NEPHRITE IN BRITISH COLUMBIA.

by

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ABSTRACT

Nephrite is a compact, microfibrous variety of actinolite-tremolite in which bundles or tufts of minute fibers of the amphibole are twisted and thoroughly felted or interwoven with one another, producing a characteristic "nephritic" microstructure.

In British Columbia, nephrite deposits, both in place and placer, are closely associated with a belt of alpine ultramafic rocks that extends for 1000 miles from the Hope area, east of Vancouver, northwestward to the Yukon border. The three major nephrite producing regions are the Bridge River - lower Fraser River area, the Takla Lake area and the Dease Lake area.

The nephrite from British Columbia contains, in addition to essential tremolite, small amounts of chlorite, uvarovite, chrome spinel, diopside, talc, carbonate, sphene, phlogopite and pyrite. Grains of chrome spinel and uvarovite are usually visible in hand specimen. The colour of the majority of the specimens is yellowish green; this colouration is caused by the presence of iron in both the divalent and trivalent states. Polished surfaces of the nephrite have an average Vickers hardness of 950 Kg/mm^2 and an average Mohs hardness of 7. The average specific gravity is 3.00.

The unit cell parameters of tremolite from British Columbia nephrite specimens are similar to those of nephritic tremolite from Siberia. X-ray diffraction data for the tremolite from these specimens are also in good agree-

ment with those for nephritic tremolite from other localities.

The nephrite specimens contain an average of 3.05 percent iron; small amounts of cobalt, nickel, manganese, copper, lead, zinc, chromium, titanium and vanadium are also present. Significant regional variations in the averages for iron, cobalt, manganese, copper, lead, zinc and vanadium are not observed when the specimens are grouped according to the area of origin; slight variations are observed in the average contents of nickel, chromium and titanium. The general similarity of the regional average values for these elements suggests that the nephrites have been formed in similar environments.

At the O'Ne-ell Creek deposit in central British Columbia, nephrite occurs in a zone of tremolite-chlorite rock developed in serpentinite at the contact with metasomatically altered sediments. The nephrite has resulted from the metasomatic alteration, by addition of calcium and silica, of the serpentinite during the process of serpentinization. The calcium was derived from the pyroxenes contained in the original ultramafic rock; the source of the silica was the enclosing sediments. High concentrations of calcium and magnesium and relatively lower concentrations of sodium, iron, aluminum and silicon characterized the environment in which the nephrite formed. Calcium and sodium were perfectly mobile while the other elements were relatively inert. These conditions of mobility and concentration account for the fine fibrous nature of the nephritic tremolite. A temperature range of approximately $300^{\circ}C$ to $500^{\circ}C$ and a pressure in excess of 4 kilobars are suggested for the formation of the nephrite.

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I. INTRODUCTION

Nephrite and jadeite are the two minerals that are collectively referred

to as jade. Nephrite is a compact, fibrous variety of actinolite-tremolite, an

amphibole, and jadeite is a pyroxene. Other minerals such as serpentine,

grossularite and vesuvianite are often presented as varieties of jade, usually

with a geographical prefix, but should be termed pseudojades. An example is

massive vesuvianite from California which is known, in lapidary circles, as

California jade, American jade or Feather River jade.

NOMENCLATURE AND HISTORY

The earliest mention of jade in the European literature is after the

return from Central and South America of the early Spanish explorers (Hansford,

1969; Palmer, 1967; Foshag, 1957). They brought with them green stones that

were reported to be useful for the cure and prevention of diseases of the

kidneys and gave them the name "piedra de yjada" meaning "stone of the loins"

or "colic stone". Latin scholars translated this term into its Latin equiva-

lent, "lapis nephriticus". The French translations of the Spanish and Latin

terms became "pierre l'ejade" or simply jade and "pierre nephritique",

respectively. In the middle of the nineteenth century, Alexis Damour, a

French chemist, studied various jades and distinguished, on the basis of chemical

composition, two varieties which he termed nephrite and jadeite.

Because of its fine colouration, its peculiar translucency and its ability

to take and keep a keen edge, nephrite was worked into tools, weapons and ornaments by prehistoric and later cultures in many parts of the world (Hansford, 1969; Palmer, 1967). Jadeite was also used but to a much lesser extent and was more or less restricted to the indigenous cultures of Mesoamerica (Foshag, 1957).

The earliest recognized use of nephrite was by the inhabitants of the neolithic lake dwellings in Europe, especially in Switzerland (Hansford, 1969). Nephrite was used extensively by the aboriginal peoples of Oceania, particularly the Maoris of New Zealand. Explorers in the Amazon River basin in the early sixteenth century found nephrite celts in use by the natives of the region. In northwestern North America, the natives of Alaska and British Columbia employed simple nephrite tools up to the time of the introduction of iron by the first European traders (Emmons, 1923; Dawson, 1887). In China, the history of nephrite is long and may extend as far back as neolithic time. To the Chinese, the true jade is nephrite and jadeite, which was imported from Burma, did not come into use until the end of the eighteenth century. Although nephrite has been worked by the Chinese throughout their long history, the mineral is not known to occur anywhere in the eighteen provinces of China Proper or in Manchuria, Mongolia or Tibet. Since the Han Dynasty (206 B.C. - A.D. 220), most of the nephrite used by the Chinese has been obtained from Turkistan.

NEPHRITE OCCURRENCES

Deposits of nephrite are not common and it is estimated that there are not more than fifty in the world (Kolesnik, 1970) although this figure should be revised upward in light of recent discoveries in Canada. The nature of the occurrence of nephrite accounts for its relative rarity; it generally occurs in lensoidal or discontinuous vein-like masses seldom exceeding ten feet in width and the appearance of nephrite in outcrop is often very similar to that of the enclosing rocks.

Nephrite deposits are known in North America, South America, Europe, Asia, Africa and Oceania. Brief descriptions of a number of occurrences, exclusive of those in British Columbia, are presented in Appendix I. The deposits in North America are located in British Columbia, Yukon, Northwest Territories, California, Washington, Oregon and Wyoming. The only known deposits in South America are situated in Brazil. In Europe, occurrences are known in Switzerland, Poland, Italy, West Germany, East Germany and the Union of Soviet Socialist Republics. The Asiatic deposits are located in Chinese Turkistan, Taiwan and Japan. In Africa, nephrite has been reported from Nyasaland and Southern Rhodesia and in Oceania, from New Zealand and New South Wales, Australia.

The majority of nephrite deposits are found within serpentinized alpine ultramafic bodies; nephrite has not been reported from unserpentinized ultra-

mafic rocks. The nephrite occurs as vein-like to lens-like segregations in the serpentine, usually at the contact with country rocks, tectonic inclusions and dykes. The rocks in contact with, or contained within, the serpentinites are often metasomatically altered. The nephrite is commonly associated with asbestos, chlorite, coarse fibrous tremolite, talc and diopside.

Nephrite also occurs in environments in which ultramafic rocks are absent. Deposits of this type are those in Wyoming and in Chinese Turkistan. The nephrite in Wyoming occurs in amphibolites that are contained in, or cut by, siliceous intrusive rocks and is associated with epidote and clinozoisite. In Chinese Turkistan, nephrite occurs in diabase and gabbro that have been intruded into shales, sandstone and syenite and in greenstone bodies contained in mica schists.

<div align="center">PREVIOUS WORK</div>

The number of previous studies regarding British Columbia nephrite is very limited. The earliest reference is by Dawson (1887) in which he describes the manufacture and use of nephrite implements by the Indians of British Columbia and speculates on the source and origin of the material. A monograph by Emmons (1923) deals with the use of nephrite by the native people of British Columbia and Alaska. The only known reference pertaining to nephrite deposits in the Province is by Holland (1961).

SCOPE OF PRESENT WORK

This investigation was undertaken to determine the geographical distribution of nephrite deposits in British Columbia, to study the petrology, physical properties, chemistry and crystallographic structure of nephrite from a number of British Columbia occurrences and to describe, and propose an origin for, the O'Ne-ell Creek nephrite deposit in central British Columbia.

Twenty-six specimens of nephrite were examined by standard petrographic procedures and by X-ray diffraction methods. The physical properties investigated are fracture, specific gravity, colour and hardness, both Vickers and Mohs, of polished surfaces. The microstructure of three specimens was examined with the aid of a Cambridge Stereoscan MK II-A scanning electron microscope operated by the Department of Biological Sciences, University of British Columbia.

The unit cell parameters were calculated for the tremolite from ten nephrite specimens to determine if differences exist between this variety of tremolite and common prismatic tremolite.

Thirty-one nephrite specimens were analysed for iron, cobalt, nickel, manganese, copper, lead, zinc, chromium, titanium and vanadium. The reasons for the analyses are two-fold; to ascertain if nephrites from the three major producing areas in British Columbia can be characterized by their trace element content and to determine, in qualitative manner, what elements are responsible

for the colouration of nephrite. The analyses were performed using atomic-

absorption and emission spectrography techniques. Eight samples of serpentinite

from O'Ne-ell Creek and the weathered rind from three alluvial nephrite boulders

were also analysed for the same elements.

The geology of the O'Ne-ell Creek nephrite deposit was mapped, at 1 inch to

40 feet, in September 1969, using a tripod-mounted Brunton compass and a chain.

The map covers an area 700 feet long by 250 feet wide. For this report, the

map scale was reduced to 1 inch equals 80 feet. Twenty-nine thin sections were

examined. Additional information was obtained from feldspar staining, using

the procedures of Bailey and Stevens (1960), and from X-ray diffraction studies.

ACKNOWLEDGMENTS

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Special recognition is due Mrs. W. Robertson who arranged for the author to

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The author is grateful to Professor W. R. Danner, Department of Geology,

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II. BRITISH COLUMBIA DEPOSITS

Nephrite, presumably obtained from the Fraser River, was utilized by the

Kwakiutl, Salish, Tsimshian, Haida and Tlingit tribes of the coast and south-

western interior of British Columbia and the coast of southeastern Alaska.

for fashioning cutting implements and property pieces (Emmons, 1923). These

tools and ornaments were highly valued and were used long before European

traders had introduced iron tools. The high value placed on such tools is

illustrated by the fact that, among the Tlingit tribe, a nephrite adze several

inches long was considered to be worth from one to three slaves. The nephrite

was laboriously worked into useful objects by means of slabs of sandstone and

sand abrasives.

After the Fraser River gold rush, many of the original gold-bearing river

bars were reworked by Chinese miners and numerous shipments of jade were made

to China in the years before 1900 (Holland, 1961). In the late 1940's,

interest was renewed in Fraser River jade and since that time numerous placer

and in place deposits have been found throughout the province.

Much of the information presented in this section has been drawn from two

annual publications of the British Columbia Department of Mines and Petroleum

Resources; these are Geology, Exploration and Mining in British Columbia and

the Annual Report of the Minister of Mines and Petroleum Resources. For the

sake of brevity, these are referred to as G. E. M. and M. M., respectively.

ALPINE ULTRAMAFIC ROCKS OF BRITISH COLUMBIA

The nephrite deposits in the province are associated with a belt of alpine

ultramafic rocks that extends for 1000 miles from the Hope area, east of

Vancouver, northwestward through central and northern British Columbia to the

Yukon border (Figure 1). This belt is traceable into Yukon and Alaska. The

following brief description of these rocks is taken largely from McTaggart (1971).

The ultramafic bodies, most of which are peridotite or dunite, range in

size from a few tens of feet across to batholiths with areas greater than 70

square miles. In shape, they are sill-like and lenticular to equidimensional,

although elongate bodies are the most common. Many are cut by veins and dykes

of dunite, pyroxenite and gabbro. Chromite, in pockets, lenses and vein-like

masses, is almost always present. The bodies are commonly serpentinized, the

degree of which ranges from incipient or partial in the larger masses to almost

complete in the smaller, lenticular bodies. Talc rocks and mariposite bearing

quartz-carbonate rocks are common but are usually restricted to shear zones and

contacts (Cairnes, 1929; Armstrong, 1949; Leech, 1953; Roots, 1954; Gabrielse,

1963). Zones of hornblende, actinolite-tremolite or chlorite are reported to

occur at the contacts of several of the ultramafic bodies (Armstrong, 1949;

Roots, 1954; Gabrielse, 1963).

Most of the ultramafic rocks are enclosed by sediments and volcanics of the

late Paleozoic Cache Creek Group although in a few places in central British

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FIG. 1
INDEX MAP OF BRITISH COLUMBIA
SHOWING ULTRAMAFIC BELTS, NEPHRITE PRODUCING
AREAS AND "IN SITU" NEPHRITE OCCURRENCES.
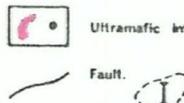
Ultramafic intrusions; large, small.

Fault.   Nephrite producing areas.
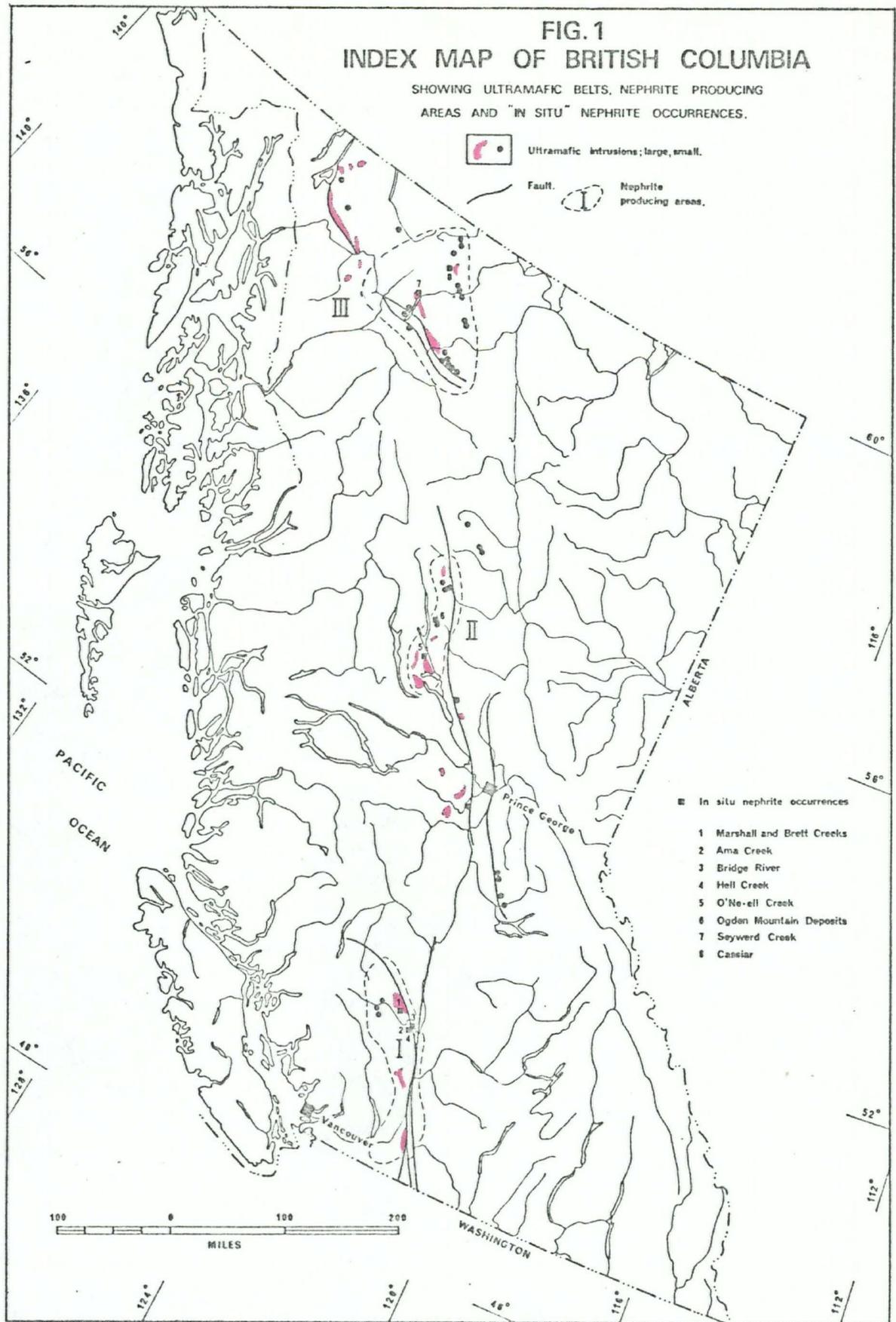
In situ nephrite occurrences

1 Marshall and Brett Creeks
2 Ama Creek
3 Bridge River
4 Hell Creek
5 O'Ne-ell Creek
6 Ogden Mountain Deposits
7 Seywerd Creek
8 Cassiar

PACIFIC OCEAN

ALBERTA

WASHINGTON

Prince George

Vancouver

MILES

Columbia and Yukon, they occur in Upper Triassic or Jurassic rocks. Several of the larger bodies lie along major northwest-trending faults that separate the Cache Creek strata from younger rocks.

PLACER OCCURRENCES OF NEPHRITE

All of the nephrite produced in British Columbia in the 1950's and the early 1960's was obtained from placer deposits in streams draining areas of ultramafic rocks. The three major regions of placer occurrences are the Bridge River - lower Fraser River area, the Takla Lake area and the Dease Lake area which, in Figure 1, are labelled I, II, and III, respectively.

In area I, placer nephrite has been found along the Bridge River from its confluence with the Fraser River to Mission Dam (Holland, 1961) and on its tributaries Marshall Creek (M. M., 1961), Yalakom River (Holland, 1961), Jim Creek (M. M., 1963), Brett Creek (M. M., 1968), Cadwallader Creek (M. M., 1968), Noel Creek (G. E. M., 1969) and Hell Creek (M. M., 1968). On the Fraser River, nephrite has been collected from Chilliwack to the mouth of the Bridge River (Holland, 1961). The Coquihalla River, a tributary of the Fraser River, has yielded nephrite from its junction with the Fraser to the mouth of Dewdney Creek (Holland, 1961). The alluvial nephrite occurs as pebbles, cobbles and boulders ranging in weight from a few tens of pounds to as much as ten tons. The largest boulders occur on the Bridge River and its tributaries; those from the Fraser River are smaller in size, mostly in the range of a few tens of pounds,

but many are of the finest quality.

Placer boulders of nephrite have been reported from a number of creeks in the Takla Lake area, an area containing extensive outcrops of ultramafic rocks belonging to the pre-Upper Triassic Trembleur intrusions (Armstrong, 1949). In the southern part of the area, O'Ne-ell Creek (M. M., 1968; G. E. M., 1969), Van Decar Creek (M. M., 1963; p. c. Forsythe, 1969) and Baptiste Creek (M. M., 1963) have yielded alluvial boulders of generally poor quality material. To the north, nephrite has been found along Vital Creek (M. M., 1963), Quartz Creek (M. M., 1963), Fall River (p. c. Robertson, 1969), Ogden Creek (M. M., 1968; G. E. M., 1969), Kelly Creek (p. c. Robertson, 1969), Teegee Creek (p. c. Robertson, 1969) and Silver Creek (p. c. Knauer, 1971; p. c. Owen, 1972), all of which are tributaries of the Omineca River, and along Kwanika Creek (M. M., 1963, 1968), a tributary of the Nation River. The boulders from Kwanika Creek are reported to be up to 7 or 8 tons in weight.

In the Dease Lake area, nephrite boulders have been found on the Liard River (Holland, 1961), Wheaton Creek (Holland, 1961; M. M., 1968; G. E. M., 1969), Thibert Creek (p. c. Larson, 1969) and Seywerd Creek (M. M., 1963, 1969; p. c. Seywerd, 1970). On the Liard River, boulders are found at the mouth of the Hyland River and Holland (1961), on the basis of glacial movement in this area, suggests that the probable source is the ultramafic rocks at Cassiar and at the head of Blue River. The boulders in Wheaton Creek occur along the lower

2 miles of its course and are presumably derived from a band of serpentinized peridotite that crops out some 1.5 miles upstream from the creek mouth. Little is known of the occurrences on Thibert and Seywerd Creeks, except that in the latter, nephrite occurs in place in serpentine.

BEDROCK OCCURRENCES OF NEPHRITE

In British Columbia, there are at least 10 "in situ" occurrences of nephrite and with one exception, the deposit on O'Ne-ell Creek, very little information is available regarding these deposits (Figure 1). All are intimately associated with serpentinized alpine ultramafic rocks.

Four bedrock nephrite deposits are known in the Bridge River area and are located on Ama Creek (M. M., 1962), Brett and Marshall Creeks (Saunders, 1969), on the west side of Bridge River near Applespring Creek (Holland, 1961) and on Hell Creek. The deposit on Ama Creek occurs in a 3-foot wide pale green alteration zone in serpentine along the contact of a diorite dyke. The jade, which is associated with pectolite (Uncataloged Sutton-Thompson Collection specimen), consists of subparallel bands of greenish tremolite and grey diopside that enclose irregular shaped masses of serpentine. This material, because of its banded nature and resemblance to intestines, is known locally as "intestinal" or "gut jade" but due to this texture it has little use as a gemstone. A number of small showings and one large deposit are situated in the vicinity of Marshall Creek and its tributary Brett Creek. The large deposit, which has

produced nephrite commercially, is located on Brett Creek approximately ½ mile

upstream from its confluence with Marshall Creek. In this deposit, vein-like

masses of nephrite occur in a 50 foot wide, N 60° E striking zone of sheared

serpentine that is in contact with sediments of the Cache Creek Group to the

north and a light grey chert-like rock, which in turn is in contact with a

quartz diorite, to the south. The nephrite vein has a strike length of 50 feet,

a vertical extent of 30 to 40 feet and a width, over the vertical extent, of

1 foot to 10 feet. The "in situ" deposit near Applespring Creek consists of

sheared lenses, nodules and folded layers of waxy, greenish-grey nephrite

enclosed in sheared tremolite along a fault in serpentine. Nothing is known of

the Hell Creek deposit.

Nephrite has been produced from four deposits in the Takla Lake area,

three of which are on Ogden Mountain and the fourth is on O'Ne-ell Creek. In

the largest of the Ogden Mountain deposits, nephrite lenses occur in serpentine

in contact with a dense, light greenish-grey rock composed of radial aggregates

of diopside in a matrix of tremolite (p. c. Owen, 1972). Much of the nephrite

from this deposit has a bright green colour and is of high quality. Chrome

rich varieties containing numerous minute grains of bright green uvarovite

garnet are common. Little is known of the other two Ogden Mountain deposits

except that the nephrite occurs in serpentine (G. E. M., 1970; p. c. Owen, 1972).

On O'Ne-ell Creek, lenses of nephrite occur in a 20 to 25 foot thick, moderately

west dipping zone of tremolite, chlorite and minor talc at the contact between

serpentine and metasediments and metavolcanics of the Cache Creek Group. This

deposit will be described in some detail in a later section of this report.

In the Dease Lake area, only two deposits are known. The largest, and

sole producer, is situated on Seywerd Creek, a small creek entering the west

side of Dease Lake at Steamboat Point. The nephrite occurs in serpentine

(M. M., 1963; G. E. M., 1970; p. c. Seywerd, 1970). The second occurrence is

in the open-pit asbestos mine on Mount McDame near Cassiar (G. E. M., 1970).

PRODUCTION

Annual production figures for British Columbia nephrite have been kept

since 1959; these are graphically portrayed in Figure 2. During the period

1959 to 1970, a total of 596,394 pounds of nephrite were produced worth

$531,670 (M. M., 1962 - 1970). In 1970, due largely to production from recent-

ly discovered "in situ" deposits, the quantity mined was 262,602 pounds, a ten-

fold increase over the previous year. Undoubtedly production will continue to

increase in future years as the "in situ" deposits are able to produce large

quantities of consistent quality material for such potential high volume

consumers as the construction industry.

Nephrite production data for the Lillooet, Omineca and Liard Mining

Divisions, which enclose all or large portions of areas I, II and III, respect-

ively, for the period 1962 to 1970 are presented in Table 1.
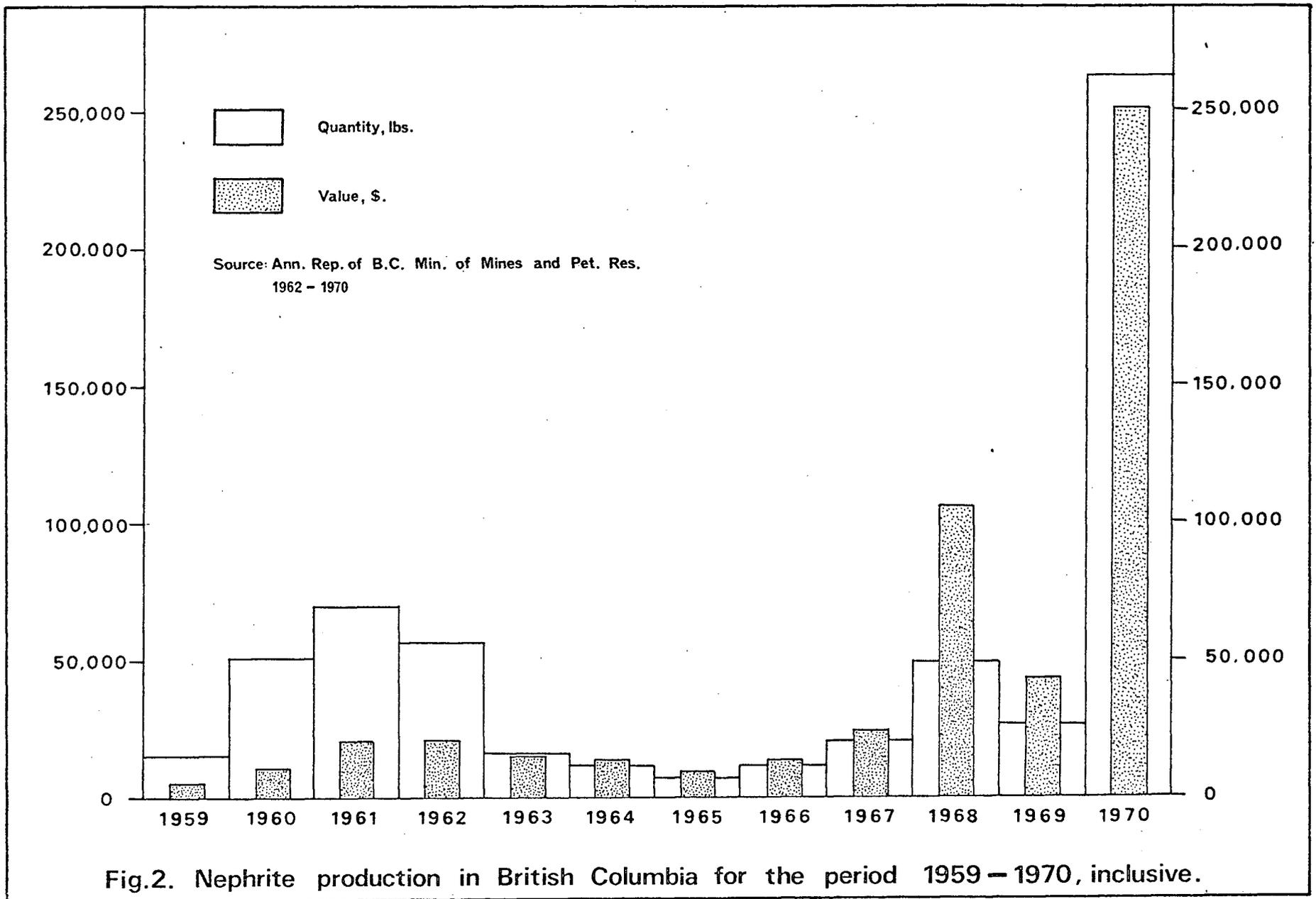
Fig.2. Nephrite production in British Columbia for the period 1959 – 1970, inclusive.

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Table 1

Nephrite Production from Mining Divisions, British Columbia

Year	Mining Division	Quantity (lb.)	Value ($)	Total to Date Quantity (lb.)	Value ($)
1962	Lillooet	56,935	20,760		
1963	Lillooet	16,000	15,529	207,986	72,490
1964	Lillooet	10,337	11,404	218,323	83,894
	Omineca	1,200	2,400	1,200	2,400
1965	Liard	2,000	2,000	2,000	2,000
	Lillooet	4,129	5,249	222,452	89,143
	Omineca	1,000	2,000	2,200	4,400
1966	Liard	8,493	8,648	10,493	10,648
	Lillooet	3,140	4,577	225,592	93,720
1967	Liard	14,920	19,714	25,413	30,362
	Lillooet	5,240	4,627	230,832	98,347
1968	Liard	1,810	2,125	27,223	32,487
	Lillooet	42,095	83,899	272,927	182,246
	Omineca	5,110	19,646	7,310	24,046
1969	Liard	5,825	11,960	33,048	44,447
	Lillooet	6,060	5,237	278,987	187,483
	Omineca	14,447	25,438	21,757	49,484
1970	Liard	5,322	9,099	38,370	53,546
	Lillooet	14,280	27,583	293,267	215,066
	Omineca	243,000	213,574	264,757	263,058

Source: Annual Reports, British Columbia Minister of Mines and Petroleum Resources, 1962 - 1970.

MINING METHODS

The methods employed in mining "in situ" nephrite vary from deposit to

deposit. As with any gemstone, the ultimate goal is to remove the maximum

amount of material with the minimum amount of physical damage to it; this is

often a difficult task due to the hardness and extreme toughness of nephrite and

the fact that it often occurs as discontinuous lenses and veins in moderately

to steeply dipping zones. Factors influencing the choice of extraction method

are the geometry of the deposit, the topography of the immediate area, the

nature of the enclosing rocks and the accessibility of the mine site.

Stripping the overburden and the enclosing rocks from the nephrite pods

is usually accomplished by using heavy equipment such as bulldozers although at

one deposit in the Takla Lake area, the overburden was washed away with high

pressure water jets and the harder material in the hanging wall was broken with

pneumatic hammers and very light explosive charges. Due to the potential danger

of fracturing the nephrite, explosives must be used sparingly and with caution.

Once the nephrite is exposed, individual lenses or large fragments are extracted

with heavy equipment or hydraulic jacks or the nephrite is sawn, in place, into

easily removed blocks. Several small diameter core samples are usually taken

from the large pieces in order to ascertain their quality. The extracted

nephrite is sawn into smaller blocks to trim waste or low quality material, to

provide an easily handled piece and to provide quality control. The sawing is

accomplished by means of large diameter diamond saws, diamond impregnated drag

saws or large wire saws.

MARKETS, PRICES AND USES

The bulk of the nephrite produced in British Columbia is exported in a raw

or semi-processed form to Germany, Japan, Taiwan, Hong Kong, the Peoples

Republic of China and the United States of America. A smaller though significant

amount, generally as thin slabs or small blocks weighing 5 pounds or less, is

sold locally through retail outlets to collectors and amateur lapidaries.

Prices for nephrite are variable and are dependent upon colour, competency,

purity and amount of processing that has gone into preparing the material for

sale. High quality nephrite has a uniform green colour, very few fractures and

veins of cross fiber tremolite and a low content of impurities such as magne-

tite, chromite and chlorite. Botryoidal nephrite and "mutton fat" jade or white

nephrite, two extremely rare varieties, command exceptionally high prices.

Medium and select grades of nephrite range in price from $4.00 to $20.00 per

pound and in rare instances the price may be as high as $100.00 per pound.

Low grade material has a price range of $0.50 to $2.00 per pound.

At present, the major users of nephrite are the manufacturers of jewelry,

carvings and novelties. This market will account for a very small percentage

of the total nephrite sales if applications can be developed in the construction

industry. The nephrite producers envision the use of this material for internal

and external building facing, counter tops, floor tiles and, in the crushed form,

for terrazzo floors. Its hardness, extreme toughness, and resistance to corrosion and weathering make nephrite an ideal material for construction applications. The discovery of relatively large tonnage in place deposits has made it possible for the producers to supply the large quantities of consistent quality material that would be required by this industry. Research is presently being conducted in Europe to establish the feasibility of using nephrite for the fabrication of bearings for watches and other instruments (p. c. Owen, 1972; p. c. Smith, 1972).

III. PETROLOGY AND PHYSICAL PROPERTIES OF BRITISH COLUMBIA NEPHRITE

Jade is a term that is applied to two mineralogically distinct species, nephrite and jadeite. Nephrite is a compact, dense, microfibrous form of tremolite-actinolite $(Ca_2(Mg,Fe)_5(OH)_2(Si_4O_{11})_2)$, an amphibole, and jadeite $(NaAl(SiO_3)_2)$ is a massive, microgranular form of the pyroxene of the same name. True nephrite consists of microscopic bundles of tremolite fibers (Plates 1, 2) that have been completely felted or interwoven with one another, producing the characteristic nephritic structure (Turner, 1935). In poor quality nephrites this structure is poorly developed or even completely absent.

NEPHRITE CLASSIFICATIONS

The nephrite classification commonly used by North American geologists is one established by Turner (1935) during an investigation of New Zealand greenstones. This classification is based on microstructure and consists of five divisions, three of which deal with nephrites and two with tremolite rocks lacking a nephritic structure. The Turner classification is used in this report. European geologists use a classification, consisting of seven divisions, that was devised by Kalkowsky (1906) during his study of the Appenine nephrite deposits in northern Italy. Both classifications are presented below.
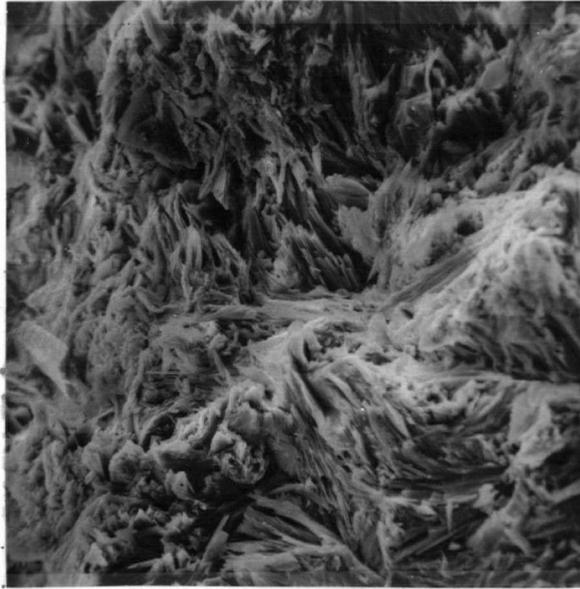
Plate 1: Scanning electron micrograph of a schistose nephrite transitional to a semi-nephrite illustrating the twisted and interwoven nature of the component tremolite fibers (#37; O'Ne-ell Creek), X 300.
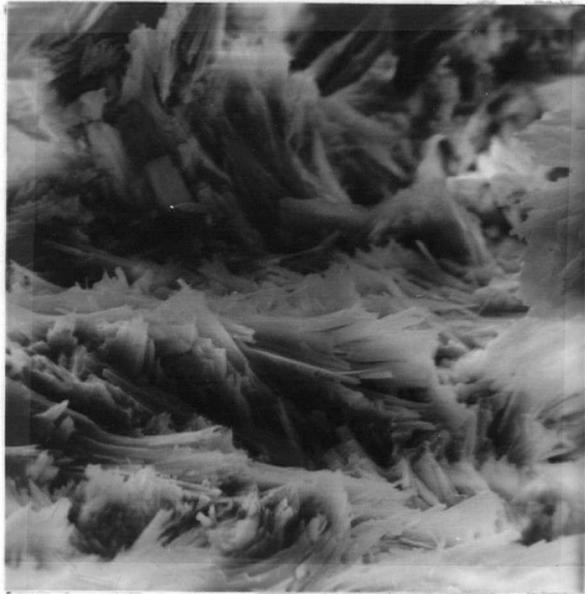
Plate 2: Scanning electron micrograph of a schistose nephrite transitional to a semi-nephrite illustrating the fine fibrous nature of the tremolite (#37; O'Ne-ell Creek), X 1270.

Turner Classification

The three varieties of nephritic rocks according to the Turner classification are non-schistose nephrites, schistose nephrites and semi-nephrites, with transitional varieties being rather common.

Non-schistose Nephrites

Nephrites in this division are characterized by the consistantly small size (0.02 mm to 0.3 mm) and unoriented arrangement of the individual tufts of tremolite fibers (Plate 3). The tufts are twisted and felted forming a perfectly developed nephritic structure. Occasionally, prisms and acicules (up to 1.5 mm x 3.0 mm) of tremolite are present indicating a transition to a semi-nephrite. Transition to the schistose nephrites is indicated by the presence of bundles of mutually parallel coarser than average fibers of tremolite.

Schistose Nephrites

The schistose nephrites are distinguished by the presence of abundant parallel tufts (0.3 mm to 0.5 mm) of tremolite set in a fine nephritic base, the base often comprising only a small percentage of the specimen (Plate 4). The schistosity is due to the parallelism of the fibrous aggregates although the average orientation of the fibers may be inclined to that of the aggregate. The presence of a small amount of coarse prismatic tremolite indicates a transition to a semi-nephrite. In hand specimen, schistose nephrites may

0.5 mm
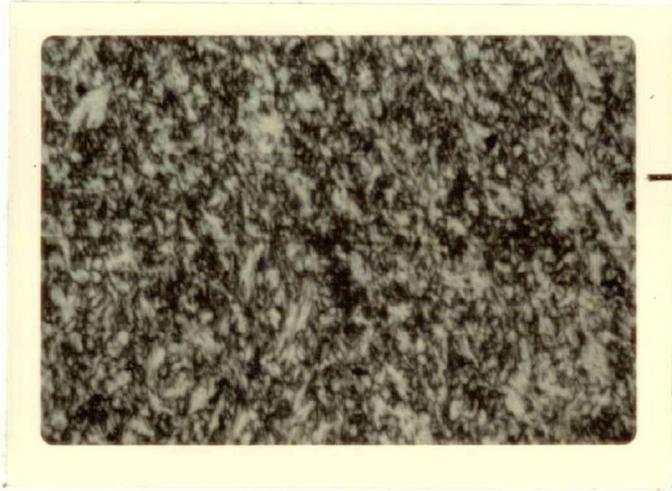
Plate 3: Photomicrograph of a non-schistose nephrite transitional to a
schistose nephrite (#7; Fall River), crossed nicols.

0.5 mm
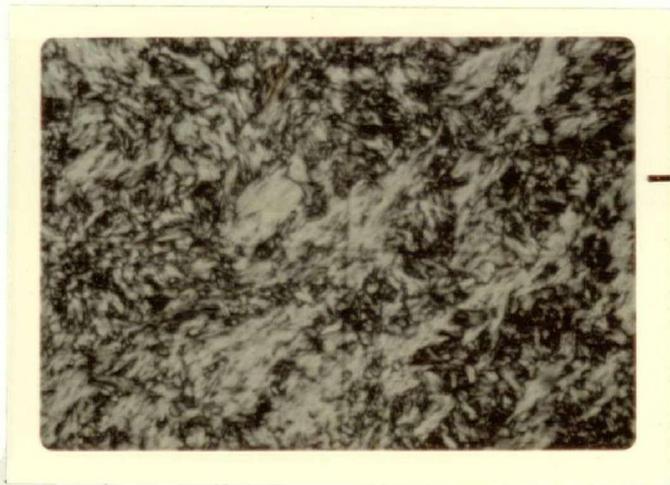
Plate 4: Photomicrograph of a schistose nephrite (#10; Kelly Creek), crossed
nicols.

exhibit a well-developed schistosity.

Semi-nephrites

The semi-nephrites are composed partly of nephritic material and partly of abundant coarse crystalline tremolite as acicular crystals (1 mm x 0.05 mm to 3 mm x 0.25 mm) or as large sheaves (4 mm x 2 mm) of parallel unfelted fibers (Plates 5, 6). In some instances, the ends of the coarse prismatic crystals fray out into the enclosing nephritic base. The coarse material is not necessarily parallel throughout the section. Accessory minerals, especially chlorite, are much more abundant in the semi-nephrites than in the non-schistose and the schistose nephrites. In hand specimen, the semi-nephrites are usually somewhat fissile.

Kalkowsky Classification

The following is the Kalkowsky classification as presented by Kolesnik (1970).

"1. Matted fibrous (nephritic), with the individual finest fibers or tufts closely intertwined with a simultaneous extinction.
2. Radial, with the tufts reminiscent of a coxcomb.
3. Spherulite.
4. Fibrous, a long tuft of nearly parallel fibers.
5. Wavy, with parallel fibers in regularly alternating short bands locally visible with naked eye.
6. Fluffy, with the fibers undistinguishable even at highest magnification. The entire mass is reminiscent of coarse fluff with gradually interchanging interference colours.
7. Coarse-grained (mosaic). The grains, 2 - 3 mm, consist of short and extremely fine fibers with a nearly simultaneous extinction. The grains have smooth faces and often are pierced by narrow bands of similar fibers."

0.5 mm
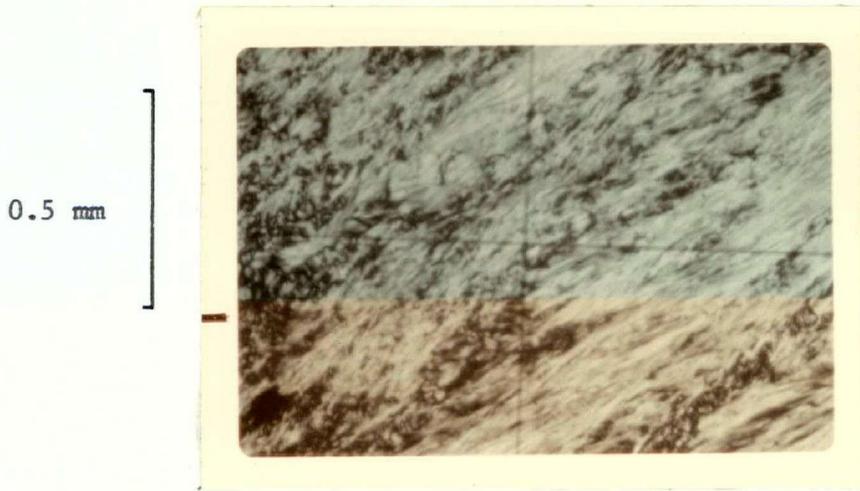
Plate 5: Photomicrograph of a semi-nephrite, with large sheaves of parallel unfelted fibers (#8; Fall River), crossed nicols.

0.5 mm
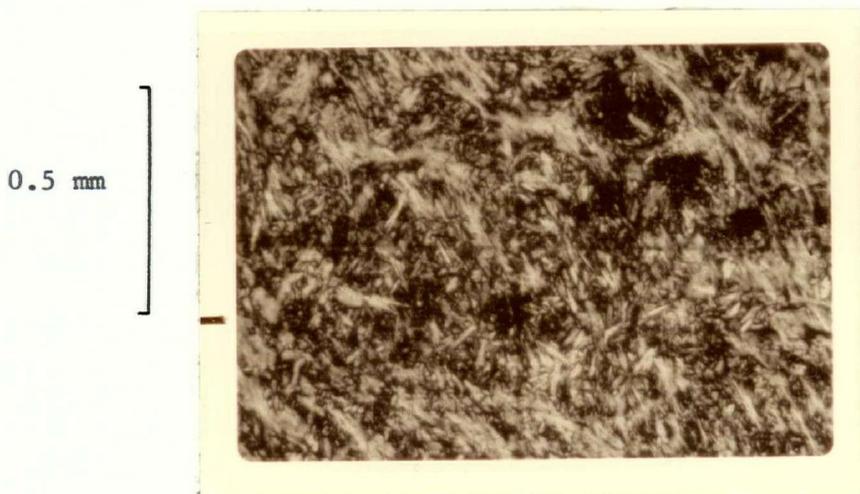
Plate 6: Photomicrograph of a schistose nephrite transitional to a semi-nephrite (#40; Seywerd Creek), crossed nicols. The transition to a semi-nephrite is indicated by the development of acicular crystals of tremolite.

PETROLOGY

The twenty-six nephrite specimens examined in thin section are composed largely of tremolite. Accessory minerals include chlorite, diopside, carbonate, uvarovite, picotite, chromite, sphene, pyrite, talc, and phlogopite with chlorite being the most abundant. Present are non-schistose nephrites, schistose nephrites, semi-nephrites and transitional varieties. The classification, mineralogy and visually estimated mode of the specimens are tabulated in Table 2.

Tremolite

Tremolite is the most abundant mineral present, comprising at least 89 percent of any section. In thin section the tremolite is colourless and under crossed-nicols the interference colours range from low first order to middle second order. Extinction angle $(c \wedge Z)$ determinations on the tufts and crystals of coarser tremolite were between 16° and 19° although in many cases the extinction was either parallel or wavy and indistinct. Indices of refraction were not determined but those obtained from the literature for nephritic tremolite are presented in Table 3. The individual tufts of fine fibers forming the nephritic base of the specimens generally range in length from 0.01 mm to 0.20 mm, although in one section (#35) the smallest tufts are 0.004 mm long. In the schistose nephrites, the oriented aggregates of interwoven and subparallel fibers are 0.02 mm x 0.10 mm to 0.10 mm x 1.30 mm. The acicular crystals and

Table 2

Classification, Mineralogy and Mode of British Columbia Nephrites

Specimen No.	Locality	Classification	Mineralogy	Percentage
6	Junction of the Bridge and Yalakom Rivers	Schistose nephrite	Tremolite	98
			Chlorite	1
			Picotite	
			Carbonate	1
			Sphene	
7	Fall River	Non-schistose nephrite transitional to schistose nephrite	Tremolite	100
			Picotite	
			Uvarovite	< 1
			Sphene	
8	Fall River	Semi-nephrite	Tremolite	99
			Picotite	
			Uvarovite	
			Phlogopite	
			Chlorite	1
			Pyrite	
			Sphene	
9	Ogden Mountain	Schistose nephrite	Tremolite	99
			Diopside	1
			Sphene	
10	Kelly Creek	Schistose nephrite transitional to semi-nephrite	Tremolite	99
			Picotite	
			Uvarovite	
			Chlorite	1
			Chromite?	
			Sphene	

Table 2 continued

Specimen No.	Locality	Classification	Mineralogy	Percentage
11	Kelly Creek	Schistose nephrite	Tremolite	99
			Picotite	
			Uvarovite	
			Chlorite	1
			Pyrite	
			Sphene	
12	Kwanika Creek	Schistose nephrite transitional to semi-nephrite	Tremolite	99
			Unknown (zoisite?)	< 1
			Picotite	
			Uvarovite	1
			Pyrite	
			Sphene	
14	Dease Lake	Non-schistose nephrite	Tremolite	99
			Chlorite	1
			Sphene	
15	Van Decar Creek	Schistose nephrite transitional to semi-nephrite	Tremolite	99
			Picotite	
			Uvarovite	
			Chlorite	1
			Pyrite	
			Sphene	
16	O'Ne-ell Creek	Schistose nephrite transitional to semi-nephrite	Tremolite	92
			Diopside	5
			Picotite	1
			Chlorite	
			Opaques	1
			Uvarovite	1
			Pyrite	<< 1
			Sphene	

Table 2 continued

Specimen No.	Locality	Classification	Mineralogy	Percentage
19	Fall River	Schistose nephrite	Tremolite	100
			Chromite Sphene	} < 1
23	Coquihalla River	Semi-nephrite	Tremolite	95
			Diopside	3
			Picotite	1
			Uvarovite	1
			Carbonate Pyrite Sphene	} < 1
24	Brett Creek	Semi-nephrite	Tremolite	97
			Chlorite	3
			Pyrite Sphene	} ≪ 1
26	O'Ne-ell Creek	Non-schistose nephrite	Tremolite	96
			Chlorite	3
			Picotite Sphene	} 1
30	Cassiar area	Semi-nephrite	Tremolite	94
			Chlorite	4
			Uvarovite	1
			Picotite Pyrite Sphene Talc	} 1

Table 2 continued

Specimen No.	Locality	Classification	Mineralogy	Percentage
33	O'Ne-ell Creek	Schistose nephrite	Tremolite Chlorite Diopside Picotite Sphene	98 2 } < 1
35	O'Ne-ell Creek	Non-schistose nephrite	Tremolite Opaques Sphene	100 } < 1
36	O'Ne-ell Creek	Schistose nephrite	Tremolite Chlorite Picotite Pyrite Sphene	97 2 } 1
37	O'Ne-ell Creek	Schistose nephrite transitional to semi-nephrite	Tremolite Chlorite Picotite Pyrite Sphene	89 10 } 1
39	O'Ne-ell Creek	Schistose nephrite	Tremolite Chlorite Uvarovite Picotite Chromite Pyrite Talc Sphene	98 1 } 1

Table 2 continued

Specimen No.	Locality	Classification	Mineralogy	Percentage
40	Seywerd Creek	Schistose nephrite transitional to semi-nephrite	Tremolite Chlorite Chromite Uvarovite Pyrite Sphene	99 1
41	Silver Creek	Schistose nephrite	Tremolite Chlorite Picotite Pyrite Sphene	96 3 1
42-B	Marshall Creek	Schistose nephrite transitional to semi-nephrite	Tremolite Chlorite Picotite Uvarovite	92 7 1
43	Ogden Mountain	Schistose nephrite transitional to semi-nephrite	Tremolite Picotite Uvarovite Diopside Pyrite Sphene	99 1
44	Ogden Mountain	Schistose nephrite	Tremolite Diopside Uvarovite Picotite Sphene	95 4 1

Table 2 continued

Specimen No.	Locality	Classification	Mineralogy	Percentage
45	Dease Lake	Semi-nephrite	Tremolite Uvarovite Picotite Pyrite Sphene	99 1 <1

sheaves of coarse parallel fibers present in the semi-nephrites exhibit a size

range of 0.008 mm x 0.06 mm to 0.02 mm x 0.60 mm and 0.70 mm x 0.10 mm to

5.40 mm x 1.90 mm, respectively. The ends of the acicular crystals are often

frayed in the manner described by Turner (1935), (Plate 7). Thin section #45

is characterized by the presence of large radial masses of tremolite-actinolite

fibers set in a much finer nephritic base (Plate 8). Veins of cross-fiber

tremolite, up to 0.6 mm wide are observed in a number of sections.

Table 3

Indices of Refraction of Tremolite in Nephrites

n_α	n_γ	$n_\gamma - n_\alpha$	% Fe	Colour in Hand Specimen	Reference
1.597	1.625	0.028	0.98	Yellowish grey-green	Washington (1922)
1.601	1.621	0.020	4.03	---	Rose and Fromme (1932)
1.609	1.631	0.022	3.22	Spinach green to yellow green	Huang (1966)
1.609	1.632	0.023	4.44	---	Kolesnik (1970)
1.609	1.629	0.020	3.65	Bluish green	Yoshimura et al (1966)

0.5 mm
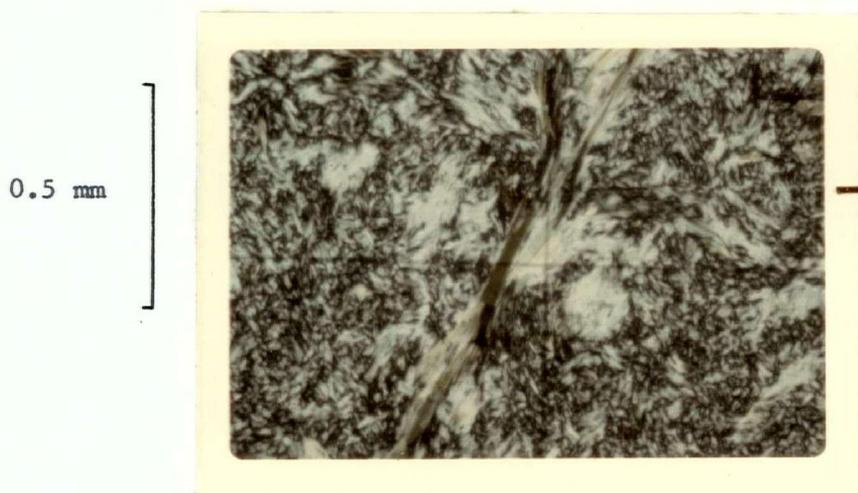
Plate 7:   Photomicrograph of coarse acicular tremolite in a schistose nephrite
transitional to a semi-nephrite (#10; Kelly Creek), crossed nicols.
Note the frayed ends of the crystals.

0.5 mm
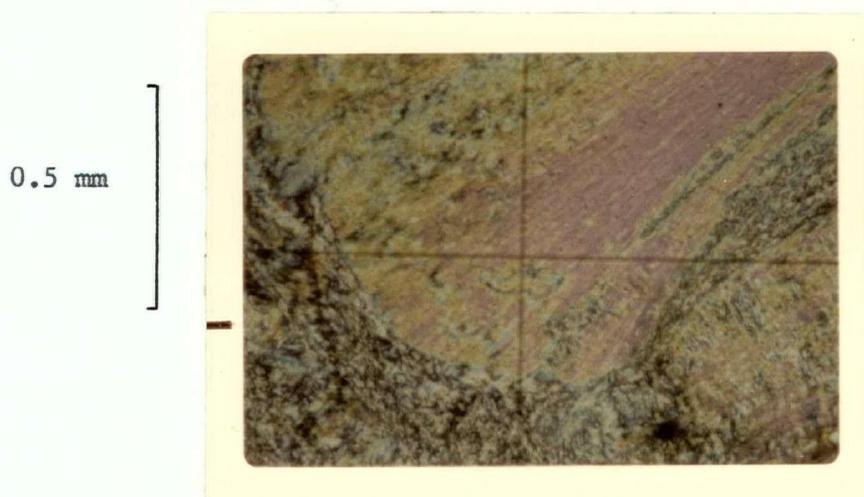
Plate 8:   Photomicrograph of a radial mass of tremolite fibers set in a fine
nephritic base (#45; Dease Lake), crossed nicols. The specimen is
classified as a semi-nephrite.

Chlorite

Chlorite is present in eighteen sections in amounts up to 10 percent. In thin section, it is colourless and has a very low birefringence. The interference colours are usually a peculiar dark olive green, although in several sections, an anomalous blue colour is seen. X-ray diffraction data indicate that the chlorite is very similar to kammererite, a chromian penninite (Table 4). It occurs as aggregates of flakes, the individual flakes not exceeding 0.007 mm x 0.002 mm in size. The aggregates range in shape from roughly circular, up to

Table 4

X-ray Diffraction Data for Kotschubeite (chromian clinochlore), Clinochlore, Kammererite (chromian penninite), Penninite, and for Chlorite from British Columbia Nephrite Specimens

Sample	d(002) Å	d(003) Å	d(004) Å
Kotschubeite A.S.T.M.: 12 - 185	7.11	4.757	3.570
Clinochlore A.S.T.M.: 19 - 749	7.12	---	3.56
Kammererite A.S.T.M.: 12 - 240	7.14	4.774	3.589
Penninite A.S.T.M.: 10 - 183	7.19	4.80	3.60
Nephrite #30 Cassiar area	7.15	4.77	3.56
Nephrite #36 O'Ne-ell Creek	7.15	4.76	3.57
Nephrite #42-B Marshall Creek	7.13	4.75	3.56
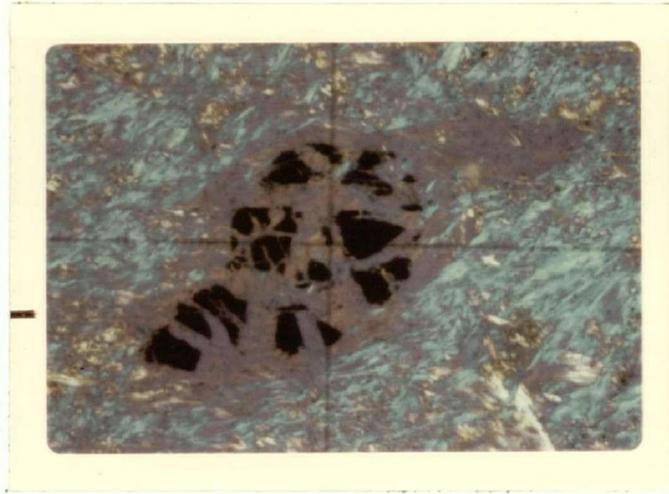
Plate 9: Photomicrograph of an aggregate of chlorite surrounding fragments of chrome spinel (#15; Van Decar Creek), crossed nicols with gypsum plate.

0.5 mm

Plate 10: Photomicrograph of a fractured chrome spinel grain, partially replaced by chlorite (#15; Van Decar Creek), plane polarized light.

0.5 mm

0.12 mm. in diameter, to elongate and irregular with the long axis generally parallel to the direction of schistosity. The circular aggregates usually have a core of picotite or chromite and, more often than not, uvarovite garnet (Plate 9).

Spinel

Members of the spinel group of minerals observed in the nephrite are picotite, a chromian variety of hercynite, and chromite. The picotite is dark reddish brown to light yellowish brown and occurs as rounded fractured grains up to 1.3 mm x 0.90 mm (Plate 10). According to MacGregor and Smith (1963), the redness of a chrome spinel in thin section increases with chrome content. The individual picotite fragments are often strongly corroded due to replacement by garnet or chlorite. The chromite is opaque except on thin edges where it is translucent and dark brown. It occurs as discrete grains up to 0.5 mm in diameter or as partial rims on picotite fragments.

Ilmenite

In one section, #16, a slightly magnetic, finely disseminated mineral, probably ilmenite, occurs as poorly developed skeletal crystals in diopside.

Diopside

Diopside is present in six sections, #9, #16, #23, #33, #43, and #44. In thin section it is colourless, optically positive, and has an extinction angle, c $\wedge$ Z, of 41°. It occurs as aggregates of subhedral crystals in narrow bands

39
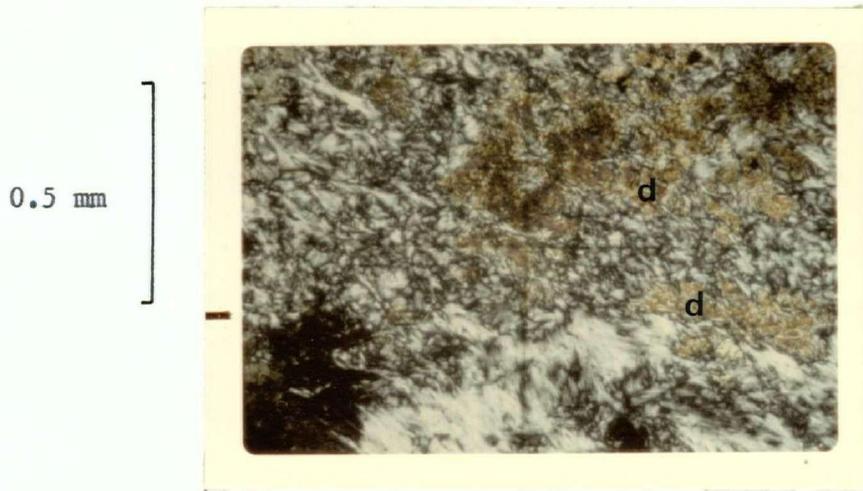
Plate 11: Photomicrograph of corroded remnants of diopside (d), (#16; O'Ne-ell Creek), crossed nicols.
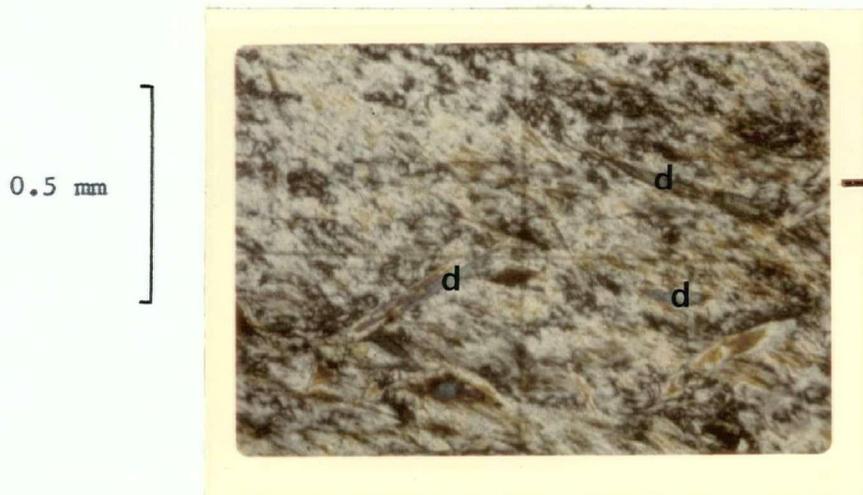
Plate 12: Photomicrograph of spindle-shaped diopside crystals (d), (#43; Ogden Mountain), crossed nicols.

(to 0.2 mm wide), as corroded remnants (0.1 mm x 0.3 mm to 0.9 mm x 2.8 mm),

(Plate 11), as spindle-shaped, often corroded crystals (0.03 mm x 0.5 mm),

(Plate 12) and as large subhedral crystals (to 0.1 mm x 1.9 mm). The latter

are present in one section only and occur in a vein with coarse tremolite.

Twinning is occasionally observed in the diopside, the twin plane being parallel

to (100). The spindle shape of the diopside crystals is very similar to that

described by Kolesnik (1970) for the diopside in Siberian nephrites. Replace-

ment of the diopside by tremolite is suggested by the corroded nature of the

diopside grains.

Kolesnik (1970) has determined, on the basis of 1000 measurements, that the

majority of the spindle-shaped diopside crystals in Siberian nephrites are

elongated perpendicular to the direction of the tremolite-actinolite fibers.

Similar measurements were not made on the specimens examined as diopside

crystals of this type are few in number and are restricted to two sections.

Uvarovite

Fourteen of the sections examined contain uvarovite garnet; in most cases

it is visible in hand specimen as bright green grains or clusters of grains.

In thin section, this mineral is pale to bright green and often exhibits some

degree of anisotropism. It usually forms replacement rims around corroded

picotite fragments (Plate 13) but also occurs as minute anhedral grains (Plate 14),

often in elongate aggregates that are parallel to the schistosity of the

0.5 mm
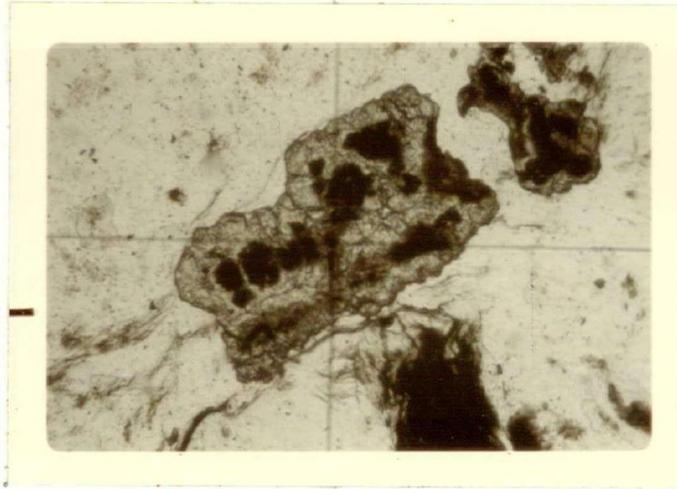
Plate 13: Photomicrograph of uvarovite garnet, containing corroded grains of chrome spinel (#7; Fall River), plane polarized light.

0.5 mm
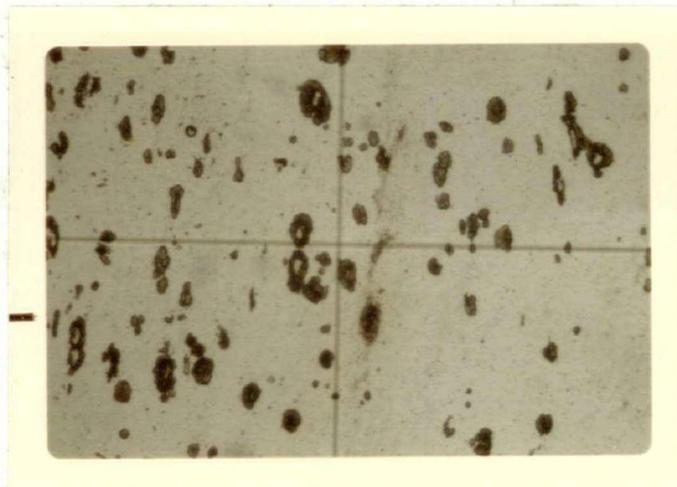
Plate 14: Photomicrograph of anhedral grains of uvarovite garnet (#8; Fall River), plane polarized light. The cores of the garnet grains usually contain phlogopite.

specimen. In some sections, the uvarovite surrounding the picotite fragments
is, in turn, surrounded by a halo of chlorite.

Unknown

A mineral thought to be zoisite occurs as an augen-like mass of subhedral
crystals in thin section #12. The mineral is colourless, has parallel extinction
and a positive optic sign. Contained within the mass are patches of chromite
and uvarovite garnet.

Sphene

Sphene is present in variable amounts in the majority of the sections
examined. It occurs as brownish dustings of microlites that are best observed
in plane light.

Carbonate

A carbonate, probably magnesite, is present in two sections (#6, #23).
In one section, it occurs in microveinlets and in the other as rare rounded
grains up to 0.3 mm in diameter.

Phlogopite and Talc

A very minor amount of phlogopite, identified by X-ray diffraction, is
present in one section (#8) as small, strongly birefringent patches surrounded
by uvarovite garnet. Talc, present in two sections (#30, #39), occurs in
microveinlets cutting tremolite.

Pyrite

Small, sparsely disseminated, euhedral to anhedral pyrite grains are

present in 13 of the 26 sections examined. The average grain size is 0.03 mm.

PHYSICAL PROPERTIES

Fracture

Only generalized observations can be made regarding the fracture of the nephrite specimens studied. The non-schistose nephrites usually have an irregular fracture with a fine flaky surface. In the schistose nephrites, surfaces parallel to the schistosity are relatively smooth but are finely to coarsely flaky; surfaces perpendicular to the schistosity are irregular to hackly. The semi-nephrites that exhibit a pronounced foliation have a coarsely flaky to splintery fracture.

Turner (1935) described the fracture of non-schistose and schistose nephrites as finely flaky and that of semi-nephrites as coarsely flaky.

Specific Gravity

The specific gravity was determined, on a Jolly balance at $18^{o}C$, for 34 specimens. Four determinations were made on each specimen and averaged; the results are tabulated in Table 5. The average specific gravity is 3.00 with the maximum and minimum being 3.04 and 2.95, respectively. The average of seven determinations obtained from the literature (Washington, 1922; Rose and Fromme, 1932; Coleman, 1966; Huang, 1966; Kolesnik, 1970) is 2.97. As a generalization, specimens containing several percent chlorite (S.G.: 2.6 to 3.3) have lower than average specific gravities while those containing several

Table 5

Specific Gravity of British Columbia Nephrite Specimens

Specimen Number	Locality	Specific Gravity	Specimen Number	Locality	Specific Gravity
4	Marshall Creek	3.01	28	Dease Lake area	3.00
6	Junction of Bridge and Yalakom Rivers	3.01	30	Cassiar area	2.98
7	Fall River	3.00	31	Dease Lake area	2.99
8	Fall River	3.01	33	O'Ne-ell Creek	2.99
9	Ogden Mountain	3.00	34	O'Ne-ell Creek	2.99
10	Kelly Creek	2.98	35	O'Ne-ell Creek	3.00
11	Kelly Creek	3.01	36	O'Ne-ell Creek	2.99
12	Kwanika Creek	3.04	37	O'Ne-ell Creek	2.98
13	Kwanika Creek	3.01	38	O'Ne-ell Creek	2.98
14	Dease Lake	3.00	39	O'Ne-ell Creek	3.00
15	Van Decar Creek	3.00	40	Seywerd Creek	2.98
16	O'Ne-ell Creek	3.02	41	Silver Creek	3.00
19	Fall River	3.01	42-A	Marshall Creek	3.00
20	Fall River	3.01	42-B	Marshall Creek	2.97
23	Coquihalla River	3.02	43	Ogden Mountain	3.02
24	Brett Creek	3.02	44	Ogden Mountain	3.01
26	O'Ne-ell Creek	2.99	45	Dease Lake area	2.96

Mean specific gravity = 3.00 (34 specimens).

percent diopside (S.G.: 3.22 to 3.56) have higher than average specific gravities.

The specific gravity was also determined for the weathered rind from three placer specimens and the results, along with those for corresponding unweathered nephrites, are presented in Table 6. The weathered nephrite has a slightly lower specific gravity due to its fractured less compact nature.

Table 6

Specific Gravity of Weathered and Unweathered Nephrite from Placer Boulders

Sample Number	Locality	S.G. Unweathered Nephrite	S.G. Weathered Nephrite
7	Fall River	3.00	2.93
39	O'Ne-ell Creek	3.00	2.88
41	Silver Creek	3.00	2.96

The tonnage factor for nephrite, based on an average specific gravity of 3.00, is 10.7 cubic feet per ton.

Colour and Lustre

The colour of the nephrite specimens was measured qualitatively by comparing a polished slab with the Geological Society of America Rock Colour Chart (G.S.A., 1963). This method appears to be reasonably satisfactory for all samples except one (#19) with a dark blue green colour, a colour not present in the colour chart.

Of the 34 specimens examined, more than 60 percent are dusky yellowish green (10GY 3/2) or a mixture of greyish green and dusky yellowish green (10GY 4/2). The remainder of the specimens are various shades of the blue green and green yellow hues. In Table 7, the specimens are grouped according to colour. A number of the specimens contain dark yellowish green (10GY 4/4) lenses and patches of uvarovite garnet.

White, yellow and black nephrites have been reported in the literature (Palmer, 1967; Kolesnik, 1970) but none were seen during the course of this study.

Upon weathering, nephrite becomes discoloured, either bleached or darkened, and deposits of iron hydroxides are formed along fractures and on external surfaces.

An opaque white rind resembling bone is often seen on nephrite artifacts that have been subjected to burning. The original shape of the object is not altered in any way (Palmer, 1967). This fact may be of use to archaeologists, particularly in British Columbia, in recognizing nephrite artifacts in excavations of old Indian settlements.

Fractured surfaces of nephrite have a dull somewhat waxy lustre while polished surfaces have a greasy lustre.

Hardness

Both the Vickers hardness number (V. H. N.), in Kg/mm^2, and Mohs hardness

Table 7

Colour of British Columbia Nephrite Specimens

Nephrite Colour	Munsell* Numerical Colour Designation	Specimen Nos.
Dusky yellowish green	10GY 3/2	6,7,9,10,12, 13,24,38,41, 42-B, 43,44
Mixture of greyish green and dusky yellowish green	10GY 4/2	11,14,28,30,33,36,37,39,40
Greyish olive green	5GY 3/2	4,8,16,26,42-A
Greenish grey	5GY 6/1	34,35
Mottled greyish green and dark yellowish green	10GY 5/2 10GY 4/4	15,23
Dark greenish grey	5GY 4/1	20
Greyish blue green	5BG 5/2	31
Pale blue green	5BG 7/2	45
Dark blue green	Not covered by G.S.A. Rock Colour Chart	19

* Rock-Colour Chart distributed by the Geological Society of America, reprinted 1963.

were determined for fourteen polished specimens mounted in bakelite briquettes.

These are tabulated in Table 8. The method of preparing the samples and

obtaining the hardness values is outlined in Appendix II.

The Vickers hardness number is a measure of hardness which is calculated

from the size of the indentation produced by a pyramidal-shaped, diamond-tipped

indenter falling, under a given load and over a set period of time, onto a

specimen.

The mean Vickers hardness number is 950 Kg/mm^2; the maximum and minimum

values are 1115 Kg/mm^2 and 789 Kg/mm^2, respectively. The range of the hardness

values is shown in Figure 3, a graph of Mohs hardness values against the

logarithm of Vickers hardness number (Bowie, 1967). From Figure 3, it can be

seen that the maximum and minimum values of Vickers hardness correspond to Mohs

hardnesses of approximately 6½ and slightly greater than 7, respectively.

Mohs hardness values of the polished surfaces were determined by comparison

with standard hardness points. None of the specimens were scratched by the

point with a hardness of 6½ but all were readily scratched by the point

corresponding to a hardness of 7.

Both Turner (1935) and Finlayson (1909) report Mohs hardnesses for

polished surfaces of New Zealand nephrite that are slightly lower than those

determined in this study. Turner observed that non-schistose and schistose

varieties had a hardness of 6 to 6.5 while Finlayson recorded a value of 6.5.

Table 8

Vickers Hardness Number and Mohs Hardness of Polished Specimens of British
Columbia Nephrite

Sample Number	Locality	Number of Determinations	Mean V.H.N. (Kg/mm^2)	Standard Error of the Mean	Measured Mohs Hardness
4	Marshall Creek	5	993	25	7
6	Junction of Bridge River and Yalakom River	5	950	25	7
7	Fall River	5	861	67	7
9	Ogden Mountain	5	851	58	7
10	Kelly Creek	5	1025	52	7
11	Kelly Creek	4	919	25	7
12	Kwanika Creek	5	1115	50	7
13	Kwanika Creek	5	933	30	7
14	Dease Lake	5	819	40	7
15	Van Decar Creek	5	789	32	7
16	O'Ne-ell Creek	5	1062	32	7
26	O'Ne-ell Creek	5	941	44	7
33	O'Ne-ell Creek	5	1017	14	7
34	O'Ne-ell Creek	5	1018	42	7

Fig. 3

A graph of Mohs hardness values against the log of Vickers hardness numbers.
(after Bowie, 1967)

Range of the Vickers hardness numbers of 14 British Columbia nephrite specimens.

VICKERS HARDNESS NUMBER, Kg/mm^2

2000

1000

100

20

2   3   4   5   6   7   8

MOHS HARDNESS
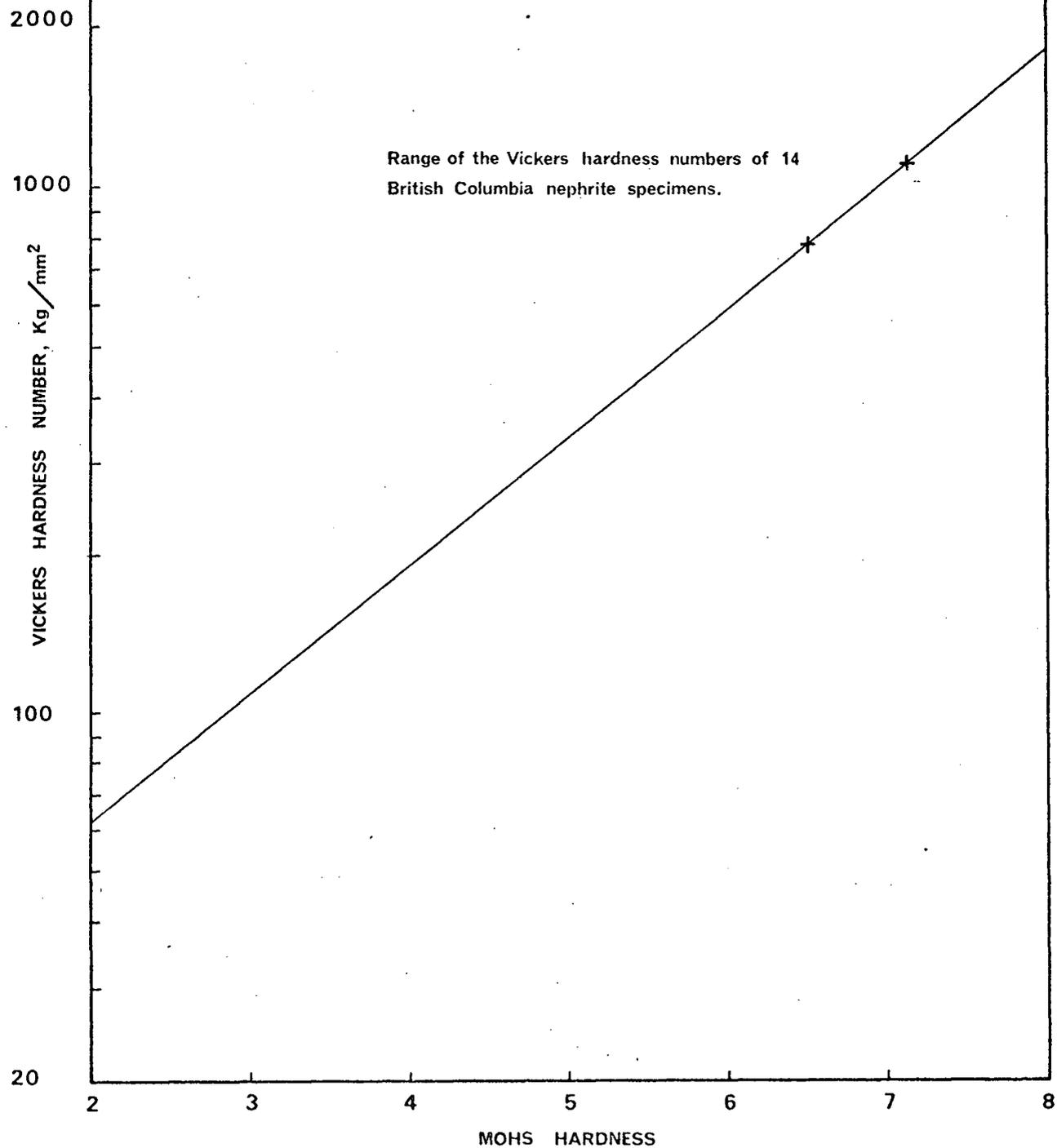
Polished specimens of semi-nephrite examined by Turner were found to have a

hardness of 5.5 to 6.0. The lower hardness of semi-nephrite is readily

explained by the poorly developed nephritic microstructure and by the abundant

impurities that characterize this variety of nephrite.

There does not appear to be any obvious correlation between the hardness

of the specimens studied and the microstructure or the mineralogic composition.

The observed hardness variations are probably due to minute flaws produced dur-

ing the process of sawing, mounting and polishing.

Crushing Strength and Relative Corrosion Hardness

Values for these properties were not determined for the British Columbia

specimens; those presented below have been obtained from the European litera-

ture and are included in this report because of the unavailability of such

information.

The crushing strength of high quality Siberian nephrite is reported to be

7,759 Kg/cm^2 (Kolesnik, 1970). The high value is understandable in light of

the characteristic microstructure of this material.

Eppler (1941) has determined that the relative mechanical corrosion

hardness, or resistance to abrasion, of nephrite is 36 percent higher than that

of quartz.

IV. THE CHEMISTRY AND CRYSTALLOGRAPHIC STRUCTURE OF NEPHRITE

Nephrite possesses an unique microstructure, one in which fine fibers of

tremolite occur in tufts which are felted and twisted. This microstructure,

which imparts to nephrite its distinctive characteristics, is a function of the

limited conditions under which it forms (Kolesnik, 1970). These conditions are

quite different to those under which common broad-prismatic tremolite-actinolite

forms. This section attempts to outline the chemical and structural features

of nephritic tremolite and broad-prismatic tremolite-actinolite.

CHEMISTRY

The general formula of an amphibole may be expressed as (Ernst, 1968;

Whittaker, 1960; Deer et al, 1966; Gibbs, 1966):

$$W_{0-1}X_2Y_5Z_8O_{22}(OH,O,F,Cl)_2$$
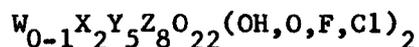
where W represents ten- to twelve-fold coordinated cations, commonly Na and K,

occupying the A structural sites (Figure 6); X refers to six- or eight-fold

coordinated cations with ionic radii from 0.7 Å to 1.1 Å, chiefly Ca, Na, Fe^{+2}

and Mn; Y stands for six-fold cations with ionic radii from 0.57 Å to 0.91 Å,

chiefly Mg, Fe^{+2}, Fe^{+3}, Al, Mn, and Ti; and Z refers to small highly charged

cations within the tetrahedral groups, largely Si, but may be replaced by Al up

to about 25 percent. Hydrogen may be present to balance excess charges. The

common cation replacements for the amphibole group are Mg = Fe, Al = Si,

(Mg,Fe) = Al and Na = Ca; in the tremolite-actinolite series, the predominant

replacement is iron for magnesium. A replacement of the type Al = Si,

(Mg,Fe) = Al or Na = Ca must be accompanied by an additional replacement of

this type to maintain charge balance. The above formula represents one-half of

the atoms in the unit cell.

The crystallographic formulae of nephritic tremolite and broad-prismatic

tremolite-actinolite have been computed by Kolesnik (1970) from the analyses of

57 nephrite specimens and 72 actinolite-tremolite specimens. They are present-

ed below:

Broad-prismatic tremolite-actinolite:

$$(Ca_{1.83}Mg_{0.15}K_{0.04}Na_{0.11})_{2.13}(Mg_{4.31}Fe^{+2}_{0.54}Fe^{+3}_{0.10}Al_{0.05})_{5.00}$$

$$(Si_{7.75}Al_{0.25}O_{22})(OH)_{1.93}O_{0.07}$$

Nephritic tremolite:

$$(Ca_{1.91}Mg_{0.05}K_{0.03}Na_{0.12})_{2.11}(Mg_{4.53}Fe^{+2}_{0.36}Fe^{+3}_{0.11})_{5.00}$$

$$(Si_{7.77}Al_{0.20}O_{22})(OH)_2 \quad 0.47 \ H_2O$$
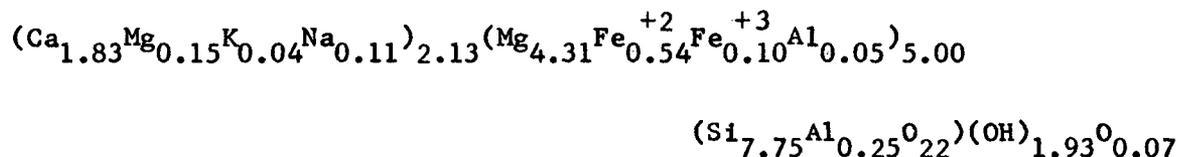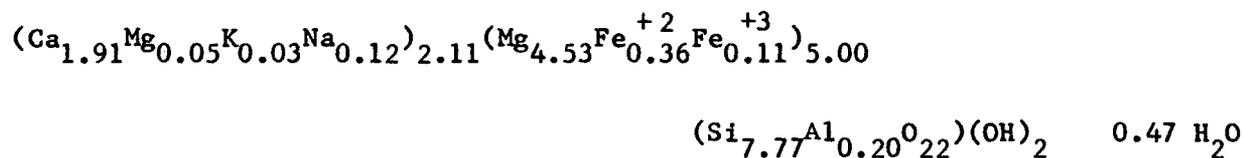
The most notable differences between the broad-prismatic amphiboles and the

nephritic amphiboles are the increased Ca content and the almost total absence

of Mg in the X position of the latter. Other features of nephritic tremolite

are the absence of Al^{+3} in the Y position, a decrease in the Fe^{+2} content of

the Y position and a decrease in the Al^{+3} content of the Z position. Also,

the amount of water liberated from nephrite at temperatures in excess of $100^{o}C$,

the so-called crystallographic water, is much higher than that in broad-

prismatic tremolite.

Kolesnik attributes the high magnesium content in the X position of the tremolite-actinolite to mechanical additions of anthophyllite. To explain the higher calcium content and the almost total absence of magnesium in the X position of nephritic tremolite, he suggests that Ca^{+2}-Mg^{+2} isomorphism is operative under the conditions at which nephrite forms. Crystallographic and thermal studies indicate that the bulk of the excess water contained in nephrite does not enter the crystal lattice but is probably associated with the extremely fine fibrous structure that is characteristic of the nephrites. This structure would allow nephrite to adsorb a significant amount of water and retain it on heating. The weight loss curves in Figure 4 illustrate that the water in nephrite is liberated at a considerably slower rate and at higher temperatures than in the acicular broad-prismatic tremolite-actinolite. Huang (1966) also found a slight excess of water in the computed formula for nephrite from Taiwan.

The analyses, of 42 nephrite specimens, obtained from the literature, are presented in Appendix III and are plotted in Figure 5, a plot of MgO-CaO-FeO + Fe_2O_3. All of the analyses fall on or close to the tremolite-ferroactinolite line and are grouped at the tremolite end of the line. The compositional field of New Zealand nephrites (Finlayson, 1909; Coleman, 1966) is outlined by a broken line and represents a total of 22 samples (Analyses 1 - 20, 25 - 26;
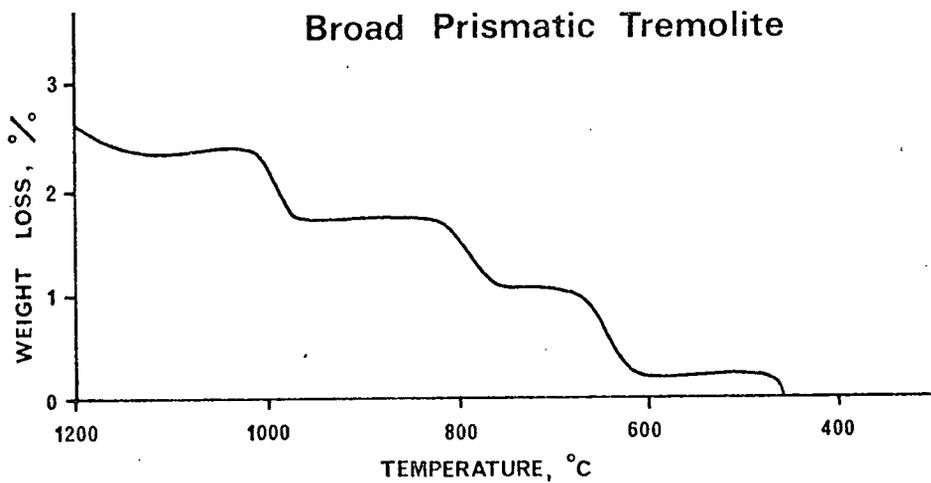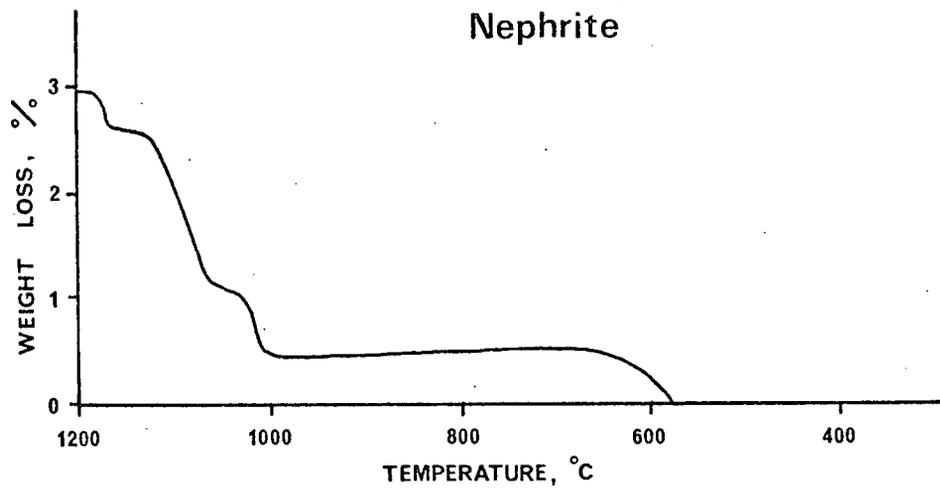
Fig.4. Curves of weight loss in heating for nephrite and broad prismatic tremolite from Siberia, U.S.S.R.(after Kolesnik, 1970.)

Fig.5

MgO− CaO−Fe₂O₃+FeO in nephrites from various world localities.
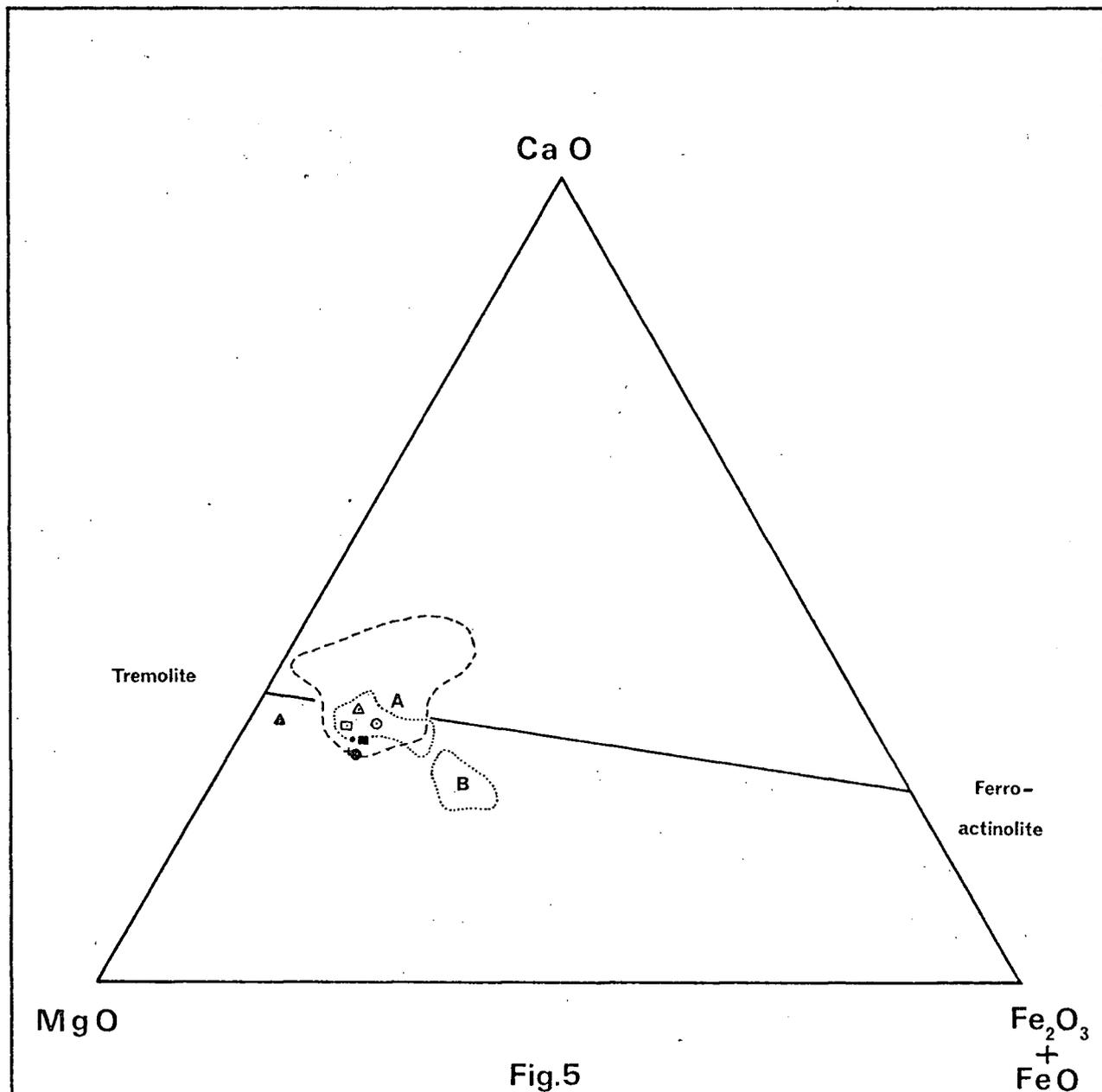
MgO− $CaO−Fe_2O_3+FeO$ in nephrites from various world localities.

Field of New Zealand nephrites (Finlayson, 1909; Coleman, 1966)
Field of Wyoming nephrites (Sherer, 1969)
    A: Granite Mountains; Sage Creek locality, Seminoe Mountains
    B: Laramie Mountains; Seminoe locality, Seminoe Mountains
+ Harz area, East Germany (Uhlig, 1910)
▲ Bahia, Brazil (Washington, 1922)
⊕ Haudères, Valais Canton, Switzerland (Preiswerk, 1926)
▨ Koleborn, Harz area, East Germany (Rose and Fromme, 1932)
▣ Fengtien, Taiwan (Huang, 1966)
· Hakuba-mura, Negano Prefecture, Japan (Yoshimura et al, 1966)
△ Jordanów, Poland (Heflik, 1968)
⊙ East Sayans, Siberia, U. S. S. R. (Kolesnik, 1970)

Appendix III). The dotted lines define the compositional fields of Wyoming

nephrites (Analyses 31 - 42; Appendix III), (Sherer, 1969). A description of

the occurrences of the other specimens is given in Appendix I. Sherer (1969)

has determined that trace amounts of Ni, V, Cr, Co, Cu, Sr, Ba, B, Ga, Zr, and

Zn are present in the Wyoming nephrites. It is probable that these elements

are present, in variable amounts, in the nephrites from other localities but

have not been looked for. Possibly the amounts or the ratios of certain of

these trace elements could be used to characterize the nephrites from various

localities.

CRYSTALLOGRAPHIC STRUCTURE

The structure of the amphiboles is characterized by the presence of

$(Si,Al)O_4$ tetrahedra linked in double chains with the composition $(Si_4O_{11})_n$.

The structure of the monoclinic amphibole, tremolite, projected upon (001)

and parallel to c, is shown in Figure 6. The c-cell edge of the unit cell is

defined by the repeat of the chain along its length. The sites marked M_1, M_2

and M_3 are occupied by the octahedrally coordinated Y cations. The two Si-O

chains with the hydroxyl groups and the M_1, M_2 and M_3 cations sandwiched in

between them is equivalent to a narrow strip of the talc structure (Whittaker,

1960). Intermediate size Y cations are distributed nearly randomly in M_1 and

M_3 and the smallest Y cations tend to be concentrated in M_2 (Ernst, 1968). At

the edges of the talc strips are the M_4 or X cations, Ca, Na and Mn, which
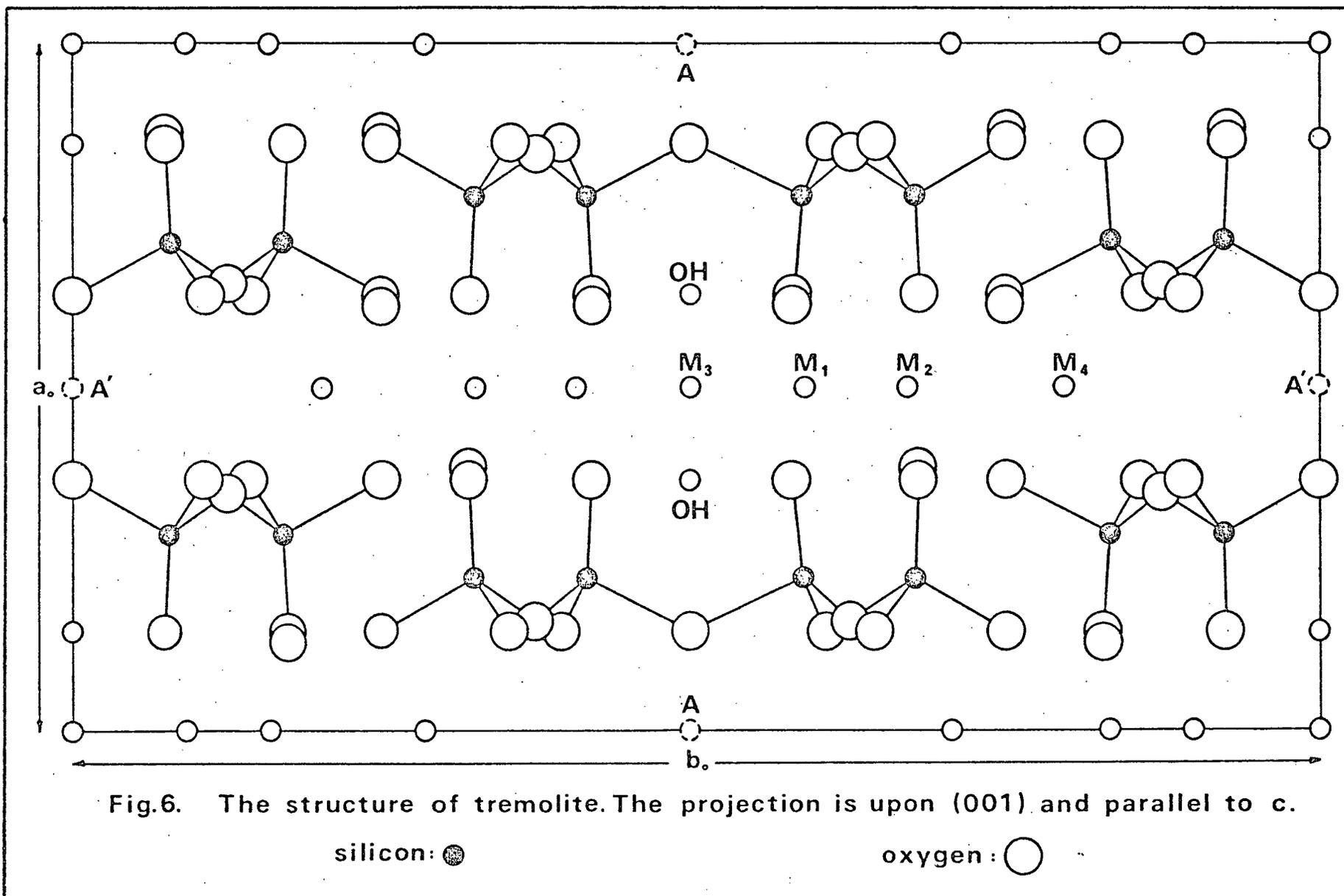
Fig.6.   The structure of tremolite. The projection is upon (001) and parallel to c.

silicon: ●   oxygen: ◯

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serve to link the strips together. The cations at M_2 also serve this purpose but to a lesser extent than M_4 cations. The positions marked A and A' are not occupied in tremolite but in some amphiboles which contain in excess of 2(Ca,Na,K) ions per formula unit, these positions may be partially or completely occupied.

The tremolite-actinolite amphibole series belongs to the monoclinic crystal system; the space group is C 2/m.

Amphiboles possess a well-developed prismatic cleavage, the planes of which meet at angles of about 55° and 125°, yielding cleavage fragments which appear diamond-shaped in cross section. This cleavage, which is developed along those surfaces in which a minimum number of bonds are broken, passes through the amphibole structure parallel to the chains by stepping successively along their backs through the A-site and thence to the next layer at the periphery of the octahedral layer (Shappell, 1936). In nephrite, due to the very fine nature of the component tremolite fibers, the cleavage is never observed except at the extreme magnifications offered by the scanning electron microscope (Plate 15).

Studies of synthetic monoclinic amphiboles have shown the effects of ionic substitution on the dimensions of the unit cell (Ernst, 1966). The b_o parameter is controlled by the sizes of the cations in M_4 and M_2, but because the occupancy of M_4 is constant in any particular synthetic series, the control on

60
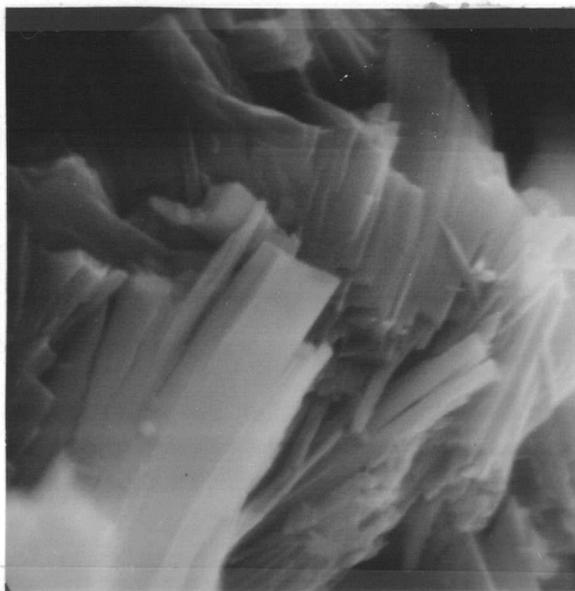
Plate 15: Scanning electron micrograph of a schistose nephrite transitional to a semi-nephrite illustrating the (110) cleavage of tremolite, (#37; O'Ne-ell Creek), X 6500.

this parameter shifts to the cations occupying M_2. With an increase in the mean size of the octahedrally coordinated cations, there is an increase in a_o sin B. A slight increase in the chain length c_o is observed when the size of the cations in M_1 and M_3 is increased. The cell volume increases with the number of large ions contained within the structure.

The unit cell parameters of tremolite from ten British Columbia nephrite specimens are tabulated, with those for tremolite and nephritic tremolite obtained from the literature, in Table 9. Details of the method employed in obtaining the unit cell data are given in Appendix II. As can be seen from this data, the a_o and c_o parameters are virtually the same for both broad-prismatic tremolite and for nephritic tremolite. The major difference, however, is in the length of the b_o parameter; that in the latter is considerably larger probably reflecting the increased amount of Fe^{+2} contained in the M_2 position. There does not appear to be any relationship between the length of the c_o-cell edge and the extreme elongation of the nephritic tremolite fibers.

X-ray diffraction data for tremolite (A.S.T.M.: 13 - 437) and for nephritic tremolite from British Columbia (#39; O'Ne-ell Creek), New Zealand (Coleman, 1966), Taiwan (Huang, 1966) and Siberia (Kolesnik, 1970) are presented in Table 10.

Table 9

Unit Cell Parameters for Tremolite from British Columbia Nephrite,
Tremolite from Siberian Nephrite and Common Tremolite

Sample Number	Locality	a_o Å	b_o Å	c_o Å	B	Cell Vol. Å^3
7	Fall River	9.883 ∓0.018	18.116 ∓0.022	5.261 ∓0.004	105° 11' ∓10'	909.2 ∓1.7
11	Kelly Creek	9.880 ∓0.017	18.112 ∓0.021	5.261 ∓0.004	105° 11' ∓10'	908.6 ∓1.6
12	Kwanika Creek	9.879 ∓0.017	18.110 ∓0.020	5.259 ∓0.004	105° 11' ∓10'	908.6 ∓1.6
19	Fall River	9.878 ∓0.018	18.127 ∓0.023	5.262 ∓0.005	105° 9' ∓11'	909.5 ∓1.7
23	Coquihalla River	9.888 ∓0.017	18.130 ∓0.021	5.263 ∓0.004	105° 11' ∓10'	910.6 ∓1.6
35	O'Ne-ell Creek	9.886 ∓0.017	18.132 ∓0.021	5.263 ∓0.004	105° 10' ∓10'	910.6 ∓1.6
36	O'Ne-ell Creek	9.889 ∓0.016	18.134 ∓0.020	5.267 ∓0.004	105° 12' ∓ 9'	911.5 ∓1.5
40	Seywerd Creek	9.890 ∓0.018	18.131 ∓0.022	5.266 ∓0.004	105° 12' ∓10'	911.3 ∓1.7
41	Silver Creek	9.873 ∓0.017	18.106 ∓0.021	5.259 ∓0.004	105° 12' ∓10'	907.2 ∓1.6
42-B	Marshall Creek	9.885 ∓0.018	18.116 ∓0.022	5.262 ∓0.004	105° 10' ∓10'	909.5 ∓1.7
	Siberian Nephrite (Kolesnik, 1970)	9.878 ∓0.007	18.12 ∓0.005	5.29 ∓0.006	104° 47'	---
	Tremolite A.S.T.M.: 13 - 437	9.84	18.02	5.27	104° 57'	---

Table 10

X-ray Diffraction Data for Tremolite (I) and for Nephritic Tremolite
from British Columbia (II), New Zealand (III), Taiwan (IV)
and Siberia (V)

	I		II		III		IV		V	
hkl	d Å	I	d Å	I	d Å	I	d Å	I	d Å	I
020	8.98	16	9.05	35	9.00	20	9.01	37	9.04	20
110	8.38	100	8.45	90	8.43	100	8.38	95	8.48	100
130, 001	5.07	16	5.10	16	5.06	10	5.07	16	5.09	12
1̄11	4.87	10	4.89	19	4.85	7	4.87	18	4.87	13
200	4.76	20	4.77	10	4.73	7	4.75	15	4.77	15
040	4.51	20	4.53	30	4.50	20	4.52	24	4.53	15
220	4.20	35	4.22	15	4.20	10	4.20	12	4.22	25
1̄31	3.870	16	3.888	17	3.87	5	3.87	13	3.91	8
150, 041	3.376	40	3.387	45	3.38	20	3.38	24	3.391	15
240	3.268	75	3.282	50	3.27	50	3.27	40	3.285	46
310	3.121	100	3.130	100	3.12	100	3.12	100	3.133	100
31̄1, 24̄1	3.028	10	3.037	5	--	--	--	--	--	--
1̄51	2.938	40	2.944	35	2.94	25	2.940	24	2.940	16
330	2.805	45	2.809	13	2.805	15	2.805	12	2.808	35
42̄1	2.730	16	2.734	30	2.731	10	--	--	2.736	22
151	2.705	90	2.710	80	2.702	45	2.702	65	2.709	35
1̄12, 061	2.592	30	2.597	30	2.593	15	2.592	22	2.602	12

Table 10 continued

hkl	I d Å	I	II d Å	I	III d Å	I	IV d Å	I	V d Å	I
$\bar{2}$02, 002	2.529	40	2.537	30	2.524	15	2.529	25	2.545	12
$\bar{1}$32	2.407	8	2.415	7	2.411	3	--	--	--	--
350, 400	2.380	30	2.388	10	2.386	5	2.380	11	2.390	18
35$\bar{1}$	2.335	30	2.340	30	2.338	18	--	--	2.341	26
42$\bar{1}$	2.321	40	2.328	25	2.327	16	2.321	28	2.307	10
420, 071	2.298	12	2.302	14	2.304	10	2.298	22	2.285	5
112	2.273	16	2.282	20	2.266	6	2.276	18	--	--
$\bar{2}$42, 042	2.206	6	2.238	9	--	--	--	--	--	--
44$\bar{1}$	2.181	6	--	--	--	--	2.181	7	--	--
171, 261	2.163	35	2.167	25	2.161	19	2.161	25	2.167	16
081, 280	2.042	18	2.046	9	2.043	6	2.040	10	2.048	8
202	2.015	45	2.020	19	2.016	15	2.014	15	2.019	16
351, 370	2.002	16	2.001	8	2.001	7	2.002	17	2.007	12
28$\bar{1}$, 190	1.963	6	1.978	17	1.961	6	1.963	9	1.965	5
152	1.929	6	--	--	--	--	1.933	7	--	--
510	1.892	50	1.903	10	1.892	10	1.888	9	1.898	47

Radiation: CuKα

I: Tremolite, A.S.T.M.: 13 - 437
II: Nephritic tremolite, British Columbia (#39; O'Ne-ell Creek)
III: Nephritic tremolite, New Zealand (Coleman, 1966)
IV: Nephritic tremolite, Taiwan (Huang, 1966)
V: Nephritic tremolite, Siberia, U.S.S.R. (Kolesnik, 1970)

V. IRON AND TRACE ELEMENT GEOCHEMISTRY OF BRITISH COLUMBIA NEPHRITES

Thirty one nephrite specimens from British Columbia, five from area I,

twenty from area II and six from area III, were analysed for the following

elements: iron, cobalt, nickel, manganese, copper, lead, zinc, chromium,

titanium and vanadium. The reasons for the analyses are two-fold. The first,

and foremost, is to determine if there is any regional variation in the trace

element content of the nephrites. Such a variation, if systematic, could

prove to be extremely important to archaeologists attempting to trace the

sources of the nephrite used by early British Columbia Indians for the fabrica-

tion of tools. The second is to determine, in a qualitative way, what minor

and trace elements are colouring agents.

The first seven elements were determined by atomic-absorption spectro-

photometry. The analytical precision (95% confidence level) of these deter-

minations, based on duplicate analyses, is: Fe,Mn $= \pm$ 4%; Ni,Zn $= \pm 10\%$;

Co,Cu,Pb $= \pm$ 20%. The last three were analysed with an emission spectrograph

and, hence, are semi-quantitative. Accessory minerals, because of their small

grain size and intergrown nature, were not removed from the nephrites prior to

analysis. Details of the analytical procedure are discussed in Appendix II;

the results are presented in Table 11. Ionic radii given in the following

discussion are obtained from Krauskopf (1967).

Table 11

Iron and Trace Element Analyses of British Columbia Nephrite Specimens

Sample Number	Locality	Fe %	Co ppm	Ni ppm	Mn ppm	Cu ppm	Pb ppm	Zn ppm	Cr ppm	Ti ppm	V ppm
4	Marshall Creek	3.63	61	831	1043	23	25	60	4000	1000	200
6	Junction of Bridge and Yalakom Rivers	3.19	45	919	481	15	27	35	10000	400	200
7	Fall River	2.68	36	1100	606	10	22	36	4000	500	200
8	Fall River	3.38	24	719	1243	13	32	82	5000	400	150
9	Ogden Mountain	2.55	87	1181	812	16	30	67	4000	400	200
10	Kelly Creek	2.36	21	750	762	13	11	64	4000	200	100
11	Kelly Creek	2.68	46	1112	1243	16	30	97	5000	150	180
12	Kwanika Creek	3.63	70	1188	962	5	32	74	600	300	100
13	Kwanika Creek	2.49	116	1043	725	13	18	58	4000	400	80
14	Dease Lake	3.00	62	925	885	15	19	50	10000	300	200

Table 11 continued

Sample Number	Locality	Fe %	Co ppm	Ni ppm	Mn ppm	Cu ppm	Pb ppm	Zn ppm	Cr ppm	Ti ppm	V ppm
15	Van Decar Creek	2.88	59	1012	575	6	22	22	4500	150	120
16	O'Ne-ell Creek	3.25	65	1393	869	17	19	69	6000	250	150
19	Fall River	3.38	100	919	969	6	20	90	1500	400	150
23	Coquihalla River	2.94	70	787	813	33	33	58	3000	500	150
24	Brett Creek	3.25	64	1038	1537	15	21	89	3000	500	180
26	O'Ne-ell Creek	3.38	47	1630	732	35	22	47	8000	200	180
28	Dease Lake area	2.94	40	325	468	3	32	43	200	350	100
30	Cassiar area	3.06	37	956	1125	5	11	44	1000	200	180
31	Dease Lake area	3.13	28	212	587	4	17	33	100	100	80
34	O'Ne-ell Creek	3.38	41	544	813	10	29	39	200	10000	200
35	O'Ne-ell Creek	3.13	19	134	725	3	12	35	100	2000	180
36	O'Ne-ell Creek	2.94	59	1370	581	13	10	35	3500	350	100

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Table 11 continued

Sample Number	Locality	Fe %	Co ppm	Ni ppm	Mn ppm	Cu ppm	Pb ppm	Zn ppm	Cr ppm	Ti ppm	V ppm
37	O'Ne-ell Creek	3.13	50	1394	606	14	21	42	10000	325	100
39	O'Ne-ell Creek	3.13	63	1370	512	7	13	32	3000	300	100
40	Seywerd Creek	3.00	6	562	1212	2	16	39	1000	150	80
41	Silver Creek	2.71	44	1025	380	9	24	32	2500	150	80
42-A	Marshall Creek	3.63	37	556	643	6	22	32	5000	800	200
42-B	Marshall Creek	2.74	30	1600	725	3	32	43	6000	30	100
43	Ogden Mountain	3.31	19	1207	937	3	10	65	6000	300	180
44	Ogden Mountain	2.90	21	1269	738	3	20	44	5000	150	180
45	Dease Lake area	2.81	47	512	493	4	29	29	1500	250	100
	Mean $\bar{X}$	3.05	49	954	800	11	22	55	4000	700	150

Fe, Co, Ni, Mn, Cu, Pb, Zn: Atomic absorption analyses; analyst J. R. Fraser. The precision of the analyses, at the 95% confidence level, is: Fe,Mn = ∓4%; Ni, Zn = ∓10%; Co, Cu, Pb = ∓20%.

Cr, Ti, V: Spectrographic analyses, semi-quantitative; analyst, D. Marshall, Department of Geology, University of British Columbia.

DISCUSSION OF RESULTS

Iron

The average for iron in the nephrites studied is 3.05%; the maximum and minimum values are 3.63% and 2.36%, respectively. The results are shown as a histogram in Figure 7. The histogram approximates a normal distribution. With the exception of the small amount contributed by iron bearing accessory minerals such as chromite, picotite and pyrite, the iron is contained in the actinolite-tremolite structure in octahedrally coordinated positions. The iron content of the nephrites in Appendix III ranges from 0.47% to 9.45%.

Cobalt and Nickel

The cobalt content of the samples ranges from 6 ppm to 116 ppm, with the average being 49 ppm. The average nickel concentration is 954 ppm and the range is 134 ppm to 1630 ppm. The results are plotted as histograms in Figure 7; cobalt is normally distributed while nickel exhibits a slight negative skewness. A weak positive correlation exists between cobalt and nickel, the correlation coefficient being 0.45 (calculated by the method of Lepeltier, 1969). The average cobalt and nickel contents of four nephrite specimens from Wyoming (Sherer, 1969) are 34 ppm and 650 ppm, respectively.

Carr and Turkian (1961) found that the amount of cobalt contained in a mineral is closely correlative with the total concentrations of iron and magnesium. Rankama and Sahama (1950) suggest that nickel, on the basis of
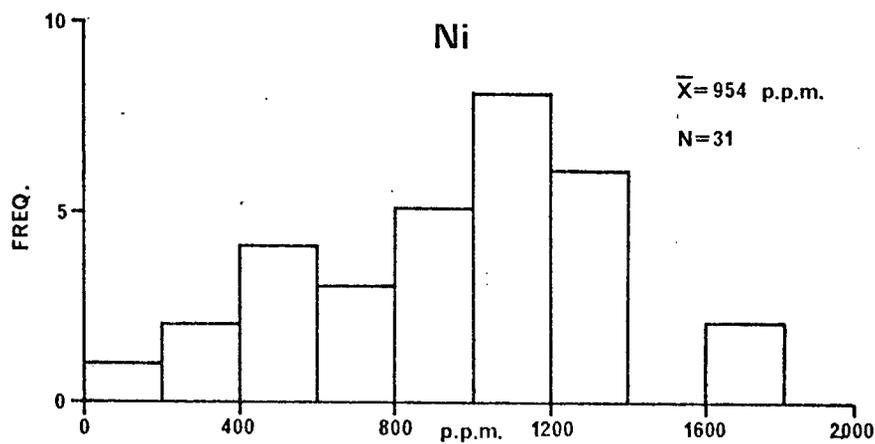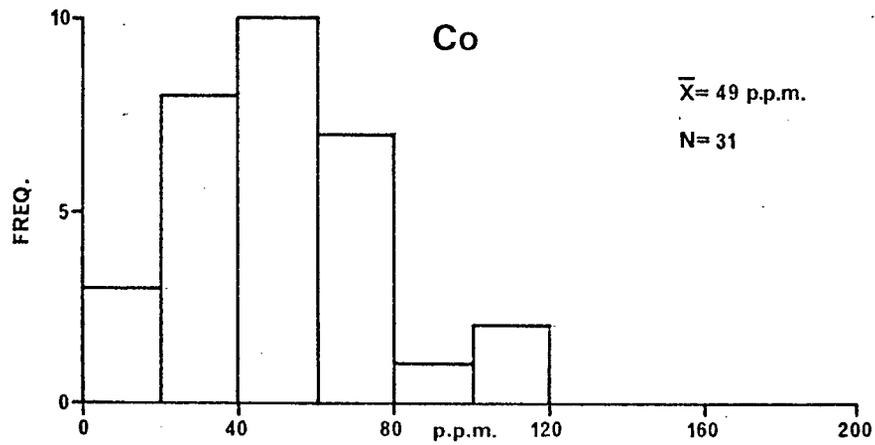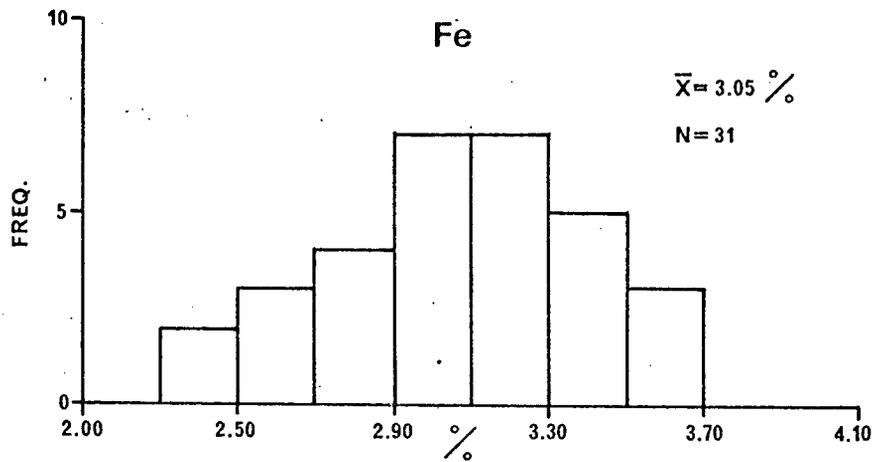
Fig.7. Histograms of the Fe, Co and Ni contents of British Columbia nephrites.

ionic radius (0.69 $\overset{\circ}{A}$), is closely associated with magnesium (0.66 $\overset{\circ}{A}$).

Unfortunately, these hypotheses cannot be tested as the magnesium contents of

the nephrites studied were not determined. Both the cobalt and the nickel

would be contained in the amphibole as octahedrally coordinated cations

occupying Y positions.

The average cobalt-nickel ratios for British Columbia and Wyoming nephrites

are 0.051 and 0.052, respectively.

Manganese

The average concentration of manganese in the nephrites is 800 ppm; the

range of concentration is 300 ppm to 1537 ppm. A histogram of the results

(Figure 8) approximates a normal distribution.

The bulk of the manganese is undoubtedly concealed in the actinolite-

tremolite structure. Rankama and Sahama (1950) state that because of the large

size (0.80 $\overset{\circ}{A}$) of the Mn^{+2} ion, it is incorporated into calcium and magnesium

silicates only with difficulty. They suggest that the Mn^{+2} ion is capable of

replacing Fe^{+2} (0.74 $\overset{\circ}{A}$), Mg^{+2} (0.66 $\overset{\circ}{A}$) and Ca^{+2} (0.99 $\overset{\circ}{A}$). In the tremolite-

actinolite series, the manganese could be contained in the octahedrally coord-

inated Y positions and in the M_4 sites with calcium. Of the analyses in

Appendix III, 31 of the 42 list the presence of Mn, as an oxide, in amounts

ranging from trace to 0.69% MnO.
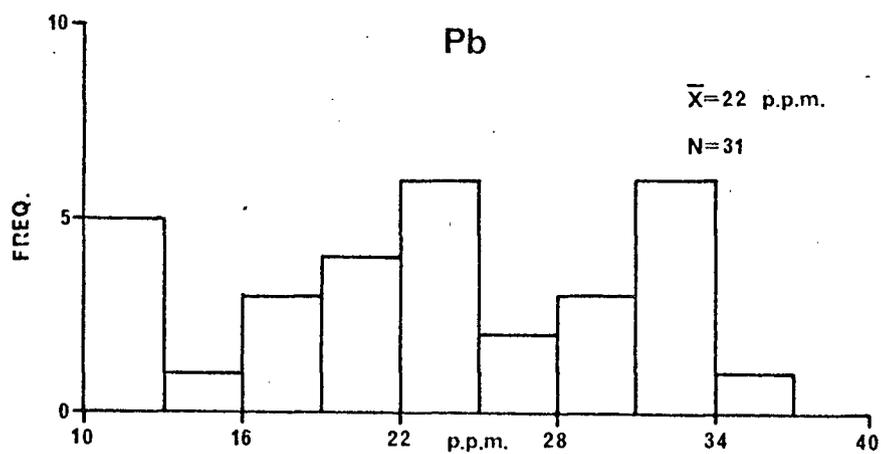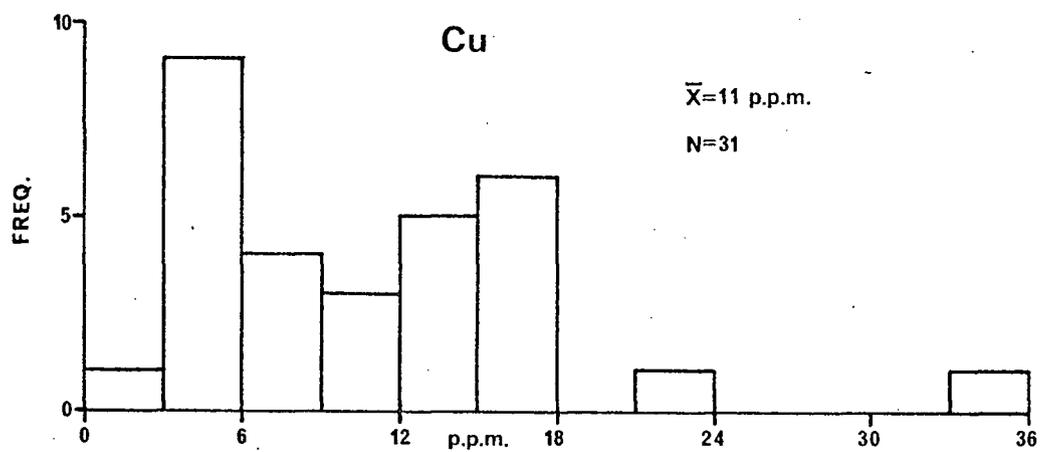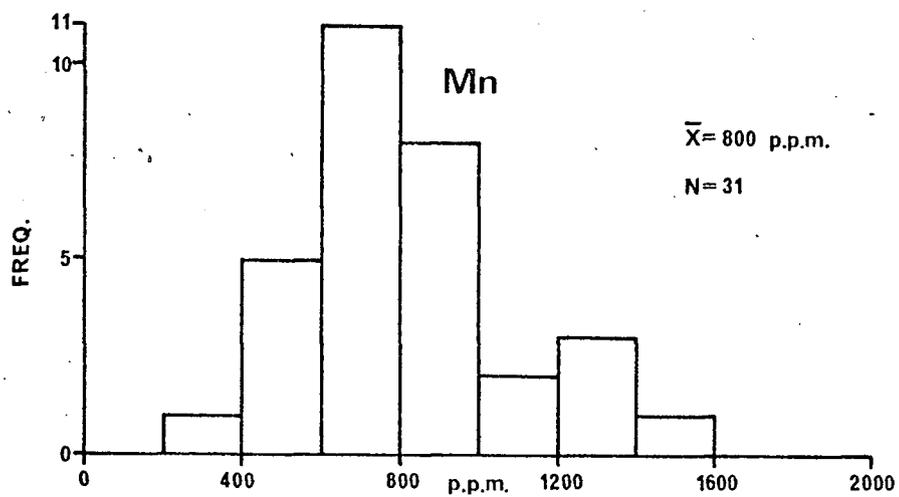
Fig.8. Histograms of the Mn, Cu and Pb contents of British Columbia nephrites.

Copper

The concentration of copper in the nephrites is very low, the mean being 11 ppm and the range 2 ppm to 35 ppm. A histogram plot of the results (Figure 8) shows a bimodal distribution suggesting the presence of two distinct populations, possibly reflecting the presence of minute grains of copper sulphide. The mean copper content of the four Wyoming nephrite specimens analysed by Sherer (1969) is 9 ppm.

Lead

The lead values range from 10 ppm to 33 ppm, the mean being 22 ppm. The results are plotted as a histogram in Figure 8.

Zinc

The average zinc content of the 31 nephrite specimens is 55 ppm and the values range from 22 ppm to 97 ppm. The results are graphically presented in the histogram in Figure 9 which indicates a log normal distribution. Zinc was detected in only one of the nephrites analysed by Sherer (1969), this value being 150 ppm.

Zinc, with an ionic radius of 0.74 $\overset{\circ}{A}$, is capable of replacing ferrous iron and magnesium in mineral structures (Rankama and Sahama, 1950) and in the case of the actinolite-tremolite series, it would occupy octahedrally coordinated Y positions.
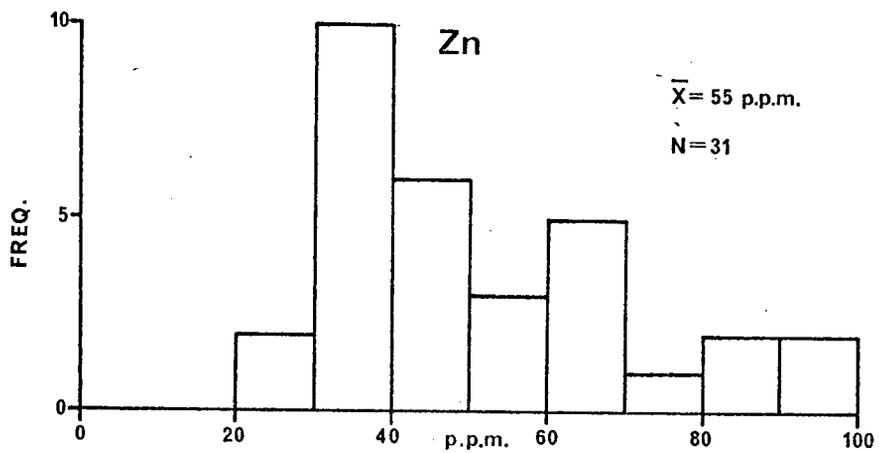
Fig. 9. Histogram of the Zn content of British Columbia nephrites.

Chromium, Titanium and Vanadium

Because the analyses for chromium, titanium and vanadium are semi-quantitative, histograms are not plotted and only the average values for these elements are presented. The average abundance of chromium is 4000 ppm, titanium 700 ppm and vanadium 150 ppm.

The bulk of the chromium present in the nephrites is undoubtedly contained in accessory minerals such as picotite, chromite, uvarovite and kammererite (chlorite) but since the ionic radius of trivalent chromium (0.63 Å) is very similar to that of ferric iron (0.64 Å), some may be accommodated in octahedrally coordinated sites in the amphibole structure. The average chromium content of the four Wyoming specimens (Sherer, 1969) is 30 ppm which probably reflects the different geologic environment in which this nephrite was formed compared with that from British Columbia. Two of the analyses, 9 and 14, in Appendix III list chromium as a detectable constituent, the concentrations being 0.42% Cr_2O_3 (approximately 2900 ppm Cr) and 0.30% Cr_2O_3 (approximately 2100 ppm Cr), respectively. Both of these samples are from New Zealand and are associated with ultramafic rocks (Finlayson, 1909).

The majority of the thin sections examined contained fine dustings of microlites of a brown mineral, identified by X-ray diffraction as sphene, which would account for the bulk of the titanium detected in the analyses. According to Rankama and Sahama (1950), titanium may also be contained in the amphibole

structure as replacements of Fe^{+3}, Mg and Al, but the oxidation state is unknown due to analytical difficulties in determining Ti^{+3} and Ti^{+4} in the presence of ferrous and ferric iron. These authors suggest the possibility that Ti^{+3} rather than Ti^{+4} is present in amphiboles and pyroxenes even though TiO_2 is reported in analyses. Most general formulae for the amphiboles indicate that titanium is contained in the Y positions. The average titanium content of 13 nephrites in Appendix III is approximately 790 ppm.

The vanadium content of the nephrites is remarkably uniform. This element is similar to titanium in behaviour and may be concealed in the sphene microlites described above although some is probably contained in the actinolite-tremolite. Goldschmidt (1937) considers vanadium to be present as V^{+3} (0.74 Å) in ferromagnesian minerals; as such it would easily be admitted to positions of six-fold coordination, presumably replacing Fe^{+2} (0.74 Å). Moxham (1965) suggests that the behaviour of vanadium in ferromagnesian minerals is analogous to that of iron. The four Wyoming nephrites analysed by Sherer (1969) contained an average of 93 ppm vanadium.

Element Distribution in Fresh and Weathered Nephrite

Three of the nephrite specimens examined exhibited a conspicuous, discoloured weathering rind up to 0.5 cm thick. All three specimens were from alluvial boulders. The weathered material is softer than the unweathered nephrite and is usually fractured, the fractures being subparallel to the

Table 12

Iron and Trace Element Contents of Fresh and Weathered Nephrite from Alluvial Boulders

Sample Number and locality	Fe %	Co ppm	Ni ppm	Mn ppm	Cu ppm	Pb ppm	Zn ppm	Cr ppm	Ti ppm	V ppm
#7; Fall River										
Fresh	2.68	36	1100	606	10	22	36	4000	500	200
Weathered	3.06	41	919	725	6	22	33	3000	125	120
#39; O'Ne-ell Creek										
Fresh	3.13	63	1370	512	7	13	32	3000	300	100
Weathered	3.63	48	1350	612	8	23	38	3500	100	100
#41; Silver Creek										
Fresh	2.71	44	1025	380	9	24	32	2500	150	80
Weathered	2.81	59	975	406	6	20	69	3500	2	115

external surface of the specimen. The results of the analyses of the fresh and weathered nephrite from each specimen are presented in Table 12.

From this data, it is seen that there is an increase in the amount of iron and manganese contained in the weathered nephrite and a decrease in nickel and titanium. The results for the other elements are inconclusive.

The increase in the amount of iron and manganese is readily explained by the precipitation during weathering of the relatively insoluble hydroxides of ferric iron and quadravalent manganese. These hydroxides are seen as brown earthy deposits on fractures and external surfaces.

REGIONAL CHEMICAL VARIATIONS IN BRITISH COLUMBIA NEPHRITES

The nephrites were grouped according to area of origin (as in Figure 1) and averages calculated for each element. The values for the nephrites from area II exclude two greenish grey specimens from O'Ne-ell Creek as they are rare and contain anomalously low chromium and high titanium.

Significant regional variations of the averages for iron, cobalt, manganese, copper, lead, zinc and vanadium are not observed; variations are present in the averages for nickel, titanium and chromium, that for the latter being the most pronounced. The lowest average values for these three elements are found in the specimens from area III; the highest average chromium and titanium contents are in the samples from area I while those from area II have the highest average nickel content. Because of the overlapping range of values for

Table 13

Average and Range of Iron and Trace Element Contents of Nephrites from the Three Major Nephrite
Producing Areas of British Columbia

Area	Fe %	Co ppm	Ni ppm	Mn ppm	Cu ppm	Pb ppm	Zn ppm	Cr ppm	Ti ppm	V ppm
Bridge River-lower Fraser River I 5 samples	3.23 2.74- 3.63	49 30- 70	939 787- 1600	741 481- 1043	16 3- 33	28 22- 33	46 32- 60	5600 3000- 10000	500 30- 1000	170 100- 200
Takla Lake II 18 samples	3.00 2.36- 3.63	55 19- 116	1151 719- 1630	822 380- 1537	12 3- 35	21 10- 32	58 22- 97	4400 600- 10000	300 150- 500	140 80- 200
Dease Lake III 6 samples	2.99 2.81- 3.13	37 6- 62	582 212- 956	795 468- 1212	6 2- 15	21 11- 32	40 29- 50	2300 100- 10000	230 100- 350	120 80- 200

Note: The averages for nephrites from area II do not include the values for two greenish grey
specimens (#34, #35) as they are rare and contain anomalously low chromium and high titanium.

each element from each area, it is not possible to state that a nephrite

specimen with a given trace element content originated in a particular area.

The probable reason for the lack of regional variations is that the nephrites

from the three areas have formed in similar geologic environments.

However, on a much larger scale, the British Columbia nephrites are

distinguishable, by chromium content, from the Wyoming nephrites which have been

derived from amphibolites and are not associated with ultramafic rocks. The

average concentration of chromium in the former is 4000 ppm while in the latter

it is 30 ppm.

COLOUR OF NEPHRITES

The colour of nephrite is one of its most conspicuous physical properties

and is certainly its most valuable. The following discussion of the causes of

colour in silicate minerals is presented for this reason and is taken largely

from Burns (1970).

The majority of silicate minerals owe their colour to the presence, in

major or trace amounts, of transition metals such as titanium, vanadium,

chromium, manganese, iron, cobalt, nickel and copper or lanthanide elements.

The most common cause of colour is the absorption of radiation through electron-

ic processes and if such absorption is in the visible (4000 Å to 7000 Å) region

of the electromagnetic spectrum, colours are produced in transmitted and

reflected light. The two most important colour producing processes are internal

electron transitions within transition or lanthanide elements and inter-element electron transitions or charge transfer.

Internal electron transitions are produced through the absorption of light by excitation of electrons between d or f orbitals. The actual colours observed are determined by the position of the absorption bands and the intensity of the colours may be correlated with the band intensity. In ferrous iron compounds, absorption, by d electron transitions, of red radiation gives rise to the commonly observed green or blue-green colour.

Charge transfer or inter-element electron transitions occur when electrons migrate between neighbouring ions in a crystal structure. These processes are favored when transition metals can exist in two or more oxidation states, such as Fe^{+2} and Fe^{+3}, and are facilitated by local misbalance of charge accompanying isomorphous substitution by multivalent ions. Faye and Nickel (1970) state that the green hues of the calcic amphiboles are a direct consequence of the absorption of violet-blue light (O^{-2} - Fe^{+2} charge transfer) and red-orange light (Fe^{+2} - Fe^{+3} charge transfer). The complementary colours for violet-blue light and red-orange light are red-green, which appears yellow to the eye, and green-blue (Pauling, 1958; Monk, 1963), respectively. The combination of the two complementary colours produces green or yellow-green.

In the tremolite-actinolite series, it is probable that both electronic processes are operative to some degree. This is due to the presence of iron in

both divalent and trivalent states, although predominating in the former, and
to the occurrence of isomorphic substitutions such as $Si^{+4} = Al^{+3}$.

The colour of the majority (85%) of the British Columbia nephrites
examined is a hue of green with a distinct yellowish cast. This colour is due
to the presence of multivalent iron and is readily explained in terms of the
electronic processes outlined above. The cause of the colour of two anomalous
specimens, #34 and #35, from O'Ne-ell Creek is unknown. Both these specimens
have low chromium contents (100 ppm - 280 ppm), above average iron contents
(3.38% - 3.13%) and are a greenish grey colour (G.S.A. Rock Colour Chart); in
general terms, the specimens are grey with a very faint tint of green. The
lack of green colouration cannot be explained by the paucity of chromium
which is readily accounted for by the lack of picotite, chromite, uvarovite and
chlorite; in nephrites most of the chromium is contained in the aforementioned
accessory minerals. Another anomalous specimen, #19, is a dark blue green
colour and contains much higher than average cobalt (100 ppm) and higher than
average iron (3.38%). The probable cause of this colour is a strong charge
transfer of the type $Fe^{+2} - Fe^{+3}$, causing absorption in the red-orange part
of the spectrum giving rise to the complementary blue-green colour.

VI. THE O'NE-ELL CREEK NEPHRITE DEPOSIT

The O'Ne-ell Creek nephrite deposit is located in central British Columbia (Figure 1) near the south end of Takla Lake, approximately 130 air miles N 60° W from Prince George, B. C. Specifically, the showings are situated on the north side of O'Ne-ell Creek, at an elevation of 3400 feet, 3.5 miles upstream from its confluence with Middle River (Figure 10). Roads do not reach the property and access is either by air, generally a helicopter from Smithers or Fort St. James, or by boat from Fort St. James.

The deposit was discovered in 1968 by Mrs. W. Robertson. The original find was placer boulders which she traced upstream to the nephrite outcrop. Limited production, from alluvial boulders, took place in 1968 and in 1969, nephrite was produced from both the outcrop and the stream boulders. The property has been inactive since the end of the 1969 field season.

The following brief description of the regional geology is taken largely from Armstrong (1949) and Little (1949).

REGIONAL GEOLOGY

The rocks in the Takla Lake-Middle River area (Figure 10) range in age from Pennsylvanian or mid-Permian to Oligocene or later and comprise a great variety of sedimentary, volcanic and intrusive types. The bulk of the rocks exposed belong to four formations; the Pennsylvanian to Permian Cache Creek Group, the pre-Upper Triassic Trembleur intrusions, the Upper Triassic to Upper
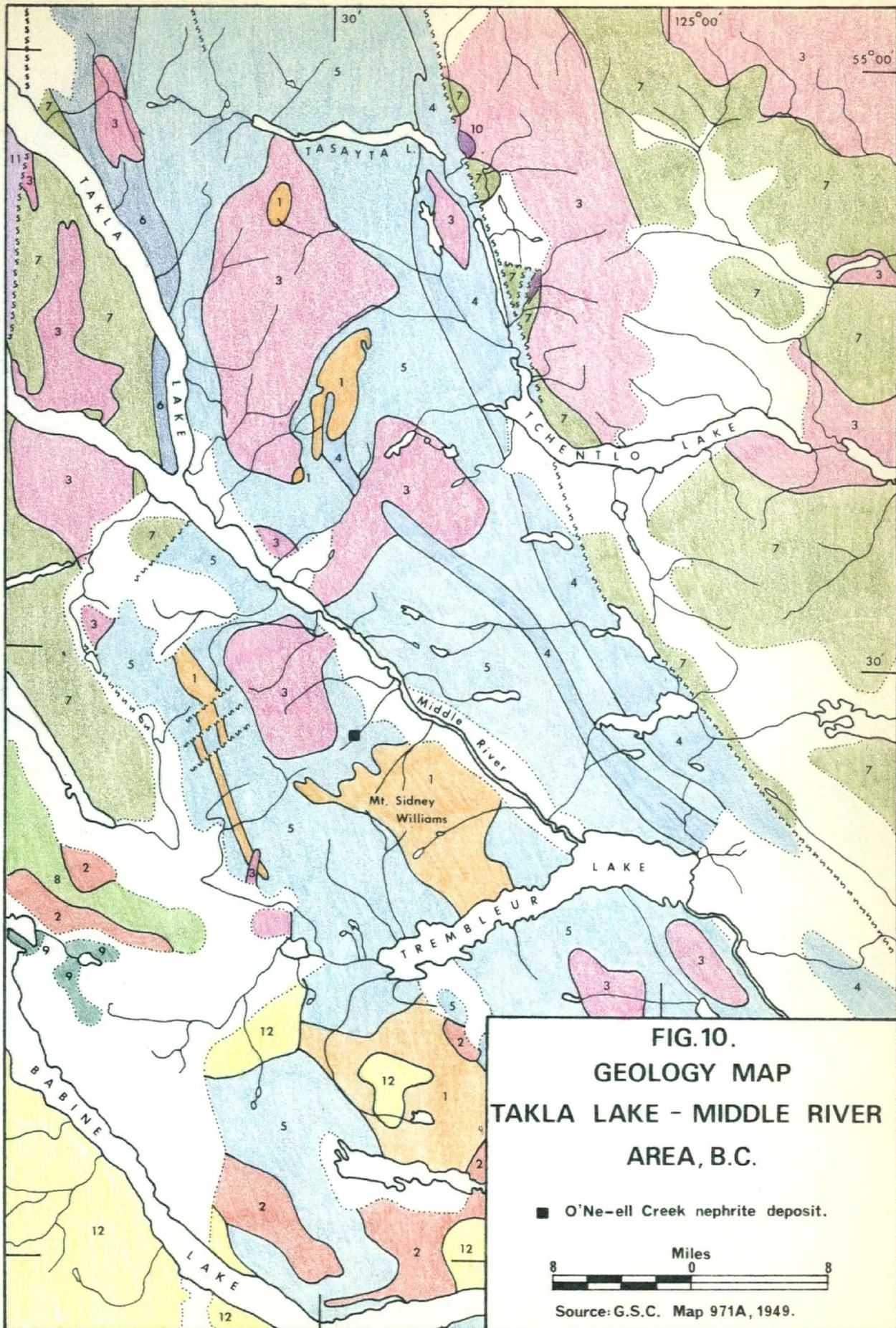
FIG. 10.
GEOLOGY MAP
TAKLA LAKE - MIDDLE RIVER
AREA, B.C.

■ O'Ne-ell Creek nephrite deposit.

Miles
8   0   8
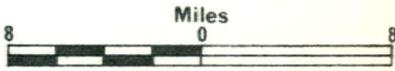
Source: G.S.C. Map 971A, 1949.

Fig.11. Legend for Fig.10.

SEDIMENTARY AND VOLCANIC ROCKS

TERTIARY
    OLIGOCENE OR LATER
        ENDAKO GROUP

| 12 | *Mainly vesicular and amygdaloidal basalt, andesite and dacite; flow breccia and agglomerate* |

CRETACEOUS OR LATER
    UPPER CRETACEOUS AND PALEOCENE
        SUSTUT GROUP

| 11 | *Conglomerate, shale, greywacke, and tuff* |

CRETACEOUS
    LOWER CRETACEOUS

| 10 | *USLIKA FORMATION: conglomerate; minor sandstone and shale* |

JURASSIC AND CRETACEOUS
        HAZELTON GROUP

| 9 | *Andesite, rhyolite, trachyte, basalt, and related breccia and tuff; minor argillite, arkose, sandstone, and limestone. May include some undifferentiated Triassic rocks* |

JURASSIC OR (?) CRETACEOUS
        TACHEK GROUP

| 8 | *Andesite and andesite breccia; basalt and rhyolite* |

TRIASSIC AND JURASSIC
    UPPER TRIASSIC AND LATER
        TAKLA GROUP

| 7 | *Andesitic and basaltic flows, tuffs, breccias, and agglomerate; interbedded conglomerate, shale, greywacke, limestone, and coal* |

CARBONIFEROUS (?) AND PERMIAN
    PENNSYLVANIAN (?) AND LATER
        CACHE CREEK GROUP

| 6 | *Andesitic flows, tuffs, and breccias, with minor basic intrusions (greenstone); chlorite and hornblende schists; minor argillite, chert, and limestone. May include some undifferentiated younger rocks* |

| 5 | *Ribbon chert, argillaceous quartzite, argillite, greenstone similar to 6, limestone; minor conglomerate and greywacke. Mainly younger than 4 and older than 6* |

| 4 | *Massive limestone; minor argillite, slate, chert, and greenstone; mainly older than 5 and 6* |

INTRUSIVE ROCKS

JURASSIC OR CRETACEOUS
    UPPER JURASSIC OR LOWER CRETACEOUS
        OMINECA INTRUSIONS

| 3 | *Granodiorite, quartz diorite, diorite; granite, syenite, gabbro, pyroxenite* |

JURASSIC
    TOPLEY INTRUSIONS

| 2 | *Granite and granodiorite syenite, diorite* |

PERMIAN (?) AND/OR LATER
    POST-MIDDLE PERMIAN, PRE-UPPER TRIASSIC (?)
        TREMBLEUR INTRUSIONS

| 1 | *Peridotite, dunite; minor pyroxenite and gabbro; serpentinized and steatitized equivalents.* |

Fault or fault zone (mainly inferred) .... ᴎᴎᴎᴎᴎᴎ

Jurassic Takla Group and the Upper Jurassic to Lower Cretaceous Omineca

intrusions. Rock units of lesser abundance are the sedimentary and volcanic

Tachek and Hazelton groups of Jurassic to Cretaceous age, the sedimentary Uslika

Formation of probable Lower Cretaceous age, the sedimentary Upper Cretaceous

Sustut Group, the volcanic Endako Group of Oligocene age and the Topley

granitic intrusions that were emplaced in Jurassic time.

The Cache Creek Group consists of a thick succession of steeply folded and

intensely faulted sediments, volcanics and derived metamorphic types that crop

out in the map area as a northwest trending belt up to 25 miles wide.

Foraminiferal limestones and ribbon cherts are characteristic of the group but

other rocks interbedded with them are argillite, slate, quartzite, tuff, breccia,

andesite and basalt. The andesite and basalt are largely altered to greenstone.

There are three major divisions; a lower group of massive recrystallized lime-

stone, a middle group of slate, argillite and ribbon chert, with minor limestone,

greenstone and related schists, and an upper group of greenstone, with lesser

argillite, slate and minor limestone. The sequence is not less than 22,000

feet thick. The metamorphic grade of these rocks is transitional between the

prehnite-pumpellyite metagreywacke facies and the greenschist facies (Monger

and Hutchison, 1971).

The Trembleur ultramafic intrusions are the oldest intrusive rocks present

in the map area and are confined to the Cache Creek Group. They consist of sills,

stocks and batholiths of peridotite, dunite and pyroxenite and their serpent-
inized equivalents. Included with these rocks is a minor amount of gabbro,
usually uralitized and saussuritized. Peridotite and dunite are the most
abundant rock types, the latter occurring as sills, as irregular zones or bands
between similar zones of peridotite in thick, undifferentiated sills or as
irregular masses in the Mount Sidney Williams batholith. All the ultramafic
rocks have been partially or completely altered to serpentine. Talc-carbonate
and lesser quartz-carbonate rocks are abundant; the former are marginal to
stocks and batholiths of peridotite and the latter predominate in zones of
shearing, faulting and fracturing. Along the contacts of serpentine and
siliceous sedimentary rocks, reaction zones have been formed, up to 100 feet
wide, that consist of talc, chlorite, actinolite-tremolite and carbonate.

Flanking the Cache Creek Group on the west and east is a conformable
succession of interbedded volcanic and sedimentary rocks known as the Takla
Group. It is at least 10,000 feet thick and in the lower part sediments and
volcanic tuffs predominate while in the upper part andesitic and basaltic flows
predominate. This rock unit, which unconformably overlies the Cache Creek
Group, has also been intensely folded and faulted.

The Omineca intrusions of Upper Jurassic or Lower Cretaceous age are
exposed in the map area in great abundance. They range in size from small sills
and dykes to batholiths and in composition from granite to pyroxenite, with

granodiorite predominating. Many of the bodies are elongated in a northwest direction. In the vicinity of O'Ne-ell Creek, the largest body is the stock immediately to the north. This stock consists of a core of grey soda granite surrounded by a border of pink granite and some syenite. Related acidic and basic dykes are fairly common.

The rocks of this area have been subjected to at least two periods of deformation, (Armstrong, 1949) one in Jurassic or early Cretaceous time and the other in post-Paleocene, probably Eocene time. It is probable that most of the major faults were formed during the latter disturbance.

GEOLOGY OF THE DEPOSIT

General Description

The nephrite in this deposit occurs as veins and lenses in a zone of foliated tremolite-chlorite rock developed at the contact between serpentinite of the Trembleur intrusions and cherts, quartzites and argillites of the Cache Creek Group (Figure 12).

In the map area, rocks of the Cache Creek Group consist of interbedded chert and quartzite with lesser argillite and minor greenstone, all of which are sheared and crumpled. The cherts and quartzites commonly contain wisps of argillaceous and graphitic material. Acicules and clots of radiating fibers of amphibole and patches of brown stilpnomelane are readily visible in hand specimens of the argillite. Often, the stilpnomelane forms rims around the clots of

amphibole. Individual beds are discontinuous and are not traceable from out-crop to outcrop. The general strike of the bedding is north to north-northwest; dips on the north side of the creek are 29° to 54° to the west and on the south side, 30° to 70° to the east.

The serpentinite is generally massive and granular although, locally, it is sheared and partially altered to talc, tremolite, carbonate or chlorite. The shape of the serpentinite body is unknown and unaltered ultramafic rocks such as peridotites and dunites are not observed. The contact between the serpentinite and the country rock is not seen at the surface but is expressed by outcrops of tremolite-chlorite rock. Yellowish orange weathering quartz-carbonate rock crops out along, and is displaced by, a vertical, east-west trending fault in the southern portion of the map area. Talc and talc-carbonate rocks are present at the contact between quartz-carbonate rock and serpentinite and in the tremolite-chlorite zones developed in the serpentinites at the con-tact with sedimentary rocks.

Foliated tremolite-chlorite rock commonly occurs along the contact between sediments and serpentinite; it is also present in shear zones in the serpenti-nite. Because of diamond drill hole information and the relatively good rock exposures brought about by brush clearing operations, the extent of the tremolite-chlorite rock is best known on the north side of the creek. In this area, these rocks occur in a zone at least 25 feet thick that dips, in the

vicinity of the drill holes, 15° to 30° to the northwest. The foliation of these rocks has a much steeper dip than does the zone in which they are contained. Slab-like inclusions of foliated, highly altered Cache Creek volcanic rock are present in the contact zone and in the adjacent serpentinite.

The largest mass of nephrite, and the only one exposed at the surface, is located on the north side of the creek, 40 feet southeast of diamond drill hole #5 (Plate 16). The nephrite exhibits a weak foliation which is parallel to that in the enclosing tremolite-chlorite rock. This body is 23 feet wide and has an average true thickness of 5 feet. Information obtained from the aforementioned drill hole indicates that the nephrite lens continues down dip for at least 30 feet but its thickness is decreased to 1.5 feet. One other vein of nephrite, 6 inches thick, was intersected by this hole and in hole #8, a vein 3 feet thick was intersected; in both cases the nephrite is foliated and should be termed a semi-nephrite. The nephrite in the outcrop contains numerous patches and streaks of picotite and, along fractures, lensoid segregations of greenish grey nephrite. These lensoid masses, which are up to 8 inches x 5 inches x 3 inches, have slickensided surfaces and when the enclosing nephrite is broken along the fracture, they are easily extracted. A light grey, scaly rind, up to 0.5 cm thick, is developed on weathered surfaces of the outcrop. The rind consists of tremolite, chlorite and iron and manganese hydroxides. Much of the chlorite is believed to be a weathering product of the tremolite. At the base of the
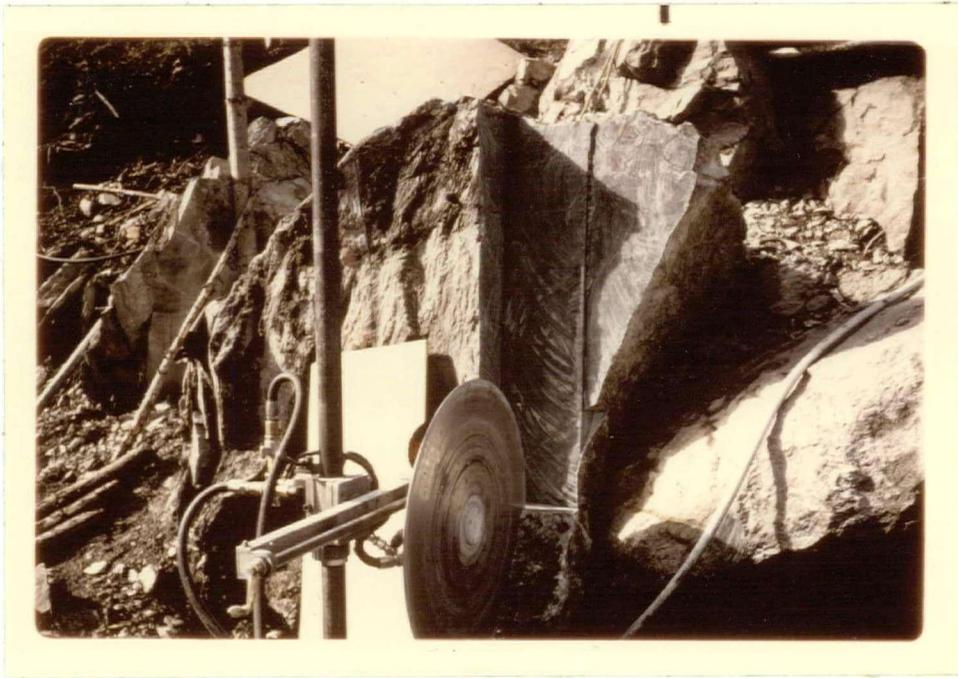
Plate 16: A portion of the nephrite outcrop at O'Ne-ell Creek. In this
deposit, the nephrite was removed from the outcrop by means of the
specially designed diamond saw shown in the foreground. The saw
blade is three feet in diameter.

nephrite outcrop, and resting on serpentinite, is a large slab of nephrite weighing approximately 150 tons. Undoubtedly, this slab was originally part of the above described nephrite body. Numerous boulders of tremolite-chlorite rock and semi-nephrite are present, in an area some 60 feet in diameter, approximately 30 feet southeast of hole #8. These have been derived, by weathering, from the band of similar rock intersected by this hole.

Across the creek from the nephrite showing is an outcrop of a dense, very tough, dark green rock composed largely of amphibole. It is situated between outcrops of quartz-carbonate rock and serpentinite but unfortunately, as contacts are not exposed, the relationship between these rocks is unknown.

Four varieties of dyke rock are present in the map area; these are porphyritic diabase, aplite, an amphibole-plagioclase rock and a porphyritic plagioclase-clinozoisite rock. The dykes are later than the Trembleur intrusions and may be related to the Omineca intrusions. With the exception of the aplite, these rocks exhibit chilled, fine-grained phases at contacts.

Three major directions of faulting have been recognized; east-west, northwest and northeast. All of the faults appear to be steeply dipping or vertical.

Lithology

Cache Creek Group

In hand specimen, the quartzites are light grey, have a fine sugary

texture and are cut by a reticulate network of quartz veins up to 2 mm wide. In thin section they are composed almost entirely of interlocking grains of quartz up to 0.1 mm in diameter. The larger quartz grains exhibit an undulose extinction. Also present are tremolite, in amounts up to 10 percent, and stilpnomelane, up to several percent. The tremolite, in colourless, hairlike fibers, occurs as tufts or "birds-nest" like aggregates (Plates 17, 18). The stilpnomelane occurs as irregular aggregates of minute plates and as fracture fillings.

The cherts are generally dark grey to black, have a very fine sugary texture and are cut by numerous veins of white quartz. Under the microscope, they are seen to consist essentially of interlocking grains of cryptocrystalline quartz. Stilpnomelane is present as fracture fillings.

The argillites are dark grey to black and weather to a yellowish or reddish orange colour. The lighter coloured specimens are quite siliceous while the darker rocks contain abundant graphite. Tremolite is present in both varieties but is especially conspicuous in the graphitic rocks where it occurs as bundles of radiating fibers in lenses and discontinuous veins. Stilpnomelane, in veinlets and patches, is visible in hand specimen. In thin section, these rocks consist essentially of quartz, albite and argillaceous material with variable amounts of tremolite, stilpnomelane, green biotite, muscovite and iron oxide (Plates 19, 20).

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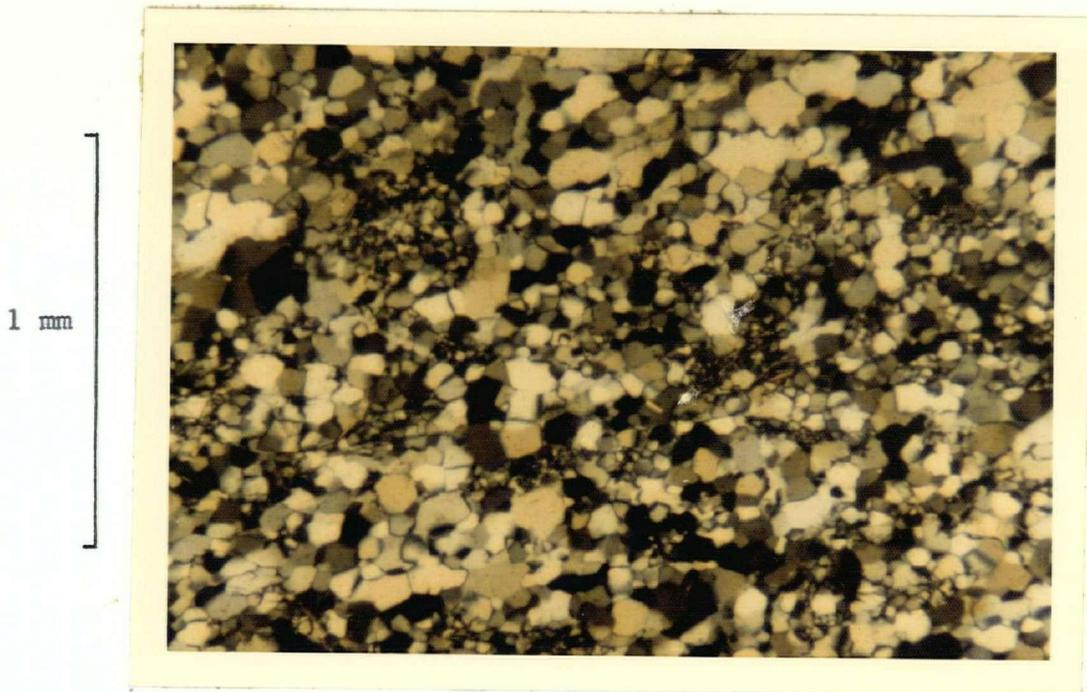
Plate 17:   Photomicrograph of a quartzite from O'Ne-ell Creek, crossed nicols.
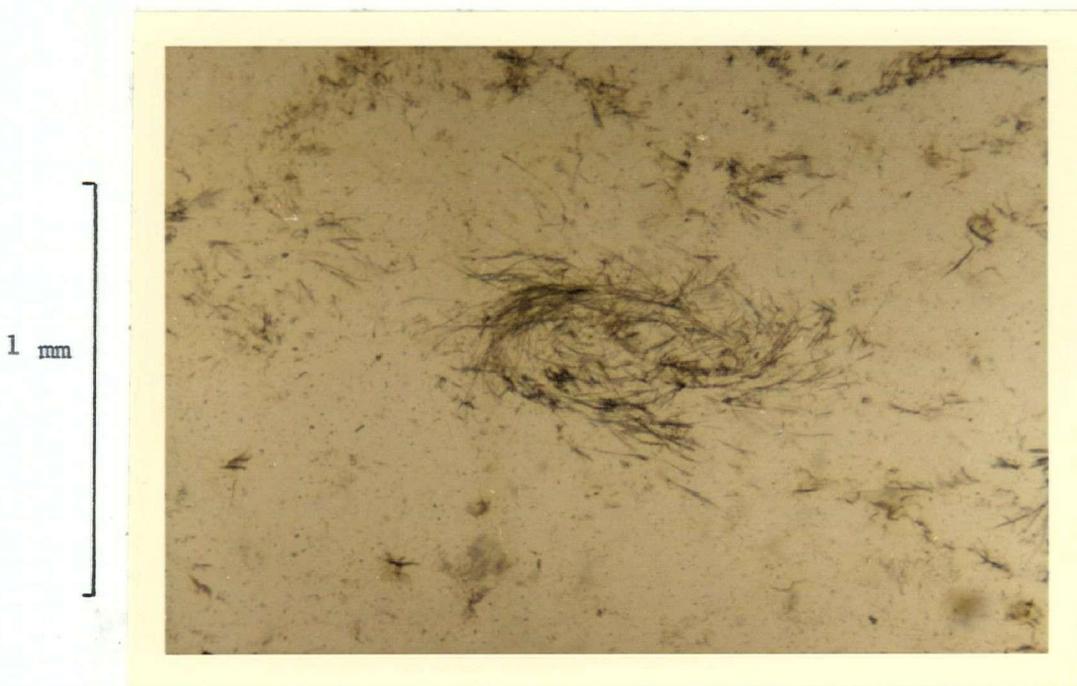
Plate 18:   Photomicrograph of "birds-nest"-like aggregate of tremolite fibers
            in a quartzite from O'Ne-ell Creek, plane polarized light.
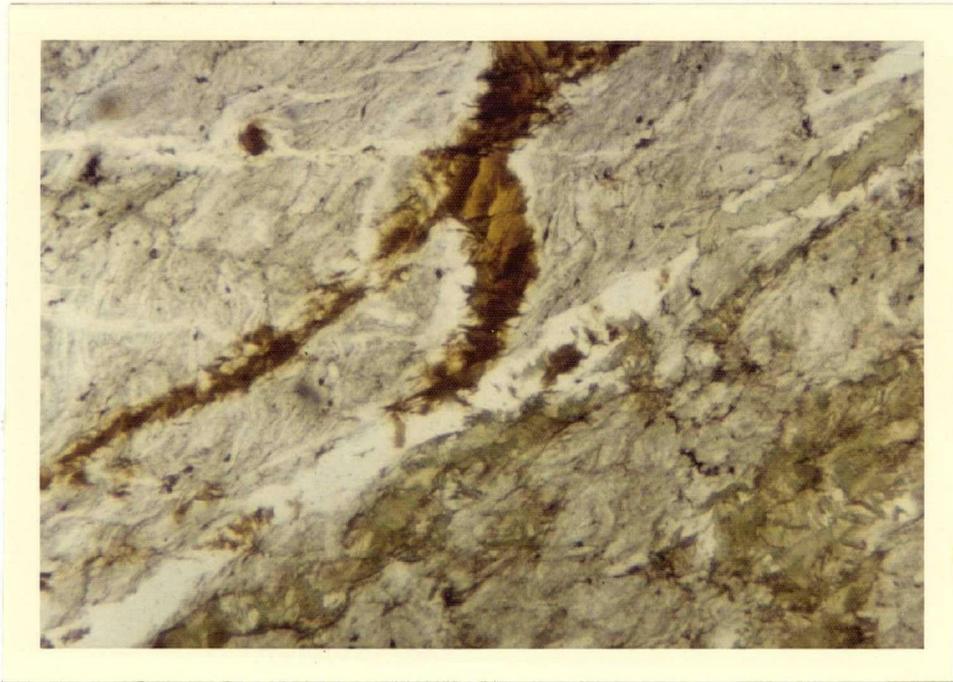
Plate 19: Photomicrograph of stilpnomelane (brown) and biotite (green) in
fractures in a siliceous argillite from O'Ne-ell Creek, plane
polarized light.

Plate 20: Photomicrograph of stilpnomelane (brown) and needles of tremolite in
an argillite from O'Ne-ell Creek, crossed nicols.

Slabs of Cache Creek greenstone contained in the contact zone near the nephrite outcrop are completely altered to a mixture of chlorite, zoisite, phlogopite and minor talc.

Trembleur Intrusions

The serpentinites are emerald green to black and, locally, weather to a yellowish orange colour. Most of the specimens are strongly magnetic and many contain veins of chrysotile, up to 0.5 cm wide, and patches and lenses of magnesite and talc. They consist almost entirely of antigorite, with a characteristic fibro-lamellar structure, (Plate 21) and lesser serpophite in irregular, almost structureless masses. Other minerals present are magnesite, talc, chlorite, chromite and magnetite. The latter mineral occurs in two forms; as opaque rims on grains of chrome spinel and as trains of grains, with carbonate, forming a mesh structure. Bastite serpentine or remnants of pyroxene were not observed.

When fresh, the quartz-carbonate rocks are medium greenish grey to bluish grey but upon weathering, they assume a conspicuous yellowish orange colour. They are weakly to strongly magnetic and are cut by a network of white quartz-carbonate veins. The largest veins are 6 to 8 inches wide, are open and drusy and consist of alternating layers of chalcedonic and coarsely crystalline quartz and minor carbonate. In thin section, veins and patches of magnesite and ankerite, comprising up to 75 percent of the rock, enclose irregular shaped

masses of cryptocrystalline quartz (Plate 22). Minor amounts of chlorite, talc, mariposite, chromite, magnetite and pyrite are also present. Locally, the mariposite is abundant enough to impart a brilliant green colour to the rock.

The talc-carbonate rocks are medium to dark green and contain up to 85 percent talc, and lesser amounts of magnesite, serpentine, either antigorite or serpophite, magnetite, chrome spinel and pyrite.

Hand specimens of the very fine grained, greenish grey tremolite-chlorite rock yield little information regarding their mineralogy. Under the microscope, they are seen to consist of tremolite, chlorite (penninite) and minor talc, carbonate and chrome spinel. The amount of tremolite contained in these rocks may reach 95 percent while in some specimens, chlorite may comprise 15 percent of the rock. The tremolite occurs as bundles of parallel to subparallel fibers set in a matrix of fine tufts, much in the manner of a semi-nephrite. The chlorite occurs in irregular, elongate patches and vein-like masses that are parallel to the foliation and in envelopes surrounding fractured grains of reddish-brown chrome spinel. Talc and carbonate occur in fine discontinuous veinlets.

The nephrite seen in the outcrop and in the alluvial boulders ranges from a non-schistose variety to a semi-nephrite not far removed from the tremolite-chlorite rock described above. The petrology and microstructure of the specimens from the deposit are described in Chapter III.

1 mm
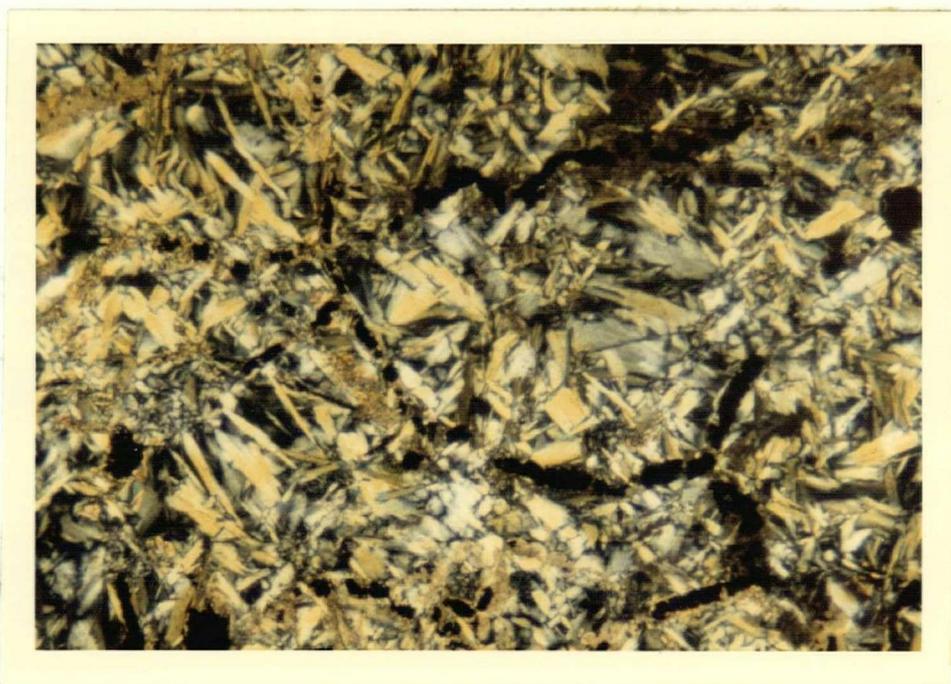
Plate 21: Photomicrograph of a serpentinite from O'Ne-ell Creek illustrating
the fibro-lamellar structure of the antigorite, crossed nicols.
Note also the mesh structure formed by magnetite grains.

1 mm
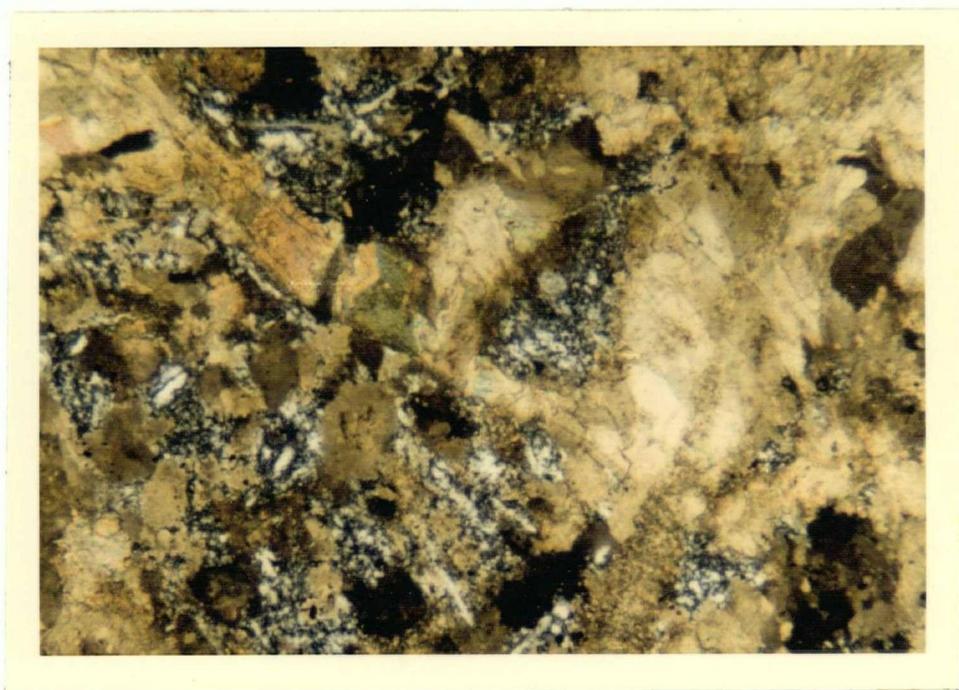
Plate 22: Photomicrograph of a quartz-carbonate rock from O'Ne-ell Creek,
crossed nicols.

Miscellaneous Rock Types

Amphibole-zoisite rock: The previously mentioned dense, tough dark green rock

of unknown association is seen, in thin section, to consist of 80 percent pale

green to colourless hornblende, 15 percent zoisite and 5 percent sphene, chlor-

ite and apatite. The hornblende occurs as large, ragged crystals, up to 3 mm

by 4 mm, that are altered to chlorite along cleavages. Interstitial to the

hornblende is a finer grained, interlocking aggregate of zoisite crystals.

Euhedral crystals of sphene are present in both the chloritized hornblende and

the zoisite.

Meta-diabase: The diabase is light olive grey, porphyritic and weathers to a

dark yellowish brown colour. Phenocrysts of feldspar, up to 1.5 mm x 3.0 mm,

comprise at least 1 percent of the rock. These are set in a finer grained

matrix containing abundant laths of feldspar with an average size of 0.1 mm x

0.5 mm. In the chilled selvages, which are 6 to 8 inches wide, the groundmass

is aphanitic. The feldspars, both the phenocrysts and the laths, consist of

"dusty" albite and contain granules of clinozoisite and scales of white mica.

A fine grained mixture of chlorite, clinozoisite, tremolite (?), quartz and

carbonate occupies the interstices between the laths. Rod-like to granular

opaques are disseminated throughout.

Albite-amphibole rock: This rock is greyish olive green, hypidiomorphic

granular and medium grained although fine-grained phases are observed at

contacts. It is composed essentially of albite (40 to 50 percent) and amphibole (40 to 50 percent). Chlorite (penninite), clinozoisite, sphene, carbonate and red iron oxide are also present. The amphibole grains have cores of pale brown to pale green hornblende and rims of pale green actinolite. The hornblende is altered along cleavages to chlorite. Granules of sphene are present in both the chlorite and the actinolite. The albite is interstitial to the amphibole grains and contains prisms and granules of clinozoisite and, occasionally, wisps of white mica. Quartzites in contact with this dyke rock are metasomatically altered, over a distance of one foot, with the formation of albite, carbonate, muscovite, tremolite, clinozoisite, chlorite, chalcopyrite and pyrrhotite.

Porphyritic albite-quartz-clinozoisite rock: In this rock type, phenocrysts of pinkish grey plagioclase, are contained in a fine grained, light greenish "speckled" matrix. The phenocrysts constitute up to 15 percent of the rock, range in size from 0.7 mm x 1.0 mm to 2.0 mm x 3.5 mm and have rather diffuse boundaries. In thin section the rock consists of quartz and albite (75 percent), chlorite (penninite), and clinozoisite (20 percent) and minor muscovite, sphene, and carbonate. The phenocrysts are albite and are set in a fine grained matrix consisting of quartz and albite. Prisms and granules of clinozoisite are present throughout the rock and are largest in the phenocrysts. The muscovite and the chlorite generally occur together in elongate, ragged aggregates.

Meta-aplite: Hand specimens of this rock are greyish pink, fine-grained and have a sugary texture. Under the microscope, the rock is seen to be composed of quartz and albite (90 percent), muscovite (5 percent), carbonate, pyrite and iron oxides. The albite occurs both as subhedral laths, up to 0.15 mm x 0.25 mm, and as fine anhedral grains, with quartz, in the matrix in which the laths are contained. Ragged shreds of muscovite that average less than 0.1 mm long are disseminated throughout the rock.

Summary

The nephrite at O'Ne-ell Creek occurs in a zone, 20 to 25 feet wide, of foliated tremolite-chlorite rock developed in serpentinite at the contact with quartzites, cherts and argillites of the Cache Creek Group. Contained within this zone are slabs of similarly foliated Cache Creek volcanic rock that have been altered to a mixture of zoisite and chlorite. Most of the nephrite from this deposit is classified as either schistose nephrite or semi-nephrite. The nephrite in outcrop exhibits a weak foliation which is parallel to that observed in the altered inclusions and in the enclosing tremolite-chlorite rock.

Serpentinite is the only ultramafic rock observed in the map-area. Related rocks, in addition to the nephrite and the foliated tremolite-chlorite rock, are talc and quartz-carbonate rocks; these are restricted to fault zones and contacts.

Four varieties of altered dyke rock are present; these are aplite,

porphyritic diabase, an amphibole-albite rock and a porphyritic albite-quartz-clinozoisite rock. These dykes are observed in the tremolite-chlorite zones but they are not foliated, suggesting that they post-date the formation of the nephrite.

The quartzites, cherts, and argillites adjacent to the serpentinite have been metasomatically altered. New minerals formed in the cherts and quartzites are tremolite and stilpnomelane; those in the argillites include tremolite, stilpnomelane, albite, green biotite and muscovite. These minerals have been observed in the sediments at distances up to 30 feet from the contact with the serpentinite.

PETROGENESIS

General Statement

Nephrite is often associated with serpentinized ultramafic rocks and usually occurs in the serpentinite at the contact with country rock, dykes or tectonic inclusions (Coleman, 1966; Coleman, 1967; Kolesnik, 1970). The rocks in contact with the serpentinite are metasomatically altered, usually with the formation of calcium silicates. Altered basic igneous rocks are characterized by the presence of hydrogrossular, which predominates, prehnite, idocrase, diopside, tremolite-actinolite and chlorite. The alteration of sedimentary rocks produces albite, potassium feldspar, fibrous tremolite-actinolite and prehnite. The serpentinites at the contacts are altered to rocks containing

actinolite-tremolite and chlorite. The alteration of the serpentinite and the inclusions, dykes and country rocks involves the movement of calcium and, in some cases, magnesium away from the serpentine, the movement of alkalis away from the contact into the country rock or inclusions and the movement of silica towards the serpentine. Rocks in the reaction zone generally have a higher specific gravity than the unaltered rocks and the altered sedimentary and igneous rocks generally contain more water than do the unaltered equivalents.

Coleman (1966) has described mineral zoning at the contact between serpentinite and metasomatized argillite and greywacke in New Zealand (Figure 13). At the contact, a monomineralic zone of actinolite-tremolite is developed. This zone may contain small amounts of prehnite, chlorite or diopside. Away from the contact, into the sediments, the amphibole zone gradually changes to an albite-amphibole rock characterized by the predominance of amphibole over albite. This amphibole-rich rock then changes to a hard, flinty albite-amphibole-quartz rock. Accessory minerals that may be present in the albite-amphibole zones are chlorite, diopside, prehnite and stilpnomelane. This zoning is very similar to the situation that occurs at O'Ne-ell Creek.

Origin of the Nephrite

The nephrite and the tremolite-chlorite rock have been formed by the metasomatic alteration of the serpentinite. This is suggested by the presence of chrome spinel in all three rock types, and by the similarity in the average

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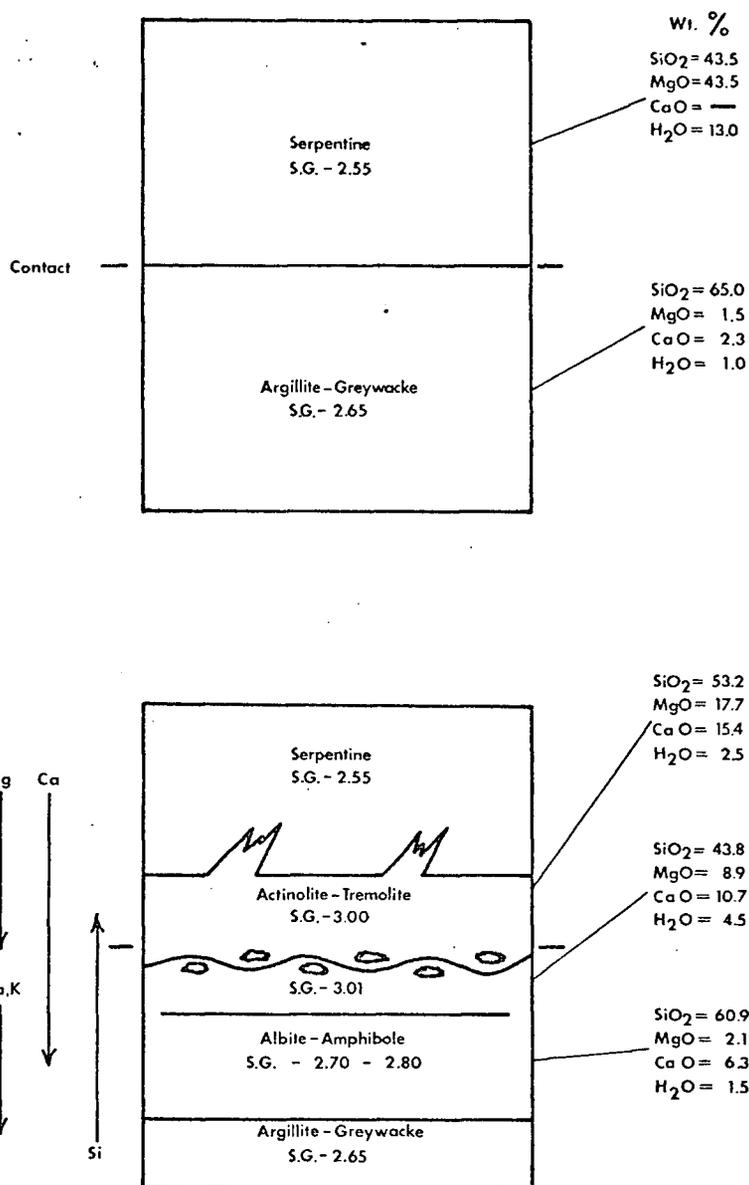
Fig.13. Diagrammatic representation of mineral zoning at the contact between serpentinite and metasomatized argillite and greywacke.(after Coleman,1966)

amounts of nickel, manganese, lead, zinc and chromium contained in the

nephrites and the serpentinites (Table 14).

Table 14

Average Iron and Trace Element Contents of Nephrite and Serpentinite from
O'Ne-ell Creek

	Fe %	Co ppm	Ni ppm	Mn ppm	Cu ppm	Pb ppm	Zn ppm	Cr ppm	Ti ppm	V ppm
Nephrite (5 samples)	3.17	57	1431	660	17	17	45	6100	285	126
Serpentinite (8 samples)	6.05	91	1597	680	35	20	34	5750	41	14

Note: The averages for nephrite do not include the values for two greenish
grey specimens (#34, #35) as they are rare and contain anomalously low
chromium and high titanium.

The metasomatic alteration of serpentinite is dependent upon the activities

of silica and calcium, (Coleman, 1967). An activity diagram showing the

stability fields of serpentine, diopside, tremolite and talc is presented in

Figure 14. Several assumptions are made concerning this diagram; the activity

of water is high and constant and the activity of magnesium is constant. Also,

temperature and pressure are constant but not specified. From the diagram, it

can be seen that if the activities of calcium and silica are increased, serp-

entine will react to form tremolite. A possible reaction of this type is given

below (Coleman, 1966).

$$5(3MgO \cdot 2SiO_2 \cdot 2H_2O) + 14\ SiO_2 + 6CaO \longrightarrow 3(2CaO \cdot 5MgO \cdot 8SiO_2 \cdot H_2O) + 7H_2O$$

chrysotile   added   tremolite   lost
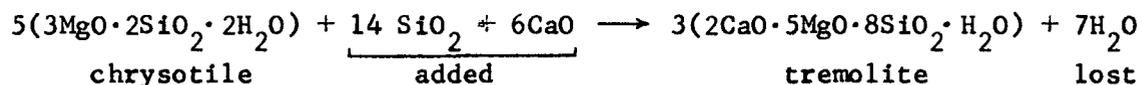
Temperature and pressure constant but not specified.
The activity of water is high and constant; the activity
of magnesium is constant.
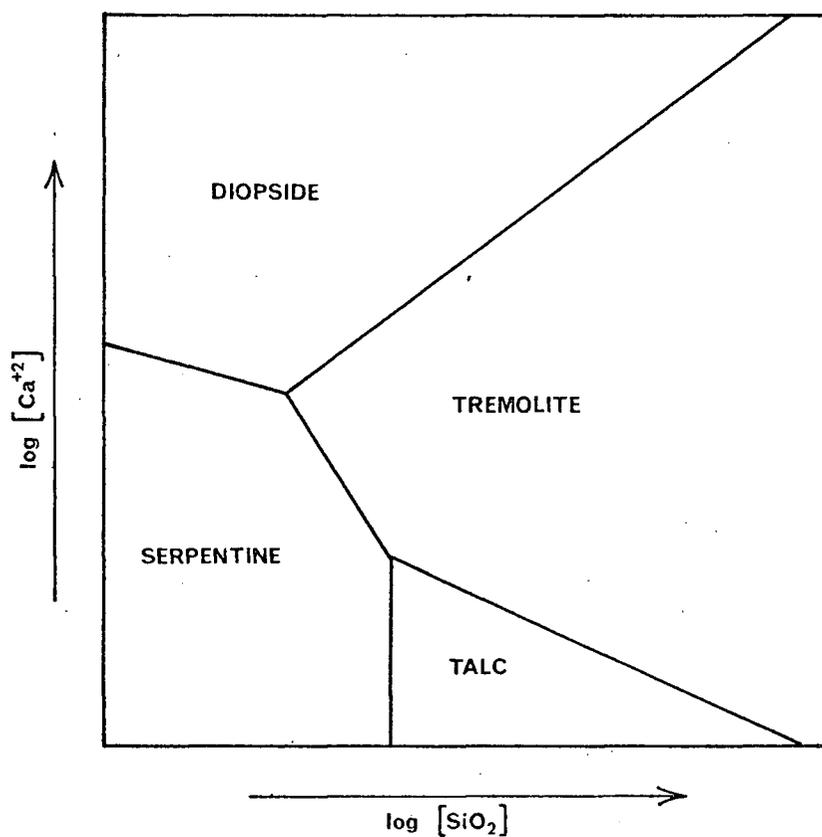
Fig.14. Ca(activity)−SiO₂(activity) for calcium and magnesium
silicates.(after Coleman,1967)

Coleman suggests that the serpentinite becomes unstable as silica moving towards the ultramafic body meets calcium migrating away, forming tremolite at the boundary. The products of this reaction have a smaller volume than the reactants ($\triangle V$ = 13 percent) and, hence, is favored by high pressure.

The source of the calcium is the pyroxenes that are altered during the process of serpentinization. The average CaO content for 23 peridotites and 19 dunites is 3.5 weight percent and 0.75 weight percent, respectively (Poldervaart, 1955). The average CaO content of 26 serpentinites investigated by Faust and Fahey (1962) is 0.08 weight percent. This considerable difference in the amount of CaO contained in peridotite-dunites and serpentinites indicates that calcium is liberated during serpentinization. Much of the calcium may combine with CO_2 to produce carbonate but some could migrate to contacts and raise the activity of calcium in the reaction zone.

The silica required for the reaction is readily obtained from the quartzites, cherts and argillites in the surrounding country rock.

The origin of the fine fibrous habit, characteristic of nephrite, is explained by Kolesnik (1970) in the following manner. Crystals of actinolite-tremolite have two types of faces with very different structures. One type of face corresponds to lattices made up of similar ions, that is a cation layer superimposed on an anion layer. The second type of face corresponds to lattices with a maximum total density of anions and cations. If the actinolite-tremolite

forms in an environment in which calcium and sodium are perfectly mobile, and magnesium, silicon, aluminum and iron are relatively inert, the crystal form is dependent upon the availability of ions. Under these conditions, growth of the faces corresponding to lattices made up of similar ions is hampered by the low mobility of magnesium, silicon, aluminum and iron. Faces corresponding to a lattice of maximum total density of ions grow more rapidly because they require fewer of the less mobile ions. The resulting amphiboles have a prismatic habit. Elongation along the c-axis is variable but is markedly higher for a high activity of calcium and, hence, prismatic forms give way to fine fibers.

Shearing stress has been considered to be the critical factor in producing the characteristic nephritic microstructure (Finlayson, 1909; Turner, 1935; Crippen, 1951) but recent studies by Kolesnik (1970) and Sherer (1969) suggest that this is not the case. Kolesnik reports that in many of the European and Siberian nephrite deposits, the tremolite fibers exhibit a preferential orientation that is perpendicular to the walls bounding the nephrite body. Sherer describes euhedral crystals of quartz in Wyoming nephrite; if shearing stress had been operative during the nephrite formation, the crystals would not have retained their form. The foliation observed in many specimens is a result of the environment in which most nephrite forms. The majority of occurrences are situated in alpine serpentinites at or near the contact with the enclosing rocks. The contacts of these serpentinite bodies are sheared and mylonitized

due to the tectonic events that followed the initial emplacement of the ultra-
mafic mass and continued during serpentinization. Reaction rocks formed at the
contacts, including nephrite, are usually involved in these tectonic movements
and, as a result, are foliated and brecciated.

The foliation in the tremolite contact rocks at O'Ne-ell Creek has
provided channel-ways for the migration of the aluminum bearing solutions that
have caused the partial alteration of the tremolite to chlorite. The source of
the solutions is either the dyke rocks or the ultramafic body.

Temperature and Pressure Conditions

At O'Ne-ell Creek, the tremolite-chlorite rock containing the nephrite is
in direct contact with serpentinite. In other nephrite deposits associated
with ultramafic rocks the metasomatites are always in contact with or are
surrounded by serpentinite. Such rocks in contact with unserpentinized ultra-
mafic rocks have not been reported. This suggests that the metasomatic
reactions take place at temperatures below the breakdown of olivine and/or
pyroxene to serpentine. Bowen and Tuttle (1949) have determined that, at a
pressure of 1 kilobar, pure magnesium serpentine cannot exist at temperatures
above $500^\circ C$; at higher pressures the breakdown temperature increases only a few
degrees.

In New Zealand, semi-nephrite often occurs at the contact between serpen-
tine and hydrogrossular bearing inclusions of altered gabbro (Coleman, 1966).

The temperature of formation of the garnet has been determined by Coleman (1967), on the basis of the relative hydration state, to range from 290°C to 450°C. Although hydrogrossular was not observed at O'Ne-ell Creek, the presence of this mineral in other nephrite occurrences also suggests that the metasomatism takes place in the temperature range where serpentine is stable.

Minerals, such as aragonite or jadeite, that could be used to estimate the pressure during metasomatism were not observed in the O'Ne-ell Creek deposit. Because of the general increase in the density of the rocks in the reaction zones and the substantial water content of the metasomatized country rock, Coleman (1967) postulates that the total pressure is high, probably in excess of 4000 bars, and that the water pressures are nearly equal to the total pressure.

VII. CONCLUSIONS

In British Columbia, deposits of nephrite are closely associated with a belt of alpine ultramafic rocks that extends for 1000 miles from the Hope area, east of Vancouver, northwestward to the Yukon border.

The nephrite from these deposits contains, in addition to essential tremolite, small amounts of chlorite, uvarovite, chrome spinel, diopside, talc, carbonate, sphene, phlogopite and pyrite. The felted and twisted nature of the component tremolite fibers accounts for the high hardness and extreme toughness of nephrite. Iron, which is present in both the divalent and trivalent states, is responsible for the yellowish green colour observed in most specimens.

The average amounts of iron, cobalt, manganese, copper, lead, zinc, and vanadium contained in the nephrites do not exhibit regional variations when the samples are grouped according to area of origin; slight variations are observed in the average contents of nickel, chromium and titanium. The general similarity of the regional average values for these elements suggests that the nephrites have been formed in similar environments. This assumption is supported by the constant association of nephrite deposits with alpine ultramafic rocks.

At the O'Ne-ell Creek deposit, the nephrite has resulted from the metasomatic alteration, by the addition of calcium and silica, of serpentine during the process of serpentinization. The source of the calcium was the pyroxenes

contained in the original ultramafic rock; the source of the silica was the sediments enclosing the ultramafic body. High concentrations of calcium and magnesium and relatively low concentrations of sodium, iron, aluminum and silicon characterized the environment in which the nephrite formed. Calcium and sodium were perfectly mobile while magnesium, iron, aluminum and silicon were relatively inert. These conditions of mobility and concentration account for the fine fibrous habit of the nephritic tremolite. Shearing stress is not considered to be the critical factor in producing the nephritic microstructure. A temperature range of approximately $300^{\circ}C$ to $500^{\circ}C$ and a pressure in excess of 4 kilobars are suggested for the formation of nephrite.

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APPENDIX I

SURVEY OF WORLD DEPOSITS

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SURVEY OF WORLD DEPOSITS

EUROPE

Switzerland

Small deposits of nephrite are known at Salux (Welter, 1911), Val de

Faller (Welter, 1911), Poschiavo, Canton Graubunden (Schmidt, 1917; Staub,

1925), Hauderes, Valais Canton (Preiswerk, 1926) and in the Gotthard Range

(Schneider, 1912).

The deposits at Salux, Val de Faller and Hauderes occur at the contact

between spilites or saussuritized gabbro and serpentine. The nephrite is

usually schistose and partially altered to chlorite. At Salux, it contains

garnet, picotite and magnetite. In the Gotthard Range and at Poschiavo, the

nephrite occurs as lenses and veins in serpentine.

East Germany

Rimann (1938) describes small bodies of nephrite and fibrous diopside

(carcaro) formed in a transition zone between Paleozoic sediments and

serpentinized picrites in the Thuringian Hills area.

At Koleborn in the Harz (Uhlig, 1910; Rose and Fromme, 1932), nephrite

occurs at the contact between a partly serpentinized harzburgite and

inclusions of chloritized, tremolitized and prehnitized hornblende gabbro.

The nephrite is associated with fibrous diopside and forms as vein-like to

lenticular bodies 20 to 30 cm. thick.

West Germany

Near Frankenwalde, Bavaria (Welter, 1911) sheared and chloritized lenses of nephrite are present at the contact between saussuritized gabbro and serpentinite.

Poland

Deposits of nephrite are known at Jordanow and Zloty Stok, in southwest Poland (Gawel, 1949; Heflik, 1968). At Jordanow, the large deposit of nephrite is situated in lenses of white altered rock between the Sobotka gabbro massif and serpentinite. The altered rock consists of albite, hornblende, garnet, epidote, zoisite, quartz, prehnite and biotite and is considered to be the result of the calcium metasomatism of the gabbro (Kolesnik, 1970). The partially serpentinized and chloritized nephrite contains numerous small spindle shaped crystals of diopside that are locally replaced by coarse grained, colourless tremolite. Often present in the nephrite are fine grains of sulphides, arsenides, hematite and magnetite. No information is available on the deposit at Zloty Stok.

Italy

The largest European deposit of nephrite is situated in northern Italy between Sestri Levanto and Monterosso (Kalkowsky, 1909). In this area flysch deposits contain large massifs of serpentinite with subordinate gabbro. The

nephrite occurs as lenses and vein-like bodies in the serpentine and at the serpentine-gabbro contacts. Accessory minerals observed in the nephrite include garnet, picotite, magnetite, hematite, iron hydroxides, apatite, sphene and spindle-shaped diopside crystals which locally merge to form carcaro. Also present are relicts of diallage. The nephrite is almost always somewhat sheared with the development of chlorite and carbonate.

Union of Soviet Socialist Republics

Nephrite deposits are known in two widely separated areas in the Soviet Union; in the southern Urals near the village of Kundrava and in Siberia in the East Sayan Mountains, east of Lake Baikal (Kolesnik, 1970).

In the southern Urals, the nephrite occurs in a gabbro massif surrounded by serpentinite. The gabbro is altered to an aggregate of zoisite, albite and hornblende and contains relicts of diopside and saussurite. The nephrite, which is slightly chloritized and replaced by acicules of broad prismatic tremolite is in contact with a zoisite-bearing diopside rock.

Two similar nephrite deposits are known in the East Sayan Mountains, one in the watershed of the Khusha-Gol and Ilchir Rivers and the other is situated in the upper course of the Khara-Zhalga River, approximately 40 km northwest of the aforementioned deposit. The former deposit, the larger of the two, is associated with serpentinites of the Ospinsk-Kitoy ultrabasic massif that have been intruded by gabbros and diorites. These basic rocks and the adjacent

ultrabasic rocks have been metasomatically altered to garnetite and rodingite-type calcium-silicate rocks and varieties of albitites. Veins and lenses of nephrite are developed along the contact between the serpentinites and the altered basic rocks. In the Khara-Zhalga deposit, nephrite occurs at the contact between albitite and serpentinized peridotites. The albitite in this deposit is thought to have been derived from a gabbro.

An unusual feature of the Siberian nephrites is the presence of inclusions of graphite, a mineral not recorded as occurring in nephrites from other localities.

The Khara-Zhalga deposit contains 3 to 4 tons of low grade nephrite while the Ospinsk-Kitoy deposit has reserves of approximately 100 tons.

ASIA

Peoples Republic of China

The nephrite deposits of Chinese Turkistan in western China have been known since ancient times, at least since the Han dynasty (206 B.C. - A.D. 220) (Palmer, 1967). The deposits are situated on the northern and southern slopes of the K'un Lun Mountains. On the northern slopes, the area of outcrops and boulders extends from the valley of the Yarkand River to Lake Lop Nor (Kolesnik, 1970). In one deposit, on the Lyushtag River, the nephrite occurs in diabase and gabbro that have been intruded into Devonian shales, sandstone and syenite. Near the nephrite, individual zones of serpentine, wollastonite,

epidote and calcite are developed. Surrounding the nephrite body is a zone

composed of serpentine, radial hornblende, wollastonite, calcite, augite and

pyrite. The deposits on the Kara-Kash or Black Jade River, a tributary of the

Yarkand River, consist of small bodies of nephrite bearing greenstone

contained in mica schists. The nephrite bodies are surrounded by a zone of

friable talc.

Taiwan

The only known deposit of nephrite is located in eastern Taiwan, near

Fengtien, in the province of Hualien (Huang, 1966). The nephrite, which is

slightly schistose, occurs with asbestos and talc in serpentinized peridotite

and pyroxenite sills near the contact with graphite schists. Accessory minerals

in the nephrite are picotite, chromite, magnetite, chlorite, and chrome garnet.

Japan

Greenish blue nephrite has been observed in amphibolite with prehnite,

calcite and feldspar at Hakuba-mura, Nagano Prefecture, Japan (Yoshimura et al,

1966).

West Pakistan

Two pebbles of good quality nephrite have been reported from the bed of the

Teri-Toi River near Kohat in West Pakistan (Butler, 1963). Butler suggests

that the pebbles have been derived from late Pliocene to Pleistocene conglomer-

ates that occur in the southeastern part of the Teri-Toi basin.

AFRICA

Nyasaland

Nephrite, with coarse tremolite and actinolite, occurs in association with amphibolites in a serpentinized peridotite at Chimwadzulu Hill, southern Nyasaland (Bloomfield, 1958). Bloomfield believes that the amphibolites have been derived from pyroxenites and that the tremolite-nephrite-actinolite rocks have been formed directly from the amphibolite by retrograde metamorphism accompanied by metasomatism and shearing stress.

Rhodesia

Good quality nephrite has been found in the Mashaba area (Anderson, 1961) approximately 35 miles west of Fort Victoria. The nephrite occurs in Precambrian serpentinites that have been altered to talc schists and talc-carbonate rocks.

OCEANIA

Australia

Two nephrite localities are known in Australia, both in eastern New South Wales, one at Lucknow and the other near Nundle, east of the Dungowan Dam (Chalmers, 1967). At Lucknow, poor quality nephrite occurs at the contact between serpentine and andesite. The nephrite from Nundle is dark bluish green and is associated with silicified serpentine.

New Zealand

Nephrite has been known and used in New Zealand for at least 1000 years (Beck, 1970). It was used extensively by the Maori tribes for the fashioning of tools, weapons and decorative objects and was even used as currency. To date, commercially viable "in situ" deposits have not been found and present production is from placer deposits formed in streams draining the ultramafic rocks of the South Island.

A number of small occurrences of poor quality nephritic material have been reported in the literature. In the Griffin Range area, Westland, nephritic amphibole is reported to occur as nodules and veins in a serpentine-talc-carbonate rock (Finlayson, 1909; Coleman, 1966). In the Wakatipu Lake area of northwest Otago, semi-nephrite occurs in serpentine, in association with talc and actinolite-tremolite, near the contact with the enclosing greywackes and schists (Turner, 1935; Coleman, 1966). Coleman mentions the numerous occurrences of semi-nephritic amphibole along the borders of rodingites, tectonic inclusions and at serpentine-country rock contacts. These amphibole segregations also occur as veins extending into the serpentinite.

Turner (1935) has studied the petrology of a number of nephrite specimens from Otago and South Canterbury, South Island. In addition to tremolite, the major constituent, these specimens contained accessory amounts of chlorite, serpentine, garnet, diopside, chromite and picotite.

NORTH AMERICA

United States of America

Alaska

Large "in situ" and placer deposits of nephrite are located on the northern side of the Kobuk River in northwestern Alaska, north of the Arctic Circle (Anderson, 1945). These deposits occur over a distance of approximately 35 miles between Jade Mountain and the Kogoluktuk River, a tributary of the Kobuk River. The Eskimos have known and made use of the nephrite from this area for at least several hundred years; the deposits were discovered by white men in 1898. The nephrite, some of which is of excellent quality, occurs in veins and lenses in serpentinized peridotites in association with chrysotile asbestos and fibrous tremolite. The ultramafic rocks are enclosed by schists and limestone. The constant association of nephrite and asbestos prompted the original placer miners in the area to give the name "asbestos rock" to nephrite boulders observed in the creeks.

California

Nephrite deposits have been reported in nine counties; the largest and best described deposits are in Marin, Monterey, Mariposa and Mendocino Counties.

The deposit in Marin County (Chesterman, 1951) is located on the east side of Massa Hill, 5 miles southwest of Petaluma, California. The nephrite occurs as short lenses and veins, up to 6 inches wide and several feet long, in sheared

and massive serpentine near the contact with albite-clinozoisite-muscovite schist. Both the schist and the serpentine belong to the Upper Jurassic to Upper Cretaceous Franciscan Group. The veins and lenses of nephrite cut narrow veins containing a mixture of actinolite, talc and chrysotile.

In southern Monterey County pebbles and boulders of nephrite are found on beaches adjacent to bedrock occurrences of nephrite near Cape San Martin, midway between Monterey and Morro Bay (Crippen, 1951; Coleman, 1967). At the Plaskett-Jade Cove deposit, the nephrite occurs as a large lens, with an apparent width of ten feet, and a number of smaller pods in sheared and recrystallized sediments near the contact with a sill of serpentinized peridotite. The altered sediments consist of albite, quartz and tremolite, and locally, are replaced by talc. The nephrite is of poor quality, with a flaky or schistose structure, and is termed a semi-nephrite. Both the serpentinite and the sediments are assigned to the Upper Jurassic to Upper Cretaceous Franciscan Group. At Cape San Martin, approximately two miles south of Jade Cove, massive and botryoidal nephrite occurs at the contact between serpentinite and a large inclusion of greywacke and shale. At the contact, over a width of 2 feet, the greywacke is altered to a light grey calcium metasomatite consisting predominantly of prehnite and varying amounts of diopside and actinolite. Good quality nephrite is reported to occur both in serpentine and in beach deposits between Point Sur and the Salmon Creek Ranger Station (Rogers, 1940). Beaches

near Cambria Pines, San Simeon Creek and Salmon Creek are reported to yield

pebbles of nephrite (Sinkankas, 1966).

A number of "in situ" nephrite occurrences are located north of the town

of Bagby in Mariposa County (Evans, 1966). The nephrite is generally found in

irregularly shaped, discontinuous bodies of talc-rich rock contained entirely

within serpentine or along the contacts between serpentine and country rocks or

dykes.

At Leech Lake Mountain in Mendocino County, approximately 12 miles north-

east of Covelo, nephrite occurs as irregular bodies and veins in serpentine

sills and at the contact between the serpentine and greywacke (Chesterman, 1952).

The nephrite is associated with idocrase, hydrogrossular, pectolite and a

diopsidic pyroxene. The greywacke adjacent to the serpentine is weakly meta-

morphosed to a dark-grey, dense, hard rock and contains round grains of

glaucophane rimmed hornblende.

Nephrite has also been found in Santa Barbara, Siskiyou, Trinity, Tulare,

and Eldorado Counties (Murdock and Webb, 1959; Sinkankas, 1967). The nephrite

in Tulare County occurs in serpentine at Lewis Hill, 2 miles north of Porter-

ville.

Oregon

Lenses and stringers of nephrite occur in serpentine underlying Sugarloaf

Peak in Curry County, southeastern Oregon (Sinkankas, 1967).

Washington

Boulders of nephrite have been reported from an undisclosed locality near Darrington (McLeod, 1968; p. c. Danner, 1972). The description of the boulders occurring in a "jumble of soil and countryrock" suggests a nearby source.

Wyoming

A number of nephrite deposits are known in the Precambrian rocks of the Granite, Seminoe and Laramie Mountains, Wyoming (Sherer, 1969). In the Granite Mountains, the deposits are found associated with amphibolite inclusions in a quartzofeldspathic gneiss of quartz diorite composition. Those in the Laramie Mountains occur where quartz veins are emplaced in orthoamphibolite dykes. Deposits in the Seminoe Mountains are associated with amphibolite inclusions contained in quartz diorite and amphibolite dykes that are cut by quartz veins. In all deposits, epidote and clinozoisite are abundant in the immediate vicinity of the nephrite.

Canada

Only three occurrences of nephrite are known outside of British Columbia and all are located in northern Canada.

Yukon Territory

Nephrite pebbles have been found in the gravels of the Lewes River, the best specimens being obtained near Miles Canyon, about 4 miles south of

Whitehorse (Dawson, 1887). Specimens of apple-green nephrite have been report-

ed from the mountain slope east of the south end of Klukshu Lake, south of

Dezadeash Lake (Kindle, 1952).

Northwest Territories

On the Rae River, near the Coronation Gulf, nephrite is reported to occur

in a deposit of soapstone (Wilson, 1926).

CENTRAL AND SOUTH AMERICA

Nephrite has not been found in either Mexico or Central America although

jadeite was used extensively for carving by the native races of this area prior

to the Spanish conquest in the early sixteenth century (Palmer, 1967). In

South America, the only country in which nephrite artifacts or deposits have

been found is Brazil (Washington, 1922). Nephrite deposits, both in place and

placer, and numerous nephrite artifacts are found in Amargoza, in the state of

Bahia. Geological information regarding the nephrite deposits is not available.

APPENDIX II

DETERMINATIVE METHODS

APPENDIX II

DETERMINATIVE METHODS

Vickers Hardness Number Determinations

The nephrite samples were prepared in the following manner:

1. A small slab, approximately ½ inches x ½ inches x 1/8 inches was ground

    flat with #240 carborundum powder on an iron lap.

2. The specimen was hot mounted in a bakelite briquette measuring 1¼ inches in

    diameter by an average of ½ inches thick.

3. The mounted sample was ground with #600 carborundum powder on an iron lap

    for 1 minute.

4. This was followed by 1 minute of grinding with #950 carborundum on a glass

    plate and then by 1 minute of rough polishing with the same abrasive on a

    high-speed rubber-faced lap.

5. The final polish was imparted with tin oxide on a high-speed lap surfaced

    with felt.

The instrument used for the hardness determinations is a Leitz Mini-load

Pol Hardness Tester equipped with a built in analyser and a rotating polarizer.

This instrument employs a diamond-tipped indenter that is allowed to fall onto

the specimen under a given load over a set period of time; in this study the

load was 15 grams and the period approximately 20 seconds. The diamond tip of

the indenter is a square pyramid with a 136° included angle between opposite

faces. This produces a square pit, the diagonals of which are seven times the depth of penetration. The instrument was calibrated against a steel plate having a hardness of 625 Kg/mm^2.

Each sample was indented five times; for each indentation, the hardness was calculated from the average diagonal length using the following equation taken from the instruction manual for this instrument:

$$\text{Vickers hardness number} = \frac{(1854.4)(P)}{d^2}$$

where P = load = 15 grams
        d = average diagonal length in μm.

A correction factor was applied to each hardness and an average hardness calculated for each specimen.

Unit Cell Parameter Calculations

Four x-ray diffraction records, two up scan and two down scan, were obtained for each of the nephrite samples investigated. The records were obtained with a Philips X-ray diffractometer using nickel filtered CuK_α radiation. The scan speed was 1° 2θ /minute and the chart speed was 120 cm/hour. Quartz was used as an internal standard. The average interplaner spacings of the following reflections were used in the calculations: (110), (130), (001), ($\bar{1}$11), (040), ($\bar{1}$31), (240), (310), ($\bar{1}$51), (151), ($\bar{1}$12), (061), ($\bar{2}$02) and (002). The parameter computations were done on the I.B.M. 360 computer at the University of British Columbia; the program is one devised by Evans, Appelman and Handwerker (1963). Data for the parameter card was obtained from A.S.T.M.

card #13 - 437 (tremolite).

Chemical Analyses

Crushing and Grinding

Small pieces of each of the 31 nephrite specimens analysed were crushed

with a hammer on a steel plate. The crushed fragments were hand picked to

eliminate any visible iron contamination. A tungsten carbide lined grinding

vial containing a tungsten carbide ball was used to reduce the crushed material

to a -100 mesh powder. The grinding time for each sample was 15 minutes. Both

the vial and the ball are manufactured by Spex Industries, Inc., New Jersey.

The serpentine specimens and the weathered nephrite specimens were crushed

in the manner described above but were reduced to powder, by hand, in a mullite

mortar. Four nephrite specimens were also ground in a mullite mortar in order

to provide a correction factor for cobalt contamination introduced by the

tungsten carbide vial.

Atomic Absorption Analysis (Fe,Co,Ni,Cu,Pb,Zn)

The powdered samples were decomposed in a teflon dish using a perchloric

acid-hydrofluoric acid digestion. The sample weight was 0.4 grams. To ensure

complete digestion of the powders, each sample was treated with the acid mixture

twice. The procedure followed is given below:

1. To each powdered sample, 3 ml of distilled water, 5 ml of hydrofluoric acid

   and 0.5 ml of perchloric acid were added. This mixture was allowed to

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evaporate to dryness at 180° C. This process was repeated twice.

2. The digestion residue was cooled and dissolved in 3 ml of distilled water

    and 3 ml of concentrated hydrochloric acid. This solution was transferred

    to a 25 ml volumetric flask and was made up to the mark with distilled

    water. The final solutions were stored in polythene bottles.

3. A blank solution containing only the reagents was prepared for each batch

    of samples dissolved.

The samples were analysed for iron, manganese, copper and zinc with a

Techtron AA-4 atomic absorption spectrophotometer. A Perkin-Elmer 303 atomic

absorption spectrophotometer was used for the cobalt, nickel and lead analyses.

The Perkin-Elmer instrument was equipped with a hydrogen lamp to simultaneous-

ly correct for background absorption.

The standards used were prepared by the Department of Geology, University

of British Columbia.

<p style="text-align:center">Spectrographic Analysis (Cr,Ti,V)</p>

For the spectrographic analyses, 0.10 gram of each sample was weighed and

placed in a small plastic vial with 0.10 gram of graphite containing 30 ppm

indium. The graphite-indium mixture was used as an internal standard for the

spectrograph. After agitation to ensure thorough mixing of the sample and the

indium bearing graphite, the prepared samples were placed in cup electrodes and

analysed in a Hilger Automatic Quartz Spectrograph. Spex Mix (Spex Catalogue

#1000) diluted to the approximate concentration of the elements being detected

was used as a standard. The spectrographic plates were read on an ARL Spectro-

line Scanner. Both the analyses and the plate readings were performed by

Mr. David Marshall of the Department of Geology, University of British Columbia.

Correction for Cobalt Contamination

The four nephrite samples ground by hand in the mullite mortar were found

to contain an average of 34 ppm less cobalt than the corresponding samples

ground in the tungsten carbide vial. The cobalt contents of the nephrite

specimens were reduced by this amount. This figure is in good agreement with

the 32 ppm obtained by Thompson and Bankston (1970) for the cobalt contamina-

tion of pure quartz when ground in a similar vial.

APPENDIX III

NEPHRITE ANALYSES OBTAINED FROM THE LITERATURE

APPENDIX III

Nephrite Analyses Obtained from the Literature

	1	2	3	4	5	6	7	8	9
SiO_2	58.14	57.78	56.41	56.63	56.73	57.35	57.38	56.55	55.99
TiO_2	--	--	--	--	--	--	--	--	--
Al_2O_3	0.98	2.35	0.91	2.14	3.22	0.22	0.22	0.21	--
Fe_2O_3	3.39	1.60	3.84	3.99	--	--	--	--	--
FeO	0.85	2.83	1.92	--	5.96	5.94	3.50	6.21	5.20
Cr_2O_3	--	--	--	--	--	--	--	--	0.42
MnO	0.22	--	0.15	--	--	--	--	--	--
MgO	22.38	14.80	19.09	21.69	19.42	20.70	22.32	19.78	21.67
CaO	12.53	15.02	12.81	13.41	13.24	13.47	13.68	13.60	14.18
Na_2O	0.36	1.63	2.64	0.20	--	--	0.69	--	--
K_2O	--	1.00	--	0.69	--	--		--	--
H_2O+ / H_2O-	1.69	2.75	2.56	1.67	0.83	3.13	2.78	2.81	2.56
P_2O_5	--	--	--	--	--	--	--	--	--
CO_2	--	--	--	--	--	--	--	--	--
NiO	--	--	--	--	--	--	--	--	--
ign.	--	--	--	--	--	--	--	--	--
Totals	100.54	99.76	100.33	100.42	99.40	100.81	100.57	99.16	100.02

-- Not looked for
Nd Not detected

APPENDIX III CONTINUED

	10	11	12	13	14	15	16	17	18
SiO_2	55.59	57.96	52.38	57.75	51.70	56.34	56.25	56.01	55.89
TiO_2	--	--	--	--	--	--	--	--	--
Al_2O_3	1.43	--	2.07	0.90	0.65	1.60	0.42	0.65	2.34
Fe_2O_3	--	--	--	0.38	--	--	1.67	1.88	2.39
FeO	6.15	6.40	4.36	4.79	7.62	4.86	5.61	5.02	2.34
Cr_2O_3	--	--	--	--	0.30	--	--	--	--
MnO	--	--	--	0.46	Tr.	--	0.33	0.29	0.41
MgO	21.24	22.15	20.74	19.86	23.50	20.23	20.55	20.65	18.72
CaO	12.93	13.49	15.73	14.89	13.09	13.51	12.67	13.41	13.97
Na_2O	--	--	--	--	--	0.58	0.35	0.45	0.51
K_2O	--	--	--	--	--		--	0.28	--
H_2O+	2.35	--	2.77	0.68	2.42	3.57	1.89	2.03	2.21
H_2O-		--							
P_2O_5	--	--	--	--	--	--	--	--	--
CO_2	--	--	--	--	--	--	--	--	--
NiO	--	--	--	0.22	--	--	--	--	--
ign.	--	--	--	--	--	--	--	--	--
Totals	99.86	100.00	98.05	99.93	99.28	100.69	99.74	100.67	98.78

Note: Analysis #10 includes 0.17% Cu.

APPENDIX III CONTINUED

	19	20	21	22	23	24	25	26	27
SiO_2	57.45	58.28	56.51	59.79	56.02	54.43	51.90	55.00	55.28
TiO_2	--	--	0.02	0.23	0.02	0.01	0.45	0.40	0.17
Al_2O_3	1.09	0.88	1.80	0.88	1.15	1.58	5.50	0.90	1.43
Fe_2O_3	0.24	0.29	--	0.33	1.66	1.31	1.30	1.60	0.67
FeO	1.35	0.35	4.38	0.96	3.69	4.00	5.80	3.80	3.53
Cr_2O_3	--	--	Tr.	--	--	--	--	--	--
MnO	0.28	Tr.	0.06	0.10	0.26	0.69	0.20	0.19	0.11
MgO	20.61	22.08	21.32	24.31	23.54	21.54	15.75	21.80	21.99
CaO	15.41	14.98	12.72	12.52	11.64	11.70	14.90	11.80	12.91
Na_2O	--	0.42	--	0.35	0.29	--	0.18	0.20	0.34
K_2O	0.51	0.38	--	0.06	0.34	--	0.04	0.02	0.02
H_2O+	2.65	1.98	1.33	2.10	1.43	4.05	3.04	3.16	2.95
H_2O-			0.28	0.32	0.05	0.30	0.44	1.16	0.51
P_2O_5	--	--	--	--	--	--	0.10	0.06	--
CO_2	--	--	--	--	--	--	0.09	0.02	--
NiO	--	--	0.03	--	--	--	--	--	--
ign.	--	--	1.37	--	--	--	--	--	--
Totals	99.59	99.64	99.82	99.95	100.07	99.61	99.69	99.75	99.91

APPENDIX III CONTINUED

	28	29	30	31	32	33	34	35	36
SiO_2	56.20	56.76	57.58	57.30	56.70	56.70	55.90	57.00	57.10
TiO_2	--	Tr.	0.10	0.06	0.05	0.06	0.10	0.10	0.10
Al_2O_3	1.40	1.12	1.35	1.60	1.40	1.40	2.80	1.50	3.00
Fe_2O_3	0.06	0.81	0.15	0.38	1.60	0.69	4.80	4.50	4.50
FeO	5.65	3.96	4.02	3.20	6.50	7.10			
Cr_2O_3	--	--	--	--	--	--	--	--	--
MnO	0.18	0.02	0.15	0.04	0.08	0.09	0.10	0.10	0.10
MgO	21.09	22.50	20.65	22.40	20.20	19.80	23.10	21.30	21.40
CaO	13.22	11.83	13.10	13.00	11.80	12.40	12.80	14.50	12.80
Na_2O	0.14	0.21	0.12	0.02	0.30	0.40	Nd.	--	--
K_2O	0.21	0.18	Tr.	0.11	0.04	0.08	0.30	0.10	0.10
H_2O+	2.09	2.54	2.61	0.12	0.20	0.04	--	--	--
H_2O-	Nd.	0.24		0.53	1.30	0.60	--	--	--
P_2O_5	--	--	--	0.02	0.04	0.05	--	--	--
CO_2	--	--	--	0.65	0.05	0.68	--	--	--
NiO	0.24	--	--	--	--	--	--	--	--
ign.	--	--	--	--	--	--	--	--	--
Totals	100.48	100.17	99.83	99.43	100.26	100.09	99.90	100.00	99.10

APPENDIX III CONTINUED

	37	38	39	40	41	42
SiO_2	55.50	57.00	54.10	53.30	51.20	55.50
TiO_2	0.10	0.05	0.10	0.10	0.10	0.10
Al_2O_3	3.60	1.70	3.30	3.60	3.00	1.00
Fe_2O_3	9.60	0.75	12.30	11.30	13.50	10.70
FeO		4.60				
Cr_2O_3	--	--	--	--	--	--
MnO	0.10	0.07	0.20	0.20	0.20	0.10
MgO	20.00	21.30	20.30	21.30	21.40	21.20
CaO	11.60	12.90	10.30	9.60	10.60	11.50
Na_2O	--	0.03	--	--	--	--
K_2O	0.20	0.10	0.20	0.20	0.20	0.20
H_2O+	--	0.05	--	--	--	--
H_2O-	--	0.56	--	--	--	--
P_2O_5	--	0.03	--	--	--	--
CO_2	--	0.05	--	--	--	--
NiO	--	--	--	--	--	--
ign.	--	--	--	--	--	--
Totals	100.70	99.19	100.80	99.60	100.20	100.30

APPENDIX III CONTINUED

Analyses	Locality	Reference
1 - 20	New Zealand	Finlayson, 1909
21	Harz area, East Germany	Uhlig, 1910
22	Bahia, Brazil	Washington, 1922
23	Hauderes, Valais Canton, Switzerland	Preiswerk, 1926
24	Koleborn, Harz area, East Germany	Rose and Fromme, 1932
25 - 26	New Zealand	Coleman, 1966
27	Fengtien, Taiwan	Huang, 1966
28	Siberia, U. S. S. R.	Kolesnik, 1970
29	Hakuba-mura, Nagano Prefecture, Japan	Yoshimura et al, 1966
30	Jordanow, Poland	Heflik, 1968
31 - 36	Granite Mountains, Wyoming	Sherer, 1969
37	Seminoe locality, Seminoe Mountains, Wyoming	Sherer, 1969
38	Sage Creek locality, Seminoe Mountains, Wyoming	Sherer, 1969
39 - 42	Laramie Mountains, Wyoming	Sherer, 1969

LEGEND

LITHOLOGY

Meta – aplite

Porphyritic albite – quartz – clinozoisite rock

Amphibole – albite rock

Meta – diabase

Hornblende – zoisite rock

PERMIAN (?) AND/OR LATER
POST-MIDDLE PERMIAN, PRE-UPPER TRIASSIC (?)
TREMBLEUR INTRUSIONS

Nephrite

Tremolite – chlorite rock

Tak – carbonate – serpentine rock

Quartz – carbonate rock

Serpentinite

PENNSYLVANIAN (?) AND PERMIAN
CACHE CREEK GROUP

Chert, quartzite, argillite, minor greenstone

SYMBOLS

Foliation (inclined, vertical)

Bedding

Contact (defined, inferred, estimated)

Fault (defined, estimated)

Diamond drill hole

Hole	Brg.	Dip	Depth(ft.)
5	126°	-60°	65
6	285°	-60°	52
8	130°	-67°	82

Boulders of semi–nephrite and
tremolite–chlorite schist

O'Ne-ell Creek

Falls

Bridge

Rapids

N
29° 19'
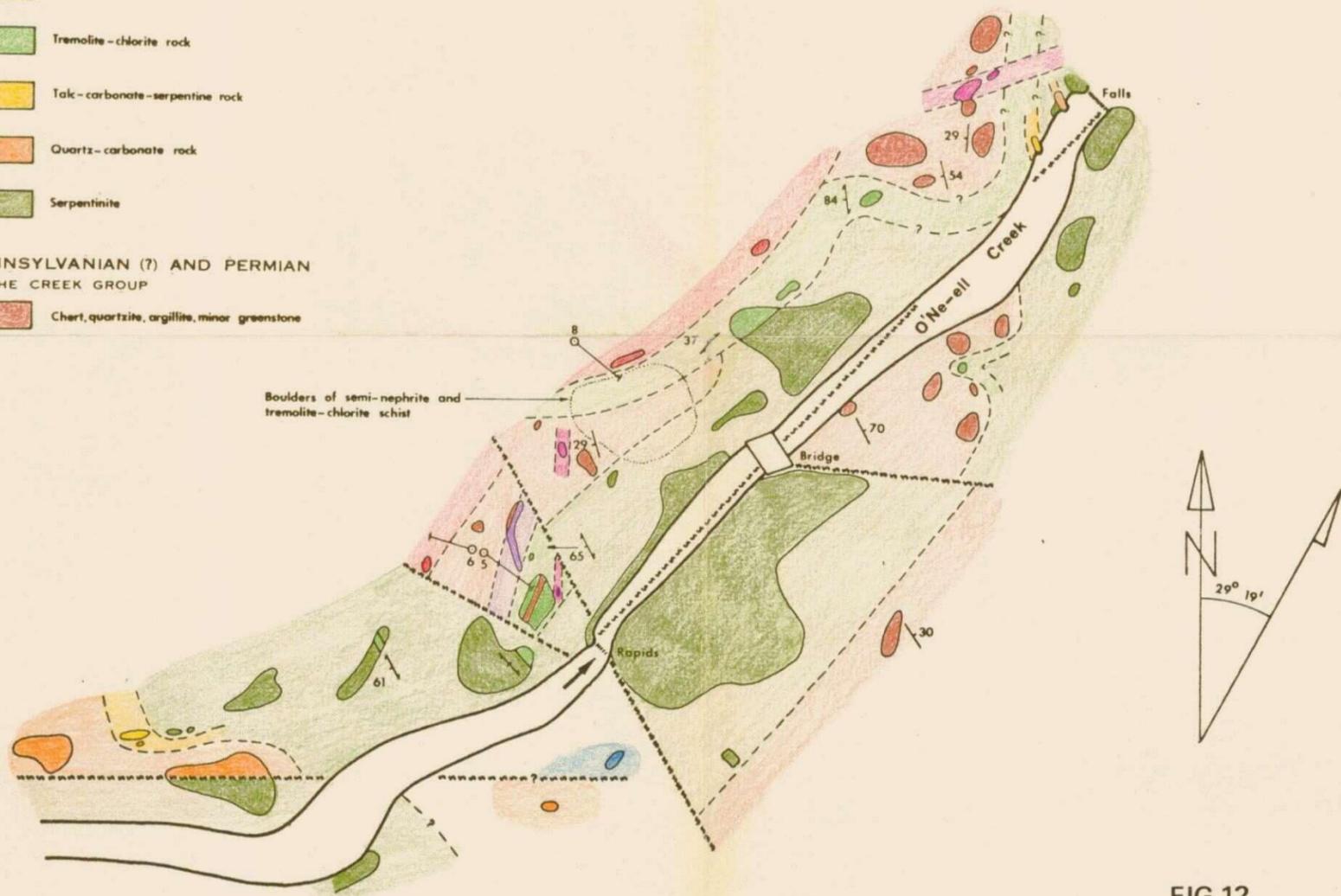
FIG.12.
GEOLOGY
O'NE-ELL CREEK NEPHRITE
DEPOSIT
O'NE-ELL CREEK, BRITISH COLUMBIA

80   40   0   80   160

FEET

Mapped by J.R. Fraser, September, 1969.