Geochemistry and Genesis of Two Unconformity-Associated Gold Deposits at the Base of the Flinton Group, Grenville Province, Southeastern Ontario, Canada

LUC HARNOIS[*] AND JOHN M. MOORE

Department of Earth Sciences and Ottawa-Carleton Geoscience Centre, Carleton University, Ottawa, Ontario, Canada K1S 5B6

Abstract

The Addington and Ore Chimney mines are Proterozoic gold-bearing quartz-carbonate vein deposits that occur in lower amphibolite facies metamorphic rocks, on and near a major regional unconformity.

The Ore Chimney deposit has a typical opaque mineral association of galena-sphalerite-pyrite-chalcopyrite-pyrrhotite-Ag-rich tetrahedrite-ilmenite. The vein system is hosted by a 4-m-thick biotite schist enclosed by metabasaltic lava flows. The metavolcanic rocks are unconformably overlain successively by a 10-m-thick metapelitic garnet-biotite schist (the Ore Chimney Formation) and a coarse siliciclastic succession (the Flinton Group). The Ore Chimney deposit occurs 30 m below the unconformity.

The Addington deposit has a typical opaque mineral assemblage of arsenopyrite-pyrite-chalcopyrite-pyrrhotite-ilmenite. This deposit is hosted by the Ore Chimney Formation and is located 8 km along strike from the Ore Chimney mine.

Arsenopyrite geothermometry and sphalerite geobarometry yield temperature and pressure estimates ranging from 420° to 530°C and 0.35 to 0.59 GPa, respectively, consistent with estimated peak metamorphic conditions. Geochemical, textural, and structural evidence suggest that vein formation and mineralization occurred during the main episode of metamorphism and deformation and that gold was deposited by metamorphic fluids. The mineralizing process was associated with weak carbonatization of the wall rock. Gold and base metals may have been remobilized from preexisting concentrations resulting from hydrothermal and/or weathering processes.

Introduction

SINCE the first Ontario gold strike at Eldorado in 1866, the southwestern Grenville province of the Canadian Shield has been recognized as a lode gold province. Although now far outweighed by the yield from Archean deposits to the north, production from numerous small mines (among them the Cordova, Deloro, and Golden Fleece) was more or less continuous until the 1930s.

Despite this long history, the gold deposits of southeastern Ontario remain poorly known and understood. The recent rise in the value of gold has led to increased exploration activity and to a number of reconnaissance and metallogenetic studies (Sangster, 1970; Sangster and Bourne, 1982; Carter, 1984; Barron, 1985; Carter and Colvine, 1985; Malczak et al., 1985), but few detailed field or geochemical studies have been conducted. In this paper we present the results from our study of two representatives of an important deposit type of this region: polymetallic, auriferous vein systems hosted by volcanogenic metasedimentary rocks, on or near a major regional unconformity within the Precambrian succession.

It has been recognized that gold deposits in the Grenville province of southeastern Ontario are primarily restricted to a region of relatively low-grade metamorphism in the Central Metasedimentary belt (Fig. 1), that is unique for its high proportion of volcanic rocks (Lumbers, 1964). Gold-bearing quartz vein deposits constitute by far the most abundant gold deposit type in this region. There are two major concentrations of deposits: in greenschist facies rocks around Madoc and in upper greenschist-lower amphibolite facies rocks of the Flinton-Fernleigh area (Figs. 1 and 2).

Although gold exhibits various lithologic associations in both areas (Carter, 1984; see below), many deposits in the Flinton-Fernleigh area are strikingly associated with the base of the Flinton Group. This clastic metasedimentary succession unconformably overlies the volcanic rocks, as well as a number of sedimentary units and major plutons in the region (Fig. 2). These deposits are of particular interest because the unconformity is a widespread, readily recognized exploration target. Most were originally described by Harding (1944) and Meen (1944), and all of them were recently reexamined by Malczak et al. (1985). Two of these deposits were remapped by Flegg (1983; deposit OCM; Fig. 2 and Table 1), Dillon

[*] Present address: 755 d'Iberville - #1, Longueuil, Québec, Canada J4H 2G7.
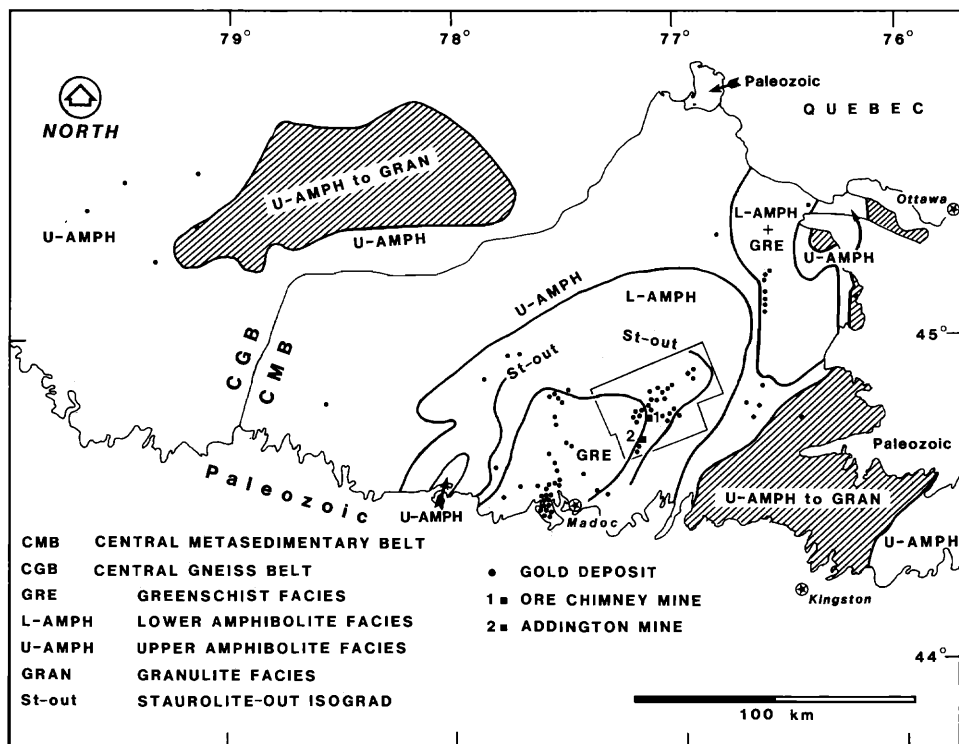
FIG. 1. Gold occurrences in the Grenville province of southeastern Ontario. Gold deposits are from Gordon (1977) and Malczak et al. (1985). Metamorphic boundaries are modified from the metamorphic map of the Canadian Shield (Geological Survey of Canada, 1978). The study area (Fig. 2) is outlined.
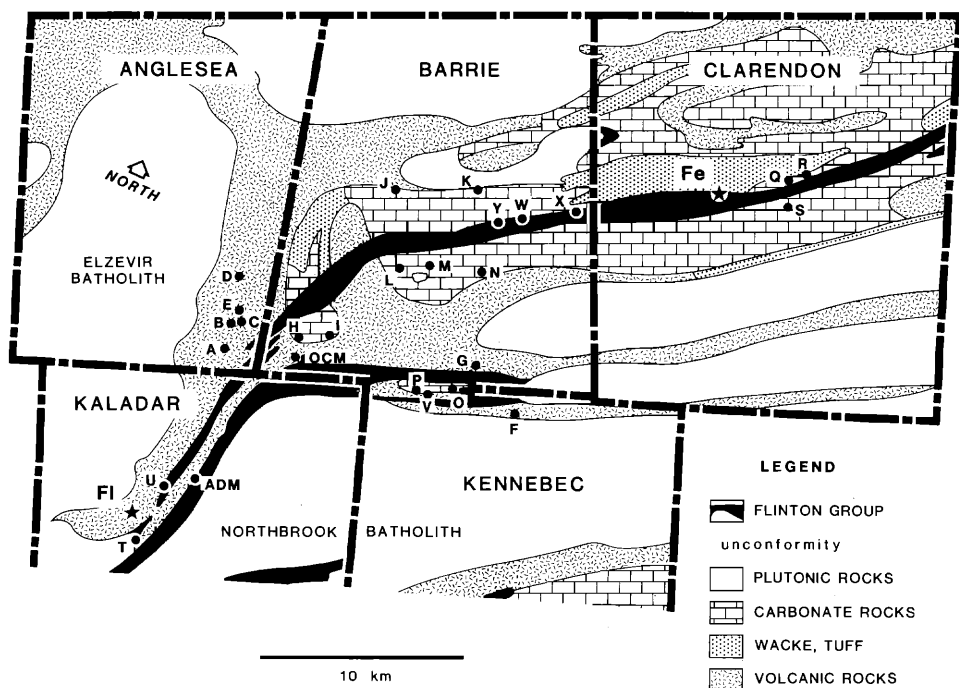

FIG. 2. General geology of the Flinton-Fernleigh area (from Moore and Thompson, 1980), with township boundaries. All rocks are metamorphosed; original lithology is indicated. Star = village, solid circle = gold deposit, Fl = Flinton, Fe = Fernleigh. Deposits: ADM = Addington mine, OCM = Ore Chimney mine. A = O'Donnell I, B = O'Donnell II, C = O'Donnell III, D = Kennefic, E = Ultimate Energy, F = Gold Base, G = Cobalt-Frontenac, H = Mill, I = Natto, J = Star, K = Big Dipper, L = Stead, M = Helena, N = Kashwakamak, O = Pay Rock, P = Dome, Q = Webber, R = Boerth, S = Cook, T = Ewing, U = Stone, V = Emery, W = International, X = Gough-Hardie, Y = Mazinaw base metal (see Table 1).

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(1985; deposits ADM and OCM), Young (1985; deposit ADM), and Moore and Morton (1986; deposit OCM). These studies were, however, essentially descriptive and involved mapping and petrography, with very little chemistry. Limited mineral and whole-rock chemical data for the Addington mine and Ore Chimney mine deposits were presented by Harnois and Moore (1986), Laing (1986), and Laing et al. (1987).

The aim of this paper is to characterize and interpret two deposits that occur immediately below the Flinton Group: the Addington mine and the Ore Chimney mine (ADM and OCM, Fig. 2 and Table 1). These two deposits were selected because they have greater proven tonnage and grade than other deposits of this type; the Addington mine is a past producer.

Availability of underground samples was also an important factor in the selection. During the summer of 1983, the Ore Chimney mine was temporarily dewatered and retimbered to the 150-ft level, allowing sampling and examination of the vein system, which is not exposed on surface. Drill core of the Addington mine was available through a drilling program underway on this property at the time of field work.

General Geology and Geochronology

The area of interest lies within the Elzevir terrane (or subzone IV) of the Central Metasedimentary belt (Wynne-Edwards, 1972; Davidson, 1986) and is underlain by mid-Proterozoic metavolcanic and meta-

TABLE 1.   Gold Deposits of the Flinton-Fernleigh Area

Group	Deposit	Status	Township	Lot	Concession	Host	Mineralogy
I	O'Donnell I (A)	O	Anglesea	8	II	Maf volc	Apy, ccp, gn, sp, py, men, po
I	O'Donnell II (B)	O	Anglesea	7	III	Maf volc	Py, ccp
I	O'Donnell III (C)	O	Anglesea	6	III	Maf volc	Apy, py, gn, sp, ccp, men
I	Kennefic (D)	O	Anglesea	7	V	Maf volc	Apy
I	Ultimate Energy (E)	O	Anglesea	6	IV	Sed , maf volc	Py, apy, po, ccp
I	Gold Base (F)	O	Kennebec	30	V	Maf volc, marb	Py, ccp
I	Cobalt-Frontenac (G)	O	Barrie	13	I	Int volc	Sp, py, po
I	Ore Chimney mine (OCM)	PD	Barrie	35	I	Maf volc	Gn, sp, py, ccp, po, tth, ilm, mar, apy, co
II	Mill (H)	O	Barrie	36	II	Dol	Tth, apy, py, ccp
II	Natto (I)	O	Barrie	30–32	III, IV	Dol, maf volc	Py, apy, tth, ccp, bmt, sp
II	Star mine (J)	PP	Barrie	24, 25	X	Dol, dac volc	Py, ccp, sch, tur, bmt, po
II	Big Dipper (K)	P	Barrie	16	X	Gran, calc	Py, tur, mag, jms, bul
II	Stead (L)	P	Barrie	25	VI	Calc, dol	Sp, gn, py, ccp, tth, hem, cnn
II	Helena (M)	P	Barrie	20	VI	Marb, gran	Py, ccp, po, sp
II	Kashwakamak (N)	O	Barrie	14	VI	Dol	Ccp, tth, tur, py, sp, gn
II	Pay Rock (O)	O	Barrie	16	I	Dol	?
II	Dome (P)	P	Kennebec	32	II	Dol, maf volc	Py, ccp, cc, gn, hem
II	Webber (Q)	P	Clarendon	28	IX	Pgn, dol	Py, apy
II	Boerth (R)	P	Clarendon	29	IX	Cl sed, calc	Py, apy, tur, po, ccp
II	Cook (S)	O	Clarendon	23	IX	Dior, marb	Apy
III	Ewing (T)	O	Kaladar	20	IV	Sed, maf volc	Po, py, tur
III	Stone (U)	O	Kaladar	23	V	Sed, maf volc	Apy, py, ccp, po, gn sp
III	Addington mine (ADM)	PP	Kaladar	24, 25	VI	Sed, maf volc	Apy, py, tur, ccp, ilm, po, bmt, gn, sp, mar
III	Emery (V)	O	Kennebec	31	II, III	Maf volc, cl sed	Py, apy, sp, gn
IV	International (W)	O	Barrie	8	IX	Dol	Tth, sp, ccp, py, bul, jms, apy
IV	Gough-Hardie (X)	P	Barrie	3	IX	Dol, cl sed	Py, sp, apy, bul, ccp, tth, hem, tur
IV	Mazinaw base metal (Y)	O	Barrie	12	VIII	Dol, cl sed	Sp, tth, ccp, bul, py, apy, jms/bul

Group I, II, III, and IV: see text. Deposits are keyed to letters in Figure 2. Lot and concession numbers refer to Ontario Land Survey system. Abbreviations, status: O = occurrence, P = prospect, PD = prospect developed, PP = past-producer. Abbreviations, Host: calc = calcitic marble, cl sed = clastic metasediments, dac volc = dacitic metavolcanic, dior = metadiorite, dol = dolomitic marble, gran = metagranite, int volc = intermediate metavolcanics, maf volc = mafic metavolcanics, marb = marble, pgn = paragneiss, sed = metasediments. Mineralogy listed for each deposit is compiled from various sources, and all minerals do not necessarily occur in a single sample. Abbreviations, Mineralogy: apy = arsenopyrite, bmt = bismuthinite, bul = boulangerite, ccp = chalcopyrite, co = cobaltite, cnn = cinnabar, gn = galena, hem = hematite, ilm = ilmenite, jms = jamesonite, mag = magnetite, mar = marcasite, men = meneghinite, po = pyrrhotite, py = pyrite, sch = scheelite, sp = sphalerite, tth = tetrahedrite, tur = tourmaline (Kretz, 1983); compiled mainly from Malczak et al. (1985)

sedimentary rocks of the Grenville Supergroup, metasedimentary rocks of the Flinton Group, and metagranitoid intrusive bodies (Fig. 2 and Table 2). The geology of the area has been described by Harding (1944), Meen (1944), Sethuraman and Moore (1973), Moore and Thompson (1980), Wolff (1982), and Moore and Morton (1986). All rock units of the area have been metamorphosed, but the degree of metamorphism and deformation is relatively low compared to most of the Grenville province. As protoliths are readily identified, the prefix "meta" will hereafter be omitted in this paper. The oldest rocks in the area are the volcanics of the Tudor formation (Hermon Group; Lumbers, 1967). They are tholeiitic basalts with minor intermediate pyroclastics (Sethuraman and Moore, 1973) which have been dated at $1,279 \pm 3$ Ma by the U-Pb isotope method on zircons (Heaman et al., 1987). These are overlain successively by basaltic to felsic subalkaline volcanic rocks of the Mazinaw Lake formation (Ayer, 1979) and the Kashwakamak formation (Harnois and Moore, 1987) and by clastic and carbonate sedimentary rocks cut by numerous small mafic to intermediate intrusions (Moore and Morton, 1986). This succession has been intruded by large granitoid plutonic bodies, of which the Elzevir batholith (Fig. 2) has been dated at ca. 1,270

Ma by the U-Pb isotope method on zircons (L. M. Heaman, pers. commun., 1988). The volcanic rocks are unconformably overlain by the Ore Chimney Formation, a locally transported paleoregolith derived from them (Moore and Thompson, 1980; Harnois and Moore, 1988).

The Flinton Group is a succession of clastic sediments that overlies the Ore Chimney Formation with minor unconformity (?) and the older rocks with major angular unconformity (Thompson, 1972; Moore and Thompson, 1980). The stratigraphic order established by these authors in the study area is reproduced, slightly modified, in Table 2.

Xenoliths of volcanic rocks, with variably oriented hornblende schistosity and lineation, are found in relatively undeformed rocks of the Elzevir batholith, which is overlain by Flinton rocks. These relationships show that metamorphism as well as deformation preceded deposition of the Flinton Group. However, the polyphase deformation responsible for the major map pattern, and the regional metamorphic zonation clearly postdate all units of the Flinton Group.

Thompson (1972) recognized four post-Flinton phases of deformation, of which D_1 and D_2 account for most features of the map pattern. The Flinton Group is preserved in isoclinal D_1 synclines (Fig. 2);

TABLE 2. Table of Formations

Flinton Group

Myer Cave Formation
   Dolomitic marble, graphite metapelite, carbonate metaconglomerate
Bishop Corners Formation
   Quartzite, metapsammite, metaconglomerate

<div align="center">Minor unconformity (?)</div>

Ore Chimney Formation
   Pelitic metasediments (biotite schist, garnet-biotite schist, muscovite-biotite schist, hornblende-biotite schist, hornblende schist)

<div align="center">Major unconformity</div>

Plutonic rocks
   Metagranite to metatonalite batholiths

<div align="center">Intrusive contact</div>

Grenville Supergroup

Metasediments
   Marble, wacke, minor metamorphosed shallow instrusions
Mazinaw Lake formation
   Predominantly felsic to basaltic metavolcanic rocks
   Minor epiclastic metasediments and metamorphosed
     subvolcanic intrusions
Metasediments
   Wacke, tuff, marble
Tudor formation
   Metabasalt flows, pillowed flows, flow and pillow
     breccia
   Minor metagabbroic intrusions
   Minor mafic interflow metasediments

Kashwakamak formation
   Felsic to basaltic metavolcanic rocks (predominantly
    andesitic)
   Minor epiclastic metasediments, metamorphosed
    intrusions, and quartzofeldspathic interflow
    metasediments

After Ayer (1979), Moore and Thompson (1980), and Moore and Morton (1986)

although these have been refolded on a regional scale during D_2, the structural pattern of the deposits studied is related to D_1.

Connelly (1985, 1987) suggested that the Flinton Group was tectonically emplaced into its present position, and thus, that the supposed unconformity is a folded thrust plane. However, the close lithologic relationships between pre-Flinton and Flinton rock units (Moore and Thompson, 1980; Harnois and Moore, 1988) preclude any major displacements along the base of the Flinton Group.

Only one period of regional metamorphism affected the sedimentary rocks of the Flinton Group. Metamorphic grade increased during D_1 and attained a maximum shortly before D_2. Regional isograds thus transect the major structural trends (Thompson, 1972). The rocks described in this chapter are at lower amphibolite grade (staurolite zone; Fig. 1).

Gold Deposits of the Flinton-Fernleigh Area

The 27 known gold deposits of the Flinton-Fernleigh area (deposits are listed by letter in Fig. 2 caption) occur within the volcanics and carbonate sediments of the Grenville Supergroup, within the Ore Chimney Formation and in carbonate rocks in the lower part of the Flinton Group. The gold is contained in networks of concordant to subconcordant quartz and quartz-carbonate veins. The deposits are separable into four groups on the basis of their host rock lithology and stratigraphic position (Table 1).

Group I deposits (A–G and OCM)

The deposits of this group are mafic to intermediate, volcanic hosted. Deposits G and OCM occur close to the base of the Flinton Group. Chalcopyrite is abundant and antimony sulfosalts are rare. Arsenopyrite is abundant in deposits A, C, D, and E. Some of these deposits (A, B, C, E, G, OCM) were reported by Malczak et al. (1985) as occurring within shear zones.

Group II deposits (H–S)

Deposits H to S are marble hosted and occur in the pre-Flinton carbonate sediments. Antimony sulfosalts are common and arsenopyrite less abundant than in the volcanic-hosted deposits. All these deposits are associated with at least one mafic to felsic shallow intrusive body (generally a sill or dike) or are close to the contact with the underlying volcanics. Approximately 4,170 g of gold were produced by the Star mine (deposit J) which is the only past-producer of this group.

Group III deposits (T–V and ADM)

These deposits either are hosted by the Ore Chimney Formation (deposits T, U, and ADM), which is overlain by the Bishop Corners Formation (Flinton

Group), or occur in an analogous stratigraphic position (deposit V). Arsenopyrite is the main sulfide in deposits U and ADM and sulfosalts are rare.

Group IV deposits (W, X, and Y)

Deposits W, X, and Y occur within the carbonate and clastic sediments of the lower part of the Flinton Group (Myer Cave Formation). Antimony sulfosalts are common and arsenopyrite is rare.

The sulfide content of all four groups is highly variable and erratic and includes, in addition to the above-mentioned minerals, sphalerite, galena, and pyrite.

Although ADM and OCM were chosen as representing deposits associated with the base of the Flinton Group, detailed study has shown them to be very different in many respects. For example, the Addington deposit (group III) is As rich and hosted by the Ore Chimney Formation, whereas the Ore Chimney deposit (group I) is Cu-Pb-Zn rich and lies in mafic volcanics just below the Ore Chimney Formation.

Addington Mine

History and economic features

The Addington mine (Figs. 2, 3, and 4) was discovered in 1881 and was first known as the "Golden Fleece." Little work was done on the property before 1887, when two shallow shafts were sunk and visible gold was exposed. Up to the end of 1921 total pro-
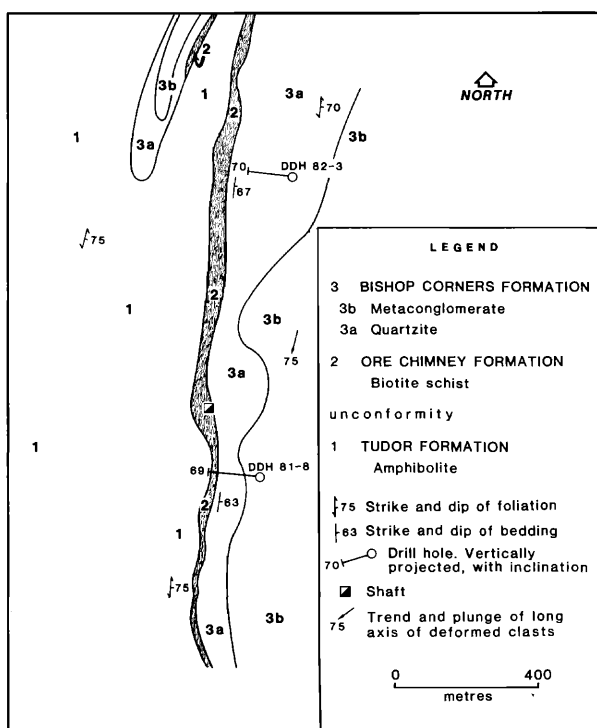

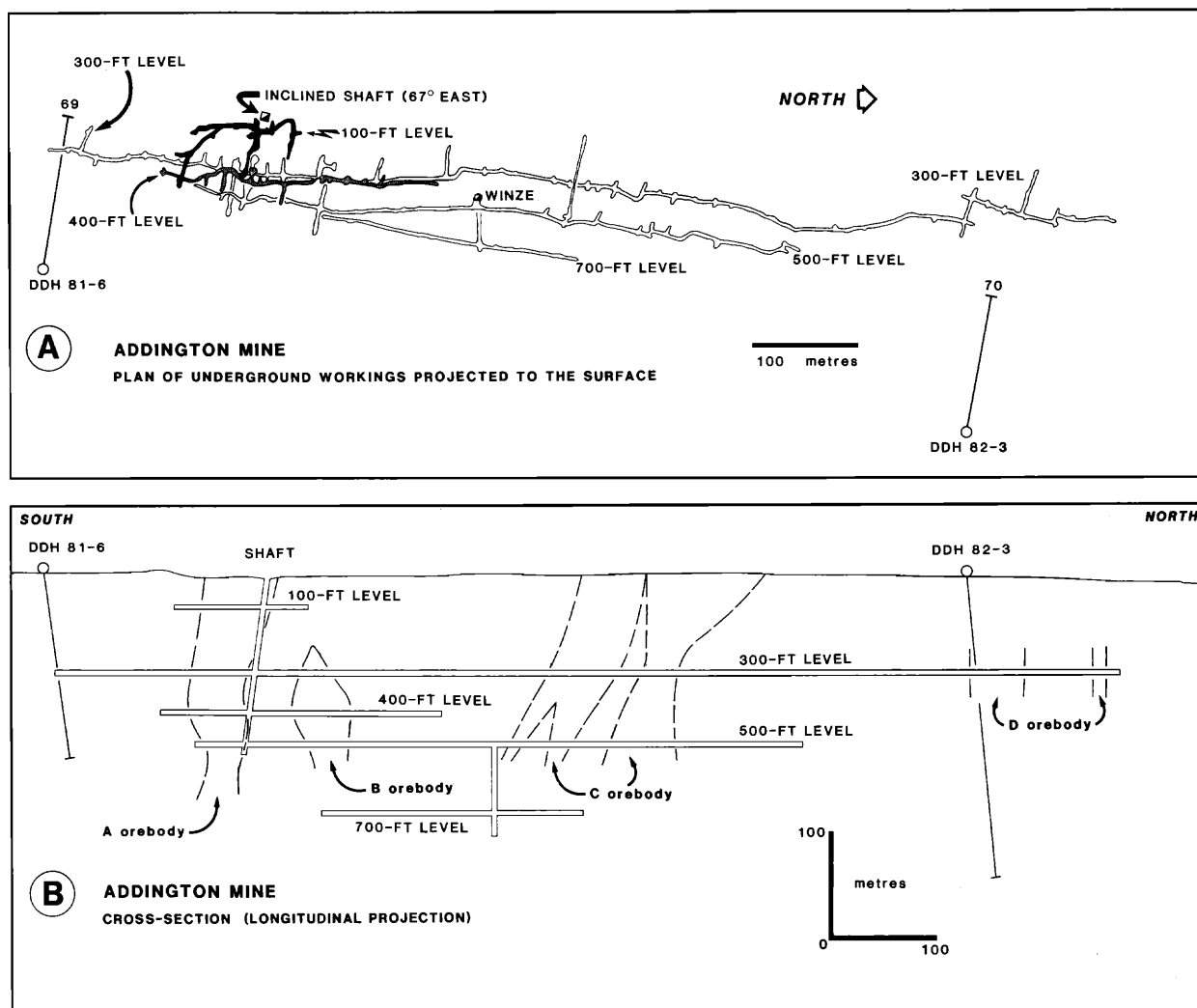FIG. 3. Geology of the Addington mine area (modified from Dillon, 1985).

FIG. 4. Underground workings of the Addington mine. Modified from Harding (1944) and Young (1985). Drifts are essentially restricted to the Ore Chimney Formation.

duction is reported to have been valued at $10,000 (Harding, 1944), which corresponds to a production of 14,800 g of gold assuming a price of $0.675/g Au ($21/oz Au). Attempts to operate the mine since 1921 have not been successful. In 1980 the property was reevaluated based on diamond drilling carried out from 1981 to 1983; it has since been optioned by Campbell Resources, Ltd. The mine is presently flooded. The deposit has been explored to a depth of approximately 220 m and a length of 1,700 m by diamond drilling and underground development (Fig. 4). Reserves are 256,000 metric tons grading 5 g/metric ton Au (Carter, 1984).

Geologic setting

The Addington mine deposit lies within the pelitic Ore Chimney Formation, between the Tudor for-

mation mafic volcanic rocks and the Bishop Corners Formation sediments. These strata (Fig. 3) are tightly folded into synclines and anticlines that plunge moderately to steeply toward the north. There is a poorly preserved, earlier foliation within the volcanics that strikes northeasterly (Dillon, 1985). The biotite schists of the Ore Chimney Formation have been interpreted to be a shear zone (Harding, 1944; Dillon, 1985; Young, 1985).

Tudor formation: The mafic volcanic rocks are dark green, foliated, fine- to coarse-grained amphibolites, with minor quartz, chlorite, and biotite and accessory tourmaline, pyrite, magnetite, and carbonate. Sulfide-free, millimeter-wide, calcite veinlets are common. Amphibolite immediately adjacent to the contact with the Ore Chimney Formation contains up to 30 percent tourmaline. The amount of tourmaline and the fre-

quency of calcite veinlets decrease as the distance from this contact increases. Rare biotite schist layers up to 30 cm thick occur within the amphibolites.

Ore Chimney Formation: This formation is composed of alternating layers of garnet-free and garnet-bearing mafic biotite schist, hornblende schist, and hornblende-biotite schist, with chlorite and muscovite. Tourmaline, apatite, kyanite, and staurolite are accessories; tourmaline, however, locally constitutes up to 40 percent of the rocks. A few garnet (with inclusions of ilmenite, arsenopyrite, chalcopyrite, pyrrhotite, and tourmaline) and hornblende porphyroblasts have syn- to post-tectonic growth textures. Sulfide-free calcite veinlets, 0.5 to 2 mm wide, are concordant to subconcordant with the schistosity, erratically distributed within the biotite schist and may compose up to 5 percent of the rock. Calcite occurs also as disseminated grains in the matrix and as inclusions in hornblende porphyroblasts. Within the limits of the Addington mine property, this unit contains numerous sulfide-bearing quartz-carbonate-tourmaline veins. Semiquantitative electron microprobe analyses of 20 tourmaline grains from the Ore Chimney Formation and the mineralized zones at the two mines show that the tourmaline is not significantly different from one setting to another. Quantitative partial analyses of three selected grains indicate that the tourmaline has molar $Fe/(Fe + Mg) = 0.33$ to 0.50 and is an intermediate member of the series schorl-dravite.

Young (1985) found micaceous quartzite interbedded with the mafic schists. The contacts between this rock unit and the Tudor and Bishop Corners formations were reported to be gradational (Dillon, 1985; Easton et al., 1986); however, the contacts are sharp in the two drill holes examined in this study.

Bishop Corners Formation: Immediately overlying the Ore Chimney Formation is a 10- to 30-m thickness of massive, fine- to medium-grained, feldspathic quartzite with minor magnetite, hematite, muscovite, and biotite. Overlying the quartzite, in sharp contact, is a quartzite-pebble conglomerate which also contains 0.5- to 2-m-thick discontinuous quartzite interbeds.

Sampling

All samples used in whole-rock and mineral chemistry are from drill holes 81-6 and 82-3 (Figs. 3 and 4).

Gold and sulfide distribution

Lenses and stringers of quartz are irregularly distributed throughout the Ore Chimney Formation, with a tendency toward concentration within certain sections. The lenses usually are parallel to the penetrative planar metamorphic fabric but in places transect it (Carter, 1984; Easton et al., 1986). Young

(1985) recognized deformed early barren quartz veins cut by late, sulfide-bearing, quartz-carbonate-tourmaline veins that transect the foliation at angles ranging from 5° to 90°. The latter veins contain up to 10 percent sulfide minerals, range from 1 to 20 cm in thickness, and constitute up to 15 percent of the biotite schist; none of these veins contains more than 5 percent carbonate minerals by volume. The predominant carbonate is ferroan calcite (identified by chemical staining; Dickson, 1965), but Harding (1944) and Young (1985) reported lesser amounts of ankerite. The quartz is medium grained (>1 mm) and shows no evidence of mylonitic texture or grain size reduction. A few veins of drill hole 82-3 are essentially composed of fine-grained tourmaline and subordinate sulfides. Four ore zones have been outlined (Fig. 4); they grade into lower grade material, both along strike and downdip (Malczak et al., 1985). These zones are steeply plunging and subparallel to the stretching lineation defined by the long axes of deformed quartz clasts (Fig. 3; Dillon, 1985; Young, 1985).

The typical opaque mineral associations are for drill hole 81-6, pyrite-chalcopyrite-pyrrhotite-ilmenite, and for drill hole 82-3, arsenopyrite-pyrite-chalcopyrite-pyrrhotite-ilmenite.

Sulfide minerals and tourmaline are strongly segregated at the vein margins. Coarse euhedral arsenopyrite, anhedral pyrite, and chalcopyrite are by far the most abundant sulfides. Arsenopyrite contains rare tourmaline, chalcopyrite, and pyrrhotite inclusions. Pyrrhotite occurs also as independent anhedral to euhedral grains. Traces of anhedral bismuthinite and gold, having an average grain size of 10 μm and occurring between quartz grains, were observed in one sample from drill hole 82-3 containing 17,220 ppb Au, in addition to the typical opaque mineral association. No arsenopyrite was seen in samples from drill hole 81-6. Ubiquitous ilmenite is disseminated in the silicate gangue as anhedral to euhedral, lath-shaped grains. Pyrite is partly replaced by marcasite. Subordinate amounts of scheelite, galena, and sphalerite have been reported to occur (Carter, 1984; Young, 1985). Galena and sphalerite were not observed in any of the 45 polished thin sections examined from drill holes 81-6 and 82-3. All samples from both drill holes were examined under shortwave ultraviolet light and failed to reveal scheelite.

Ore Chimney Mine

History and economic features

Gold was first discovered at Ore Chimney mine (Figs. 5 and 6) in 1902, and the first underground workings were begun in 1909. A 400-ft shaft was sunk and several northeasterly drifts were established. Diamond drilling, underground development, and surface geologic mapping were undertaken intermit-
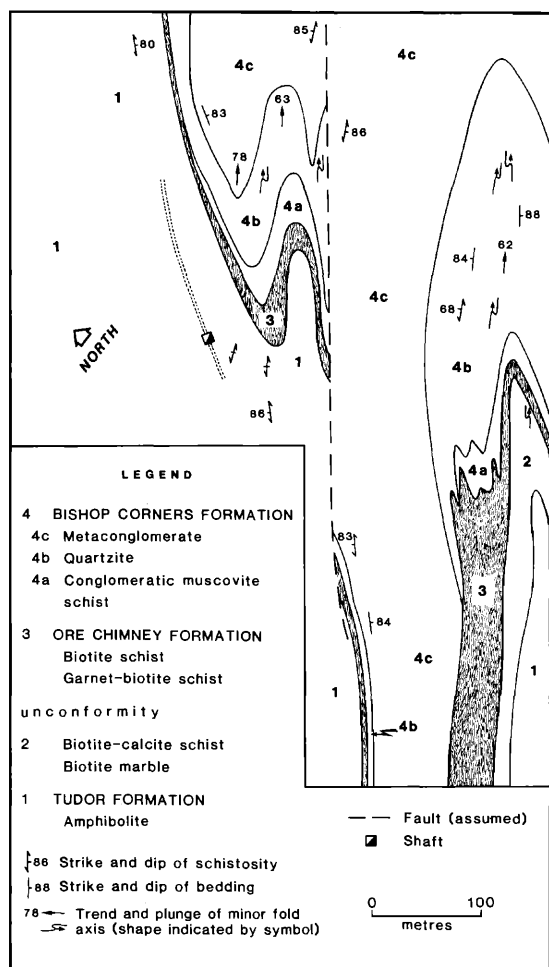
FIG. 5. Geology of the Ore Chimney mine area (modified from Moore and Morton, 1986). Dotted lines = mineralized zone projected to surface.

tently up to 1932, when the mine was flooded; exploration from surface continued to 1958. The property is presently owned by Albert Banner. From January to August 1983, the mine was dewatered and retimbered to the 150-ft level; it is presently flooded. During summer 1987, a 1,500-m drilling program was carried out to test the known mineralized zone both along strike and at depth (Northern Miner, 1987). Eleven thousand metric tons of material grading 7 g/ metric ton Au and 193 g/metric ton Ag are estimated to be present between the 108- and 500-ft levels (Carter, 1984).

Geologic setting

Mafic volcanics of the Tudor formation are overlain successively to the southeast by pelitic sediments of the Ore Chimney Formation and by crossbedded quartzite and quartzite-pebble conglomerate of the Bishop Corners Formation. The succession is de-

formed into upright isoclinal to open folds plunging steeply northeastward, with axial planes parallel to the east-northeast-striking foliation. The old mine workings are situated within the Tudor formation volcanics close to the contact of the overlying sediments (Fig. 5), near the hinge of a major fold. Although the short limb of the fold appears to be faulted parallel to the cleavage, the cross fault shown on earlier maps (see Meen, 1944) is absent.

Tudor formation: The mafic volcanic rocks exposed on the property are massive to foliated, fine- to medium-grained dark green amphibolites with minor quartz and accessory epidote, biotite, garnet, chlorite, cummingtonite, pyrite, magnetite, and carbonates. Rare sulfide-free, millimetric, quartz-calcite veinlets occur within the amphibolite. Felsic lapilli tuff layers 0.5 to 1 m thick are a minor component (<1%) of the volcanic succession, which also includes rare biotite schist layers averaging 50 cm in thickness. Carbonate sediments of the Grenville Supergroup, overlying the Tudor formation occur in the southern part of the mine property (Fig. 5), indicating that the deposit occurs stratigraphically near the top of the basaltic succession.

Ore Chimney Formation: The formation, well-exposed on the mine property, is composed of fine- to medium-grained mafic biotite schist, muscovite-biotite schist, and hornblende-biotite schist, alternating in layers up to 0.5 m thick. The schist is typically studded with garnet and less commonly contains staurolite and epidote porphyroblasts. Accessory minerals include apatite, pyrite, and magnetite.

Bishop Corners Formation: At the OCM deposit a 5-m thick layer of magnetite-bearing muscovite-quartz schist, typically containing small flattened clasts, lies between the Ore Chimney Formation and the quartzite. The quartzite is light gray or white and exhibits crossbedding throughout, marked by hematitic laminae. Abruptly overlying the quartzite is an oligomictic conglomerate comprising a framework mainly of quartzite pebbles and cobbles in a hematite-bearing muscovite schist matrix. The conglomerate is overlain by quartzofeldspathic pebbly psammite.

Sampling

Samples used in whole-rock and mineral chemistry were collected from the mine shaft, the 108- and 150-ft levels, and (amphibolite and biotite schist) the surface.

Gold and sulfide distribution

Detailed mapping (Fig. 5; Moore and Morton, 1986) indicates that the zone containing the gold and the sulfides is hosted by a biotite schist layer, within the Tudor formation, the top of which is about 30 m below the unconformity. This layer strikes 030° to 040° and dips 85° to the southeast, parallel to the
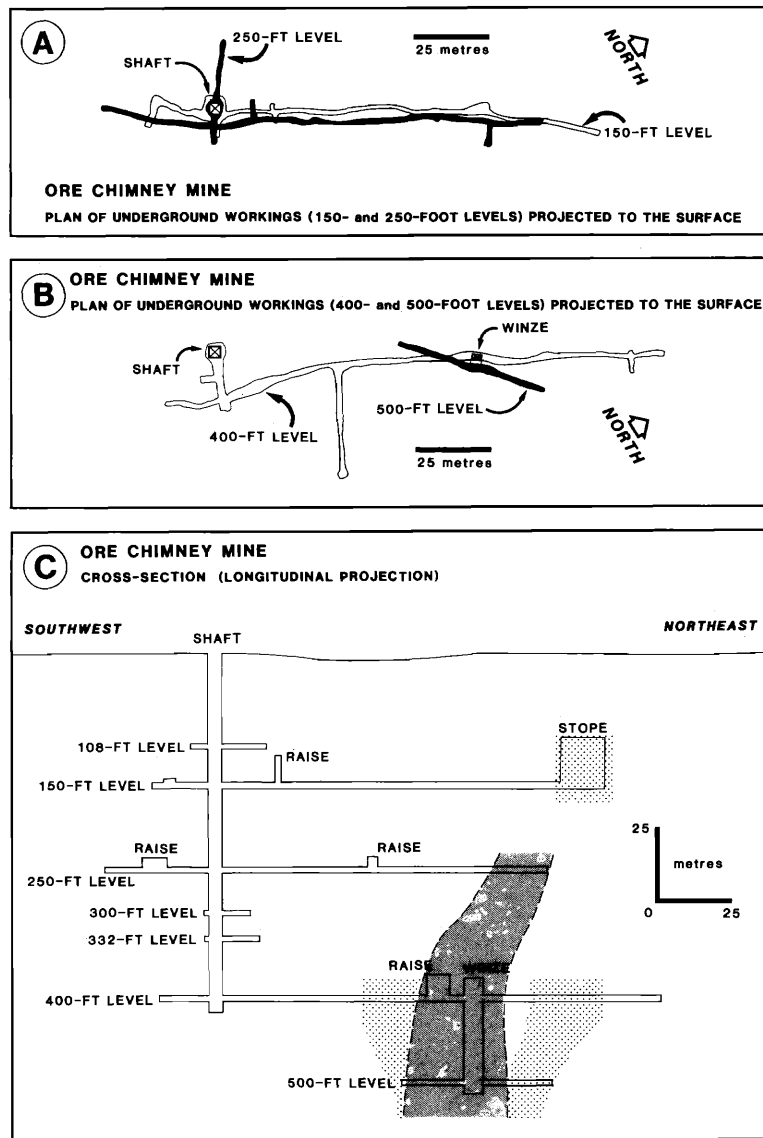
FIG. 6. Underground workings enclosing the vein system of the Ore Chimney mine. Shaded pattern = 1.0- to 1.3-m-wide zone containing 7,500 metric tons of rock averaging 8 g/metric ton Au; in this zone, gold concentration varies from 5 to 12 g/metric ton and increases with depth. Dotted pattern = lower grade mineralized zones in which gold concentration is erratic but varies commonly between 1 and 3 g/metric ton. Sources of data: original blueprints, assessment files, Ontario Geological Survey, Toronto.

base of the Flinton Group. A biotite schist layer exposed in a trench, 30 m southwest of the mine shaft, is correlated with the biotite schist zone of the mine which otherwise was not observed on surface (see fig. 5 of Moore and Morton, 1986). Examination in 1983 showed that this zone, to the 150-ft level, comprises a layer of mafic biotite and biotite-hornblende schist, locally with muscovite and chlorite, averaging 4 m in thickness and enclosed by amphibolite. A 1 to 2-m-thick zone within the schist is occupied by an irregular system of lenticular, sulfide-bearing, white quartz

veins (3 mm–1 m wide) with subordinate carbonate. The vein system consists in places of a single dominant quartz-carbonate vein 0.5 to 1 m thick. The veins are primarily concordant with the main D_1 foliation but locally cut it at angles up to 90° (Fig. 7). They are commonly folded on steeply plunging hinges that are parallel to D_1 hinges in the enclosing rocks; the folds have D_1 cleavage parallel to their axial surfaces. The quartz is coarse grained (>1 mm) and shows no evidence of mylonitic texture. These observations combined indicate that the veins filled fractures which
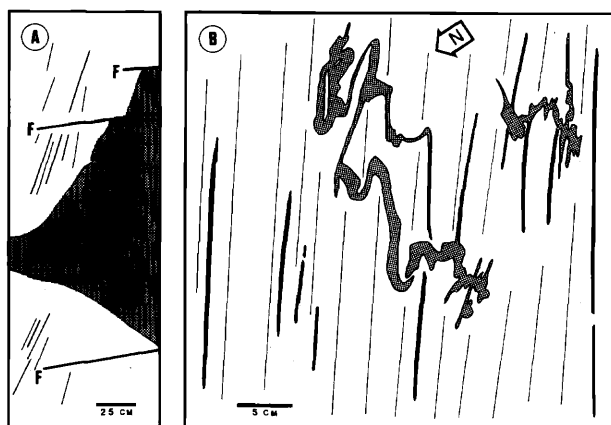
FIG. 7. Cross sections of quartz veins in biotite schist, Ore Chimney mine (drawn from photographs). Dotted pattern = quartz vein, F = subhorizontal late fault, N = north, straight lines = schistosity. A. Vertical section in shaft, 3 m below surface, looking northeast. B. Back of 108-ft level, northeasterly drift.

were formed early during D_1. The two carbonate minerals identified by chemical staining (Dickson, 1965) are ferroan calcite and ferroan dolomite, the former being by far predominant; the average calcite and dolomite content of the veins is less than 5 percent by volume but may locally compose up to 20 percent. Carbonate minerals occur also disseminated within the matrix of the biotite schist and as inclusions in hornblende porphyroblasts. Tourmaline is present as an accessory mineral in the biotite schist and the quartz-carbonate veins but is much less abundant than at the Addington mine. Sulfide minerals constitute up to 20 percent of the vein and associated wall rock; they occur as disseminations and pods up to 10 cm across and concentrated mainly along quartz vein margins, and as disseminations within host rocks between quartz stringers. The biotite schist zone hosting the gold and the sulfides was interpreted by Meen (1944), Dillon (1985), and Malczak et al. (1985) to be a shear zone. However, no kinematic features indicative of simple shear deformation such as en echelon veins, S-C fabrics, shear bands, or mylonites were observed, so this contention could not be supported.

The typical opaque mineral association is galena-sphalerite-pyrite-chalcopyrite-pyrrhotite-sulfosalt-ilmenite. In addition, traces of cobaltite and arsenopyrite were observed in two samples. The only sulfosalt observed, consisting of anhedral grains penetrating (and included within ?) galena, is an Ag-rich member of the tetrahedrite group. It exhibits molar Ag/Cu ranging from 0.7 to 1.5. The terms argentian tetrahedrite and freibergite are both appropriate for this mineral, because molar Ag varies from less than to greater than Cu (Riley, 1974; Fleischer, 1975). The freibergite from the Ore Chimney mine with the

highest Ag has 34.38 wt percent Ag and the formula $(Ag_{6.49}Cu_{4.55}Fe_{1.69})Sb_{4.31}S_{13.00}$. This is very close to the most Ag-rich freibergite (for which a complete analysis is available) from the Mount Isa deposit, which has 36.0 wt percent Ag and the formula $(Ag_{6.37}Cu_{3.72}Fe_{1.41}Zn_{0.18})(Sb_{3.95}As_{0.13})S_{13.00}$ (Riley, 1974). Freibergite occurring in the Mount Isa deposit has a very high Ag content compared to freibergite of other deposits, thus the OCM freibergite is unusually Ag rich.

Anhedral galena and sphalerite are the most common sulfides. Sphalerite contains a small amount of chalcopyrite and exsolved pyrrhotite inclusions. Chalcopyrite and pyrrhotite occur also as anhedral masses and euhedral grains, respectively. Chalcopyrite is commonly twinned. Anhedral to euhedral, lath-shaped, ilmenite crystals are disseminated throughout the gangue. Gold was not observed in any of the 45 polished thin sections examined; however, Moore and Morton (1986) reported one occurrence of visible gold in a sulfide-free sample of the biotite schist that hosts the veins. Galena, sphalerite, pyrite, and exsolved pyrrhotite are partly replaced by marcasite. A few quartz-filled millimetric fractures cut galena, sphalerite, pyrite, and marcasite and clearly postdate the marcasite replacement event. Sphalerite, typically red in thin section, is partly altered to a yellow, iron-poor variety. Galena crystals and coarse lath-shaped ilmenite are bent. Late planar fractures, 1 to 2 mm wide, filled with chalcopyrite, marcasite, galena, and pyrite cut the main quartz-carbonate veins; the sulfides may have been remobilized into these fractures.

P-T-f_{S_2} Conditions of Mineralization

The metamorphism in the Flinton-Fernleigh area has been discussed and summarized by Sethuraman and Moore (1973) and Carmichael et al. (1978). Metamorphic conditions at the Addington and Ore Chimney mines are above the upper stability limit of chloritoid; biotite and garnet are a widespread mineral pair, and staurolite and kyanite are also found in nearby biotite-rich pelites. In the mafic volcanic rocks hornblende coexists with biotite and chlorite, and cummingtonite is also present in some samples. Both gold deposits are thus within the staurolite zone of the lower amphibolite facies, although they lie very close to the upper greenschist-lower amphibolite facies transition. Regionally, the metamorphic grade increases from west to east, and staurolite in the pelites is stable up to the sillimanite isograd, which indicates that the regional pressure lay near, but higher than, the aluminosilicate triple point (Sethuraman and Moore, 1973). The pressure of metamorphism in the region thus corresponds to that of Carmichael's (1978) bathozone 4 (0.4–0.5 GPa).

Mineral chemistry and application of the sphalerite geobarometer (Hutchison and Scott, 1981) and of the

arsenopyrite and garnet-biotite geothermometers (Thompson, 1976; Sharp et al., 1985) are discussed in detail in Harnois (1987). Arsenopyrite geothermometry and sphalerite geobarometry yield temperatures and pressure estimates ranging from 420° to 530°C and 0.35 to 0.59 GPa, respectively. Application of the garnet-biotite geothermometer to the biotite schist host of both deposits gives temperatures ranging from 475° to 535°C (Harnois, 1987; Fig. 8). At a pressure of 0.5 GPa and a temperature range of 420° to 530°C, $\log f_{S_2}$ = -2.8 to -5.5 using the pyrrhotite-pyrite relationships in the Fe-S system, determined experimentally by Toulmin and Barton (1964) and Sharp et al. (1985).

Whole-Rock Chemistry

Analytical techniques

Samples of host rocks and veins from the Addington and Ore Chimney deposits were analyzed. Major elements, Ba, Cr, Nb, Ni, Rb, Sr, Y, Zn, and Zr, were determined by X-ray fluorescence; Co, Cs, Hf, Sc, Th, U, La, Sm, Eu, Yb, and Lu by instrumental neutron activation analysis (Muecke, 1980); CO_2, H_2O, and S by volatilization and nondispersive infrared absorptiometry (Bouvier and Abbey, 1980); ferrous iron by a modified cold Wilson method (Johnson and Maxwell, 1981); Au by solvent extraction and flameless atomic absorption spectroscopy (Hall, 1979; Brooks and Naider, 1985); As, Ga, and Sb by direct current plasma atomic emission spectroscopy; Ag, Cu, and Pb by atomic absorption spectroscopy; and Sb by instrumental neutron activation analysis or direct current plasma atomic emission spectroscopy. The analytical procedures are described in detail in Harnois (1987).

Results

Since the Ore Chimney Formation is believed to have been derived by weathering of the underlying rocks (Harnois and Moore, 1988; see below), its compositional relations to the Tudor formation are significant. At the Addington mine, the biotite schist of the Ore Chimney Formation is significantly enriched in Al_2O_3, K_2O, Ba, Cs, Rb, S, and H_2O and depleted in CaO, Na_2O, and Cu compared to the underlying Tudor formation amphibolite (Table 3). Some sections of the drill cores containing up to 5 percent calcite veinlets were not analyzed, thus the analytical results are biased toward low CO_2. The two chemical profiles through the Ore Chimney Formation (DDH 81-6 and DDH 82-3; Harnois, 1987) show that both biotite schist and quartz veins of this zone have a greater Au and Ag content than the Tudor formation rocks. Sb is anomalously high only in three quartz veins of drill hole 82-3. The quartz veins of the Ore Chimney Formation and the Tudor formation have low Zn abundances compared to the biotite schist and amphibolite. Rocks of the Ore Chimney Formation in drill hole 82-3 have greater As contents than in drill hole 81-6; Tudor formation rocks have low As contents compared to the rocks of the Ore Chimney Formation.

At the Ore Chimney mine, the biotite schist of the mineralized zone is significantly enriched in S, CO_2, H_2O, K_2O, Ba, Rb, and Zn and is depleted in CaO and Na_2O compared to the enclosing amphibolite (Table 3). The Ag, Au, and Pb contents of the biotite schist are slightly greater than in the amphibolite.

The Ore Chimney Formation at the Ore Chimney mine has much lower S and carbonate mineral contents and is more oxidized than at the Addington mine and in comparison with the mineralized biotite schist at the OCM deposit. The biotite schist of the mineralized zone, the amphibolite and the Ore Chimney Formation at the OCM deposit have greater Sr and $(La/Yb)_N$, and lower Cr and Ni than the biotite schist of the Ore Chimney Formation and the amphibolite at the Addington mine. These are consistent with the
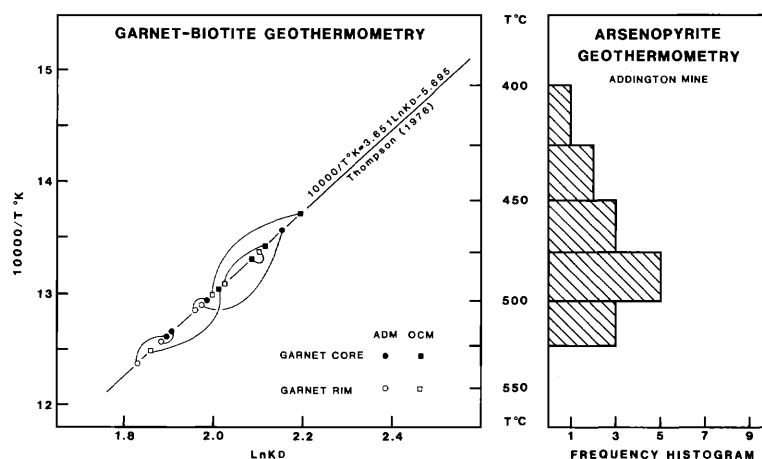

FIG. 8.   Garnet-biotite and arsenopyrite geothermometry. ADM = Addington mine, OCM = Ore Chimney mine. Lines join core and rim of the same garnet grain.

TABLE 3. Weighted Mean of Major and Trace Elements and Volatiles in Rocks from the Addington and Ore Chimney Mines

	1		2		3		4		5	
No. of samples	18		20		19		9		7	
	$\bar{x}_w$	SD	$\bar{x}_w$	SD	$\bar{x}_w$	SD	$\bar{x}_w$	SD	$\bar{x}_w$	SD
SiO_2	49.07	4.2	50.68	4.9	52.76	3.5	49.60	6.9	53.27	4.7
Al_2O_3	14.71	2.8	17.79	1.2	16.26	1.2	17.74	2.0	17.13	2.1
Fe_2O_3	2.35	1.1	1.93	1.0	3.71	1.0	1.64	0.8	3.70	2.8
FeO	11.80	3.2	11.39	2.7	8.64	2.1	11.48	3.0	8.37	2.2
FeO_{total}	(13.92)	3.5	(13.13)	3.3	(11.98)	1.9	(12.96)	3.2	(11.70)	1.2
MgO	7.55	1.9	6.32	1.2	5.17	0.9	5.20	2.3	4.51	1.5
CaO	10.38	2.4	5.53	1.9	8.68	1.4	6.57	2.2	5.77	2.3
Na_2O	2.28	1.1	0.80	0.8	2.74	0.7	1.45	0.9	0.85	0.3
K_2O	0.34	0.4	3.82	1.2	0.82	1.2	4.89	1.8	5.04	0.6
TiO_2	1.32	0.5	1.46	0.2	0.91	0.2	1.04	0.2	0.97	0.2
P_2O_5	—	n.d.	0.07	0.07	0.13	0.07	0.19	0.09	0.20	0.10
MnO	0.20	0.03	0.21	0.04	0.19	0.03	0.20	0.05	0.19	0.06
Total	100.00		100.00		100.00		100.00		100.00	
Ag	—	n.d.	3	1.5	—	n.d.	3	34	3	1.1
As	4	46	8	695	<1	n.d.	—	n.d.	<1	n.d.
Au (ppb)	<12	n.d.	17	1,872	—	n.d.	23	30	<12	n.d.
Ba	80	61	621	255	194	202	458	135	459	169
Co	46	29	47	13	38	7	36	15	35	11
Cr	155	141	225	125	77	36	86	165	99	4
Cs	6	27	126	177	1	1.7	2	0.8	5	1.3
Cu	41	165	17	21	59	42	40	111	3	158
Ga	26	8	25	4	25	2	28	5	25	1
Hf	2	0.7	3	1.3	3	1.5	4	1.6	3	1.5
Nb	—	n.d.	—	n.d.	—	n.d.	<5	n.d.	—	n.d.
Ni	45	41	61	73	19	12	14	34	26	11
Pb	3	38	4	6.9	3	3.1	9	1,734	4	0.8
Rb	3	12	90	72	15	32	90	39	127	17
Sb	—	n.d.	—	n.d.	1	1.1	1	1.4	—	n.d.
Sc	48	9	47	12	34	5	32	9	30	6
Sr	115	75	115	66	258	112	207	70	194	93
Th	—	n.d.	—	n.d.	1	1.5	4	3.8	2	1.5
U	—	n.d.	1	0.7	1	1.6	1	1.1	1	0.5
Y	37	12	28	12	27	5	21	6	22	8
Zn	87	31	72	24	111	22	304	2,192	99	40
Zr	63	29	81	39	55	9	59	45	58	14
La	1.8	1.1	2.0	1.2	5.2	2.4	3.5	17.1	6.2	1.3
Sm	2.3	1.2	2.8	1.0	3.1	0.6	2.7	1.3	4.0	0.7
Eu	0.9	0.5	1.2	0.4	1.1	0.2	1.1	0.5	1.1	0.2
Yb	2.7	1.6	2.2	1.3	2.4	0.9	1.8	0.8	2.7	0.7
Lu	0.4	0.2	0.5	0.2	0.4	0.3	0.4	0.2	0.5	0.1
Oxiratio	17	8	13	4	28	9	12	6	29	18
$(La/Yb)_N$	0.45	0.17	0.74	0.32	1.59	0.87	0.72	12.2	1.61	0.32
Ti/Zr	129	48	120	26	102	19	109	37	102	4
Zr/Y	1.67	0.51	2.56	1.41	2.11	0.33	2.83	2.82	2.53	1.44
Nb/Y	<0.10	n.d.	<0.10	n.d.	<0.10	n.d.	<0.10	n.d.	<0.10	n.d.
K_2O/Na_2O	0.11	0.30	5.04	3.31	0.25	0.67	5.27	5.17	5.82	1.81
K_2O/CaO	0.30	0.04	0.73	0.83	0.09	0.18	0.72	0.61	0.83	0.75
CaO/Na_2O	4.73	1.99	6.92	4.47	3.07	2.41	5.85	6.71	8.06	3.05
K/Rb	>1,000	n.d.	333	80	>1,000	n.d.	435	61	337	44
Ba/Rb	>1,000	n.d.	6.35	1.57	>1,000	n.d.	4.96	1.29	3.73	1.25
S	0.13	1.02	0.30	0.36	0.01	0.03	0.26	0.30	0.01	0.14
CO_{2total}	1.97	1.18	0.31	1.63	0.48	0.75	3.26	1.96	1.28	1.28
H_2O_{total}	1.79	1.15	2.66	0.75	1.49	0.31	2.76	1.06	2.78	0.75

1. Amphibolite, Tudor formation, Addington mine; rare earth elements based on 16 samples
2. Schist, Ore Chimney Formation, Addington mine
3. Amphibolite, Tudor formation, Ore Chimney mine
4. Biotite schist, mineralized zone, Ore Chimney mine
5. Schist, Ore Chimney Formation, Ore Chimney mine

Major elements are in wt percent; trace element abundances are in parts per million (ppm) unless otherwise stated; n = number of samples averaged; $\bar{x}_w$ = weighted mean; SD = one standard deviation, absolute value; n.d. = not determined; — = not detected; FeO_{total} = total iron as FeO (values are not included in total); Oxiratio = $[2Fe_2O_3/(FeO + 2Fe_2O_3)] \times 100$ (molecular proportions); $(La/Yb)_N$ = chondrite-normalized ratio; volatile values are in wt percent; S = sulfur; CO_{2total} = total carbon as CO_2; H_2O_{total} = total water

TABLE 4. Correlation of Selected Elements (Addington Mine)

Correlation matrix of selected elements from samples of the Ore Chimney Formation

	Ag	As	Au	Cu	Pb	Sb	Zn	Fe	S	CO_2
Ag	1.00									
As	−0.20	1.00								
Au	−0.01	0.67	1.00							
Cu	0.16	−0.08	0.26	1.00						
Pb	−0.11	−0.04	−0.03	−0.02	1.00					
Sb	−0.24	0.98	0.69	−0.06	0.03	1.00				
Zn	0.61	−0.25	−0.14	0.11	−0.24	−0.33	1.00			
Fe	0.68	−0.12	−0.01	0.17	−0.21	−0.19	0.86	1.00		
S	0.18	0.12	0.43	0.89	0.02	0.13	0.15	0.24	1.00	
CO_2	−0.02	0.00	0.02	0.05	0.12	−0.06	0.13	0.10	0.14	1.00

Correlation matrix of selected elements from 26 samples (biotite schist and quartz-carbonate-tourmaline veins) of the Ore Chimney Formation (Addington mine)

less differentiated character of the Tudor formation at the ADM deposit. The large standard deviation of K_2O/Na_2O in the volcanics is a result of the very low abundance of K_2O in these rocks.

Correlation matrices (Tables 4 and 5) of biotite schist and quartz veins from the Ore Chimney Formation at the Addington mine and the mineralized zone at the Ore Chimney mine show that there is no good correlation between gold and any major components of the sulfides. This strongly suggests that the gold occurs free in the quartz veins and the biotite schist and is not associated with a particular sulfide. Ag has a good positive correlation (0.84) with Pb in the mineralized zone of the Ore Chimney mine and reflects the close association of Ag-rich tetrahedrite with galena.

Discussion

The Addington and Ore Chimney deposits show some similarities to Archean lode gold deposits of the Canadian Shield as described by Boyle (1979), Hodgson and MacGeehan (1982), Kerrich (1983), Colvine

et al. (1984), and Roberts (1987). The Archean deposits are typically associated with tholeiitic basalt, surrounded by narrow carbonate alteration halos and exhibit similar associated ore minerals. On a regional scale at least, they are also associated with major geologic breaks and with volcano-sedimentary contacts. In contrast, most Archean lode deposits contain felsic intrusive and/or extrusive rocks within the mine workings and many occur in greenschist facies terranes. The ADM and OCM deposits are not evidently related to small intrusions, and since they occur in a lower amphibolite rather than greenschist facies terrane, represent a slightly higher temperature of mineralization. They are also notably smaller than many Archean deposits.

Origin of the Ore Chimney Formation

It has been suggested that the Ore Chimney Formation represents either a mafic metasediment (Moore and Thompson, 1980) or a shear zone alteration product of the Tudor metavolcanic rocks (Carter, 1984; Malczak et al., 1985; Laing et al.,

TABLE 5. Correlation of Selected Elements (Ore Chimney Mine)

Correlation matrix of selected elements from samples of the mineralized zone

	Ag	As	Au	Cu	Pb	Sb	Zn	Fe	S	CO_2
Ag	1.00									
As	0.42	1.00								
Au	0.43	0.42	1.00							
Cu	0.52	0.72	0.10	1.00						
Pb	0.84	0.47	0.43	0.45	1.00					
Sb	0.28	0.36	0.53	−0.02	0.31	1.00				
Zn	0.54	0.20	0.65	−0.03	0.62	0.31	1.00			
Fe	0.30	0.12	−0.09	0.36	0.32	−0.10	−0.03	1.00		
S	0.73	0.76	0.49	0.77	0.78	0.30	0.57	0.33	1.00	
CO_2	0.39	0.15	0.25	0.24	0.30	0.18	0.15	0.65	0.36	1.00

Correlation matrix of selected elements from 23 samples (biotite schist and quartz-carbonate veins) of the mineralized zone (Ore Chimney mine)

1987). The geochemistry and origin of the Ore Chimney Formation were discussed in detail by Harnois and Moore (1988). Their data (although they do not preclude a local overprint of shearing and metasomatism) are most consistent with a hypothesis of origin as a locally reworked sediment derived by weathering of the volcanic rocks.

The mineralized zone of the Ore Chimney mine

The mineralized biotite schist zone of the Ore Chimney mine is, chemically, quite similar to the Ore Chimney Formation rocks hosting the Addington deposit, except for Cs and Ba (Table 3). The absolute abundances as well as the K_2O/Na_2O, K_2O/CaO, CaO/Na_2O, and the immobile element ratios are not significantly different. The chemistry of this biotite schist zone is compatible with either of these two origins: (1) the rocks are metamorphosed interflow sediments (or mafic tuff), to which potassium has been added during weathering or alteration; or (2) the biotite schist is an altered equivalent of the surrounding amphibolite.

The isocon graphical method of Grant (1986) neither rules out nor confirms hypothesis (2) because the immobile element contents of the biotite schist are within the range of variation of the enclosing mafic lava flows. The biotite shows no evidence of reaction textures with other minerals; therefore, the timing of any possible K metasomatism, with respect to peak metamorphism, is similar to that at the Addington mine.

The high CO_2 content of the biotite schist from the mineralized zone, compared to the enclosing amphibolite, may either be of sedimentary origin or result from a weak carbonatization of the wall rock during gold and sulfide deposition.

Origin of the mineralizing fluid

At the Addington and Ore Chimney deposits the gold- and sulfide-bearing quartz veins exhibit strain and fold geometry comparable to their host rocks, indicating that the veins were present throughout most of the deformation history. Although approximately concordant to the main regional, axial plane foliation, they locally cut the schistosity (Fig. 7), suggesting that these veins were synchronous with D_1 deformation. At the Addington mine, garnet porphyroblasts overgrowing the foliation have sulfide and tourmaline inclusions, indicating that metamorphism outlasted the mineralizing event. The agreement between arsenopyrite geothermometry (420°–530°C) and garnet-biotite geothermometry (475°–535°C), and the concordance of sphalerite geobarometry (0.35–0.59 GPa) with the pressure range deduced from metamorphic mineral assemblages (0.4–0.5 GPa), suggests that the gold- and sulfide-bearing quartz veins were formed near peak metamorphic conditions and that the mineralizing fluid was a supercritical metamorphic fluid. The absence of post-peak metamorphic hydrothermal alteration and the close association of gold with the sulfide-bearing veins suggest that gold and base metals were transported and deposited by the same fluid.

The voluminous Tudor metavolcanic rocks immediately underlying the deposits, at a metamorphic grade just above greenschist facies, are the most probable source of the fluid. Approximately 5 wt percent structural water (contained mainly in chlorite) is typically released from a rock of basaltic composition during metamorphic outgassing at the greenschist-amphibolite transition (Fyfe and Kerrich, 1984).

The composition of the ore-forming fluid and the physico-chemical conditions under which gold was carried and deposited cannot be accurately specified. The assemblage pyrite + pyrrhotite ± arsenopyrite occurs at conditions of relatively low oxygen fugacity ($<10^{-20}$ at 500°C and 0.5 GPa; Froese, 1976) and high sulfur fugacity ($10^{-3.5}$ at 500°C and 0.5 GPa; Toulmin and Barton, 1964; Sharp et al., 1985). In such reduced conditions gold is soluble as a bisulfide complex over a wide range of pH (Romberger, 1986).

Possible gold preconcentration mechanisms

The overlap in mineralogy of the pre-Flinton volcanic-hosted deposits (group I; Table 1), sediment-hosted deposits (group II), and the deposits associated with the base of the Flinton Group (group III) suggests similar mineralizing fluids. This is supported by limited lead isotope data of Fletcher and Farquhar (1977, 1982) for deposits OCM and W and a marble-hosted base metal occurrence 2.8 km northeast of Fernleigh not listed in Table 1 (deposit G of Fletcher and Farquhar, 1982; also described by Malczak et al., 1985, as base metal and pyrite occurrence 51). The Pb isotope ratios of galenas from these deposits are fairly similar to each other and are the most radiogenic of the entire Central Metasedimentary belt data set of these authors. They concluded that the genesis of these galenas required substantial interaction of the mineralizing fluid with the country rocks.

It is possible that the gold and base metals in the deposits were leached from average Tudor basalts. It is reasonable to suppose, however, that they were mechanically and/or chemically concentrated before being remobilized by metamorphic fluids during the main episode of metamorphism and deformation. Possible concentration mechanisms include the following eluvial-alluvial processes and synvolcanic-hydrothermal processes:

1. Gold concentration in a paleosol derived from basaltic rocks has been documented by Martini (1986). Gold may have been concentrated in a rego-

lith developed on Tudor formation volcanics, which was then locally transported and alluvially deposited as Ore Chimney Formation sediments, thus providing an Au-enriched source bed for the gold deposits associated with the base of the Flinton Group and the Ore Chimney Formation (group III deposits; Table 1 and Fig. 2).

2. Marble-hosted gold deposits of group II (Table 1 and Fig. 2) are all associated with at least one shallow intrusion or are close to the contact with the underlying volcanics. The presence of an abundance of small mafic to intermediate intrusions within the sedimentary clastic and carbonate rocks intercalated with, and overlying, the volcanics of the Flinton-Fernleigh area indicates that igneous activity was continuing at the time of sedimentation, providing thermal energy for hydrothermal systems. Gold may have been leached from the underlying volcanics, in a process similar to that occurring in modern ocean-floor basalts (Nesbitt et al., 1987), and precipitated with sediments. Such a process may have contributed to the genesis of the volcanic-hosted gold deposits of group I (Table 1 and Fig. 2), and more specifically, to the genesis of the Ore Chimney deposit. This hypothesis is supported by the occurrence of marble and calcitic schist in the southern part of the Ore Chimney mine property, below the Ore Chimney Formation (Fig. 5), and by the location of this deposit close to the inferred top of the Tudor formation in the area.

3. Gold-arsenic occurrences (deposits A–E of group I, Table 1 and Fig. 2), probably of volcanic-exhalative origin, occur well within the Tudor formation, associated with interflow sediments. Although it is possible that this mechanism led to preconcentration of Au at the Addington mine, the absence of documented interflow sediments in the vicinity makes this suggestion highly speculative.

4. Gold may also have been deposited as volcanic-and/or sediment-hosted epithermal vein deposits prior to the main metamorphic event.

Hydrothermal alteration

The high K_2O and low Na_2O and CaO contents of the Ore Chimney Formation rocks, compared to the volcanics (Table 3) are consistent with those of an isochemically metamorphosed argillaceous sediment with or without a superimposed potassic alteration. The high Ba and Cs contents of the Ore Chimney Formation at the Addington mine (621 ppm Ba and 126 ppm Cs) compared to those of the underlying volcanics (80 ppm Ba and 6 ppm Cs; Table 3) suggest that these rocks were altered. The high tourmaline content associated with the sulfide- and gold-bearing veins and the presence of numerous small carbonate veins at the Addington mine also suggest that these rocks were affected by hydrothermal alteration. In

contrast, there are no such evident chemical anomalies or alteration at the Ore Chimney mine.

The CO_2 contents (Table 3) and the presence of accessory carbonate minerals and small calcite veins suggest that the Tudor and the Ore Chimney formations at the Addington mine, and the Ore Chimney Formation at the Ore Chimney mine were weakly carbonatized. This evidence indicates that carbonatization is not restricted to the Ore Chimney Formation nor is it restricted to the biotite schist lithology. Staurolite, kyanite, garnet, and hornblende do not show evidence of reaction textures with carbonate, indicating that any carbonatization occurred before peak metamorphism. Hynes (1980) and Murphy and Hynes (1986) showed that Ti, Y, and Zr may be mobile during carbonatization. The lack of any significant correlation between CO_2 and these elements, the small range in concentrations of Ti, Y, and Zr, and the coherence of the ratios Ti/Zr and Zr/Y indicate that these elements remained relatively immobile in the Ore Chimney Formation.

Potassic alteration is a common feature of gold deposits occurring in Archean greenstone belts, where it is typically associated with intense carbonatization. Although the Ore Chimney Formation as a whole contains more K_2O than the adjacent rock units, rock analyses show no significant correlation between K_2O and CO_2. The main difference between the Ore Chimney Formation rocks at the Addington mine and the Ore Chimney mine is that those of the former are mineralized and carbonatized, and those of the latter are only carbonatized. There are no significant differences between the K_2O/Na_2O, K_2O/CaO, CaO/Na_2O, and K/Rb ratios of the Ore Chimney Formation at Addington and Ore Chimney mines (Table 3). The coherence of these ratios suggests that the mineralizing process increased the As, Au, B, Ba, Cs, S, and carbonate contents of the Ore Chimney Formation rocks at the Addington mine without significantly changing their K_2O content. It also suggests that potassic alteration associated with mineralization was very weak or absent.

The only possible evidence of K metasomatism is of very local scale. The biotite content of the underlying amphibolite increases sharply within 0.5 m from the contact with the Ore Chimney Formation, suggesting that at some time before peak metamorphism, potassium moved into the underlying volcanic rocks over a short distance. This increase in potassium may alternatively be a result of K enrichment of the volcanic rocks most exposed to paleoweathering.

Chemical controls of gold deposition

Mechanisms of precipitation of gold include, among others: (1) a decrease or increase in pH, (2) dilution or reduction of the activity of the ligand species car-

rying gold, and (3) changes in the redox conditions of the fluid (Henley, 1973; Cathles, 1986; Romberger, 1986; see also Barnes, 1979).

The Addington and Ore Chimney deposits are stratigraphically 0 to 10 m and 30 m, respectively, below the Bishop Corners Formation. The mafic volcanics and the Ore Chimney Formation (hornblende, biotite, garnet, staurolite, epidote, iron sulfides, ilmenite, minor magnetite) are more reduced than the overlying magnetite-hematite-bearing coarse clastic sediments, thus there is a rather sharp change in redox properties of the rocks at the boundary between the Ore Chimney Formation and the Bishop Corners Formation.

It is suggested that this redox front played a major role in gold deposition at the two deposits described in this paper (see also Laing et al., 1987), and therefore, that process (3) was the predominant mechanism of gold deposition. As a gold-bearing fluid, originating in the mafic rocks, approached the redox front, oxidation of the fluid would have caused destabilization of the Au-carrying complexes and precipitation of gold under pyrite-pyrrhotite equilibrium conditions. However, precipitation of gold by a combination of the three processes mentioned above is not ruled out.

Structural controls of gold deposition

The formation of these two gold deposits near the base of, and immediately below, the Flinton Group may be related to the difference between the mechanical properties of the coarse clastic sediments of the Flinton Group and the underlying rocks, and to the presence of a regional unconformity. Mills and Eyrich (1966) have stressed the role of unconformities as potential plumbing systems. The regional unconformity may have focused the discharge of the mineralizing fluids. Probable porosity and permeability contrasts between the pre-Flinton rocks and the clastic sediments of the Flinton Group raise the possibility that vein formation through hydraulic fracturing occurred. A possible, although unproven, scenario would be that the fluid escaping from the Tudor formation volcanics was trapped below impermeable quartzite of the Bishop Corners Formation and accumulated within the Ore Chimney Formation. As pore fluid accumulation increased, the overpressure became sufficient that brittle failure resulted. As the pore fluids created more porosity and eventually permeability for themselves, vein formation occurred.

Conclusions

Mineralization and vein formation at the Addington and Ore Chimney gold deposits occurred during the main episode of deformation (D_1) and near peak metamorphism ($475°-535°C$ and 0.4 to 0.5 GPa).

Gold was carried under reduced conditions in a metamorphic fluid, which was most likely focused through the unconformity plumbing system. The redox front at the boundary between the Ore Chimney Formation and the Bishop Corners Formation may have been a major factor in gold deposition. The mineralizing process was associated with a weak carbonatization of the wall rock. Gold and base metals may have been remobilized from preexisting concentrations in the basalts and/or the Ore Chimney Formation itself.

The Flinton-Fernleigh area has not yet been sufficiently explored to prove or disprove the presence of potentially economic gold deposits. Moreover, the presence of a subeconomic gold deposit, such as the Addington mine, in this area raises the possibility that larger and/or higher grade gold deposits might exist. Future exploration work should be directed primarily toward carbonatized biotite schists near or at the base of the Flinton Group, where it overlies mafic volcanic rocks. The occurrence of several marble-hosted gold deposits, such as the formerly producing Star mine (deposit J; Table 1 and Fig. 2), near the top of the volcanic rocks suggests that this contact is also an interesting target. The highest gold potential in the region may occur where this contact is overlain by rocks of the Flinton Group.

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