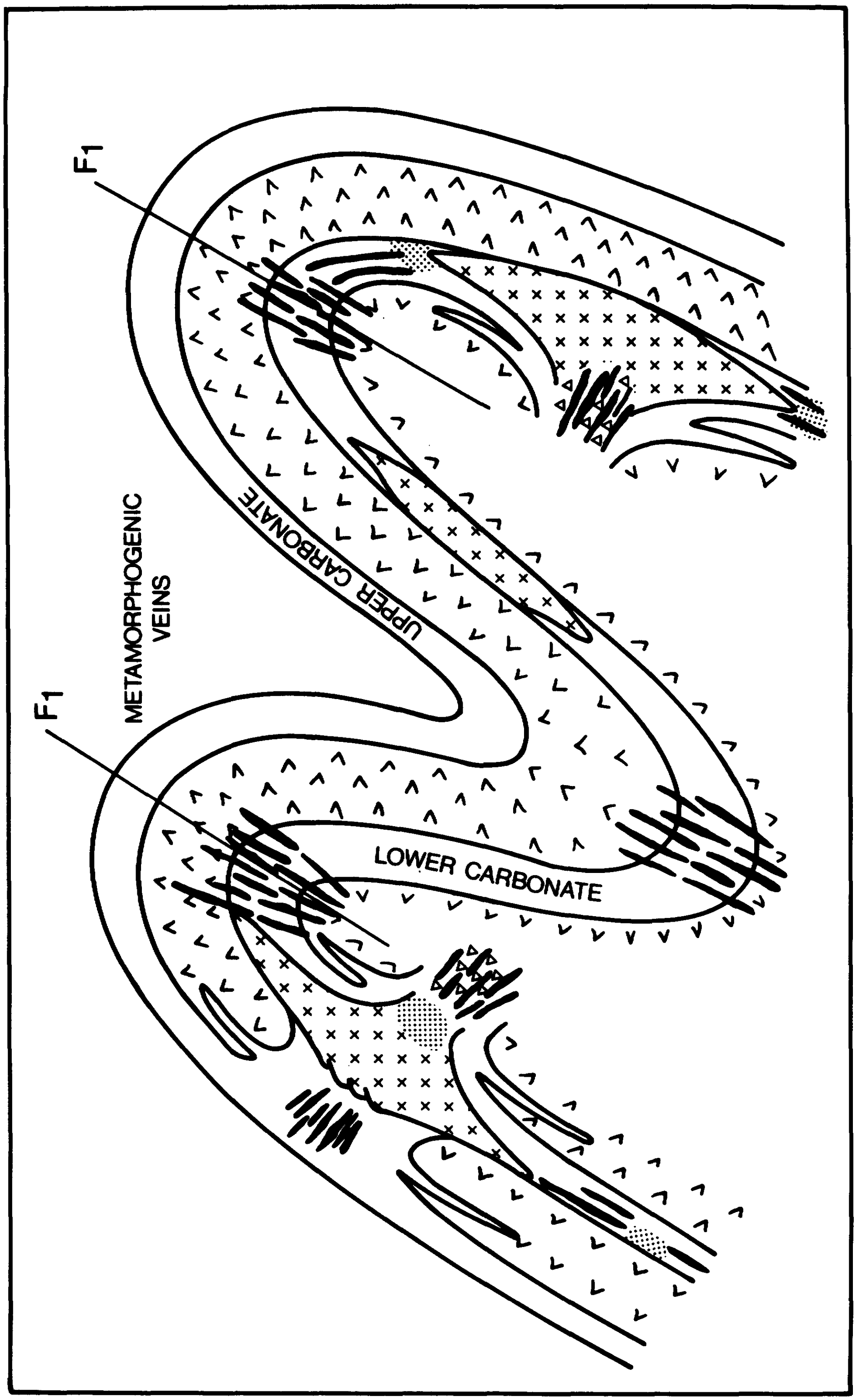

Figure 3-15—Development of metamorphogenic veins during folding and regional metamorphism.

nified a resurgence of hydrothermal-exhalative activity and the formation of synvolcanic gold deposits (Figure 3-14). No known felsic units are spatially associated with the Upper Member away from the vent area; it is therefore assumed that felsic volcanic activity was subdued.

4)A period of waning exhalative activity and deposition of mafic flows was followed by violent explosive activity. As a consequence, part of the volcanic edifice at the Dome mine was destroyed, and at Pearl Lake, debris and felsic material was ejected from the vent. The large quantity of coarse debris material was deposited as the Krist Formation. The Timiskaming sedimentary rocks were deposited in basins or troughs formed as a consequence of this explosive activity. The youngest phase of magmatic activity exposed in the Pearl Lake area resulted in the intrusion of albitite dikes and small porphyry bodies such as the Crown porphyry.

5)Subsequent to volcanic activity, the area underwent tectonic deformation. The earliest folding was isoclinal about north-northwest-trending axes. This was followed by a second phase of folding in an east-northeast direction. Structural and thermal conditions during this period resulted in further enrichment of gold from the source bed carbonates and synvolcanic deposits into networks of metamorphogenic quartz veins (Figure 3-15).

Exploration Guidelines

The results of this investigation suggest the following exploration guidelines.

1)Stratabound carbonate horizons serve as important indicators of volcanic hydrothermal-exhalative activity. If they are anomalously rich in gold or associated trace elements, economic concentrations should be explored for by locating fossil vents, structurally complex areas, or facies changes into volcaniclastic sedimentary rocks.

2)In poorly exposed areas, gold-bearing sulphide-type orebodies in carbonates can be detected using conventional geophysical techniques; however, the other types of mineralization could easily be missed, even by diamond drilling. In such cases basal till geochemical surveys may prove to be useful.

Volcanic Environment of Carbonate Alteration and Stratiform Gold Mineralization, Timmins Area

J.A. Fyon[1] and J.H. Crocket[1]

Abstract

In the Timmins area many gold deposits and carbonatized rocks are spatially associated, implying a genetic relationship between the two. However, the presence of carbonatized rocks not associated with gold mineralization indicates that carbonate alteration is only one of a set of geological criteria which collectively define the optimum environment for gold deposition. Carbonatized rock occurs throughout the volcanic stratigraphic section. The alteration zones do not define discrete, regionally extensive, stratabound units. The carbonatization process was contemporaneous with the volcanic evolution of the Tisdale Group.

Samples of altered rock were classified into Productive and Unproductive groups. Productive samples were taken from within 30 m of ore zones. Unproductive samples were taken from areas not associated with known gold mineralization. Altered magnesium tholeiitic basalt which host the chert-dolomite type mineralization is enriched in Li (>30 ppm), B (>30 ppm), Au (>5 ppb), As (>0 ppm), Sb (>0.35 ppm) and depleted in Cu (<70 ppm). Altered komatiitic flows from a mineralized environment are enriched only in Au (>5 ppb) and As (>70 ppm). CO_2, S, Ba, Zn, K_2O and Ag cannot be used to screen altered rocks which host this type of gold mineralization.

Introduction

The spatial association of carbonate-rich volcanic rock[2], stratabound quartz-feldspar porphyry, and gold deposits in the Porcupine camp was recognized by A.G. Burrows (1924) and S.A. Ferguson *et al.* (1968), and has been reiterated by D.R. Pyke (1975) and W.O. Karvinen (1976, 1978). This association is illustrated in Figure 4-1. That many gold deposits and carbonatized rock are spatially associated implies that a genetic relationship links the two. The absence of gold deposits from stratigraphically and chemically equivalent sequences of volcanic rocks lacking carbonate alteration further emphasizes this possible genetic link. However, the presence of carbonatized rocks not associated with gold mineralization indicates that carbonate alteration is only one of a set of geological criteria which collectively define the optimum environment for gold deposition.

It is possible to discriminate between the carbonate alteration zones of the mineralized and unmineralized volcanic environments using selected trace element screens and field relations. Two control areas, one hosting mineable gold deposits and the other only gold prospects, were selected for detailed study. Both study areas are characterized by relatively simple structure, by the presence of carbonate-rich rocks, and by stratigraphic and geochemical equivalence of their lithologies. The Deloro Township study area represents a mineralized control area, whereas the Tisdale Township study area represents an unmineralized control area (Figure 4-1).

Carbonate Alteration

Carbonate alteration occurs as stratabound and discordant zones throughout the Lower Volcanic Formation of the Tisdale Group.

Distribution of Carbonatized Rock

Figure 4-3 illustrates the geology of the study area in Tisdale Township. It is apparent from this map that carbonatized rock occurs throughout the volcanic stratigraphic section, and that the alteration zones do not define discrete, regionally extensive, stratabound alteration zones. Carbonatized rocks occur in many localized zones. Similarly in the Deloro Township study area, carbonate alteration occurs throughout the volcanic stratigraphy.

Alteration Assemblages

Petrographic descriptions of the alteration assemblages according to rock type are given in Table 4-1. The carbonate alteration of basaltic rock is defined by three assemblages: chlorite; chlorite-carbonate; and carbonate-rich. The three alteration assemblages are spatially and genetically related to a chlorite-rich subzone enclosing a carbonate-rich core (Figure 4-2). For convenience, this alteration assemblage trinity is referred to as carbonatized rock. On a regional scale all mafic and ultramafic volcanic rocks contain at least 3.3 weight percent loss on ig-

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[1] Department of Geology, McMaster University

[2] All rocks in the area have been metamorphosed, therefore the prefix 'meta' is not used.

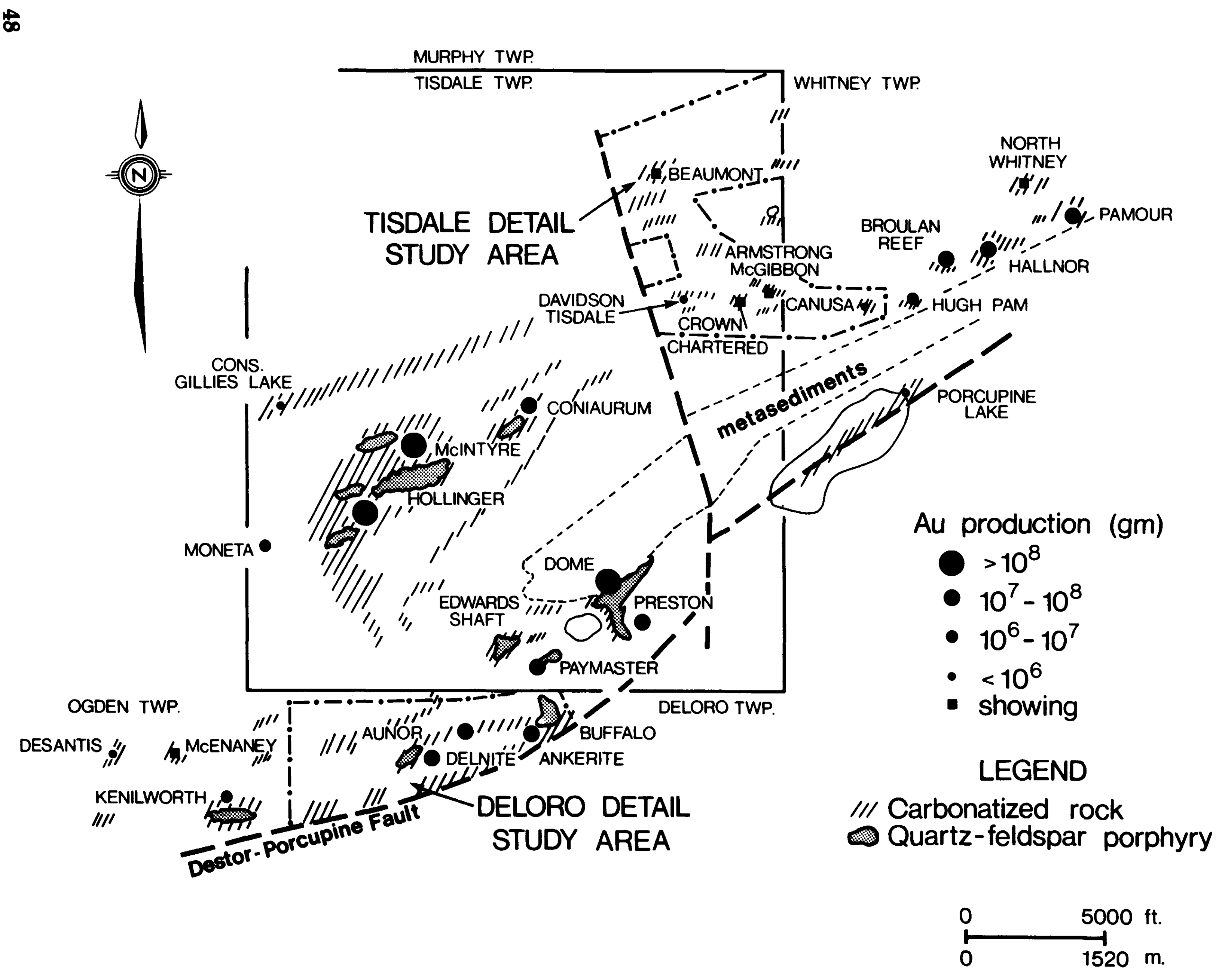
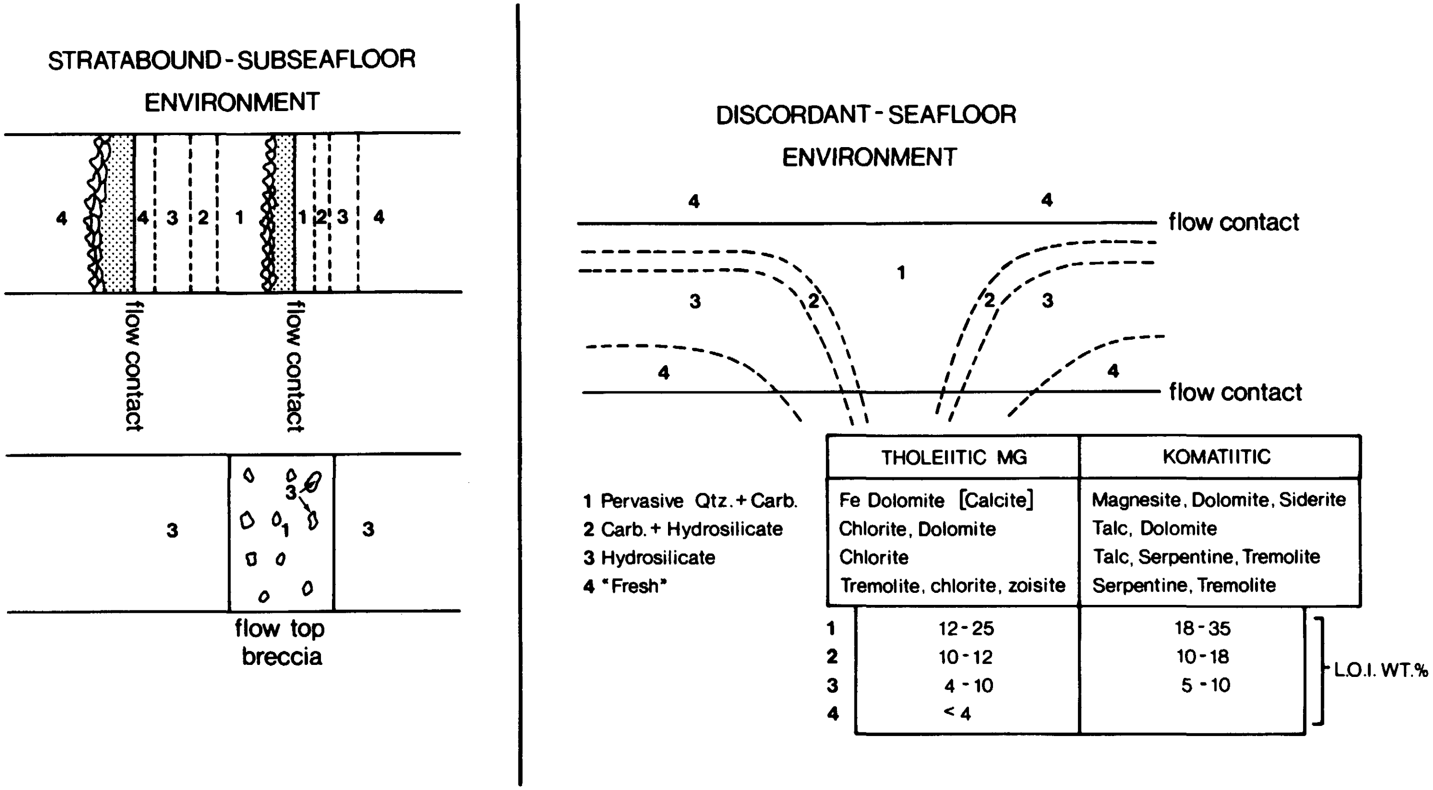


Figure 4-1—Distribution of porphyries, gold deposits, and carbonatized volcanic rocks in the Timmins area (after Karvinen 1978; Pyke 1975; Ferguson 1958a, 1958b).

TABLE 4 - 1 ALTERATION ASSEMBLAGES AS A FUNCTION OF ROCK TYPE AND DEGREE OF ALTERATION

Rock Type		Alteration Assemblage	L.O.I. Range	Field Name
Ultramafic Komatiite		Lizardite, tremolite, chromite, magnetite, sulphides	? - 7 wt %	Serpentinite
		Lizardite, tremolite, chlorite, chromite, magnetite, sulphides	7 - 8.5 wt %	
	Carbonate Alteration	Serpentine, talc, chlorite, tremolite, dolomite, chromite, magnetite, sulphides	8.5 - 12 wt %	Disseminated Carbonate
		Dolomite, quartz, chlorite, chromite, magnetite, sulphides, trace magnesite and calcite		
		Dolomite, quartz, chromite, magnetite, sulphides, trace magnesite and calcite	12 - 40 wt %	Pervasive Carbonate
Magnesium		Tremolite, non-ferroan zoisite, quartz-albite, chlorite, magnetite, pyrite, sphalerite, chalcopyrite	? - 4 wt %	Spilite
Tholeiitic		Tremolite, chlorite, quartz-albite, non-ferroan zoisite, leucoxene, trace dolomite, pyrite, sphalerite, chalcopyrite	4 - 8 wt %	Chloritic
Basalt	Carbonate Alteration	Chlorite, dolomite, quartz-albite, trace sericite, leucoxene, pyrite, sphalerite, chalcopyrite	8 - 12 wt %	Disseminated Carbonate
		Dolomite, quartz-albite, trace chlorite, sericite, leucoxene, pyrite, sphalerite, chalcopyrite (Calcite predominated in some assemblages)	12-18 wt %	Pervasive Carbonate



	THOLEIITIC MG	KOMATIITIC
1 Pervasive Qtz.+Carb.	Fe Dolomite [Calcite]	Magnesite, Dolomite, Siderite
2 Carb.+Hydrosilicate	Chlorite, Dolomite	Talc, Dolomite
3 Hydrosilicate	Chlorite	Talc, Serpentine, Tremolite
4 "Fresh"	Tremolite, chlorite, zoisite	Serpentine, Tremolite

	THOLEIITIC MG	KOMATIITIC
1	12-25	18-35
2	10-12	10-18
3	4-10	5-10
4	<4	

L.O.I. WT.%

Figure 4-2—Synthesis of carbonate alteration assemblages and styles.

nition (L.O.I.), and consist of hydrous, greenschist alteration assemblages. The mafic equivalent of this rock is referred to as 'spilite' in Table 4-1.

Geometry of the Carbonate Alteration Zones

The alteration zones are subdivided into discordant and stratabound types based on their geometry and their relationships to the stratigraphy (Figure 4-2). Discordant alteration zones are characterized by boundaries which trend across the local stratigraphy. For example, on the Beaumont property (Figure 4-4) a sequence of magnesium tholeiitic basalts overlies carbonatized, komatiitic flows. The carbonate alteration is most extensive in the komatiites, and crosscuts into the massive base of the overlying magnesium tholeiitic basalt flow. The alteration zone dies out gradually within this massive base and does not extend into the pillowed facies of the flow. This is an example of a discordant alteration zone (Fyon and Karvinen 1978) which terminates gradually in the vertical dimension rather than abruptly at a flow contact.

In stratabound alteration zones the alteration assemblages trend parallel to or occur along flow contacts. When developed along flow contacts, the top and base of the adjacent flows are altered to the same degree (Figure 4-2). On the Kinch property (Figure 4-5) both discordant and stratabound types of alteration are exposed. Discordant alteration zones appear to link parallel, stratabound zones, and locally fingers of stratabound alteration extend laterally away from the discordant alteration zone, following along flow contacts. Similar alteration zone geometries are exposed on the Davidson-Tisdale, Armstrong-McGibbon, and Crown Chartered properties (Figure 4-3)

The alteration zones exposed in the Tisdale Township study area are believed to have developed in a subseafloor, volcanic environment by passage of hydrothermal fluids up through joint or fracture systems (e.g. discordant zones) or along flow contacts (e.g. some stratabound zones).

In some instances, however, the carbonate alteration zones are restricted to one flow unit which is overlain by carbonate-free flows. For example, the ore zone of the Aunor, Delnite, and Buffalo Ankerite mines (Figure 4-6) lies within a sequence of carbonatized, magnesium tholeiitic basalts, and locally derived volcaniclastic sedimentary rocks (Figures 4-6 and 4-7). However, this unit is overlain by carbonate-free, ultramafic, komatiitic flows. This type of alteration is thought to have taken place in a submarine environment prior to the emplacement of the overlying, younger, komatiitic flows.

Discordant and stratabound carbonate alteration zones occur throughout the volcanic stratigraphy of the Lower Metavolcanic Group. Collectively, the distribution of carbonatized rock does not define two, discrete, regionally continuous, stratabound units. In detail, the carbonate alteration zones transgress flow contacts (e.g. Beaumont property, Figure 4-4), are focused along flow contacts in which situation the adjacent flows are both altered, (e.g. Kinch property, Figure 4-5), or may terminate abruptly at a major lithological contact such that pervasively, carbonatized flows are overlain by carbonate-free flows (e.g. Buffalo Ankerite and Aunor mines, Figures 4-6 and 4-7).

Environment of Alteration and Ore Deposition

The subseafloor, carbonate alteration environment is characterized by the absence of chemogenetic, interflow sedimentary and felsic volcanic rocks (represented in part by quartz-feldspar porphyry). Conversely, the seafloor alteration environment is characterized by the presence of quartz-feldspar porphyry or felsic volcanic rocks, and exhalative, auriferous, cherty dolomite (Figures 4-8 and 4-9).

Timing of the Alteration Event

It is imperative to establish whether the regional 'spilitic' and the localized chlorite and carbonate-rich alteration assemblages represent a mineralogical equilibration attained during burial or contact metamorphism under greenschist facies conditions, or whether these assemblages represent a high temperature (>250°C) seawater-rock alteration of the type described by K. Muehlenbachs and R.N. Clayton (1976), E.T.C. Spooner *et al.* (1974), and S.E. Humphries and G. Thompson (1978a, 1978b). Within the localized, carbonate alteration zones, chlorite and carbonate veins are not necessarily oriented parallel to the foliation planes associated with the F_1 and F_2 folds (Fyon 1980), and many veinlets are isoclinally folded. Vein quartz has a strained, undulose extinction and both quartz and carbonate grains are polygonized and annealed. On an outcrop scale both the carbonatized and least altered host rocks have the same tectonic fabrics imprinted during the initial north-south deformation of the Timmins area. Carbonatized, volcanic rock clasts occur within the turbiditic, komatiitic conglomerate and mudstone of the Porcupine Group exposed on the Pamour, Buffalo Ankerite, and Thomas Ogden properties, and at Wawaitin Falls.

The microscopic textures indicate that the localized chlorite-carbonate alteration assemblages have undergone a superimposed, tectonic re-equilibration. Furthermore, the megascopic field data indicate that not only were the rocks carbonatized prior to the earliest north-south period of deformation, but the sedimentalogical evidence demonstrates conclusively that a carbonatized, volcanic rock terrain was present as a source area from which the Porcupine Group turbidites were derived. Recalling that Pyke *et al.* (1978) demonstrated that the lower part of the Porcupine Group is time equivalent with the entirety of the Tisdale Group, it must be concluded that the carbonatization process was contemporaneous with the volcanic evolution of the Tisdale Group.

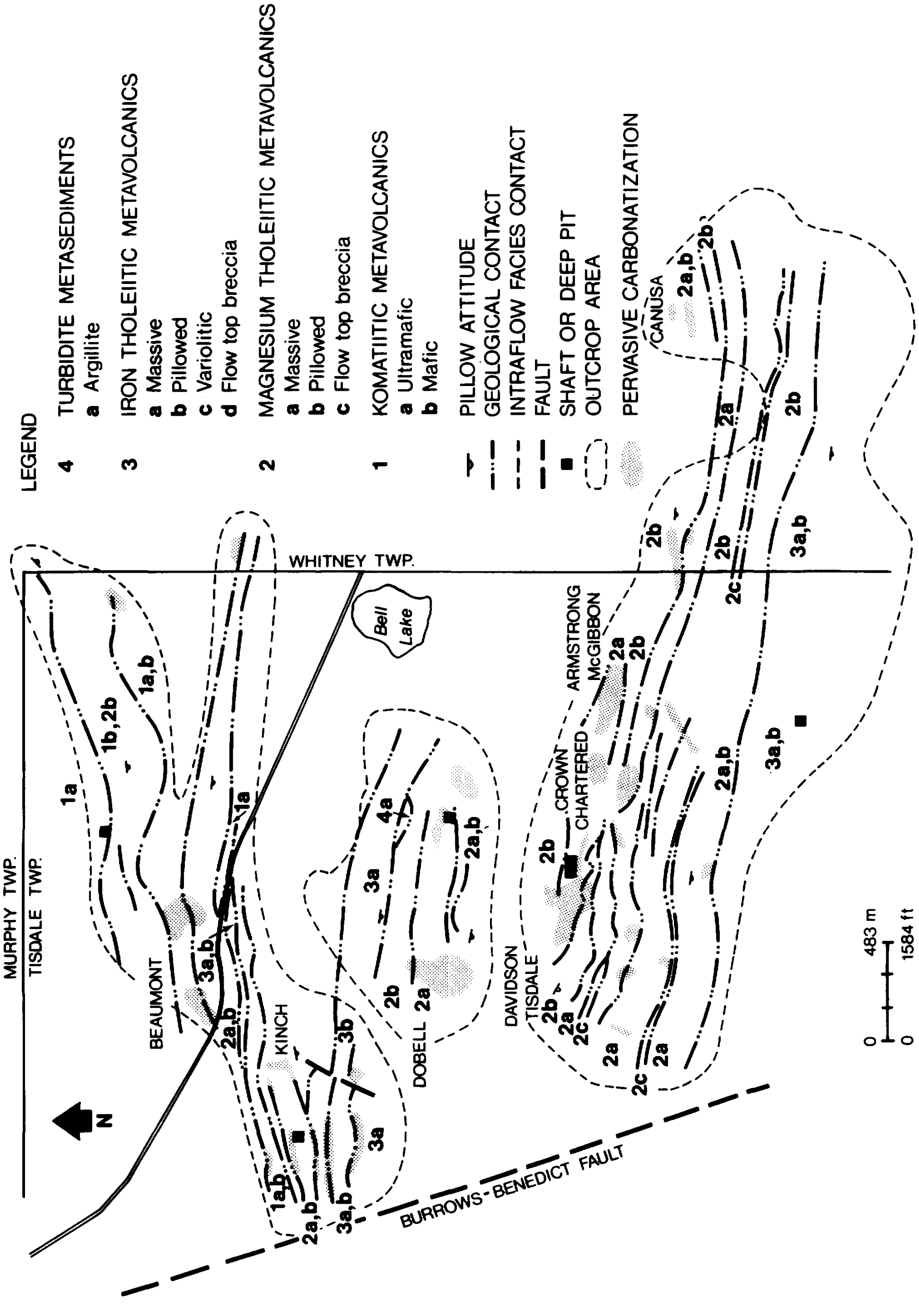


Figure 4-3—Geological map of the Tisdale Township study area (Geology by Fyon, modified after Pyke 1975; Ferguson 1958c, 1960). Note that carbonatized rocks occur throughout the volcanic stratigraphy.

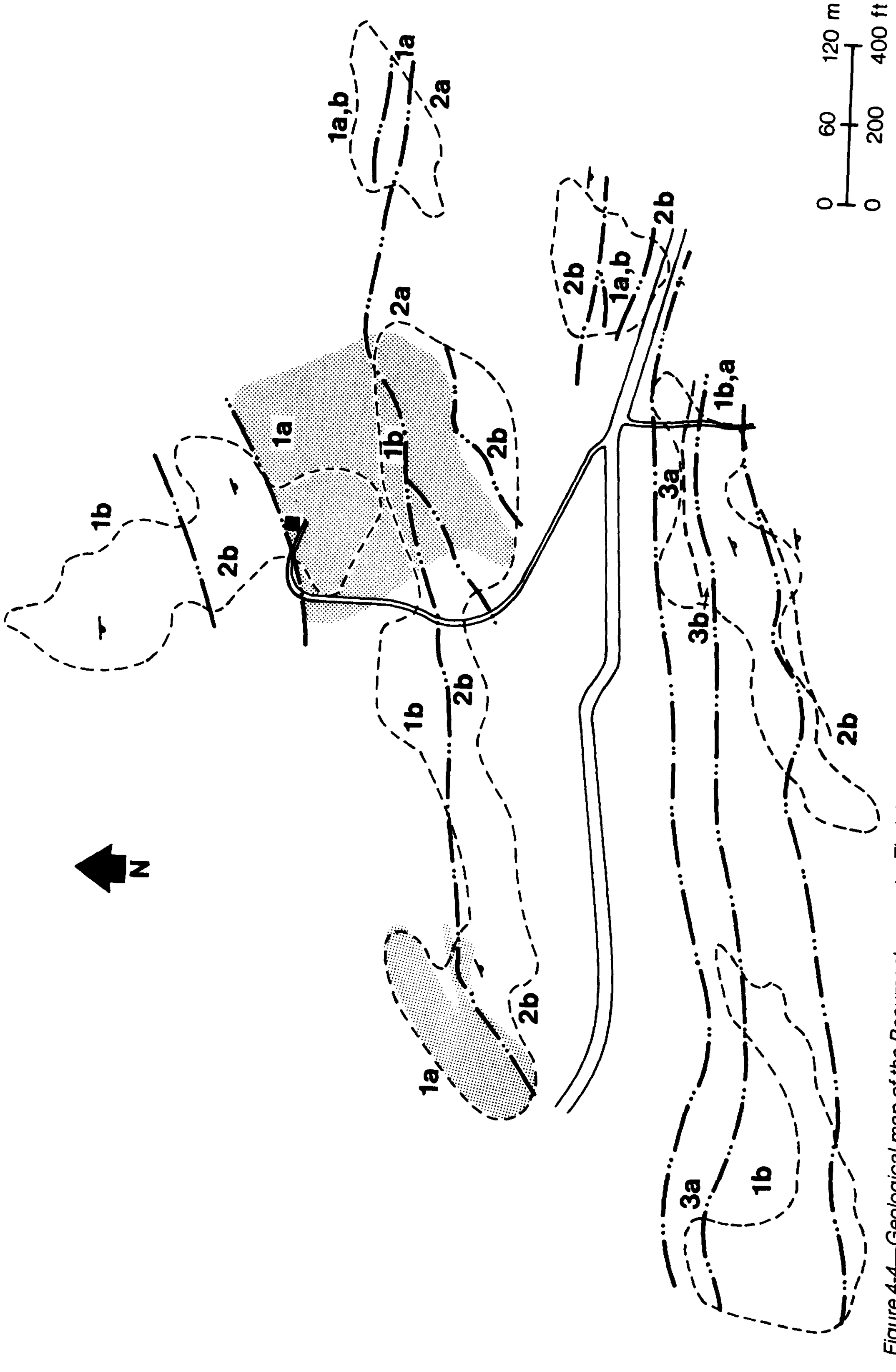


Figure 4-4—Geological map of the Beaumont property, Tisdale Township study area (Geology by Fyon, modified after Ferguson 1960). A discordant carbonate alteration zone transects the komatiitic and magnesium tholeiite flows. The alteration terminates gradually within the massive phase of the magnesium tholeiite flow. (See Figure 4-3 for legend).

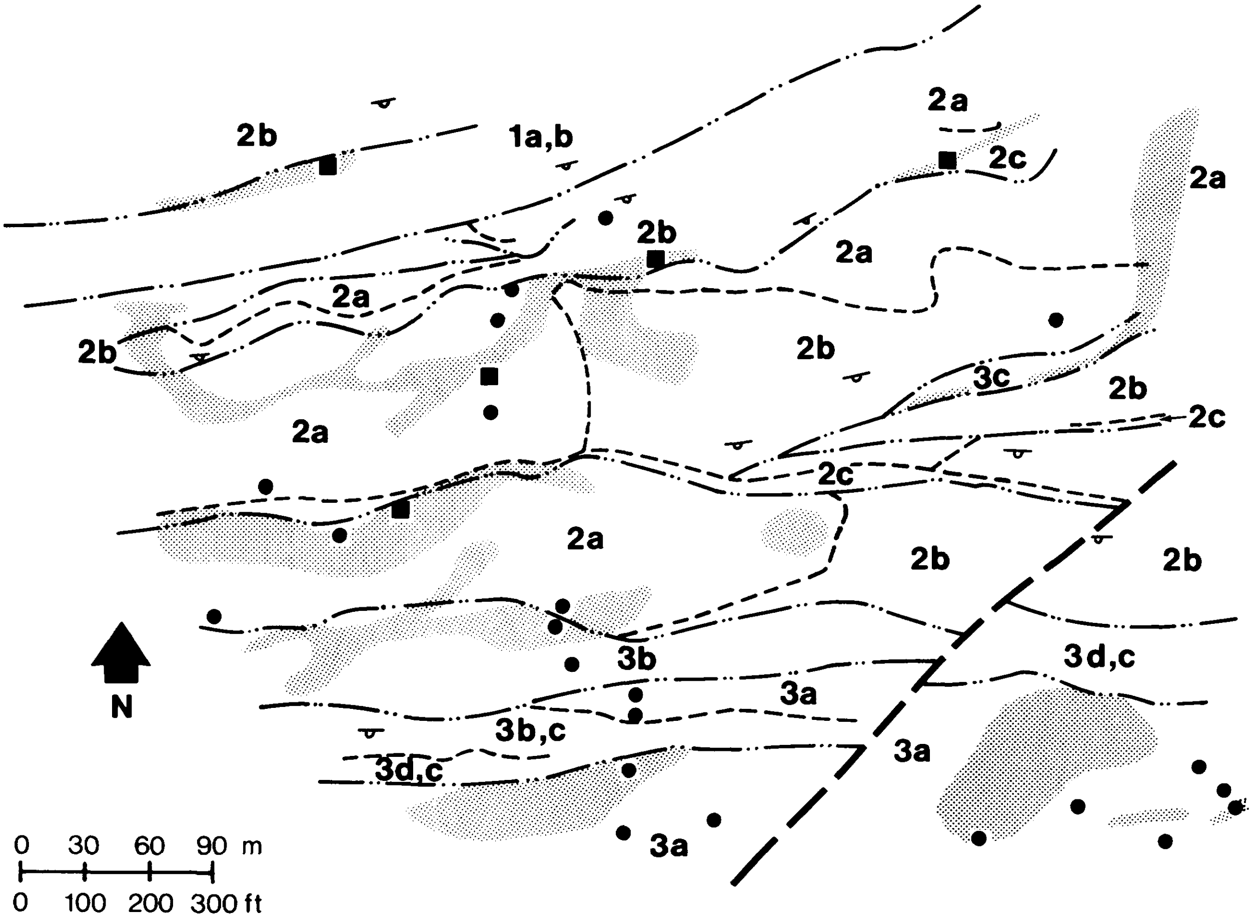


Figure 4-5—Geological map of the Kinch property, Tisdale Township study area. (Geology by Fyon, modified after Ferguson 1960). Stratabound alteration zones occur along or subparallel to flow contacts. On the northeast edge of the map-area, a discordant alteration zone transects massive and pillowed phases of a magnesium tholeiitic flow and a finger of stratabound alteration extends laterally out from this discordant zone along the first major flow contact encountered. (See Figure 4-3 for legend).

Trace Element Exploration Screens

An orientation, lithogeochemical survey was carried out on altered volcanic rocks to evaluate its use as an exploration tool, to augment geological and geophysical parameters. Samples of altered rock were classified into Productive and Unproductive groups. Samples were taken from altered rock located within 30 m (100 feet) of the ore zones in the Aunor, Delnite, and Buffalo Ankerite mines, whereas other samples were taken from the numerous alteration zones not associated with known gold mineralization in both study areas. Because element abundances vary as a function of rock type (komatiitic *vs.* tholeiitic), flow facies (pillowed *vs.* spinifex *vs.* cumulate) and degree of rock alteration, the data were plotted on binary plots as a function of alteration intensity (CO_2 weight percent) and magnesium tholeiitic and komatiitic rock-types have been distinguished.

A more complete discussion of the trace element screens is given by Fyon and Crocket (1979). Altered magnesium tholeiitic basalts which host the chert-dolomite type mineralization are enriched in Li (>30 ppm), B (>30 ppm), Au (>5 ppb), As (>70 ppm), and Sb (>0.35 ppm) and depleted in Cu (<70 ppm), whereas altered komatiitic flows from this mineralized environment are enriched only in Au (>5 ppb) and As (>70 ppm). CO_2, S, Ba, Zn, K_2O, or Ag cannot be used to screen altered rocks which host this type of gold mineralization. To minimize the effects of geochemical fliers, binary element screens such as Au-As or Au-B should be used routinely. Figure 1-10 Plot shows fields of calc-alkalic (1), tholeiitic (2), and komatiitic suites (3), as taken from Figure 1-9.

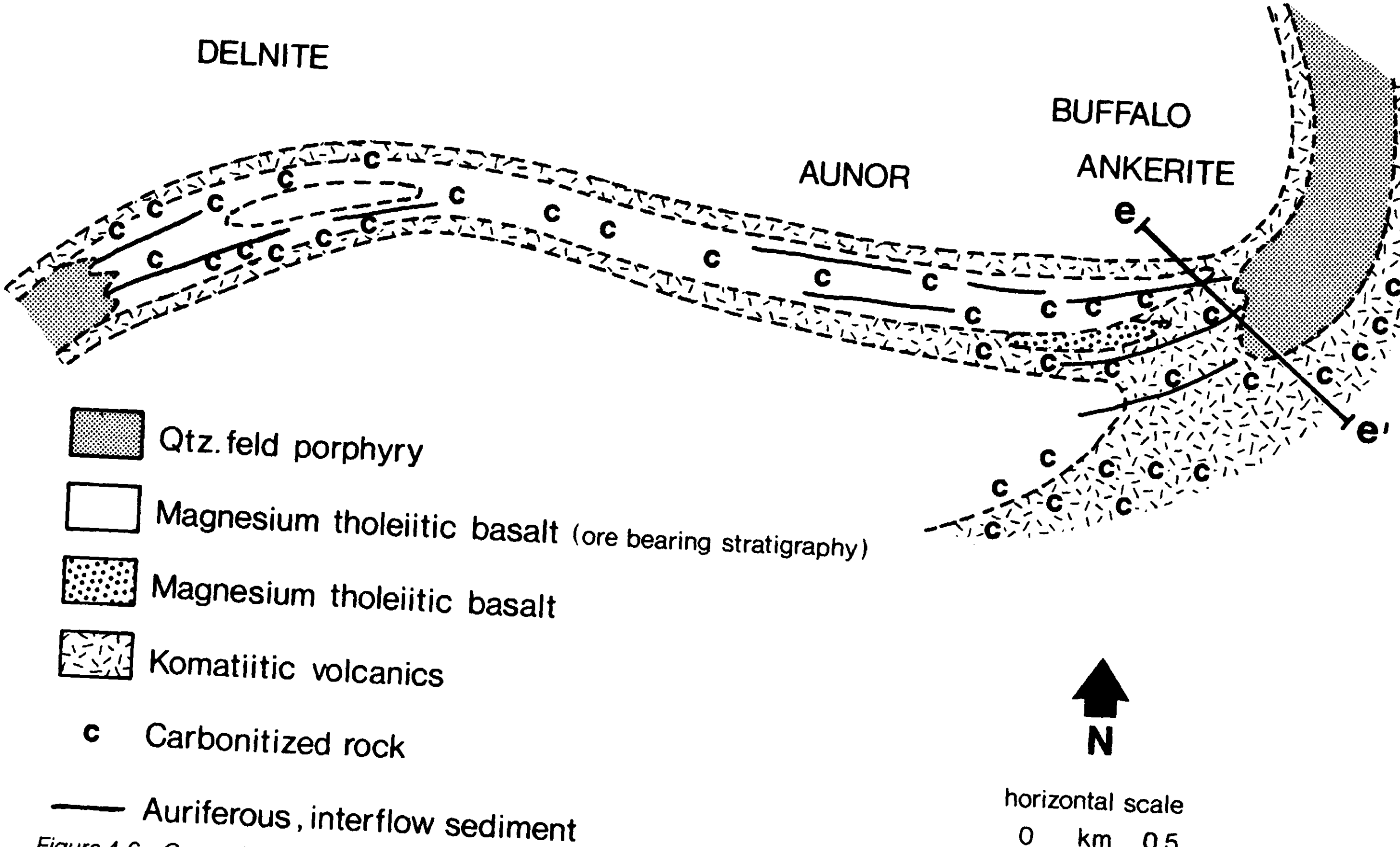


Figure 4-6—Generalized geological map at approximately 1000 feet below surface of the Delnite, Aunor, Buffalo Ankerite area. The map illustrates the relationships of the exhalative dolomites, stratabound felsic volcanic rocks (quartz-feldspar porphyry), and carbonatized rock. (Geology after Taylor 1948 and Kinkel 1948)

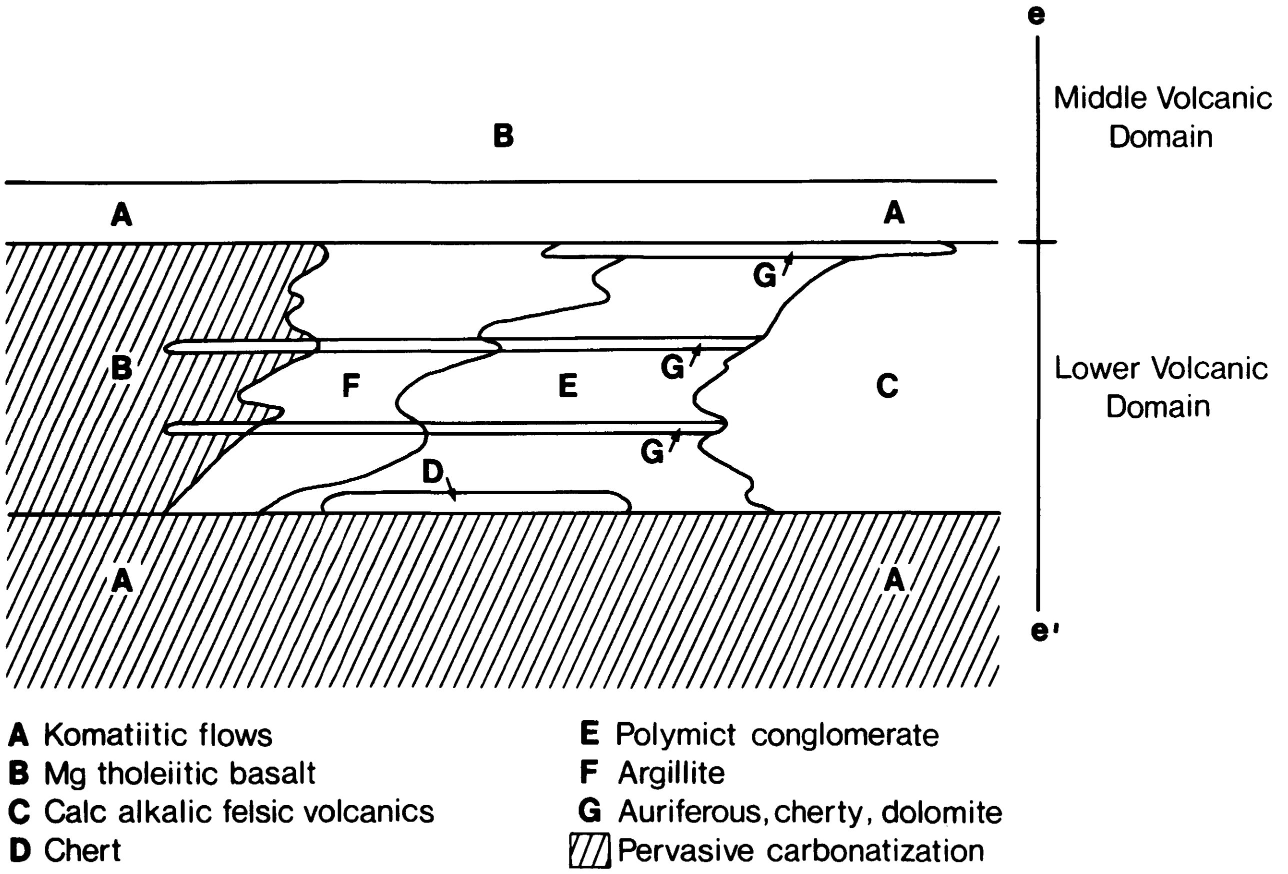


Figure 4-7—Schematic cross section e-e' through the Buffalo Ankerite ore zone illustrating the stratigraphic restriction of the carbonate alteration to the komatiitic and Mg tholeiitic volcanic rocks of the Lower Volcanic Domain. The volcaniclastic sedimentary rocks (E,F) which were derived primarily from a pre-existing, carbonatized komatiitic source area (A?) contain clasts of quartz-feldspar porphyry and flow banded rhyolite.

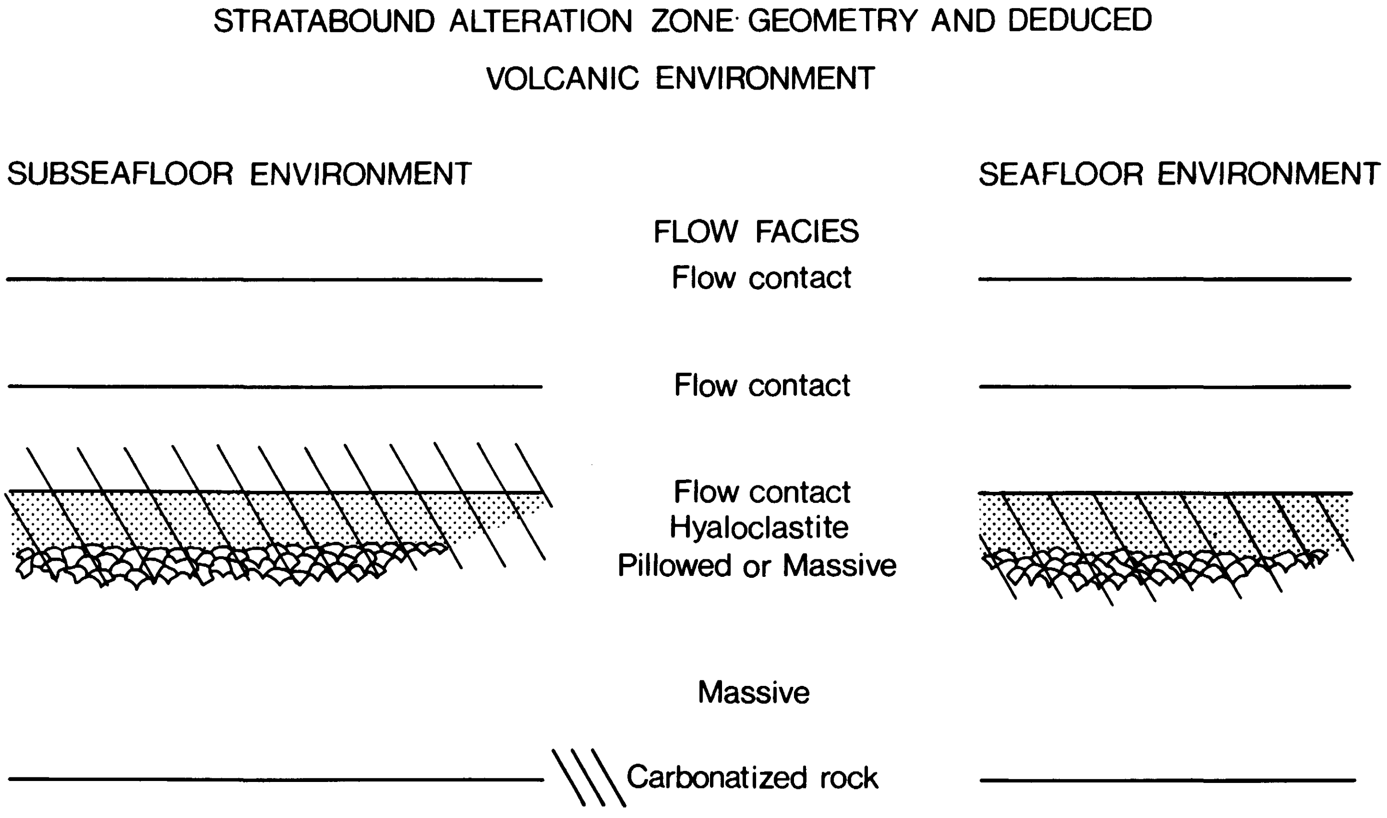


Figure 4-8—Schematic representation of the geometry of stratabound carbonate alteration characteristic of subseafloor and seafloor environments. In the subseafloor environment the top and base of juxtaposed flows are altered, implying that solutions flowed through the permeable flow-top after the emplacement of the overlying flow. In the seafloor environment alteration is restricted to the top of the basal flow, implying that alteration took place prior to the emplacement of the overlying flow.

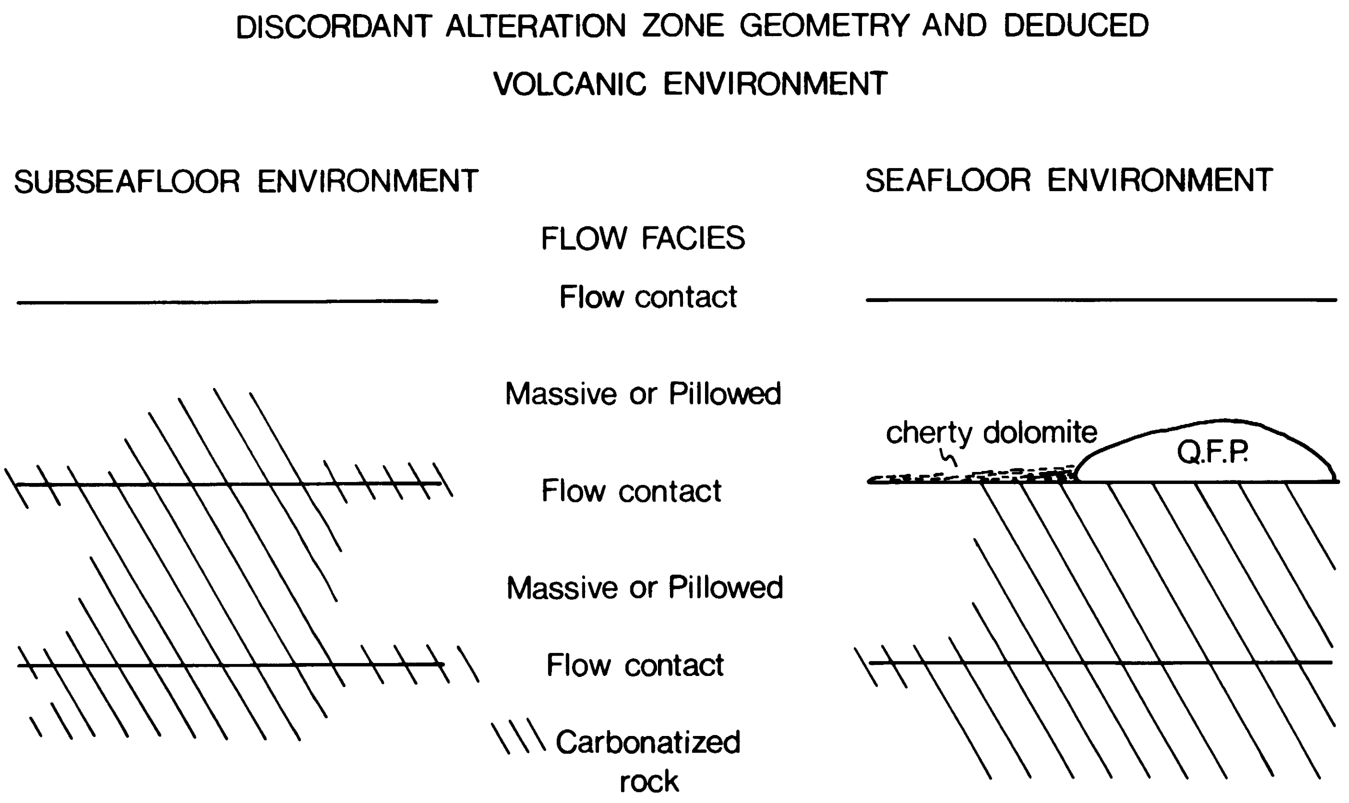


Figure 4-9—*Schematic representation of discordant alteration zone morphologies which are characteristic of subseafloor and seafloor environments. Subseafloor environment characterized by discordant alteration zones which terminate gradationally in a flow. Carbonatized rock which developed at the seafloor is overlain by carbonate-free flows, implying that the overlying flows were emplaced after the carbonatization process had terminated. Extrusive, felsic volcanic rocks and exhalative, auriferous, cherty dolomite are restricted to the seafloor environment. Q.F.P. in figure is quartz-feldspar porphyry.*

Gold Mineralization in the Kirkland Lake-Larder Lake Areas

L.S. Jensen[1]

Abstract

Gold mineralization in Archean 'Greenstone' Belts as illustrated by the Kirkland Lake-Larder Lake area is a process that occurs in several stages along major fracture zones. These fracture zones form along the boundaries between developing volcanic piles, and older stabilized volcanic piles and granitic terrains.

In the first stage, gold is precipitated in carbonaceous and clay-rich environments on the edge of the older volcanic pile or granitic terrain. This is followed by stages of downward displacement of the gold-bearing sedimentary rocks where they become heated by felsic magmas. The felsic magmas carry the gold toward surface again where it is found in high-level felsic intrusive rocks and in quartz-carbonate veins.

Introduction

The old axiom 'gold is where you find it' is still very much applicable to Archean volcanic terrains. It may be either that our knowledge of gold mineralization and Archean terrains is still primitive or that we have not been able to discover the relation between the two in order to systematically discover new gold mining camps. The purpose of this paper is to demonstrate a relationship between gold mineralization and Archean 'greenstone' terrains as it applies specifically to the Kirkland Lake-Larder Lake area of Ontario.

Rock types associated with gold mineralization, when found elsewhere in Archean terrains, tend to contain less that 10 ppb Au. Therefore, gold must undergo processes which concentrate it 10,000 times greater than 'background' before it can be considered an economic deposit. This requires that if the gold is extracted from a source rock, the volume of the source rock is likely to be at least 10^{10} to 10^{20} larger than the deposit itself and that the volume of the transporting medium is of the same order of magnitude as the source rock. It also requires that the mineralized rock-type acted as a focal point for the process of gold concentration. This process occurred during the formation of the rock or during its modification by diagenesis, metasomatism, metamorphism, or deformation. Some of the above requirements may be met by more than one beneficiation 'step' prior to the final deposition of gold. Nevertheless, large-scale sources and processes were required which must have been related to the development of the 'greenstone' belt itself.

Geology of the Kirkland Lake Area

Regional Setting

The volcanic rocks of Kirkland Lake form part of a large east-plunging synclinorium located between the Lake Abitibi Batholith and the Round Lake Batholith (Figure 5-1). The Destor-Porcupine Fault zone and the Kirkland Lake-Larder Lake Fault zone are located at the north and south limbs of the synclinorium, respectively. The major gold mines of northwestern Quebec and northeastern Ontario are near these fault zones.

The volcanic rocks were formed during cycles of volcanism that consisted of komatiitic volcanism followed by tholeiitic, calc-alkalic, and ultimately, alkalic volcanism. The rocks of each cycle are referred to as a supergroup. A supergroup is divided into groups according to major changes in the chemistry of the rocks. In the Upper Supergroup, the basal komatiitic succession is referred to as the Stoughton-Roquemaure Group on the north limb of the synclinorium and as the Larder Lake Group on the south limb of the synclinorium. These komatiitic successions can be correlated by tracing the komatiites around the nose of the synclinorium (Pyke, this volume). The overlying tholeiitic, calc-alkalic, and alkalic successions are referred to as the Kinojevis, Blake River, and Timiskaming Groups respectively. Each group of volcanic rocks has its own set of associated sedimentary[2] and intrusive rocks. In the Kirkland Lake area, the Upper Supergroup is over 35 km thick.

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[1] Ontario Geological Survey.

[2] All the rocks in the area have been metamorphosed, therefore the prefix 'meta' is not used.

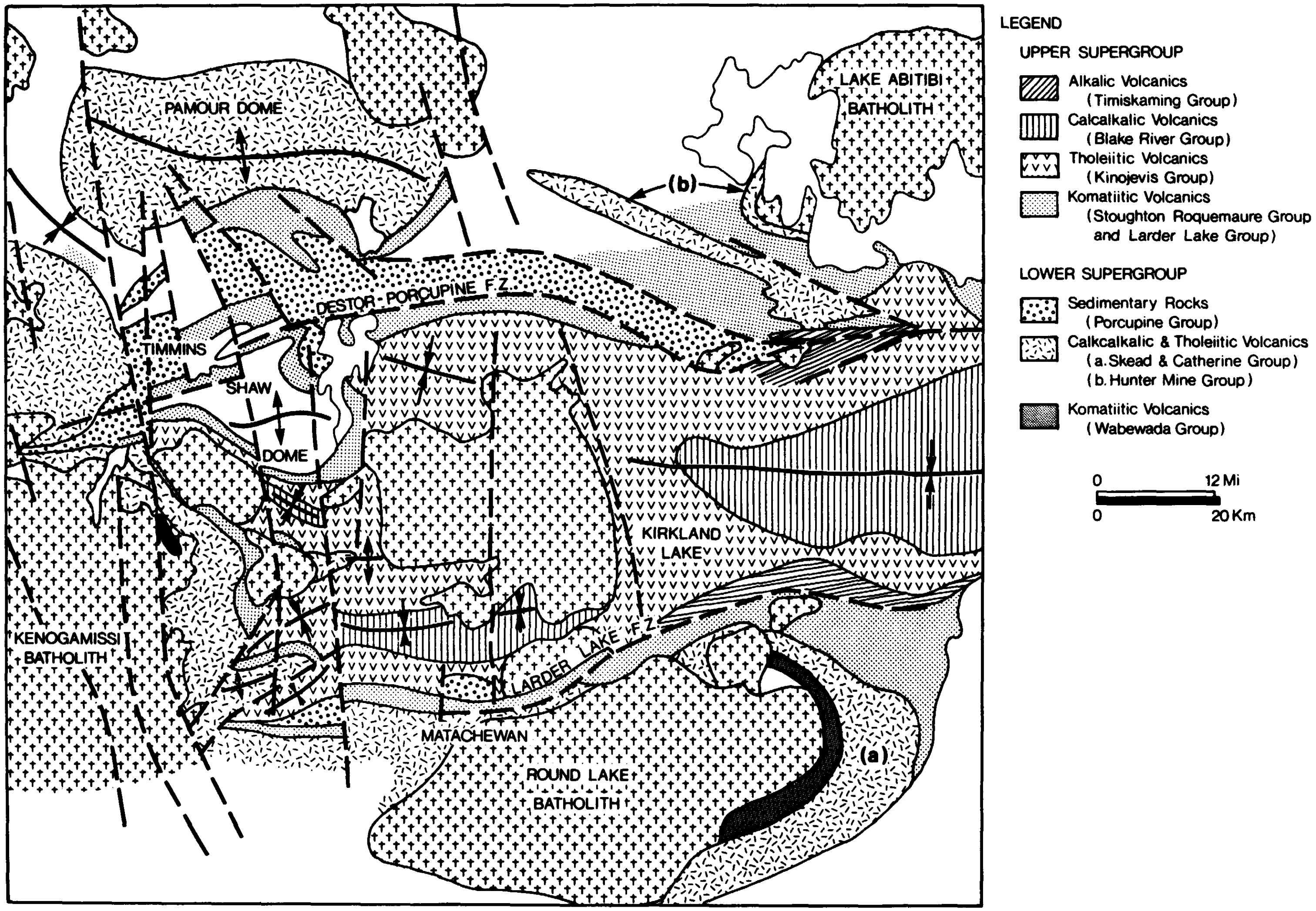

Figure 5-1—Stratigraphy and structural geology of the Timmins-Kirkland Lake area.

Rocks belonging to the older supergroups are present on the outer parts of the synclinorium where they are intruded by tonalitic batholiths. On the northern limb of the synclinorium, only the upper calc-alkalic rocks (Hunter Mine Group) of the older supergroup are preserved. They extend as far south as the Destor-Porcupine Fault zone. On the southern limb, a complete volcanic cycle is preserved. This lower supergroup has been referred to as the 'Skead Group' by R.H. Ridler (1970). It is here defined as a supergroup consisting of a komatiitic succession at its base overlain by tholeiitic and calc-alkalic successions. The successions are referred to as the Wabewawa, Catherine, and Skead Groups, respectively. Older calc-alkalic rocks, the Pacaud Tuffs (Ridler 1975), occur below the Wabewawa Group. They are cut by the granitic rocks of the Round Lake Batholith, as are some of the rocks of the Wabewawa Group.

To the east in Quebec, a lower supergroup appears to be absent south of Noranda and Cadillac. Instead, a large granitic batholith, which has intruded a thick group of sedimentary rocks called the Pontiac Group, occurs south of the extension of the Kirkland Lake-Larder Lake Fault zone. In places, komatiitic lava is interlayered with these sedimentary rocks.

Local Geology

The dominant feature of the Kirkland Lake-Larder Lake area is the major fault system that appears to extend from Matachewan in the west through Noranda towards Val d' Or. In many places this fault system is obscured by only slight displacement of the younger Proterozoic rocks. The older the rocks, the greater is the displacement. This suggests that the fault system has been active since the initial deposition of volcanic and sedimentary rocks in the area and without doubt has influenced the deposition of these rocks and their alteration along its length.

A volcanic succession, the Larder Lake Group of ultramafic and mafic komatiitic rocks and tholeiitic basalt which thickens northward from the Skead Township area is present on the south side of the fault zone. The komatiites are underlain by calc-alkalic felsic fragmental rocks and sedimentary rocks that probably were deposited on the margins of an older volcanic pile to the south. In the lower part of the succession, towards the south, the komatiitic lava is interlayered with felsic tuff suggesting that felsic volcanism overlapped the komatiitic volcanism. The felsic tuff thins northward suggesting that the source was to the south and that a basin existed to the north. It is probable that this basin deepened rapidly north of the fault. Komatiitic volcanism was more prevalent in the basin than on the shelf south of the fault zone. Numerous plugs and sills of peridotite intrude the felsic volcanic rocks as well as the komatiites, suggesting that the komatiites south of the fault had a local source.

The komatiites are interlayered with turbiditic conglomerate, greywacke, and argillite composed mainly of clasts and matrix material derived from the komatiites with lesser amounts of material derived from the felsic volcanic pile. To the north, the sedimentary rocks contain finely layered iron formation, chert, limestone, and dolostone. In addition, sericitic argillite, carbonaceous sedimentary rocks and sandstone with detrital quartz, calcite, dolomite, and feldspar are abundant in the northern part of the sequence, particularly along the southern margins of the fault zone from Kirkland Lake to Virginiatown. These rocks were formerly considered to be part of the Timiskaming Group together with sedimentary rocks in Hearst and McElroy Townships (Thomson 1941). Since these rocks are interlayered with komatiitic lava and komatiitic debris flows, they are considered to be older than the Timiskaming rocks found along the northern part of the fault zone. These sedimentary rocks and the komatiitic rocks host the gold mineralization along the southern margin of the fault zone in the Larder Lake area (M. Downes, this volume).

Tholeiitic flow rocks of the upper part of the Kinojevis Group are in outcrop on the north side of the fault zone. Elsewhere, the Kinojevis Group is more than 10 km thick and the underlying komatiites (Larder Lake Group) are 10 km thick indicating a downward displacement of approximately 20 km on the north side of the fault zone. Calc-alkalic volcanic rocks of the Blake River Group are in outcrop to the north, in the core of the synclinorium.

The Timiskaming Group unconformably overlies the Kinojevis and Blake River Groups north of the fault zone. In the fault zone, the Timiskaming Group is in fault contact with the older rocks to the south. The Timiskaming Group consists of alkalic volcanic flows and breccia and fluviatile conglomerate and sandstone (Hyde 1978). It is probable that the Timiskaming Group represents a period when tensional stresses in the fault zone were produced by an inward collapse of the synclinorium to the north. This created a graben structure along the fault which allowed felsic magma to penetrate upward through the older sedimentary and volcanic rocks. Felsic magma may have been derived from the mantle by the melting of older volcanic and sedimentary rocks. Numerous inclusions of ultramafic rock in the syenitic stocks suggest the magmas cut komatiites as they rose to the surface.

The last event effecting the area was the closure of the fault zone by compressive stresses. This produced tight folding and shearing of the Timiskaming Group rock formations on the southern edge of the fault.

Gold Mineralization

Gold Mineralization, Rock-Types, and Fault Zones

In a given mining camp, gold mineralization is rarely confined to one rock-type. Rather, it is found in several rock-types, which elsewhere in the 'greenstone' belt contain insignificant amounts of gold. For example, gold-bearing ultramafic intrusions, lava flows (komatiites), and debris flows are common in many mining camps; e.g. Larder Lake (Downes, this volume), Timmins (Pyke, this volume), Red Lake (Pirie, this volume), Val d'Or (Latulippe 1976), and mining camps in South Africa and Australia (Viljoen *et al.* 1969). On the other hand similar ultramafic intrusions and extrusions found elsewhere are barren. Similarly, in many mining camps, gold mineralization occurs in altered tholeiitic flows which are apparently identical to nonmineralized tholeiitic flows. Other common rock-types in which gold is found are: felsic tuff, chert, iron formation, carbonaceous sedimentary rocks, argillite, conglomerate, porphyritic intrusions, and granitic intrusions (Ferguson 1966a). These rock-types occur in the Kirkland Lake-Larder Lake area and in many other gold mining camps. A wide range of mineralization is associated with the gold deposits. It includes sulphides, sulphates, carbonates, and silicates of iron, copper, lead, arsenic, antimony, boron, fluorine, silver, barium, uranium, chromium, and others. The range of mineralization is much greater than that associated with massive sulphide deposits.

The factor common to gold-bearing rock-types appears to be that they occur in structurally complicated zones such as the Kirkland Lake-Larder Lake Fault zone and the Destor-Porcupine Fault zone. It is therefore important to understand the significance of such fault zones.

Gold Mineralization and the Development of Major Fault Zones

Major fault zones such as the Destor-Porcupine Fault zone and the Kirkland Lake-Larder Lake Fault zone evolved during the deposition of volcanic and sedimentary rocks of the Upper Supergroup along the margins of the older volcanic piles represented by the Lower Supergroup. The evolution of the Kirkland Lake-Larder Lake Fault zone and its relationship to the associated gold deposits are described below.

Stage I: Prior to the deposition of the Upper Supergroup, the older volcanic piles consisted of calc-alkalic cone-like volcanoes surrounded by a shallow water shelf that extended outward toward a deeper water ocean basin (Figure 5-2). Turbidites and chemical sediments and tuff were probably deposited on the shelf and nearby ocean basin by currents eroding the older volcanic pile. The sedimentary processes included the deposition of clastic gold and gold from solution. During this process, gold particles and gold from solution were deposited towards the edges of the shelf in troughs and sedimentary traps where gold chloride and sulphide complexes came in contact with acid-reducing environments. The gold was trapped by organic carbon and fine clay particles (Golding and Walter 1979; Radke and Scheiner 1970; Anhaeusser 1976; Staplin 1969). Sedimentary carbonate units indicate fluctuations of the sedimentary chemical conditions.

Stage II: At the onset of the next volcanic cycle, ultramafic flows were emplaced on the floor of the ocean basin and the sedimentary and calc-alkalic volcanic rocks marginal to the older volcanic piles (Figure 5-3). Ultramafic to mafic lava began to fill the basin and engulf the older felsic volcanics and associated sediments. Between episodes of mafic and ultramafic volcanism, gold was deposited in cherty pyritic sediments and carbonaceous sediments, as may be observed at the Kerr Addison mine. As the ultramafic lava accumulated, the weight probaby depressed the floor of the basin and initiated fracturing and slumping along the margins of the older volcanic piles. In this way, local sedimentary environments with reducing and acid conditions, favourable for the precipitation of gold, may have formed from chloride- and sulphide-gold complexes. The fractures probably provided channelways for hydrothermal brines rising to the surface. The brines may have originated at a dehyd-

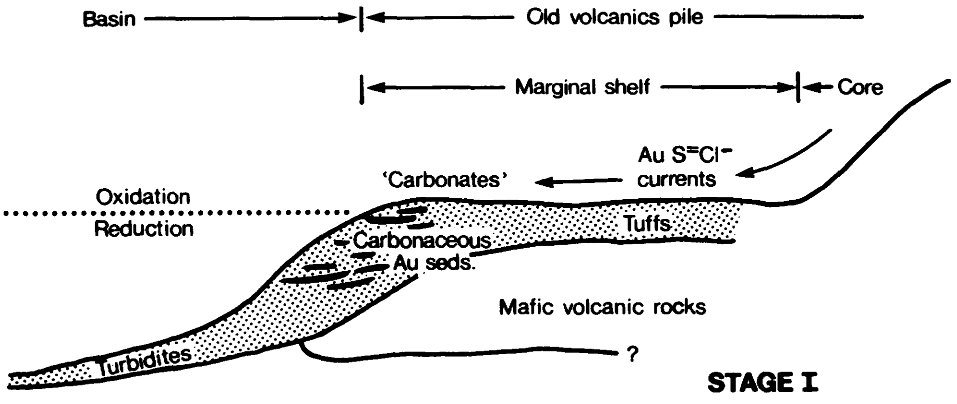

Figure 5-2—Stage I. Gold is deposited in sedimentary, acid reducing environments at the marginal zone of an older calc-alkalic volcanic pile.

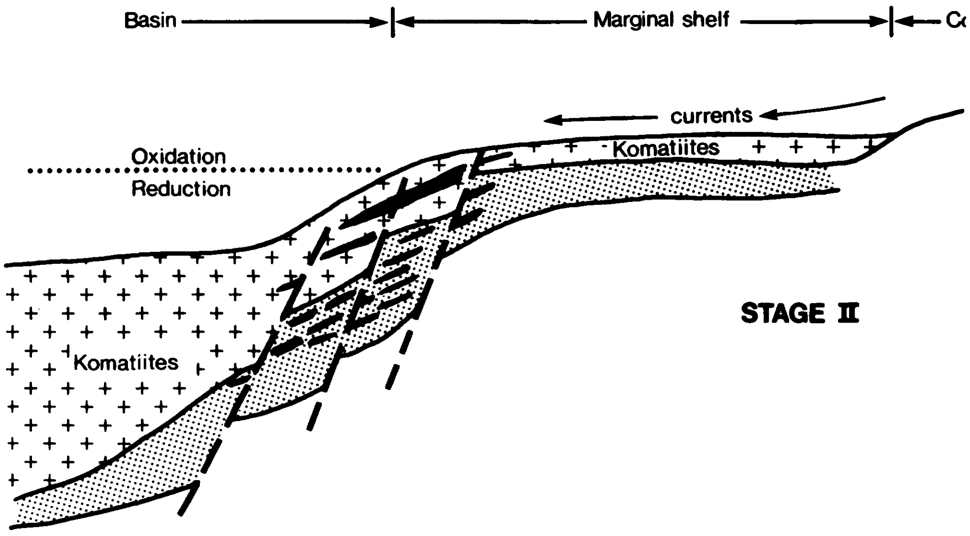

Figure 5-3—Stage II. The basin floor subsides as fractures form at the edge of the shelf. Ultramafic and mafic flows form this cycle. Erosion of the older volcanic pile continues. Peridotitic magmas are marble derived.

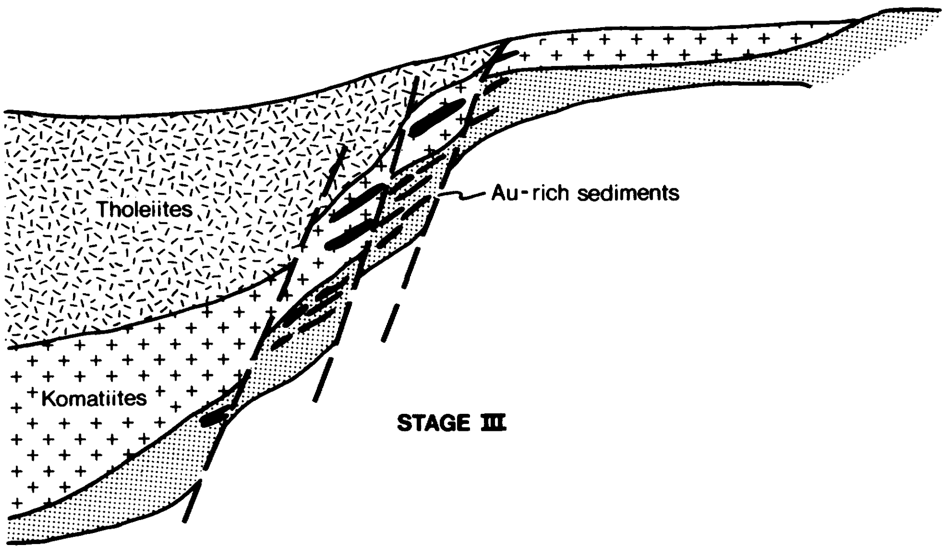

Figure 5-4—Stage III. The filling of the basin with tholeiitic flows depresses the basin still further. Movement is focused on the faults at the edge of the basin. Here ultramafic rocks are altered to serpentinites and talc-chlorite schists.

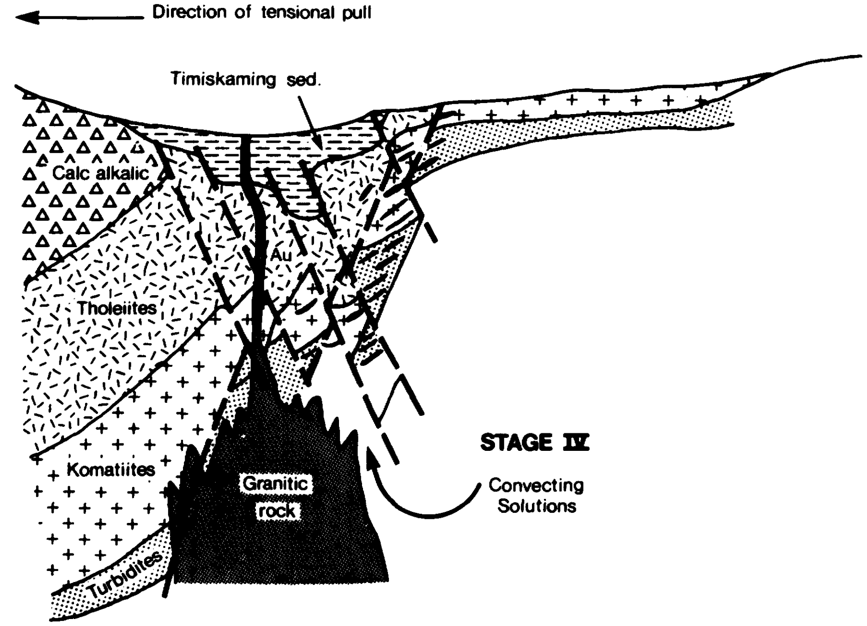

Figure 5-5—Stage IV. The inward collapse of the volcanics towards the centre of the basin results in dilation of the fault zone. The resulting graben structure is filled with Timiskaming sediments. Pressure release at depth causes melting and the generation of felsic magma which rises to intrude the upper rocks and redistributes Au, SiO_2, CO_2 and H_2O. If Au-rich sediments are assimilated by magmas that reach the surface, Au will be found in feldspar porphyry dikes and granite stocks. Heat from the magmas will drive Si-CO_2-S-Au-rich solutions upwards into tholeiitic flows to form quartz-carbonate veins in fractures or silicified and carbonatized zones. Gold in sedimentary rocks at surface will be only partially modified.

rating mantle source or as the result of hydrous convective cells that leached gold from older sedimentary and felsic tuffaceous units.

Stage III: As the basin filled with komatiitic rocks and sedimentary rocks and ultimately tholeiitic rocks, the weight of the accumulating rocks continued to depress the floor of the basin. Much of this movement probably occurred in the komatiites and sediments near the margin of the shelf (Figure 5-4) resulting in the serpentinization of the komatiites and the formation of talc-chlorite schist. The movement produced downward displacement of the rocks on the basin-side of the fault zone relative to the same rocks resting on the shelf of the older volcanic pile. In the Kirkland Lake area, this displacement is estimated to be 20 to 30 km.

Stage IV: At this stage, the emplacement of calc-alkalic volcanic rocks, towards the core of the newly formed volcanic pile was probably associated with an inward collapse of the older volcanic rocks towards the centre of the original basin (Figure 5-5). Melting of the down-dropped sedimentary and volcanic rocks at the base of the volcanic pile may have produced felsic magma and hydrothermal solutions which penetrated upward along the fault zones resulting in extensive carbonatization, silicification, and deposition of gold in fracture zones of the younger rocks. Such a mechanism would explain the presence of gold in felsic intrusive rocks of the Kirkland Lake area, and gold in quartz-carbonate veins of tholeiitic and komatiitic flow-rocks in other mining camps.

Stage V: The final event was the compression of the fracture zone, possibly associated with the intrusion of granitic batholiths on either side of the fault zone. This caused tight folding and additional fracturing along the fault zones. Migration of the gold into the hinge zones of folds and other dilation zones probably occurred at this stage.

Exploration Guidelines

Gold exploration should be concentrated near major fault zones which mark the tectonic boundary between volcanic piles or between volcanic piles and gneissic terrains which have sedimentary aprons. The tectonic boundary may or may not correspond to a lithological boundary between volcanic piles because of the onlapping of younger volcanic piles on the margins of older volcanic piles. In places, this tectonic boundary will be obscured by younger rocks showing little or no displacement. However, it will be indicated by a major change of sedimentary or volcanic rock-types across the fault zone.

Acknowledgments

The author has benefited greatly from mine tours and conversations with several mine geologists. He is particularly indebted to Mr. G. Hinse who contributed greatly to the author's knowledge of the Larder Lake area. Discussions with M. Downes and D.R. Pyke have also been of great value to the author as have been discussions with colleagues from Western, Waterloo, Toronto, Ottawa, Carleton, and Queen's Universities.

Structural and Stratigraphic Aspects of Gold Mineralization in the Larder Lake Area, Ontario

M.J. Downes[1]

Abstract

Gold mineralization along the Larder Lake 'Break' is discussed with particular reference to the mineralization at the Kerr Addison mine. Recent detailed mapping of this section of the Kirkland Lake-Larder Lake area has led to the following conclusions.

Carbonate alteration followed by auriferous hydrothermal quartz veining and potassic metasomatism occurred later than the principal phase of folding. Carbonatization most closely followed komatiitic volcanism in tectonically thickened hinge zones. It also is spatially related to, and crosscuts the Larder Lake 'Break'. The 'Break' possesses a strong structural expression separating two domains of fold-axes oriented at 60° to each other.

Introduction

Work in the Kirkland Lake-Larder Lake area has demonstrated that gold mineralization occurs within two distinct stratigraphic groups, an older Larder Lake Group and a younger Timiskaming Group, which were previously considered to constitute a single group (Thomson 1941). Mineralization within the Larder Lake Group and its relationship to the 'Break' will be discussed.

These two stratigraphic groups are distinguished on the basis of their associated lithologies and relative position to one of two structural discordances (Figure 6-1).

Structural Discordances

Two structural discordances are recognized in the area.

Structural Discordance 'A'

Structural Discordance 'A' separates the Timiskaming Group and the Larder Lake Group. Over much of the area both groups face south yet the younger Timiskaming lies to the north, implying that the Larder Lake Group has been thrust up against the Timiskaming.

The discordance is marked by: 1) conflicting tops (back to back relationship) with no possibility of intervening fold closures; 2) sheared and highly schistose rocks, in particular sericite schist.

Structural Discordance 'B'

This is synonymous with what has previously been called the Larder Lake 'Break'. It is essentially a structural discordance as the lithologies on either side are related. This contrasts with Discordance 'A' which is a stratigraphic as well as a structural discordance. It separates two domains, one to the north with fold-axes plunging steeply to the east and one to the south with axes plunging moderately to the southwest (Figure 6-2). Both types of folds on the north and south domains have approximately the same axial planar orientations with no interference zone. The mean plunge values of 50° to the southwest on the south side and 70° to the northeast on the north side indicate a rotation of 60° in the plane of Discordance 'B'. An example of the intensity of isoclinal folding in turbidites just south of Barber Lake is manifest as fold-axes with associated bedding reversals over 46 m perpendicular to strike representing a true thickness of only 5.75 m. The fold-axes in Figure 6-2 represent mean azimuths of minor folds or bedding cleavage intersections in the sedimentary and volcanic rocks. This style of folding is common throughout the sedimentary rocks and is not affected by proximity to the 'Break'.

At the Kerr Addison mine, the orebodies straddle the Kerr Fault (Figure 6-3). Carbonate-type orebodies on the north side plunge 60° to 70° to the east and orebodies on the south side (predominantly flow ore) plunge about 50° to the southwest. This reflects the regional attitude of structures across Discordance 'B'.

Stratigraphy

North of Discordance 'A' basal grit of the Timiskaming Group unconformably overlies tholeiitic basalt of the Kinojevis Group (Jensen 1978a). Alkalic volcanic rocks[2] of this group are dominantly pyroclastic breccia but also contain monomictic conglomerate. A diagnostic feature

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[1] Ontario Geological Survey.

[2] All rocks in the area have been metamorphosed, therefore the prefix 'meta' is not used.

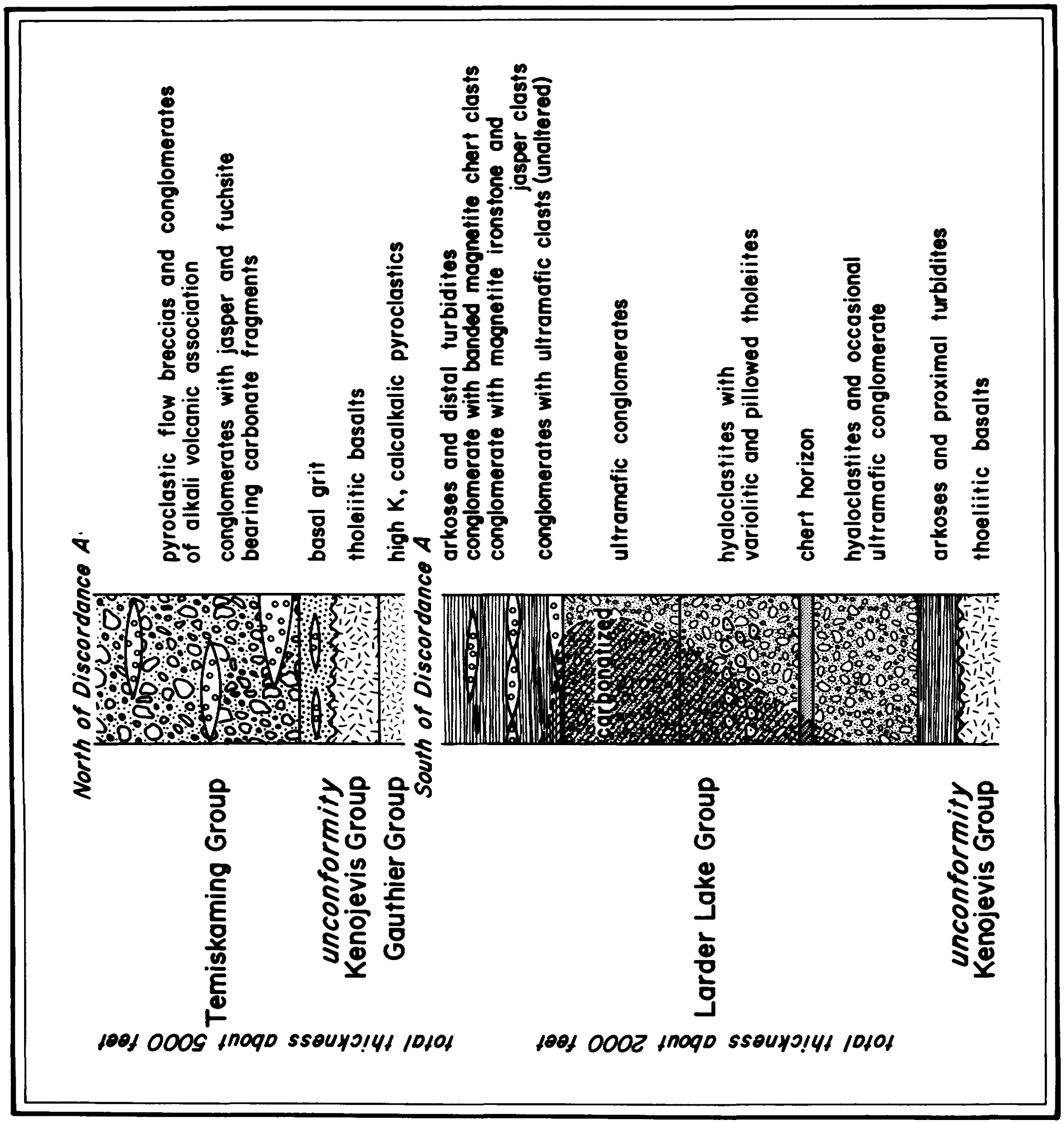

Figure 6-1—Stratigraphic sections north and south of Discordance A.

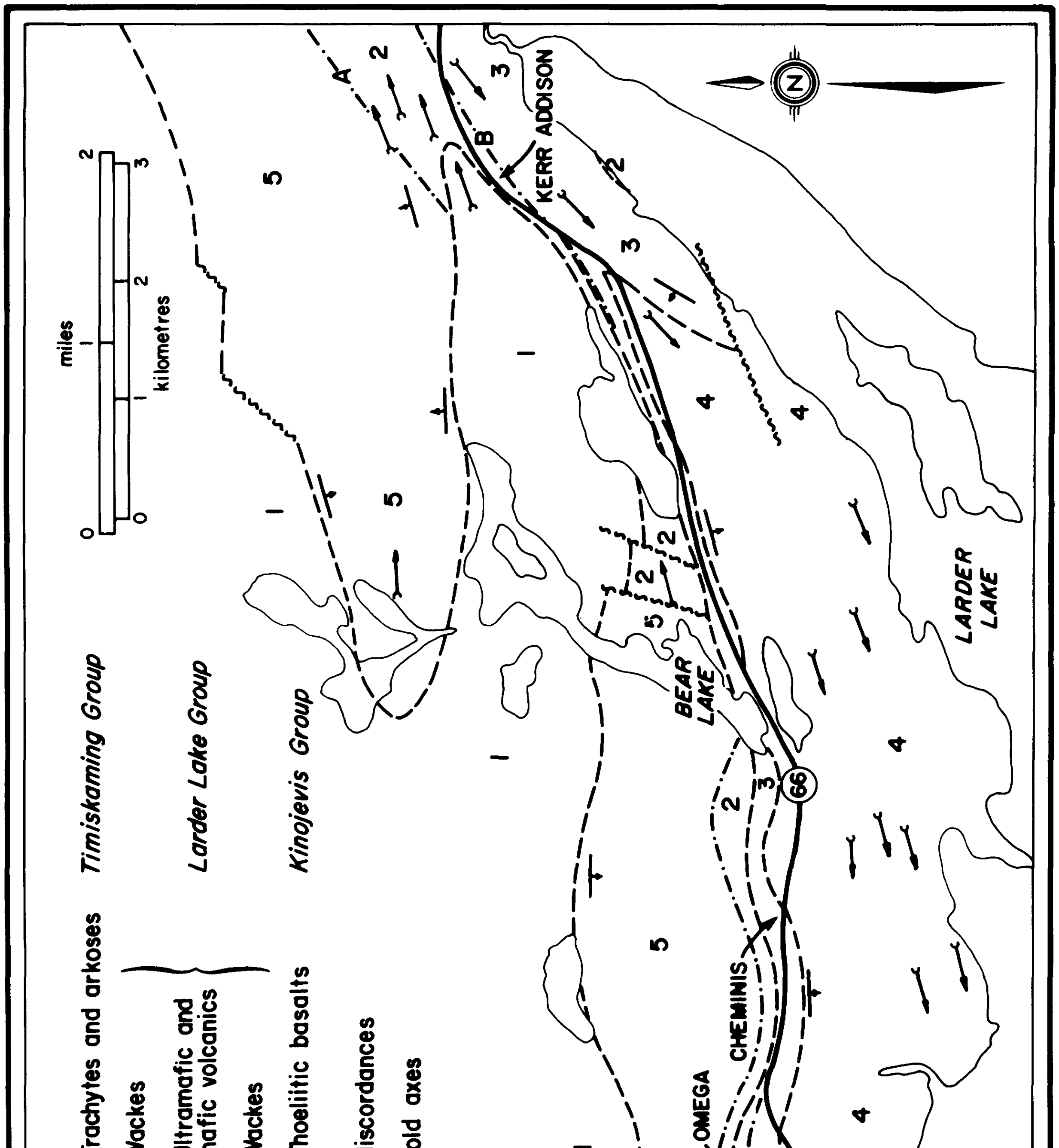

Figure 6-2—Distribution of major units, discordances and minor fold-axis azimuths.

of the polymictic conglomerate and grit is the presence of jasper- and fuchsite-bearing carbonate clasts. Ultramafic rocks are absent from the Timiskaming Group so far delineated.

South of Discordance 'A', Kinojevis tholeiitic basalt lying at the base of the sequence is overlain unconformably by proximal turbidites which may contain thin (10 to 50 cm thick) magnetite ironstone beds in a wacke association. Within the volcanic package, flows are dominated by both magnesium- and iron-rich tholeiitic basalt. Pillowed and variolitic iron tholeiite is common. Komatiitic flows per se have not been observed in the area. Though massive polysutured units are present, most of the ultramafic rocks occur in conglomerate as mixed polysutured and less commonly, spinifex-textured clasts.

The volcanic rocks described above are overlain by distal, chloritic turbidites containing units 10 to 20 cm thick of interbedded magnetic ironstone and less abundant carbonaceous sedimentary rocks. Near the Cheminis property (Figure 6-2), a rhythmite occurs which consists of layers of magnetite ironstone 1 to 2 cm thick, spaced at 30 to 40 cm intervals, through approximately 5 m of fine-grained turbidites. Some conglomerate within the Larder Lake Group contains fragments of banded magnetic ironstone-chert and felsic pyroclastic rocks similar to the Skead Group (Jensen 1978a, 1978b).

Alteration and Gold Mineralization

Carbonatization

The bulk of the carbonate units contain relict textures making possible their assignment to ultramafic or mafic volcanic, or sedimentary units, and it is possible to trace most altered rocks along strike to their unaltered equivalents. The timing of the carbonatization can best be demonstrated by the following observations.

1) Ultramafic clasts in conglomerate stratigraphically overlying the carbonatized volcanic rocks are not altered indicating that synvolcanic alteration reaching the seafloor is unlikely.

2) The presence of fuchsite-bearing carbonate clasts in the Timiskaming Group indicates that the cabonatization was active or complete at that time. In addition this indicates that the Timiskaming is younger than the Larder Lake Group.

3) In the area of the Kerr Addison mine, carbonatization crosses Discordance 'B' from the volcanic rocks on the south side to sedimentary rocks on the north side, suggesting that alteration postdated the development of the fault. The altered sedimentary rocks can be traced along strike to unaltered equivalents (arkose).

It is important to note that the most common lithology carbonatized was of ultramafic composition thus giving an apparent lithostratigraphic appearance to the carbonates.

Potassic Metasomatism

This takes the form of sericitization with the development of quartz veins, (stockwork and ladder types) within the carbonatized volcanic rocks. Buff sericite is common within shear zones and is associated with quartz veins in the alkalic volcanic rocks and sedimentary rocks. Within the carbonatized ultramafic units the sericite contains sufficient chromium to form the emerald green mica fuchsite. The 'green' alteration has been observed as a zone extending away from the contacts of the quartz veins. Alteration widths vary with the width of the vein and may be a few centimetres to several metres. This type of alteration occurs in the Dome mine near Timmins and in altered ultramafic rocks in South Africa (T. Pearton, personal communication).

Gold Mineralization

At the Kerr Addison mine there are two principal ore types

1) 'Green carbonate' (a fuchsite-bearing dolomitized ultramafic volcanic rock): Gold occurs as free gold in quartz veins related to the metasomatic alteration but not actually in the green carbonate itself.

2) Flow ores: This includes several lithological types, the only common denominator being that they are all pyritic. Gold is hosted by the pyrite. The grade of the ore has an inverse relationship to the grain-size of the pyrite (Kerr Addison Staff, personal communication). The nature of these ores is currently under investigation by the author.

At Barber-Larder and Cheminis, ore zones are in a pyritic, carbonatized hyaloclastite unit and a pyritic, cherty tuff.

Conclusions

1) The Larder Lake 'Break' possesses a strong structural expression and separates two domains of fold-axis orientations.

2) Carbonate alteration cuts across this 'Break' and also appears to be most intensely developed in fold hinge zones. It thus appears to be a late tectonic event.

3) The quartz veining and potassic metasomatism at the Kerr Addison mine is spatially related to the carbonate alteration and is therefore a late tectonic event.

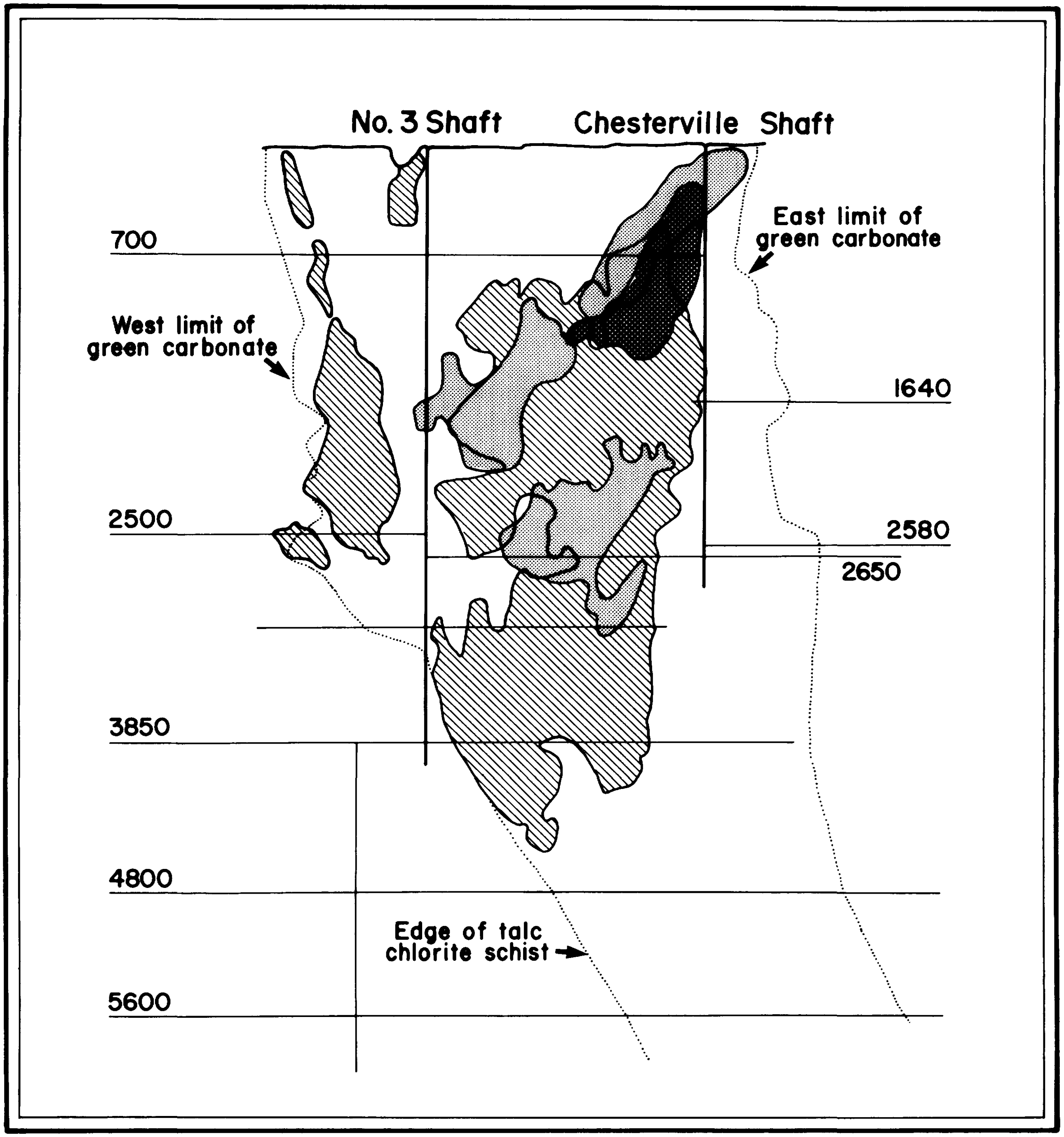

Figure 6-3—East-west longitudinal section in Kerr Addison mine.

Regional Geological Setting of Gold Deposits in the Red Lake Area, Northwestern Ontario

James Pirie[1]

Abstract

The major Archean gold deposits in the Red Lake 'greenstone' belt, which have produced over 12 million ounces of gold since 1930, occur near the top of the lower komatiitic to tholeiitic mafic to ultramafic metavolcanic sequence. The upper calc-alkalic mafic to felsic rocks form three discrete and separate edifices overlying this lower sequence.

The gold deposits are classified according to their stratigraphic or lithologic associations into:
1) mafic volcanic hosted deposits;
2) felsic intrusive hosted deposits;
3) statabound deposits.

Group 1 and to a lesser extent Group 2 deposits occur within zones of alteration several square miles in extent. The nature of this pervasive alteration can be characterized by comparison of petrochemical data from the altered rocks and their fresher equivalents some distance away. The altered rocks have substantial addition of SiO_2, CO_2, K_2O, As, and Sb and subtraction of Na_2O, CaO, MgO, and total Fe. Cr, Ni, Co, and Zr appear to have been relatively immobile. Hydrothermal alteration and gold deposition probably accompanied early fumarolic activity and continued during subsequent deformation of the metavolcanic sequence with gold eventually being mobilized and concentrated into major vein structures to form the present orebodies. The smaller Group 2 deposits were formed by emplacement of felsic intrusions into already altered, anomalously gold-bearing mafic metavolcanics with the heat from the intrusions setting up parasitic hydrothermal systems which mobilized the gold and deposited it along with minor sulphides in fractures in the cooling intrusions.

Introduction

The Red Lake metavolcanic-metasedimentary or 'greenstone' belt is located in northwestern Ontario and forms part of the Uchi Subprovince of the Archean Superior Province (Figure 7-1). The belt, which covers approximately 880 km^2 is about 48 km long with a maximum width of approximately 25 km. It is bounded on all sides by granitoid batholithic masses which give the belt its precise outlines.

Over 12 million ounces of gold have been produced from the Red Lake gold camp since mining commenced in 1930, an amount surpassed in Ontario only by the prolific Timmins and Kirkland Lake gold camps in the Abitibi Subprovince of northeastern Ontario.

Previous Work

The Red Lake belt was examined in reconnaissance fashion by several Ontario government geologists in the 1920s and 1930s and was systematically mapped by H.C. Horwood (1940), who also wrote a comprehensive report on the geology, mining, and exploration of the area. In the 1960s S.A. Ferguson (1962, 1965, 1966b, 1968) carried out detailed mapping in Dome, Heyson, and Baird Townships and, by 1971, R.A. Riley had mapped the western half of the belt in detail. Between 1976 and 1979 the author completed detailed mapping of the eastern half of the belt (Pirie and Grant 1978a, 1978b).

Volcanic Stratigraphy

General Geology

As is typical of Archean supracrustal terrains, the base of the volcanic sequence is nowhere seen in the Red Lake belt. The lower part of the supracrustals (the lower mafic sequence, Figure 7-2) comprises a thick sequence of mafic to ultramafic metavolcanics with minor intercalated units of felsic metavolcanics and metasediments. Overlying these lower sequence rocks (Figure 7-2) are substantial thicknesses of felsic and intermediate rocks, and minor mafic metavolcanics, with some metasedimentary units interspersed throughout the succession (the calc-alkalic sequences, Figure 7-2). The relative configuration and overall petrochemical data of the metavolcanics give an impression similar to other Archean 'greenstone' belts of an extensive basin development of tholeiitic to komatiitic basalt with a number of discrete calc-alkalic andesitic to rhyolitic edifices built on this lower sequence. The whole volcanic assemblage was then deformed coeval with the emplacement of the main phases of the granitoid batholiths bordering the belt, followed somewhat later by the intrusion of the discordant granitoid Dome stock in the centre of the belt and similar bodies in the surrounding batholithic terrain. With the exception of the immediate vicinity of the main batholiths, the supracrustal rocks have undergone only low-grade metamorphism and most primary textures and structures are preserved.

All the gold production in the Red Lake camp has

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[1] Ontario Geological Survey.

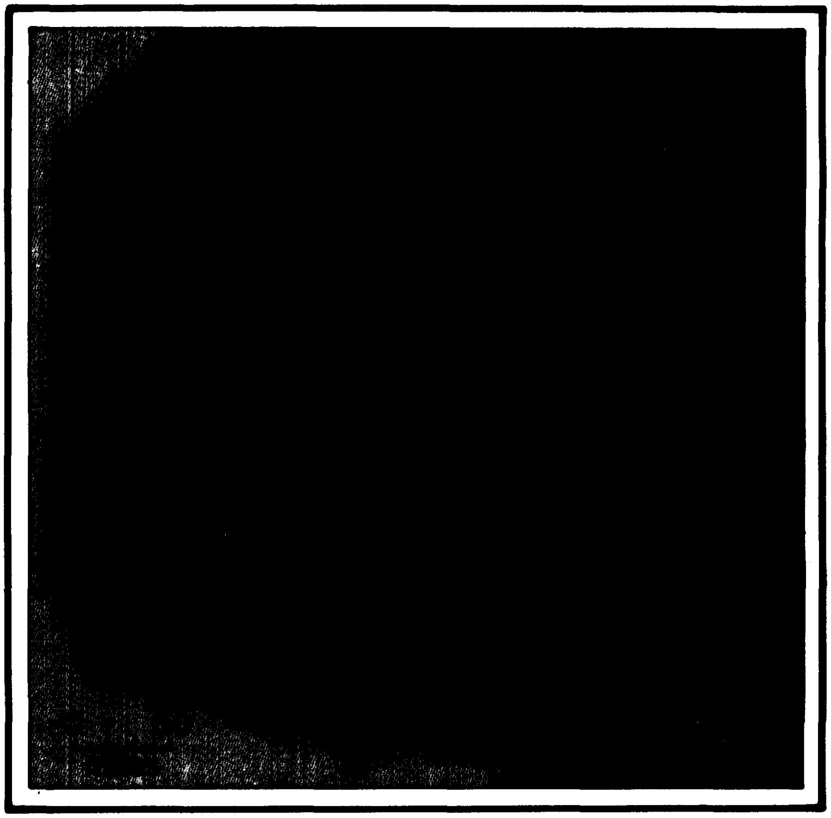


Figure 7-1—Location of Red Lake area and subprovinces of Superior Province in northwestern Ontario.

come from the eastern half of the belt (Figure 7-3); therefore only this part will be the subject of further discussion.

The Lower Mafic Sequence

The lower mafic sequence is best exposed around the shores of Red Lake in McDonough and Bateman Townships (Figure 7-4). The sequence here comprises a substantial accumulation of mafic to ultramafic flows subdivided into three main types: tholeiitic basalt, variolitic basalt, and basaltic komatiite. These three end-members are fairly easily distinguished in the field but there are gradations between the three which, because of their fine grain size and macroscopic textural similarities, are more easily identified by petrochemistry and thin section examination.

Basaltic Komatiites

Normal Flows: In McDonough, Bateman, and Balmer Townships most of the major ultramafic to mafic metavolcanic units contain a considerable proportion of actinolite-rich flows of basaltic komatiite composition with colour indices up to 100, interspersed with more typical mafic flows with colour indices between 35 and 50. Whole-rock chemistry and study of thin sections taken from various parts of these units suggest that there is a continuum of flow compositions from ultramafic to mafic. This is typical of the 'greenstone' belts of northwestern Ontario (Figures 7-5a, 7-5b, 7-5c).

The actinolite-rich metavolcanics, which originally were pyroxenite and feldspathic pyroxenite, form fine-grained massive flows, some of which are pillowed. Thicker flows may have coarse-grained interiors. The flows are between 10 m and 100 m thick. Pillowed zones may be over 10 m thick. Spinifex-textured flows less than 2 m thick also occur locally.

Locally rubbly monolithic mafic breccia beds occur above the pillowed zones and are interpreted to be flow-top breccia material. The fragments are generally well altered and carbonatized and are set in a medium-grained carbonate-rich matrix.

The typical basaltic komatiitic metavolcanics are dark green and may have small stubby actinolite phenocrysts scattered through a matrix of stubby to prismatic actinolite and interstitial plagioclase. In some localities more orderly radiating clusters of elongate prismatic actinolite are present. Between the prisms are sheaves of very fine grained elongate actinolite. The radiating texture

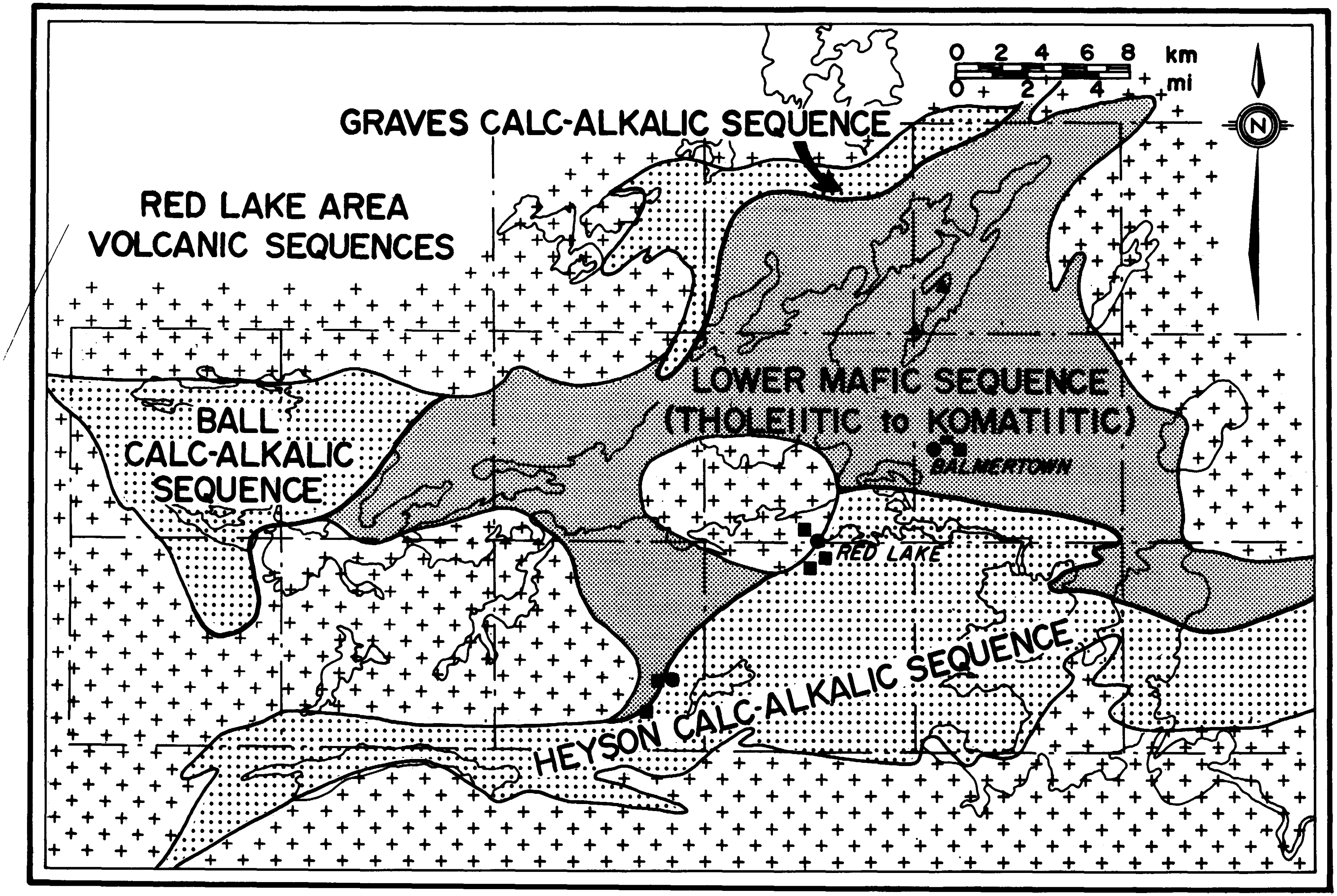


Figure 7-2—Major volcanic sequences in the Red Lake area.

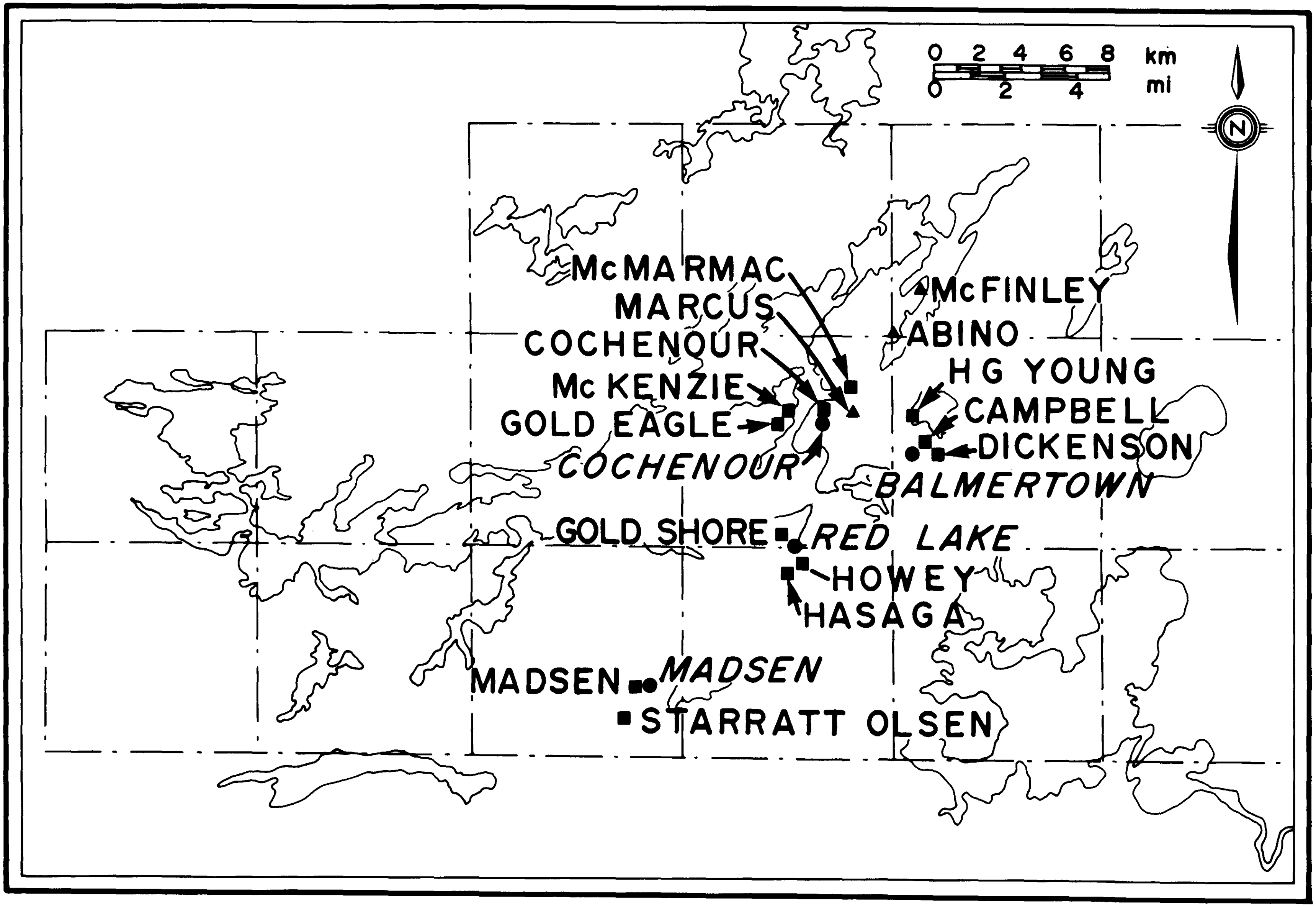
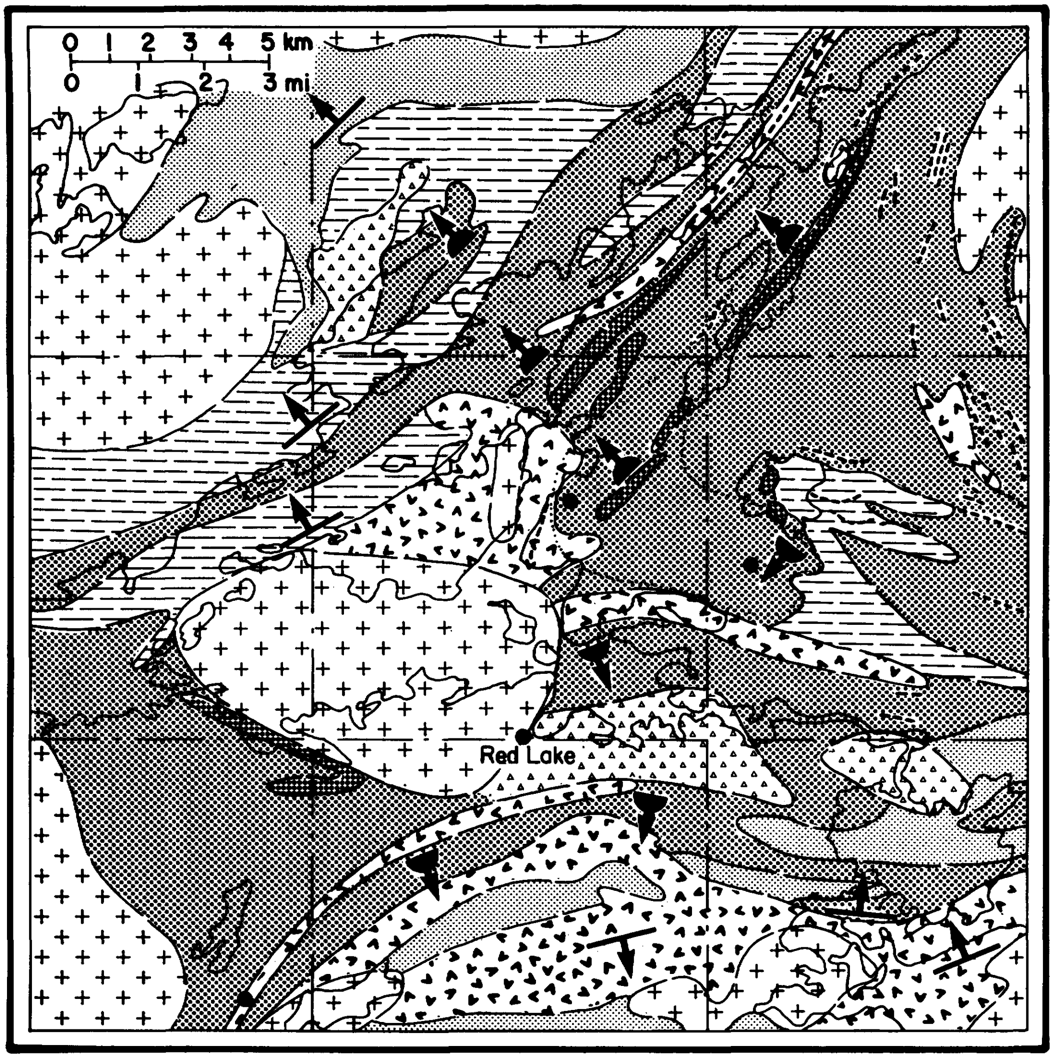


Figure 7-3—Location of past and present gold producers in the Red Lake area (squares) and properties with significant underground development but no production (triangles).



LEGEND

▒ Mafic to ultramafic metavolcanics

░ Intermediate metavolcanics

▲ Felsic metavolcanics

☰ Clastic, chemical metasediments

▓ Mafic to ultramafic intrusives

△ Felsic subvolcanic intrusives

+ Felsic to intermediate
batholithic intrusives

Figure 7-4—General geology of the eastern part of the Red Lake supracrustal belt. Top directions are from pillows and sedimentary structures.

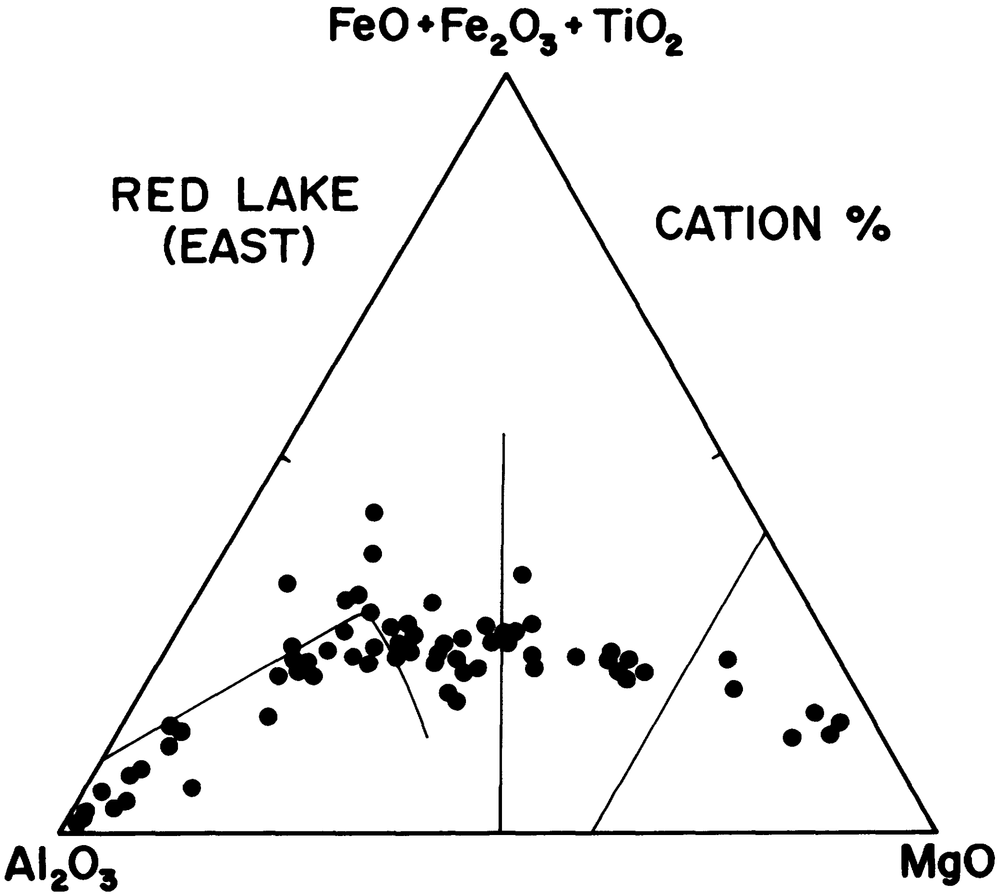


Figure 7-5a—Al_2O_3 – (FeO † Fe_2O_3 † TiO_2) – MgO cation plot of metavolcanics from the eastern Red Lake belt. The four samples near the MgO apex are intrusive peridotite.

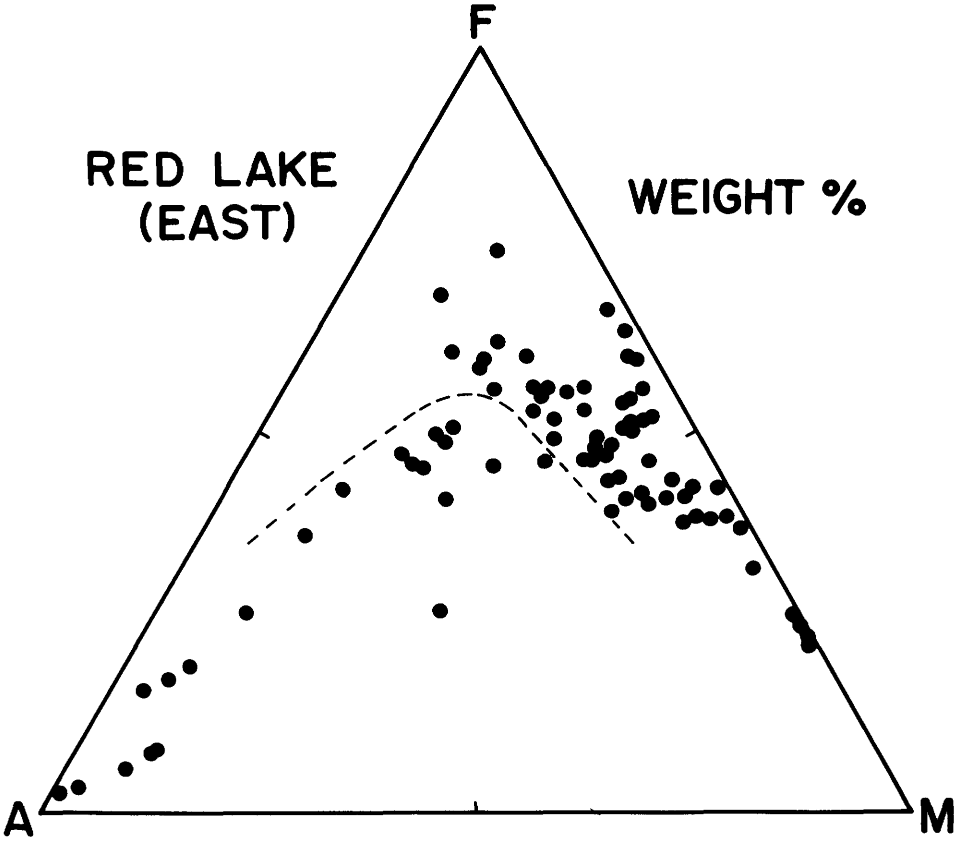


Figure 7-5b—AFM plot of the rocks in Figure 7-5a.

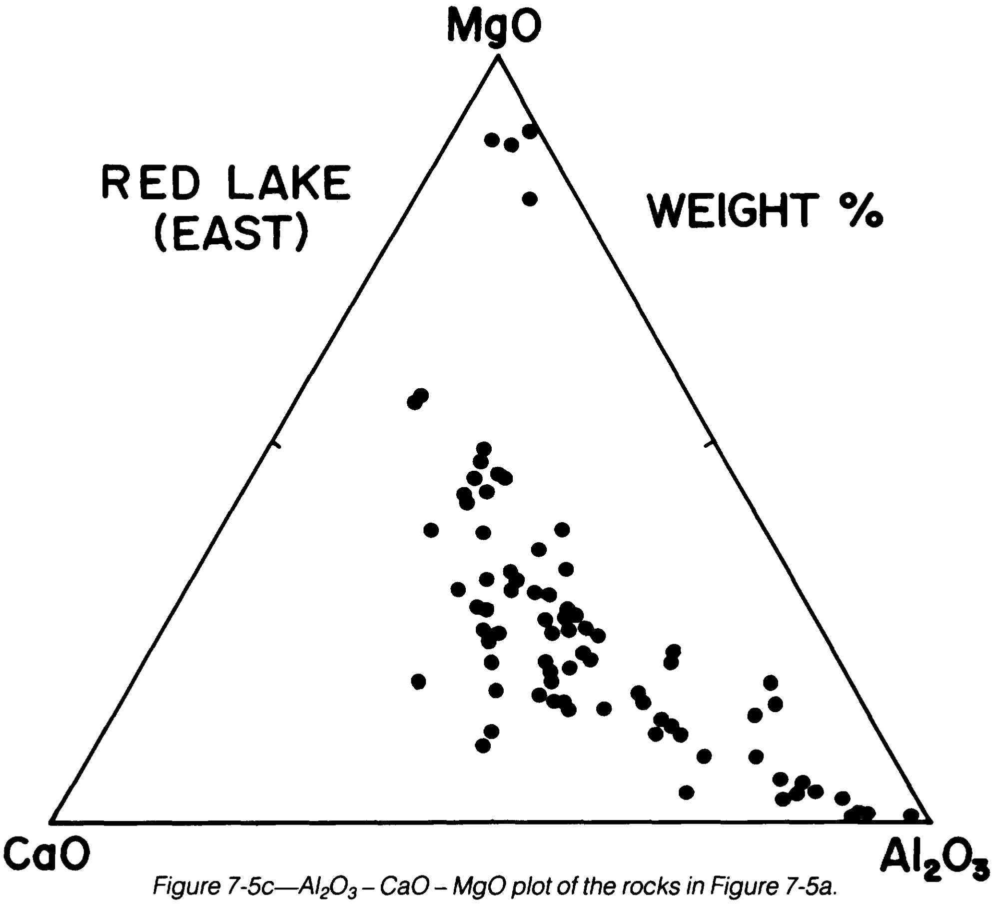


Figure 7-5c—Al_2O_3 – CaO – MgO plot of the rocks in Figure 7-5a.

is interpreted by the author to be due to rapid initial cooling of the lava as with the more classical spinifex texture.

Spinifex-Textured Flows: The development of classical spinifex texture in the ultramafic flow units is extremely rare in the map-area. The texture was observed along the west shore of Post Narrows in McDonough Township, with the best development occurring on the extreme southeastern part of the island at the northwest end of Post Narrows itself. Here two main spinifex types are present. The first is the classical "string-beef" type, formed of parallel to slightly divergent aggregates of actinolite needles aligned approximately perpendicular to the flow contacts. These narrow, cone-shaped aggregates have their apices towards the flow top and diverge downwards into the flow. The second type is a more radiating pattern of acicular to prismatic actinolite forming sheaf-like aggregates which interlock throughout the rock in a random fashion. Actinolite grains in these are generally less than 0.4 mm wide and 1 cm long. This second type appears to be a smaller scale version of the first type in which nucleation and growth of the aggregates began at many centres simultaneously in the liquid magma, giving a large number of restricted randomly arranged aggregates. A more detailed description of the textures and structures is given elsewhere (Pirie 1980).

Variolitic Flows: Variolitic flows occur throughout many of the major mafic to ultramafic metavolcanic units, especially in McDonough and western Bateman Townships. They are invariably pillowed, and the pillows which are variolitic, have similar size, shape, and selvage thickness to those of the basaltic komatiitic flows described earlier.

Tholeiitic Basalts

As stated above, a continuum of compositions, structures, and textures apparently exists from the ultramafic, actinolite-rich metavolcanics of komatiitic affinity to the typical tholeiitic mafic metavolcanics with colour indices between 35 and 50. Typical tholeiitic basalts, such as occur along the south shore of East Narrows, are medium to dark green, fine grained and pillowed, or medium grained and massive. The long dimension of the pillows is less than 1 m and is parallel to the lithologic contacts. Locally their packing arrangement indicates facing direction.

Tholeiitic Felsic Volcanics

Narrow units of felsic metavolcanics occur throughout the lower mafic sequence. They are typically pyroclastic with minor flow material. The best exposed felsic volcanic sequence is located along the eastern side of Hoyles Bay in Bateman and McDonough Townships. This felsic metavolcanic sequence is subdivided into an upper and lower unit by a continuous metasedimentary unit, up to 30 m thick, comprised mainly of layered chert with magnetite and minor pyrrhotite ironstone layers.

The lower felsic unit comprises a number of coarse, monolithic, fragmental, unbedded subunits with both lithic and flattened pumice breccia fragments set in a fine-grained tuff-size matrix. These are separated by narrow thin- to medium-bedded tuff layers, some of which show good grading of sand-size material. Top directions are to the northwest. Higher in the lower felsic unit, the breccia is heterolithic. Here the fragment size decreases and the grain size of individual adjacent fragments is more variable. Fragments are generally even grained and nonporphyritic, although quartz mosaic areas in the matrix were probably original phenocrysts. Small apple green fuchsite-rich wisps and patches occur locally and may be fragments of chromium-rich material introduced with the felsic magma.

The upper felsic metavolcanic unit, above the chert ironstone unit, comprises, at the base, fine-grained porphyritic rhyolite tuff, with lesser lapilli-tuff and lapillistone. This is overlain by monolithic, unsorted tuff-breccia with minor lapilli-tuff material. Both fragments and matrix contain phenocrysts of quartz, microcline, and plagioclase. Flattened pumice and welded textures suggest an ash-flow type process for the formation of this unit.

Another thick rhyolitic unit trends west-northwest across Balmer Township through McNeely Bay to Bruce Channel and may link up with a larger unit underlying much of McKenzie Island. Narrower, more restricted lenses occur in McDonough Township at the north end of Slate Peninsula and on the west side of Hoyles Bay, in Dome Township around Cochenour and Rahill, and in Balmer Township to the south of Balmertown, on the Campbell Red Lake Mines Limited property, and northwest of Balmer Lake.

Calc-Alkalic Sequences

The metavolcanic pile which underlies most of Heyson and Byshe Townships contains the variety of lithologies and compositions typical of the upper calc-alkalic sequences in the Red Lake supracrustal belt (see Figures 7-2, 7-4). Substantially different lithologies are intimately interbedded and interdigitate laterally suggesting contemporaneous extrusion of volcanic material of different compositions. Quartz porphyry flows of rhyolitic composition, tuff, lapillistone, and breccia are intermixed with dacitic and andesitic breccia, lapillistone, and flows. Andesitic and basaltic flows are commonly pillowed and porphyritic. The colour indices of these rocks range from 20 to 40. In places thick units of monolithic mafic breccia and lapillistone are present attesting to the more explosive nature of the mafic volcanism in the calc-alkalic sequence compared to the tholeiitic to komatiitic sequence.

Metasediments

Throughout the lower mafic sequence are thin interflow units of argillite, graphitic argillite, chert, ferruginous chert, and marble. Locally thicker units of thin-bedded and laminated chert and magnetitic or pyritic ironstone occur. These reach a considerable thickness east and south of Balmer Lake. At the top of the lower mafic sequence there is commonly a considerable development of thin- to medium-bedded, graded wacke-mudstone and polymictic conglomerate.

Felsic to Intermediate Subvolcanic Intrusions

The supracrustal rocks have been intruded by a number of felsic to intermediate stocks and dikes many of which contain porphyritic quartz and plagioclase. Most are of trondhjemitic composition with less than 10 percent mafic minerals (mainly biotite and chlorite). Typical examples of these intrusions are exposed around Slate Bay, East Bay, and in drill holes near Abino and Cochenour. At Cochenour they contain gold mineralization.

The larger "Howey Diorite" intrusive complex, which occurs in two main parts in the vicinity of Red Lake townsite and east into Byshe Township south of the Chukuni River, is comprised of a mixture of biotite-hornblende-quartz diorite and trondhjemite with more mafic dioritic phases. Later leuco-trondhjemite phases occur throughout. Strong shearing and mylonitization of the rocks in the complex near the Red Lake townsite makes identification and classification of the rocks very difficult.

Mafic to Ultramafic Intrusions

Dikes and sheets of fine- to medium-grained diabase occur throughout the mafic metavolcanics and cannot be distinguished from the metavolcanics except where crosscutting relationships are seen. Larger gabbroic bodies with subophitic textures occur on Hoyles Bay and form sheets and dikes southwest of Red Lake townsite in Heyson Township. Locally sheet-like intrusions of basaltic komatiitic material also occur.

Serpentinized peridotite intrusions occur at various localities within the lower mafic tholeiitic to komatiitic sequence in the eastern half of the Red Lake supracrustal belt. Fairly large bodies of peridotite occur in a zone from East Bay southwest through Cochenour Village and also south of St. Paul Bay in Heyson and Baird Townships. These are coarse-grained serpentine-talc-magnetite rocks but are commonly highly sheared and deformed to talc-carbonate-chlorite schists. These units have been eroded to form topographical lows usually occupied by lakes or covered with overburden. Similar small peridotite intrusions occur in Balmer Lake and underground at Campbell, Dickenson, and Cochenour Willans mines. In the mines they are thoroughly altered and are referred to as "altered rock" (Campbell) and "chicken feed" (Dickenson). Their original ultramafic composition is indicated by the high concentrations of Cr and Ni which must have been relatively immobile during hydrothermal alteration.

Batholithic Rocks

The supracrustal rocks of the Red Lake belt are bounded by large batholithic bodies which generally have concordant relationships with bedding and foliation. In a narrow zone along the margins of the supracrustals, crosscutting dikes and sheets of intrusive batholithic material are common, and the batholithic rocks themselves contain xenoliths of the country rock over a fairly wide area near their margins. The batholithic rocks are coarse-grained, weakly foliated, biotite quartz monzonite, hornblende granodiorite, trondhjemite, and less abundant quartz diorite. In places later bodies of coarse porphyritic microcline quartz monzonite to granodiorite cut the earlier phases. Remnants of mafic metavolcanics, recrystallized to medium-grained amphibolite, form mappable bodies within the batholiths. Where felsic metavolcanics and metasediments are adjacent to the batholiths, they are migmatized over extensive areas, with quartz monzonite and pegmatite sheets, dikes, and stringers. On the other hand where mafic metavolcanics are adjacent to the batholiths, the contact is quite sharp with only a few minor granitoid dikes and stringers. The metavolcanics near the batholiths are usually more foliated and recrystallized than similar rocks in the interior of the supracrustal belt.

The Dome stock, which intrudes the centre of the supracrustal belt, has many of the characteristics of the batholithic masses. The composition of the stock varies from coarse-grained massive biotite-hornblende granodiorite to trondhjemite. The McKenzie Island stock is composed of similar material plus a more mafic porphyritic quartz diorite phase.

Structural Geology

Facing-directions were determined from sedimentary structures and pillow shapes in mafic metavolcanics in many places throughout the belt. Pillows are more abundant than sedimentary structures but facing-directions are generally more ambiguous. At the margins of the belt the rocks are more severely deformed and recrystallized than in the interior and consequently facing-directions here cannot be determined.

The major structure in the eastern half of the belt is a northeast-trending "anticline" immediately east of Cochenour village (see Figure 7-4). Subsidiary anticlinal and synclinal folds occur on both limbs but in general the metavolcanics and metasediments dip steeply, face northwest, and trend north-northeast in Bateman, McDonough, Graves, and part of Dome Townships; they dip steeply, face southward, and trend eastward in Balmer, Byshe, Heyson, and part of Dome Townships. The penetrative foliation is parallel to the lithologic units, except in northern Dome Township where the east-trending foliation cuts sharply across the northeast-trend of the rock units. This major structure appears to be due to the emplacement of batholiths to the east and northeast of the supracrustal belt as suggested by a "wrapping around" of the supracrustal rocks, giving the appearance of an anticlinal structure. The structure is also complicated by the variations in the thicknesses of the units. The mafic metavolcanics attain maximum thickness between Cochenour and Walsh Lake and thin northeastward toward the head of East Bay and eastward toward Balmertown where they interdigitate with a sequence of chert-rich chemical metasediments, wacke, and conglomerate. East of the metasediments there is another facies change to a sequence again dominated by mafic metavolcanics.

In the Heyson calc-alkalic sequence (see Figures 7-2 and 7-4), facing-directions are contradictory along strike but this is probably due to the fact that the amplitude of the anticlines and synclines in this sequence are comparatively small and there are insufficient determinations to properly interpret the structure.

No major faulting was documented in the area as outcrop is generally poor and lineaments which cross the lithologic units are absent. It is possible that strike-slip faulting complicates the structure and that the serpentinized peridotite from East Bay to Cochenour may represent a major break.

Petrochemistry

The major element chemistry shows a continuum of compositions from komatiitic basalt through tholeiitic basalt to calc-alkaline andesite, dacite, and rhyolite (see Figures 7-5a, 7-5b, and 7-5c). Most of the major gold deposits in the Red Lake area (see Figure 7-3) are located in the upper part of the thick lower tholeiitic to komatiitic sequence of metavolcanics.

Tholeiitic to Komatiitic Metavolcanics

The range of compositions of typical basaltic komatiitic flows is illustrated by Samples 621, 1545, and 1608 in Table 7-1. Spinifex-textured samples (615 and 617) have compositions which fall close to that of Sample 621 but Sample 615 is quartz normative; Sample 617, which contains a network of wafers now replaced by chlorite, contains some 5 percent normative olivine; Sample 621, which is part of a fine-grained pillowed flow, contains approximately 22 percent normative olivine. The three samples are taken from separate flows over a 9 m thick stratigraphic section. Sample 911 and 1027 are typical of fine-grained tholeiitic flows. Sample 911 contains less than 2 percent normative quartz and Sample 1027 contains 9 percent normative olivine. The differences in the chemistry of the two phases of the variolitic pillowed flows are shown by Sample 1465, taken from the mafic-rich rim and matrix material, and Sample 1466, which is from coalesced varioles. Unlike variole types reported elsewhere (Gelinas *et al.* 1976) the varioles here have the composition of tholeiitic basalt and the matrix has the composition of basaltic komatiite. The separation of the two phases is well illustrated in Figure 7-7. However, lava compositions intermediate between the two phases occur in the metavolcanic sequence. This suggests that there was a continuum of liquid compositions during the evolution of the magmatic sequence; therefore an origin for the varioles by spherulitic formation rather than by immiscibility may be more tenable.

Within this lower mafic metavolcanic sequence there were a few intervals of felsic volcanism. On Hoyles Bay two distinct units of felsic metavolcanics are separated by a chert and magnetite ironstone unit. The lower unit represented by Sample 623 is more typical of the felsic metavolcanics elsewhere in the sequence whereas the upper unit, represented by Sample 1004, is highly potassic and contains potassic feldspar with quartz and plagioclase as phenocrysts, set in a very fine grained groundmass.

The minor element data correlate with the classification derived from the major elements. The komatiites are markedly higher in Cr and Ni, and lower in Sr, Y, and Zr than the tholeiitic basalts. The similarity in minor element and P_2O_5 concentrations between the two phases of the variolitic pillows suggests that the spherulites formed by crystallization from a magma. It should be noted that all the samples with the exception of Sample 1608 contain less than 5 ppm As.

Calc-Alkalic Metavolcanics

The gold mineralization is not generally associated with the calc-alkalic sequence of basalt, andesite, dacite, and rhyolite but a representative sample of each of these is given in Table 7-1 for purposes of comparison (Samples 426, 11, 94, and 421). The Zr data for three of these samples indicate the more evolved state of the calc-alkalic liquids.

Hydrothermal Alteration

During the detailed geological mapping in the eastern half of the Red Lake area, extensive zones of pervasive alteration were noted, especially in the mafic metavolcanics. These altered mafic rocks are much lighter grey to buff or pale green compared with the dark green fresh metavolcanics. In the past these rocks have been termed andesite in mine terminology, but it has become apparent from comparison of the textures, structures, and chemistry of the altered metavolcanics with those of the fresh rocks, that these rocks were originally the same composition as the typical mafic metavolcanics seen throughout the belt.

The alteration is most marked where it has pervaded the whole rock although in places it is less intense and is confined to the vicinity of narrow fractures filled with quartz and carbonate. In some places the altered rocks are sheared and veined but they are commonly undeformed and retain pillow structures, inter-pillow hyaloclastite, pipe-shaped amygdules, and variolitic structures. The altered rocks are comprised of a fine-grained assemblage of quartz, carbonate, epidote, plagioclase, and chlorite has replaced the primary mineralogy and textures.

The area stretching from McFinley Peninsula in Bateman Township, southwest to Cochenour, and east over the airport to Balmertown is one of the most intensely altered zones in the Red Lake area (see Figure 7-6) and it is no coincidence that this area hosts three of the largest gold mines in the camp. The rocks are poorly exposed but there appears to be some 20 km^2 of pervasively altered rocks at the bedrock surface. A second zone which is less extensive and which is more patchily altered, stretches east from Balmer Lake towards McDougal Lake. Pervasively altered mafic metavolcanics similar to those around Cochenour and Balmertown also occur northeast of Madsen and around St. Paul Bay, Coin Lake, and Snib Lake.

Analyses of hydrothermally altered metavolcanics are given in Table 7-2. Samples 491, 1436, and 1496 can

Table 7-1: Major and minor element chemistry in weight percent and ppm respectively of typical samples of tholeiitic, komatiitic and calc-alkalic metavolcanics from the east half of Red Lake area

	615	617	621	1545	1608	911	1027	1465	1466	623	1004	426	11	94	421
SiO_2	50.90	49.30	45.30	49.10	46.70	49.50	47.30	50.20	58.30	72.30	74.60	52.10	54.50	59.30	75.10
TiO_2	0.31	0.29	0.31	0.41	0.29	1.19	1.16	0.63	0.56	0.31	0.03	1.34	0.55	1.02	0.19
Al_2O_3	8.93	8.35	9.03	9.10	5.09	14.80	16.10	10.40	10.40	14.70	13.90	15.60	18.40	15.40	13.90
Fe_2O_3	1.20	1.10	1.10	11.20	11.10	13.80	13.00	13.30	8.13	0.27	0.25	10.50	6.96	9.06	1.37
FeO	10.20	9.67	10.80	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.	0.42	N.D.	N.D.	N.D.	N.D.	N.D.
MnO	0.19	0.18	0.21	0.20	0.21	0.24	0.23	0.28	0.19	0.01	0.05	0.15	0.10	0.14	0.05
MgO	14.00	15.90	17.80	15.50	20.30	6.63	6.36	10.20	7.26	0.78	0.11	4.98	5.51	2.54	0.26
CaO	7.88	9.18	9.49	11.30	11.10	10.40	11.30	12.70	10.90	1.82	1.29	8.43	9.06	5.23	1.03
Na_2O	0.95	1.07	0.50	0.68	0.24	2.29	2.77	0.71	2.12	3.33	2.53	2.91	2.61	3.75	4.21
K_2O	0.04	0.05	0.03	0.12	0.42	0.14	0.20	0.53	0.13	3.54	6.23	1.35	0.82	1.57	3.19
P_2O_5	0.06	0.06	0.06	0.05	0.06	0.13	0.13	0.08	0.08	0.11	0.05	0.37	0.11	0.26	0.02
CO_2	1.68	1.26	1.88	1.00	3.00	0.14	1.08	0.44	1.28	1.36	0.0	0.08	0.11	0.14	0.37
S	0.02	0.02	0.01	0.01	0.0	0.02	0.27	0.01	0.01	0.01	0.0	0.10	0.01	0.01	0.02
H_2O^+	3.64	3.31	4.19	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.	0.81	N.D.	N.D.	N.D.	N.D.	N.D.
H_2O^-	0.21	0.24	0.23	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.	0.19	N.D.	N.D.	N.D.	N.D.	N.D.
TOTAL:	100.21	99.98	100.94	98.67	98.51	99.28	99.90	99.48	99.36	99.96	99.04	97.91	98.74	98.42	99.71
L.O.I.	N.D.	N.D.	N.D.	2.50	5.70	0.30	1.40	1.00	2.00	N.D.	1.30	2.20	0.40	0.30	0.30
As	2	4	1	3	14	1	1	1	1	2	1	2	1	1	1
Ba	20	20	20	40	90	50	90	170	110	260	60	310	160	330	470
Co	66	81	82	71	83	47	51	59	46	5	5	40	31	22	5
Cr	1240	2540	2210	1700	3160	180	318	640	550	70	8	174	200	27	5
Cu	128	69	16	50	69	112	130	111	108	11	6	200	65	74	5
Li	8	10	12	16	26	8	24	16	7	12	4	17	13	16	12
Ni	220	500	420	420	630	82	142	152	133	15	5	111	131	15	5
Pb	38	50	40	22	60	10	110	35	41	202	93	11	12	12	10
Rb	10	10	<10	10	20	10	20	30	<10	50	320	30	40	10	50
Sb	3.3	0.8	5.9	1.7	0.5	0.2	1.1	0.4	0.3	27.8	0.4	0.3	0.1	0.1	0.2
Sr	30	20	10	30	30	110	140	70	50	130	30	320	50	130	60
Y	10	10	10	10	10	30	30	10	<10	10	40	30	130	10	110
Zn	77	76	85	76	54	107	120	110	70	12	112	110	69	97	27
Zr	10	<10	<10	10	<10	70	50	<10	<10	90	60	210	330	50	240

Sample descriptions for Table 7-1

615	basaltic komatiitic flow with stringbeef spinifex
617	basaltic komatiitic flow with radiating and wafer spinifex
621	pillowed basaltic komatiitic flow, fine-grained
1545	massive basaltic komatiitic flow, medium-grained
1608	massive komatiitic flow medium-grained
911	foliated tholeiitic basaltic flow, fine-grained
1027	pillowed tholeiitic basaltic flow, fine-grained
1465	pillowed variolitic flow non-variolitic mafic matrix
1466	pillowed variolitic flow, coalsced varioles
623	tholeiitic rhyolitic flow-breccia fragment
1004	porphyritic tholeiitic rhyolitic breccia
426	porphyritic pillowed calc-alkalic basaltic flow
11	porphyritic massive calc-alkalic andesitic flow
94	porphyritic calc-alkalic dacitic tuff
421	aphanitic calc-alkalic rhyolitic flow

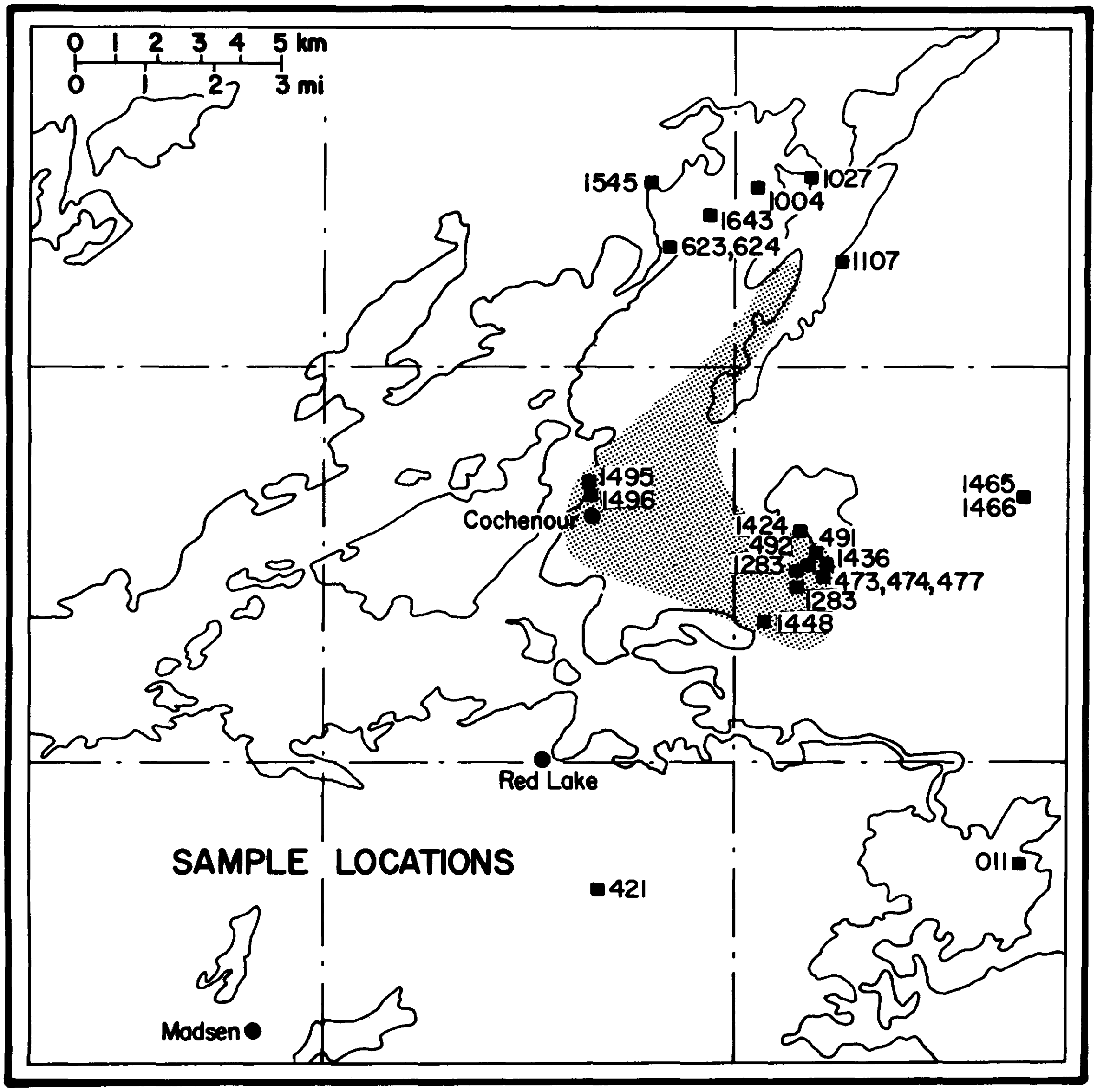


Figure 7-6—Location of samples listed in Tables 7-1, 7-2, and 7-3. Samples 94 and 426 are just south of the map-area and Sample 911 is to the northeast of the area. Shaded area covers zone of most intense hydrothermal alteration.

TABLE 7-2 Major and minor element chemistry in weight percent and ppm respectively of altered metavolcanics from Balmertown and Cochenour townsites, along with less altered rocks for comparison

	491	1436	1496	492	1643	1283	1448	1495
SiO_2	60.40	62.60	61.30	52.60	55.60	72.80	75.70	84.70
TiO_2	0.89	0.97	0.72	0.92	0.62	0.16	0.16	0.12
Al_2O_3	16.20	16.00	15.70	14.90	11.50	15.60	13.80	13.00
Fe_2O_3	9.13	9.50	8.46	10.20	8.21	1.67	0.26	0.43
FeO	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
MnO	0.17	0.16	0.11	0.14	0.23	0.03	0.01	0.02
MgO	4.31	4.15	3.34	5.91	5.42	1.86	0.21	0.15
CaO	4.65	1.97	2.03	7.63	13.80	3.15	0.90	0.15
Na_2O	0.00	0.11	0.11	0.00	1.80	0.60	6.13	0.00
K_2O	0.17	0.19	2.68	0.33	0.02	1.72	0.93	0.29
P_2O_5	0.08	0.08	0.10	0.09	0.08	0.06	0.07	0.04
CO_2	1.74	1.36	3.60	8.24	1.74	0.28	0.52	0.85
S	0.16	0.19	0.23	0.33	0.00	0.09	0.01	0.04
H_2O+	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.
H_2O-	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.
TOTAL:	97.90	97.28	98.38	101.29	99.02	98.02	98.70	99.79
L.O.I.	3.50	4.40	5.40	7.80	2.50	2.30	1.30	1.20
As	54	128	168	45	1	27	25	70
Ba	80	60	110	70	40	130	250	40
Co	45	47	63	58	96	6	5	3
Cr	390	264	167	410	460	19	25	16
Cu	128	152	230	148	74	10	6	7
Li	36	55	92	37	3	69	12	32
Ni	105	88	119	111	132	22	10	15
Pb	10	72	61	10	20	48	52	75
Rb	10	10	80	10	<10	40	20	10
Sb	15.6	65.0	4.2	14.0	0.1	20.6	2.1	3.7
Sr	50	20	40	90	70	60	220	<10
Y	10	10	20	20	20	<10	<10	<10
Xn	80	88	57	78	67	24	12	9
Zr	50	30	40	50	20	50	40	20

SAMPLE DESCRIPTION

491	altered pillowed mafic flow (probably tholeiitic) Balmertown.
1436	altered pillowed mafic flow (probably tholeiitic) Balmertown.
1496	altered pillowed mafic flow)probably tholeiitic) Cochenour.
492	altered variolitic pillowed mafic flow (greater than 80 per percent coalesced varioles) Balmertown.
1643	unaltered variolitic pillowed mafic flow (almost entirely coalesced varioles) Hoyles Bay.
1283	altered felsic flow ("siliceous rock"), Campbell Mine.
1448	unaltered felsic flow, south of Balmertown.
1495	altered felsic flow? ("Point rock"), Cochenour.

be compared with typical tholeiitic basalt samples 911 and 1027 listed in Table 7-1. It is immediately apparent that the altered rocks have had substantial SiO_2, variable CO_2 and K_2O added, and MgO, CaO, Na_2O, and total Fe subtracted. Among the minor elements As and Sb concentrations have been enormously increased, Sr decreased, and the others, especially Cr, Ni, CO, and Zr, appear to be relatively immobile. Samples 492 and 1643 in Table 7-2 are respectively altered and unaltered variolitic metavolcanics and like the tholeiite examples there is substantial loss of Na_2O and CaO and addition of CO_2, K_2O, As, Sb, and Li. Samples 1283 and 1495 are highly altered felsic metavolcanics in the vicinity of the mines and these can be compared with Sample 623 (Table 7-1) and Sample 1448 (Table 7-2) located about 1 km south of Balmertown. It should be noted that there is little visible evidence that these felsic metavolcanics are altered but the analyses show major losses of Na_2O, Ba, and Sr and additions of As. However, the As content of Sample 1448 is anomalously high and may indicate that it has been partially hydrothermally altered. The Sb content of these felsic rocks is highly erratic and is not considered to be diagnostic of the alteration process.

Serpentinized peridotites, intrusive into the mafic metavolcanics, occur in the zone of intense alteration. In the mines they may be so completely altered with none of the diagnostic minerals of the ultramafic rocks, such as serpentine and talc, that they are unrecognizable as ultramafic rocks. The rocks may have a dark grey to buff appearance and are both silicified and carbonatized and heavily veined with quartz and carbonate stringers. At the Campbell mine these rocks are termed "altered rock"; at Dickenson mine "chicken feed", and at Cochenour-Wilmar "granular altered rocks" and talc schists. However, these rock terms may encompass other altered lithologies in the mine areas.

Table 7-3 shows the chemical data on three samples from the Dickenson mine taken from a diamond drill hole which passed through "chicken feed" (Samples 473 and 474) and into easily recognizable serpentinized peridotite (Sample 477) over a distance of some 14 m. Samples 1107 and 1424 are fresher serpentinized peridotites. The data show that the "altered peridotites" are much higher in Fe_2O_3, MnO, CaO, CO_2, S, Au, As, Sb, and Sr and lower in MgO and H_2O (H_2O = LOI-CO_2-S) than serpentinized peridotite. Cr and Ni, although variable, have values of the same order as peridotitic rocks and must have been relatively immobile during the alteration process.

Figure 7-7 shows a cation plot of unaltered and altered rocks listed in Tables 7-1, 7-2, and 7-3. The diagram illustrates the displacement of altered compositions away from the fresh rock compositions. The ultramafic rocks show the greatest displacement as demonstrated by Samples 473, and 474 away from 477. The composition of the altered variolitic rock, Sample 492, is only slightly displaced towards the Al_2O_3 corner from the fresh variolitic Sample 1643. However, there is no way of telling the original composition of this mafic flow; thus Sample 492 may have had a composition before alteration similar to the variole Sample 1466, in which case the displacement would be substantial. In the tholeiitic basalt there is a significant displacement of the composition of the altered rocks (Samples 491, 1436, and 1496) away from the fresh rocks (Samples 911 and 1027). In the felsic rocks it is more difficult to be certain of comparing rocks of originally similar compositions. The hand specimens of Samples 1448 and 1283 are similar, and since Sample 1283 is from the Campbell mine it is probably well altered and is displaced away from the Al_2O_3 apex. Sample 1495, however, which is thoroughly altered according to its SiO_2, Na_2O and trace element content plots close to Sample 1448 which it resembles in hand specimen.

Gold Deposits

Gold Production

Gold production began in 1930 at the Howey mine, and in the next 15 years most of the other mines were developed. Substantial production from the camp, however, did not commence until the Dickenson and Campbell mines began operation in the late 1940s (Figure 7-8). Production continued to increase to over 400,000 ounces a year in the early 1960s. Since then due to the closure of mines, production has tapered off to some 230,000 ounces in 1979 all of which was produced by the Campbell and Dickenson mines.

Table 7-4 shows the total number of ounces produced by the individual mines to the end of 1979 and the average grade of ore mined. It is interesting to note that the first mine to be put into operation, the Howey mine, has also the lowest grade of ore produced, whereas the last substantial mine to be found and put into operation, the Campbell mine, has the greatest gold production and the highest grade in the camp.

Classification of Gold Deposits

Gold occurs in a variety of settings in the Red Lake area. However, because all but two of the producing mines are closed down it is not possible to collect material and data from most of the deposits except from surface exposures. Information on structural and stratigraphic controls for these deposits is available only in the literature. Virtually all of the gold mineralization has an epigenetic aspect and is structurally controlled in lenses, veins and fractures but some types have definite stratigraphic or lithologic associations and it is on this basis that they are classified here into the following groups:

1) Deposits hosted in mafic metavolcanics;
2) Deposits hosted in felsic intrusions;
3) Stratabound deposits.

Deposits Hosted in Mafic Metavolcanics

The gold deposits located in the mafic metavolcanics include those which have produced most of the gold and have the highest ore grades of the camp: Campbell mine, Dickenson mine, and Cochenour mine (Table 7-4).

The Campbell mine is in the process of increasing its milling capacity from 800 to 1000 tons per day. It is the lowest cost, most productive gold mine in Canada today,

Table 7-3 Major and minor element chemistry in weight percent and ppm respectively, of unaltered serpentinized peridotite and its altered equivalent: "chickenfeed" from Dickenson Mine.

	473	474	477	1107	1424
SiO_2	31.1	43.8	41.0	42.00	36.20
TiO_2	0.19	0.17	0.21	0.28	0.12
Al_2O_3	3.68	2.74	3.47	5.21	2.89
Fe_2O_3	19.2	19.8	10.5	10.10	11.10
MnO	0.38	0.38	0.11	0.17	0.18
MgO	20.3	14.0	30.6	31.90	34.50
CaO	8.11	8.68	1.38	2.05	1.56
Na_2O	0.00	0.00	0.00	0.31	0.05
K_2O	0.00	0.27	0.00	0.02	0.0
P_2O_5	0.04	0.03	0.04	0.05	0.04
CO	16.4	11.50	6.05	0.52	2.72
S	0.26	0.20	0.01	0.0	0.01
TOTAL:	99.7	101.6	93.4	92.61	89.37
LOI	16.7	11.0	12.2	9.20	13.30
As	1360	256	45	2	24
Ba	30	110	20	30	40
Ca	135	87	107	91	111
Cr	1620	1100	1360	1660	2450
Cu	15	12	56	25	8
Li	25	50	4	5	3
Ni	1960	1360	2020	1800	2600
Pb	10	10	10	65	126
Rb	10	10	10	10	10
Sb	36.2	13.9	4.3	1.9	15.5
Sr	50	50	10	10	10
Y	10	10	10	10	10
Zn	66	61	42	48	20
Zr	10	10	10	10	10
Au	20ppb	10ppb	10ppb		

473	Altered fine-grained pale coloured "chickenfeed" 29th level Dickenson Mine
474	Altered fine-grained pale coloured "chickenfeed" 29th level Dickenson Mine
477	Unaltered, serpentinized peridotite, 29th level Dickenson Mine
1107	Unaltered serpentinized peridotite, East Bay
1424	Unaltered serpentinized peridotite, Balmer Lake

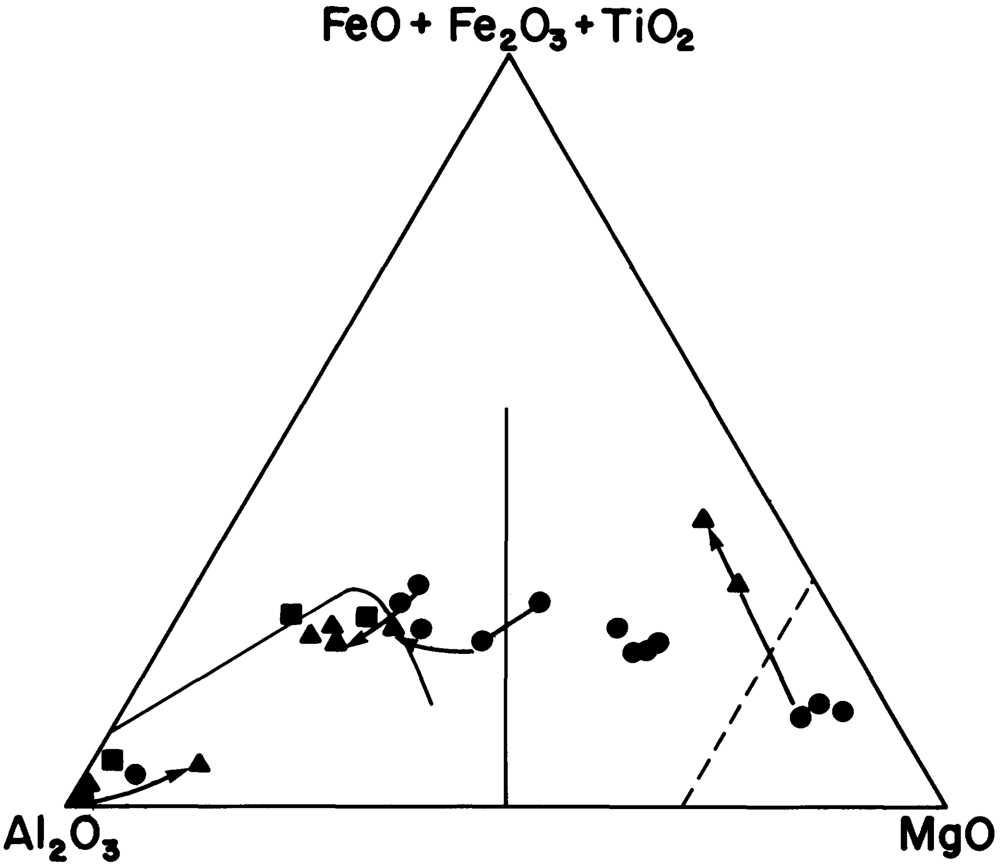


Figure 7-7—Cation percent plot of altered and unaltered rocks of the eastern Red Lake area. Fresh rocks indicated by circles; altered rocks by triangles; calc-alkalic rocks by squares. The bar connects a variole matrix pair. Arrows show trends from unaltered to altered compositions.

and in 1979 produced 185,005 ounces of gold from 300,178 tons of ore at an average grade of 0.656 ounces of gold per ton. In 1978, operating costs were $71.43 per ounce and bullion revenue was $378.70 per ounce (1979 Annual Report, Campbell Red Lake Mines Limited).

The gold-bearing zones in the Campbell mine, such as the "A" and "F" zones, are steeply dipping quartz-carbonate veins with associated veinlets and stringers, containing minor amounts of pyrrhotite, pyrite, arsenopyrite, and locally sphalerite and visible native gold. In general the veins are parallel to the main foliation (which strikes east-southeast and dips about 70 degrees south) in the surrounding area. The veins occur in intensely altered mafic metavolcanics which are locally pillowed and in places variolitic. Where the veins transect "altered rock" (highly altered, carbonatized, chloritic, ultramafic rock), gold values are usually lower, and where they cut "siliceous rock" (very fine grained, pervasively altered felsic metavolcanic) the veins carry little or no gold values. In the "G" and "L" zones, the veins trend south-southeast and dip steeply to the west. In contrast to the "A" and "F" zones, these zones are quartz-rich with arsenopyrite, pyrrhotite, pyrite, sphalerite, and, locally, stibnite and native gold. The veins transect the local foliation and the main lithologic units and gold values show a similar relationship to rock types as noted in the "A" and "F" zones. The overall Au:Ag ratio of the ores is about 10:1.

For more details on the geology and mineralization of the Campbell mine the reader is referred to papers in this volume by P.J. MacGeehan and C.J. Hodgson, and D.M. Rigg and H. Helmstaedt.

At the Dickenson mine which adjoins the Campbell mine to the east, the "South C" zone is the extension of the Campbell "A" zone. The Dickenson "North C" and "F" zones are the extensions of the Campbell "North L" ore zones.

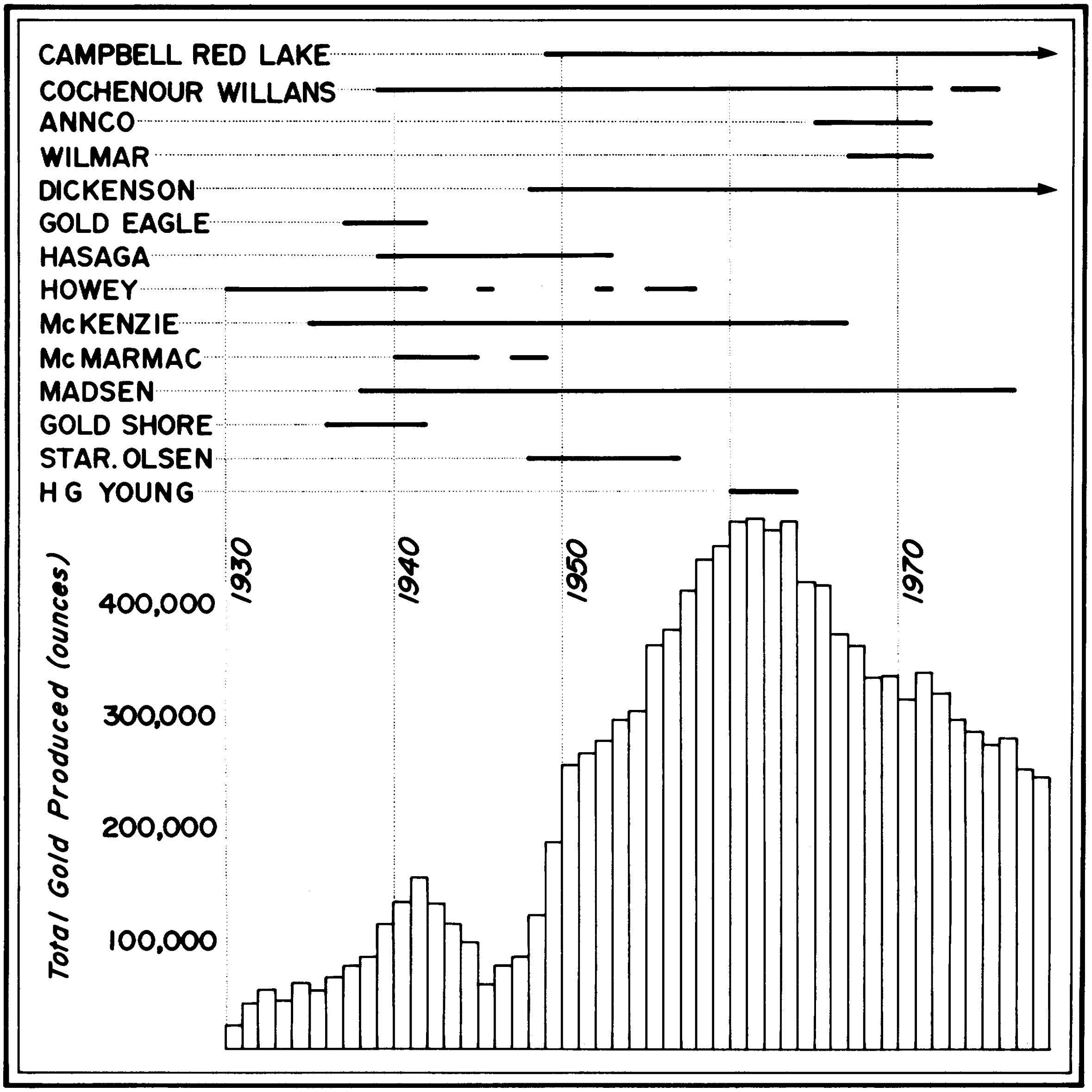


Figure 7-8—Annual gold production and operating periods of gold mines in the Red Lake area.

TABLE 7-4: Gold production from all mines in Red Lake Area to end of 1979 and average gold grade of ore produced during life of each mine. (Wilmar and Annco ore was milled at Cochenour .)

MINE	OUNCES GOLD PRODUCED	AVERAGE GOLD GRADE (OUNCES PER TON)
ANNCO	53,903	-
CAMPBELL	5,099,102	0.61
COCHENOUR WILLANS	1,131,689	0.46
DICKENSON	2,162,393	0.46
GOLD EAGLE	40,204	0.22
HASAGA	218,213	0.14
HOWEY	421,593	0.09
McKENZIE	651,156	0.27
McMARMAC	45,246	0.29
MADSEN	2,416,609	0.29
GOLD SHORE	21,100	0.24
STARRATT OLSEN	163,990	0.18
WILMAR	52,204	-
H.G. YOUNG	55,244	0.19

The "East South C" zone which is exposed in mine workings between the 13 and 30 levels is along strike and to the east of the "South C" zone. It is a major producing zone on the property and has a distinctive lithology. The gold values occur in narrow layers and laminations of fine- to medium-grained pyrite, pyrrhotite, and arsenopyrite with minor sphalerite and stibnite. Minor quartz veining occurs and in places this contains sulphide minerals and visible gold but does not constitute a significant part of the ore zone. Carbonate and quartz-carbonate veins generally are absent. The sulphide layers and laminations and associated cherty material are parallel to the foliation in the wall-rocks of altered, pillowed, mafic metavolcanics. It is tempting to interpret the layering and lamination of sulphides and cherty material as an interflow chemical sedimentary unit but it is possible that the material is highly silicified metavolcanics with lenses and stringers of sulphides and quartz veining, all of which have been severely deformed following alteration and mineralization. Only the discovery of unequivocal primary sedimentary structures and textures within the zone would definitely prove an exhalative origin.

The smaller "E" and "I" zones are lithologically similar to the "East South C" zone. Fine-grained disseminated sulphide mineralization occurs in the enclosing altered mafic metavolcanic wall-rock. A similar zone in the East South "C" footwall zone has recently been developed as a substantial low-grade orebody in places over 15 m wide. The gold values are found in pyrrhotite and pyrite lenses, stringers, and disseminations in altered mafic metavolcanics.

A different type of ore characterizes the "H" zone around the 17 level. Gold values associated with 1 to 5 percent pyrite, plus pyrrhotite, arsenopyrite, sphalerite, and chalcopyrite occur within a unit of felsic metavolcanics a few metres from the contact of the unit with the enclosing wall-rock. Where the mineralized zone strikes into "chicken feed" (Dickenson mine terminology) or serpentinized peridotite and related talc-carbonate schist, no gold mineralization is present.

At the Cochenour mine, gold mineralization occurs in a similar setting of altered mafic metavolcanics with associated peridotite and altered felsic metavolcanics. Most of the mineralization at the Cochenour and adjacent Annco property is related to a low-dipping overthrust fault zone (Hutton 1972). Prior to mineralization this thrust zone was displaced by several north-striking, steeply dipping normal faults. Both the thrust zone and the subsidiary faults were silicified, carbonatized, and hydrothermally altered resulting in the formation of sericite, talc, and mariposite. The main mineralization is intimately associated with a further hydrothermal silicification which accompanied the gold-bearing arsenopyrite-pyrite-stibnite-sphalerite assemblage (Hutton *et al.* 1964). Gold mineralization is also found in banded carbonate veins within and parallel to the thrust zone, in shear veins in the country rock near the thrust area, in dikes and carbonate veins in the footwall of the thrust zone, and in silicified carbonatized lenses in talc schist (Hutton *et al.* 1964). Good gold values were found in narrow, silicified, layered chert units close to the thrust zone. The mineralization is epigenetic in character (D.A. Hutton, personal communication). The Wilmar central zone, which was mined from the Cochenour mine workings, has a rather different type of mineralization. Some of the ore is silver-rich (Au:Ag ratio, 1:11) and is associated with silver and gold tellurides (hessite, petzite, and calaverite), chalcopyrite, pyrrhotite, gersdorffite, pyrite, and rutile set in minute dolomite stringers in altered metavolcanics, schist, and dikes (Hutton *et al.* 1964). However, the average Au:Ag ratio in the Wilmar deposits is about 1:3. (D.A. Hutton, personal communication).

At McMarmac mine, northeast of Cochenour, gold mineralization is restricted to cherty quartz zones within narrow but extensive carbonate bodies. The quartz zones are steeply dipping and are parallel to both the northeast-trending foliation and the enclosing altered, pillowed, tholeiitic and variolitic mafic metavolcanics. The better gold values occur where the cherty quartz contains fine (rather than coarse) arsenopyrite needles, pyrite, sphalerite, stibnite, pyrrhotite, and chalcopyrite. Visible native gold is rare. Later white quartz veinlets which crosscut the carbonate bodies contain tourmaline and minor native gold (Ferguson 1966b). It is worth mentioning that a minor amount of tungsten was noted in analyses of millfeed from the mine (Ferguson 1966b). There is no evidence that the carbonate body is exhalative in origin but rather has the appearance of a medium- to coarse-grained carbonate vein.

At the H.G. Young mine, now part of the Campbell mine property, mining was carried out between 1960 and 1963, and although details are scarce it appears that gold mineralization occurred in narrow north-south-trending quartz-carbonate veins. The veins are enclosed in mafic metavolcanics which are apparently altered. The setting of the mineralization appears to be similar to, but lower grade than, that at the Campbell mine.

As well as the above producers, several properties in the mafic metavolcanic setting have been explored and partly developed but did not produce gold in commercial quantities. On East Bay, at the McFinlay property gold values are associated with narrow chert and sulphide ironstone units between mafic metavolcanic flows which are variably silicified and carbonatized. Locally the sulphide ironstone contains coarse arsenopyrite, chalcopyrite, sphalerite, and galena as well as the typical pyrrhotite and pyrite. Elsewhere gold values are present in later quartz and quartz-carbonate veins and stringers in the altered mafic metavolcanics. The gold accompanies minor amounts of the sulphides noted above (Pirie and Grant 1978a).

On East Bay at the Abino property, exploration indicated that gold mineralization occurs in three different settings: 1) within quartz and quartz-carbonate veins cutting altered pillowed mafic metavolcanics; 2) within an interflow chert-sulphide ironstone unit in association with pyrite, pyrrhotite and chalcopyrite; 3) within zones of silicified mafic metavolcanics adjacent to altered peridotite and cut by quartz veinlets carrying pyrite and arsenopyrite (Ferguson 1962). The gold mineralization here is very similar to that on the McFinlay property on strike to the northeast.

Near the old shaft on the Marcus property east of Cochenour, gold values are associated with pyrite in a carbonate vein with minor quartz. The vein is parallel to the main foliation in the enclosing altered pillowed mafic metavolcanics.

Deposits Hosted in Felsic Intrusions

Gold production from the McKenzie, Gold Eagle, and Gold Shore mines came mainly from mineralization in the McKenzie and Dome intrusive stocks. On surface in the vicinity of these mines, there are no broad areas of pervasive alteration on the scale of that seen in the mafic metavolcanic hosted deposits.

At the McKenzie mine, gold is associated with quartz-rich zones in a main shear dipping 75 degrees west, located close to the contact of the granodiorite with more mafic diorite phases of the McKenzie Island stock. Veins and lenses of gold-bearing quartz occur in the hanging-wall parallel to the main shear. The wall-rocks of the main shear and veins are highly altered and sheared, and are comprised of mainly sericite, carbonate, and chlorite. The ore-bearing quartz veins carry minor pyrite, sphalerite, and lesser galena, chalcopyrite, pyrrhotite, arsenopyrite, tellurides, jamesonite, scheelite, and native gold (Ferguson 1966b). Virtually all the gold was "free milling".

At the Gold Eagle mine, towards the south end of the McKenzie Island stock, the ore occurs in quartz veins in south-dipping shear zones which cut the granodiorite and diorite phases of the stock as well as the adjacent wacke metasediments. The gold accompanies minor arsenopyrite, pyrite, pyrrhotite, sphalerite, scheelite, galena, chalcopyrite, and tellurides. The enclosing wall-rocks are generally altered to sericite, carbonate, and pyrite (Ferguson 1966b).

The Gold Shore mine is located within the Dome stock and the mineralized zone was located at the junction of two shear zones which contain quartz lenses and stringers carrying some pyrite, chalcopyrite, and minor sphalerite, tetrahedrite, tellurides, and native gold. Wall-rocks are silicified, sericitized, and carbonatized.

The Howey and Hasaga mines occur in a mineralized shear zone which trends east-northeast. It is enclosed in highly deformed rocks which include various trondhjemite and quartz diorite phases of the Howey diorite intrusive complex as well as related extrusive intermediate to felsic, heterolithic and monolithic lapilli-tuff and tuff-breccia. The intense shearing and mylonitization brecciated some of the intrusive phases, consequently it is difficult to properly identify the rocks in outcrop.

The host rock to the mineralization is described by Horwood (1940) as a quartz porphyry dike which is hydrothermally altered and sericitized in the vicinity of ore. The gold occurs in quartz veins, lenses, and stringers, typically less than 12 inches wide. Pyrite, sphalerite, and lesser galena, chalcopyrite, tellurides, arsenopyrite, pyrrhotite, tetrahedrite, tourmaline, and scheelite are associated with the gold (Horwood 1940). As with the other felsic intrusive hosted deposits, the ore was "free-milling". The Au:Ag ratio over the life of the two deposits was approximately 3:1 which is almost identical to that of the McKenzie mine.

On the Abino property, southwest of the shaft and under the waters of East Bay, a mineralized, medium-grained granodiorite to trondhjemite intrusion has been located by diamond drilling. The intrusion, which is fine grained and porphyritic near the contacts with the country rocks, and which contains minor disseminated pyrrhotite and pyrite throughout, is crosscut by numerous quartz-filled fractures. These veinlets and stringers are commonly mineralized with pyrite, pyrrhotite, and locally galena, sphalerite, chalcopyrite, and native gold. An estimated 405,000 tons, grading 0.20 ounces gold per ton, occur in three main zones (Pirie and Grant 1978b).

On the Wilmar part of the Cochenour mine property a small granodiorite body intrudes the metavolcanics and carries mineralization similar to that in the Abino granodiorite zone.

Stratabound Deposits

The orebodies at the Madsen and Starratt Olsen mines in Baird Township are in north-northeast-trending units termed "tuff horizons" (Ferguson 1965) which occur near the top of a thick sequence of mafic tholeiitic metavolcanics and associated serpentinized peridotite intrusions. At the Madsen mine the main tuff horizon is described as a fine-grained brownish to greenish rock with localized, narrow banding. In places angular felsic fragments up to 1 cm constitute a substantial component of the beds. Garnets are commonly associated with ore, and staurolite and andalusite are frequently developed near the hanging-wall (Ferguson 1965). The main tuff horizon, which dips steeply southeast, has altered mafic metavolcanics and serpentinized peridotite or talc schist on its footwall and a feldspar porphyry unit on the hanging-wall. The feldspar porphyry has been variously described as intrusive, metasedimentary, and metavolcanic. The wall-rocks and the tuff appear to have undergone severe hydrothermal alteration including silicification, carbonatization, sericitization, and probably substantial loss of Na_2O resulting in an aluminous mineral assemblage. The ore occurs in silicified lenses in the tuff horizon. Native gold is associated with pyrite, pyrrhotite, and minor arsenopyrite, magnetite, ilmenite, chalcopyrite, sphalerite, and scheelite (Ferguson 1965). Au:Ag ratios vary from 4.5:1 to 6:1.

The main zone at the Starratt Olsen mine appears to be on the same stratigraphic tuff horizon as the Madsen mine. The tuff has a similar mineralogy and alteration assemblage.

Genesis of the Gold Deposits

A critical problem in developing a genetic model for gold deposition in the Red Lake area is the precise identification of ore-related wall-rocks and structures in the field. Where silica and carbonate are present, the lithologies appear to be defined by three end-members:

1) sedimentary, chemically precipitated chert or carbonate;
2) veins of quartz or carbonate;
3) totally silicified or carbonatized metavolcanics.

It is possible with care to properly identify the end-members in the field, but combinations which may involve silicification or the deformation of original veins or primary sedimentary material, may be difficult to recognize. There is no guarantee that field identification and subsequent modelling of gold deposition are correct. In the Red Lake area, where most of the mines have closed down, modelling of gold deposition must be based largely on data from the literature, and therefore many of the conclusions on the genesis of the deposits are necessarily tentative.

Despite the variety of modes of occurrences of gold in the Red Lake area there are common features which may ultimately suggest a common source for the gold relating back to the initial volcanic activity. As mentioned earlier, many of the gold deposits occur close to the top of the lower mafic metavolcanic sequence, where minor felsic metavolcanics are interlayered with mainly mafic flows. Thicker units of both chert-ironstone and wacke-mudstone overlie and are intermixed with these mafic flows. Above this, over a fairly narrow stratigraphic interval, the character of the volcanic rocks changes to interbedded mafic to intermediate porphyritic flows and intermediate to felsic breccia, lapillistone, and minor flows of calc-alkalic affinity (see Figure 7-2). Another feature common to both the mafic metavolcanic hosted and the stratabound deposits is the close association of serpentinized peridotite and talc schist bodies, although they generally do not themselves host mineralization.

Perhaps the most important observation to be made at surface exposures close to the mafic metavolcanic-hosted deposits is the intense alteration of the mafic metavolcanics. This alteration is directly related to gold deposition. The altered rocks are pale green to grey or buff rather than the dark green of the unaltered mafic volcanics, and appear to be much more felsic. It is important to realize that these rocks are not a more felsic phase of volcanism of perhaps andesitic composition but are hydrothermally modified basaltic rocks with an alteration mineralogy.

The hydrothermal fluid, that produced the alteration, deposited SiO_2, CO_2, and K_2O and almost completely extracted Na_2O, over a wide area. Lesser amounts of CaO, MgO, and Fe_2O_3 have also been removed from the rocks.

Of the trace elements, the most conspicuous additions to the pervasively altered rocks (see Tables 7-1, 7-2, and 7-3) are those of As and Sb. In the only example (serpentinized peridotite), for which Au data are presently available, there is a measurable increase in Au in the most altered material. The data and the fact that, in the area, Au concentration is generally directly proportional to the As content suggest that the highly altered, As-enriched rocks were also enriched in Au during the alteration process. If this is the case, then the altered rocks are not the source from which background amounts of Au have been mobilized and concentrated to form the ore deposits.

Close examination of the ore deposits invariably shows that there were several phases of both alteration and gold mineralization but the general composition of the fluids over this period is likely to have varied within narrow limits. It is possible that the process of alteration began with volcanic-related fumarolic activity in which gold was mobilized from deeper in the volcanic pile, carried upwards, and may even have been deposited on the seafloor as exhalative, sedimentary deposits (Weissberg 1969). Evidence for this at present in the Red Lake area is inconclusive. Following this possible initial stage it appears that hydrothermal fluids continued to circulate and deposit gold, focusing on the areas of intense alteration, during subsequent deformation of the metavolcanic sequence. At this time the main channelways may have served for the development of veins with ore-grade gold values. During later brittle deformation the anomalous concentrations of gold in the large volumes of intensely altered rocks may have been mobilized over short distances into subsidiary fractures, veinlets, and lenses to form local concentrations of ore-grade material.

The smaller felsic to intermediate intrusive hosted deposits such as at the Abino and Wilmar granodiorite zones are likely to have formed by the intrusion of felsic material into already highly altered, anomalously gold-bearing mafic metavolcanics. The heat from the intrusion may have set up a hydrothermal system which mobilized the gold and deposited it with minor sulphides in fractures in the cooling granodiorite. The McKenzie, Gold Eagle, and Gold Shore mines are contained in much larger felsic intrusions but nevertheless even they are not too distant from zones of altered mafic metavolcanics, and may have formed by a similar process.

The deposits at Howey and Hasaga mines are epigenetic concentrations in a quartz porphyry intrusion which has been strongly deformed. It may not, however, be coincidental that these deposits are approximately stratigraphically aligned with the Madsen deposits, and the gold may have been mobilized from anomalous concentrations in a tuff horizon or in the mafic metavolcanics stratigraphically below the pyroclastic rocks.

The stratabound deposits at the Madsen and Starratt Olsen mines have similar mineralization and alteration characteristics as the mafic metavolcanic-hosted deposits, but the actual host-rock tuff does not have an equivalent in the latter deposits. It is possible that the gold here was deposited by fumarolic processes at the seafloor interface following tuff deposition, and was subsequently mobilized within the porous tuff unit into veins and lenses by later hydrothermal activity and deformation.

In exploration for the mafic metavolcanic hosted deposits, which are the most productive deposits in the Red Lake area, close attention should be paid to the upper part of the lower mafic metavolcanic sequence where pervasive alteration of the rock is evident. The chemical signature of the gold related alteration is anomalously high values of arsenic, and to a lesser extent antimony, and anomalously low values of sodium using the values for the various unaltered rock-types given in Table 7-1, 7-2, and 7-3 as background levels.

Acknowledgments

The author thanks the staff of the various mines in the Red Lake area for their cooperation during the mapping program. Chemical analyses were carried out by Geoscience Laboratories, Ontario Geological Survey. Production figures for the mines were provided by the Resident Geologist and staff, Ministry of Natural Resources, Red Lake. The manuscript has benefited considerably from review by D.A. Hutton.

The Relationship of Gold Mineralization to Volcanic and Alteration Features in the Area of the Campbell Red Lake and Dickenson Mines, Red Lake Area, Northwestern Ontario

P.J. MacGeehan[1] and C.J. Hodgson[1]

Abstract

The gold deposits at the Campbell and Dickenson mines consist of epigenetic quartz-carbonate fissure veins and silicified replacement bodies located in an anomalously fissile deformed zone within hydrothermally altered volcanic rocks flanking a sedimentary (dominantly exhalative) basin. Geothermal activity contemporaneous with volcanism leached Fe, Mg, and Au from the volcanic rocks to form the exhalites, and later pre-, syn-, and post-mineralizing hydrothermal alteration and deformation also affected the volcanic rocks on a regional scale, indicating that both the geological setting of these ores and the identification of regional alteration-deformation patterns may provide important criteria to be used in exploration for this deposit type.

At the present time, the most important criteria appear to be: 1) geological setting within seafloor altered basalts where Au was leached and redeposited in contemporaneous exhalites or carbonate altered zones in a primary enrichment stage; 2) structurally favourable traps in linear deformed zones that transect both the volcanic rocks and exhalites, and which form depositional sites for Au remobilized during regional metamorphism and deformation; 3) the ore-bearing environment outlined by zones of Fe-Mg carbonate alteration and veining within the deformed belt; and 4) a large-scale aureole of intense alkali depletion which encompasses, but has a wider lateral extent than either the zone of Fe-Mg carbonate enrichment or the deformed zone.

Introduction

The Red Lake area lies 130 km north of Kenora, Ontario, and is underlain by a 60 km x 30 km enclave of Archean volcanic rocks[2], flanked on either side by diapiric granitic plutons (Figure 8-1). This area, which forms a western extension of the Birch-Uchi Lake 'Greenstone' Belt (Goodwin 1977), is one of Ontario's major gold-producing camps, containing over 15 current or past-producing mines and 26 additional major prospects. The gold occurs in a wide variety of geological settings: as silicified veinlet zones in rhyolite; as disseminated zones in tuff and iron formation; as major vein systems in volcanic rocks; and in or closely associated with a variety of porphyritic stocks (Horwood 1940). The Campbell Red Lake and adjacent Dickenson mines, the two current gold producers, are located on major vein systems in mafic volcanic rocks in Balmer Township, on the east side of the 'greenstone belt' (Figure 8-1).

In this paper the geological setting of the gold mineralization will be outlined with particular emphasis on those features of the geological environment which appear, at this time, to be relevant to mineral exploration and serve to distinguish the ore-bearing zones at the mines from the region as a whole. The data on which this paper is based form part of a continuing research program; the ideas presented here are therefore tentative.

Geological Setting of the Campbell and Dickenson Mines

The two mines embrace a system of over 15 vein or replacement-type auriferous lodes that occur within a highly deformed succession of mafic and felsic extrusive flows, differentiated mafic to ultramafic sills, and volcaniclastic and volcanogenic exhalative sedimentay rocks on the eastern side of Balmer Township (Figure 8-2). Traditionally, this area was regarded as a complexly deformed zone that had suffered at least two phases of isoclinal folding (Chisholm 1951; Ferguson 1966a; Ferguson *et al.* 1970, Compilation Map 2175, see Figure 8-1), but recent synoptic 1:10 560 scale mapping of the township by J. Pirie and A. Grant (1978a)has shown that, contrary to previous interpretations, no major fold closures are present in the area *except* within a thick sequence of sedimentary rocks that occupy the central part of the township. Later follow-up 1:1200 scale stratigraphic map-

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[2] All the rocks in this area have been metamorphosed, therefore the prefix 'meta' is not used.

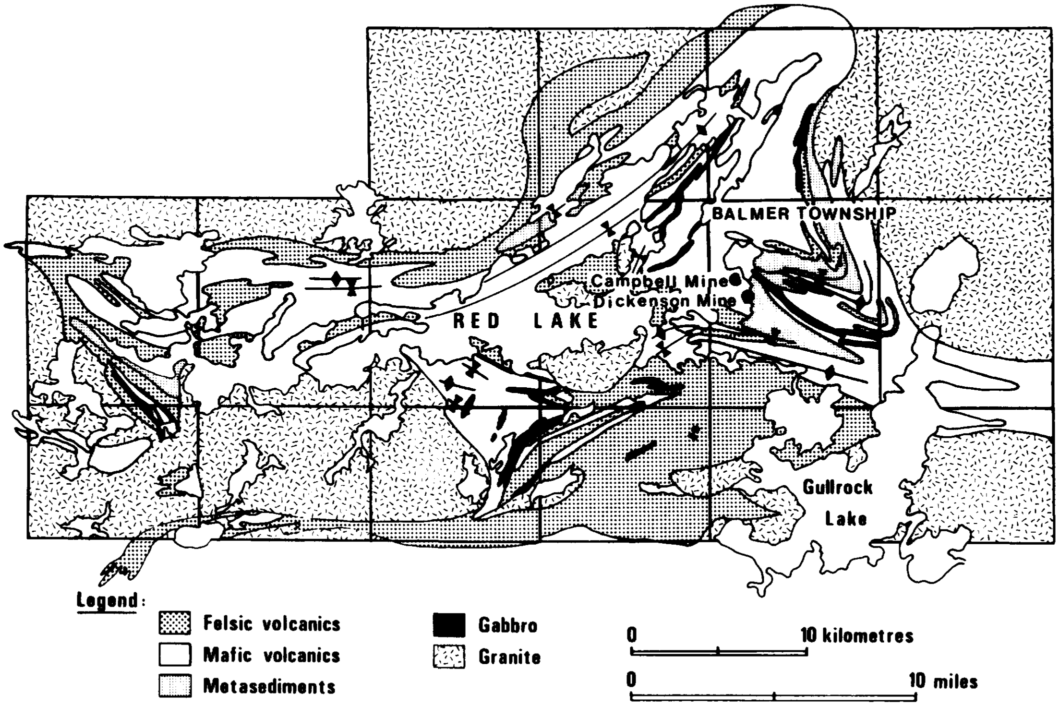


Figure 8-1—Simplified geology of the Red Lake 'greenstone' belt, from the ODM Geological Compilation Map 2175 (Ferguson et al. 1970).

ping in the township by P.J. MacGeehan in 1978 and 1979, and by J. Thompson (1979) on the Campbell property has confirmed this interpretation. A simplified geological map embodying the work of all these workers is shown in Figure 8-2.

For the purpose of description the map has been divided into four areas: 1)the Western Volcanic Complex (WVC), 2) the Central Sedimentary Belt (CSB), 3) the Eastern Volcanic Belt (EVB), and the Southern Volcanic Belt (SVB) (Figure 8-2). Facing-directions from mafic pillowed flow-units indicate that the volcanic rocks face south throughout the township (Figure 8-3). In general the flow-units strike between 090° and 110°, parallel to the penetratively developed cleavage (Figure 8-3) and to the elongation (flattening?) direction of individual pillows, but both the cleavage and flow-contacts swing north to between 125° and 150° in volcanic rocks bordering the CSB. These sediments have been intensely deformed; an early cleavage (S_1) that was axial planar to large folds in bedding (Figure 8-4a) was later folded on southwest-trending axial planes (Figure 8-4b). Whereas most volcanic rocks and associated intrusions have only one penetrative cleavage, two superposed cleavages are developed in several spatially restricted and generally northwest-striking linear belts of anomalously fissile and strained (relative to the area as a whole) volcanic rock, one of which hosts the Campbell and Dickenson vein systems.

The orebodies at the Campbell and Dickenson mines lie at the eastern border of a major volcanic complex (WVC), composed of a thick pile of extrusive volcanic rocks including massive to pillowed basalt, lesser andesite, rhyolite, and minor interflow exhalative and volcaniclastic sedimentary rocks (Figure 8-5a) that are intruded by concordant sills ranging from ultramafic to gabbroic or dioritic in composition, and by a large but poorly exposed mafic-ultramafic intrusion, outlined by diamond drilling under the southwest end of Balmer Lake (see Figure 8-2). Several clastic interflow-units in the WVC have been traced eastward as graded wacke-mudstone that are intercalated with exhalative sedimentary rocks in the CSB and with basic pillowed flows in the EVB, indicating that the eastern border of the WVC marked a rapid facies change from a site of active submarine volcanism to one of dominantly sedimentary accumulation. Several lines of evidence (including the eastward pinch-out of rhyolite units, the thickening and pinch-out of individual pillowed flows, the changing proportion of volcaniclastic material, and the eastward gradation from coarse epiclastic conglomerate and wacke to finer mudstone) indicate that the WVC was a topographic high. This high was a source of detrital material for the sedimentary basin during volcanic activity.

The coarse clastic wedge of epiclastic conglomerate and greywacke which flanks the WVC in the region of the Dickenson mine grades eastward into graded wacke and mudstone that are intercalated with a thick sequence of exhalative sedimentary rocks including chert, cherty car-

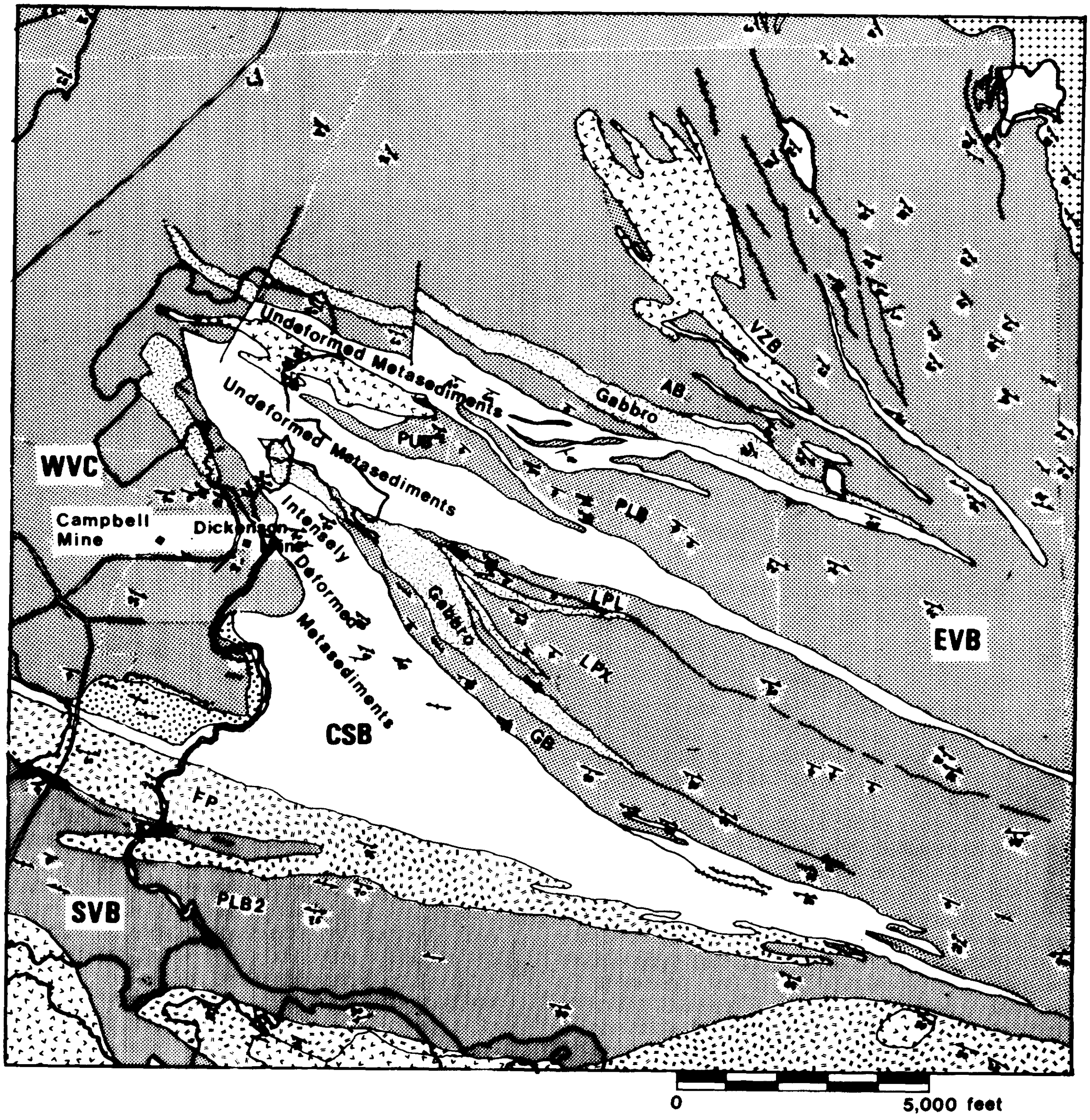


Figure 8-2—Geology of the western part of Balmer Township simplified from Pirie and Grant (1978), with additional information from mapping by MacGeehan in 1978 and 1979, and by Thompson (1979). WVC–Western Volcanic Complex; **CSB**–Central Sedimentary Belt; **EVB**–Eastern Volcanic Belt; **SVB**–Southern Volcanic Belt. Mappable subunits of basalt; **VZB**–variolitic basalt; **AB**–aphyric basalt; **PLB**–plagioclase-phyric basalt; **PUB**–plagioclase-phyric basalt (unit 2); **LPL**–plagioclase-microphenocrystic aphyric basalt; **LPX**–pyroxene-microphenocrystic aphyric basalt; **GB**–basalt containing single elongate ferromagnesian and plagioclase, set in a quartzo-feldspathic matrix.

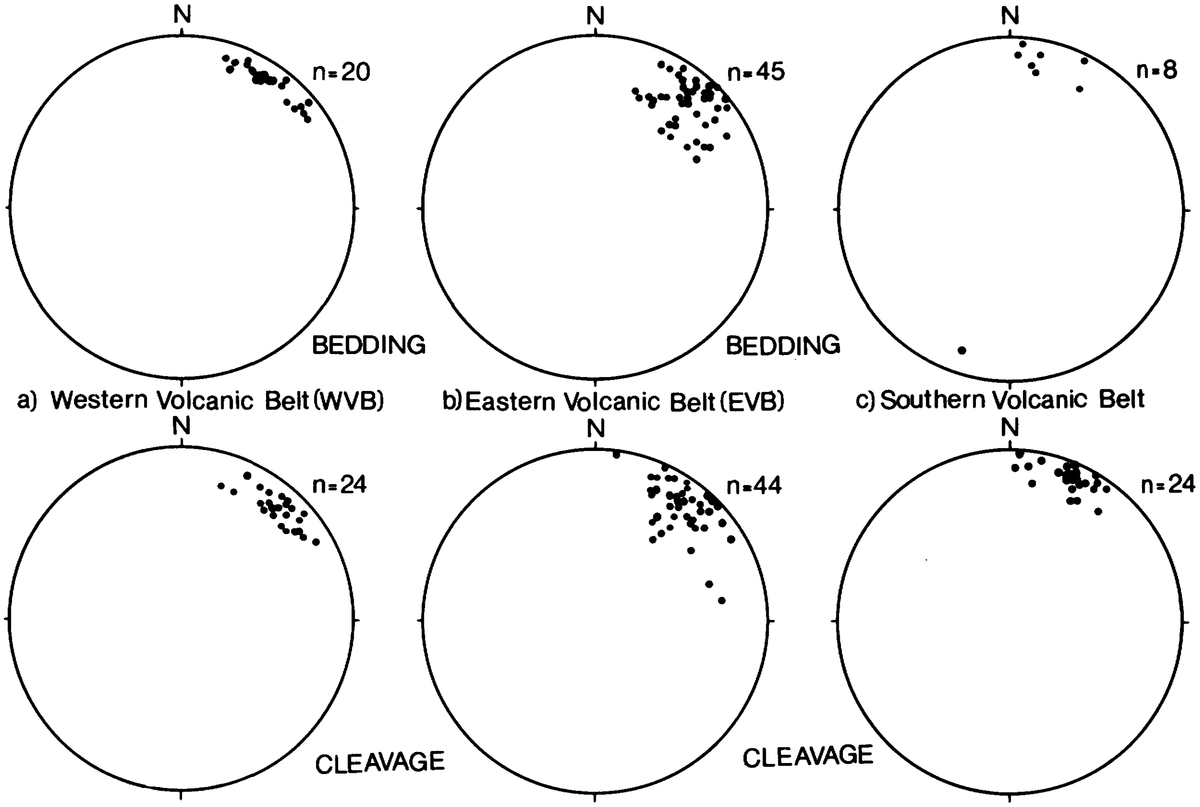
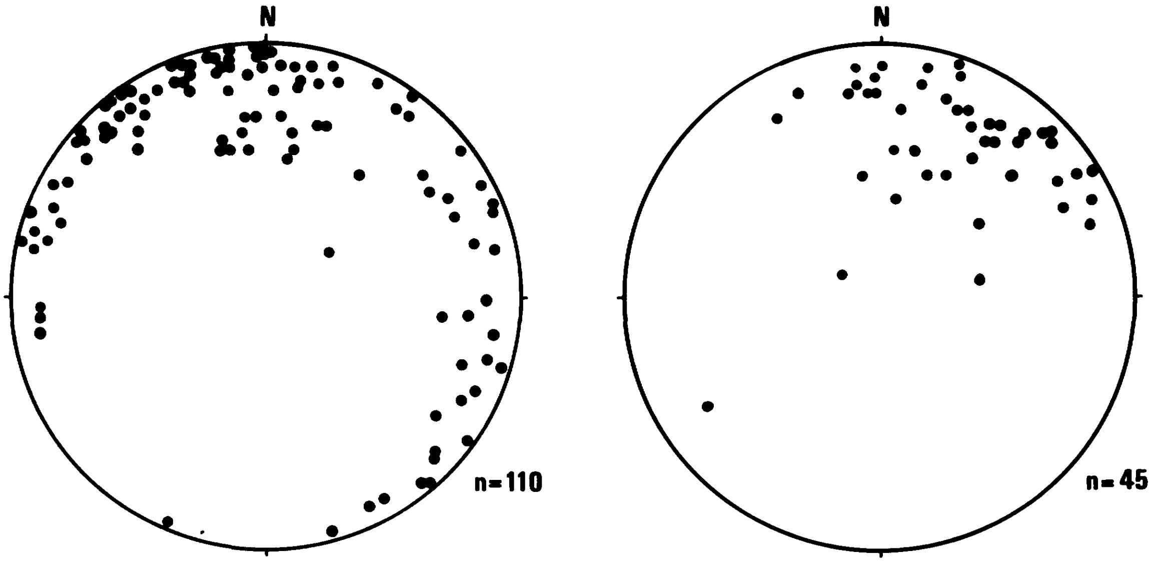


Figure 8-3—Lower hemisphere equal area pole plot of bedding and cleavage orientations in surface outcrops of the volcanic rocks in Balmer Township. Bedding orientations are based on the elongation direction of pillows where facing-directions could be determined.



a) Bedding **b) Cleavage**

Figure 8-4—Lower hemisphere equal area pole plot of a) bedding, and b) penetrative cleavage in pelitic beds that is axial planar to F_1 folds.

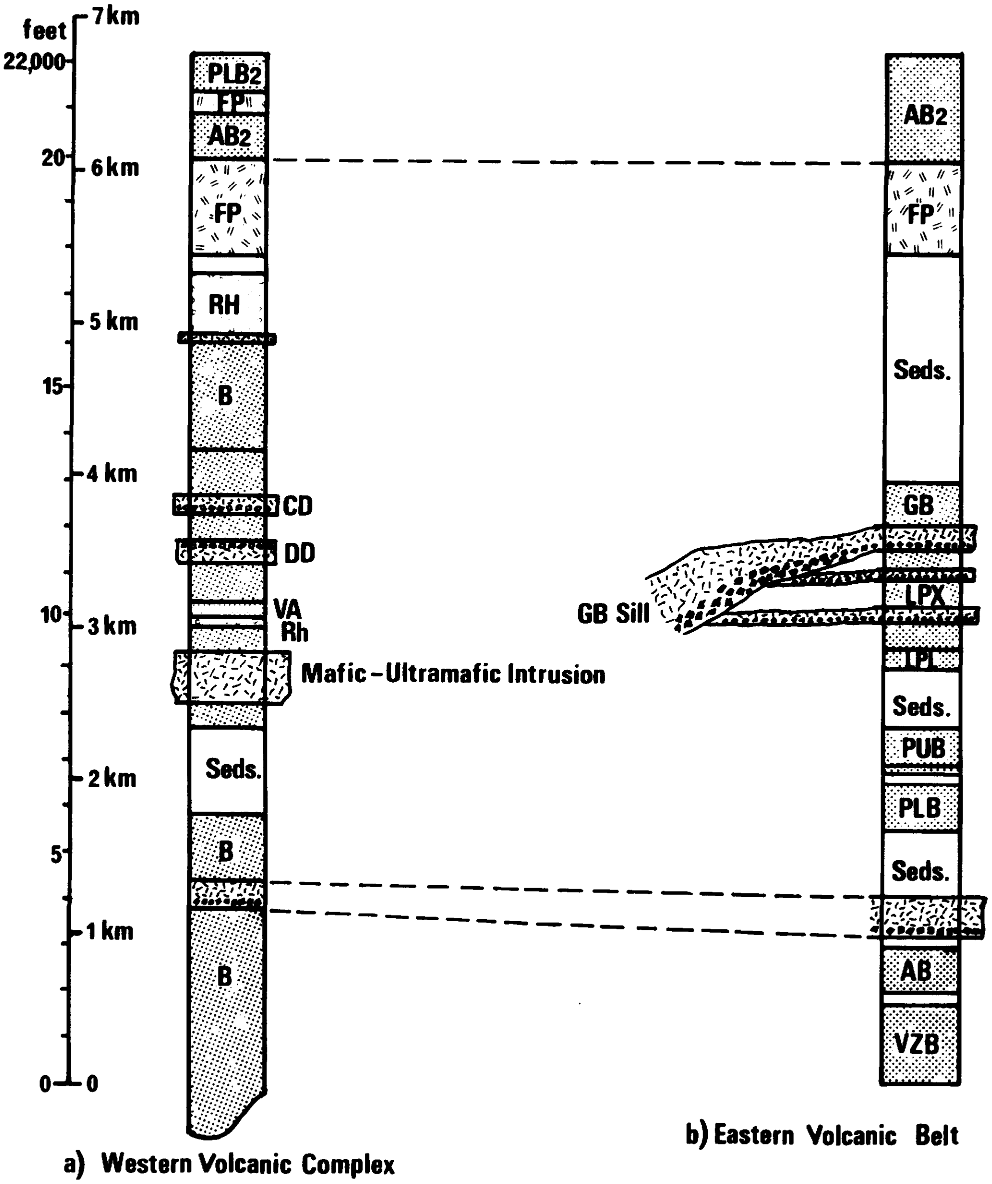


Figure 8-5—Restored stratigraphic section through the extrusive volcanic rocks, sedimentary rocks (no symbol), and synvolcanic intrusions in (a) the ***WVC*** *and (b) the* ***EVB*** *(see text for explanation). Volcanic rocks occupying the southern part of the township (Units FP and stratigraphically higher units) are common to both stratigraphic sections. Cumulate zones in some of the intrusions are illustrated: filled squares = cumulate pyroxene; open squares = cumulate plagioclase. Symbols for stratigraphic columns:* ***VZB****–variolitic basalt;* ***AB_1****–aphyric basalt;* ***PLB_1****–plagioclase-phyric basalt;* ***PUB****–plagioclase-phyric basalt (unit 2);* ***LPL****–plagioclase-microphenocrystic aphyric basalt;* ***LPX****–pyroxene-microphenocrystic aphyric basalt;* ***GB****–basalt containing isolated elongate ferromagnesian and plagioclase crystals, set in a quartzo-feldspathic matrix;* ***FP****–plagioclase porphyry intermediate extrusive rock, mainly pyroclastic;* ***AB_2****–aphyric basalt (unit 2); a)* ***WVC****:* ***B****–undifferentiated basalt;* ***Rh****–rhyolite;* ***VA****–variolitic andesite;* ***DD****–Dickenson 'diorite' and* ***CD****–Campbell 'diorite' (both 'diorites' are differentiated mafic to ultramafic intrusions - see text);* ***PLB_2****–plagioclase-phyric basalt (unit 3).*

bonates, and sulphide and oxide iron formation in the central part of the CSB. The exhalites exhibit graded bedding, convolute laminations, and slump, scour, and breccia structures, indicating they were transported from an initial depositional site (presumably on the flanks of the adjacent volcanic complex) into the sedimentary basin. The turbidites are interbedded with fine-grained chemical sedimentary rocks, and both are transected by synsedimentary breccia dikes containing both locally derived and exotic clasts of bedded chert and iron formation, set in a black siliceous and sulphidic matrix. These breccia dikes are flanked by zones of hydrothermal alteration, evidently the result of a synsedimentary hydrothermal exhalative activity within the sedimentary basin.

A series of thin pillowed basalt flows which thicken eastward into a major volcanic build-up (EVB) are intercalated with exhalative sedimentary rocks along the eastern border of the CSB (see Figure 8-2). Several of these flows are distinctive stratigraphic markers (Figure 8-5b) that have been traced for more than 4 km along strike. The eastward thickening of each flow appears to be a primary feature, reflecting the site in which these pillowed units were extruded. Several intrusive gabbroic bodies emanating from the WVC contain thick pyroxenitic cumulate zones where they transect the CSB (shown diagrammatically, Figures 8-5, 8-6), but they grade eastward into sills that are overlain by, and grade laterally into pillowed flow-units with almost identical mineralogical composition (Figure 8-5b). These sills, rooted in the WVC, thus formed high-level feeder zones to the extrusive flow-units of the EVB.

The gold-bearing zones at the Campbell and Dickenson mines thus occur on the eastern flanks of a thick pile of proximal volcanic rocks, with strong topographic relief, flanked by a thick sequence of dominantly exhalative sedimentary rocks, and by distal flows fed through lateral feeder zones from around the periphery of the complex (Figure 8-6). These volcanic rocks were thus extruded during a period of continuous exhalative activity, and the gold-bearing zones at the mines are at the *same stratigraphic horizon* as some of the exhalative sedimentary rocks in the eastern part of the CSB.

Hydrothermal Alteration

Most of these volcanic rocks have been hydrothermaly altered on a regional scale. They have been variably spilitized, silicified, chloritized, carbonatized, and alkali-depleted in a series of alteration events, some of which were

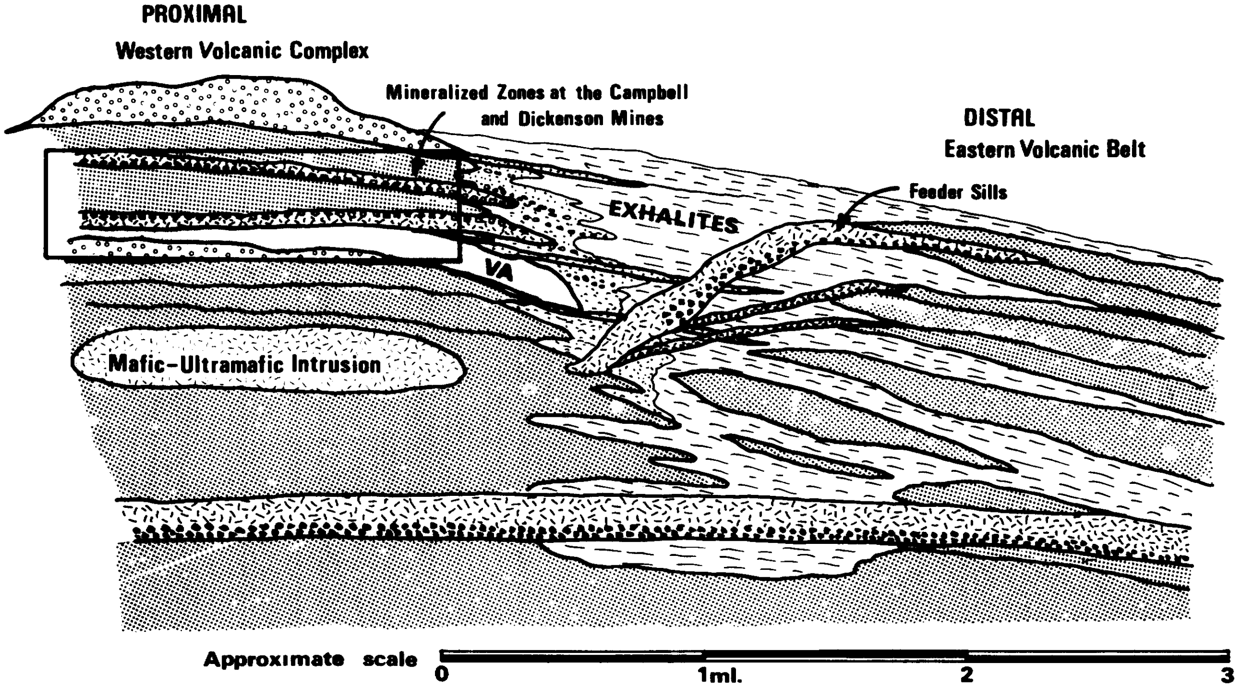


*Figure 8-6—Interpreted stratigraphic section through the volcano-sedimentary sequence at the time of active volcanism (lithologic symbols as per Figure 8-5). Paleo-topographic reconstruction based on lateral facies changes in the **WVC** and **CSB**; as discussed in the text. Cross-correlation between the **WVC** and **EVB** provided by the feeder sills and by interflow volcaniclastic sedimentary rocks in the **WVB** which extend out as graded wacke-mudstone units (fine dot symbol) into the **CSB**, and partly intercalated with individual flow-units in the **EVB**.*

synvolcanic, whereas others preceded, were contemporaneous with, or postdated deformation and regional metamorphism. In the vicinity of the mines these large-scale alteration events are superposed by hydrothermal alteration accompanying ore deposition, and the geochemistry of these rocks is indeed so strongly disturbed that their original primary geochemistry and volcanic affinity have not yet been established. However, the volcanic rocks in the EVB are generally less severely altered; they retain vestiges of their original igneous fabric, and the geochemistry of unaltered or least-altered samples of each flow (Table 8-1) indicate they are highly fractionated iron-rich basalt of undoubted tholeiitic association (Figure 8-7). As these distal flows were sequentially extruded during a continued period of active volcanism in the WVC (Figure 8-6), this strongly suggests that the volcanic centre itself was also of tholeiitic affinity.

The earliest synvolcanic alteration (in mafic pillowed flow-units) consists of bleached zones which developed around pillow rims or flanking quartz-epidote-carbonate filled veinlets, fractures, cylindrical 'pipes', and other irregular permeable structures that are interpreted to have been the conduits through which a hydrothermal fluid moved (Harrigan and MacLean 1976; MacGeehan 1978). The basalt has been intensely bleached in zones up to one or more metres wide bordering these structures. The bleached zones grade outward from light grey to grey-green domains into dark green unaltered or less altered basalt. This alteration clearly predated deformation and cleavage development; geochemical studies of individual flow-units indicate the enrichment in Na ± Si and the leaching of massive quantities of Fe and Mg from within the bleached zones, as shown by plotting these elements against the normative quartz plus alkali feldspar content (i.e. Differentiation Index; Figure 8-8). There is no evidence for the later reprecipitation of these leached elements within basalt. The close association of this early alteration in the volcanic rocks with the deposition of exhalative sedimentary rocks suggests that the two are geneticaly related. Both appear to have resulted from subseafloor geothermal activity contemporaneous with volcanism which leached and transported Fe, Mg, ± Si from the volcanic rocks and then precipitated them at the seafloor to form the exhalites. The hydrothermal alteration and brecciation of the interbedded exhalative sedimentary rocks is consistent with this hypothesis.

The geochemical history of Au during this alteration is particularly important. Using the example of one flow-unit (Figure 8-5b, PLB_1), the Au content of unaltered or least altered samples ranges from 4 to 14 ppb (Figure 8-9), whereas that of the majority of hydrothermally altered samples is less than 1 ppb, indicating that Au was 1) mo-

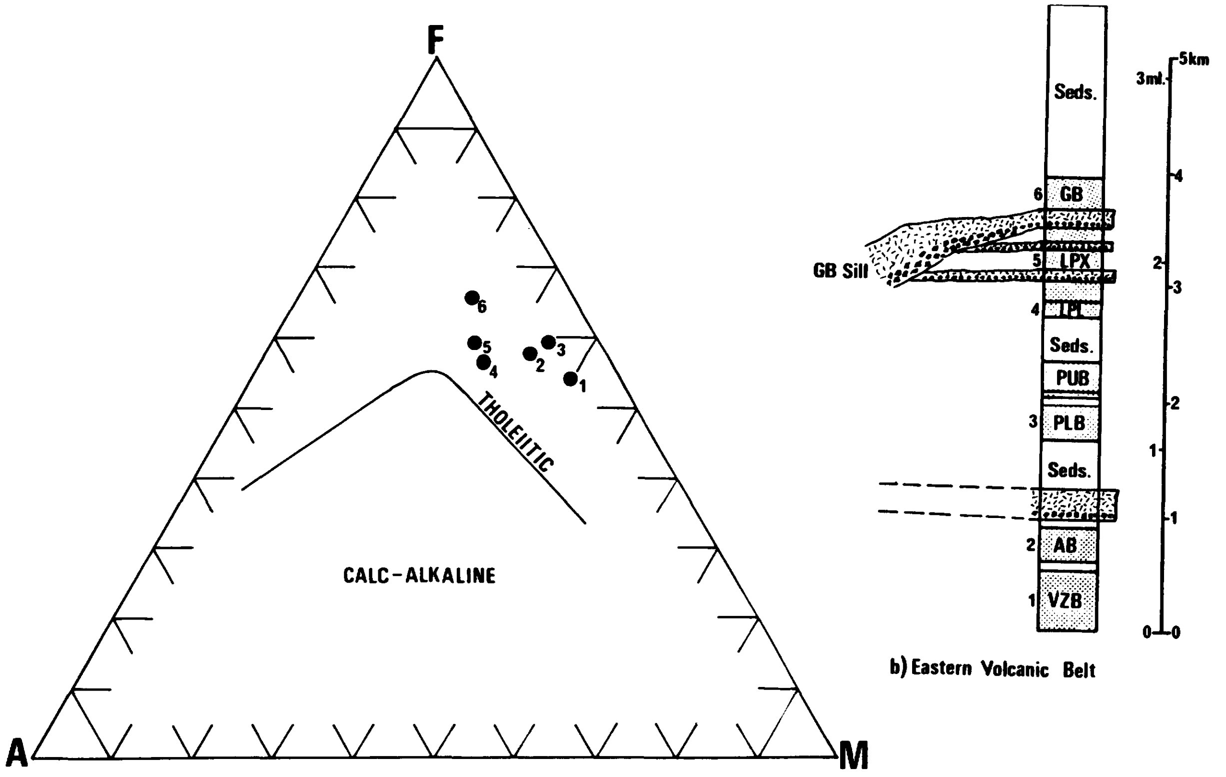


*Figure 8-7—AFM plot of the mean composition of unaltered or least-altered samples of each flow-unit in the **EVB** (Table 1). The tholeiitic-calc-alkaline dividing line is after Irvine and Baragar (1971).*

TABLE 8-1 | Normalized Major Element Composition[1] of Unaltered and Least Altered Samples of Each EVB flow-unit (Fig. 5b).

Rock Unit:	VZB	AB1	PLB1	LPL	LPX	GB
NO. Samples:	2	4	4	6	3	4
SiO_2	45.87	50.08	49.93	50.76	50.76	50.96
TiO_2	.74	.92	1.03	.85	.86	.95
Al_2O_3	12.68	14.56	16.07	16.75	17.21	15.36
Fe_2O_3	2.29	1.51	2.11	2.35*	.18	1.75
FeO	13.71	9.87	10.66	8.71	10.64	9.86
MnO	.40	.42	.21	.21	.20	.32
MgO	11.49	6.48	7.34	5.37	4.60	3.75
CaO	11.03	14.27	11.11	11.87	10.86	14.64
Na_2O	1.56	1.54	1.22	2.83	2.72	2.10
K_2O	.18	.28	.07	.23	.14	.15
P_2O_5	.06	.08	.10	.07	.08	.09
FeO*	15.71	11.23	12.56	10.82	10.80	11.43

Note 1: Analyses were completed by X-Ray Assay Laboratories, Don Mills, Ontario by XRF on fused pellets, and checked using Seimens type VRS Vacuum Spectrograph at Queen's University. Fe_2O_3* is calculated as TiO_2+1.5%, after the method of Irvine and Baragar, 1971. FeO** is total iron as ferrous oxide. (Fe_2O_3 converted plus FeO)

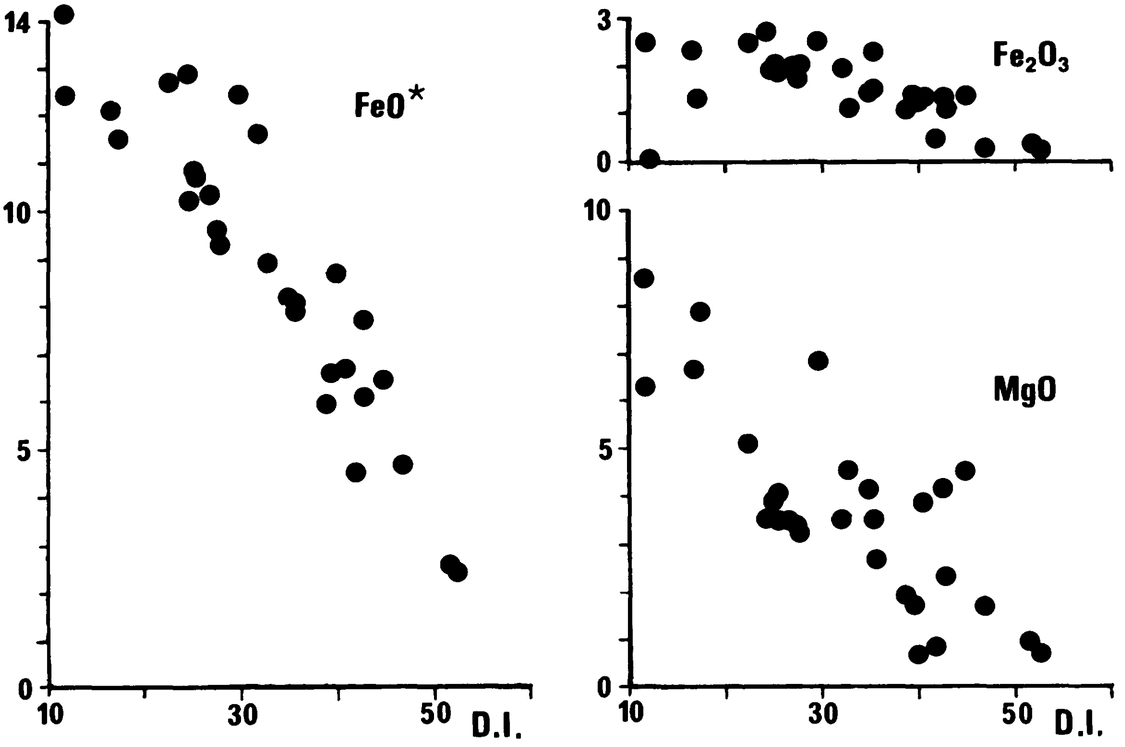


Figure 8-8—FeO* (total iron as FeO), MgO and Fe_2O_3 against D.I. (Differentiation Index; Thornton and Tuttle 1960) plot of samples from the **PLB$_1$** basalt (Figure 8-5b).

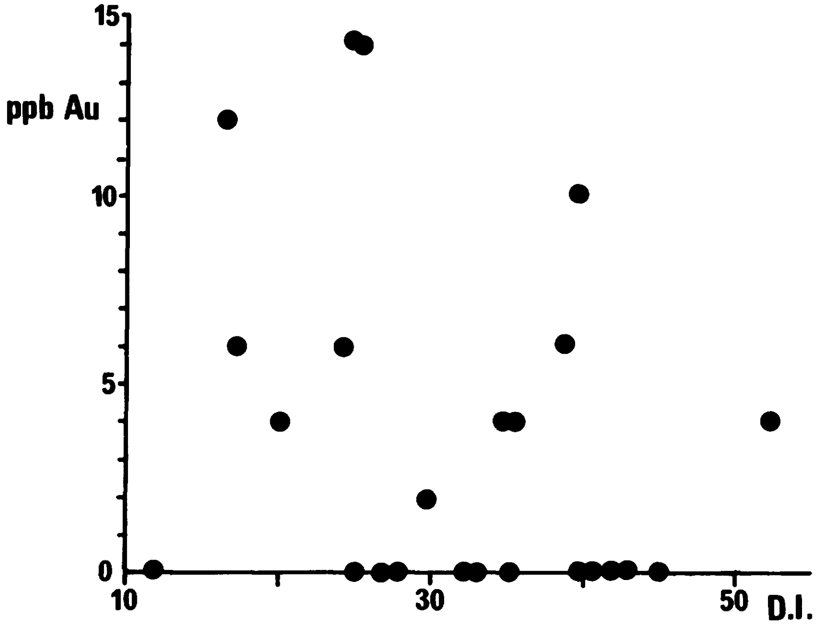


Figure 8-9—Au in ppb against D.I. plot for samples from the **PLB$_1$** basalt (Figure 8-5b). Au concentration was determined using Neutron Activation analysis by X-Ray Assay Laboratories, Don Mills, Ontario.

Figure 8-10—Contoured Peraluminosity Index (Mole percent $Al_2O_3/(Na_2O + K_2O + CaO)$; (Spitz 1973) plot of analyzed samples (filled circles) in Balmer Township.

bile, 2) leached from the volcanic rocks, and 3) probably enriched within contemporaneous exhalite horizons during subseafloor geothermal activity.

Other alteration types, some formed before and others certainly synchronous with and continuing after deformation, are superposed on this early hydrothermal alteration event. Carbonate forms a ubiquitous phase in most alteration assemblages, and whereas this consists for the most part of calcite/aragonite on a regional scale (for example in seafloor alteration), local zones of abundant iron-magnesium-rich carbonate alteration (ankerite-ferrodolomite-dolomite) occur as fine disseminations and as variably transposed veinlets within the schist zones at the mines, and in other linear belts of schistose volcanic rocks in the EVB. It is not clear, at this stage in our studies, if this syn-deformational carbonatization represents a metasomatic influx or a localized re-distribution of earlier synvolcanic or predeformational cabonate, as described by W.O. Karvinen (this volume) in the Porcupine mining camp. Similarly, other mineralization-alteration types, including larger scale but gold-barren iron-magnesium cabonate veins within the mines, and local zones of intense carbonate-talc-chlorite alteration within and bordering the mafic and ultramafic sills and the large mafic-ultramafic intrusion north of the mine (see Figure 8-2), cannot at this time be unambiquously assigned to either a 'synvolcanic' or 'metamorphic-deformational' event.

Most significant, from the point of view of exploration, is a wide aureole of intense alkali depletion which encloses, but has a much wider lateral extent than the ore-bearing schist-zones at the Campbell and Dickenson mines (Figure 8-10). That this alteration postdates at least some of the early synvolcanic alteration is demonstrated by the detailed preservation of quartz-epidote-carbonate structures and flanking bleached zones (of the type that are alkali-enriched elsewhere) *within* the zone of alkali depletion. Other alterations which appear to be syn- or post-deformational in age include the development of 1) narrow silicified replacement zones localized along the borders of pre-existing quartz-carbonate veinlets and later faults and fractures in the volcanic rocks, and 2) bleached zones of carbonate-rich alteration that transect the chert-banded iron formation in the CB.

The existence of such widely distributed syn- to post-deformation alteration types within the region as a whole appears to be particularly significant to the genesis of the gold mineralization, which, from evidence in the mines (Rigg and Helmstaedt 1980), also formed over the same time-period.

Mine Geology

At the Campbell and Dickenson mines, over 15 gold-bearing mineralized zones occur within a sequence of massive to pillowed mafic flows, andesite, rhyolite, and interflow iron formation and volcanogenic sedimentary rocks that are transected by an ultramafic sill and by two fractionated gabbroic bodies (Campbell and Dickenson diorites) that may possibly have been massive flows. The geology of 14 Level (Campbell) and a restored stratigraphic section through the volcanic rocks are shown in Figures 8-11 and 8-12 respectively.

The lithological environment of the ore zones differs in several important respects from that of the area as a whole. Most conspicuous is the high degree of deformation, most rocks being highly foliated compared to lithologically similar rocks away from the mines, although the amount of strain (as indicated by the deformation of pre-existing structures, including veins), and the degree of fissility, depends in part on lithology. Least foliated and deformed are the concordant gabbroic and ultramafic intrusions. The pillowed basalt and andesite are more strongly foliated and schistose, whereas the interflow sedimentary rocks are commonly intensely deformed and internally folded. In the Campbell mine, a thick sequence of interflow sedimentary rocks including iron formation and hydrothermally altered wacke (now 'altered rock' in part) forms an intensely folded 'mobile zone' between two more stable blocks of volcanic rocks (Figure 8-11). There is no evidence of large-scale folding outside the 'mobile zone' at Campbell, but a folded exhalite that is reported to trend across the foliation at the east end of the Dickenson mine (Rigg and Helmstaedt 1980) suggests that the apparent absence of folding may be due, in part, to the difficulty in identifying stratiform contacts. However, mafic to intermediate pillowed flow-units, the dominant lithotype in the mines (Figure 8-12), face consistently south throughout the Campbell and Dickenson mines (R. Church, M. Chowaniec respectively, personal communication, 1979), indicating that no major fold closures are present in the area.

The rock sequence in the mine is also lithologically more complex than that in the area as a whole. The stratigraphy is inflated by a number of synvolcanic intrusions (Figure 8-12), and by a large dome-shaped body of rhyolite at the west end of the Campbell mine (Figure 8-11) that thins and grades rapidly eastwards into a rhyolite tuff that is intercalated with exhalative sedimentary rocks in the CSB. In addition, metamorphosed mafic to felsic (porphyry) dikes which postdate most of the deformation are more widespread in the mines than in the area as a whole.

The primary lithological complexity of the mine area is further enhanced by a variety of widespread alteration effects as noted above. The most pervasive is an alkali depletion which has affected all of the older (synvolcanic) rocks within the zone of intense deformation, and also extends beyond it into less deformed units to the south and north (Figure 8-10). Veins and pods of quartz or carbonate with variable amounts of chlorite, sericite, and sulphide minerals are also pervasively developed throughout the fissile zone which hosts the orebodies. More restricted in distribution is an intense talc-chlorite-carbonate (dominantly ankerite) zone of alteration concentrated in the ultramafic parts of the sills, but overlapping and masking the identity of the adjacent volcanic and sedimentary rocks. Both are collectively termed 'altered rock' at Campbell and 'chicken feed' at Dickenson.

All these alterations postdate the irregular leached (Fe-Mg-Au depleted) zones which developed during subseafloor geothermal activity, and they precede for the most part, the hydrothermal alteration closely associated with gold deposition (discussed below), which clearly formed synchronously with and closely following the deformation of the rocks.

Mineralized Zones and Mineralization Types

The gold-bearing zones are of three basic types: 1) *foliation-parallel veins*–elongate structures oriented approximately parallel to the dominant foliation in essentially homogeneous, generally basaltic host rock (e.g. A, F1, F2, South C; Figure 8-11); 2) *foliation-oblique veins*–wider, north- to north-northeast-trending elongate structures with less strike extent, controlled by faults (and in particular faults which juxtapose different lithotypes) that transgress the fabric (e.g. G, L, North L, etc., Figure 8-11); and 3) pod or pipe-like commonly high-grade zones, of limited size, controlled either by lithological contacts or by the intersection of faults and lithological contacts (e.g. 2151-W Zone). Types 1 and 2 which constitute the major part of the mined ore, show an impressive dip continuity. Most of the veins extend from the surface to the lowest levels of the mine.

There are two notable relationships between rock-type and mineralized zones within the mines:—

1) The mineralized zones occur almost exclusively in basalt or andesite, and in general 'fray-out' and are uneconomic where they strike into altered rock, rhyolite, or sedimentary rocks (Figure 8-11). However, as noted above in type 3, there are some unusually high-grade zones of dominantly replacement-type mineralization within altered rock and/or basalt near the contacts of the rocks and generally where the contacts are folded or faulted.

2) There is a broad spatial association of mineralized zones with bodies of altered rock. This pattern was noticed some time ago by mine geologists, and led to the hypothesis that the gold was derived from the altered rock. However, structural studies by D.M. Rigg and H. Helmstaedt (1980) indicate that rather than showing a spatial association with 'source-beds', the distribution of

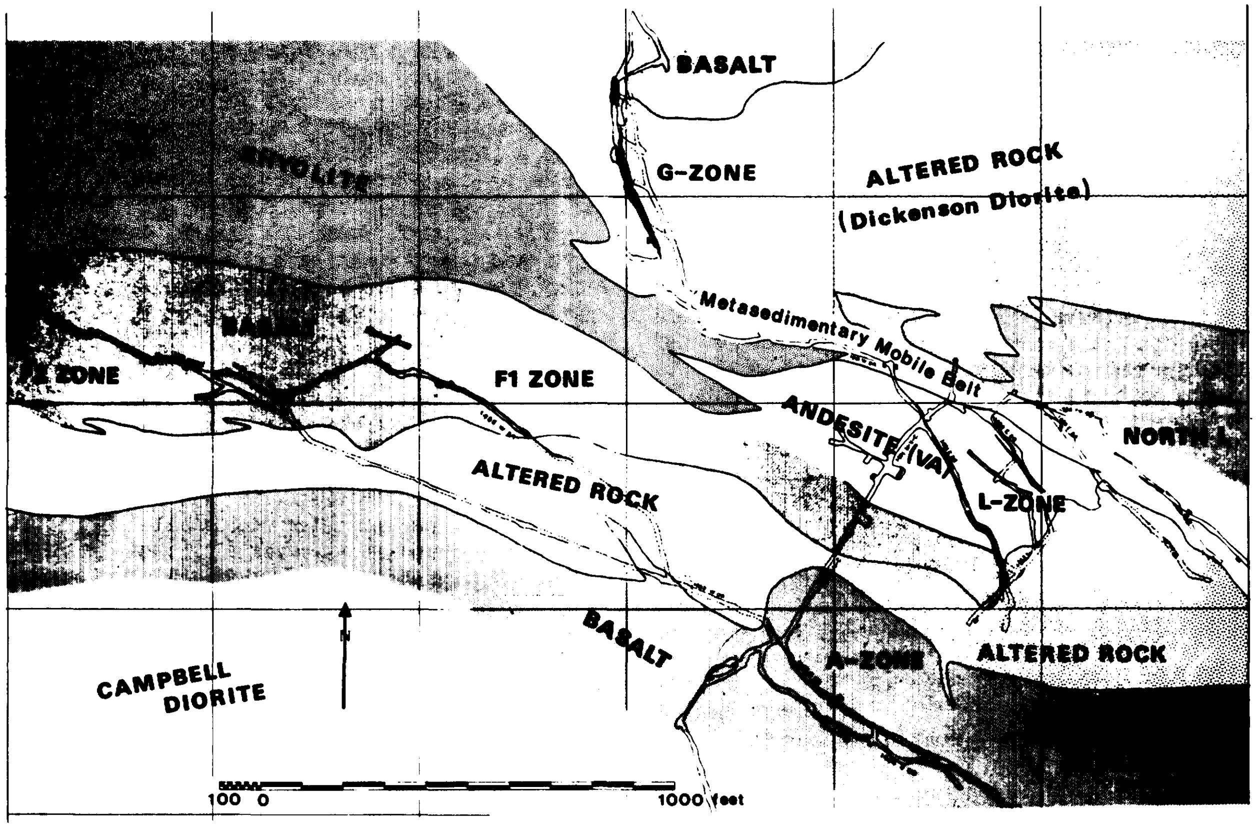


Figure 8-11—Geological compilation map of 14 level, Campbell Red Lake mine. The outline of the ore zones (black) and geology of the underground workings are from mapping by P. MacGeehan and D. Rigg. The strike continuation of the units is taken from drill core logging and interpretation by members of the Campbell Red Lake Mine Geology Department (See Jarvis 1972).

ore-grade fissure veins within the mines resulted from competency differences between the different lithotypes during progressive deformation. Indeed, the overall configuration and dip continuity of the vein systems suggest they constituted major hydrothermal conduits of the egress of massive quantities of Au-bearing hydrothermal fluid, which was preferentially channeled within the linear deformed zone in which the mines are situated, and particularly within open-space fissures and other permeable zones which opened up during deformation.

Within the gold-bearing zones, two main contrasting types of mineralization occur: 1) *layered carbonate-chert (very fine grained quartz)* with lesser arsenopyrite, pyrite, and in some areas magnetite, which appears to be an open-space fissure vein-filling, and 2) *silicified replacement* zones and bodies, where both the host rocks and pre-existing veins have been replaced by fine-grained granulose quartz, arsenopyrite, and pyrite. Most mineralized zones consist of a mixture of these two mineralization types; the open-space fissure veins, commonly having formed in a series of mineralization episodes, separated by periods of intra-vein deformation and brecciation. In most mineralized zones, there is a general tendency for the early mineralization to consist of a sequence of fissure-filling veins that is overprinted by later replacement-type mineralization (discussed below).

The character of these different mineralization types is illustrated by examples of a dominantly fissure-filled vein (G-Zone, Figure 8-13) and silicified replacement-type bodies (2151-W, Figure 8-14) at the Campbell mine.

The *G-Zone* is a foliation-oblique fissure vein about 120 m long and 4.5 m wide that occurs along the faulted contact between pillowed basalt and 'altered rock' (hydrothermally altered 'Dickenson diorite') (Figure 8-13). The fissure vein is composed almost entirely of layered carbonate-chert, and smaller veins with similar character and orientation also occur within the adjacent 'altered rock'. The western side of the vein (and similar subsidiary veins in the area) contains a zone of wall-rock breccia fragments set in a banded carbonate-chert matrix, the banding defining semispherical structures oriented convex outwards from the fragment boundaries. East of the breccia zone, finely layered (2 to 25 mm) carbonate-chert with conformable blade-shaped layers of arsenopyrite grades upward into finely layered 'chert' with minor carbonate but with some thicker (1-2 mm) arsenopyrite layers. Some concentrically zoned spherical structures up to 2 m in diameter (similar to those in the matrix of the breccia) occur on the west side of the zone, but most of the layering is broadly conformable with the G-Zone boundary, although unconformities, slump-like structures, and breccia zones occur locally (Figure 8-13). The layering is tentatively interpreted to have formed by the recrystallization of a carbonate-silica *gel* within the open-space vein structure (cf. Wright 1969), the crystallizing minerals having either nucleated along the vein wall, on the surface of the breccia fragments, at discrete nucleation points within the vein, or (predominanty) along planes that appear to be relict after depositional surfaces formed as the vein was infilled. This complicated internal structure is only characteristically developed where the G-Zone is a wide, open fissure. Traced down-plunge, the vein narrows to 1 to 2.5 m, and has a simpler internal structure more typical of the other fissure veins (A, F, L, North L, etc., Figure 8-11); the layering or banding are generally bilaterally symmetrical about the vein-axis, and were formed by inward recrystallization of carbonate-silica gel from nucleation points along the vein walls.

However, on 14 level (Figure 8-13), the wide fissure vein is transected by a strike-slip fault-breccia zone with associated weak sulphide mineralization, and then by a series of lateral faults with only minor displacement. A silicified mineralized zone from 0.5 to 2.5 m wide, which formed by replacement of both wall-rock and vein material, lies along the eastern side of the central part of the vein, and similar narrow silicified zones oriented approximately perpendicular to the vein walls transect the adjacent 'altered rock' wall-rock *only* on the east side (Figure 8-13). This silicified replacement-type mineralization healed fault-planes within the vein and adjacent wall-rock, indicating that this mineralization was a much later event, that formed *after* infilling, recrystallizaton, and two periods of faulting within the fissure vein. The juxtaposition of these narrow silicified zones which are oriented perpendicular to the vein walls in the 'altered rock', with a zone of massive silicification bordering *only* the east side of the vein (Figure 8-13), indicates that the vein itself may have formed an impermeable barrier to the movement of later silicifying fluids, causing a pod of ore-grade mineralization to form on the eastern border of the fissure vein.

The *2151-W* mineralized zone is a similar high-grade, pipe-like silicified body localized along the intersection between a fault-bounded foliation-oblique banded carbonate-chert vein, and the lithological contact of basalt and 'altered rock' (ultramafic sill) (Figure 8-14). The 'altered rock', basalt, the banded carbonate-chert vein, and other intensely boudinaged, transposed and crenulated veinlets within the basalt are silicified and mineralized with pyrite, auriferous arsenopyrite, and native gold. Silicification of the vein-form carbonate-chert resulted in the partial to complete leaching of carbonate from within the vein, and the recrystallization of the interlayered chert to coarse granoblastic quartz. The preservation of partly replaced boudinaged and crenulated veinlets within the silicified zone, allied to the obliteration of the cleavage normally associated with such deformation indicates that the silicification postdated the main (100° to 130°) mine cleavage. However, a cleavage striking between 130° and 150° occurs in rocks within and bordering the silicified zone (Figure 8-15), and two superposed cleavages can be observed in several areas. This new cleavage with different orientation may represent the overprint of a later deformational event, or it may reflect the localized recrystallization of wall-rock in the presence of a silicifying fluid under the stress regime that existed when the orebody formed.

The geometrical relationships described above indicate that the deformation and mineralization history in this general area consisted of the following sequence of developments.

1) A nearby (100° to 120°) cleavage in the 'altered rock' and adjacent basalt;

2) cleavage-parallel sheeted quartz, quartz-carbonate, and carbonate-chlorite vein-sets in the 'altered rock' (as mapped, Figure 8-14);
3) initiation of faults and displacement in excess of 30 m along major fault(s) at a high angle to the cleavage;
4) opening, infilling, and later recrystallization of major veins along these faults (some of which are mineralized), the layering in the veins making a high angle with the first cleavage;
5) subsequent faulting and brecciation of major veins (viz. the mineralized vein lying west of the 2151-W stope, Figure 8-14), and boudinage and crenulation of other, smaller veinlets in basalt;
6) and lastly, the influx of the Au-bearing silicifying fluids that formed the orebody. All this indicates a considerable period of time, marked by successive deformational events (including, possibly, the development of a new cleavage with different orientation, Figure 8-15), which separated open-space-filled, fissure-vein type mineralization from silicified replacement-type mineralization in this general area (cf. Rigg and Helmstaedt 1980). This general pattern is repeated in the G-Zone orebody (see above), and in many other fissure-veins, irrespective of whether the open-space, fissure-filled vein itself is mineralized with gold. We interpret this to indicate that the fissure veins, once formed, represented a major barrier to the movement of *later* auriferous silicifying fluids. These irregular but commonly spectacularly high-grade silicified replacement orebodies, more often than not, are localized at the borders of *pre-existing* fissure veins, or more competent and impermeable (?) lithotypes (i.e. 'altered rock'). We thus envisage a significant change in both the composition of the ore-bearing fluid and in the nature of rock-water interaction during the genesis of these rich auriferous lodes.

Summary and Conclusion

The rich gold deposits at the Campbell and Dickenson mines and similar type mineralization in other prospective areas in the Red Lake camp represent exploration targets

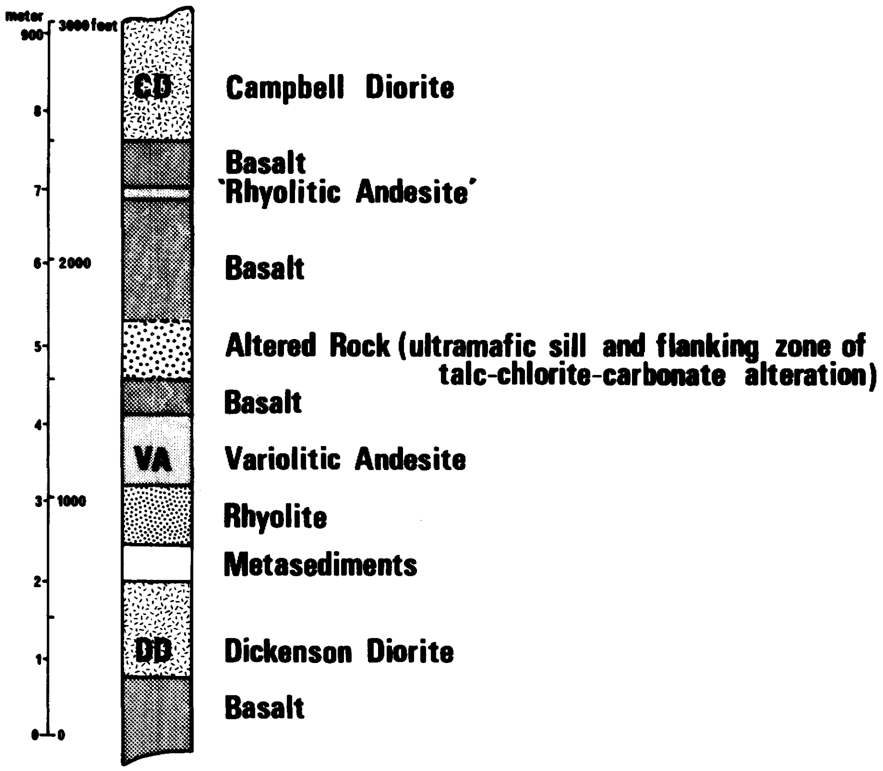


Figure 8-12—Generalized stratigraphic section, 14 level, Campbell Red Lake mine. The basalts, undifferentiated on this section, have been divided into individual flow-units in some areas based on the percentage of amygdules, varioles, other visible characteristics, and on the occurrence of interflow sedimentary rocks, but as yet these contacts have not been traced throughout the level. The Dickenson diorite is enveloped by a zone of talc-chlorite alteration and is mostly termed 'altered rock' on this level (see Figure 8-7), a name also applied to part of the overlying hydrothermally altered volcaniclastic sedimentary rocks.

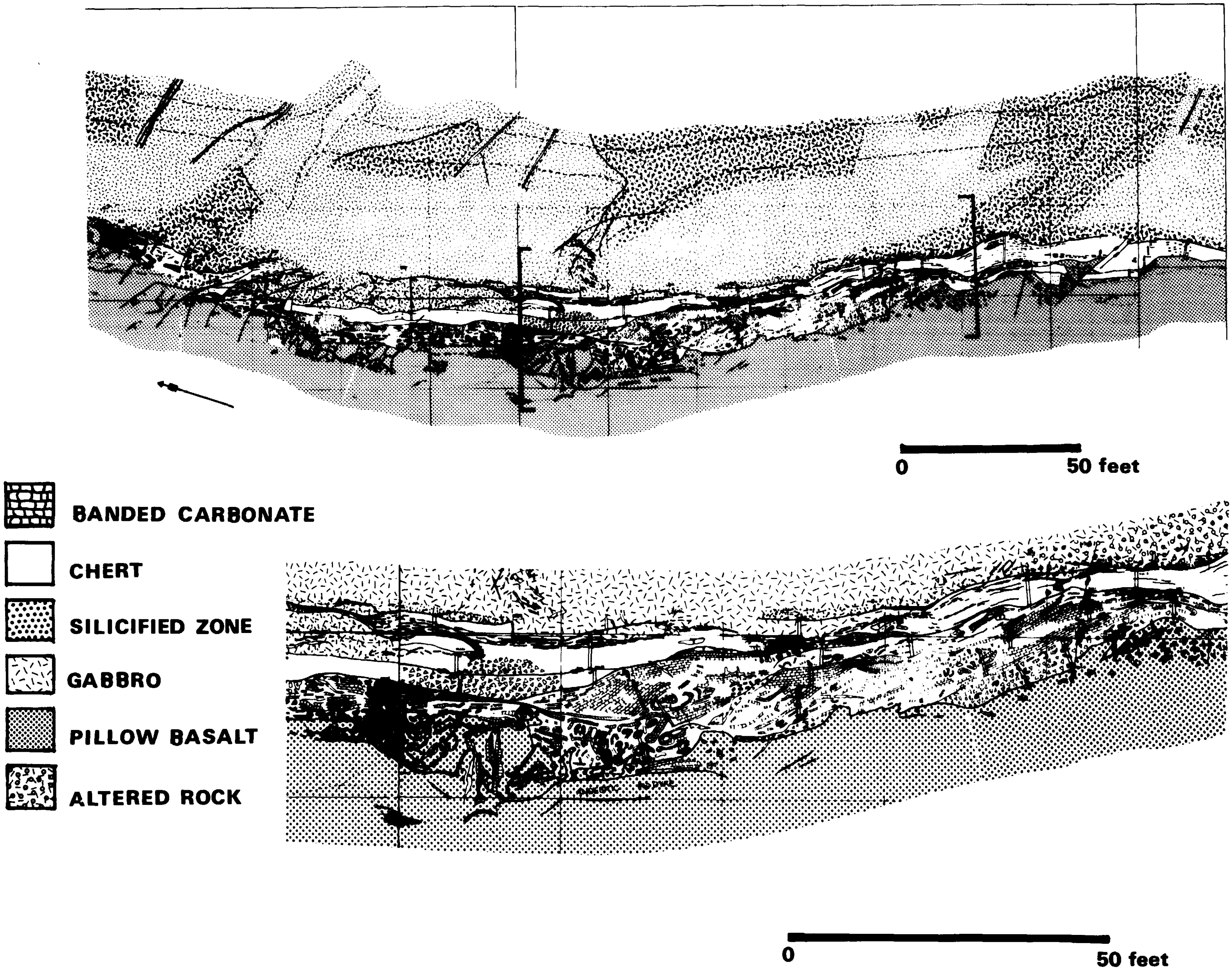


Figure 8-13—Photo-reduced 1:60 scale geological map of the G-Zone on 14 level (Figure 8-11). The orebody is a major open-space filled fissure vein that contains a zone of wall-rock breccia fragments along the west side. The vein is transected by a series of post-vein filling strike-slip faults with associated suphide mineralization (py, po, minor sph, cp), by cross-strike faults and fractures; and a silicified replacement zone that healed these fault structures lies along the eastern border of the central part of the vein.

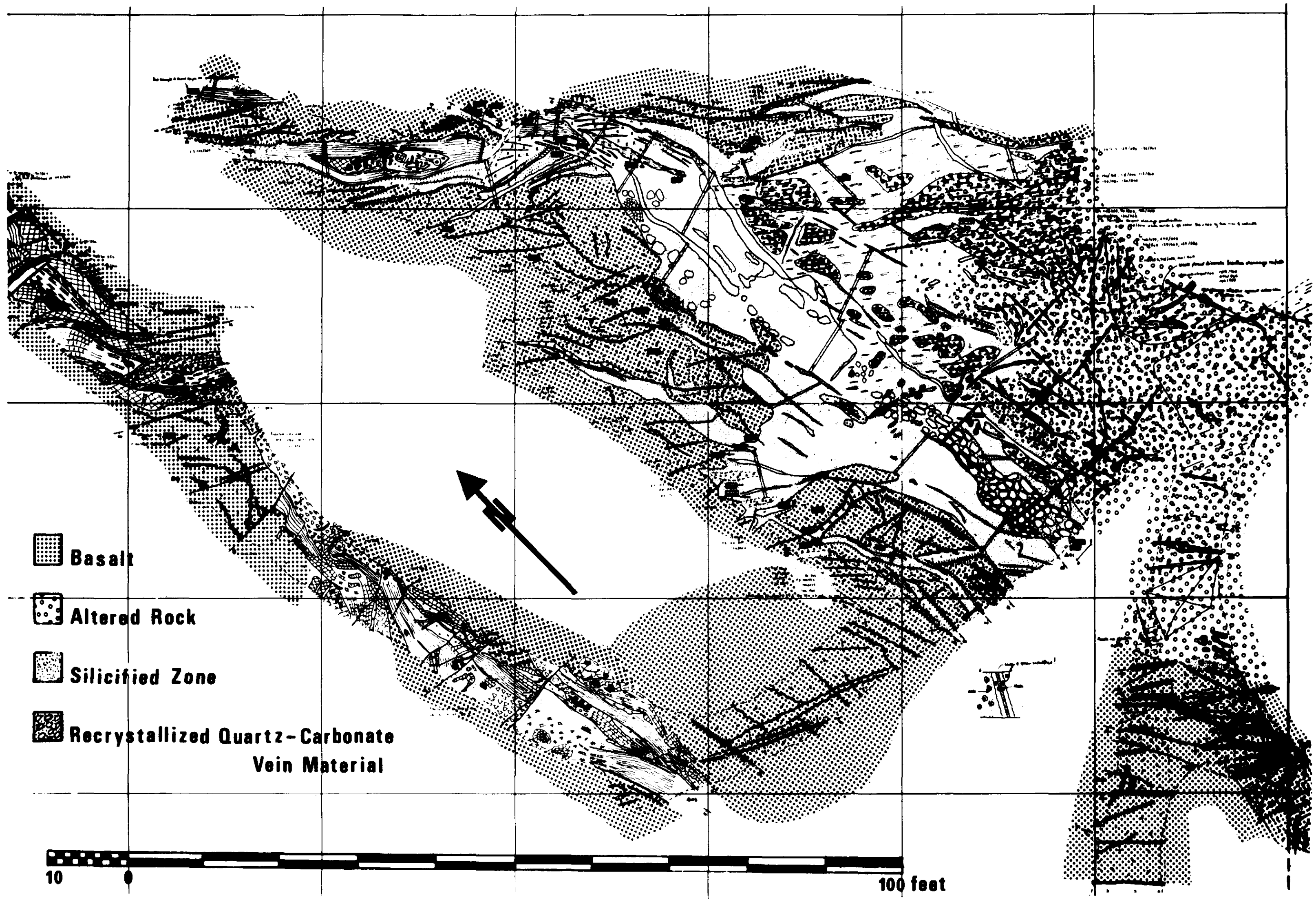


Figure 8-14—Photo-reduced 1:60 scale map of 2151-W stope, Campbell Red Lake mine. The orebody is an example of silicified replacement-type mineralization. The ore-grade material is confined to a silicified zone formed by the hydrothermal replacement of adjacent basalt and 'altered rock' lithologies where their contact intersects a fault-bounded banded carbonate-chert vein.

of some considerable economic significance. Although the gold mineralization is associated with fine-grained disseminated arsenopyrite, pyrite, and pyrrhotite, the orebodies have essentially *no geophysical expression* (C. Mark, personal communication, 1979). Thus exploration must be based both on broad genetic hypotheses, and on specific empirical associations (geological, structural, and geochemical) between ore-grade mineralization and its geological environment.

In terms of regional geological setting, these deposits occur:

1) at the margin of a thick sequence of volcanic rocks *flanking* a major (dominantly exhalative) sedimentary sequence,
2) within a paleo-subseafloor geothermal system where Fe, Mg, and Au had been leached from the volcanic rocks and enriched in contemporaneous exhalites,
3) within a linear belt of anomalously fissile deformed rocks which transects both the volcanic *and* the adjacent sedimentary rock sequences. This belt may have formed:
4) a focused zone of hydrothermal fluid discharge for a considerable period of time during deformation and regional metamorphism (the orebodies, in effect, being emplaced in major hydrothermal conduits along which metamorphic fluids escaped from the system). This prospective area is outlined geochemically by:
5) a wide zone of Fe-Mg carbonate alteration and veining within the deformed belt, and
6) by a wider aureole of intense alkali depletion that also encompasses the adjacent, less deformed volcanic rocks.

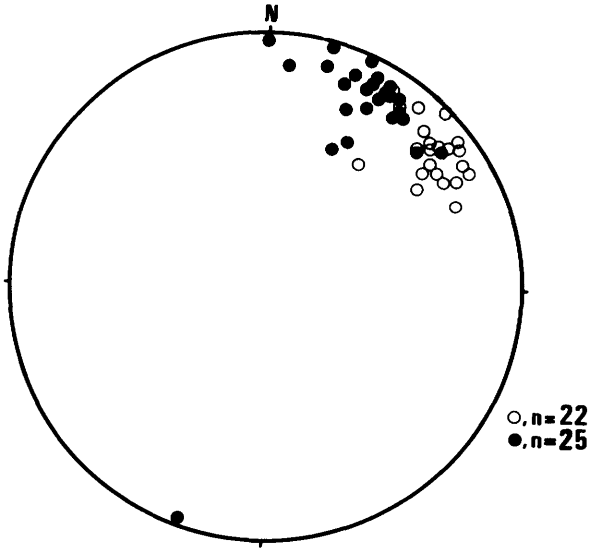


Figure 8-15—Lower hemisphere equal area pole plot of cleavage in basalt adjacent to the 2151-W stope. Filled circles = cleavage orientation in the general area; open circles = cleavage in basalt bordering the silicified zone.

On a more local scale within this broadly prospective zone, the orebodies are epigenetic deposits whose location is controlled by both structure and lithology. *Foliation-parallel* fissure veins occur in basalt; *foliation-oblique* veins occur along faulted contacts of rock units, especially along faults which juxtapose different rock types; and *silicified* replacement bodies are mostly localized along and bordering planar impermeable zones (pre-existing fissure veins, or 'altered rock' contacts) where these are intersected by other structures.

The *foliation-parallel* veins present targets up to several hundreds or even thousands of feet in length, that would be intersected by systematic diamond drill exploration programs. However, the thicker, generally higher grade and larger tonnage, *foliation-oblique* veins with more limited strike extent, and the irregular, commonly spectacularly high-grade, silicified replacement bodies are difficult to find and to assess economically by surface diamond drilling. Indeed, these two latter ore deposit types were only discovered after the mines had been in production for some considerable period of time.

Acknowledgments

This research into the genesis of gold deposits at the Campbell and Dickenson mines is funded by an Ontario Geological Survey Research Grant. The work forms part of a major O.G.S. sponsored re-assessment of the geology and economic potential of the Red Lake area. We wish to thank S.M. Reid, Cal Mark, and Ray Church of Campbell Red Lake Mines Limited and R. Tapper, Cal Mark, Lloyd Koskitello, and Mike Chowainec at the Dickenson Mines Limited for free access to the mine workings and for help, encouragement, and thoughtful discussion throughout our continuing research at the mines.

Relationships Between Structures and Gold Mineralization in Campbell Red Lake and Dickenson Mines, Red Lake Area, Ontario

D.M. Rigg[1] and H. Helmstaedt[1]

Abstract

The highly variable structures and complex vein arrays within the volcanic pile resulted from a combination of brittle and ductile deformation and were controlled by strong ductility contrasts of the rocks. The major ore zones cut across the bedding and primary volcanic structures. This precludes the possibility that they represent exhalite horizons. The ore zones cut earlier deformed veins, are themselves deformed, and are cut by later veins which are also deformed. They are restricted to the basalt[2] and do not transect the altered rock. The veins are parallel to the cleavage and have fibres perpendicular to it suggesting that the infilling of the major veins, which was a multistage process, began after the stress perpendicular to the cleavage changed from the greatest stress to the least stress.

Introduction

This paper accompanies the study of P.J. MacGeehan and C.J. Hodgson (this volume) and is a preliminary report on the structural aspects of gold mineralization in the Campbell Red Lake and Dickenson mines. We assume that the reader is familiar with the regional setting (Pirie, this volume) and the general geology and rock types within and around the mines (MacGeehan and Hodgson, this volume). This paper focuses on: 1) a description of the structural fabric and vein systems in different rock types, 2) a description of the F, A, South C, and East South C ore zones, and 3) an interpretation of the structures and a discussion of the structural controls of gold mineralization.

Underground work for this study was conducted during the summers of 1978 and 1979 and consisted of detailed mapping, and vein and fracture analyses along some 19,000 feet of drift. We concentrated on the major ore zones on three levels of the Campbell mine but, for purposes of comparison, extended our mapping along strike to various levels of the Dickenson mine (Figure 9-1).

The mines are situated within a vertical to steeply southwest-dipping pile of basic to intermediate volcanic rocks that also includes rhyolites, sedimentary rocks, and various intrusive bodies. The metamorphic grade of these rocks corresponds to the transition between greenschist and amphibolite facies of regional metamorphism (Turner 1968). Whereas the pile as a whole was flattened significantly during deformation, the highly variable structures and complex vein arrays within the pile resulted from a combination of brittle and ductile deformation and were controlled by strong ductility contrasts between different rock types. For a description of the structures and vein systems it is therefore convenient to group the rocks according to their structural style. Although heterogeneous lithologically, the major rock units used by the mine geologists (MacGeehan and Hodgson, this volume) (Figure 9-2) approximately reflect the differences in response to deformation and thus are used in this paper.

Structural Fabrics and Veins in Different Rock Units

1) Basalt Unit

This unit consists of low-grade metamorphic basaltic and andesitic flows with minor interflow sedimentary rocks. It is the host of the major auriferous veins (Figure 9-2). Most of the rocks have a penetrative cleavage which is defined by aligned amphiboles and phyllosilicates (chlorite and biotite), lenticular particles and mineral aggregates (mainly calcite), pressure shadows, and seams of pressure solution residue. The orientation of this cleavage is locally variable but ranges within rather narrow limits, from a strike of 100° to 130° and a dip of 85° to 65° to the southwest (Figures 9-3c, 9-7a). Long axes of flattened pillows and amygdules are parallel to this cleavage. Locally, where two cleavages can be recognized, the more penetrative fabric is generally the earlier one (Figure 9-3a). The somewhat wider spaced, second fabric is defined by streaks of chlorite and seams of pressure solution residue. It is also steep and its strike varies between 120° and 140° (Figure 9-3b). Corresponding to the small angle of intersection, the earlier cleavage is rarely crenulated, and the age relationships between the two planar fabrics

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[2] All the rocks in the area have been metamorphosed, therefore the prefix 'meta' will not be used.

may be difficult to recognize. As the two cleavages are relatively similar, it generally cannot be decided whether a single cleavage in a rock corresponds to the first or second cleavage (Figure 9-3c). Thin section studies of garnet-bearing interflow sedimentary rocks in the Dickenson mine show that garnets which have overgrown an early fabric, are deformed and boudinaged along a penetration fabric parallel to the inclusion fabric. Lineations are not common and their steep plunge suggests that they result from the intersection of the two planar fabrics.

Major fold structures have not been recognized in the volcanic rocks of the Campbell mine. However, interflow iron formation in the Dickenson mine outlines tight folds (Figure 9-4) with axial planes parallel to the penetrative cleavage (Figure 9-4b) and moderate to steep westerly plunges (Figure 9-4c) (Jarvis 1965).

A key to the understanding of the structural controls of the gold mineralization is the unraveling of the complex vein patterns. Detailed mapping has shown that locally within the basalt, and in rocks transitional in character between basalt and the altered rock, definite veining successions may be recognized. However, extensive flattening has normally obliterated many of the crucial crosscutting relationships within most of the unit, making a detailed correlation of vein generations from place to place impossible.

An example between the F_1 and F_2 ore zones on 14 level of the Campbell mine (Figure 9-5), where up to eight vein sets were identified on the basis of crosscutting relationships, is illustrated on Table 9-1. The third of these sets is thought to correlate with the major F vein, indicating that the through-going major gold veins cut earlier de-

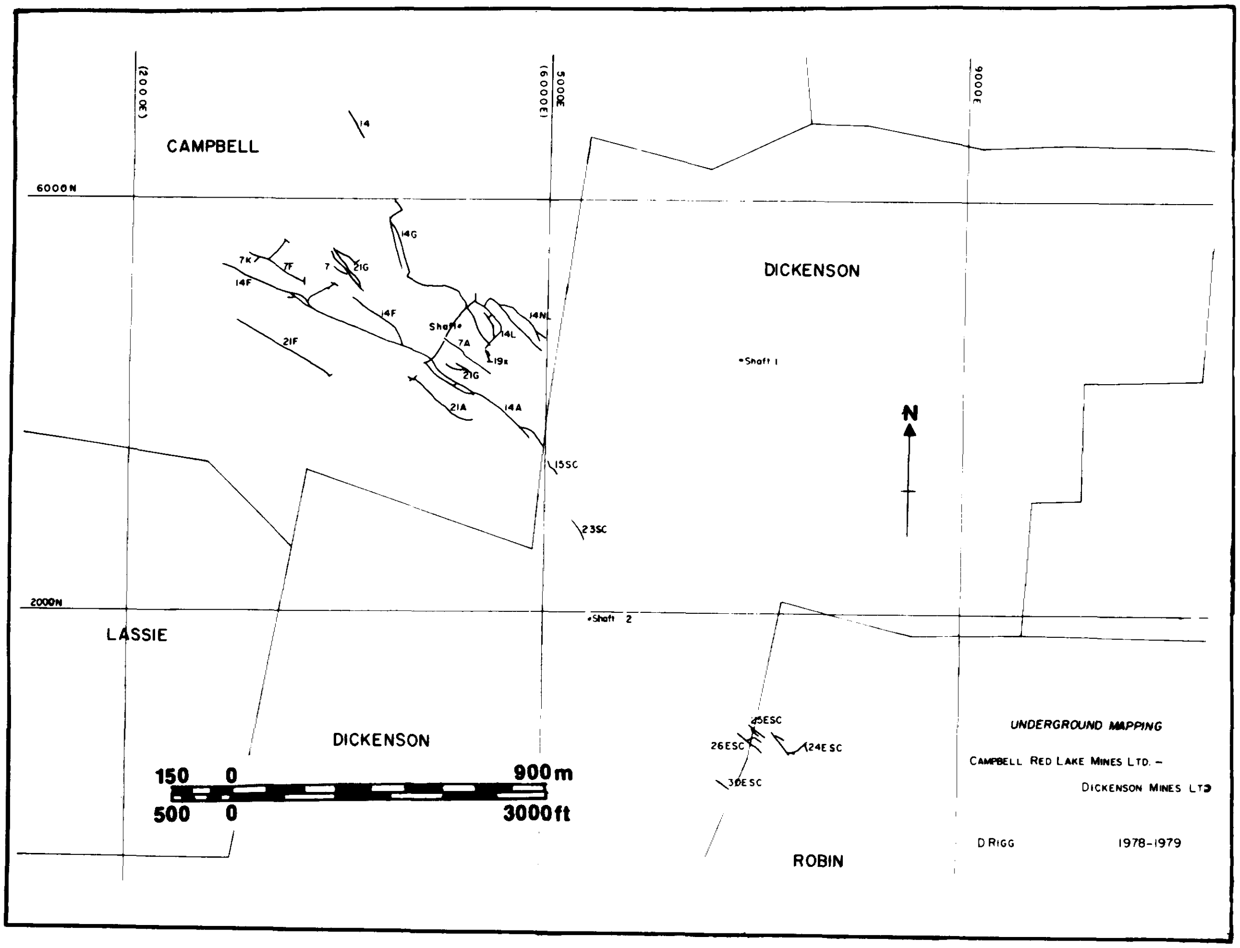


Figure 9-1—Distribution of mine workings mapped by D.M. Rigg in 1978 and 1979. Level numbers and ore zones are shown where applicable. Symbols of ore zones of a) Campbell Red Lake Mine (**CRLM**):**F** = F zone, **A** = A zone, **L** = L zone, **NL** = North L zones, **G** = G zone, **K** = K zone, **x** = veinlet zone.
b) Dickenson mine (DM): **SC** = South 'Campbell' zone, **ESC** = East South 'Campbell' zone.

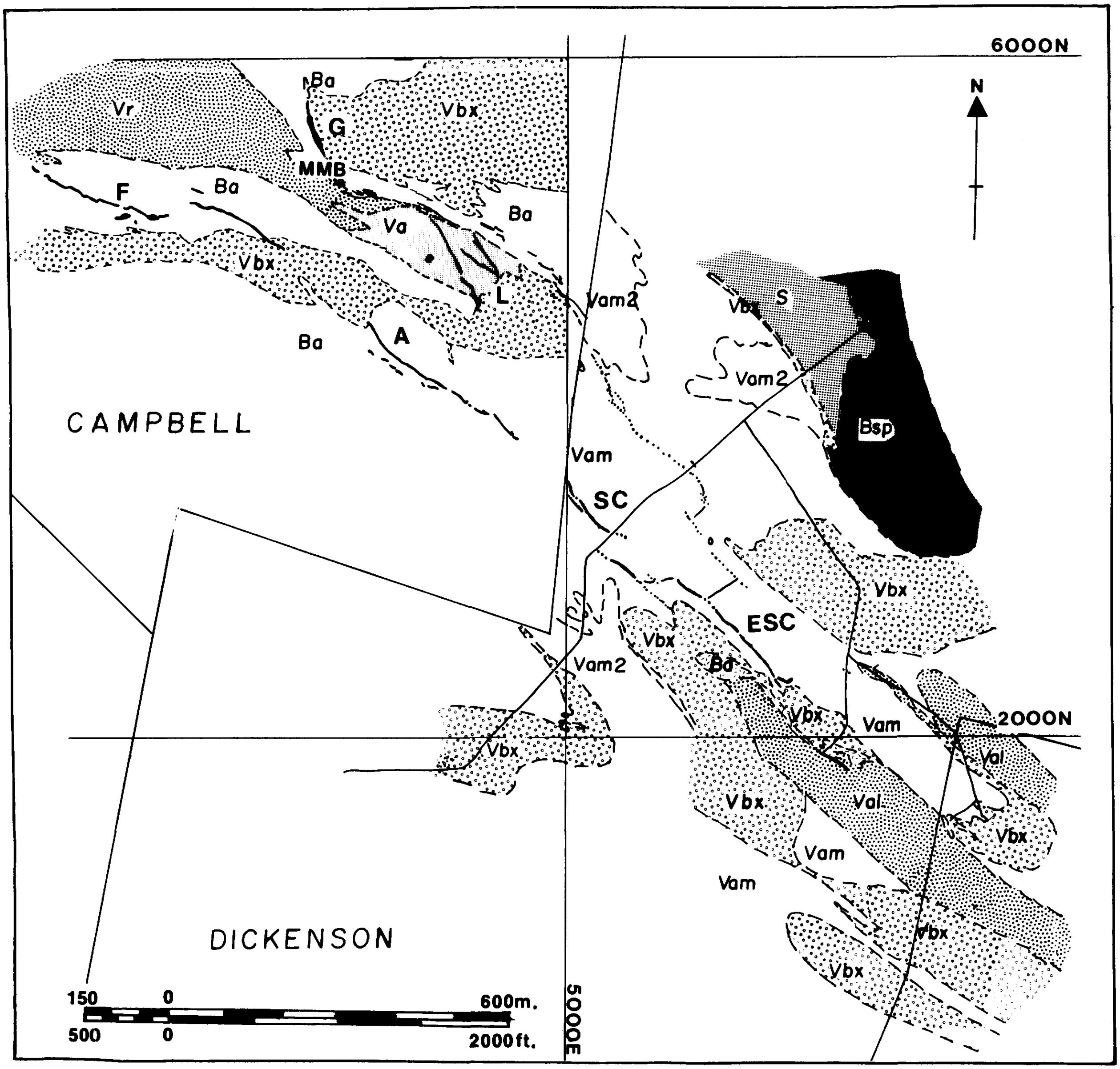


Figure 9-2—Geology compilation map of 14 level ***CRLM*** *and 15 level,* ***DM****. In the* ***CRLM*** *the outline of the ore zones (black) and geology of the underground workings are from mapping by P. MacGeeham and D. Rigg, and strike continuations are from drill core logging and interpretation by members of the* ***CRLM*** *Geology Department. In the* ***DM*** *the outline of the ore zones and geology is taken from drill core logging and underground mapping by members of the* ***DM*** *Geology Department, and from a map compiled by Derry, Michener and Booth (Private company report to* ***DM****, 1977).*

*Symbols for geology of a)****CRLM****:* ***Ba*** *= basalt undifferentiated* ***Va*** *= variolitic andesite,* ***Vr*** *= rhyolite,* ***Vbx*** *= 'Altered rock' (see text),* ***MMB*** *= metasediment mobile belt.*

b) ***DM****:* ***Vam 2*** *= medium-grained 'andesite' including Campbell 'diorite',* ***Vam*** *= fine-grained 'andesite',* ***Bd*** *= diorite,* ***Val*** *= acid lava,* ***Bsp*** *= serpentinite,* ***Vbx*** *= 'chicken feed' (≅ Altered rock'),* ***S*** *= sediments. Symbols for ore zones, see Figure 9-1.*

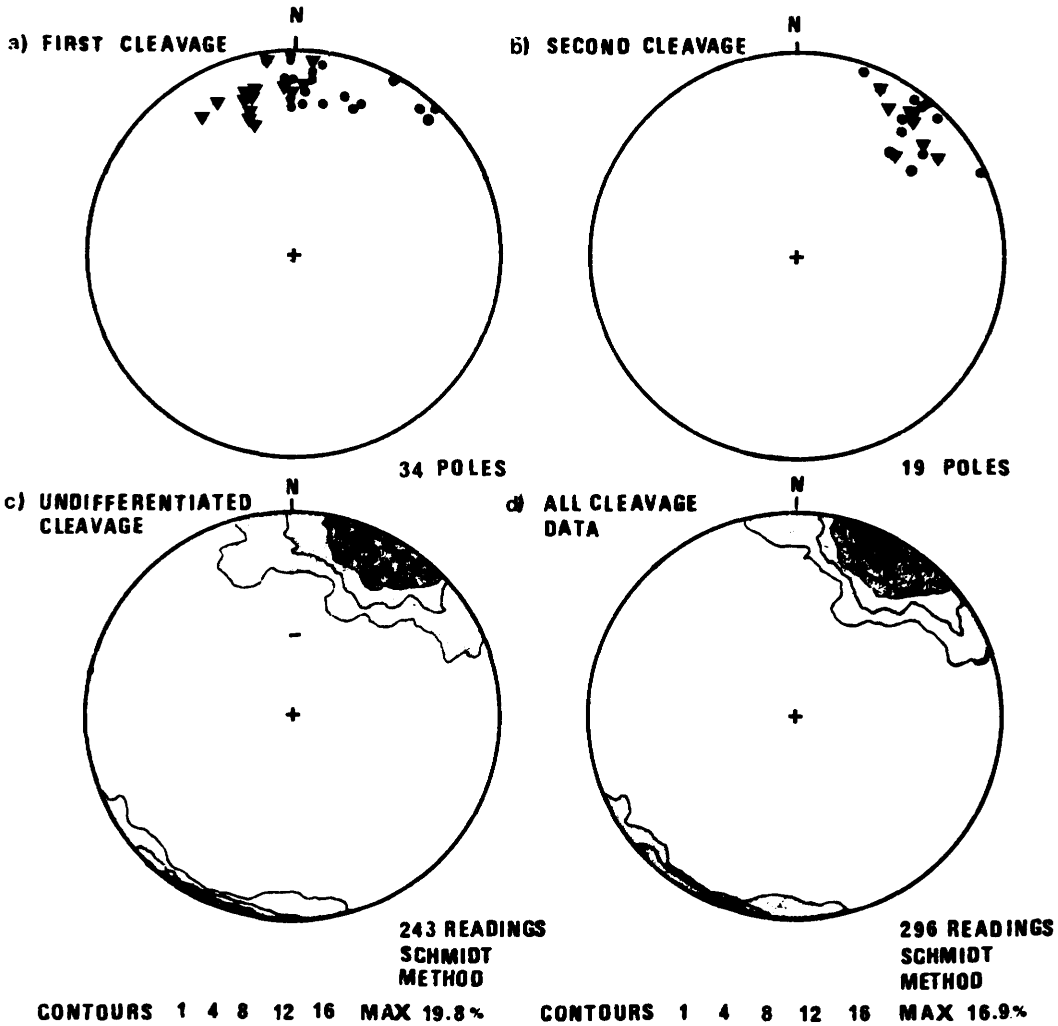
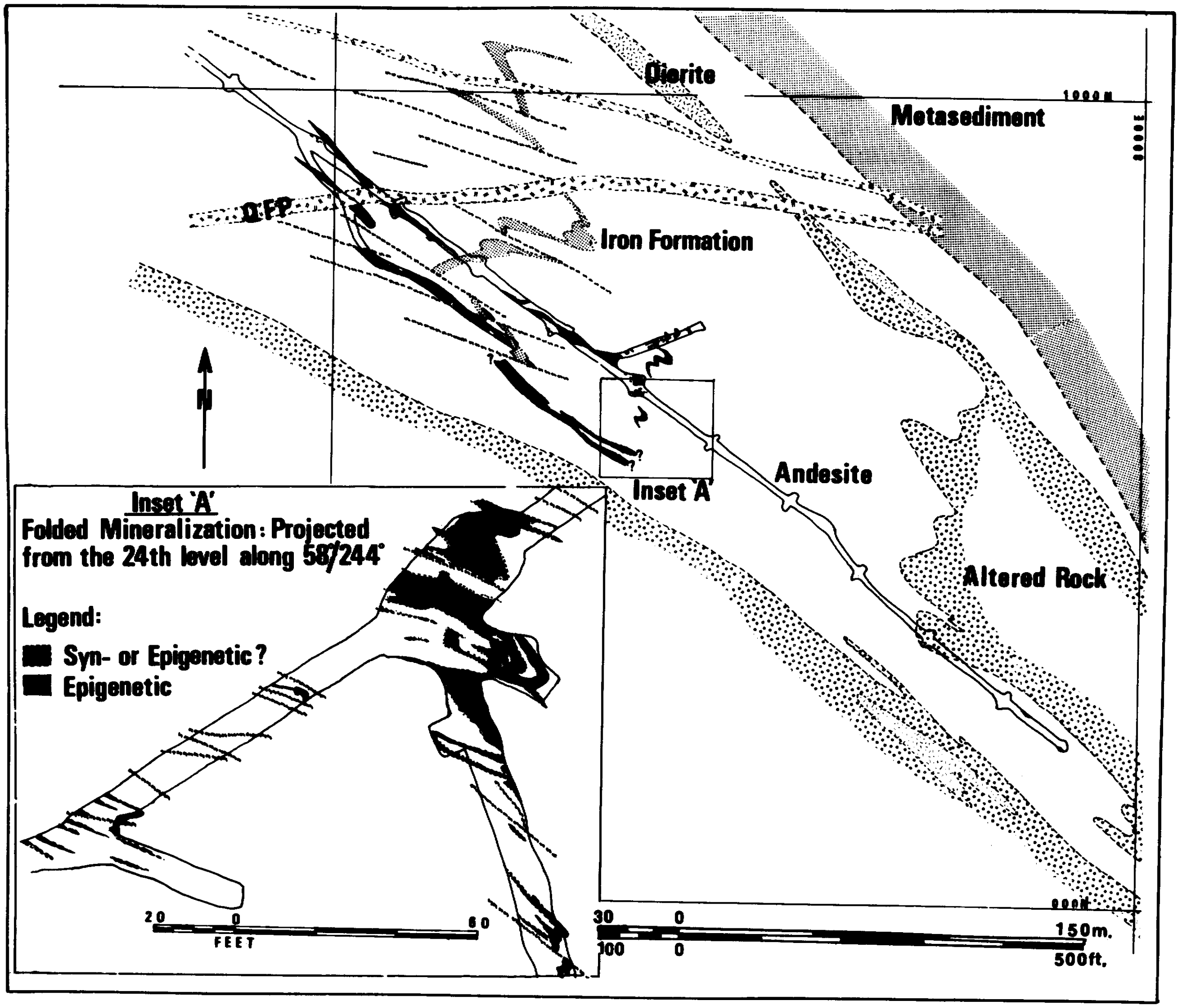


Figure 9-3—Lower hemisphere, equal area projections of all cleavages measured on the 14 and 21 levels, ***CRLM*** *(triangles = cleavage in altered rock; dots = cleavage in basalt).*



b) CLEAVAGE

c) I. F. FOLD AXES

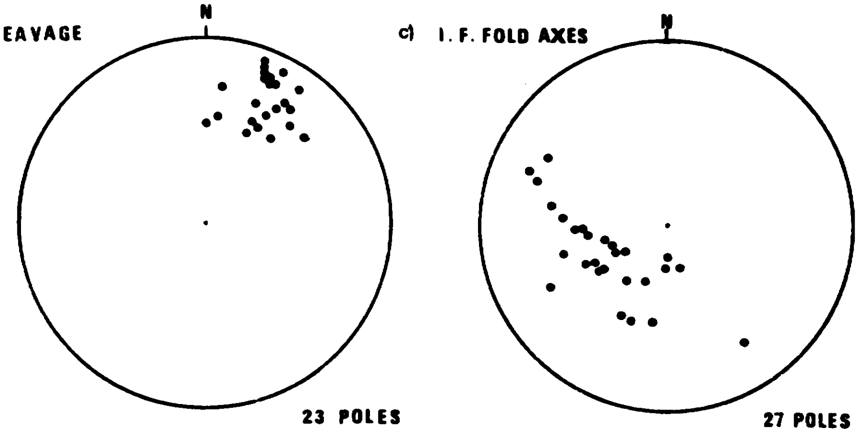


Figure 9-4—Map of the East South 'C' zone on 25 level, Dickenson mine, after mine maps and mapping by D. Rigg in 1979. The distribution of the iron formation is based on drill intersections on the level and on the down- and up-plunge projection of data from adjacent levels. Inset A shows the down-plunge projection of the folded structure from 24 to 25 level.

b, c: Lower hemisphere equal area projections of data measured on 23 to 26, and 30 levels:

b) Cleavage in mafic flow adjacent to the iron formation;

c) Fold axes and cleavage/bedding intersections of the iron formation.

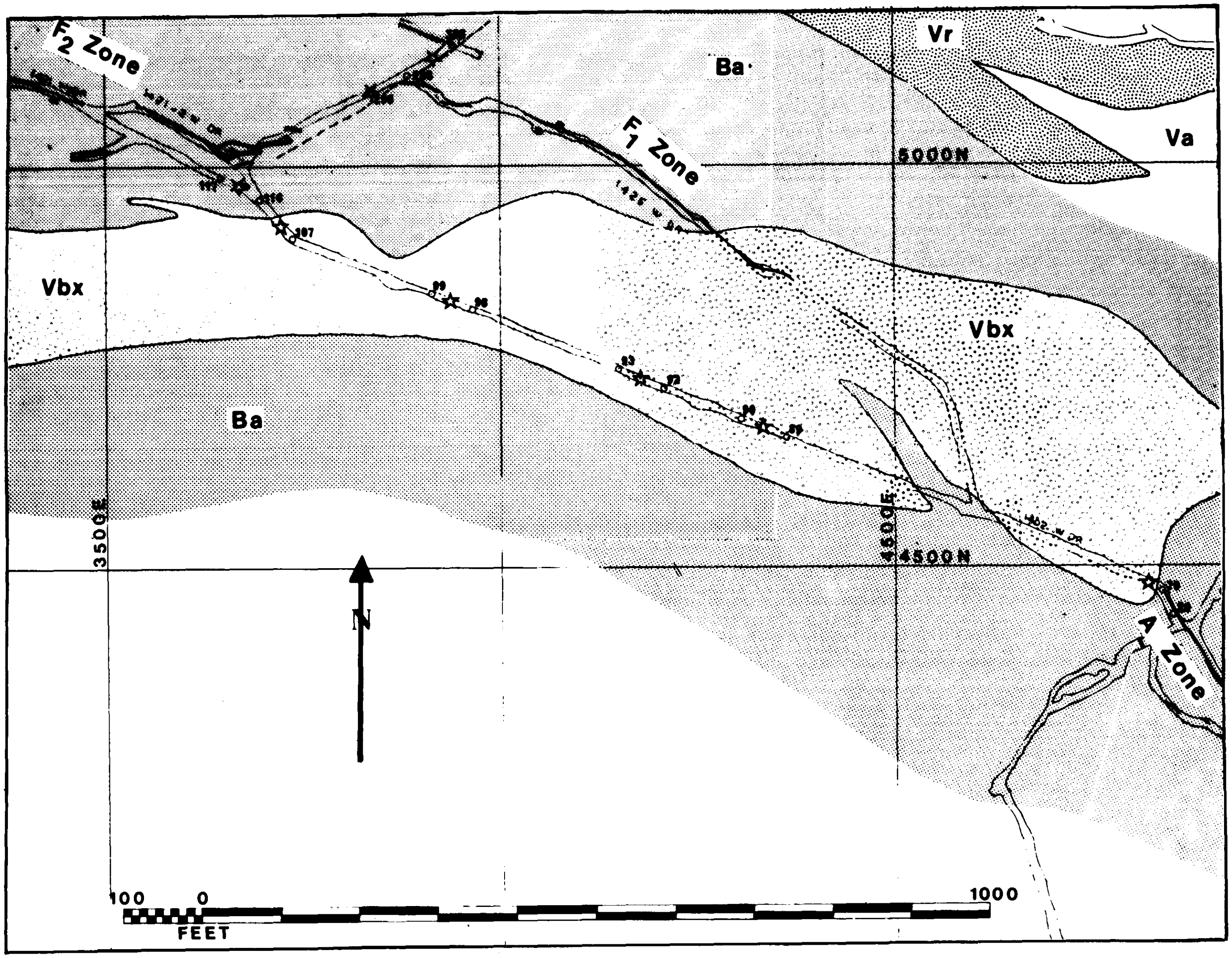
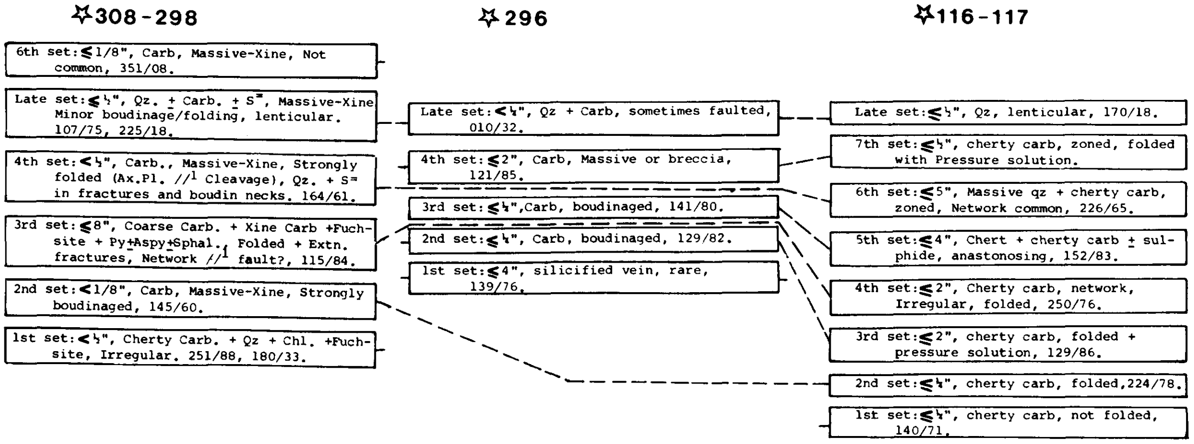


Figure 9-5—Map of the central altered rock unit between the A and F_1-F_2 ore zones, 14 level **CRLM**. Location map for Table 1 and Table 2. See Figure 9-2 for symbols for geology. Downturned open stars = fracture analyses on Table 1. Upturned opened stars = fracture analyses on Table 2. Dashed line separating the F_1 and F_2 ore zones = major fault (140 foot horizontal separation).

Table 9-1 *Vein sequences within areas in the basalt (Figure 9-5) which are transitional in character between basalt and altered rock (see text). Dashed lines = tentative correlation of sequences.*



☆308-298

6th set: ≤1/8", Carb, Massive-Xine, Not common, 351/08.

Late set: ≤½", Qz. ± Carb. ± S=, Massive-Xine Minor boudinage/folding, lenticular. 107/75, 225/18.

4th set: <½", Carb., Massive-Xine, Strongly folded (Ax.Pl. //¹ Cleavage), Qz. + S= in fractures and boudin necks. 164/61.

3rd set: ≤8", Coarse Carb. + Xine Carb +Fuchsite + Py±Aspy±Sphal., Folded + Extn. fractures, Network //¹ fault?, 115/84.

2nd set: <1/8", Carb, Massive-Xine, Strongly boudinaged, 145/60.

1st set: <½", Cherty Carb. + Qz + Chl. +Fuchsite, Irregular. 251/88, 180/33.

☆296

Late set: <½", Qz + Carb, sometimes faulted, 010/32.

4th set: ≤2", Carb, Massive or breccia, 121/85.

3rd set: ≤½", Carb, boudinaged, 141/80.

2nd set: ≤½", Carb, boudinaged, 129/82.

1st set: ≤4", silicified vein, rare, 139/76.

☆116-117

Late set: ≤½", Qz, lenticular, 170/18.

7th set: ≤½", cherty carb, zoned, folded with Pressure solution.

6th set: ≤5", Massive qz + cherty carb, zoned, Network common, 226/65.

5th set: ≤4", Chert + cherty carb ± sulphide, anastonosing, 152/83.

4th set: ≤2", Cherty carb, network, Irregular, folded, 250/76.

3rd set: ≤2", cherty carb, folded + pressure solution, 129/86.

2nd set: ≤½", cherty carb, folded, 224/78.

1st set: ≤½", cherty carb, not folded, 140/71.

formed veins and are cut by later veins which are also deformed. Most of the vein material is carbonate (ferroan dolomite to ankerite), but quartz and sulphides (pyrite-pyrrhotite ± sphalerite ± chalcopyrite ± arsenopyrite) may be locally abundant. Vein fillings may be fibrous, banded, or massive. Most veins are highly deformed and, depending on their initial orientation with respect to cleavage, are folded, boudinaged, or both (Figure 9-6). Earlier veins are more deformed than later veins. Primary textures were modified or obliterated by deformation which led to extensive remobilization of quartz, carbonates, sulphides, and gold. The orientation of the veins predating the "late set" (Table 9-1, Figure 9-7e) is similar to that of the cleavage (Figures 9-7a, 9-7b). This preferred orientation is the result of 1) rotation of veins formed at an angle to cleavage towards the flattening plane, and 2) formation of veins parallel to the orientation of the cleavage. The problem of distinguishing between the two is discussed below in the section on "Interpretation of Structures and Relationships Between Mineralization, Veins, and Structures".

The youngest regionally developed vein set, the "late set", consists of shallow-dipping lenticular, veins up to 1 inch thick. They are mainly of massive milky quartz with some carbonate and pyrite and are generally undeformed, but locally may record a vertical fabric and/or slight folding related to northeast-southwest shortening.

'Early' faults are represented by thin zones of chlorite ± tourmaline ("Black line faults" in the mine terminology) or carbonate breccia. Being generally more or less parallel to the cleavage (Figure 9-7c), they are closely spaced and have small displacements (one foot or less). In the East South 'Campbell' zone (ESC) of the Dickenson mine some faults parallel to the cleavage have larger offsets (Figure 9-4). A consistent sense of displacement was not observed which, together with the variation in sense of asymmetry of folded veins (Figure 9-6), is compatible with transposition during flattening normal to the cleavage rather than with overall shear. Most 'late' faults are oblique to cleavage and cause small offsets (up to 30 feet) of the ore zones. Some 'late' faults may also be parallel to cleavage.

Altered Rock Unit

This unit cuts across the stratigraphic layering of the supracrustal rocks (Figure 9-2) and consists of altered ultramafic and/or mafic intrusive rocks together with an envelope of altered rhyolite, basic volcanic rock, and sedimentary rocks. Due to extensive carbonatization, chloritization, and silicification, the primary nature of the rocks is very difficult to recognize (MacGeehan and Hodgson, this volume). Although talc-rich parts may be extremely incompetent, the unit as a whole was much more competent during deformation than the basalt. With a few exceptions, the major gold-bearing veins in the basalt generally terminate against the contact of the altered rock, but the unit may host silicic gold mineralization near its contacts.

Cleavage is only locally developed (generally close to the margins) and wider spaced than in the basalt. It is defined by seams of pressure solution residue, chlorite streaks, and microdomains of carbonate. Where one cleavage is present, the strike ranges from 100° to 130° (Figure 9-3c). Where two cleavages were recognized, the first is somewhat refracted with respect to the first cleavage and strikes approximately east-west (Figure 9-3a). The second cleavage has an orientation similar to that in the basalt (Figure 9-3b). Pillows and polygonal sutures

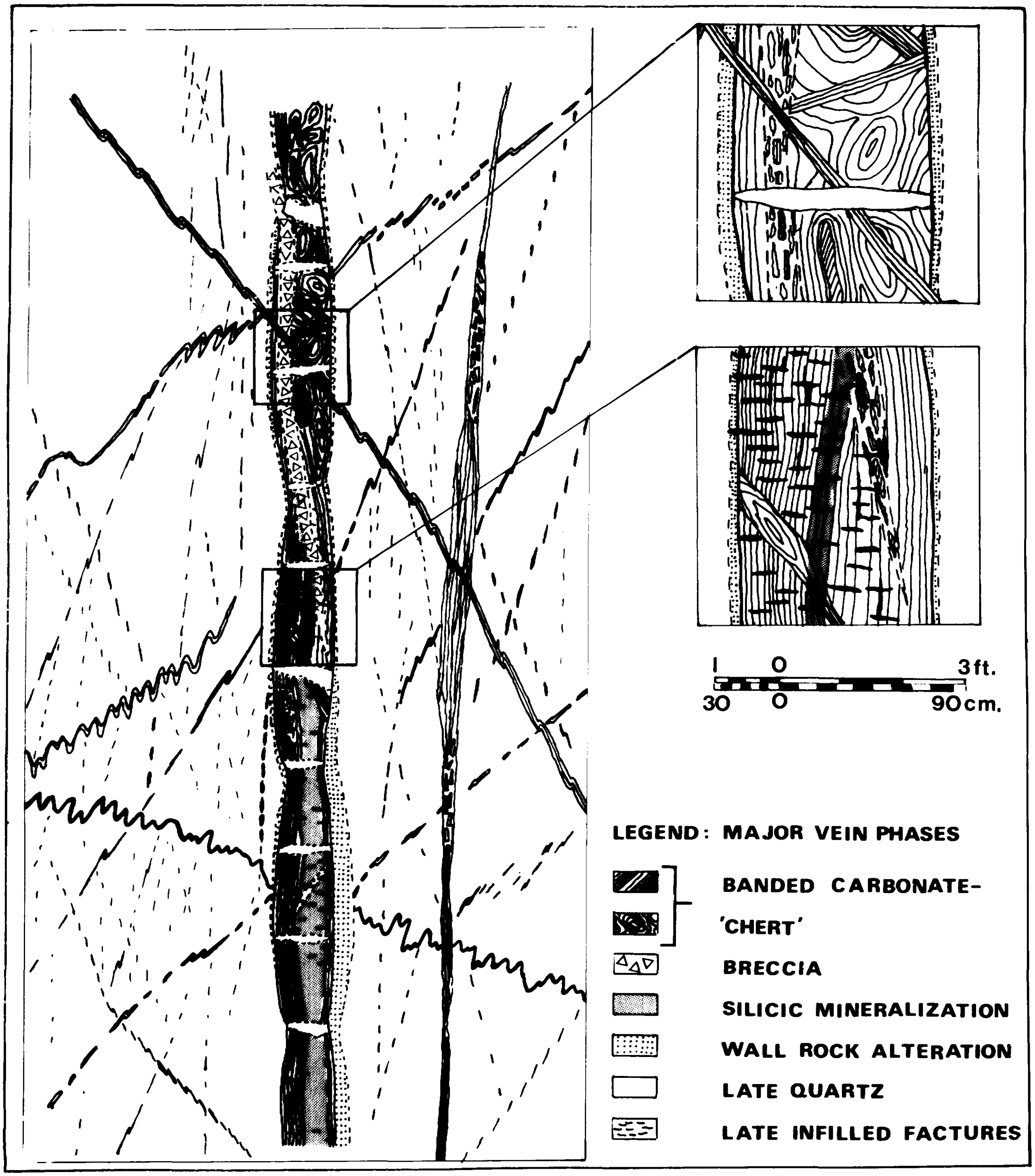


Figure 9-6—Schematic representation of the geological features within and around complex veins such as the F_2, F_1, A, and South 'C' orebodies in ***CRLM*** *and* ***DM****.*

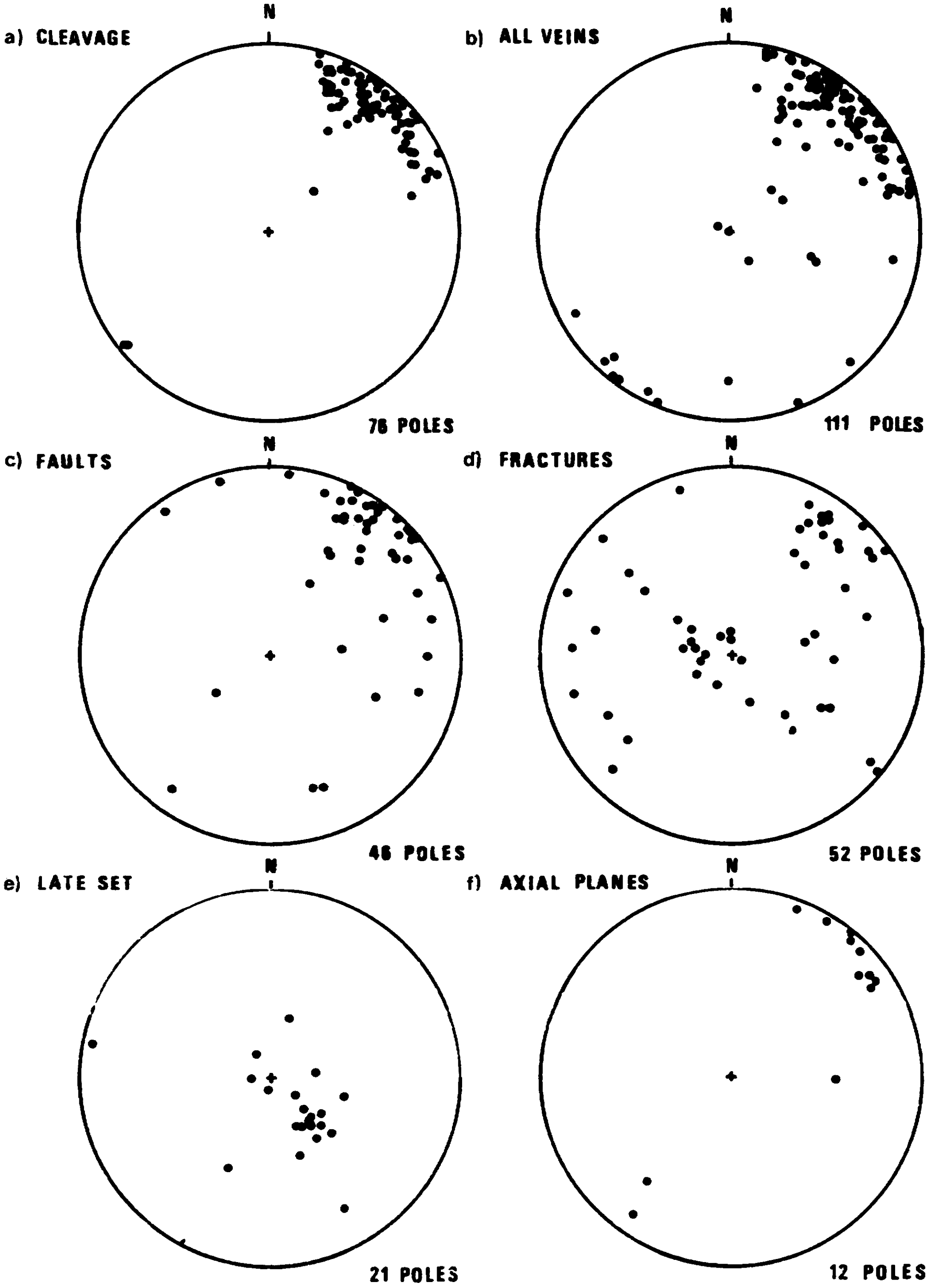


Figure 9-7—Lower hemisphere, equal area projections of fabric elements in basalt in the vicinity of the A zone, 14 level, ***CRLM****.*

are rarely deformed indicating little overall flattening within this unit. Zones of local schistosity may be developed in incompetent rocks and in shear zones.

Veining is extremely complex in this unit and many vein generations can be recognized. Although significant flattening is absent, however, it is possible to correlate certain vein sets from place to place. An example of this is shown on Table 9-2. The oldest regular set (in some places this set is preceded by thin irregular chlorite-carbonate veins), the 'chlorite set', is filled with fibrous chlorite ± carbonate, carbonate ± chlorite, or carbonate ± quartz depending on whether it is developed in chloritized, carbonatized, or silicified rocks respectively. The veins form stockworks or, if cleavage is present, sheeted veinlet zones parallel with the first cleavage (Figure 9-8). These veinlet zones are up to 20 feet wide, and vein material within the zones may constitute up to 60 percent of the total rock volume. Fibre orientation in these cleavage-parallel veins is perpendicular to the cleavage. A 'cherty set' (Table 9-2) appears to postdate the sheeted veins, although this age relationship is uncertain, since the two sets do not commonly occur together. The cherty set consists of irregular veins of cherty quartz with carbonate and minor amounts of chlorite and fuchsite that form interlocking networks (up to 2 feet in diameter) which are sometimes arranged in 15-foot wide zones approximately parallel to bedding. Locally the cherty veins give the impression of silicified interstices of pillows. Four to six additional vein sets can locally be identified on the basis of crosscutting relationships, variations in composition, internal structure, and orientation (Table 9-2). Veins of these generations are filled mainly by carbonate with some quartz and sulphide. They may be uniformly massive, or banded, fibrous or fine- to coarse-crystalline. The sets vary from regularly spaced, distinct veins to diffuse, breccia-like veins. Lateral and vertical variations in composition and internal structure of individual vein sets may be extreme and make correlations, as proposed on Table 9-2, somewhat tentative.

The youngest vein set is similar in nature and orientation to the "late set" in the basalt (Table 9-2, Figure 9-9d).

Although many veins, especially the older sets, are deformed, penetrative strain in the altered rocks is low, and large-scale rotation and transposition of veins, as in the basalt, did not occur. This is reflected in the high degree of dispersion on the orientation diagram of all veins (Figure 9-9a). Sheeted quartz-chlorite veins (Figure 9-9b) have a strong preferred orientation parallel to the cleavage. In several localities it can be seen that these veins are aligned parallel to the cleavage, have fibres which are perpendicular to the cleavage, and are overprinted by the second cleavage. Although strongly dispersed in orientation, many of the quartz-carbonate veins (Figure 9-9c) also cluster near the cleavage maximum (Figure 9-3c). As the low degree of penetrative strain makes it unlikely that many veins rotated into this position, it must be concluded that many veins formed approximately parallel to the cleavage. The fact that the 'late set' in the altered rock unit is similar in nature and orientation to the 'late set' in the basalt (Figure 9-7e) indicates diminished ductility contrast during this late fracturing event.

Faults, generally represented by chlorite ± tourmaline or carbonate ± quartz breccia, have variable orientations (Figure 9-10a). They are wider spaced and have generally larger displacements than faults in the basalt. Some have juxtaposed rocks of different alteration type. Faulting and vein formation occurred concurrently because successive vein sets have progressively smaller displacements, and some veins clearly cut across earlier faults. In the 2104 and 2102 drifts of the Campbell mine (Figure 9-8), faults which are parallel to the early east-west cleavage can be traced from the altered rock into the basalt where they refract into the 100°-120° cleavage and branch into many subparallel faults with smaller displacements. Eventually they become difficult to trace.

Talc-rich rocks within the altered rock have strong cleavage and numerous veins which are deformed to such a degree that no systematic pattern can be recognized.

Rhyolite

Original contact relationships between massive rhyolite and basalt in the western part of the Campbell mine have generally been obliterated by faulting and shearing. The rhyolite is criss-crossed by numerous irregular, chlorite-filled fractures, and the major vein sets do not continue into it. Instead, a few quartz-chlorite ± carbonate veins, some of which may be gold-bearing, occur near the contacts.

Sedimentary Rocks

In the Campbell mine, strongly folded sedimentary rocks (iron formation) occur in a "mobile zone" near the G zone (Figure 9-2) between two blocks of more competent rocks. Plunges of these folds are steep and the axial planes parallel the dominant cleavage. Thin bands of sedimentary rocks have been recognized along some rhyolite contacts in the western part of the Campbell mine and between flows within the basalt.

In the Dickenson mine interflow sedimentary rocks are more common within the basalt. Some form excellent marker horizons which outline major and minor folds with northwest-southeast-trending axial surfaces and moderate to steep westward plunges.

A major package of sedimentary rocks lies northeast of the Campbell mine and is penetrated by the No. 1 Shaft of the Dickenson mine (Figure 9-2). Surface mapping (MacGeehan and Hodgson, this volume) shows that these rocks are intensely deformed. An early cleavage, axial planar to large folds which have effected the bedding, is folded on southwest-trending axial surfaces. In the Dickenson mine these rocks are folded with axial planes parallel to the southeast-trending major cleavage, but without detailed mapping it cannot be decided whether fold interference patterns also exist underground. Significant vein systems have so far not been recognized within these sedimentary rocks.

Dikes

Numerous mafic and quartz-feldspar porphyry dikes cut across the major ore zones and are believed to postdate the mineralization. Crosscutting relationships suggest the existence of several 'sets' of mafic dikes which were intruded along major fracture systems (Figure 9-10b). They show various degrees of deformation including a penetrative vertical fabric and brecciation associated with faulting.

Description of Ore Zones

Economic gold mineralization in both mines is restricted to the basalt and to the contact areas between basalt and altered rock. A number of major auriferous veins form a northwest-southeast-trending system of ore zones, i.e. F and A zones in the Campbell mine and the South Campbell (SC) and the East South Campbell (ESC) zones in the Dickenson mine. This system cuts the stratigraphic sequence of the supracrustal rocks but does not transect the central unit of altered rock (Figure 9-2). Although two major types of mineralization (layered carbonate-chert and replacement-type silicification, see MacGeehan and Hodgson, this volume) have been distinguished, the elongate ore zones are a complex mixture of the two. In addition, deformation may have caused remobilization of gold. Replacement-type silicification is especially common near the contact of the altered rock and locally within the altered rock. In this paper the F, A, SC, and the ESC zones are described as well as an occurrence of replacement-type silicification in altered rock in the 2104 stope in the Campbell mine. For a description of the more complex G zone see MacGeehan and Hodgson (this volume).

F, A, and SC Zones

As seen on Figures 9-2 and 9-5, the F zone is situated in the basalt and extends from the rhyolite contact in the west to the central zone of altered rock in the east. Although it extends into the altered rock for distances of up to 100 feet, the ore zone does not traverse the altered rock. The A and SC zones continue to the southeast of the

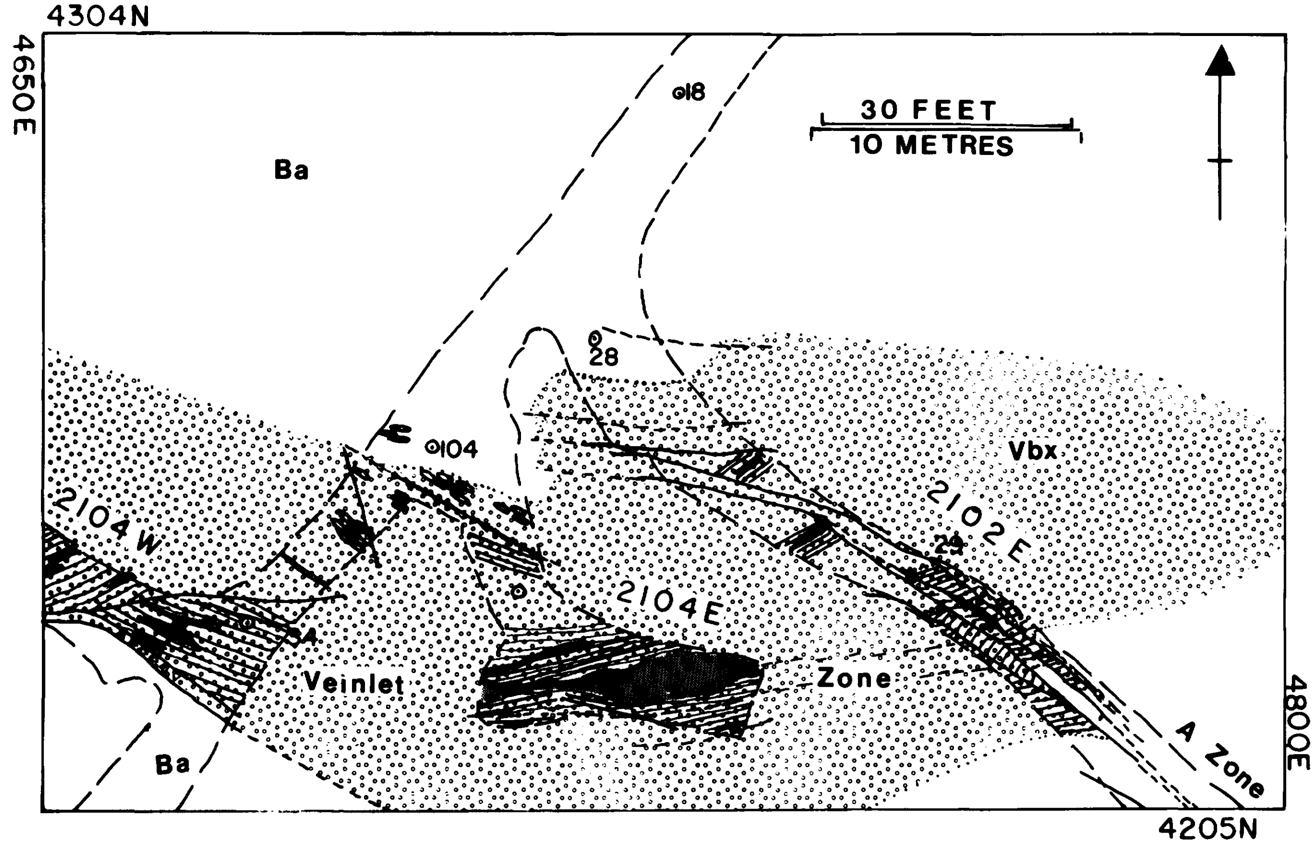
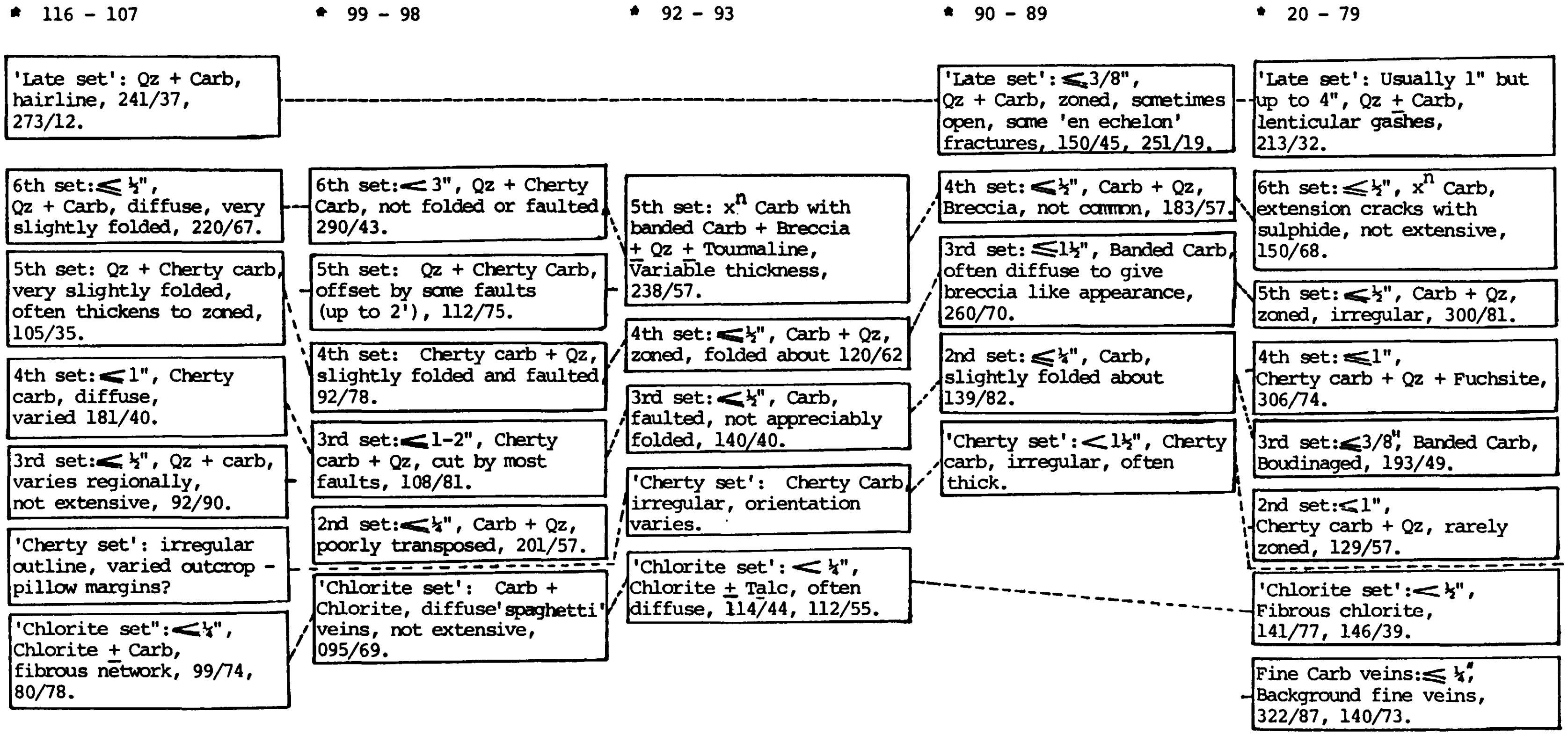


*Figure 9-8—Map of the 2104 drift, situated at the central altered rock unit - A zone intersection on the 21 level **CRLM**. Shaded area = silicified and mineralized pods and veins within the altered rock veinlet zone: ellipses = pillows in basalt or altered rock. See Figure 9-2 for symbols for geology.*

TABLE 9-2 | VEIN SEQUENCES IN THE CENTRAL ALTERED ROCK UNIT BETWEEN THE A AND F_2 ZONE 14 LEVEL **CRLM** (FIGURE 9-5).
DASHED LINES = TENTATIVE CORRELATION.



◆ 116 - 107

'Late set': Qz + Carb, hairline, 241/37, 273/12.

6th set: ≤ ½", Qz + Carb, diffuse, very slightly folded, 220/67.

5th set: Qz + Cherty carb, very slightly folded, often thickens to zoned, 105/35.

4th set: ≤ 1", Cherty carb, diffuse, varied 181/40.

3rd set: ≤ ½", Qz + carb, varies regionally, not extensive, 92/90.

'Cherty set': irregular outline, varied outcrop - pillow margins?

'Chlorite set": ≤ ¼", Chlorite ± Carb, fibrous network, 99/74, 80/78.

◆ 99 - 98

6th set: ≤ 3", Qz + Cherty Carb, not folded or faulted, 290/43.

5th set: Qz + Cherty Carb, offset by some faults (up to 2'), 112/75.

4th set: Cherty carb + Qz, slightly folded and faulted, 92/78.

3rd set: ≤ 1-2", Cherty carb + Qz, cut by most faults, 108/81.

2nd set: ≤ ¼", Carb + Qz, poorly transposed, 201/57.

'Chlorite set': Carb + Chlorite, diffuse 'spaghetti' veins, not extensive, 095/69.

◆ 92 - 93

5th set: x^n Carb with banded Carb + Breccia ± Qz + Tourmaline, Variable thickness, 238/57.

4th set: ≤ ½", Carb + Qz, zoned, folded about 120/62

3rd set: ≤ ½", Carb, faulted, not appreciably folded, 140/40.

'Cherty set': Cherty Carb, irregular, orientation varies.

'Chlorite set': < ¼", Chlorite ± Talc, often diffuse, 114/44, 112/55.

◆ 90 - 89

'Late set': ≤ 3/8", Qz + Carb, zoned, sometimes open, some 'en echelon' fractures, 150/45, 251/19.

4th set: ≤ ½", Carb + Qz, Breccia, not common, 183/57.

3rd set: ≤ 1½", Banded Carb, often diffuse to give breccia like appearance, 260/70.

2nd set: ≤ ¼", Carb, slightly folded about 139/82.

'Cherty set': < 1½", Cherty carb, irregular, often thick.

◆ 20 - 79

'Late set': Usually 1" but up to 4", Qz ± Carb, lenticular gashes, 213/32.

6th set: ≤ ½", x^n Carb, extension cracks with sulphide, not extensive, 150/68.

5th set: ≤ ½", Carb + Qz, zoned, irregular, 300/81.

4th set: ≤ 1", Cherty carb + Qz + Fuchsite, 306/74.

3rd set: ≤ 3/8", Banded Carb, Boudinaged, 193/49.

2nd set: ≤ 1", Cherty carb + Qz, rarely zoned, 129/57.

'Chlorite set': < ½", Fibrous chlorite, 141/77, 146/39.

Fine Carb veins: ≤ ¼", Background fine veins, 322/87, 140/73.

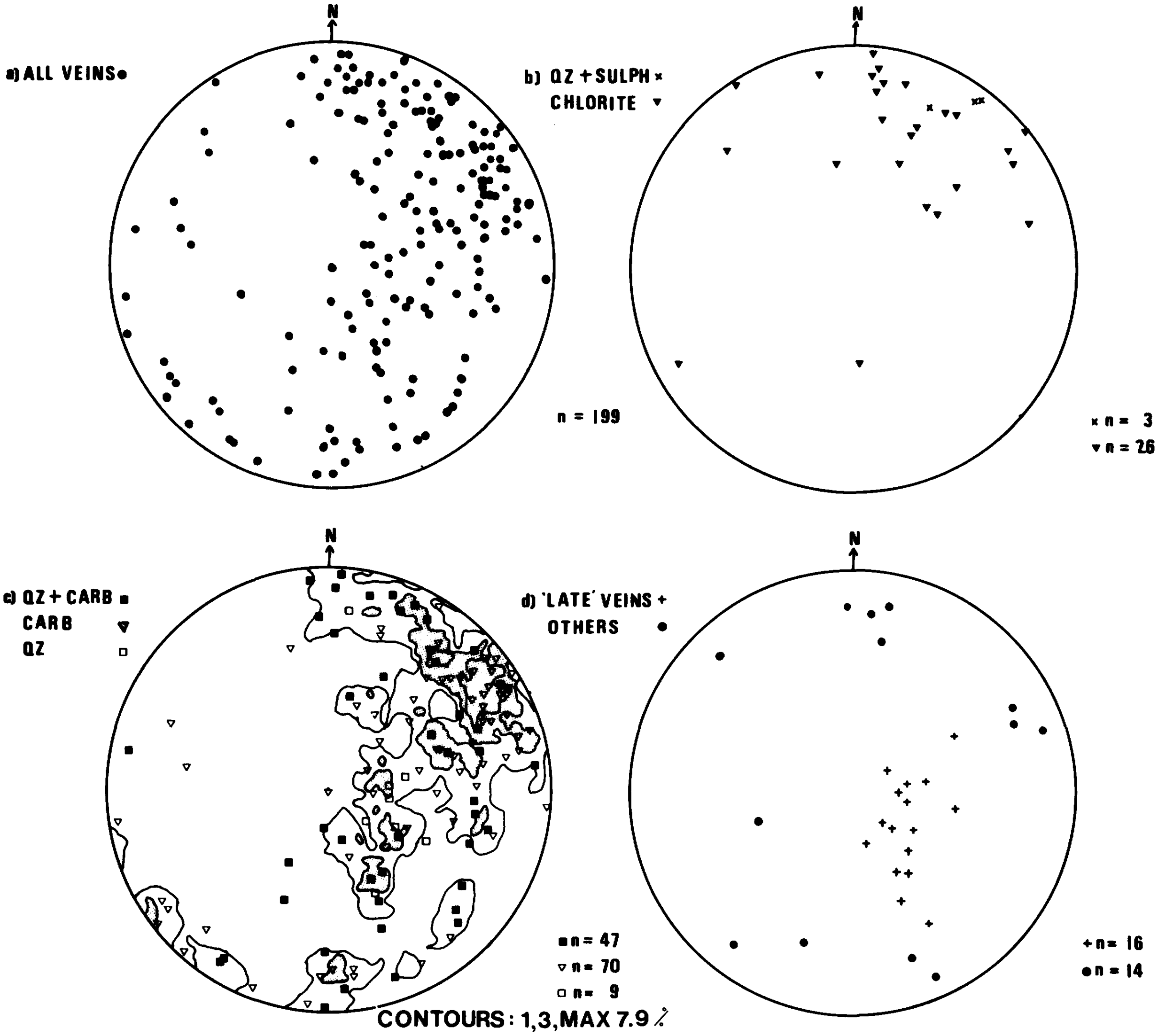


Figure 9-9—Lower hemisphere, equal area projections of veins in the central altered rock unit between th A and F_1-F_2 zones, 14 level ***CRLM****.*

a) all mapped veins, b) veins infilled with quartz and sulphides (major F_1 veins) or chlorite, c) veins infilled with either quartz or carbonate, or a combination of quartz and carbonate. Contoured using Schmidt method. d) veins classified as the 'late set' (see text) and veins infilled with a combination of minerals which do not fall into b or c.

altered rock (along strike with the F_2 zone) and trend towards the ESC zone but may not be linked with the latter. Penetration of the altered rock by the A zone is minimal, but replacement-type silicification may occur along strike in the altered rock.

The zones are one or more parallel, complex veins ranging in thickness from 6 inches to 3 feet. They are parallel to the local cleavage, are generally not folded, but may be strongly boudinaged. Veins are folded only where the ore zones are oblique to cleavage. This occurs at the jog between the F_1 and F_2 zones (Figures 9-2 and 9-5, Table 9-1), and at the K zone which is oblique to cleavage and is cut by the F zone.

Although the ore veins show strong lateral variations, several stages of infilling can be identified in most veins (Table 9-3). Not all stages may be recognized at any one locality. Most infilling stages appear to be related to opening of the veins parallel to the cleavage. Many of the non-systematic variations, especially the distribution of breccia and the width of the silicified zones are undoubtedly related to the mineralization process. Others, like the development of 'ladder' structures, the deformation of breccia, and the remobilization of gold are related to post-mineralization deformation. Because of this strong deformation and overprint it is difficult to distinguish whether the various infilling stages (Table 9-3) were interrupted by flattening, or whether all deformation textures are caused by post-infilling deformation.

Faults oblique to or almost parallel to the foliation have resulted in small horizontal separations of the ore zone (up to 30 feet). On 14 level, a major fault with horizontal separation of approximately 140 feet divides the F zone into the F_1 and F_2 zones. Folds in the adjacent F_2 zone, however, predate this fault and are related to shortening of a part of the F zone which formed oblique to cleavage.

ESC Zone

This zone lies within basalt in the eastern part of the Dickenson mine (Figure 9-2) along strike with the A and SC zones. The major part of this zone crosscuts the stratigraphic sequence (Figure 9-4) and consists of disseminated pyrite, pyrrhotite, and arsenopyrite mineralization with some silicification. Major veins do not occur in this zone, unlike the F, A, and SC zones. Earlier deformed carbonate veins are replaced by various amounts of sulphides and cherty quartz. The entire zone is affected by strong post-mineralization deformation. Where the ESC zone cuts the iron formation (Figure 9-4), gold values in the iron formation appear to be locally enriched.

At the eastern end of the ESC zone mineralization is stratiform and follows folded interflow sedimentary rock and tuff. As this part is slightly richer in gold than the rest of the ESC zone, it is possible that epigenetic mineraliza-

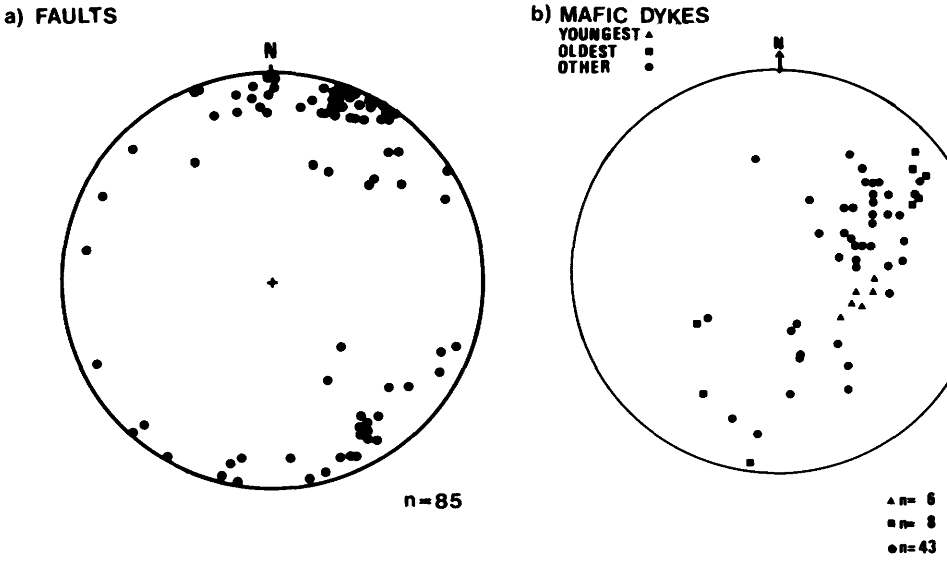


Figure 9-10—Lower hemisphere equal area projections of:
a) Faults within the central altered rock unit between the A and F_1-F_2 zones, 14 level, ***CRLM****.*
b) Mafic (lamprophyre) dikes from all areas on the 7, 14, and 21 levels, ***CRLM****.*

tion was upgraded here by gold derived from the interflow sedimentary rocks.

Replacement-Type Silicification in Altered Rock

Two areas characterized by this type of mineralization were mapped on level 21 of the Campbell mine. The 2151-6W stope is described by MacGeehan and Hodgson (this volume) and a map of the 2104 stope is illustrated in Figure 9-8. This stope is situated in a lobe of altered rock at the western termination of the A zone. Irregular pods of auriferous silicification occur within a 20 to 30 foot wide veinlet zone consisting of sheeted veins which are parallel to an east-west-striking cleavage. The vein material consists of carbonate-chlorite ± quartz ± talc, much of which is fibrous with the fibres oriented perpendicular to the cleavage. The veinlets and surrounding rocks are extensively replaced by grey-green cherty quartz with arsenopyrite, sphalerite, pyrite, pyrrhotite, chlorite, fuchsite, and native gold. The silicified pods are connected by veins up to 6 inches thick of massive quartz which, in addition to the other sulphides and some gold, contain molybdenite. The sheeted veins and the silicification are overprinted by a northwest-southeast-trending spaced cleavage. Late faulting caused block rotation of the east-west veinlets and disrupted the continuity of the silicification (Figure 9-8). Similar mineralization has been observed on several of the lower levels of the Campbell mine, and in all cases, the relationships among veins, cleavages, and silicification correspond to those described for the 2104 stope. The mineralized veinlet zones may occur up to 75 feet into the altered rock, and they also tend to occur near marked curves in the altered rock contact. Such curvatures (referred to as 'rolls') appear to be preferred locations for this type of gold mineralization.

Interpretation of Structures and Relationships Between Mineralization, Veins, and Structures

Fabric and vein patterns clearly show that the basalt was relatively incompetent and simultaneously affected by ductile flow and brittle fracturing. Flow which caused the development of cleavage was accompanied by the opening of fractures at an angle to cleavage. While veins, formed by the infilling of these fractures, were deformed and rotated towards the cleavage, new fractures formed and the process was repeated. The resulting complex pattern of intersecting ptygmatically folded and boudinaged veins resembles vein arrays in migmatites, except that the vein filling was not a partial melt but resulted from redeposition of material mobilized by pressure solution elsewhere. In contrast to the basalt the altered rock unit is less homogeneous and its main response to deformation was brittle. Cleavage is only locally developed and the vein patterns have not been significantly transposed by flow.

Of crucial importance to an understanding of the veining history is the relationship between cleavage and fracturing. This relationship is not easily recognized in the basalt because many of the earlier veins were rotated into or toward the cleavage (Figure 9-6) and it is not easy to distinguish whether all veins formed at an angle to cleavage or whether some originated parallel to the cleavage. However, this distinction is possible in those parts of the altered rocks in which cleavage is developed. Figures 9-9b and 9-9c suggest that many veins in the altered rock originated parallel to the cleavage, a relationship that is best illustrated by the spatial correlation between sheeted veins and regions of cleavage (Figure 9-8). The sheeted vein sets are parallel to the cleavage and have fibres perpendicular to the cleavage, suggesting that fractures parallel to the cleavage opened perpendicular to the cleavage. Flattening thus produced an anisotropy (the cleavage) along which fracturing could occur after the stresses responsible for the cleavage formation had relaxed, and extension became possible perpendicular to the cleavage. The sheeted veins and the silicification are overprinted by the second cleavage, indicating that the earlier stress was later reestablished, though a slight rotation of the maximum compressive stress occurred. Many of the quartz-carbonate veins also cluster near the cleavage maximum (Figure 9-9c), but so far it cannot be established whether all these fractures formed in the interval between the formation of the two cleavages, or whether fracturing also occurred parallel with the second cleavage.

For a correlation of gold mineralization with structures the following observations are pertinent:

1) The major ore zones cut across bedding of the supracrustal rocks.

2) They cut earlier deformed veins, are themselves deformed, and are cut by later veins which are also deformed.

3) They are aligned parallel with the cleavage. Banding and the general lack of folding suggest that they formed in that orientation.

4) The major ore zones are restricted to the basalt and do not transect the altered rock. Instead sheeted veins are formed in areas where cleavage was present. The veins are parallel to the cleavage and have fibres perpendicular to it. Both sheeted veinlets and zones of silicification are overprinted by the later cleavage.

The fact that the major ore zones cut across bedding precludes the possibility that they represent exhalite horizons. The relationship of the ESC zone to iron formation in the Dickenson mine confirms this. Except for the possibility of some syngenetic gold at the end of the ESC zone, gold mineralization must thus be regarded as epigenetic. Transection of earlier deformed veins by the ore zones demonstrates that deformation preceded major ore deposition. Indeed the restriction of gold veins to areas with cleavage and their alignment parallel to the cleavage suggest that openings parallel to the cleavage played *the*

TABLE 9-3 The major infilling stages of the F and A-SC ore veins observed on the 7, 14 and 21 levels CRLM, and 15 and 23 levels DM.

V Fracturing and Remobilization Stages: Grey, white and massive quartz, Fe ankerite to Fe dolomite; pyrite, pyrrhotite, stibnite, chalcopyrite; chlorite; tourmaline; calcite and visible native gold; in fractures and the necks of boudins.

IV 'Barren' 'Layered Carbonate-Chert' Stage: layered Fe dolomite-Fe ankerite and fine grained granoblastic quartz ± sphalerite ± pyrite ± pyrrhotite with minor arsenopyrite ± gold of several substages; cross cutting, or as minor veins within the major veins.

III 'Replacement-Type Silicification' Stage: Extensive replacement of vein material and adjacent wall rocks. Introduction of much grey quartz with arsenopyrite, pyrite and pyrrhotite. If the breccia stage mineralization is present, then this type of mineralization may be absent or minimal, in which case it may precede, postdate, or by synchronous with brecciation.

II Breccia Stage Mineralization: Three types have been observed and may be, in part, a variation of the replacement type silicification. Breccia fragments may be wall rock, carbonate, quartz or layered carbonate-'chert'.

a) Breccia with a matrix of grey quartz and arsenopyrite, with minor pyrite and pyrrhotite ± gold.
b) Breccia with a matrix of arsenopyrite and grey quartz with minor pyrite and pyrrhotite ± gold.
c) Breccia with a matrix of magnetite and chlorite with minor pyrrhotite, pyrite and low, but anomalous, gold. Quartz fragments and replacement type silicification are generally absent. Wall rock may be extensively chloritized.

I 'Layered Carbonate-Chert' Stage: Several substages of layered dolomite to Fe ankerite + 'chert' ± arsenopyrite ± magnetite ± chlorite ± gold. Cross cutting relationships within the vein may produce breccia-like layered fragments within a layered 'matrix'.

key role in the mineralization. Veins predating the major ore zones are generally not gold-bearing, indicating that little gold was derived from local pressure solution. Gold deposition commenced after through-going fissures had opened along structurally formed anisotropies bringing the rocks in contact with large amounts of gold-bearing fluids derived from elsewhere. The greater competency of the altered rock prevented the formation of large fissures. Ore-bearing solutions could therefore silicify the contact regions but were unable to penetrate most of the unit. The presence of 'rolls' shows that numerous special situations for the trapping of ore-bearing solutions arose from variations in geometry of the basalt-altered rock contact and the ductility contrast between the two units.

The authors tentatively make a broad correlation between the sheeted veins in the altered rocks and the banded gold veins in the basalt. Fibres as well as banding (some of which preserves remnant fibres) indicate extension parallel to the cleavage, and the difference in orientation between sheeted veins (~90±) and the A zone (more southeastward strike) is probably due to refraction of the preexisting cleavage.

The infilling of the major veins was a multistage process which began after the stress perpendicular to the cleavage changed from greatest to least, so that fluid pressure could wedge open cleavage planes, as in the F, A, and SC zones, or faults and contacts between rocks of different ductility, as in the more complex G and L zones. Present fabric data are too inconclusive to establish whether stages of infilling (Table 9-3) were interrupted by episodes of deformation, i.e., whether the orientation of principal stresses changed several times, or only once, before the previously existing stress field became reestablished and led to the deformation of the gold veins. All textures in the veins are consistent with post-infilling deformation. It is therefore possible that both the layered carbonate-chert and the silicification-type mineralization are related to the same stress-environment. Both are overprinted by the second cleavage and new veins formed during the later deformation. These veins are generally barren and contain remobilized gold only in the vicinity of previously mineralized zones.

Acknowledgments

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We are particularly thankful to the mine staff at the Campbell Red Lake and the Dickenson mines for their most generous support during the field work.

The results presented here form the structural framework of an M.Sc. thesis by D.M. Rigg to be presented to the Department of Geological Sciences, Queen's University, in the spring of 1980.

C. Mark and R. Church (Campbell Red Lake Mines Limited), M. Chowainec and L. Koskitalo (Dickenson Mines Limited), J. Pirie (Ontario Geological Survey), and C.J. Hodgson and P. MacGeehan (Queen's University) provided interesting discussions.

Gold Content of Volcanic-Hosted Interflow Sedimentary Rocks in the Red Lake Area: Implications on Ore Genesis at the Dickenson Mine

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Abstract

The objective of the study is to characterize interflow sedimentary rocks from ore-bearing and barren environments with respect to their gold content. The principal results from the barren environment are as follows:
1) In the volcanic suite, the tholeiites are more auriferous than other types. Half of the iron tholeiite samples contain more than 20 ppb gold.
2) In the sedimentary suite, oxide iron formation is significantly more auriferous than other interflow sedimentary rocks which include cherts, silicate iron formation, and three occurrences of sulphide iron formation.
3) A strong similarity in the average gold contents and distribution in the volcanic and sedimentary suites suggests that the interflow sedimentary rocks inherited gold from the volcanic pile.

Two ore-bearing environments in the Dickenson mine were sampled and studied: on the 30 level, wallrocks, for 60 feet on either side of discrete sulphide-bearing quartz-carbonate veins; on the 25 level an ore zone characterized by disseminated auriferous sulphides and lacking quartz-carbonate veins. The following generalizations are drawn from the profile on the 30 level: there is a strong positive correlation for Au, As, and S in all samples; there is little suggestion of a systematic gradient of metal values away from the ore zone; the average value of samples from the north side of the vein is 112 ppb; for samples from the south side, the average is 25 ppb. The geochemical and petrographic data from the disseminated sulphide environment on the 25 level suggest that the rocks are sedimentary. The trace element content of the rocks is distinguished by high Au, As, and S. Sixty percent of the samples contain more than 100 ppb gold and thirty percent more than 1 ppm.

Introduction

The Red Lake gold camp is in the Uchi volcanic-plutonic belt in northwestern Ontario (Figure 10-1). It hosts the Campbell Red Lake and Dickenson mines (including the Robin Red Lake) as well as several significant past producers of gold and silver (Figure 10-2). The major lithologies in Balmer, Dome, McDonough, and Bateman Townships, condensed from the maps of J. Pirie and A. Grant (1978 a,b), J. Pirie and E. Sawitzky (1977), and S.A. Ferguson (1966), are shown in Figure 10-2. Mafic volcanic rocks[2], including some ultramafic extrusive rocks, intermediate volcanic rocks, and felsic stocks and batholiths constitute the major lithologies. On a regional scale many of the gold occurrences are hosted by mafic volcanic rocks in Balmer and Dome Townships. Sedimentary rocks intercalated with the mafic volcanic rocks are a minor lithology in the volcanic pile. These rocks, which are commonly cherty and ferruginous, are collectively termed interflow sedimentary rocks in this discussion. They are of interest for several reasons. In the first place, siliceous, cherty, and commonly laminated rocks occur as thin units, commonly intercalated with mafic volcanic rocks in the Dickenson mine (J.M. Franklin, personal communication) and fine-grained, laminated rocks regarded by the authors as sedimentary in origin were mined on the 25 level as low-grade gold ore at Dickenson mine. Secondly, these sedimentary rocks were presumably deposited during breaks, or periods of relative quiescence, in active volcanism. Consequently they probably contain a significant input from chemical sedimentation or volcanic exhalation and outgassing. The significance of exhalative processes in metallogeny has been discussed by R.H. Ridler (1971) and D.F. Sangster (1979). Speculation on the possible role of exhalative volcanic processes in gold metallogeny is severely constrained by a limited data base. The main objective of this study is to characterize interflow sedimentary rocks from ore-bearing and barren environments with respect to their gold content.

Gold in Rocks from a Barren Environment

Sedimentary Rocks

The sampled area is shown on Figure 10-2. Although three past producers are located at the southwest boundary, the limited number of samples from this area are not anomalous in gold. The interflow sedimentary rocks in-

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[1] Department of Geology, McMaster University.

[2] A greenschist facies regional metamorphic grade prevails in the area, and all volcanic and sedimentary rocks discussed in this paper are metasedimentary or metavolcanic rocks. In the interests of brevity, however, we delete the prefix meta in the text.

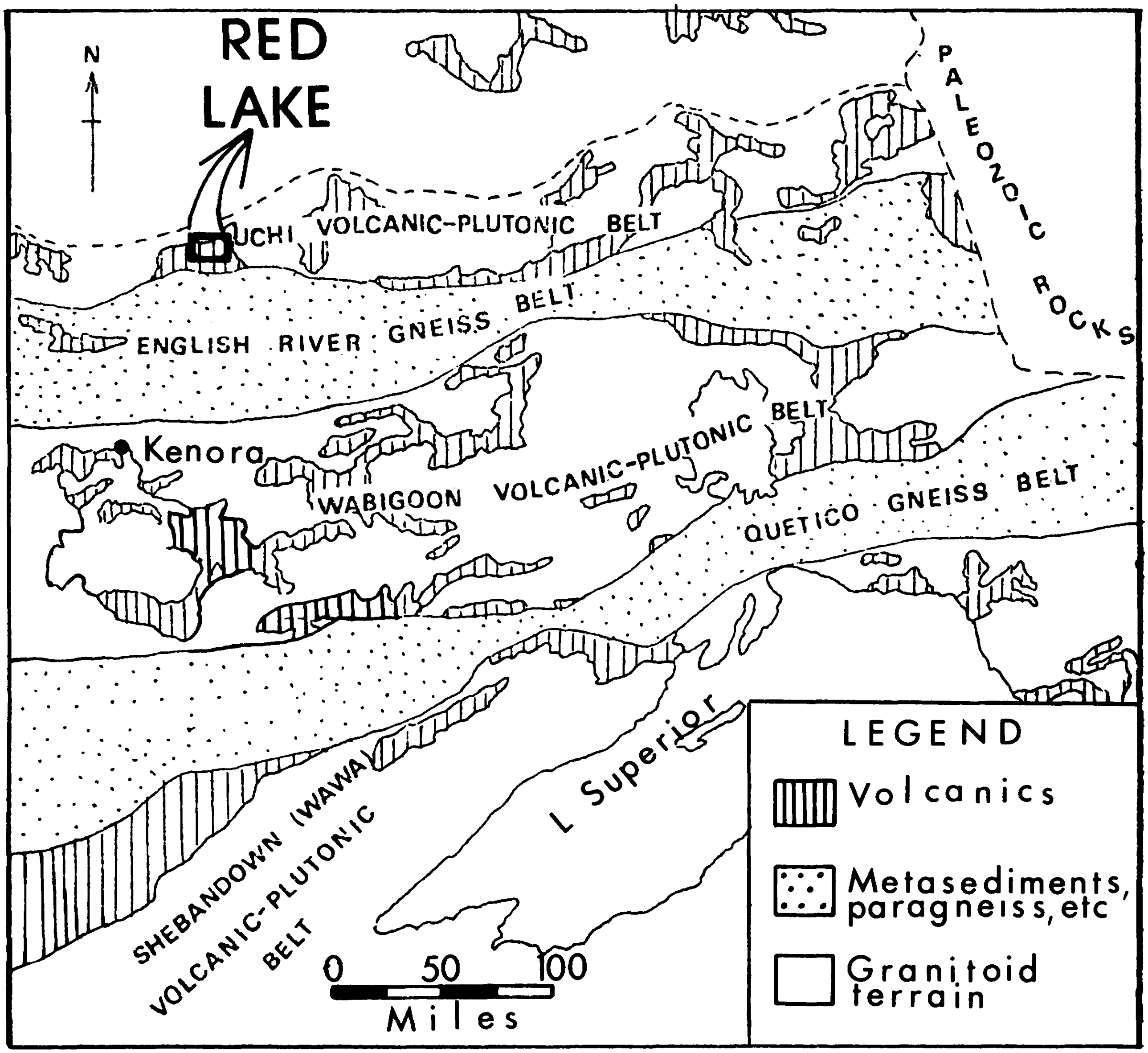

Figure 10-1—Location map showing the geological setting of the Red Lake camp in the Uchi 'greenstone' belt.

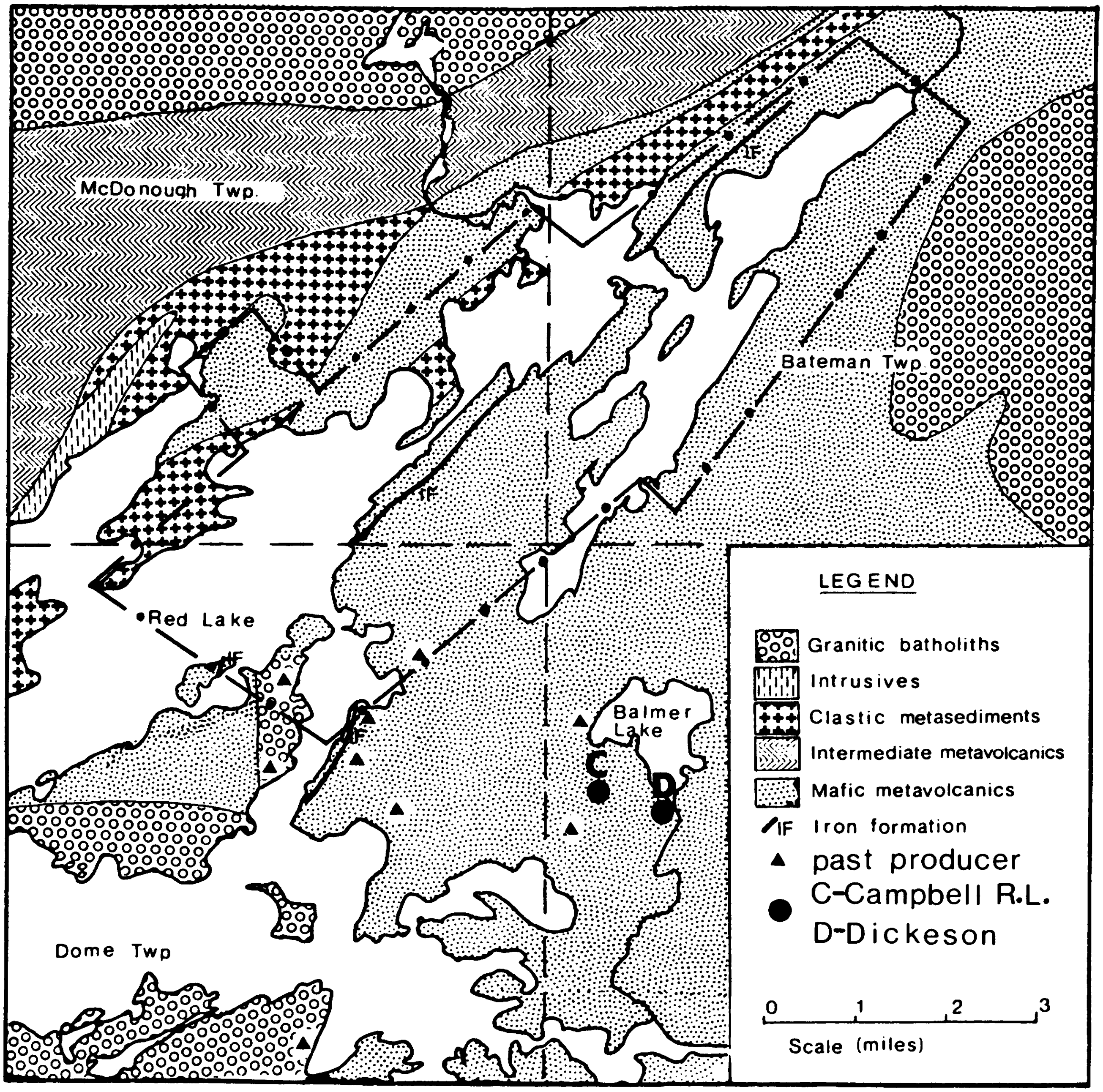

Figure 10-2—Generalized geological map of the Red Lake camp after Pirie and Grant (1978 a, b), Pirie and Sawitzky (1977), and Ferguson (1966). Mines, principal past producers, and area sampled for this study are indicated.

clude cherts, iron formation, and rocks considered to contain both chemical and clastic components. The interflow sedimentary rocks are thin discontinuous beds between volcanic flows, but some occurrences are extensive, mappable units conformable with the volcanic rocks (see Pirie and Grant 1978a, Map 1976a; 1978b, Map 1569).

The cherts are grey, massive, fine-grained rocks, exhibiting conchoidal fracture. The chemical composition of these rocks is characterized by $SiO_2 > 80$ percent, $SiO_2 + Fe_2O_3 > 95$ percent, and $Al_2O_3 < 1.5$ percent; the principal minerals are quartz with minor magnetite. Detrital material or a significant input of felsic volcanic ash is precluded by the very low Al_2O_3 contents.

The iron formations are Algoman-type (Gross 1973) and consist mainly of oxide-rich and silicate-rich types. Oxide iron formation consisting of interbanded magnetite-rich and quartz-rich layers is the most common variety. Silicate iron formation is a rock made up of alternating amphibole-rich quartz-rich layers. Magnetite may occur in significant quantity in the amphibole layers. Sulphide iron formation is rare. Where sampled pyrite, chalcopyrite, and pyrrhotite constitute the major sulphide minerals which occur in diffuse layers alternating with quartz-rich layers.

The mixed clastic-chemical interflow sedimentary rocks account for some 20 percent of the sedimentary suite. These rocks are highly variable in composition particularly with respect to silica and iron, which average 57 and 21 weight percent, respectively. Quartz, amphibole, chlorite, biotite, and calcite may be essential mineral constituents with accessory garnet, plagioclase, and opaques. The high iron content is suggestive of a chemical component in these rocks. The mixed clastic - chemical sedimentary rocks are described in detail by P. Cowan (1979).

Volcanic Rocks

The volcanic rocks include basaltic komatiite, iron tholeiite, magnesium tholeiite, and andesite. Basaltic komatiites and iron tholeiites make up 70 percent of the volcanic suite. The classification of the volcanic rocks relies heavily on the various chemical screens such as those used by N.T. Arndt *et al.* (1977) and L.S. Jensen (1976a). Figure 10-3 shows volcanic compositions plotted on a Jensen diagram. Comparison of average compositions of Red Lake rocks with averages for similar rock types from Munro Township (Arndt *et al.* 1977) and Kirkland Lake (Jensen 1976b) shows very similar compositions with the exception of Na_2O which may be strongly depleted in the Red Lake suite.

Gold Content

The average gold contents of the interflow sedimentary and volcanic suites are presented in Table 10-1 and illustrated in Figures 10-4 and 10-5. Figure 10-4 shows the distribution of gold values for the entire volcanic and sedimentary suites, and various statistics are listed in Table 10-1. The similarity in average gold content and distribution in the volcanic and sedimentary suites is striking. All measures of central tendency are comparable, and both suites show similar ranges in gold content and skewness toward high values. Only the 90th percentile value is significantly different.

Within each suite, however, significant differences in average gold content are found in different rock types. In the volcanic suite the tholeiites are distinctly more auriferous than other rock types. However, little significance can be attached to the high average for the magnesium tholeiites because this class is represented by only three samples. The iron tholeiites, however, are clearly anomalous in a geochemical sense. The high arithmetic mean of this group does not merely reflect very high gold contents in a small fraction of the suite. Half of the iron tholeiite samples contain more than 20 ppb gold. In the sedimentary suite, oxide iron formation is clearly distinguished as significantly more auriferous than other types of interflow sedimentary rock. This is somewhat unexpected as the suite does include sulphide iron formation. However, as the statistics for sulphide iron formation are based on only three occurrences, a statistically meaningful comparison between oxide and sulphide iron formation cannot be made from these data. What is clear is that oxide iron formation is distinctly more gold-rich than cherts, silicate-rich iron formation, or interflow sedimentary rock containing clastic material.

Two inferences are drawn from the gold abundance data. Firstly, the close spatial relationship between the interflow sedimentary rocks and the volcanic rocks, and the strong similarity in their average gold contents and distribution of gold values suggest that the interflow sedimentary rocks inherited gold from the volcanic pile. The mechanism may have involved outgassing of volcanic fluids and vapour during hiatuses in volcanism and/or leaching of a cooling pile by seawater. Secondly, the gold enrichment in oxide iron formation may have resulted from co-precipitation or scavenging of the metal by iron precipitates in a marine environment in which volcanic exhalation was active. The implication that oxide iron formation is metamorphosed ferruginous chemical sediment is supported by the low alumina content (<1.5 weight percent).

Gold in Rocks of an Ore Environment - The Dickenson Mine

The Dickenson mine, located in west-central Balmer Township (Figures 10-2 and 10-6), is south and southeast of the background control area. The surface geology after Pirie and Grant (1978b) is shown in Figure 10-6. Massive and pillowed basalt, iron formation, clastic and chemical sedimentary rocks and felsic to intermediate volcanic rocks including pyroclastic rocks and flows are represented in outcrop in the vicinity of the mine. The Dickenson No. 1 shaft is in altered, pillowed mafic volcanic rocks. The underground sampling, indicated in Figure 10-6, is from the general vicinity of the contact be-

Table 10-1 Gold Contents of Volcanic and Interflow Sedimentary Rocks from the Red Lake Area, Mainly Dome, McDonough and Bateman Townships

Rock Type	No. of Samples	Range ppb	Arithmetic Mean ppb	Geometric (Logarithmic) Mean ppb	Median ppb	P_{10} ppb	P_{90} ppb
Volcanics							
Pyroxene komatiites	5	0.1-13	5.3	2.5	4.6	-	-
Basaltic komatiites	7	0.5-15	4.1	2.1	1.7	0.5	4.8
High Mg Tholeiites	3	6.2-279	98	26	6.2	-	-
High Fe Tholeiites	8	4.3-380	61	15	21/4.8	4.3	44
Andesites	4	1.3-6.7	4.2	3.4	-	-	-
Amphibolite	1	7.0	-	-	-	-	-
All Volcanic rocks	28	0.1-380	31	5.6	4.8	0.9	44
Interflow Sedimentary Rocks							
Chert	8	0.4-10	3.1	2.0	2.3	0.4	3.8
Iron Formation - sulphide	3	5.0-14	10	9.2	10	-	-
- oxide	19	0.7-363	78	22	55	0.9	197
- silicate	5	1.3-6.0	8.8	13	10	-	-
- mixed oxide silicate iron formation	6	0.8-6.0	3.4	2.7	3.2	0.8	6.0
Chemical - detrital interflow sediment	9	0.8-43	8.3	4.1	3.7	0.8	7.9
All interflow sedimentary rocks	50	0.4-363	26	6.1	4.3	0.9	83

tween mafic volcanic flows and clastic-chemical sedimentary rocks. The objectives of the Dickenson study are to examine in detail the distribution of gold, sulphur, and arsenic in rocks in the immediate vicinity of ore, and to characterize in as much detail as possible the lithologies hosting gold ores.

Two types of ore environments were studied. On the 30 level wall-rocks on either side of discrete sulphide-bearing quartz-carbonate veins were sampled whereas on the 25 level an ore zone characterized by disseminated auriferous sulphides in a host rock conspicuously lacking quartz-carbonate veins and stringers was sampled.

30 Level: Quartz-Carbonate Vein Environment

Sampling was carried out in two crosscuts (North and South Crosscuts) trending approximately perpendicular to a quartz-carbonate ore zone. The ore zone is crudely conformable to the stratigraphy and the crosscuts are approximately perpendicular to the stratigraphy. Sampling extended about 60 feet on either side of the ore zone.

Lithologies

The 30 level rocks included in the sampling were mapped mainly as andesite (Dickenson mine level plans), and the surface projection of this area lies in the mafic volcanic unit as mapped by Pirie and Grant (1978b). The majority of the samples plot in the basaltic komatiite, magnesium tholeiite, or iron tholeiite fields of the Jensen cation plot. The mafic character of the rocks is further emphasized by the nickel, chromium, and cobalt levels, as indicated in the compositional data for 30 level rocks presented in Table 10-2.

Other significant compositional aspects include the marked depletion of Na_2O and P_2O_5 relative to unaltered mafic volcanic rocks. Sodium depletion is found in Dickenson rocks from all levels (30, 25, 22, 17) examined as well as in many of the volcanic rocks from the non-mineralized sampling area previously discussed (see also Pirie 1979). Some degree of hydrothermal alteration of the Dickenson rocks is implied. The hydrothermal system was presumably of regional extent.

In addition to compositional aspects certain textural features observed in thin section and on cut faces impose constraints on lithological interpretation. Many rocks are distinctly banded with individual bands or layers varying from a few millimetres to a few centimetres in thickness. Rocks with centimetre thick bands are commonly characterized by the presence of fragments. Rock fragments are common as are oval-shaped fragments consisting of aggregates of fine-grained, equigranular, polygonal grains of quartz. We suggest that these coarse fragmental rocks are mainly proximal volcaniclastic rocks consisting of transported basic volcanic material with some chert or felsic volcanic fragments. The average bulk composition of the volcaniclastic rocks is presented in Table 10-2. They are generally low in sulphur and arsenic and average 144 ppb gold.

A second distinctive textural type in the 30 level suite is distinguished by laminations of a few millimetres in thickness, very fine grain size, and the common presence of garnet. This rock type is illustrated in Figure 10-8 and average major and minor element composition is presented in Table 10-2. These rocks differ little in average major element content from the coarse volcaniclastic suite, but they are far more variable in composition. Although the magnesium, chromium, and nickel contents are typical of mafic volcanic rocks, some samples are significantly more silica- and iron-rich than unaltered mafic rocks. The authors suggest that the banding in these rocks is primary bedding and that the suite is made up largely of fine-grained sedimentary rocks derived from the erosion of a basic volcanic provenance with some chemical sedimentary (exhalative) input represented in more siliceous and ferruginous rocks.

A most significant feature of these rocks is their high gold, arsenic, and sulphur contents. They are the most auriferous rocks in the North and South crosscuts and account for three of the four samples with ppm levels of gold. Polished section examination of the highly auriferous samples has not revealed the presence of discrete gold and it is suggested that the very fine grained sulphide characteristic of these rocks is the most probable carrier. Whether these auriferous sedimentary rocks are in any way related to the quartz-carbonate ore zone is not known. In our opinion they suggest that some syngenetic, volcanogenic gold deposition did occur in the ore environment.

Gold, Sulphur, and Arsenic Contents

The variations in gold, sulphur, and arsenic contents are shown in Figure 10-7a (North crosscut) and Figure 10-7b (South crosscut). The following generalizations are drawn from the profiles:

1) There is a strong, positive correlation for gold, arsenic, and sulphur in the sense that all three elements may be well above the profile background level in the same sample. This correlation is more evident in the North crosscut. Opaque minerals observed in wall-rocks include pyrite and pyrrhotite with minor chalcopyrite, arsenopyrite, and magnetite.

2) There is little suggestion of a systematic gradient of gold, arsenic and sulphur values away from the ore zone. The most distinctive feature of the profiles is occasional high gold content confined to one sample or to a few adjacent samples.

3) The average gold content of North crosscut rocks, neglecting the three samples containing ppm levels of gold, is 112 ppb. The South crosscut averages 25 ppb, if five samples of very low gold content from a probable intrusive dike or sill are excluded. The North crosscut rocks are apparently 4.5 times higher in gold than those of the South crosscut.

25 Level: Disseminated Sulphides Environment

Sampling on the 25 level was carried out in an orebody at the eastern end of the workings about 375 feet north of

Table 10-2 Major and Trace Element Contents of the Main Lithologic Units from Dickenson Level 30 and 25 Sampling Areas.

	1		2		3	
	In Weight Percent					
	Range	$\bar{x}$	Range	$\bar{x}$	Range	$\bar{x}$
SiO_2	45.28-59.70	56.62	49.35-69.68	58.85	57.63-72.55	64.14
Al_2O_3	9.64-13.84	11.94	6.64-14.66	11.47	10.84-13.15	12.17
Fe_2O_3	7.57-12.77	10.32	8.89-17.21	12.00	11.06-22.78	17.54
MgO	7.56-9.58	8.64	4.04-9.11	7.27	1.95-7.22	4.45
CaO	8.21-16.67	12.90	3.70-12.47	8.85	0.43-1.11	0.69
Na_2O	<0.20		<0.20		<0.20	
K_2O	0.21-2.70	1.01	0.08-2.28	0.95	0.94-1.80	1.40
TiO_2	0.76-1.04	0.86	0.43-1.06	0.81	1.07-1.29	1.19
MnO	0.12-0.34	0.24	0.16-0.35	0.25	0.25-0.67	0.44
P_2O_5	0.01-0.05	0.02	N.D.-0.02	0.01	0.02-0.04	0.03
CO_2	1.42-11.82	5.93	0.67-8.56	3.55	0.36-2.40	1.17
	In PPM					
S	568-1984	1271	825-15,293	3922	962-13,516	6525
As	52-414	133	30-17,894	2080	295-3610	1960
Ni	72-200	97	50-272	123	98-345	185
Rb	2-67	19	<20-60	21	9-34	21
Sr	89-169	129	67-142	97	41-101	64
Zr	7-97	77	49-74	65	56-104	70
Cr	225-717	384	129-763	510	298-585	433
Co	20-44	33	11-62	44	39-109	77
Pb	10-15	12	0.15	9	<15	
Cu	89-135	117	36-148	114	133-241	153
Zn	50-257	83	44-1296	160	73-642	265
	In PPB					
Au	11.6-881	144	8.5-21,030		5.1-8170	1411

1. 17 fragmental rocks (probable volcaniclastics), 30 Level

2. 16 fine grained, laminated sedimentary rocks, 30 Level

3. 10 fine grained laminated sedimentary rocks, 25 Level

$\bar{x}$ arithmetic mean

the main 25-274 E drift. The ore zone is distinctive in that economic gold values are found in host rocks with little or no quartz-carbonate veins. Disseminations and thin lenses of sulphides (pyrite, pyrrhotite, chalcopyrite, and arsenopyrite) pervade the host rocks and presumably carry the gold.

Lithologies

The majority of the 25 level sample suite used in this study consists of very fine grained, laminated rocks similar to those on the 30 level. A representative photomicrograph is shown in Figure 10-9. Quartz, amphibole (usually actinolite), micaceous minerals, and garnet with minor carbonate and opaques, including magnetite, are the main mineral constituents. The average composition and compositional range for the suite is given in Table 10-2. In comparison with analogous rocks on the 30 level, the 25 level rocks are higher in silica, iron, and manganese and lower in magnesium and calcium.

On the premise that the layering is primary we suggest these 25 level rocks are sedimentary. If they are considered to be essentially detrital, their comparatively high content of nickel, chromium, and titanium on the one hand, and silica on the other, suggests that both mafic and felsic rocks were present in a volcanic source region. Alternatively, some contribution from chemical sedimentation is tentatively suggested by the high iron and manganese contents and the implication that these fine-grained sedimentary rocks were deposited in a low energy environment in which dilution of chemical components by clastics was minimal.

Gold, Arsenic, and Sulphur Contents

The trace element contents of the rocks are distinguished by high gold, arsenic, and sulphur similar to the 30 level sedimentary rocks. The average high gold content, 1.4 ppm, is not due to a severely skewed distribution, in that 60 percent of the samples contain more than 100 ppb gold and 30 percent more than 1 ppm. As noted above these rocks constituted ore.

Concluding Discussion

The authors' contention is that some of the rocks in the 30 and 25 level areas included in our sampling are sedimentary rocks. On the 25 level they constitute ore grade material. The processes leading to gold enrichment in these rocks are problematic, but we suggest that syngenetic chemical sedimentation is feasible recalling that oxide iron formations are among the most auriferous rocks outside the mine environment. Whether the more common quartz-carbonate vein type ore as in the 30 level sample area is related to auriferous sedimentary rocks is uncertain.

The metal profiles taken about the 30 level ore zone suggest some constraints on the formation of the quartz-carbonate ore zones. If this ore type is envisaged as the product of gold deposition from solutions whose flow is focused along shear zones or other permeable linear features, the process has essentially confined gold deposition to within 5 feet of the conduit. Such halo effects in the immediate vicinity of the ore zone are seen to be very weak compared to the enrichment in rocks about 50 to 60 feet distant from the ore zone. Further, any communication between ore solutions and wall-rocks has been far more intense on one side of the conduit than on the other, as judged by the fourfold difference in profile background gold content. In the absence of major differences of rock type on either side of a conduit, the distinctly asymmetrical character of the gold profiles is rather unexpected. Although these observations are not considered compelling evidence against the concept of ore deposition from focused fluid flow, they are better accommodated in a hypothesis that the ore zone is a sedimentary, exhalative phenomenon.

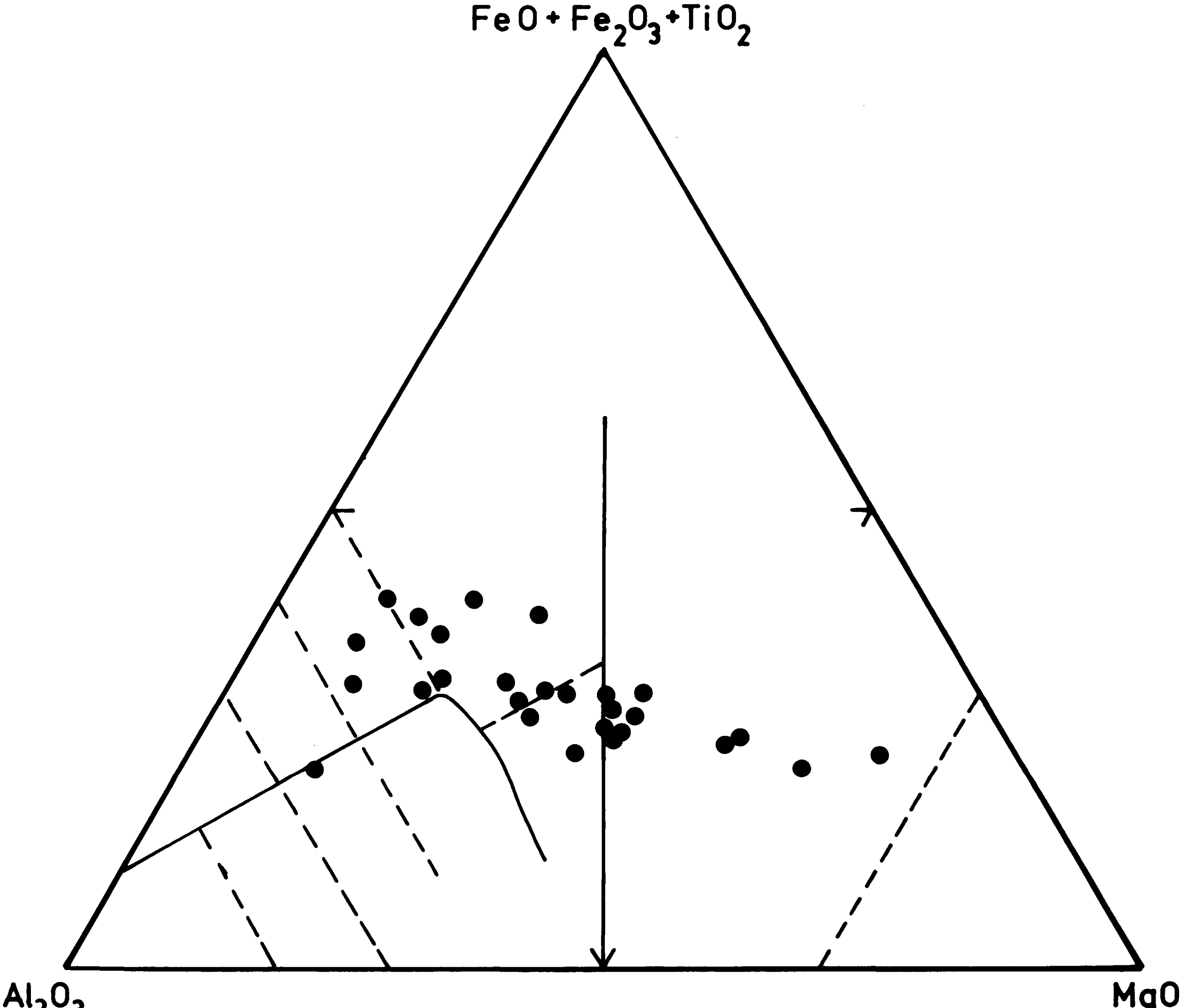

Figure 10-3—Volcanic rock classification according to Jensen plot.

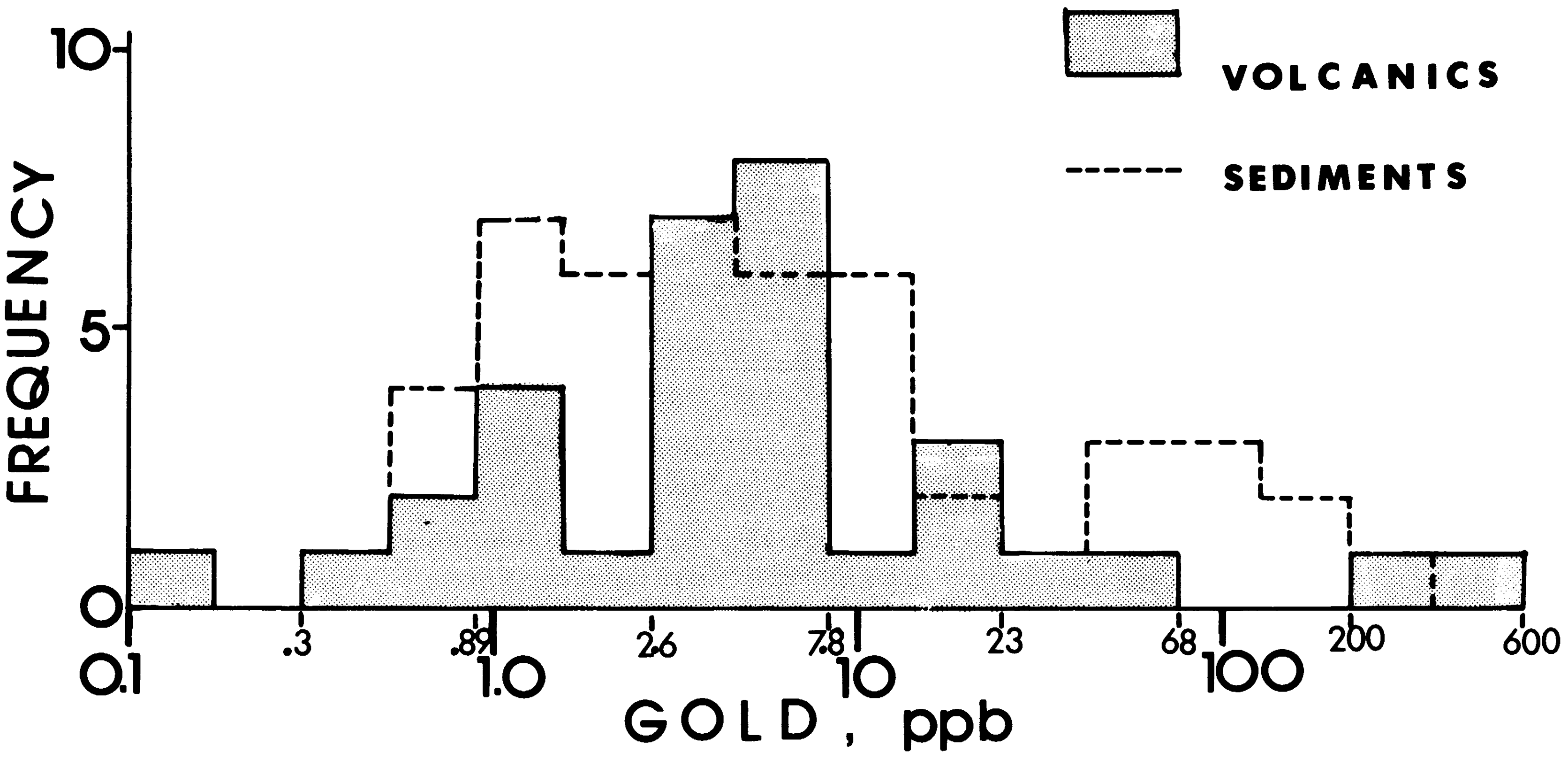

Figure 10-4—Histogram showing distribution of gold contents for entire volcanic and sedimentary rock suites from the barren environment control area.

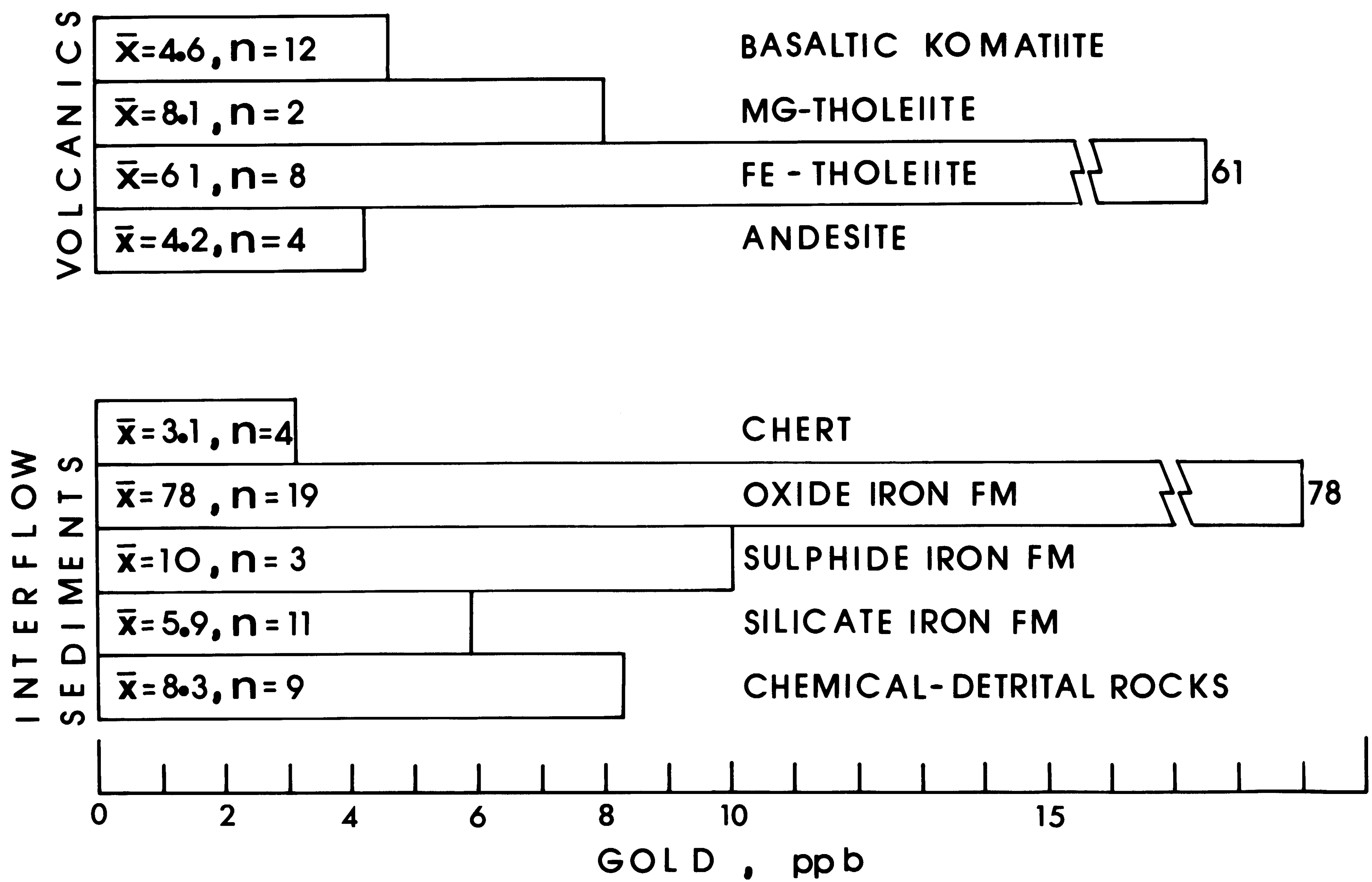

Figure 10-5—Bar graph showing average gold contents (ppb) of the main sedimentary and volcanic rock types from the barren (background) environment.

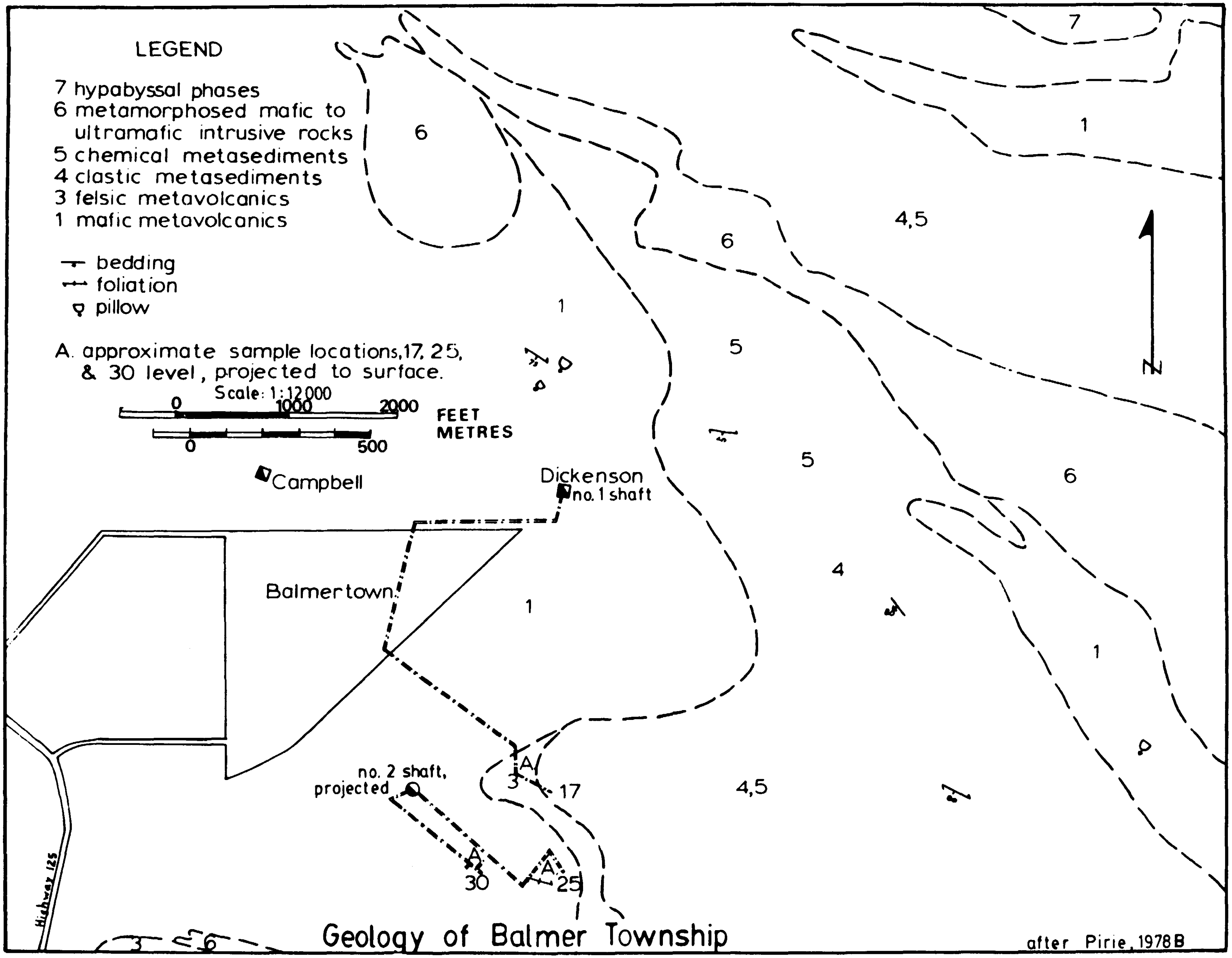

Figure 10-6—Surface projection of Dickenson mine levels 17, 25, 30.

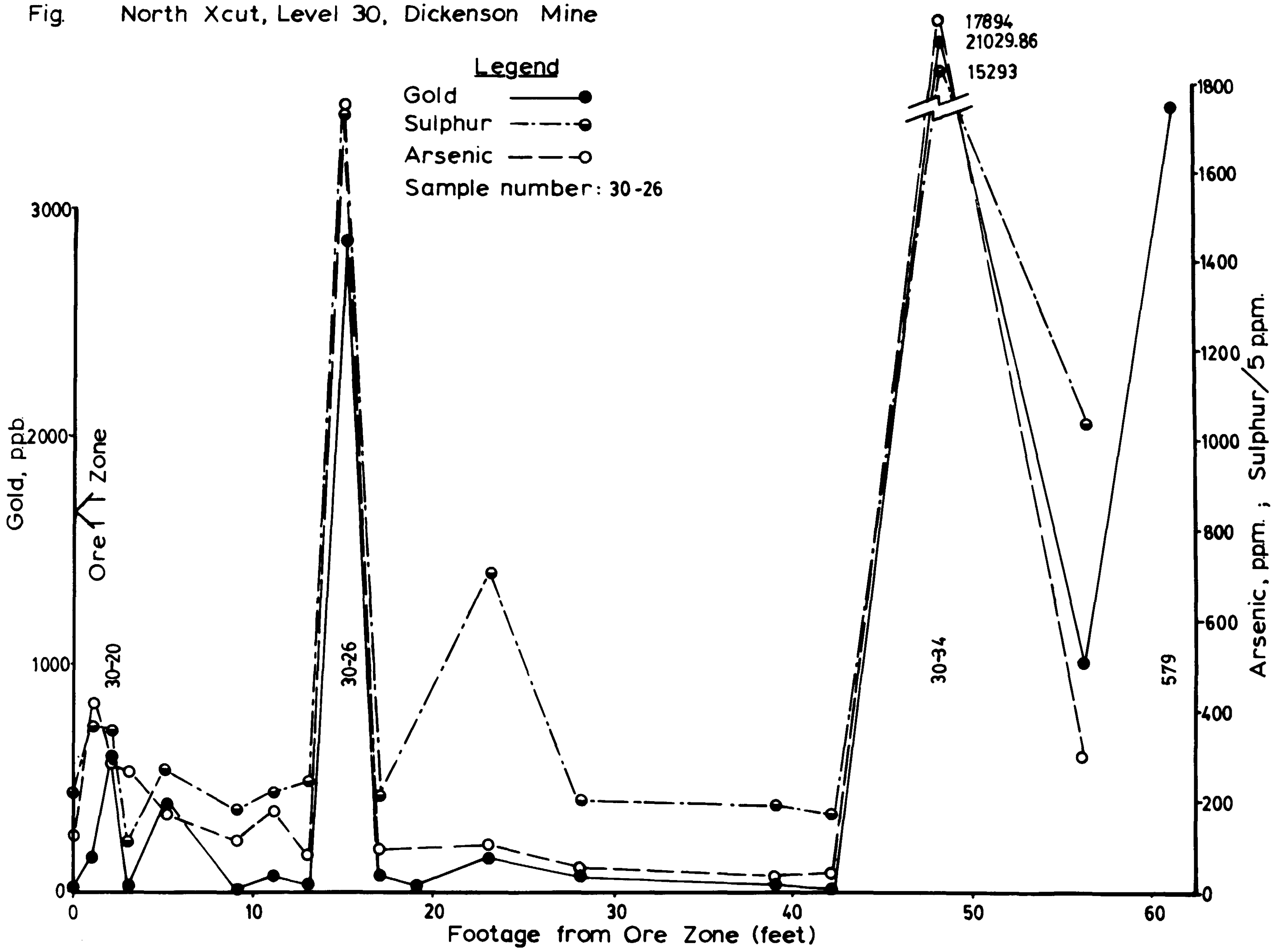

Figure 10-7a—Gold-sulphur-arsenic profiles along the North Crosscut, 30 level.

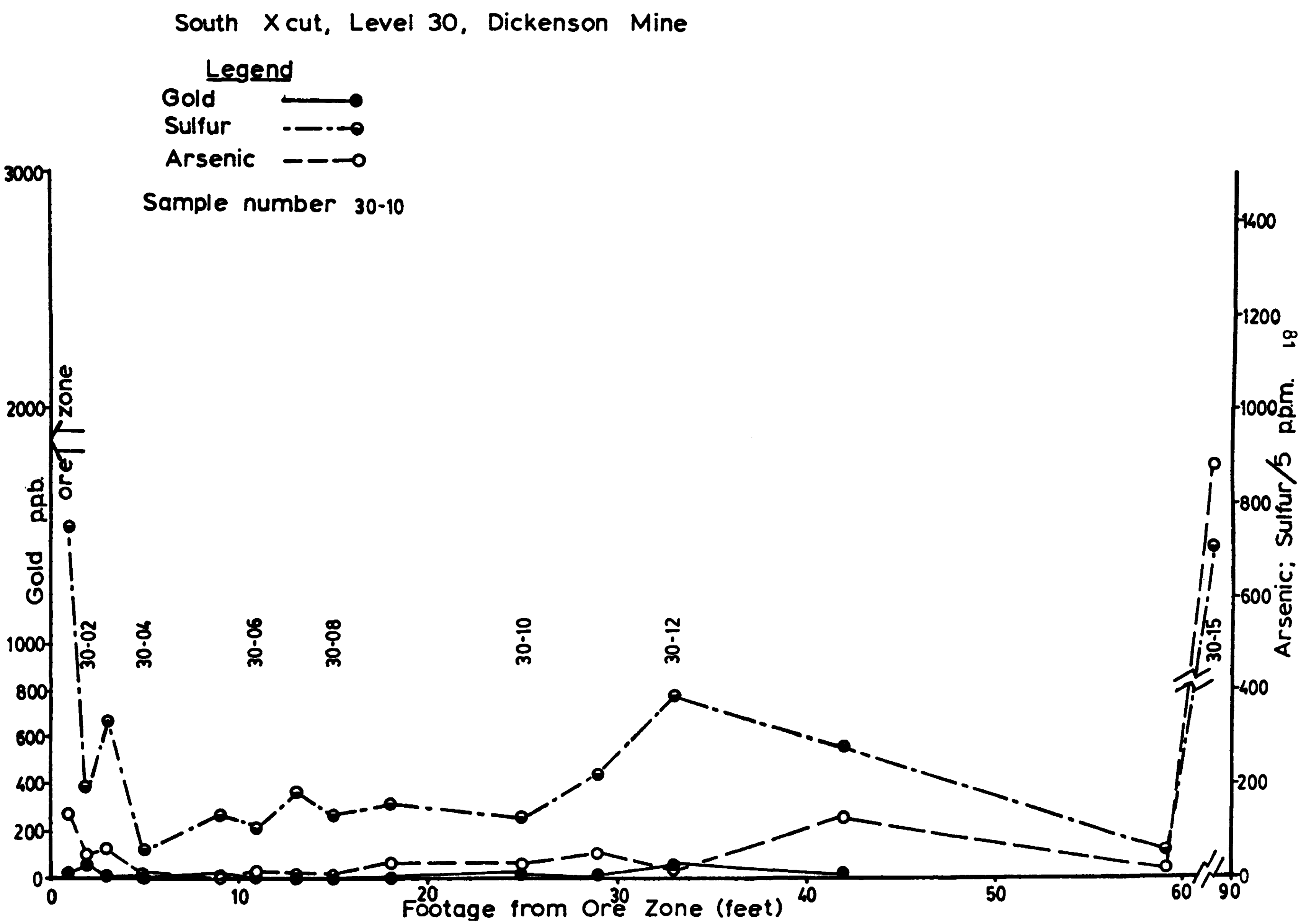

Figure 10-7b—Gold-sulphur-arsenic profiles along the South Crosscut, 30 level.

Figure 10-8—Fine-grained laminated sedimentary rock, 30 level.

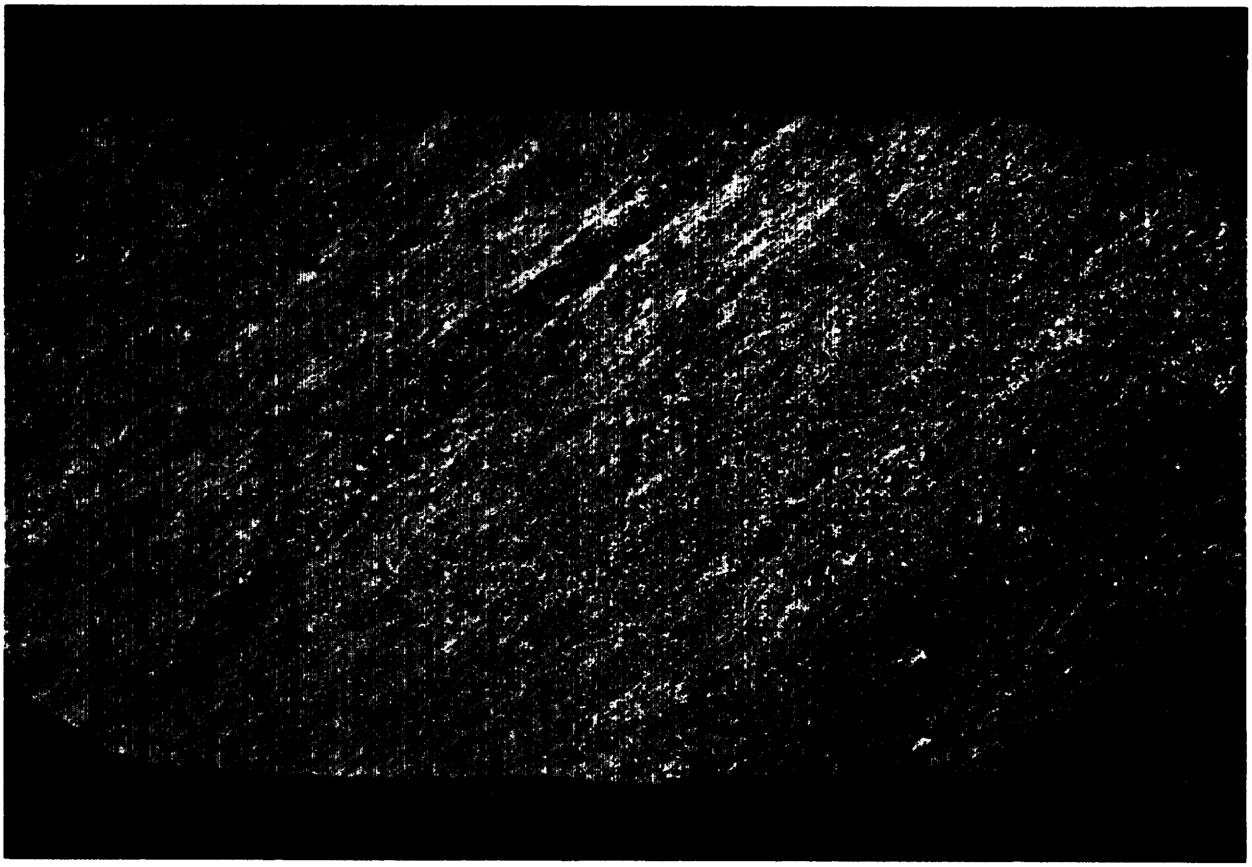

Figure 10-9—Fine-grained sedimentary rock, 25 level. Thin section, magnification X 4.

Archean Gold-Bearing Chemical Sedimentary Rocks and Veins: A Synthesis of Stable Isotope and Geochemical Relations

R. Kerrich[1]

Abstract

Studies of lode gold deposits in 'greenstone' belts reveal a number of common chemical and hydrodynamic features. The following data have been obtained from the Timmins, Yellowknife, Red Lake and Val d'Or-Malartic areas. All gold-bearing chemical sedimentary rocks have $\delta^{18}O$ quartz of 18‰ to 24‰ implying initial low-temperature equilibrium with fluids at the seafloor. REE distribution in such sedimentary rocks are typical of patterns for Archean chemical sedimentary rocks. Locally, auriferous sedimentary rocks (e.g. Timiskaming) exhibit REE distributions which parallel abundances in neighbouring subvolcanic-extrusive felsic porphyries. basic[2] volcanic rocks with background precious metal abundances (<2 ppb Au) have $\delta^{18}O$ whole rock of 7‰ to 10‰, compared to 5.5‰ to 6.5‰ for fresh basalt. The enrichment in ^{18}O is attributed to seawater interaction at temperatures of <150°C. Enrichments in ^{18}O are also present in some felsic igneous rocks.

Hydrothermal veins within given regions have a narrow range of $\delta^{18}O$ quartz (12‰ - Yellowknife; 14‰ - Timmins) and constant Δ (quartz-muscovite) implying fluids of metamorphic origin at 400-500°C — probably derived by outgassing at the greenschist-amphibolite transition. Wall-rocks are in oxygen isotope equilibrium with veins. Vein geometry requires hydraulic pressure $\geqslant$ lithostatic pressure for fluid discharge along hydraulic fractures. This stress condition is consistent with a reservoir of ponded metamorphic fluids. Filling temperature determinations on primary fluid inclusions are in the range 300 to 360°C; significant CO_2 is present.

Wall-rocks of veins have a strong iron reduction anomaly ($Fe^{2+}/\Sigma Fe = 0.92$) compared to background ($Fe^{2+}/\Sigma Fe = 0.7$), requiring the introduction of large volumes of reductant in the hydrothermal solutions. Hydrogen is probably the reductant involved, derived by dissociation of H_2O in equilibrium with the QFM system at high temperatures. REE distribution in veins, plus positive Eu^{2+} anomalies, confirm the reducing environment of ore deposition, and imply fluids at source in equilibrium with rocks of mafic to ultramafic composition. Redox and oxygen isotope anomalies correlate: both parameters give estimates for the water/rock ratio along conduits of >3:1. High-temperature reducing solutions may be critical for aqueous transport of Cr, Ni, W, Pd, and Pt which are all present at 10 times to 500 times background abundances in gold-bearing veins.

In both vein and stratiform deposits, Au, Ag, and Pd average 20, 2, and 0.1 ppm respectively, compared to background abundances of 2, 100, and 8 ppb in mafic igneous rocks. This represents concentration factors of 10,000 for Au, 20 for Ag, and 10 for Pd relative to background. The relatively immobile elements Cr, Ni, and W may be significantly enriched in lodes, whereas the abundant and mobile base metals Cu, Zn, Pb, and Co are concentrated by only 1 times to 5 times. This separation may be accounted for if fluids are generated under conditions of low water/rock such that the absolute abundance of rare elements in solution is not constrained by solubility, whereas base-metal solute concentration is. Metamorphic outgassing, where water/rock may be ~1:20, satisfies this condition. For the Timmins area simple calculations give estimates for hydrothermal fluid volumes of ~90 km^3, transport distances of ~12 km, and Au solute concentrations of ~20 ng/ml.

From these data, it is believed that the distinctive suites of metals in lode gold deposits versus massive base-metal sulphides reflect fundamentally different properties of the hydrothermal systems in terms of source, temperature, ratio of hydraulic to lithostatic pressure, water/rock ratio in source regions, and abundance of CO_3^{2-}. The predominance of lode gold deposits in Archean 'greenstone' belts may be accounted for if geothermal gradients were higher such that outgassing and ponding of metamorphic fluids were more efficient, and if Hargraves model of an early globe-encompassing hydrosphere is correct, such that metamorphic fluids debouched onto the seafloor.

Introduction

One of the salient features of metal distribution in crustal rocks is the predominance of lode gold concentrations in Archean 'greenstone' belts (Viljoen *et al.* 1970; Anhaeusser 1976; Anhaeusser and Button 1976; Hutchinson 1976; and Pretorius 1976). No completely satisfactory explanation has been advanced to account for this secular phenomenon.

Lode gold deposits in Archean 'greenstone' belts are represented by a number of stratigraphically and structurally distinctive types of auriferous concentrations. These lodes may be present singly, but generally several

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[2] All the rocks in the area have been metamorphosed, therefore the prefix 'meta' is not used.

types coexist within a mine or cluster of mines which constitute a gold camp. Two of the most abundant types of concentrations are stratiform layers and hydrothermal veins. Stratiform layers are typically disposed at interflow horizons between mafic-ultramafic flows at the stratigraphic base of 'greenstone' belts. They have been interpreted as chemical sediments precipitated on the seafloor from 'volcanic exhalations' (Ridler 1970; Hutchinson 1976 ; Fripp 1976). Hydrothermal veins transect diverse host rocks and are synchronous with or postdate deformation and metamorphism of 'greenstone' belts. They are considered to be the product of hydrothermal fluids discharging through conduits (Fyfe and Henley 1973); or derived from remobilization of metals from the stratiform layers into fractures during deformation and metamorphism (Anhaeusser 1976; Hutchinson 1976).

However, the properties, volumes, and sources of mineralizing solutions are not precisely understood for the distinctive types of gold lodes.

Whereas the distribution of a large suite of metals has been comprehensively delineated for some examples of base-metal deposits (Mercer 1976; Fryer and Hutchinson 1976), and extant metalliferous sedimentary rocks (Robertson 1978), the abundance of transition metals in lode gold deposits is not well documented. Only a limited suite of elements have been reported for a restricted number of veins (Boyle 1961, 1976) and stratiform-type (Fripp 1976) deposits. In addition, the mechanism by which gold is separated from the abundant base metals is not well understood.

This paper presents a synthesis of determinations for some of the noble metals, transition metals, and other selected elements (Au, Ag, Pd, Be, B, As, Sb, V, Cr, Co, Ni, Cu, Zn, Mo, Sn, W, Hg, Pb, and Th) on examples of gold-bearing hydrothermal veins and stratiform chemical sedimentary rocks, together with 'background' mafic volcanics, from the Yellowknife, Abitibi, and Uchi 'greenstone' belts, Canada. Comparisons are drawn with the distribution of metals in base-metal deposits, and the problem of how gold is separated from abundant metals is addressed.

An attempt is made to characterize the dominant features of chemical alteration in wall-rocks to both auriferous sedimentary rocks and veins by means of mass balance calculations. From this basis it is possible to discriminate between hydrothermal and wall-rock contributions to some of the transition metals in gold lodes.

The properties, source, volumes, and redox potential of fluids involved in gold mineralization have been evaluated in each area by means of oxygen isotope analysis, combined with studies of oxidation state and fluid inclusions. In particular, the oxygen isotope composition of auriferous chert is considered in relation to the thermal and isotopic evolution of the oceans. The data are collectively discussed in the context of the ambient crustal conditions under which the gold deposits were generated; an hypothesis is presented for the secular variation of gold concentrations.

Geological Setting

The data presented in this paper are synthesized from studies of vein and stratiform lode gold deposits in four major auriferous provinces within Archean 'greenstone' belts of Canada. The provinces investigated include the Yellowknife area, Yellowknife 'greenstone' belt, Northwest Territories; the Porcupine and Val d'Or-Malartic areas, Abitibi 'greenstone belt'; and Red Lake area, Uchi Subprovince within the Superior Province.

The Yellowknife 'greenstone' belt consists of a 6 km thick sequence of basalt and sedimentary rocks intruded by batholiths of granitic composition (Boyle 1961; Henderson and Brown 1966). Major rock units were emplaced over a relatively short duration at 2.8 Ga (Cumming and Tsong 1975). Gold-bearing quartz-carbonate veins are situated within major ductile shear zones that transect the volcanic stratigraphy at angles of 20° to 70° in the vertical plane (Kerrich and Allison 1978). Minor auriferous vein systems are located in fractures within the batholiths and sedimentary rocks. Material for this study was collected from major gold concentrations in the Campbell, Con, and Giant shear zone systems, from the Ptarmigan Mine, and from unmineralized areas of mafic volcanic rocks.

The Abitibi 'greenstone' belt is comprised of ultramafic flows; mafic to felsic volcanics with coeval intrusions; volcaniclastic sedimentary rocks; chemical sedimentary rocks including banded iron formation; and several large intrusive batholiths (Goodwin and Ridler 1977). Low- to medium-grade greenschist facies metamorphism predominates.

The Porcupine area is located at the southwestern limits of the Abitibi 'greenstone' belt. The geology of the Porcupine area has most recently been described and evaluated by S.A. Ferguson *et al.* (1968), D.R. Pyke (1976), and J.F. Davies (1977). At least two stages of lode gold emplacement may be recognized. The first involves gold-bearing ferroan dolomite layers with subordinate chert and mafic or felsic tuff deposited as laterally extensive chemical sediments at interflow horizons within the stratigraphically lower part of the mafic volcanic sequence. The second stage is represented by major gold-bearing hydrothermal quartz-carbonate-albite-dravite veins which transected diverse host rocks including the carbonate chemical sediments (Fryer *et al.* 1979).

A minimum age for mineralization and regional deformation is provided by a Rb-Sr whole-rock isochron age of 2.69 Ga on the Matachewan diabase dikes which transect Kenoran fold structures and batholiths (Gates and Hurley 1973).

Rocks containing high precious-metal abundances occur in several distinctive settings in the Dome and Aunor mines where material was collected (Holmes 1968). In this study data are reported for (1) carbonate chemical sedimentary rocks enveloped between mafic volcanic flows, (2) *en enchelon* vein arrays in massive dacite-andesite flows, (3) banded quartz-tourmaline and quartz-fuchsite-tourmaline veins, and (4) quartz veins transecting Timiskaming sedimentary rocks. In addition, material from unmineralized mafic volcanic rocks was obtained.

The Val d'Or-Malartic area is situated at the southeastern margin of the Abitibi 'greenstone' belt. Malartic gold-fields are located in greywackes, mafic flows, conglomerates, and chemical sedimentary rocks of the Kewagama, Blake River, and Cadillac Groups. Massive peridotite bodies, diorite, and felsic porphyry stocks have been intruded into the sequence. The overall disposition of rock units is dictated by the major east-west-trending Malartic synform, which is delimited to the south by a large-scale structural discontinuity, the Cadillac-Malartic break (Eakins 1962; Shaw 1975).

Two principal stages of gold concentration may be recognized. The first involves gold-bearing chert chemical sediment containing a variable proportion of felsic pyroclastic fragments. This implies that sedimentation was coeval with emplacement of the neighbouring felsic porphyry stock. The second stage is represented by gold-bearing hydrothermal quartz veins which transect diverse host rocks. For the purposes of this study the early chemical sedimentary rocks and later quartz veins at the margins of the 'East Porphyry' stock were sampled (2200 level East Malartic mine).

The Red Lake area lies within an Archean 'greenstone' belt of the Uchi Subprovince, which is part of the Kenora District of northwestern Ontario. At Red Lake the principal rock types are volcanic and sedimentary rocks including significant stratiform chemical sedimentary horizons, intruded by numerous igneous rocks (Horwood 1948; Ferguson 1962; Goodwin 1977). Gold-bearing silicate facies iron formation was obtained from the Dickenson mine. The presence of chlorite, biotite, and garnet implies upper greenschist facies metamorphism.

For the purpose of comparison, additional data are presented from the Kerr Addison, O'Brien, and Lamaque mines, Abitibi 'greenstone' belt, and the Morro Velho mine, Brazil.

Analytical Methods

Precious metal abundances were determined by flameless atomic absorption spectrophotometry, using an aqua regia extraction and tellurium precipitation preconcentration step, according to the procedure described by B.J. Fryer and R. Kerrich (1978). Be, Cr, Ni, Co, Cu, Zn, V, Mo, Pb, and Th were analyzed by conventional atomic absorption spectrophotometry. As, Sb, Sc, and W were determined by neutron activation analysis; B and Sn by emission spectroscopy; and S by X-ray fluorescence spectrometry. Fe^{2+} was measured volumetrically by the method of A.D. Wilson (1955). The extraction of oxygen from minerals and whole rocks, and conversion to carbon dioxide was conducted using standard techniques as described by R.N. Clayton and T. Mayeda (1963). Isotopic data are reported as $\delta^{18}0$ values in per mille relative to SMOW (Standard Mean Ocean Water). The overall reproducibility of $\delta^{18}O$ values has averaged about ±0.18‰(2σ). Fractionations among minerals are quoted as Δ-values, defined as:

$\Delta_{A-B} = 1{,}000\ 1n\ \alpha_{A-B} \cong \delta_A - \delta_B$

where α_{A-B} is the fractionation factor for the coexisting minerals A and B.

Distribution of Elements and Their Relative Separation

Abundances of noble metals and selected trace elements, together with their abundances in background rocks, are reported in Tables 11-1, 11-2, and 11-3 for a number of lode gold deposits. In orebodies, Au, Ag, and Pd average 10, 2, and 0.1 ppm respectively, compared to abundances of 2 ppb, 100 ppb, and 8 ppb determined for these elements in primary lithologies remote from the orebodies, and in mafic igneous rocks worldwide (Tilling *et al.* 1973; Kwong and Crocket 1978; Frueh and Vincent 1972; Parthé and Crocket 1972). Stratiform chemical sedimentary rocks display variable enrichment of Au from 5 ppb to 30 ppb above background. Locally, where the auriferous sedimentary rocks appear to have acted as a permeability barrier, such as at the Dome and Kerr Addison mines, they are pervasively transected by the late type Au-bearing hydrothermal veins, with parallel and crosscutting relationships. The chemical sedimentary rocks may therefore have undergone two stages of gold enrichment.

Concentration factors in the lodes are ~10,000 for Au, ~20 for Ag, and ~10 for Pd relative to background abundances. Several elements are present in association with gold, such as W, As, Sb, Hg, and B, which have also undergone high degrees of concentration. Tungsten is a rare and relatively immobile element with an average background abundance of 0.4 ppm in oceanic basalt (Helsen *et al.* 1978). It is common, occurring as scheelite within gold-bearing veins and has also been reported as anomalous concentrations in stratiform chemical sedimentary rocks (Harman *et al.* 1975). Arsenic is another rare element, which is typically present at the 1,000-10,000 ppm level in gold lodes, contained within the ubiquitous arsenopyrite. In the Con mine, Yellowknife, the content of As locally attains 2 percent (Boyle 1961). This implies a concentration of 10,000 times the background abundance of 2 ppm in basalt (Turekian and Wedephol 1961). Boron is abundant in many gold-bearing veins and chemical sedimentary rocks, contained principally within tourmaline and also axinite. It occurs at the Dome mine at Timmins, the Lamaque mine at Val d'Or, and Passagem de Mariana in Brazil. With a background content of 5 ppm in basalt and 100 ppm in shale (Turekian and Wedephol 1961), and levels exceeding 10,000 ppm in some gold deposits (Fleischer and Routhier 1973), the concentration factor for boron is 100 to 2,000 depending on the nature of the source region.

Ni and Cr contents of metamorphosed mafic volcanic rocks 'diluted' by vein quartz are comparable to background values (Table 11-2), but may attain levels ex-

Table 1. Average abundances of selected elements in veins and background rocks, from the Con and Giant Mines, Yellowknife (in ppm).

	Campbell I quartz veins	Campbell I mineralised schist	Campbell II quartz veins	Campbell II mineralised schist	Campbell 5300 quartz veins	Campbell 5300 mineralised schist	Con quartz veins	Con mineralised schist	Giant quartz veins	Cherty tuffs	Mafic volcanics
Au	26.0		1.4	0.1 - 5.8	19.3		16.4	0.4 - 3.		0.005	0.0016
Ag	8		2	0.9 - 18	31		2	0.8 - 42		0.0047	0.06
Pd	0.14									0.027	0.004
Be	0.12 (0.04)	0.22 (0.18)	0.10 (0.04)	0.30 (0.20)	0.10	0.10	0.10 (0.07)			0.6 (0.75)	
B	600		200		300		100				
St	1.15		2.86		0.11		0.42				
As	2700		80		9600		5300				
Sb	95		5		100		37				
V	35 (24)	124 (52)	41 (28)	200 (52)	39 (28)	77 (16)	23 (21)	132 (24)	25 (25)	145 (196)	
Cr	49 (44)	106 (22)	25 (15)	110 (50)	42 (30)	102 (52)	39 (47)	117 (37)	36 (27)	160 (159)	175 (102)
Co	55 (41)	8 (9)	3 (4)	1 (1.1)	53 (43)	1 (3.6)	109 (95)	7 (10)	47 (39)	51 (12)	85 (56)
Ni	22 (33)	36 (15)	2 (15)	24 (15)	14 (9)	31 (13)	18 (12)	54 (19)	15 (12)	60 (73)	113 (61)
Cu	46 (55)	150 (262)	9 (8)	12 (22)	381 (1082)	0.1 (2.4)	58 (64)	15 (21)	5 (6)	27 (40)	64 (32)
Zn	161 (223)	123 (82)	14 (12)	87 (46)	578 (1076)	37 (28)	34 (18)	54 (37)	22 (18)	42 (12)	72 (28)
Mo	10 (26)	-	4 (4.4)	2 (3.2)	-	-	-	-	-	-	-
Sn	3		<3		<3		3				
W											
Hg	60		60		<10		30				
Pb	168 (197)	102 (152)	2 (3)	3 (7)	334 (709)	1 (0.9)	27 (46)	2 (2.3)	34 (58)	2 (2.3)	5 (5)
Th	2 (2.6)	-	2 (2)	1 (0.8)	-	-	-	-	-	-	-
n*	18	5	7	8	10	2	3	3	7	6	34

n* = number of determinations

The figures in parentheses represent one standard deviation of the average. Where no standard deviation is quoted the abundance was determined on a composite sample.

Table 2. Average abundances of selected elements in stratiform and vein type lode gold deposits, and in their background rocks, from the Dome and Aunor Mines, Timmins, together with abundances in primary basalts world wide (in ppm).

	tuff plus carbonate sediment	carbonate sediment plus tuff	carbonate sediment	quartz-tourmaline veins	quartz-muscovite veins	quartz veins in dacite	quartz veins in porphyry	quartz veins in slates	mineralised mafic volcanics	mafic volcanics	primary basalt**
Au	4.1	19.2	8.1 (8.5)	52.1	66.4	69.9	18.5		3.2 (2.5)	0.002	0.002
Ag	3	6	3.3 (2.2)	5	6	7	54	6.0 (5.9)	1.2 (0.6)	0.084	0.11
Pd				0.18 (0.10)	0.10 (0.11)						
Be	0.1	0.1	0.1	0.1	0.1	0.1 (0.07)	0.1 (0.06)	0.4 (0.33)	0.3 (0.39)	0 (0.28)	1
B			1500	800	400	3500		2000			5
S%	0.6	3.1	0.65	0.4	0.2	5.9	0.2	1.54			0.03
As	140	20		100	140	140	340				2
Sb	3	1		3	2	4	1				0.2
V	211 (61)	90 (69)	81 (37)	19 (21)	26 (40)	3 (3)	4 (5)	54 (43)	6 (5)	156 (89)	250
Cr	246 (42)	174 (183)	51 (12)	123 (165)	340 (548)	51 (27)	20 (12)	103 (57)	113 (25)	174 (79)	170
Co	4 (4)	1 (2)	1 (2)	149 (68)	198 (124)	111 (122)	215 (114)	66 (91)	1 (1.7)	1 (2.9)	48
Ni	109 (12)	82 (94)	5 (7)	34 (42)	151 (277)	12 (5)	22 (23)	69 (49)	6 (7)	144 (77)	130
Cu	70 (13)	29 (41)	20 (71)	6 (7)	26 (43)	5 (7)	73 (110)	50 (48)	37 (21)	39 (52)	87
Zn	21 (3)	53 (11)	53 (62)	27 (24)	19 (13)	845 (1170)	943 (1423)	127 (96)	183 (13)	146 (103)	105
Mo	-	-	-	-	-	-	-	-	-	-	1.5
Sn		<3		<3	<3	5		3	-	-	1.5
W											0.4
Hg		70		60	20	50		20			0.09
Pb	1 (2)	16 (20)	44 (100)	5 (6)	329 (891)	11 (7)	1383 (2098)	160 (120)	1 (2.3)	1.4 (1.9)	6
Th	-	-	-	-	-	-	-	-	-	-	4
n*	2	2	13	6	13	5	12	8	12	7	

n* = number of determinations

The figures in parentheses represent one standard deviation of the average. Where no standard deviation is quoted the abundance was determined on a composite sample.

**data from Turekien and Wedepohl (1961), and other sources given in the text.

Table 3 . Average abundances of selected elements in stratiform and vein type lode gold deposits from specified mines (in ppm)

	DICKENSEN	EAST MALARTIC		KERR ADDISON				CHIMONIS		O'BRIEN	
	metabasic tuff	felsic tuff + chert	quartz veins in porphyry	carbonate chemical sediment	veined chemical sediment	quartz veins in syenite	spilitised mafic tuffs	ultramafic tuff + carbonate sed.	ultramafic tuff + carbonate sed.	cherts	quartz veins
Au	52.6 (19)	5.5	130	29	82	32	18	39	14	61	32
Ag	4.4 (1.5)	1	5	7	16	29	1	11	7	4	19
Pd					0.22						
Be	0.2 (0.1)	0.8 (0.4)	-	0.3 (0.06)	0.3 (0.13)	0.4 (0.10)	0.1 (0.07)	0.3 (0.2)	0.1(0.06)	0.4 (0.17)	0.4 (0.32)
B	94 (64)										
St	8.4 (8.9)	0.9	0.5							11 (10.3)	0.8 (0.99)
As	3210 (5910)	20	60							4.5 (2.6)	170 (170)
Sb	113 (132)	1	1							4 (2.6)	6 (4.6)
V	153 (76)	32 (25)	34 (46)	150 (23)	92 (28)	27 (18)	80 (0.08)	89 (23)	117 (6)	70 (22)	87 (49)
Cr	156 (49)	98 (82)	12 (7)	1807 (405)	1019 (498)	44 (20)	200 (99)	1773 (304)	2190 (501)	218 (356)	994 (164)
Co	85 (70)	66 (29)	247 (66)	116 (20)	115 (35)	74 (25)	67 (32)	108 (25)	141 (15)	88 (96)	7 (7)
Ni	341 (296)	52 (29)	16 (8)	924 (109)	712 (372)	32 (14)	137 (54)	993 (162)	1230 (340)	109 (33)	30 (13)
Cu	80 (64)	9 (9)	4 (3)	84 (50)	13 (33)	15 (10)	343 (177)	19 (10)	49 (35)	144 (26)	26 (21)
Zn	1448 (2179)	25 (19)	8 (1)	49 (5)	41 (15)	16 (9)	527 (194)	35 (10)	52 (6)	664 (400)	90 (41)
Mo	-	-	-	-	-	-	-	-	-	-	-
Sn	3 (7)										125
W	48 (22)										
Hg	1061 (2304)									80 (66)	31 (35)
Pb	-	20 (11)	4 (5)	-		-	-	-	-	15 (17)	61 (29)
Th	-	-	-	-	2 (3)	8 (0.5)				2 (3)	2 (2)
n*	8	18	9	3	9	3	6	3	3	4	7

n* = number of determinations

The figures in parentheses represent one standard deviation of the average. Where no standard deviation is quoted the abundance was determined on a composite sample.

ceeding 400 ppm in fuchsite-bearing quartz veins. These data imply significant hydrothermal transport of these elements, together with precious metals. The average content of Pb, Zn, Co, and Cu in gold-bearing veins and sedimentary rocks is only 0.2 to 5 times the abundances in nearby mafic volcanic rocks and in primary basalt worldwide. A salient question that arises from these results is why rare elements, and metals such as Cr, Ni, and W conventionally considered to be immobile, are concentrated in lodes relative to the mobile and abundant base metals.

Enrichments of elements relative to the intrinsic background abundance are plotted in Figure 11-1 for the Dickenson mine. This illustrates the magnitude by which rare elements and the abundant transition metals are separated. There is thus an overall coherence to the patterns of relative enrichment.

Chemical Relations Between Lodes and Their Host Rocks

In many examples of lode gold deposits there is field evidence that veins and sedimentary rocks have incorporated fragments or laminae respectively from their enveloping wall-rocks. For example, at the Dickenson mine, Red Lake, all of the auriferous chemical sedimentary rocks examined contain a variable proportion of laminae composed of actinolite + biotite + chlorite, which are believed to have been of mafic tuffaceous origin, and which have the same essential mineralogy as mafic tuff stratigraphically above and below the sedimentary rocks. In attempting to understand the source of the hydrothermal fluids implicated in precipitation of gold, and to identify the transported solute species, it is important to discriminate between chemical components of volcanic and hydrothermal origin. In this section chemical features of alteration in or adjacent to lodes are examined by means of mass balance calculations. The examples described below are auriferous sedimentary rocks at Red Lake, and a major quartz-carbonate vein within the Campbell shear zone, Yellowknife.

Dickenson Mine - Red Lake

The abundances of major and selected trace elements for eight auriferous chemical sedimentary rocks and two mafic tuffaceous host rocks is given in Table 11-4. To a first approximation the chemical sedimentary rocks may be considered to be composed of tuff, with an initial composition of the average host rock mafic tuff (Samples 971 and 972, Table 11-4) which have subsequently been metasomatized and diluted by hydrothermal solutions. This assumption is supported by textural evidence, and by noting that the relatively immobile elements in reducing environments, namely Ti, Al, V, Sc, and Zr maintain constant ratios to one another (within the limits of analytical error).

The gains and losses of chemical components arising from the interaction of hydrothermal fluids with mafic tuff to produce the chemical sedimentary rocks have been calculated by the method of R.L. Gresens (1966). It is evident from this analysis that the auriferous sedimentary units represent alteration of mafic tuff at volume factors (fv) ranging from approximately unity, i.e. average host → 968 (constant volume), up to 4.6, i.e. host → 969 (a dilution of 1 tuff + 3.6 hydrothermal component). By taking an unweighted grand average of the volume factors, the composition of the sedimentary rocks is given approximately by 65 percent hydrothermal component plus 45 percent mafic tuff. In general, the hydrothermal contribution involves large additions of SiO_2, Fe_2O_3, CaO, and volatiles to the incorporated parent tuff, variable additions of MgO, together with small gains or losses of K_2O and Na_2O.

Taking into account the relative volume fractions of tuffaceous and hydrothermal components comprising the sedimentary rocks, and the trace element content of host tuff, it is evident that Au, Ag, As, Sb, Co, Ni, Zn, W, and Hg have been introduced predominantly from solutions, whereas all of the Ti, Al, V, Zr, Sc, and most of the F have a volcanic provenance. Chromium and copper have comparable contributions from both sources.

Calculations of this type for many chemical sedimentary rocks, including units at the Dome, Kerr Addison, Cheminis, and East Malartic mines, reveal that to a first approximation the auriferous units may be considered as variable mixtures of chemical sedimentary and tuffaceous components. It is important, therefore, when evaluating the overall metal distribution in lodes, to resolve the indigenous volcanic contribution : in many instances it can quantitatively account for the abundant transition metals present.

Campbell Shear Zone, Con Mine

The mineral assemblage of the principal rock types at Yellowknife, together with their deformed products, and hydrothermally altered products respectively have been documented by R.W. Boyle (1961) and J.F. Henderson and I.C. Brown (1966).

Country rocks adjacent to the major shear zones are predominantly epidote-amphibolite facies basalt, composed of actinolite, albite-oligoclase, epidote, quartz, magnetite, leucoxene ± carbonate ± chlorite. Within shear zones the basalt is transformed by deformation to basic schist with a retrograde greenschist facies mineralogy of chlorite, epidote, albite, with subordinate quartz, carbonate, leucoxene, and sulphides. In the alteration domains which envelop gold-bearing quartz veins, the chlorite schist has been transformed by chemical exchange with hydrothermal fluids to sericite-chlorite-ankerite-quartz schist, containing numerous sulphides, sulphosalts, tellurides, and native metals (see Breakey 1975).

Major and trace element data on host rocks and their altered equivalents adjacent to veins have been used to construct composition-volume diagrams (see Gresens 1966), in order to evaluate the volume factors for the hydrothermal metasomatism. Four of the diagrams are reproduced in Figure 11-2. Inspection of the diagrams re-

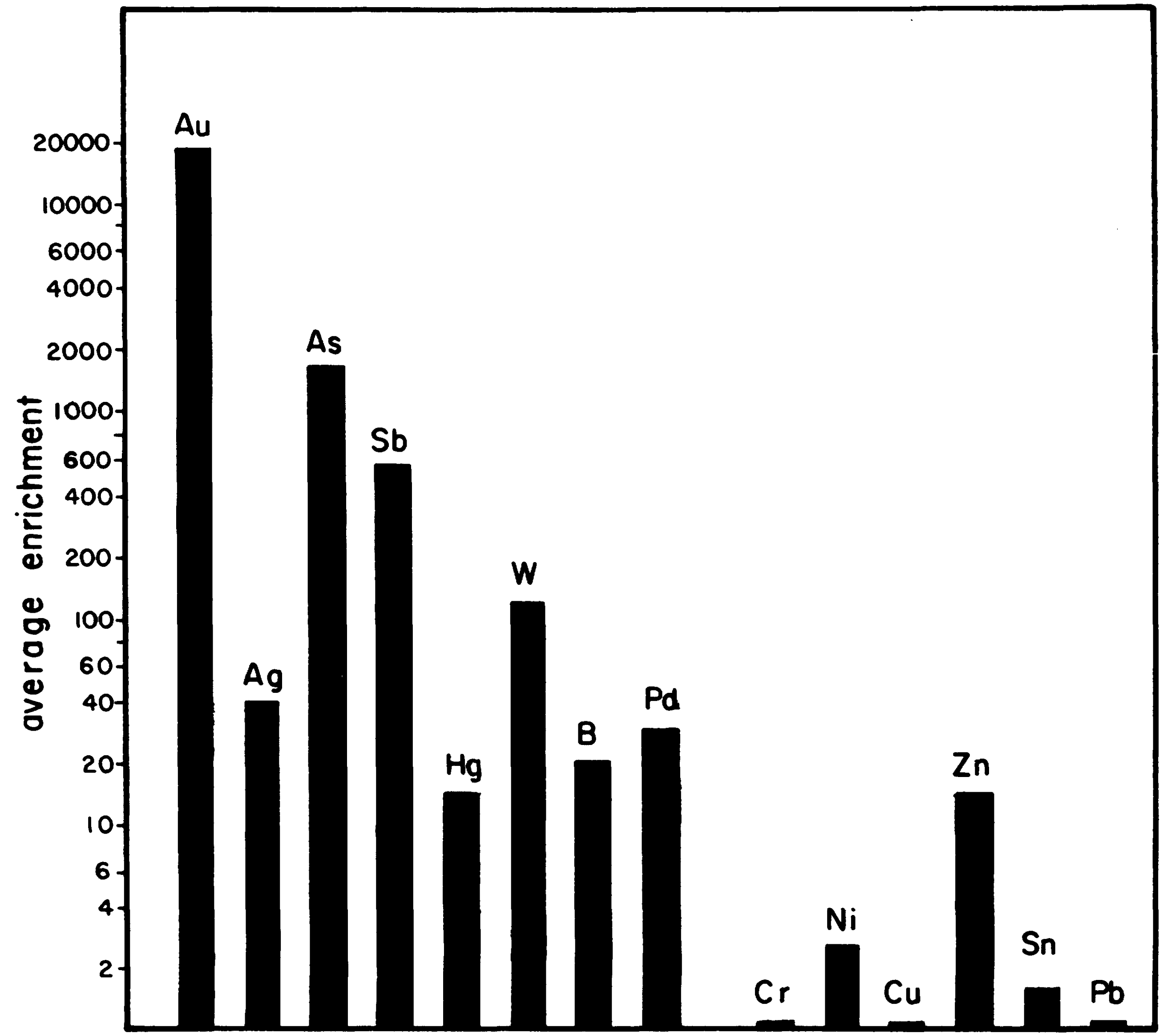

Figure 11-1—Average enrichment of selected elements relative to their intrinsic background abundance, Dickenson Mine, Red Lake.

Table 4 Abundances of major and selected trace elements in gold-bearing sediments and host rocks, Dickensen Mine, together with element abundances in primary basalts (major element oxides in weight percent, trace elements in ppm)

	967	968	969	970	KMI	971	972	973	974	974I	Primary Basalt[d]
SiO_2	64.31	50.24	63.71	56.90	49.94	60.72	60.52	52.89	38.91	57.92	49.8
TiO_2	0.31	0.85	0.15	0.62	0.33	0.93	0.87	0.92	0.28	0.55	2.3
Al_2O_3	5.18	13.23	3.31	9.24	5.63	14.62	13.39	14.82	1.29	8.78	14.7
Fe_2O_3	13.51	13.29	13.33	11.08	24.24	10.69	10.34	11.01	28.63	17.03	12.4
MnO	0.08	0.27	0.16	0.27	0.14	0.23	0.23	0.20	0.28	0.22	0.2
MgO	1.48	3.86	2.65	4.12	1.85	3.30	4.92	5.01	5.18	2.93	7.6
CaO	2.19	8.21	4.73	6.85	2.61	4.38	6.66	8.90	10.36	4.86	10.6
K_2O	0.72	2.07	0.45	1.30	0.43	1.90	1.88	0.68	0.07	1.19	1.0
Na_2O	0.19	0.41	0.11	0.43	0.08	0.26	0.43	0.56	0.10	0.15	2.4
P_2O_5	-	0.02	-	-	-	0.04	0.01	0.06	0.02	0.02	0.2
L.O.I[a]	10.87	7.83	10.19	7.84	17.94	3.61	1.31	6.15	17.96	7.27	
Total	98.84	100.28	98.79	98.65	103.19	100.68	100.56	101.20	103.08	10002	
Au	15	0·61	26	49	70	0·12	0·15	1·4	2·45	5·0	0.002[e]
Ag	4.1	5.4	3.1	3.1	6.2	3.1	3.0	6.2	5.2	2.1	0.11[f]
Pd	45		160		240						8
Li	32	36	18		36	92	98	51	10	35	17
Be	0.1	0.3	0.1	0.3	-	0.4	0.4	0.1	-	-	1
B	150	100	200		35	80	45	15	70	90	5
F	120	428	68	220	76	372	348	148	20	124	400
Cl	150	-	200	200	200	100	-	100	100	100	60
S%	5.4	4.0	9.3	7.6	5.70	0.7	0.20	0.20	9.90	5.40	0.03
As	16000	280	370	145	8400	210	1	1	380	105	2
Sb	200	320	20	20	280	36	18	20	20	20	0.2
Sc	16	42	14		15	45	42	42	34	23	30
V	94	240	57	198	123	270	264	270	98	146	250
Cr	116	209	81	152	149	222	207	231	131	181	170
Co	99	30	43	28	241	44	15	106	44	88	48
Ni	192	127	138	177	456	84	89	103	914	624	130
Cu	47	123	11	93	28	109	107	109	27	201	87
Zn	1390	72	79	4720	76	66	71	81	5076	87	105
Mo	-	-	-	-	-	-	-	-	-	-	1.5
Sn	-	-	-	-	-	-	-	-	3	3	1.5
W	-	20	-	-	60	90	20	70	-	40	0.4[g]
Hg	1200	92	360	6760	360	392	252	240	224	250	0.09
Pb	-	-	-	-	-	-	-	-	-	-	6
Th	-	-	-	-	-	-	-	-	-	-	4
U	0.2	-	-	-	-	0.2	-	-	-	-	1
Rb	24	51	19	36	13	50	47	29	10	32	30
Sr	16	81	35	58	16	74	78	75	11	34	465
Y	6	14	1	11	2	13	7	6	25	2	21
Zr	23	50	14	35	12	61	58	61	24	30	140
Nb	-	-	-	-	0.3	-	-	-	-	-	19
Cd	-	-	-	-	-	-	-	-	-	-	0.22
Ba	52	106	26	178	31	224	233	105	7	182	330
S.G.[b]	2.78	2.84	2.95	2.87	3.64	2.90	2.83	2.93	3.35	2.98	
Al/Ti	14.7	13.7	19.5	13.2	15.1	13.9	13.6	14.2	4.1	14.1	
Al/V	290	290	310	250	240	290	270	290	70	320	
Al/Sc	1710	1670	1250		1990	1720	1690	1870	200	2020	
Al/Y	4570	5000	17510	4440	14890	5950	10120	13070	270	23220	
Al/Zr	1190	1400	1250	1400	2480	1270	1220	1280	280	1550	
Fe^{2+} [c]						7.58	7.48				
$Fe^{2+}/\Sigma Fe$						0.71	0.72				

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[a] L.O.I. = weight percent loss on ignition at 1100°C. [b] S.G. = specific gravity ($2\sigma = \pm 0.01$). [c] Fe^{2+} expressed as Fe_2O_3. [d] data from Turekian and Wedepohl (1961). [e] data from Parthe and Crocket (1972) and Kwong and Crocket (1978). [f] data from Frueh and Vincent (1972). [g] data from Helsen et al (1978).

veals that, in general, the relatively immobile elements aluminum, yttrium, and zirconium behave coherently, and volume factors have been estimated from the average of the intersections of these elements on the isochemical axis.

The estimated volume factors vary systematically from 0.8 at the periphery of alteration envelopes to > 6 at vein margins where there is a significant admixture of gangue minerals to the basic schist. From mass balance calculations utilizing the calculated fv's, the essential chemical changes accompanying hydrothermal alteration are as follows. Additions of SiO_2 and volatiles occur in all the transformations considered, which is consistent with precipitation of quartz from cooling solutions, accompanied by hydration and fixation of CO_3^{2-} in carbonates. CaO and MgO are depleted at volume factors <1.3, but are added at fv's > 1.3. Na_2O is depleted and K_2O fixed over the entire range of volume factors. Small positive and negative variations of total iron occur at fv < 1.7, with additions at fv > 1.7. Precious metals, together with Cr, Ni, Co, Cu, Zn, Pb, and Rb have been added from hydrothermal solutions to the veins and altered wall-rocks. However, a variable proportion of most transition metals analyzed, and all of the V, is indigenous to the precursor basic schist.

The peripheral domains where fv <1 are interpreted in terms of hydrothermal leaching predominating over precipitation (Al_2O_3, Y, Zr all exhibit a similar proportional increase), whereas in the zones of fv >1 adjacent to veins (Al_2O_3, Y, Zr all exhibit a similar proportional decrease) the converse is believed to have operated.

Similar patterns of metasomatism, characterized by additions of SiO_2, volatiles and potassium, with abstraction of sodium, have been recorded from a number of alteration envelopes to gold-bearing veins.

Oxygen Isotope Relations in Au-Bearing Veins

A compilation of the $\delta^{18}O$ of minerals separated from gold-bearing veins and their host rocks, for several orebodies in the Yellowknife and Timmins areas, is given in Table 11-5. Analyses representing the maximum recorded variation in isotopic composition of individual vein systems are reported. The two salient features that emerge from inspection of the data are (1) the relatively uniform δ-values for vein quartz and for mineral fractionations within a given area, and (2) the close approach to isotopic equilibrium of quartz in host rocks with vein quartz.

In the Yellowknife area, vein quartz exhibits a narrow range of $\delta^{18}O$ from 11‰ to 13‰ in each of four different mineralized shear zone systems; and Δquartz-chlorite is relatively constant at 5.5‰ to 6.8‰. At the Dome mine, vein quartz has δ-values from 14‰ to 15.2‰ in all of five separate orebodies which are distinctive in their mineralogy and nature of the host rocks. Δquartz-muscovite and Δquartz-chlorite remain approximately constant at 3.5‰ to 4.0‰, and 5.5‰ to 6.1‰ respectively throughout the orebodies. The isotope systematics described above have also been recorded at the East Malartic and Lamaque mines, where the $\delta^{18}O$ of vein quartz has a small range of 12‰ to 13‰ and 13.5‰ to 14.5‰ respectively, and in each case mineral fractionations are relatively fixed.

Mineralized basic schist adjacent to gold-bearing veins has $\delta^{18}O$ whole rock of 10‰ to 15‰ (at Dome), and ~12‰ at Yellowknife, representing a shift of +2‰ to +8‰ from equivalent rock types remote from veins and with background abundances of gold. These data, taken in conjunction with the isotopic equilibrium between vein quartz and quartz in host rocks, are consistent with pervasive access of hydrothermal fluids to rocks along vein conduits, as independently deduced from the extensive reduction, elevated precious metal abundances, depletions of the REE, and magnitude of chemical alteration.

Thermal Conditions During Mineralization

Ambient thermal conditions during vein mineralization may be estimated from several independent lines of evidence. The mineral assemblage of basic rocks in alteration envelopes to vein systems, and in basic rocks external to veins, is quartz + albite, + muscovite + chlorite + epidote, implying lower greenschist facies metamorphic conditions for which temperatures of 350°C-450°C are quoted by F.J. Turner (1968) and A. Miyashiro (1973). The coexistence of abundant chlorite with almost pure albite (Ab_{94}) in veins and adjacent basic wall-rocks provides an upper limit of ~470°C for the ambient temperature, with reference to empirically determined thermal stability fields for these minerals (Liou *et al.* 1974).

Oxygen isotope fractionations between coexisting mineral pairs may be used to calculate the temperature at which minerals attained isotopic equilibrium. Isotopic temperatures have been calculated from quartz-muscovite fractionations using the three sets of published equations (Clayton *et al.* 1972; O'Neil and Taylor 1969; Bottinga and Javoy 1973; Blattner 1975); and from quartz-chlorite fractionations utilizing the equations given by Clayton *et al.* (1972) and D.B. Wenner and H.P. Taylor (1971). Temperatures are presented in Table 11-5. Given Δ quartz-muscovite = 3.4‰ at the Dome mine the equations referenced indicate 430°C, 480°C and 450°C respectively. A value of Δ quartz-muscovite = 3.8‰ corresponds to isotopic temperatures of 360°C, 400°C, and 470°C respectively. Quartz-chlorite fractionations yield temperatures of 420°C to 480°C.

Hence the temperature at which all the major gold-bearing vein systems were introduced is estimated at 380°C to 480°C. Similar calculations for orebodies in the Yellowknife area indicate mineralization temperatures of 320°C to 480°C.

Errors inherent in the calculated isotopic temperatures arising from the analytical uncertainty of ±0.18‰ amount to about ±30°C. These isotopic temperatures must be treated with caution because concordant isotopic equilibrium among mineral triplets is a necessary condition for obtaining reliable temperatures. An im-

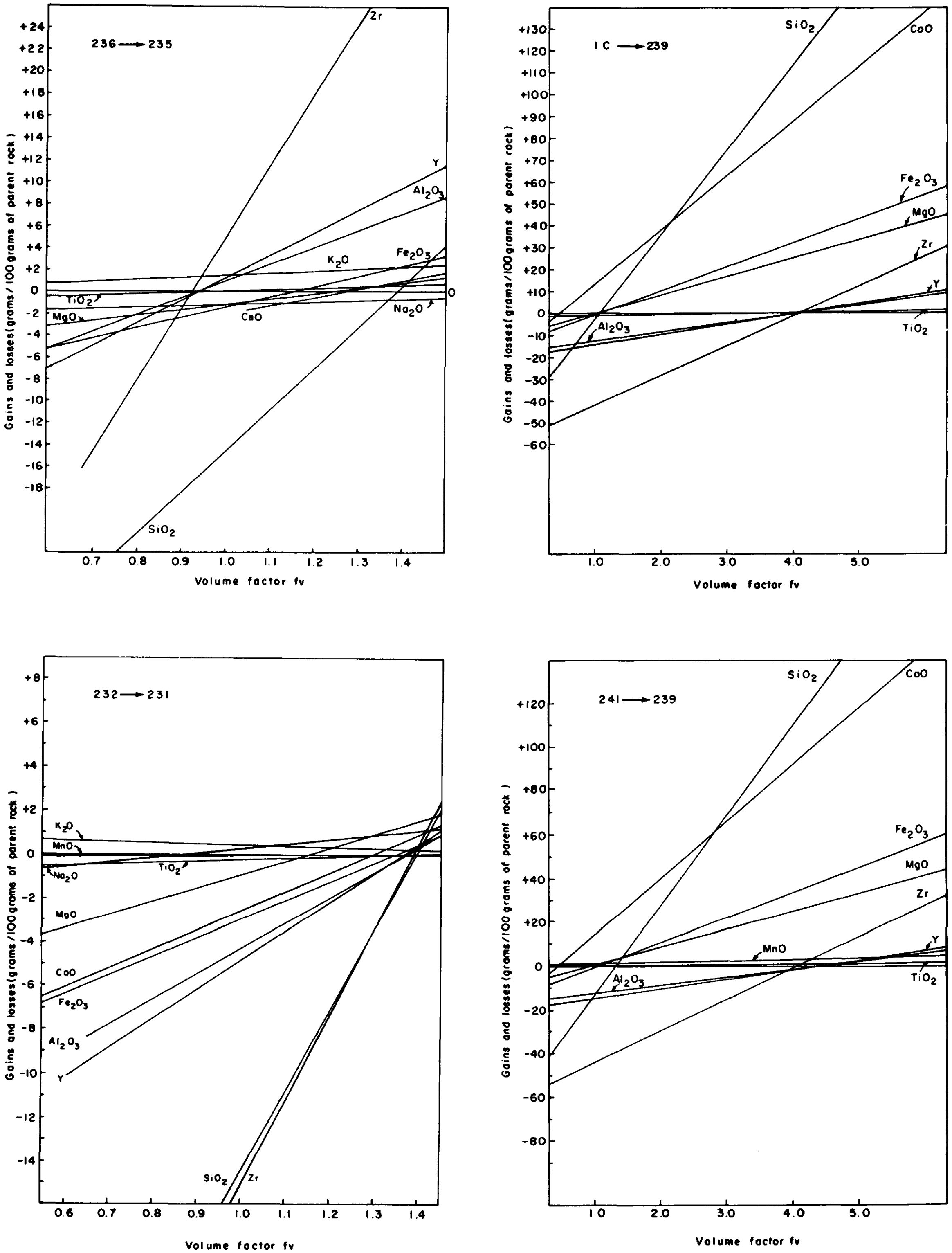

Figure 11-2—Composition volume diagrams for the transformation of basic schists to hydrothermally altered sericite schists, Campbell shear zone, Con Mine, Yellowknife.

Table 5 . Oxygen isotope composition of minerals separated from gold-bearing veins and their host rocks in mines from the Yellowknife and Timmins Districts, together with calculated isotopic temperatures and $\delta^{18}O$ fluid

		$\delta^{18}O$ vein quartz	$\delta^{18}O$ mineral	$\delta^{18}O$ host quartz	Δquartz-mineral	temperature*°C	$\delta^{18}O$ fluid
YELLOWKNIFE	gold-bearing quartz-	12.48		12.06			
DISTRICT	carbonate veins,2300	12.53	6.58 c		5.95	440	8.2
Campbell	in sericite-chlorite	11.50	5.97 c		5.53	480	7.9
shear	schist	11.59	7.03 m		4.56	320	7.5
	4900	11.43		11.29			
	5100	10.80					
Con shear	gold-bearing quartz-	12.25					
	carbonate veins, 250	11.50	5.97 c		5.53	480	7.9
	in sericite-chlorite	12.06		12.13			
	schist 1550						
Giant shear-	gold-bearing quartz-	12.28					
east zone	carbonate veins in	12.77		12.57			
H.G. zone	sericite chlorite	12.01					
open pit	schist						
Western gran-	gold-bearing quartz	13.03		13.70			
odiorite	veins emplaced into						
	shear zone within gran-						
	iorite						
Ptarmigan	gold-bearing quartz	12.60	6.67 c		5.93	440	8.2
	veins in metagreywacke	13.16		13.91			
Surface	gold-bearing quartz-	13.51	6.70 c		6.81	370	7.6
	carbonate veins in	13.56	7.45 c		6.11	420	8.9
	metabasalts						
DOME MINE -	banded quartz-muscovite	14.74	10.98 m		3.76		
TIMMINS	veins in ultramafic	14.41	11.28 m	14.66	3.13		
	schist	14.37	10.78 m		3.59	430	9.8
		14.52	10.54 m		3.98	380	8.8
		14.63		15.17			
	banded quartz-tourma-	15.07					
	line veins	15.24					
	veins in quartz-feld-	14.97		15.31			
	spar porphyry	13.93		13.87			
		14.19	8.05 c	14.26	6.14	420	9.6
	quartz-tourmaline veins	15.09	9.21 c		5.88	440	10.8
	in dacite	15.17	9.38 c		5.79	450	11.1
	quartz veins in Timis-	14.65		14.10			
	kaming slates	14.52		15.77			
		14.76	11.26 m		3.50	440	10.5
	quartz-carbonate veins	14.53	8.99 c	14.84	5.54	480	10.9
	in metabasic schists	15.20					
	quartz-carbonate veins	14.87	9.31 c	15.32	5.56	480	11.6
	parallel to auriferous						
	stratiform carbonate						
AUNOR MINE -	quartz veins parallel to	14.65					
TIMMINS	auriferous stratiform	15.01					
	carbonate						

c = chlorite, m = muscovite. * - mineral water equations for calculation of isotopic temperatures given in the text.

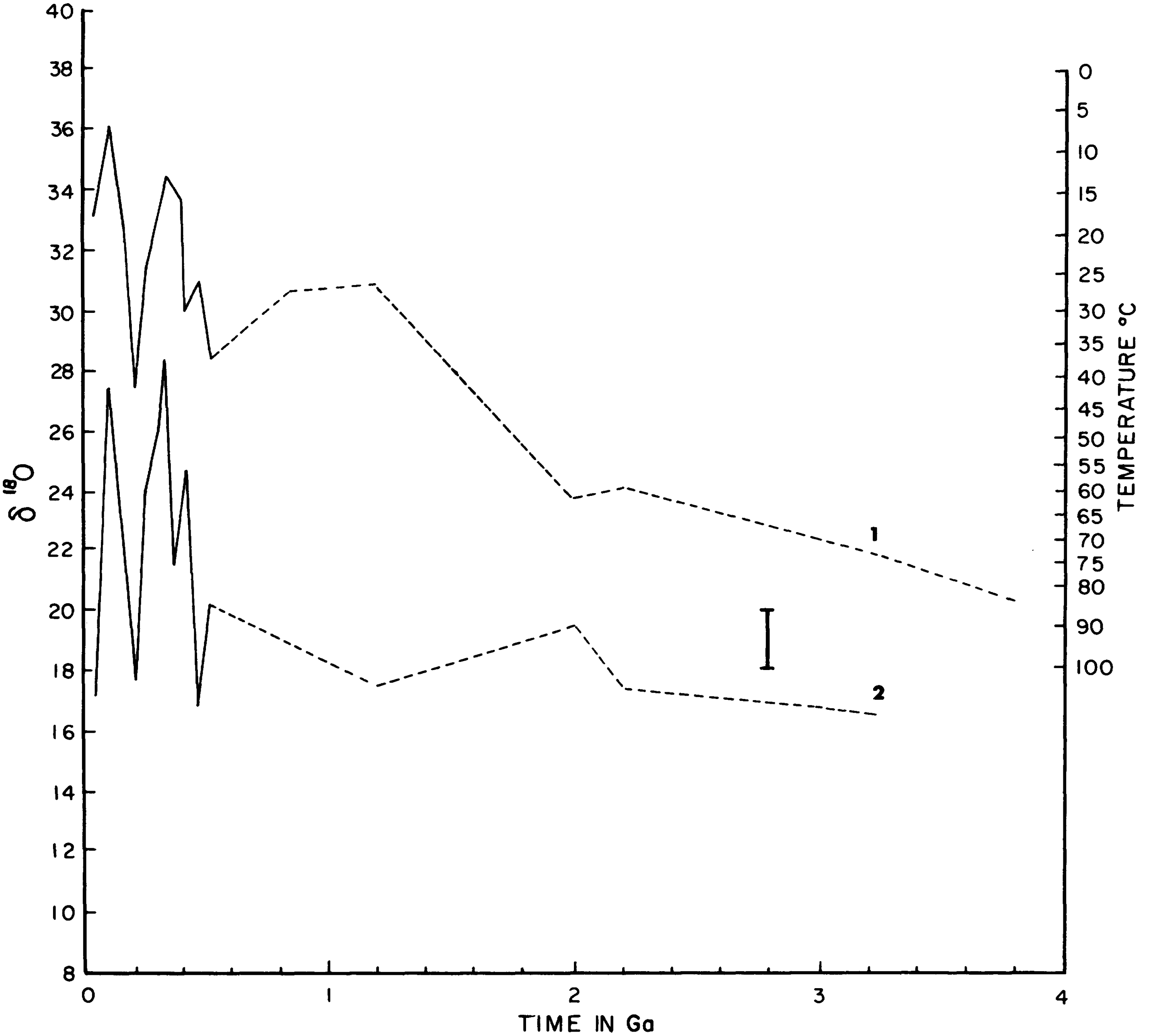

Figure 11-3—Compilation of the oxygen isotope variation of cherts with time, modified from Knauth and Lowe (1978). The upper and lower curves connect the largest and smallest - values respectively for chert at any given time. The bar represents the range in f-values recorded in this study for auriferous chert of 2.6 to 2.8 Ga.

Table 6. The $\delta^{18}O$ of quartz isolated from cherts in auriferous and other chemical sediments, together with analyses of the host rocks.

locality	rock type	chert	host rock		
		$\delta^{18}O$ quartz*	$\delta^{18}O$ quartz	$\delta^{18}O$ whole rock	$\delta^{18}O$ chlorite
DICKENSEN MINE-RED LAKE	mineralised metabasic tuffs and iron formation, enveloped by metabasalt	19.1	18.9	17.2	16.6
DOME MINE - TIMMINS	chert in mineralised carbonate chemical sediment, enveloped by metabasic tuff	17.6	15.5	14.4	13.8
AUNOR MINE - TIMMINS	chert in mineralised carbonate chemical sediment, enveloped by metabasic tuff	17.4			
E.MALARTIC MINE-VAL D'OR	chert in mineralised felsic tuff, enveloped by greywackes	15.0	12.8		
MORRO VELHO - BRAZIL	chert in mineralised carbonate chemical sediment, enveloped by metabasic tuffs	17.0	17.4	13.7	
YELLOWKNIFE DISTRICT	non-mineralised cherty felsic tuffs	14.2			

* - maximum value recorded

proved knowledge of the temperature at which gold-bearing veins were precipitated from hydrothermal solutions requires more extensive analyses of coexisting mineral triplets. However, the results obtained are consistent with independent estimates, and with fluid inclusion thermometry (Kerrich and Fryer 1979).

Oxygen Isotope Composition of the Hydrothermal Solutions

If the ambient mineralization temperatures derived above are broadly correct, then the calculated $\delta^{18}O$ of fluids from which the veins were precipitated is 10‰ to 11.6‰ at Dome, 7.5‰ to 9‰ at Yellowknife, and ~10‰ at East Malartic. These values are consistent with the range of $\delta^{18}O$ values of most fluids implicated in metamorphism (Taylor 1974), but are isotopically heavy relative to hydrothermal fluids of primary magmatic origin (involved in Cu and Mo porphyry systems), or seawater that has undergone enrichment in ^{18}O by high-temperature exchange with oceanic crust (involved in seafloor massive base-metal sulphides). The calculated $\delta^{18}O$ fluid of 8‰ to 9‰ for Yellowknife veins is close to the magmatic range. A magmatic origin is considered unlikely inasmuch as quartz veins in the nearby Western granodiorite pluton have $\delta^{18}O$ quartz of 8‰ and gold abundances of only 10-100 times background.

The data are compatible with the interpretation that within a given area the vein systems formed from a metamorphic-hydrothermal reservoir, or successive pulses of reservoirs, with a similar $\delta^{18}O$ and temperature.

It is important to note that there is a pronounced difference between the δ-values of vein quartz and either quartz in wall-rocks external to alteration envelopes or auriferous cherts (see Table 11-6). These relations contraindicate the hypotheses that vein quartz plus gold were co-derived by long-range diffusion from adjacent wall-rocks, or alternatively by remobilization of auriferous chemical sedimentary rocks under conditions that were closed isotopically and with respect to fluids.

The dominant gangue mineral in most large-scale veins is quartz. However, there exists major differences between individual veins within a given mine (e.g. Dome) in terms of the relative proportions of quartz and other gangue minerals such as carbonates, tourmaline, albite, chlorite, or muscovite, and in the relative abundances of metal oxides and sulphide minerals. If the inferred uniformity in $\delta^{18}O$ fluid and temperature for distinct vein systems has validity, then some of the variability in mineralogy may be accounted for by fluid wall-rock reactions. For example, the empirical observation generally holds that where veins transect ultramafic rock, and iron formation, the carbonate gangue is dominated by magnesite, ferroan dolomite, and siderite respectively.

Summary

The hydrothermal solutions involved in gold-bearing vein stockworks within given regions were at a relatively high uniform temperature (~350-450°C), and uniform $\delta^{18}O$. The oxygen isotope composition of fluids is within the range of δ-values for metamorphic fluids. The most probable source for such mineralization solutions is fluids evolved by dehydration reactions proceeding during prograde metamorphism at depth. Some of the vein constituents (e.g. quartz, Au) were introduced in solution, whereas other components such as carbonates may have been derived over metre distances from the adjacent wall-rocks (see Section "Chemical Relations between Lodes and their Host Rocks").

Oxygen Isotope Relations in Au-Bearing Chemical Sedimentary Rocks

Among the essential questions pertaining to chemical sedimentary rocks enriched in gold are the source and temperature of the mineralizing hydrothermal fluids, and the extent to which such fluids equilibrated with the hydrosphere during discharge. In an attempt to resolve these problems the oxygen isotope composition of pure chert (> 90 percent SiO_2) within auriferous chemical sedimentary rocks and their enveloping host rocks has been determined from several Archean gold camps. The maximum δ-values for sedimentary rock units are compiled in Table 11-6. In addition to providing information on the auriferous hydrothermal fluids, the data have a bearing on the isotopic and thermal evolution of the hydrosphere. It is therefore appropriate first to outline the parameters which determine the $\delta^{18}O$ of marine chert, and the results are then discussed within this context.

Implications for the Evolution of the Oceans

The principal factors which may influence the oxygen isotope composition of authigenic minerals and chemical precipitates formed in the presence of marine water have been comprehensively discussed by L.P. Knauth and D.R. Lowe (1978. These are:

1) the ambient temperature;
2) the $\delta^{18}O$ of ocean water, or pore water;
3) the magnitude of mineral-water fractionations;
4) transformations of chemical precipitates to mineral phases;
5) effects of post-depositional isotope exchange;
6) involvement of low ^{18}O terrestrial meteoric water, in a nearshore environment.

If the magnitude of post-depositional isotope exchange is small or of known extent, and mineral-water fractionations are accurately established for the low-temperature range of interest, then, as Knauth and Lowe (1978) point out, the $\delta^{18}O$ of chert may record information pertaining to surface conditions in the past.

From compilations of the $\delta^{18}O$ of marine chert of various ages a secular trend of ^{18}O enrichment is evident, from maximum values of 20.4‰ in the Isua cherts of 3.8 Ga (Perry *et al.* 1978), to 22.1‰ in primary chert of the Onverwacht Group, age 3.4 Ga (Knauth and Lowe 1978), to values of 33‰ - 36‰ in recent marine chert (Knauth and Epstein 1976). This secular variation in the $^{18}O/^{16}O$ ratios of chert was originally identified by E.G. Perry (1967), with subsequent refinement by E.C. Perry and F.C. Tan (1972), and most recently by Knauth and Lowe (1978) as more data became available (see Figure 11-4). A similar progressive enrichment in ^{18}O of marine carbonates through time has also been recorded by Schaidlowski *et al.* (1975) and J. Veizer and J. Hoefs (1976). $^{18}O/^{16}O$ ratios for the Archean auriferous chert typically fall within the range of δ-values for marine chert of ~2.8 Ga given by Knauth and Lowe (1978) (see also Sawkins and Rye 1974).

The secular variation in the $^{18}O/^{16}O$ ratios of chert has been interpreted in a number of different ways:

1) post-depositional isotope exchange with low-^{18}O meteoric waters (Degens and Epstein 1962);

2) secular changes in the oxygen isotope composition of ocean water (Perry 1967; Perry and Tan 1972; Perry *et al.* 1978);

3) decrease in temperature of the hydrosphere from ~80°C at 3.8 Ga to contemporary ocean bottom water conditions (Knauth and Epstein 1976; Knauth and Long 1978).

Knauth and Lowe (1978) present a comprehensive discussion of these three hypotheses. They demonstrate that metamorphism may either lower or raise the $\delta^{18}O$ of chert, depending on the ambient temperature and $\delta^{18}O$ fluid, and that some Archean chert cannot have experienced shifts of > – 0.7‰. Thus it is unlikely that post-depositional exchange accounts for the steady secular change in $^{18}O/^{16}O$ ratios of chert.

Knauth and Epstein (1978) have argued cogently that fluctuations in the $^{18}O/^{16}O$ ratios of Phanerozoic chert are due to climatic changes, and this reasoning has been extended by Knauth and Lowe (1978) to interpretation of the overall secular change in terms of a progressive decrease of terrestrial surface temperature from ~80°C at 3.8 Ga to present conditions. Compelling independent evidence for higher initial surface temperatures include:

1) the paleontological record, for which F. Hoyle (1972) pointed out that the order of emergence of organisms correlates with their temperature tolerance;

2) isotopic data that indicates uniform δD, $\delta^{18}O$ for ocean water and warmer Archean climates (Taylor and Magaritz 1975);

3) theoretical modelling of atmospheric greenhouse effects are compatible with the proposed thermal history (Sagen 1972);

4) sedimentological evidence which favours relatively warm conditions in the Onverwacht Group (Knauth and Lowe 1978).

The suggestions of Perry *et al.* (1978) that the secular trend is due to changes in the isotopic composition of seawater at approximately constant surface temperatures is difficult to reconcile with the aforementioned evidence. The low ^{18}O of Archean chert would require ocean water with a $\delta^{18}O$ of – 12‰ to – 14‰ at 3.8 Ga. However, K. Muehlenbachs and R.N. Clayton (1972) have argued that ocean water is buffered close to present values of 0‰ by isotope exchange with basalt at the mid-ocean ridges, during thermal convection.

If Archean ocean water was isotopically light, then it is probable that igneous rocks intruded in proximity to the hydrosphere, and cooled by ocean water in a submarine geothermal system, would exhibit markedly ^{18}O depleted systematics. This is by analogy with low ^{18}O surface continental intrusions at high latitudes, which attain an isotopically light character by exchange with low ^{18}O meteoric waters (Taylor and Forrester 1971; Taylor 1968), during thermally driven convective cooling. Kerrich and Fryer (1979) have shown that this is not the case in the example of the Preston Porphyry, Timmins. This is an Archean quartz-feldspar porphyry that has been spilitized by low-temperature reactions with ocean water. The quartz-feldspar fractionation value is approximately – 2 percent.

In addition, quartz-chlorite fractionations of ~8‰ in footwall rocks to the Mattagami Lake massive base-metal sulphide imply mineralizating fluids of ~0‰ at 250-300°C, i.e. hot seawater. These data are not consistent with an Archean ocean that was isotopically light.

The oxygen isotope data for Mattagami and the Preston Porphyry provide a fix on the $\delta^{18}O$ of the Archean ocean at ~0 percent, and it is therefore likely that the ocean has been buffered close to this value throughout most of geological history by basalt-seawater interaction. A corollary to this, taking into account the secular variation in $\delta^{18}O$ of chert, is that the ocean was hotter in the Archean, and has progressively cooled to ambient temperatures, with periodic fluctuations during ice ages.

In the light of the above discussion, the oxygen isotope compositon of the Archean gold-bearing chert analyzed conforms to the range of δ-values for marine chert at ~2.8 Ga (cf. Knauth and Lowe, 1978; Figure 11-4). It is probable therefore that the chert, and hence the auriferous hydrothermal solutions, attained a large measure of thermal and isotopic equilibrium with marine water at the ambient temperature of ~60°C. This conclusion is corroborated by REE distributions in some of the chert, which have patterns typical of Archean marine chemical sedimentary rocks (Fryer 1978; Kerrich and Fryer 1979).

There is a small systematic depletion of ^{18}O in the auriferous chert compared to the maximum inferred δ-values for marine chert of the appropriate age (Figure 11-4), ranging from – 3‰ at the Dickenson mine, Red Lake, to – 5‰ for the Dome mine, Timmins. This depletion could arise from post-depositional isotope exchange during diagenesis and/or metamorphism. Alternatively, it could reflect a slight increase of the ocean bottom water temperature (by 30 to 60°C) due to the discharge of heated mineralizing fluids. The inferred overall approach to thermal and isotopic equilibrium of auriferous chert with ambient marine water contrasts with some massive base-metal sulphide deposits where the $\delta^{18}O$ of quartz is much lower (8‰ to 12‰), and is believed to represent equilibrium with hydrothermal fluids at 200-300°C, possibly in gravitationally stable brine pools. Hence with laterally extensive auriferous chemical sedimentary rocks the hydrothermal discharge must have mixed efficiently with a larger quantity of seawater, reflecting the properties of the hydrothermal plume and/or seafloor topography.

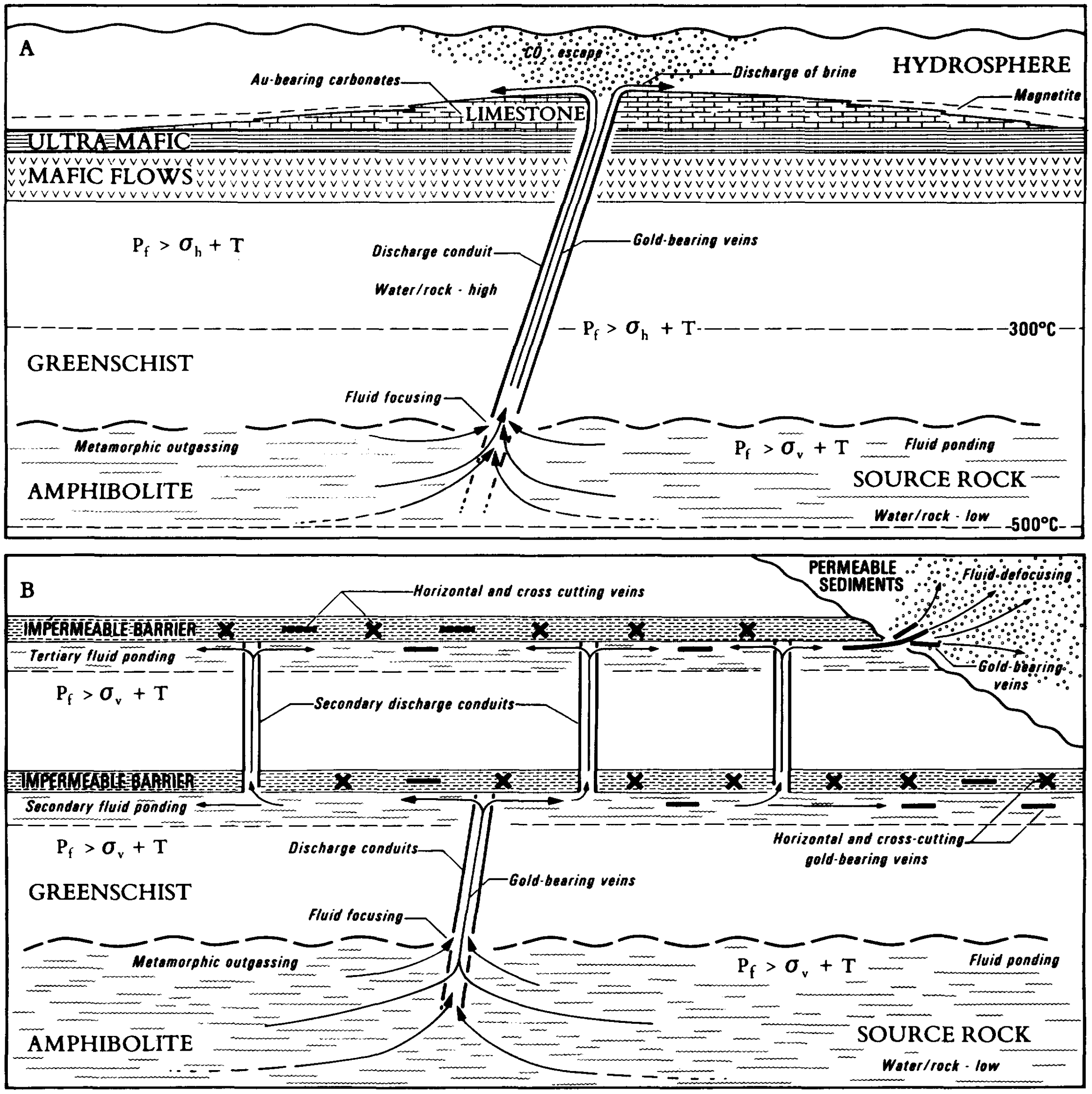

Figure 11-4—Schematic diagram of model for lode gold deposits. A–Direct discharge into hydrosphere. B–Ponding beneath permeability barriers.

Tuff Plus Chemical Sedimentary Rocks

Tuffaceous rocks with variable proportions of admixed chemical sedimentary rocks are a typical feature of stratigraphic sections in 'greenstone' belts. In contrast to pure chert which is > 90 percent SiO_2, the tuffaceous rocks may be characterized by a significant aluminum content, and ratios of aluminum or titanium to the relatively immobile trace elements (e.g. Al/Y, Ti/Zr) that to a first approximation reflect the chemical composition of the felsic, mafic, or ultramafic volcanic provenance. These rocks may be substantially enriched in gold as in the felsic tuffaceous chert at the East Malartic mine (0.1 - 30 ppm), and the mafic tuffaceous carbonate at the Dome mine; or they may have low gold abundances, as in the example of the Townsite felsic tuffaceous chert at Yellowknife (0.8 - 6 ppb).

In the manner in which the chemical composition of such rocks broadly reflects the extent of dilution of the volcanic component by chemical sedimentary rocks, so the $\delta^{18}O$ of quartz is intermediate between δ-values for the seawater-altered volcanic component and for pure chert. Thus, at the East Malartic mine it is possible to trace laterally in a single stratigraphic unit a progression from a dominant felsic pyroclastic rock with subordinate chert, to almost pure chert containing minor quantities of fine-grained pumice fragments. The $\delta^{18}O$ of quartz isolated from this unit varies from ~12‰ in the felsic pyroclastic rock to ~17‰ in the chert.

Isotopic Characteristics of the Host Rocks

Unmineralized Background Rocks

Basic volcanic rocks with background precious-metal abundances (<4 ppb Au) have $\delta^{18}O$ whole-rock values of 7 to 10‰, and average $\delta^{18}O$ or quartz of 12‰ (Table 11-4). Taylor (1968) has shown that fresh submarine basalt has $\delta^{18}O$ whole-rock of 6±0.5‰. The enrichment in $\delta^{18}O$ recorded for basic volcanic rocks relative to primary submarine basalt is attributed to oxygen isotope exchange with seawater at low temperatures in the order of 150°C, during thermally driven convective cooling of the oceanic crust. Muehlenbachs and Clayton (1972) and M. Magaritz and H.F. Taylor have discussed this process of ^{18}O enrichment associated with low-temperature hydrothermal alteration of submarine basalt.

In many gold camps of Archean age, such as the Porcupine and Kirkland Lake areas, there is a close spatial association between small bodies of quartz-feldspar porphyry and auriferous chemical sedimentary rocks (Karvinen 1979). Analyses of unmineralized parts of two such bodies, the Preston and East Malartic porphyries, reveal erratic isotopic relationships, with $\delta^{18}O$ whole-rock of 9‰ to 12‰ and Δquartz-albite +2.4‰ to −2.5‰. Based on the whole-rock δ-values these igneous bodies, which are tonalitic in composition, belong to the class of high ^{18}O 'granites' of Taylor, and compare to $\delta^{18}O$ whole-rock of about 8‰ for granitic rocks of normal oxygen isotope compostion. The data are interpreted in terms of medium- to low-temperature interaction with marine water of ~0‰ as inferred for the mafic volcanic rocks, producing the shift towards the high recorded $\delta^{18}O$ values. The positive quartz-feldspar fractionations may correspond to hydrothermal alteration by seawater at temperatures of 200-350°C. Negative quartz-feldspar may indicate that hydrothermal alteration proceeded at <200°C, such that feldspars continued to exchange oxygen with fluids down to lower temperatures than quartz (Wenner and Taylor 1976).

In view of the close association in space and time of the felsic stocks and their extrusive equivalents with mafic submarine volcanism and chemical sedimentary rocks, it is likely that the felsic bodies were emplaced in proximity to the hydrosphere. Emergence of the Preston Porphyry (Dome mine) onto the seafloor is indicated by field evidence that Timiskaming slates above the porphyry are tuffaceous derivatives of the latter, and this is confirmed by REE data. Many of these felsic igneous bodies and mafic flows exhibit independent chemical features of low-temperature spilitization, such as hydration, oxidation, and sodium addition via albitization, relative to the chemical composition of pristine trondhjemite or basalt respectively (Fyfe and Lonsdale 1979). The presence of anhydrite + calcite + hematite at the margins of certain felsic intrusions such as the Pearl Lake Porphyry and Lamaque granodiorite provides mineralogical evidence for large-scale downward penetration of cool, oxidized surface water.

Hence, during shallow emplacement, the felsic bodies cooled by convective motion of seawater over a substantial temperature range, giving rise to the erratic Δ quartz-feldspar.

In summary, most volcanic and shallow igneous intrusions appear to have undergone low-temperature spilitization by ocean water, but this did not involve substantial enrichment of gold in these rocks during spilitization. What is not clear is if any genetic relationship exists between the felsic bodies and auriferous chemical sedimentary rocks. Cooling of the felsic bodies may have initiated a seawater convective system discharging onto the seafloor, as auriferous precipitates, but if this is so the overall low base-metal content must be accounted for. Alternatively, thermal contraction fractures due to crystallization and cooling of the igneous bodies may have propagated downward to trigger the release of a hydrothermal reservoir ponded at depth.

Mineralized Tuffaceous Host Rocks

Tuffaceous wall-rocks to the chemical sedimentary rocks at the Dickenson and Dome mines are composed principally of actinolite + chlorite + biotite, with minor quantities of albite + muscovite, and a small fraction of incorporated chert laminae. The whole-rock oxygen isotope composition of the mafic tuff at 15.8‰ to 17.2‰ is unusually heavy compared to fresh submarine basalt, or the low-temperature seawater altered equivalents which range up to ~14‰, as discussed above. Possible explanation for extreme enrichment compared to average altered basalt are discussed below.

The $\delta^{18}O$ of chlorite separates at 16.8 to 17.0‰ is close to the whole-rock δ-values (Table 11-4), reflecting both the predominance of chlorite and the relatively low magnitude of oxygen isotope partitioning between chlorite, biotite, and hornblende (Javoy 1977). The Δquartz-chlorite values of < +2‰ are much too small to represent equilibrium oxygen isotope fractionations at temperatures within the thermal stability limits of chlorite.

The unusually heavy $^{18}O/^{16}O$ ratios of whole rocks, and small Δ quartz-chlorite can be interpreted in several ways: 1) chlorite crystallized under essentially closed isotopic conditions during metamorphism from a precursor phase, with a mineral-water fractionation close to that of quartz at the ambient temperature of seafloor precipitation; 2) hydrothermal solutions which are assumed to have debouched onto the seafloor to form the auriferous chemical sedimentary rocks, became capped by deposition of the overlying tuff, and thus were essentially isolated from ocean water beneath a thermal barrier (cf.

sedimentary thermal blanketing of hydrothermal systems at mid-ocean ridges, Davis and Lister 1977). The $\delta^{18}O$ and temperature of the ponded reservoir were such that chlorite, or its precursor, became enriched in ^{18}O, but temperatures were insufficient for the chert to undergo complete oxygen isotope exchange to yield an equilibrium quartz-chlorite fractionation.

Observations of weathered ocean floor basalt reveal that the most abundant low-temperature alteration products are clay minerals and zeolites (Andrews 1977). The $\delta^{18}O$ of coexisting authigenic quartz and clay minerals in warm sedimentary environments may be estimated by linear extrapolation of the empirically determined quartz-illite partition equation of E.V. Eslinger and S.M. Savin (1973a) and H.W. Yeh and S.M. Savin (1977) to lower temperatures. Based on the premise of hotter oceans in the Archean (as discussed above), chert precipitated from marine water of ~0‰ at 60°C would have a $\delta^{18}O$ of ~27‰, and the corresponding value for illite would be ~17‰, giving a Δ chert-illite of 10‰. These calculated δ-values for illite are consistent with independent measurements of $\delta^{18}O$ illite formed at known low temperatures (James and Baker 1976; Eslinger and Savin 1973b).

Analysis of smectite formed as low-temperature alteration products of basalt in the presence of ocean water (~0‰) range from 20‰ to 29‰ (Muehlenbachs and Clayton 1976; Perry *et al.* 1975; Lawrence *et al.* l979). At 60°C, 1000 $\ln\alpha$ smectite-water = 19.3‰ giving $\delta^{18}O$ quartz-smectite = 7.8‰ (Yeh and Savin 1977). Quartz-clay fractionations are lower by about 2‰ at 60°C if the empirical chert-water equation of L.P. Knauth and S. Epstein (1976) is solved simultaneously with the clay-water equations of Yeh and Savin (1977). From these considerations it is evident that the magnitude of quartz-clay fractionations at 60°C is too large to satisfy the observed quartz-chlorite systematics at Red Lake, if smectite + illite were dominant seawater alteration products of the mafic tuff, and hence precursors of metamorphic chlorite.

Determinations of the $^{18}O/^{16}O$ ratios of authigenic zeolites in low-temperature altered ocean floor basalt yield mineral-water fractionations significantly larger than for clays (Savin and Epstein 1970). For example, phillipsite ($[\frac{1}{2}Ca, Na, K]_3[Al_3Si_5O_{16}].6H_2O$) formed in equilibrium with seawater of 0‰ at ocean floor temperatures has a $\delta^{18}O$ of 33 to 34‰ with a value of α phillipsite-water of 1.034 (Savon and Epstein 1970), which is close to Δ quartz-water at 1.039.

It is possible, therefore, that the unusually heavy isotopic composition of the mafic tuff was partially inherited from precursors such as phillipsite and smectite which formed as alteration products of mafic rocks, in equilibrium with ocean water of ~0‰ at~60°C. However, from the reasoning above, even if the mafic rock was quantitatively converted to smectite + phillipsite, this alone cannot completely account for the small observed quartz-chlorite.

Muehlenbachs and Clayton (1976) have estimated that recent submarine basalt undergoes ^{18}O enrichment during progressive weathering at a rate of +0.25‰ per Ma, corresponding to a conversion of 1 percent basalt to clay per Ma. If the mafic rocks were altered to clay minerals and zeolites during submarine weathering, then the process must have been more rapid. Faster rates of weathering are likely in view of the probably higher ocean temperatures, and fine-grained nature of the mafic pyroclastic material.

If the second interpretation has validity, then the temperature of ponded fluids must have been significantly less than 340°C. Clayton *et al.* (1968) have demonstrated that detrital quartz in the presence of heated meteoric water is resistant to oxygen isotope exchange at temperatures below 340°C. However, there is a strong grain size dependence on the rate of isotope exchange reactions, and microcrystalline quartz with a grain diameter of 2-30 μm comprising chert is known typically to undergo shifts in ^{18}O of −2‰ to −6‰ during diagenesis and low-grade metamorphism (Becker and Clayton 1972; Margaritz and Taylor 1976), although this is not invariably the case (cf. Knauth and Lowe 1978).

Assuming temperatures (T) of $100°C < T < 250°C$ for the ponded metamorphic fluids, chlorite could have been enriched in $\delta^{18}O$ to the observed value of ~17‰ by equilibrium exchange with fluids having a $\delta^{18}O$ between 10.5‰ (for 100°C) and 15‰ (for 250°C). Similar calculations reveal that illite would shift to 17‰ by exchange with fluids having a $\delta^{18}O$ between 4‰ (for 100°C) and 12‰ at 250°C. This assumes illite to have been a precursor to chlorite, with a final δ-value close to that of chlorite. Involvement of smectite and/or phillipsite as a chlorite precursor would slightly lower the calculated $\delta^{18}O$ fluid over the given temperature range. These estimated δ-values for a ponded reservoir are consistent with the range of $\delta^{18}O$ of most fluids implicated in metamorphism (Taylor 1974), but are isotopically heavy relative to evolved seawater that has undergone enrichment in ^{18}O by high-temperature exchange with oceanic crust. Fluids with a δ-value in the estimated range could have been evolved by dehydration reactions involving zeolite or greenschist-facies rocks (see Fyfe *et al.* 1978).

There is no simple way of discriminating between the two alternatives given the available evidence. As stated above, warm ocean temperatures are likely to have promoted rapid submarine weathering of tuff to clay minerals and zeolites. The presence of pervasive quartz-carbonate veining within chemical sedimentary rocks and their host rocks at the Dickenson, Dome, Aunor, and Kerr Addison mines may represent evidence for local breaching of a ponded hydrothermal reservoir. This interpretation is supported by a uniform pattern of sodium depletion and potassium addition in the mineralized tuff, which parallels the behaviour of these elements in alteration envelopes adjacent to major gold-bearing quartz veins. However, these chemical features are distinct from the trend of sodium addition from albitization observed in low-temperature seawater spilitized mafic volcanic rocks and felsic porphyries, and this implies that the inferred ponded fluids responsible for altering the rocks were out of hydrological communication with the ocean. Hence it is possible that both of the proposed mechanisms have operated to produce the ^{18}O enriched basic tuff, and ^{18}O low quartz-chlorite.

Oxidation-Reduction Reactions

Mineralized basic rocks which envelop gold-bearing hydrothermal veins and sedimentary rocks display a strongly reduced state of iron ($Fe^{2+}/\Sigma Fe > 0.9$) relative to the oxidation state of unmineralized mafic volcanic rocks, and primary igneous rocks worldwide ($Fe^{2+}/\Sigma Fe \cong 0.7$). These redox relations are evident from inspection of Table 11-7, where data on total iron, ferrous iron, and the ratio of Fe^{2+} ΣFe are compiled for a number of gold-bearing rocks adjacent to veins, and their unmineralized equivalents. Note that although total iron and Fe^{2+} vary in abundance within a given set of samples, as indicated by large values for the standard deviations, the ratio exhibits a low variance. Reduction in rocks adjacent to auriferous veins was noted by G.W. Bain (1933). Inasmuch as rocks are generally resistant to changes of oxidation state during metamorphism the observed dominance of Fe^{2+} requires the introduction of large volumes of reductant in the auriferous hydrothermal solutions. It is probable that the reductant involved is hydrogen, which is a product of the dissociation of water in equilibrium with the QFM buffer system at elevated temperatures (Eugster 1959; Eugster and Wones 1962; Eugster and Skippen 1967).

The extreme reduction observed in wall-rocks implies extensive interaction with fluids originating under high-temperature reducing conditions. Hydrogen fixation in wall-rocks takes place in response to the difference in equilibrium hydrogen pressure at decreasing temperature-pressure states, as the mineralizing solutions ascend through the crust. Estimates of minimum fluid/ rock ratios obtained from shifts in the oxidation state are > 3:1 (see Kerrich *et al.* 1977). REE distributions in veins and wall-rocks to veins exhibit marked positive Eu^{2+} anomalies, which provides independent evidence for chemical exchange with fluids of low redox potential (Kerrich and Fryer 1979).

Locally, where vein systems intersect carbonaceous sedimentary rocks such as in stope 15-26-16 at the Pearl Lake Porphyry, or in Carlin type deposits (Roberts *et al.* 1971), carbon may act as the reductant.

In contrast to the pattern of reduction accompanying Au-mineralization described above, most rocks enriched in gold at the East Malartic mine are oxidized relative to background (Table 11-7), and have high contents of sodium. They thus exhibit chemical features typical of low-temperature ocean floor spilites. Patterns of oxidation with concomitant albitization have also been recorded for parts of the Lamaque granodiorite, Pearl Lake Porphyry, and Preston Porphyry, where hematite + carbonate + anhydrite are locally abundant. The time relations of oxidation to gold enrichment have not been adequately evaluated; but in at least one example of a major gold-bearing quartz vein transecting the Preston Porphyry (Dome mine) a reductive halo around the vein is clearly superimposed on a pre-existing oxidative alteration.

Oxidation accompanying hydrothermal alteration of the ocean floor has been discussed by E.T.C. Spooner and W.S. Fyfe (1973), A.J. Andrews and W.S. Fyfe (1976), and E.T.C. Spooner *et al.* (1977).

Hydrological Regime

The geometrical relations of vein systems in many Archean auriferous provinces indicate fluid discharge during hydraulic fracturing with P_{fluid}, $>\sigma_1 + T$ (where σ_1 is the maximum principal stress and T is the tensile strength of rock), and hence hydrothermal fluid reservoirs at greater than three times hydrostatic pressure (Kerrich and Allison 1978). For example, the presence of extensive gold-bearing quartz veins in a horizontal orientation beneath impermeable carbonate sedimentary rocks in the Porcupine area implies fluid ponding, and requires that the hydraulic pressure exceeded the lithostatic pressure (σ_v) (Fryer *et al.* 1979). The principal crustal regime where anomalously high fluid pressures are generated is during prograde metamorphism, due to the volume relations of metamorphic dehydration reactions (Fyfe *et al.* 1978), and differential thermal expansion of pore fluids (Norris and Henley 1976).

In contrast, during free convection of fluids in communication with the terrestrial surface the hydraulic pressure approximates hydrostatic conditions given by $P_{fluid} = pgh \cong \frac{1}{3}\sigma_{vertical}$ (where p is the fluid density, g is the gravitational acceleration, and h is depth). Thus the anomalously high pressure fluids implicated in gold-bearing veins are believed to be generated in a fundamentally different crustal-hydrological environment from fluids convecting in near surface geothermal systems associated with massive base-metal sulphides and epithermal deposits.

A common feature of stratiform lode gold deposits is the presence of tuffaceous rocks as a component of the chemical sedimentary rocks and/or as their host rocks. Thus, at the Kerr Addison and Cheminis mines certain gold-bearing stratigraphic units are comprised of a variable mixture of sedimentary carbonate plus ultramafic tuff, hosted by ultramafic rocks; at the Dome mine ferroan dolomite sedimentary rocks containing Au have a mafic tuffaceous component; and at the East Malartic mine auriferous chert incorporating felsic tuff is hosted by felsic pyroclastic rocks and greywacke. As discussed above in the section 'Distribution of Elements and their Relative Separation', the nature of the tuffaceous component in chemical sedimentary rocks, even when highly 'diluted', may be deduced in most instances from inspection of the ratios of the relatively immobile major and trace elements.

The association of tuffaceous or fragmental volcanic rocks with massive base-metal sulphides has been known for a long time (Sangster 1976); and has been accounted for in terms of either a magma chamber encountering a groundwater system, or of a mafic magma impinging upon a felsic magma and thereby superheating it (Chapin and Elston 1979; Sparks *et al.* 1977; Franklin 1976).

However, in a groundwater system under hydrostatic conditions the fluid would be out of equilibrium with a magma where P magma = P load ≅ 3 P fluid, and there would be no tendency for water to enter a liquid magma

Table 7. Summary of data for the oxidation state of iron in background and Au-mineralised rocks.

Mine	Rock description	Σ Fe	Fe^{2+}	$Fe^{2+}/\Sigma Fe$	Statistical functions*	Mean Au ppm
CON and GIANT MINES-YELLOWKNIFE	Epidote - amphibolite metabasalt - unmineralised	8.23 (1.168)	6.28 (0.950)	0.76	0.028 11	0.002
	Chlorite schist - unmineralised	8.76 (1.496)	6.88 (1.257)	0.78	0.056 15	0.012
	Epidote-amphibloite metabasalt-unmineralised	8.43 (0.707)	6.36 (1.045)	0.75	0.076 9	0.001
	Chlorite-schist-unmineralised	8.99 (2.065)	7.22 (2.025)	0.80	0.058 10	0.027
	Mineralised sericite-chlorite-quartz-pyrite schist	5.94 (2.492)	5.62 (2.378)	0.95	0.041 24	30
	Epidote-amphibolite metabasalt-unmineralised	7.82 (0.521)	6.39 (0.611)	0.81	0.061 9	0.002
DOME and AUNOR MINES-TIMMINS	Mafic to intermediate flows-unmineralised	9.45 (0.783)	6.89 (0.465)	0.73	0.026 3	0.003
	Weakly mineralised mafic flows	9.32 (1.471)	7.66 (1.516)	0.82	0.085 5	0.028
	Mineralised metabasic tuff	8.16 (0.084)	7.43 (4.698)	0.91	0.013 4	2.1
	Mineralised metabasic tuffs enveloping Au-bearing carbonate chemical sediments	8.42 (3.071)	7.46 (2.914)	0.88	0.064 8	4.0
	Mineralised Timiskaming slate	5.27 (0.864)	3.97 (0.798)	0.75	0.080 3	7.0
	Mineralised ultrabasic schist (H/A zone)	6.53 (1.872)	6.04 (1.699)	0.92	0.057 4	0.8
DICKENSEN MINE - RED LAKE	Mineralised metabasic flows enveloping Au-bearing tuffaceous chemical sediments	5.27 (0.467)	7.36 (0.172)	0.72	0.120 4	8
E.MALARTIC MINE-VAL D'OR	Metabasic tuffs-unmineralised	7.34 (4.052)	4.79 (2.008)	0.70	0.114 4	
	Weakly mineralised quartz-feldspar porphyry	2.37 (1.016)	1.11 (0.306)	0.51	0.147 4	
	Mineralised felsic cherty-tuffs	2.32 (1.608)	1.36 (0.406)	0.41	0.138 9	
	Weakly mineralised greywacke	3.33 (0.644)	1.73 (0.462)	0.53	0.068 7	
	Weakly mineralised metabasic tuffs	6.59 (3.381)	3.84 (2.336)	0.58	0.130 4	

* Standard deviation and number of determinations

chamber. It is suggested here that the association of auriferous sedimentary rocks with tuffaceous rocks could be explained in terms of an ascending magma encountering a ponded hydrothermal reservoir or aquifer where P fluid ≥ P load. Under these conditions the fluid would penetrate the magma resulting in explosive volcanism. Alternatively, the thermal envelope around an ascending magma may raise the pore fluid pressure in country rocks by differential thermal expansion such that the effective confining stress on the magma is reduced (Fyfe *et al.* 1978; Knapp and Knight 1977), permitting the exsolution of volcanic gases that presages pyroclastic activity. Fracturing consequent upon decrease of the horizontal stress due to caldera collapse may then permit the ascent of auriferous solutions to the seafloor.

Fluid Volumes - Solute Concentrations

Total production of gold from the Porcupine area up to 1976 was 1.7 x 10^9 g (Pyke 1976). If it is assumed that this mass of gold was derived by 50 percent efficient leaching of basalt with an average Au abundance of 2 ppb (Tilling *et al.* 1973; Kwong and Crocket 1978), then the source volume would be of the order of 600 km^3 (1 km^3 of rock contains 5.6 x 10^6 g Au at 2 ppb). Based on the premise that Si, Au, Ag, Pd, W, Ni, Cr together with other elements present in veins were leached and transported during metamorphic outgassing at the greenschist-amphibolite transition, when approximately 5 weight-percent structural water is released from a hydrated rock of basaltic composition, then the solvent volume would be of the order of 90 km^3.

An independent estimate of the hydrothermal fluid volume may be derived as follows, using gold-bearing quartz veins, which are essentially pure quartz, as examples. In cooling from 500°C to 300°C, 1 kg of quartz saturated water will precipitate 2.6 g of quartz assuming a thermal gradient of 100°C km^{-1}, and a hydraulic gradient equal to lithostatic gradient (Holland 1967). Gold is present in the veins at an average level of 10 ppm, and therefore if Au and quartz were co-precipitated from a solution cooling along a geothermobar then 1 kg of solvent would precipitate 2.6 x 10^{-5} g Au, and the average decrease in concentration of gold in the hydrothermal solution would be 25 ng m^{-1}. The total carrier fluid volume for 1.7 x 10^9 g Au is then 65 x 10^{12} kg, or 65 km^3, based on the generalized assumption that gold is dominantly precipitated over the stated temperature interval. Estimates of fluid volume are slightly decreased if a lower thermal gradient is assumed. Further, consider 100 g of basalt containing Au at 2 ppb. If 50 percent of the gold is taken into solution as the basalt evolves 5 weight-percent water at the greenschist-amphibolite transition, then the solute concentration will be 20 ng ml^{-1} Au, which is comparable to the figure estimated above and the value of 50 ng ml^{-1} reported by R.I. Tilling *et al.* (1973) for gold in natural thermal waters. These calculations are intended to demonstrate the magnitude of source and fluid volumes, and provide estimates of Au concentrations in metamorphic hydrothermal solutions. Similar calculations on gold transport are given by H.C. Helgeson and R.M. Garrels (1968) and W.S. Fyfe and R.W. Henley (1973).

Model for Generation of Lode Gold Deposits

Any hypothesis which encompasses geological and chemical characteristics of gold deposits in 'greenstone' belts must satisfy the following constraints:

1) At least two stages of gold concentration. The first in primary chemical sedimentary rocks typically within the mafic to ultramafic stratigraphic section of the volcanic sequence, and the second in later hydrothermal quartz veins.
2) Separation of base metals from rare elements.
3) Au concentration factors of the order of 10,000 and therefore source rock volumes of hundreds of km^3.
4) Relatively high, uniform fluid temperatures of about 350°C to 450°C.
5) Hydrothermal solutions with $\delta^{18}O$ 8‰ - 11‰.
6) Hydraulic pressure > lithostatic pressure.
7) Water/rock ratios sufficient to cause complete oxygen isotope exchange of host rock with the aqueous reservoir along flow conduits, and to extensively modify primary host rock chemistry.
8) Mineralizing hydrothermal solutions originating under highly reduced conditions, leading to extensive reduction of wall-rocks along hydrothermal conduits.
9) A mechanism which is intrinsically efficient under Archean crustal conditions.

The hypothesis which is presented to account for the origin of lode gold deposits involves focused discharge of metamorphic fluids. During burial of hydrated 'greenstone' belt assemblages devapourization reactions generate significant fluid volumes over specific PT intervals (Fyfe 1973, 1974; Fyfe *et al.* 1978). At the greenschist-amphibolite transition, which takes place at 450°to 500°C, about 5 weight-percent structural water and volatiles are released from a hydrated rock of mafic composition. Large fluid volumes are also generated from the dehydration of zeolite and clay at lower grades of metamorphism.

The volume relations of dehydration reactions are such that metamorphic fluids are evolved under conditions where $P_{fluid} \geq P_{lithostatic}$. A second factor contributing to elevated hydraulic pressures is differential thermal expansion of pore fluids (Norris and Henley 1976; Knapp and Knight 1977). This effect is enhanced under conditions of steep geothermal gradients. Hence, a metamorphic fluid reservoir satisfies the observed temperatures and $\delta^{18}O$ of the mineralizing solutions, the conditions of hydraulic pressure, and accounts for the requirement of fluids generated under high-temperature reducing conditions. In addition, metamorphic fluids generally have higher $CO_3{}^{2-}$ from decarbonation reactions, compared to seawater or meteoric water involved in geothermal systems. W.S. Fyfe and R.W. Henley (1973), R.W. Henley *et al.* (1976), R. Kerrich (1977, 1979), and R.

Kerrich and B.J. Fryer (1979) have presented models for the origin of some gold-bearing vein deposits by focused discharge of metamorphic fluids, based on several lines of geological and isotopic evidence.

The residence and accumulation of metamorphic fluids in the crust is determined by the balance between the rates of fluid generation and fluid expulsion. In the Archean crust where thermal gradients are generally accepted to have been high, particularly in provinces of continuous volcanic activity, the rate of fluid generation by metamorphic dehydration reactions must have been faster and occurred over narrower vertical crustal intervals, leading to an increased probability of generating and ponding extensive metamorphic fluid reservoirs. When the hydraulic pressure exceeds the sum of the crustal horizontal stress plus the tensile strength of the rock, subvertical hydraulic fracturing must ensue, providing focused discharge for the ponded reservoir, and high fluid/rock ratios in the conduit. High-boron concentrations in many gold-bearing veins and chemical sedimentary rocks may be a consequence of ponding hydrothermal reservoirs beneath impermeable sedimentary rocks in source regions, inasmuch as sediments have greater abundance of boron than igneous rocks (Turekian and Wedepohl 1961).

Once flow is established up a structure from a reservoir where $P_{fluid} > P_{lithostatic}$ an unstable hydraulic fracture will propagate towards the surface. If a fracture intersects a lithology with low permeability and high tensile strength then fluids may pond beneath such a barrier, with deposition of Si, Au, and other elements. This process of discharge and ponding may recur under successive impermeable lithologies through the stratigraphic sequence. The impermeable stratiform carbonates at the Dome mine containing pervasive horizontal and vertical Au-bearing veins, provides evidence for this type of discharge regime.

If the plumbing geometry permits direct ascent of fluids to the hydrosphere, and fluid discharge is rapid, significant concentrations of Au and other rare elements (B, Ag, Pd, W, Cr, Ni) may remain in solution (see Harman *et al.* 1975; Tables 11-3, 11-4). In this context, capping of discharge may be critical to maintenance of high fluid temperatures, and hence secondary enrichment of chemical sedimentary rocks during hydrothermal ponding. Along with dissolved metals, the metamorphic hydrothermal fluids contain a high proportion of CO_2. Release of CO_2 from such solutions entering the seafloor will locally raise the $^{P}CO_2$ of the hydrosphere and carbonate precipitation will commence as $^{P}CO_2$ dissipates and ambient seafloor conditions are regained. Carbonate sedimentary rocks may also be due to high Ca^{2+} in the metamorphic fluids. If significant iron remains in solution oxide facies iron formation may displace the carbonate either vertically or laterally. The continuous nature of mafic flows which host stratiform lode gold deposits (e.g., VB-Porcupine area) implies a lack of significant seafloor topography, which may have been a factor in the widespread dispersion of metamorphic brines precipitating auriferous chemical sediments.

In this context, R.B. Hargraves' (1976) model of crustal evolution has special implications. Hargraves considers an early, essentially continuous hydrosphere and thin crust under high ambient geothermal gradients, with eventual emergence of continents, after cooling and tectonic thickening of the crust. During the Archean the products of metamorphic outgassing would debouch into the hydrosphere, which is a favourable environment for chemical sediments, whereas in post-Archean times metamorphic fluids would in general feed into continental run-off.

An essential feature of metamorphic fluid reservoirs, which are generated under conditions of low water/rock ratio, is the potential to separate rare and abundant elements. In order to illustrate this process consider 100 g basalt with 2 ppb Au and 100 ppm Cu, Pb, and Zn. If 50 percent of the metals are taken into solution as the rock evolves 5 weight-percent water at the greenschist-amphibolite transition then the solute concentration of Au will be 20 ng ml^{-1} and of base metals 1 mg ml^{-1}. Whereas the Au solute concentration is comparable to that reported for natural systems (Tilling *et al.* 1973), the figure for base metals is 1000 times greater (Andrews and Fyfe 1976), and less than 0.1 percent of the available base metals would be taken into solution. Therefore, in low water/rock systems the absolute abundance of rare elements in solution is not constrained by solubility, whereas base-metal solute concentration is constrained by solubility and/or the availability of metal-complexing species.

Conversely, in submarine hydrothermal convective systems which generate massive base-metal sulphide deposits, water/rock ratios throughout the source volume may be of the order of 100:1 to 1000:1 (Spooner *et al.* 1977), and thus 200,000 times greater than for lode gold deposits. Hence the solute abundances of base and precious metals are not constrained by solubility, and probably broadly reflect background levels, giving no large separations of elements in the hydrothermal solvent or deposit. For example, in typical Archean stratabound massive base-metal sulphides, which are believed to be seafloor deposits generated by convection of marine water, Zn and Cu are present in the low percentage range (0.5-10 percent) and Au at 0.2-0.6 g $tonne^{-1}$ (Hutchinson 1973; Roberts 1975). This represents similar concentration factors for base metals (150-1000) and gold (100-300) relative to background abundances.

The higher ambient temperatures of hydrothermal gold systems compared to submarine geothermal convection may promote aqueous transport of some relatively insoluble metals. Thus, the extent of enrichment of W, Cr, Ni, and Pt documented above for lode gold deposits is much greater than is typical for massive base-metal sulphides.

Thus, it is considered that lode gold deposits are a normal consequence of prograde regional metamorphism of 'greenstone' belts under conditions of high crustal heat flux and in a submarine environment. The resulting auriferous hydrothermal reservoirs may form one or all of the following types of gold concentration: hydrothermal veins in discharge conduits, veins in association with permeability barriers, and stratiform chemical sedimentary rocks at the surface. The chemistry of metamorphic fluids is such that quartz is the dominant gangue mineral in crustal lodes, whereas carbonate (because of high $^{P}CO_2$ and/or high Ca^{2+}) predominates on the seafloor. The essential features of this model are illustrated in Figure 11-4.

Acknowledgments

This article represents a personal, and inevitably a biased, attempt to synthesize quantitative information on Archean lode gold deposits. The number of types of orebodies considered is limited, and in some instances the data are not sufficiently comprehensive; hence there are important omissions. I extend my apologies to those authors whose contributions have not been covered, or have received insufficient attention.

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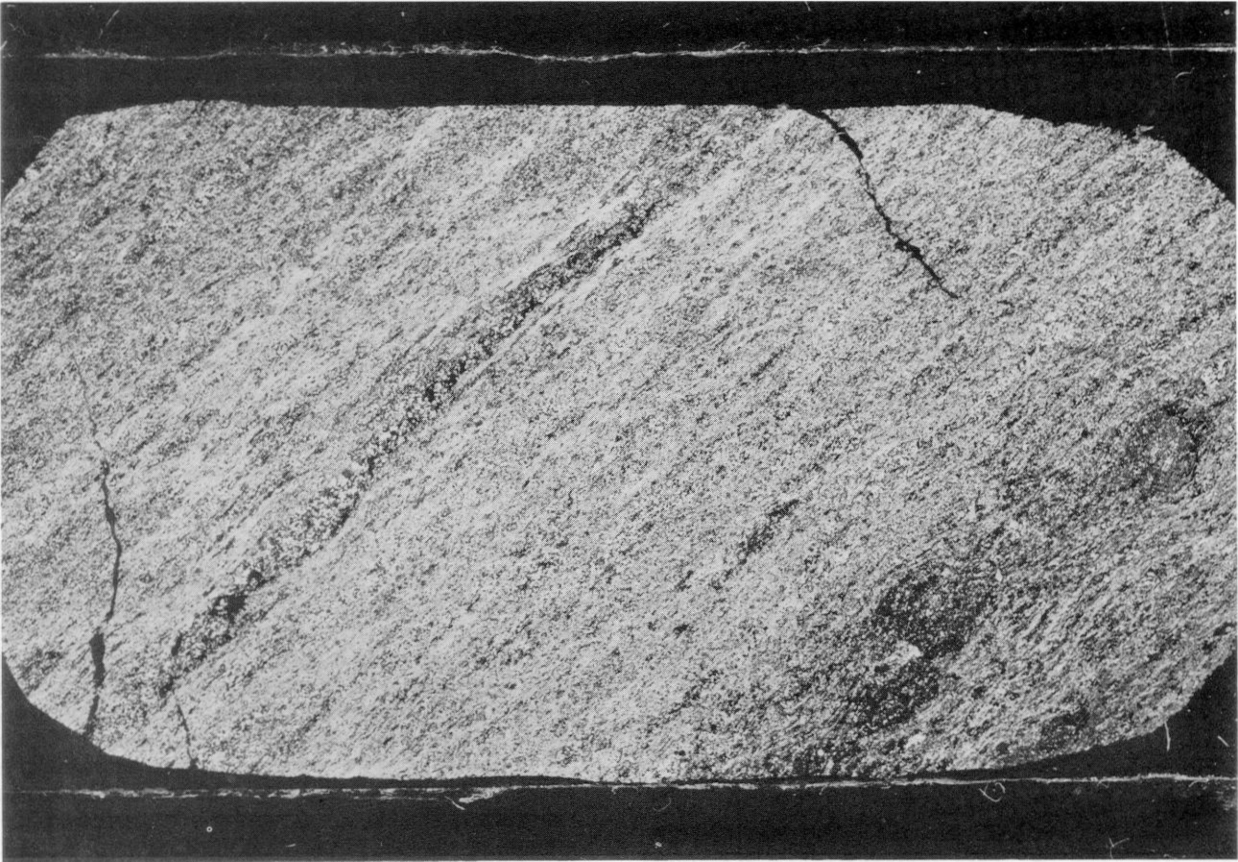

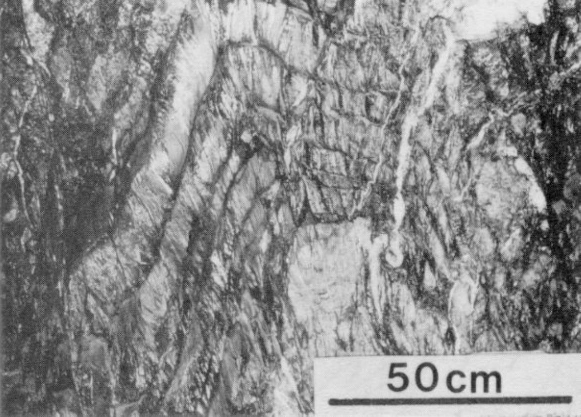
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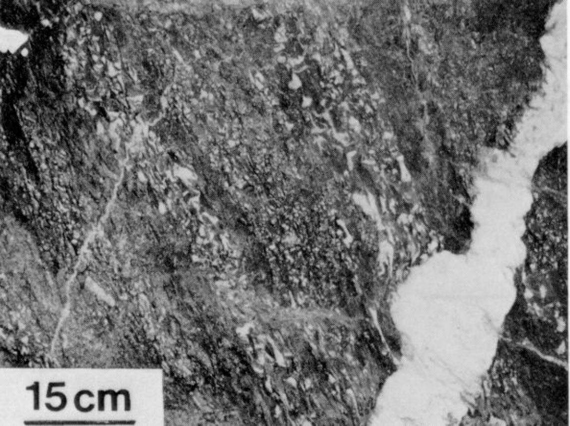
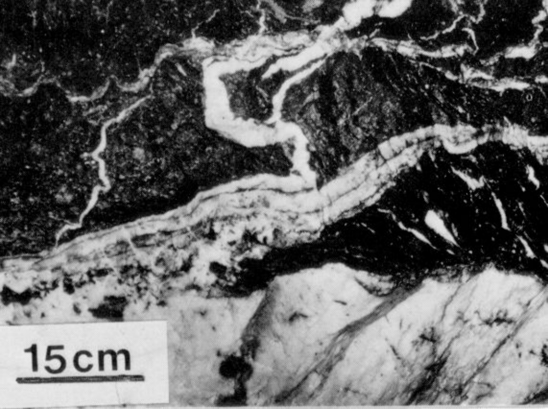

15 cm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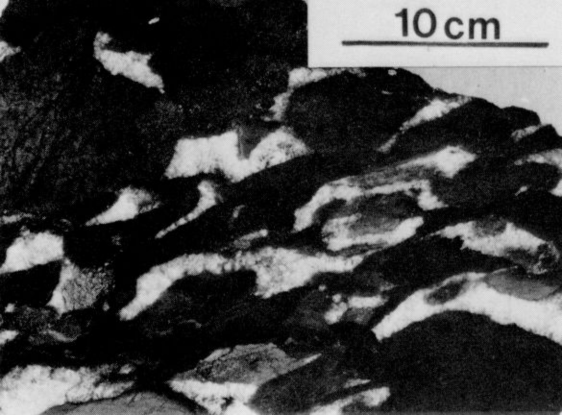
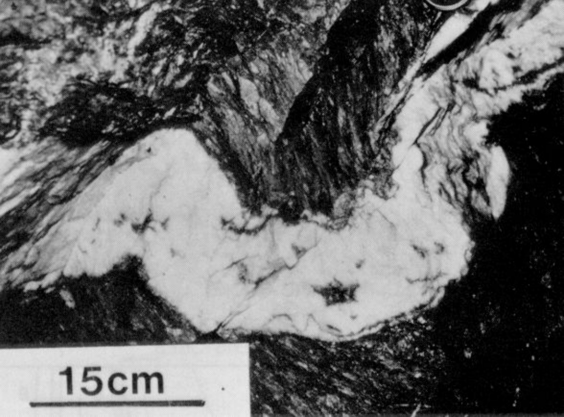

10 cm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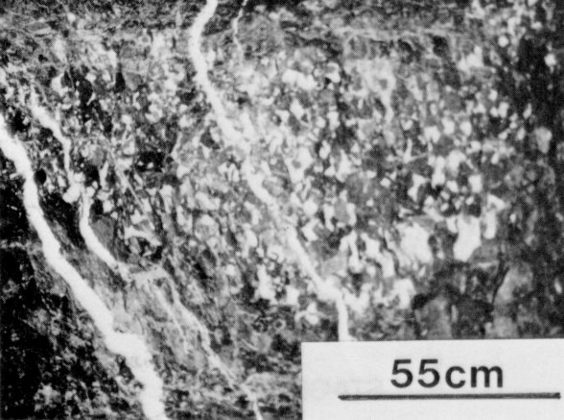
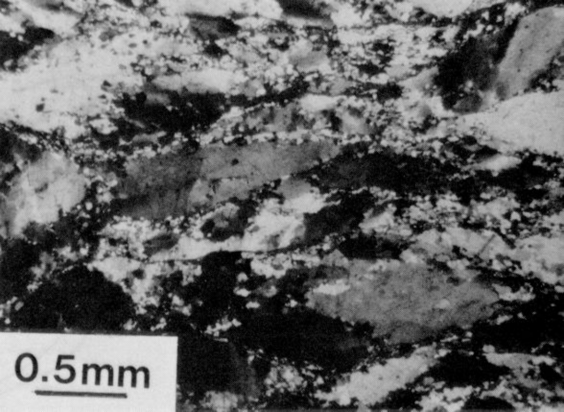

55cm


0.5mm


KONICA


1cm