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Article abstract

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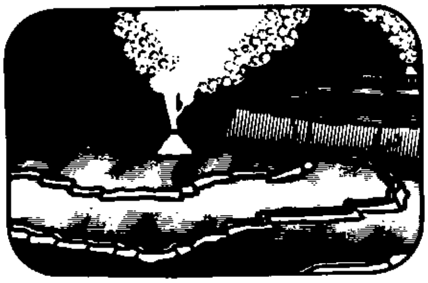
The waters which issue from the Ohakiand Champagne pools are ultimately of meteoric origin. These waters have passed to depths of at least 1.5 km in a complex sequence of volcanic and sedimentary rocks, and have returned to the surface as neutral, weakly saline fluids near their boiling points. These fluids are undersaturated, by several orders of magnitude, with respect to the gold they contain, At the surface the fluids are cooled, oxidized and acidified, causing them to precipitate much of their dissolved load. The precipitated material forms aprons of siliceous sinter richin sulphur, gold, arsenic, antimony, mercury and thallium.



The Sinters of the Ohaki and Champagne Pools, New Zealand: Possible Modern Analogues of the Hemlo Gold Deposit, Northern Ontario

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Summary

The Archean Hemlo gold deposit has many similarities with the sinters formed by two New Zealand hot springs, the Ohaki and Champagne pools. The New Zealand hot springs, therefore, warrant consideration as possible analogues of the mineralizing system which formed the Hemlo deposit.

The waters which issue from the Ohaki and Champagne pools are ultimately of meteoric origin. These waters have passed to depths of at least 1.5 km in a complex sequence of volcanic and sedimentary rocks, and have returned to the surface as neutral, weakly saline fluids near their boiling points. These fluids are undersaturated, by several orders of magnitude, with respect to the gold they contain. At the surface the fluids are cooled, oxidized and acidified, causing them to precipitate much of their dissolved load. The precipitated material forms aprons of siliceous sinter rich in sulphur, gold, arsenic, antimony, mercury and thallium.

Introduction

A recent, major development in the study of economic geology has been the discovery of *black smokers*, submarine hot springs which are depositing base metal sulphides (see, for example, Rona, 1984). The possibility that black smokers are modern analogues of volcanogenic massive sulphide deposits has opened some interesting lines of inquiry (Goldie and Bottrill, 1981). The purpose of the present report is to suggest that two currently active subaerial hot springs in New Zealand, which have precipitated gold-rich sinters, may be modern analogues of the system which formed the Main Hemlo Orebody. This comparison may have implications for the origin of other mineral deposits on the Canadian Shield. The geothermal fields of New Zealand and elsewhere are *hydrothermal systems*, as the term is used by economic geologists. In fact, Henley and Ellis (1983) have suggested that many mineral deposits, and the alteration associated with them, represent fossil geothermal fields.

There is also a historical reason for encouraging a comparison between the Main Hemlo Orebody and the New Zealand sinters. David Bell, one of the discoverers of Hemlo, has said (pers. comm., 1984) that his awareness of the New Zealand sinters encouraged him in his drill program.

The New Zealand springs recently have been the subject of scientific scrutiny, but many of the results appear in publications which are difficult to obtain, at least in North America. This paper briefly discusses Hemlo and summarizes the features of the New Zealand occurrences which may be relevant to the genesis of the Main Hemlo Orebody.

Hemlo

The Hemlo gold deposit is located in northern Ontario, on the northern shore of Lake Superior approximately 250 kilometres east of Thunder Bay (Fig. 1). Hemlo is the most spectacular mineral discovery to have been made in Canada in nearly two decades. Known reserves at the Main Hemlo Orebody are approximately 70 million tonnes grading 8.6 g of gold per tonne (Cohen, 1984). The following observations are based on Muir (1982), Quartermain *et al.* (1983), Patterson (1984) and McMillan and Robinson (1984). The deposit is within several parallel, closely-spaced tabular zones which are generally (but not always) conformable with the rocks which enclose them. These host rocks are metasediments and metavolcanic rocks of Archean age and are of amphibolite metamorphic grade. The rocks hosting the ore-body are cut by a quartz-white mica stockwork. Compared with the average composition of Canadian Archean supracrustal rocks, the ore is enriched in sulphide, sulphate, antimony, mercury, arsenic, thallium, barium and molybdenum and gold, but is not enriched in copper and zinc.

The Broadlands and Waiotapu Geothermal Systems

The following features are common to all terrestrial geothermal systems (Henley and Ellis, 1983): (1) permeable rocks; (2) a source of heat; and (3) convecting fluids. Fractures usually make a larger contribution to permeability than does primary porosity. The heat source is usually an intrusion, but may be a fault zone which generates heat by friction, or a pile of fragmental, glassy rocks which generates heat by exothermic hydration reactions. The source of the convecting fluids is usually

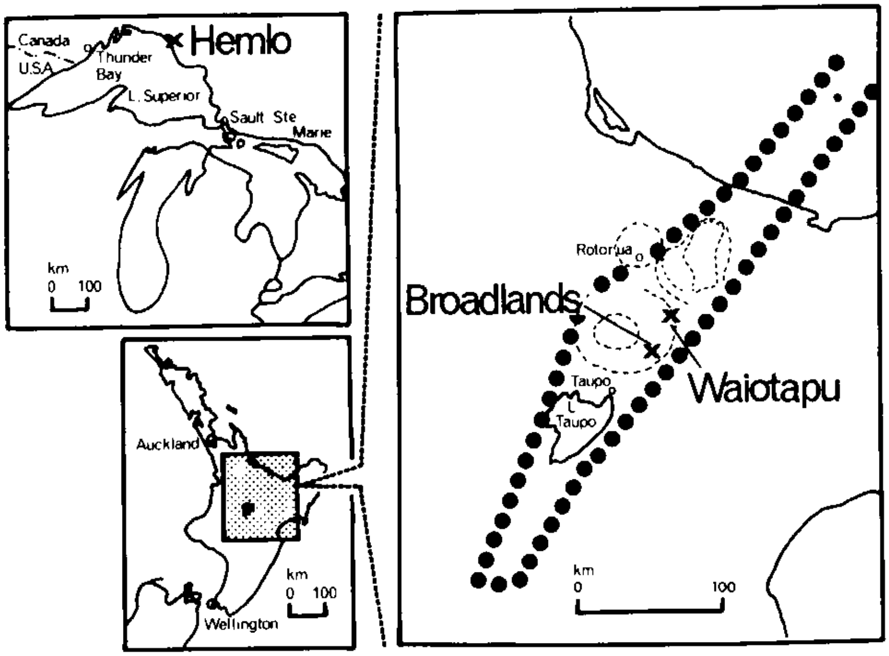

Figure 1 *Location maps.* **Top left:** *Great Lakes area of North America, showing the Hemlo gold mining camp.* **Bottom left:** *the North Island and the northern part of the South Island, New Zealand (same scale as top left map).* **Right:** *enlargement of the shaded area on the bottom left-hand map, showing the locations of the Broadlands and Waiotapu geothermal fields.* **Dots:** *border of the Taupo Volcanic Zone.* **Dashed lines:** *ring faults and caldera margins. After Cole (1979) and Hedenquist (1983a)*

either meteoric waters or seawater. Where suitable cap rocks are present, a geothermal system discharges as hot springs or fumaroles. Hedenquist, of the New Zealand Department of Scientific and Industrial Research, has stated that "virtually all the active (geothermal) systems in New Zealand have some precious and/or base metal mineralization associated with them" (pers. comm., 1984). The two occurrences of gold mineralization which I shall consider in this paper are the Ohaki pool of the Broadlands geothermal system and the Champagne pool of the Waiotapu system. This summary is based on Weissberg (1969), Browne (1971), Nathan (1976), Ewers and Keays (1977), Weissberg *et al.* (1979) and Hedenquist (1983 a, b, c).

The Broadlands and Waiotapu geothermal fields occur about 20 km apart (Fig. 1). Both are on the eastern margin of the Taupo Volcanic Zone, a complex graben which trends north-northeast and which is up to 50 km across (Cole, 1979). Both fields have been explored by drill holes: to depths of 2.4 km at Broadland and 1.1 km at Waiotapu. Only the Broadlands field is currently (or has ever been) exploited for geothermal energy.

At both fields, complexly deformed Mesozoic greywackes and argillites are overlain by at least 0.5 km of little deformed Quaternary rocks consisting of pumiceous, felsic pyroclastic deposits, felsic and intermediate lava flows, domes and intrusions, and some lacustrine muds. The pyroclastic rocks have porosities of 10%-20% and are aquifers, whereas the lake beds and lava flows have low permeabilities.

Deuterium/hydrogen ratios indicate that the waters in the geothermal fields are largely or entirely of meteoric origin. These waters descend to at least 1.5 km below the surface, and are heated by conduction when they approach magma chambers, whose exact location is uncertain: they could be as deep as 10 km or as shallow as 3 km. The heated waters rise along fissile zones and move laterally into aquifers. Although the horizontal dimensions of the aquifers may be as great as several kilometres, their lateral boundaries are not well understood. Recent work at Broadlands has failed to confirm the presence of an impermeable, vertical curtain of chemical precipitates, as postulated by M.P. Hochstein and reported in Nathan (1976).

The deep waters are relatively reducing (Hedenquist, 1983c). Partial pressures of H_2S and H_2 average about 0.1 bars. The major gas species, CO_2, has partial pressures of 1 to 5 bars at Waiotapu and 5 to 50 bars at Broadlands. The pH values are neutral, and salinities are low to moderate (1000 to 4000 ppm chloride ions); hence, these waters are referred to as "neutral-chloride" waters. Silica concentrations in these waters are approximately saturated with respect to quartz (Table I). In the depths of the Broadlands system, the deep waters are in equilibrium with the observed propylitic alteration assemblage (pyrite ± pyrrhotite ± sphalerite ± galena ± chalcopyrite ± quartz ± albite ± K-feldspar + calcite + K-mica + chlorite ± wairakite ± epidote). In deep parts of the Waiotapu the observed assemblage is similar: pyrite + pyrrhotite + quartz + albite + adularia + epidote + chlorite + calcite + wairakite. However, the albite and adularia are almost always partially or completely replaced by white mica. This replacement suggests that the present partial pressures of CO_2, of up to 50 bars, are at least ten times greater than they were when the albite and adularia were formed.

At a depth of one km, the boiling point of the neutral-chloride waters is about 300°C. Below this depth, no temperatures greater than the boiling point have been measured or inferred. Above one km, however, actual temperatures approximate boiling temperatures. The steam released during boiling is rich in H_2S and CO_2 and poor in chloride ions. In the Waiotapu field, some of this steam condenses within 50 m of the surface, oxidizes, and mixes with shallow meteoric waters. The resulting *steam-heated* waters are acidic, rich in sulphate ions and poor in chloride ions (Table I); hence their alternate name, *acid-sulphate* waters. These waters produce advanced argillic alteration (alunite + kaolinite + pyrite + cristabolite ± sulphur) in the rocks near the surface.

The Ohaki and Champagne Pools

The Ohaki and Champagne pools both occupy and are fed through old hydrothermal eruption vents. The eruption which formed the Champagne pool occurred about 900 years ago when a discharge zone became clogged with silica. Both vents appear to be located at the intersections between cross fractures, and faults parallel to the north-northeasterly regional trend. The cross fractures trend northwest at the Ohaki pool and west at the Champagne pool.

The Ohaki pool occupies an area of about 800 m² and is the major natural surface outlet of the Broadlands field. Before commercial exploitation, the pool discharged about 10 L/sec of water at 98°C. The Champagne pool occupies an area of about 3000 m² and has a temperature of 75°C. Bubbles of CO_2 give the pool its name.

Table I *Characteristics of some New Zealand geothermal waters (1)*

	"Neutral-chloride" Broadlands waters (2)	"Neutral-chloride" Waiotapu waters		"Acid-Sulphate" (or "steam-heated Waiotapu waters")
		(3)	(4)	
Temperature	261°C	–	75°C	99°C
pH	6.2	8.6-8.9	4.9-6.5	2.2
free CO_2	121 pppm	–	170 ppm	–
total SiO_2	545 ppm	199- 470 ppm	385- 495 ppm	308 ppm
sulphide	101- 120 ppm	80- 100 ppm	6- 18 ppm	–
sulphate	5 ppm	≒ 40 ppm	99- 145 ppm	338 ppm
chloride	1180 ppm	1950-1450 ppm	1879-2000 ppm	6 ppm
Fe	250- 360 ppb	–	–	–
Cu	0.9-2.0 ppb	–	–	–
Zn	0.6-7.0 ppb	–	–	–
As	5.5-5.7 ppm	–	4.9 ppm	–
Ag	0.3-6.0 ppb	–	–	–
Sb	0.2 ppm	–	–	–
Au	0.04 ppb	–	–	–
Pb	1.3-5.5 ppb	–	–	–

(1) analyses performed and/or compiled by Grange (1937), Nathan (1976), Weissberg *et al.* (1979), Hedenquist (1983b and pers. comm., 1984).

(2) waters from drill-hole 2 BR-2, depth not published

(3) discharges from Wt-6, a 1 km deep well 340 m west of the Champagne pool, flashed to 100°C

(4) discharges from the Champagne pool; these waters have mixed with some "acid-sulphate" water.

Dashes mean "not analyzed".

The waters of the Ohaki pool are of the deep, neutral-chloride type; those of the Champagne pool are of the neutral-chloride type, diluted with "steam-heated" meteoric waters.

The Ohaki pool has deposited a grey-white siliceous sinter over an area of 10,000 m^2 (although the words "sinter" and "exhalite" are synonymous, current Canadian practice seems to be to use them to describe, respectively, subaerial deposits and submarine deposits). Between 1957 and 1966 a gold-rich, red-orange layer was laid down within the sinter. Inside the Champagne pool a gold-rich, orange-brown precipitate has been forming intermittently, probably at least since the 1920s. (Grange (1937), who did his field work in the 1920s, mentioned "fretted brown sinters" containing 5 ppm gold at the Champagne pool.) This orange-brown material is interlaminated with a grey siliceous sinter. Waters from the Champagne pool spill over and drain first to the east and then to the south (Fig. 2). This overflow has built up the Primrose terrace (Grange, 1937), a terraced apron of sinter up to 50 m wide and extending up to 200 m from the Champagne pool.

Both the Ohaki pool and the Champagne pool sinters are rich in sulphides as well as gold. Table II presents analyses of these sinters, with Hemlo analyses for comparison.

Source, Transportation and Deposition of Metals

As shown in Table I, the concentrations of precious and base metals are very low in the deep *neutral-chloride* waters of the Broadlands and Waiotapu systems. However, boiling, and subsequent cooling, are sufficient to precipitate base metal sulphides from these fluids. This mechanism can account for the enrichment in galena, sphalerite and chalcopyrite which occurs at depths ranging from 200 m to over one km in both the Broadlands and Waiotapu systems.

Gold is probably transported in these systems as a thio-complex, such as $Au(HS)_2^-$ (Seward, 1973). However, the deep fluids are undersaturated by several orders of magnitude with respect to compounds of gold and sulphur. It is difficult to supersaturate these fluids by simple boiling or cooling (in fact under certain conditions, boiling would increase the solubility of gold; Hedenquist (1983a)). Four mechanisms have been proposed for precipitation of gold from "neutral-chloride" waters (Hedenquist and Henley, 1984):

(a) Boiling. Boiling causes oxidation (as H_2S and H_2 are lost) and an increase in pH (as CO_2 is lost). The latter effect converts H_2S to HS^- and both reactions reduce the amount of H_2S available for gold complexing. Hedenquist (1983a) has inferred that boiling is most likely to precipitate gold from fluids with oxygen fugacities buffered by sulphide-sulphate assemblages, rather than by the pyrite-pyrrhotite assemblages present at Waiotapu; (b) Cooling at or near the ground surface; (c) Near-surface mixing with "steam-heated" (acid-sulphate)

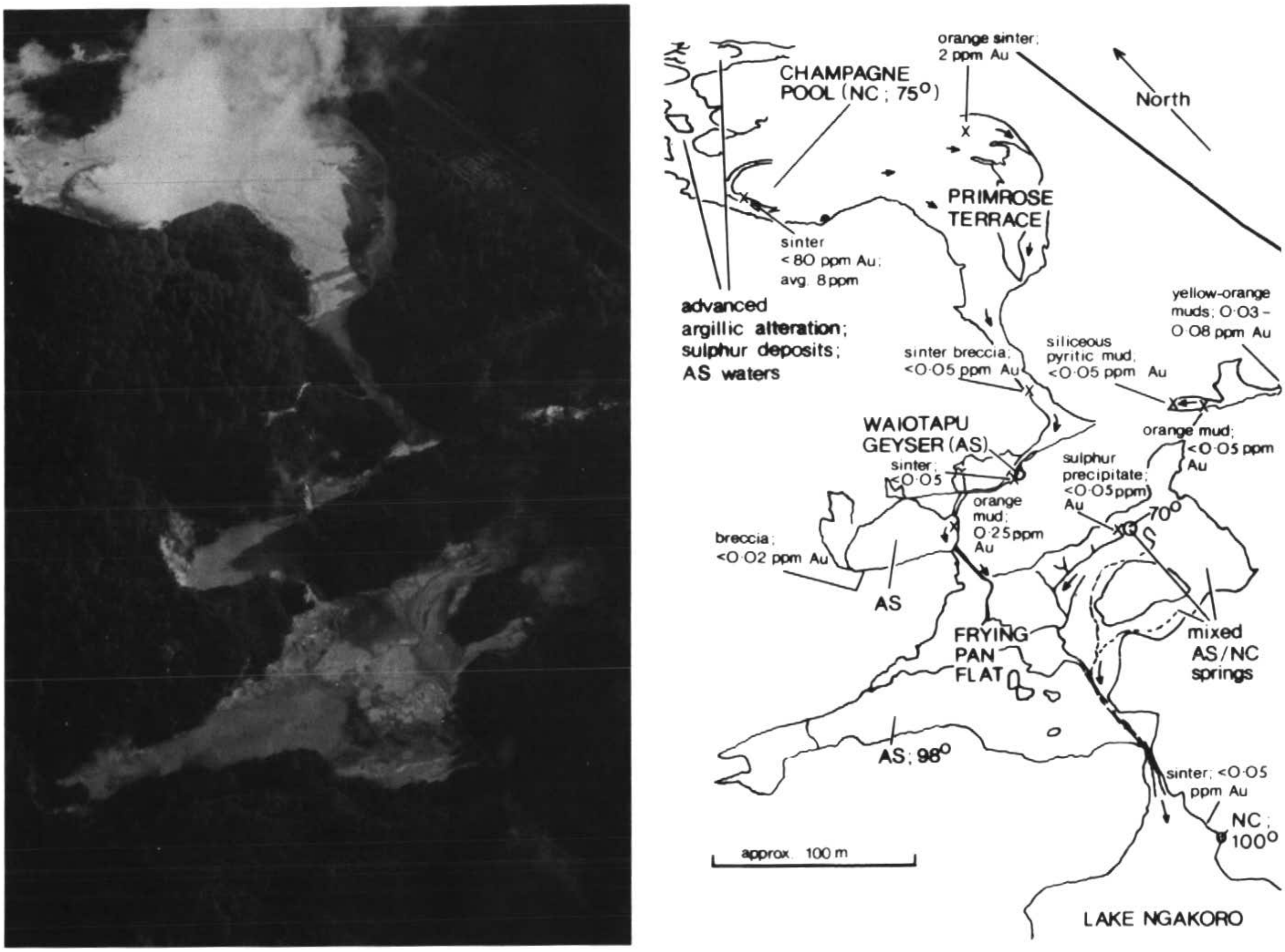

Figure 2 *The Champagne pool and vicinity, Waiotapu geothermal field, New Zealand, 1976. Arrows show flow of surface waters; AS: acid-sulphate; NC: neutral-chloride (Table 1). Crosses represent sample locations. Information from Grange (1937) and Hedenquist (1982b); photograph and sketch by R. Goldie*

waters; and (d) Adsorption of gold onto arsenical sulphide sols. Note that the sols themselves would form only if the neutral-chloride waters were first slightly acidified by, for example, mixing with acid-sulphate waters.

Ewers and Keays (1977) proposed that the gold, antimony and arsenic in the gold-rich precipitate at the Ohaki pool were deposited as a result of oxidation and cooling, but that the thallium was precipitated by cooling alone. At the Champagne pool, Hedenquist (1983a) concluded that the gold-rich precipitate formed as a result of (c) – mixing with acid sulphate waters, possibly aided by adsorption onto sols.

The source of the gold in the New Zealand sinters is unknown. However, the Mesozoic greywackes and argillites which underly the Taupo Volcanic Zone are one possible source because their metamorphosed equivalents (greenschist) in the South Island of New Zealand are extensively mineralized by metamorphogenic gold veins (Staff of New Zealand Geological Survey, 1968).

Comparison of the Ohaki and Champagne Sinters with Hemlo

I have noted the following similarities between the Main Hemlo Orebody and the New Zealand sinters:

1. Hemlo and the sinters are enriched in gold, sulphur, arsenic, antimony, mercury and thallium; they are not enriched in copper and zinc.
2. Both Hemlo and the sinters occur as tabular zones conformable with the host rocks, and in both cases the host rocks are volcanic and sedimentary.
3. The rocks underlying the New Zealand sinters have been altered to an argillic assemblage. At Hemlo, the rocks hosting the Main Orebody are cut by a quartz-white mica stockwork, probably reflecting argillic alteration.
4. Although there is no *direct* evidence that the Main Hemlo Orebody formed subaerially, as did the New Zealand sinters, two recent studies support this possibility. First, analyses of sulphur isotopes show that Hemlo did not form in the open ocean (Cameron *et al.*, 1984; Hattori and Cameron, 1984). Second, the lack of enrichment in copper and zinc at Hemlo suggests that the Main Orebody was precipitated from fluids of lower salinity than seawater (cf. Kerrich, 1980).

Thus, there are sufficient similarities between the Ohaki and Champagne pool sinters, and the Hemlo gold deposit, to suggest similar origins. According to this hypothesis, the gold at Hemlo was transported to the surface as a thio-complex in neutral waters of low salinity and precipitated subaerially along with silica, sulphur, arsenic, antimony, mercury and thallium as a result of one or more of the following: boiling, oxidation, cooling, acidification and adsorption onto sols. The most important differences between the Hemlo deposit and the sinters (other than their relative sizes!) are their barite and molybdenite contents. *Barite* is a major constituent of the Main Hemlo Orebody, yet this mineral is absent from both the Ohaki and the Champagne sinters. However, the presence of barite at Hemlo is not an argument against a subaerial origin, since barite is common in other subaerial sinters (e.g., at Tauhara, New Zealand; Hedenquist, pers. comm., 1983), and in Kamchatka, USSR (Naboko and Glavatskikh, 1970). *Molybdenite* is another major mineral at Hemlo which is absent from the Ohaki and Champagne sinters. This fact could be used as an argument against a subaerial origin for Hemlo, because molybdenite is usually precipitated at depth, adjacent to or in plutons of intermediate to felsic composition (Kirkham *et al.*, 1982). However, a sinter at Waimangu contains 500 ppm Mo (Hedenquist, pers. comm., 1983), a concentration comparable to that at Hemlo (Table II). Furthermore, the subaerial Kamchatka sinter contains 200 ppm molybdenum and is also enriched in barium (Naboko and Glavatskikh, 1970).

Table II *Gold-rich material from Ohaki and Waiotapu, New Zealand and from Hemlo (analyses reported in ppm)*

	Red-orange precipitate, Ohaki pool (1)	Orange-brown precipitate, Champagne pool (1)	Bulk sample of sinter, Champagne pool (2)	Orange sinter, Primrose terrace (3)	Hemlo (4)
Cu	n.f.	n.f.	–	–	20
Zn	85	75	5	< 5	80
As	850	16,900	12,000	5,500	–(5)
Mo	8(6)	–	9(5)	–	1.000
Ag	373	100	6	2	2
Sb	≃ 100,000(7)	20,000	600	440	200
Au	70	60	8	2	9
Hg	2,000	170	90	16	–(8)
Tl	1,460	420	280	40	–(9)
Pb	25	15	< 5	< 5	–

n.f. means "not found"
dashes mean "not analyzed"

(1): averages after Weissberg (1969) and Ewers and Keays (1977)
(2): average of 2 analyses compiled by Hedenquist (1983b)
(3): Ward (pers. comm., 1982 to Hedenquist, 1983b)
(4): the concentration of gold is for the entire Main Hemlo Orebody; other values are for the Golden Giant portion of the orebody
(5): N.B. realgar and orpiment are present
(6): J. Hedenquist (pers. comm., 1984)
(7): in the form of "metastibnite"
(8): N.B. cinnabar is present
(9): N.B. thallium-bearing minerals are present (Harris, 1984).

Any further comparison between Hemlo and the New Zealand occurrences should address the following questions: Are there any base metal sulphides and a propylitic alteration zone in the rocks stratigraphically below the Hemlo Ore-body? Does the unusual geochemistry of Hemlo reflect mineralization from more than one source? What is the sedimentology of the rocks at Hemlo? Similarly, a comparison with Hemlo may stimulate further studies in New Zealand. For example, do bacteria or algae play any role in precipitating gold in the Ohaki or Champagne sinters?

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