Gem-quality Cordierite Deposits, Slocan Valley, British Columbia (NTS 82F/12E)

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KEYWORDS: *Economic Geology, Cordierite, Iolite, Anthophyllite-gedrite, Gemstone, Sapphirine, Valhalla Complex, Passmore Dome.*

INTRODUCTION

Cordierite is typically an orthorhombic magnesium-iron aluminosilicate and its high temperature form, indialite (alpha-cordierite), is isostructural with beryl (Deer *et al*.,1963). It has the formula $X_{0\text{-}1}M_2T_9O_{18}$ where X=H_2O, CO_2, Ar, Xe, Na and K may be present within channels parallel to the c axis. M= Mg^{2+}, Fe^{2+} and possibly Li^+. T=Al_4Si_5 and possibly Be^{2+}. Cordierite is a common constituent in contact metamorphosed argillaceous or arenaceous sediments and in regionally metamorphosed settings where it occurs only in high grade gneiss (Deer *et al*., 1963; Nathan *et al*., 1995; Nicollet, 1985; Lal, 1997). Cordierite-anthophyllite assemblages or their granulite facies equivalents have been identified and described from many localities including the famous West Uusinaa Complex, Finland (Escola, 1915). A number of these localities are closely associated with base metal deposits, and this assemblage is considered an indirect prospecting tool for volcanogenic massive sulphide deposits in highly metamorphosed terrains (Schreurs and Welstra, 1985; Robinson *et al*., 1982). Cordierite also occurs in a variety of intrusive rocks, including granites, pegmatites, norites (Deer *et al*., 1963; Heinrich, 1950), where critical parameters controlling its stability field are low temperature and pressure, high Mg^{2+} and Fe^{2+}, A/CNK, aAl_2O_3, and fO_2 (Clarke, 1995).

Cordierite is commonly used by geologists as a metamorphic index mineral, but its stability field on petrogenetic grids remains controversial because of uncertainties in its thermodynamic properties (Gunter, 1977; Skippen and Gunter, 1996; Lal, 1997). Cordierite may also have a potential as a CO_2-H_2O sensor for fluids and melts (Visser *et al*., 1994; Harley, 1994; Carrington and Harley, 1996).

Iolite, dichroite and “water sapphire” are the names used to designate the gem-quality cordierite in the gem trade.

Gem-quality cordierite is much less common than its rock forming equivalent. It is transparent to translucent with vitreous to greasy luster and comes in a variety of colours, mainly in shades of blue or violet, greenish, yellowish, or colorless. It is strongly pleochroic making cutting more challenging. No matter the shape of the rough, iolite crystals have to be oriented exactly to take advantage of the most desirable color and consequently the weight of stone may be severely reduced during the cutting. It is a hard mineral (7 to 7.5 on the Moh’s hardness scale) with conchoidal fracture and one moderately well-developed cleavage direction. This cleavage makes it less durable than sapphire. Its density varies from 2.53 to 2.78 g/cm^3. The main sources of gem-quality cordierite are Sri Lanka, Mozambique, Madagascar, Burma and India. Other sources are Tanzania, Namibia, Canada and USA.

In Canada, gem-quality material and excellent specimens have been extracted from number of areas (Wight, 1999), including the Geco Mine (Ontario), Great Slave

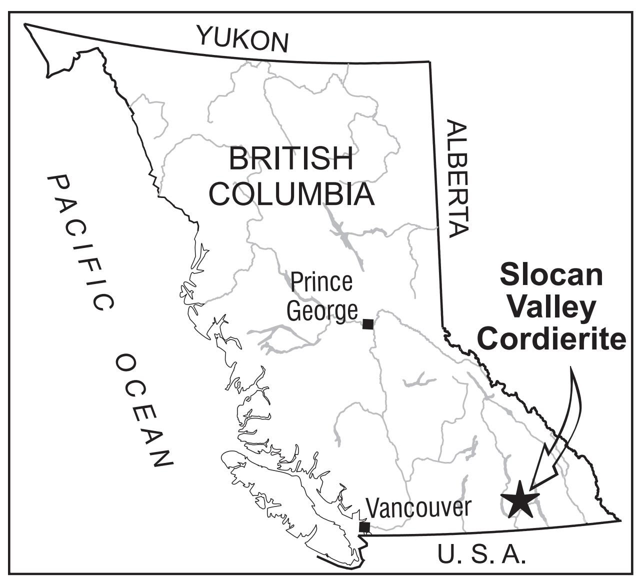

Figure 1. Location of Slocan Valley cordierite occurrences.

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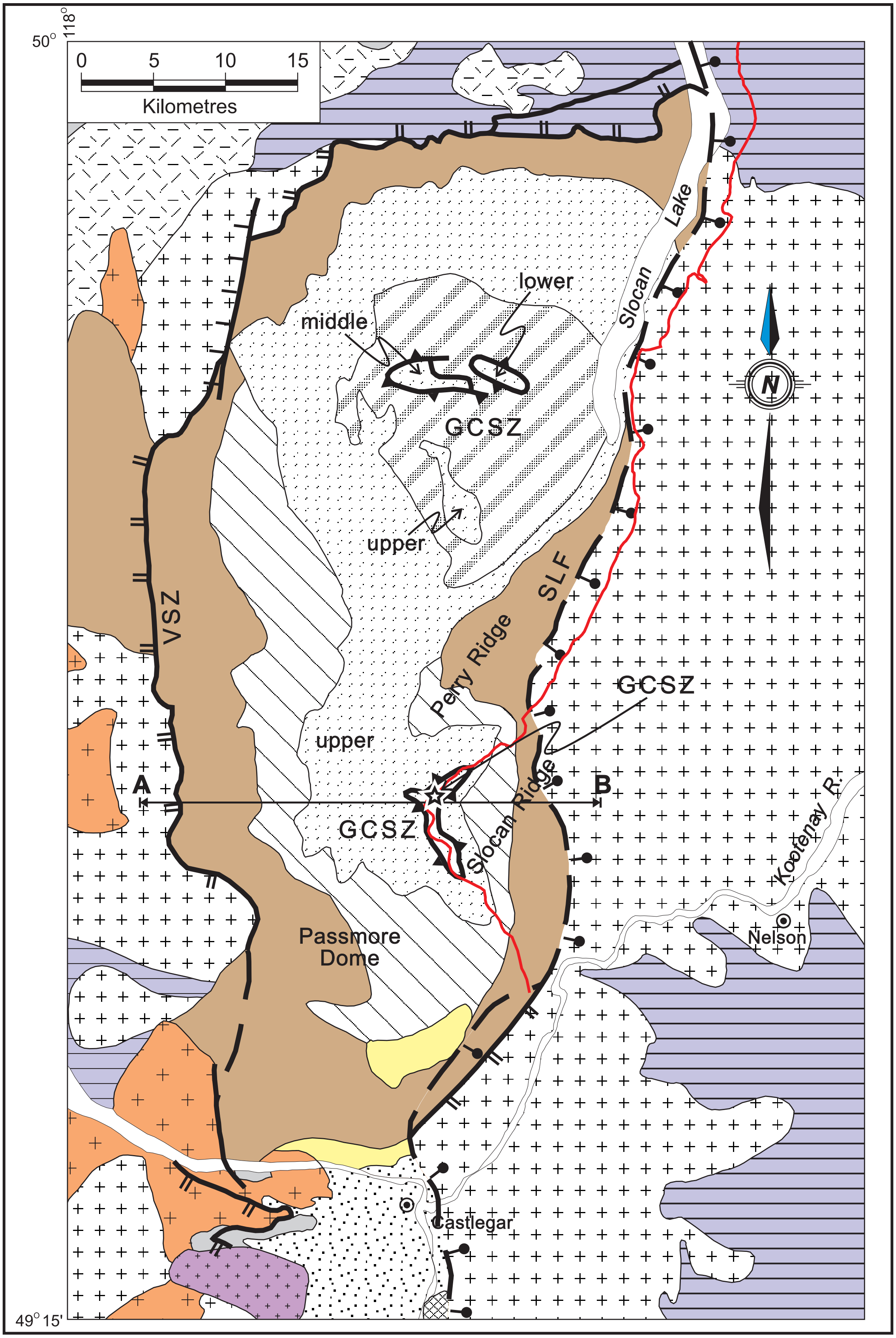

Figure 2. The geological setting of the Slocan Valley and cordierite occurrences (from Schaubs and Carr (1998). SLF: Slocan Valley Fault, VSZ: Valkyr Sheer Zone, GCSZ: Gwillim Creek Shear Zone.

LEGEND

Upper Plate

- Middle Eocene Coryell syenite, granite
- Eocene College Creek granite
- Late Cretaceous granitic rocks
- Middle Jurassic granitic rocks
- Middle Paleozoic - Early Mesozoic allochthonous Quesnelia

Valhalla complex (Lower Plate)

- Early Eocene Ladybird granite
- Paleocene Airy Quartz Monzonite
- Late Cretaceous Mulvey granodiorite
- Late Cretaceous Kinnaird Gneiss
- Middle Devonian Trail Gneiss
- Metasedimentary rocks
- Castlegar Gneiss

- Thrust fault
- Steep normal fault
- Slocan Lake fault
- Valkyr shear zone

- Cordierite Occurrences

Lake and Ghost Lake areas (Northwest Territories), Snow Lake area (Manitoba) .

Other blue minerals, well established in the gemstone trade, are sapphire, benitoite, spinel and tanzanite (a variety of zoisite). Gem-quality cordierite, currently available on the market, is considered as a moderately priced stone. It is marketed and promoted as an affordable substitute for tanzanite, benitoite or blue sapphire. According to Wight (1999): "Iolite is not seen frequently in jewelry, but it is not rare except in sizes over 30 carats". This perception is now deeply anchored within the colored stone industry and may be difficult to change. As with other gemstones, exceptional stone quality in combination with highly effective marketing programs may enhance the price.

Gemstone Evaluation - General Comments

Conceptual and market studies by independent specialists should be done in the first stages of gemstone deposit evaluation. Such studies are essential to determine if any follow-up work leading to the pre-feasibility stage (including the grade and tonnage estimates) is warranted. The grade and tonnages of hard rock gemstone deposits are difficult to predict. A single large, high quality stone may double cash flow of a mid-size gemstone mining operation, when diamonds, emeralds, sapphires or other high-value stones are involved. Bulk sampling and sorting of the stones into facet, cabochon and specimen grades provide the basis for grade estimates, evaluation of potential product, recovery rate evaluation and the material for test marketing. Bulk sampling also provides a useful check on mining and gemstone extraction cost estimates. The extraction of gemstones from small, "hard rock" deposits tends to be relatively costly, technically demanding and/or labour intensive because care must be taken to minimize gemstone fracturing.

Location and History

The gem-quality cordierite in the Slocan Valley occurrences in southeastern British Columbia, were first reported by Jim Laird, while working for of Anglo Swiss Resources Inc. The occurrences were discovered during the exploration for star corundum and are located on the Blu Starr property (Minfile number 082FNW259) that belongs to Anglo Swiss Resources Inc., approximately 25 kilometres west of Nelson and 30 km south of Slocan near highway 6 (Figure 1).

REGIONAL GEOLOGY

The cordierite occurrences are located within the Omineca Belt and more precisely within the Valhalla metamorphic core complex (Reesor, 1965) which is characterized as a structural culmination with outward-dipping metamorphic layering and foliation (Schaubs and Carr, 1998; Simony and Carr, 1996). The complex consists of the Valhalla and Passmore domes and is delineated by ductile Valkyr shear zone to the north, west and south and Slocan Lake fault to the east. The Valhalla complex forms the footwall of the Valkyr and Slocan Lake shear zones (legend of Figure 2 and Figure 3). It consists of Castlegard Gneiss, metasedimentary rocks, Middle Devonian Trail Gneiss, Late Cretaceous Kinnaird Gneiss, Late Cretaceous Mulvey granodiorite, Paleocene Airy Quartz monzonite and Early Eocene Ladybird granite (Legend of Figure 2). The complex contains three sheets of supracrustal rocks identified as upper, middle and lower. The upper sheet consists of the "Valhalla assemblage" metasedimentary rocks sandwiched between Paleocene granitoids and the Mulvey granodiorite (Figures 2 and 3). The middle sheet and upper portion of the lower sheet are interlayered with Mulvey granodiorite (Figure 2).

The hanging wall of the Valkyr and Slocan Lake shear zones (so called upper plate, legend of Figure 2) consists of Middle Paleozoic to Early Mesozoic rocks of allochtonous Quesnelia, Middle Jurassic and Late Cretaceous granitic rocks, Eocene College Creek granite and Middle Eocene Coryel syenite and granite.

In the Passmore dome area, metasedimentary rocks within the upper sheet are overlain by Airy quartz monzonite (Figure 3) and are interpreted to be underlain by Mulvey granodiorite gneiss (Schaubs and Carr, 1998). The cordierite-bearing lenses lie within or near the mylonites of the Gwillim Creek Shear Zone (GCSZ) which separates the metasediments of the upper sheet from the lower sheet (Figure 2).

The lenses occur within the metasedimentary sequence, described by Schaubs and Carr (1998) as consisting of pelitic schists (biotite>50%, quartz, feldspar, sillimanite and garnet), semipelitic schists (biotite <50%, quartz, feldspar ± sillimanite and garnet) and psammitic gneiss (mainly quartz and feldspar, with minor biotite) and at least one quartzite layer more than 1 metre thick. Mafic and ultramafic rocks form lenses. Most of these lenses can be described as amphibolites with or without garnet. Peak metamorphic assemblages in pelitic schists contain garnet, sillimanite, alkali feldspar and melt indicating temperatures over 800±20ºC and pressure of 8±1kb (Spear,1994). Further thermal history of the complex is discussed by (Parish, 1995). Structural geology of the metasedimentary rocks in the Passmore dome area, where the cordierite deposits are located is covered in detail by Schaubs and Carr (1998). These authors describe metasedimentary rocks displaying nearly flat lying subhorizontal transposition foliation and strong east or west plunging stretching lineation, rootless folds with strongly sheared limbs and sheet folds. All these features were also observed during our visit at the deposit scale.

Geology of the Slocan Valley Cordierite Occurrences

Three cordierite-bearing lenses are reported in the area, however only two of these were examined during our short visit. Both visited occurrences are exposed on

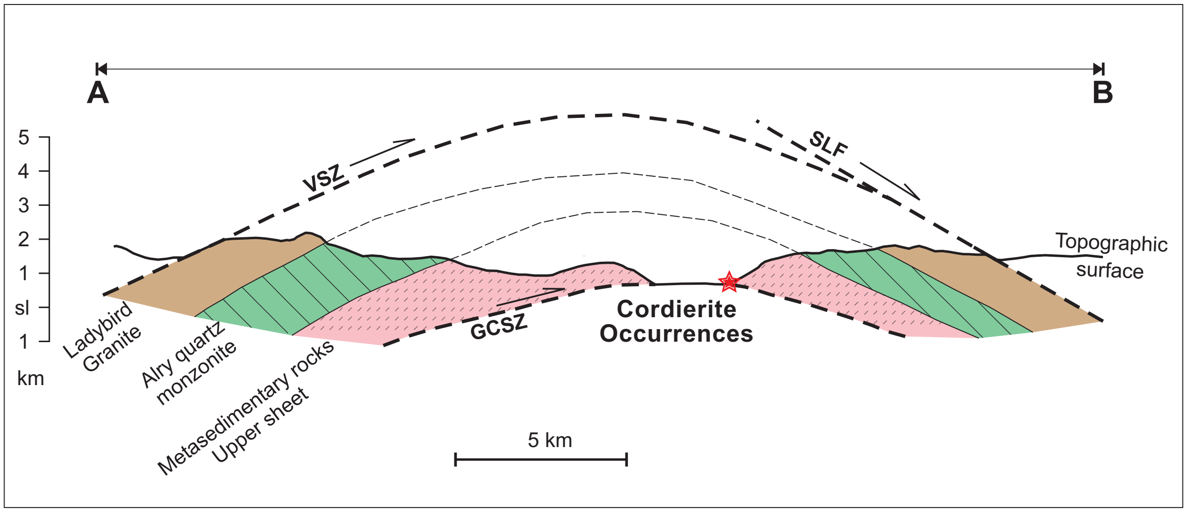

Figure 3. Cross section of the Passmore dome in the area of cordierite occurrences (modified from Schaubs and Carr (1998). For location, *see* Figure 2.

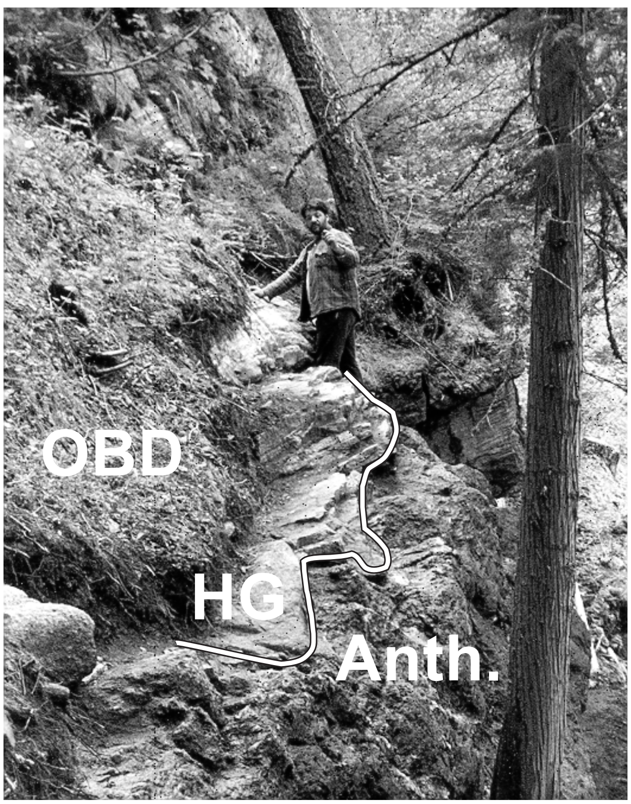

Photo 1. The main cordierite-bearing, anthophyllite rock lense, Slocan Valley; HG: hangingwall gneiss; Ant: anthophyllite-rich rock; OBD: overburden. For approximate location, *see* Figure 2.

the cliff faces approximately one kilometre apart. Lenses are located within or near the Gwillim sheer zone (Figure 3).

Both lenses are located in or near noses of folds that have subhorizontal fold axes plunging 65 to 85°E. The long dimension of the lenses is expected to be collinear with the fold axis and mineral lineations. The larger of the lenses is only partially exposed for nearly 20 metres along strike (Photo 1 and Figure 4). Its maximum exposed thickness is nearly 6 metres with its extent in the third dimension unknown. The smaller lens is exposed for greater than 10 metres along the cliff side and its maximum thickness exceeds 2 metres (Figure 5). The contacts between the lenses and the surrounding gneiss are sharp and irregular or sheared.

Cordierite-bearing, anthophyllite lenses have characteristic rough hummocky appearance. The lenses are brown to dark green on weathered and dark green on fresh surfaces. They are coarse grained, typically 0.5 to 2 centimetres and characterized by interlocking blades of gedritic anthophyllite and irregularly distributed heavily included garnet porphyroblasts up to 5 centimetres in diameter. The mineralogy is approximately gedritic-anthophyllite (55 % or more), quartz (20%), garnet (0 -15%), biotite (0-90%) generally restricted to quartz vein or pegmatite contacts with anthophyllite-rich rock, plagioclase feldspar (5%) with minor clino-amphiboles and cordierite (0-25%). Potassic feldspar may be also present.

The lenses of anthophylite rock are cut by tourmaline-bearing pegmatites, quartz veins and garnet-bearing feldspar veins (Figure 4), fractures and irregular zones consisting mainly of coarse-grained biotite are found adjacent to pegmatite and quartz veins or controlled by the same fractures. Coarse cordierite occurs mainly within quartz veins, along the contact of these veins with the host anthophyllite lens, or in biotite zones. The cordierite crystals are completely embedded in the host rock. Cordierite crystals, in many cases partially or entirely converted to pinite may measure up to 10 centimetres in length. There is a transition from transparent, blue or gray cordierite in the unaltered core of the crystal to pale green translucent to opaque aphanitic rim entirely consisting of pinite.

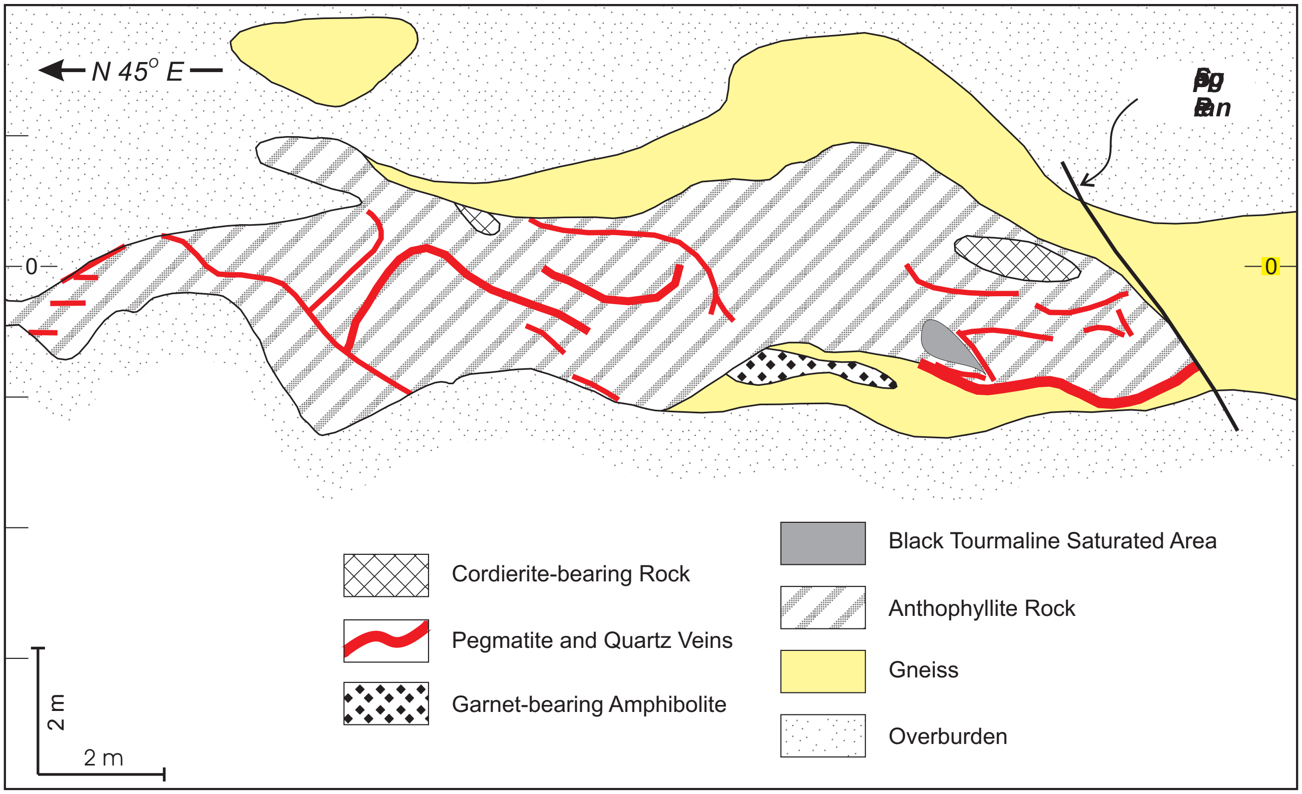

Figure 4. Idealized vertical section along the main cordierite-bearing cliff face (main outcrop).

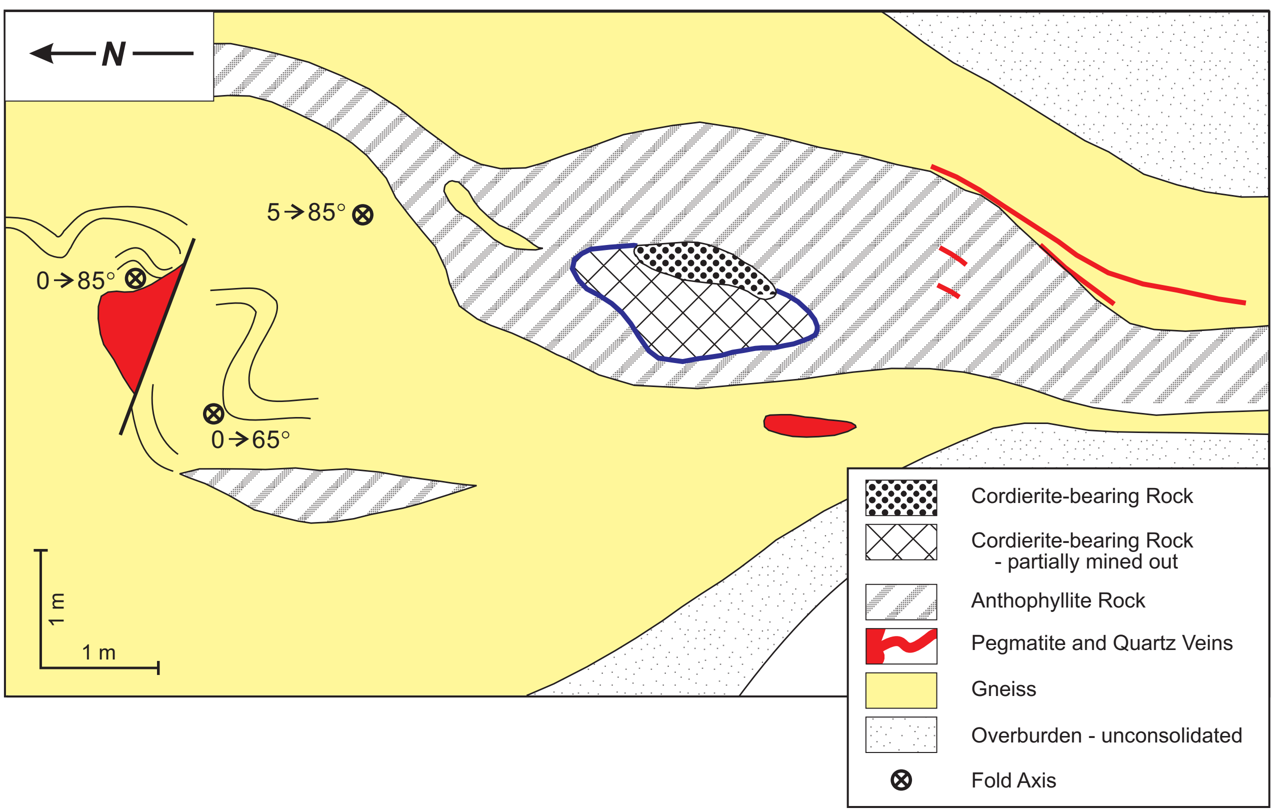

Figure 5. Idealized vertical section, along cliff exposure of the second cordierite-bearing lens, located approximately 1km south from the main outcrop. For approximate location, *see* Figure 2.

TABLE 1
ELECTRON MICROPROBE ANALYSES OF CORDIERITES FROM THE SLOCAN VALLEY

SAMPLE	SiO_2	Al_2O_3	TIO_2	Cr_2O_3	FeO	MgO	MnO	CaO	K_2O	Na_2O	Total
Cord 99-2-10	49.53	35.07	0.03	0.01	3.16	11.96	0.13	0.03	0.00	0.13	100.05
Cord 99-2-10	49.20	34.86	0.09	0.00	3.25	11.73	0.12	0.07	0.01	0.13	99.46
Cord 99-2-10	49.17	35.03	0.09	0.00	3.19	11.78	0.04	0.04	0.00	0.14	99.48
Cord 99-2-19	50.84	33.62	0.00	0.02	3.64	11.33	0.05	0.03	0.02	0.25	99.80
Cord 99-2-19	50.46	33.88	0.00	0.01	3.69	11.45	0.00	0.02	0.00	0.27	99.78
Cord 99-2-19	50.41	33.25	0.04	0.01	3.57	11.53	0.00	0.02	0.01	0.22	99.06
Cord 99-2-19	50.84	33.57	0.10	0.01	3.36	11.56	0.04	0.04	0.01	0.26	99.79

The intensity of the replacement decreases progressively from the crystal edges inward. The cores are commonly clear, blue or bluish gray in color, but fracture networks reduce the maximum size of the stones suitable for cutting. As a result, the majority of the cordierite exposed at the site in July 1999 were of specimen quality. Few stones up to 5 mm in longest dimension, of gem or near-gem quality were extracted during our visit. Table 1 shows results of the microprobe analyses of the iolite. Photo 2 shows an enlarged finished stone from this property.

Terminated amethystine and colorless transparent quartz and tourmaline crystals occur in cavities within the anthophyllite rock and elsewhere on the property.

The gneiss, country rock to the lenses, is characterized by folds with severed limbs and centimetre- to metre-scale layering. The leucosomes are thicker and more continuous than melanosomes. Mineralogy is variable, consisting of quartz (60%), green or brown biotite (20%), plagioclase (8%), potassic feldspar (2%) and sillimanite, titanite, cordierite, garnet (~10%). Melanosomes are composed of quartz (30%) plagioclase (30%), biotite (30%), potassic feldspar (7%), and garnet (3%). The gneiss also contains centimetre to metre thick lenses of clinoamphibolites that may also contain garnet. Representative mineral analyses are given in Table 2.

Photo 2. Raw and cut iolite from the Slocan Valley occurrences, the faceted stones (from left to right) weight 0.5, 0.5, 0.5 and 0.6 carat respectively (courtesy of Anglo Swiss Resources Inc.).

TABLE 2
REPRESENTATIVE MICROPROBE ANALYSES OF MINERALS WITHIN THE ANTHOPHYLLITE LENSES AND COUNTRY GNEISS

Sapphirine	SiO_2	Al_2O_3	TiO_2	Cr_2O_3	FeO	MgO	MnO	CaO	K_2O	Na_2O	Total			
Cord 99-2-10	11.45	65.23	0.03	0.26	9.02	14.93	0.16	0.03	0.00	0.00	101.11			
Cord 99-2-10	11.01	65.17	0.06	0.32	9.04	14.94	0.09	0.10	0.00	0.00	100.73			
Ortho-Amphibole	SiO_2	Al_2O_3	TIO_2	Cr_2O_3	FeO	MgO	MnO	CaO	K_2O	Na_2O	NiO	Cl	F	Total
Cord 99-2-4	48.38	11.86	0.29	0.04	14.64	19.90	0.37	0.75	0.00	0.77	0.00	0.02	0.05	97.07
Cord 99-2-4	47.61	11.92	0.40	0.11	14.54	19.63	0.39	0.70	0.00	0.84	0.00	0.01	0.02	96.17
Cord 99-2-4	47.70	11.89	0.22	0.05	14.57	19.79	0.48	0.69	0.00	0.83	0.00	0.04	0.01	96.27
Clino-Amphibole														
Cord 99-6 #6	41.44	13.18	1.53	0.05	18.50	8.88	0.12	10.86	0.79	1.41	0.00	0.00	0.10	96.86
Cord 99-6 #7	41.50	13.31	1.43	0.05	18.66	8.68	0.11	10.97	1.03	1.33	0.00	0.00	0.05	97.12
Cord 99-6 #8	42.92	12.21	0.91	0.04	18.69	9.17	0.13	11.05	0.58	1.35	0.00	0.01	0.15	97.21
Cord 99-6 #9	42.99	12.44	0.96	0.04	18.34	9.19	0.12	11.00	0.55	1.34	0.00	0.01	0.12	97.10
Garnet	SiO_2	Al_2O_3	TIO_2	Cr_2O_3	FeO	MnO	MgO	CaO	Total					
Cord 99-2-1	38.58	21.75	0.00	0.00	27.02	0.88	9.46	1.63	99.32					
Cord 99-2-10	40.71	22.77	0.00	0.08	18.35	0.73	13.60	3.13	99.37					
Cord 99-2-10	40.71	22.78	0.00	0.07	18.34	0.79	13.63	3.30	99.62					
Cord 99-5 #3	37.66	21.00	0.02	0.04	26.85	1.29	2.90	10.06	99.82					
Cord 99-5 #5	38.53	20.51	0.00	0.05	24.09	1.91	2.68	11.93	99.70					
Cord 99-5 #6	38.58	19.98	0.00	0.04	22.97	2.71	1.92	12.79	98.99					
Cord 99-2-8	39.76	22.67	0.00	0.15	19.85	0.38	14.01	2.42	99.24					
Biotite	SiO_2	Al_2O_3	TIO_2	Cr_2O_3	FeO	MnO	MgO	CaO	K_2O	NiO	Na_2O	BaO	Cl	F
Cord 99-2-10	37.91	18.18	1.59	0.11	10.89	0.01	17.22	0.03	8.85	0.00	0.47	0.05	0.09	0.11
Cord 99-2-10	38.17	18.20	1.75	0.09	10.36	0.03	17.45	0.03	8.83	0.00	0.50	0.00	0.08	0.13
Cord 99-2-1	37.97	16.32	1.42	0.07	12.74	0.08	16.02	0.01	8.23	0.00	0.43	0.00	0.02	0.18
Cord 99-2-6	37.96	16.45	1.37	0.07	13.39	0.07	16.07	0.01	8.29	0.00	0.41	0.00	0.04	0.10
Cord 99-2-8	37.78	17.88	1.69	0.13	9.85	0.06	18.41	0.00	8.51	0.00	0.58	0.00	0.08	0.14
Cord 99-5	36.62	15.97	3.00	0.05	20.24	0.15	10.34	0.02	8.66	0.00	0.37	0.54	0.11	0.22
Cord 99-2-19	38.08	16.89	1.93	0.05	11.59	0.05	16.60	0.00	8.85	0.00	0.47	0.01	0.08	0.17
Cord 99-6 #10	36.62	15.22	2.79	0.04	19.17	0.04	12.14	0.04	8.82	0.00	0.32	0.00	0.03	0.23
Cord 99-2-8	38.43	17.98	1.48	0.15	9.54	0.08	18.48	0.02	8.67	0.00	0.55	0.08	0.07	0.22
Feldspar	SiO_2	Al_2O_3	K_2O	CaO	Na_2O	FeO	Total							

Exploration Potential

The Slocan Valley occurrences are the first discoveries of gem-quality cordierite in British Columbia. It is probable that future prospecting activity within the Passmore or Valhalla dome areas, or similar geological environments elsewhere in British Columbia, will result in new iolite discoveries. Non-gem quality cordierite is also present in the country gneiss that contains iolite-bearing lenses. Cordierite-orthoamphibole assemblages were also reported within Thor-Odin gneiss dome (Smith and Duncan), 1995.

As far as the two occurrences described here, the cordierite occurs mainly in association with quartz veins and pegmatite contained within the anthophyllite lenses. Quartz veins, pegmatites and cordierite bearing zones represent probably about 10% of the exposed face (surface) of the lens. The face of the main lens is still not fully exposed. To evaluate the cordierite content of the lenses, bulk sampling would be required. Small panel samples, if taken adjacent to quartz vein may result in unrealistic high cordierite content. Only a small proportion (<3%) of the recovered cordierite is expected to be suitable for faceting. At this stage it is impossible to estimate what the cut stone to rough ratio will be. The largest faceted stone from this property (Photo 2) is reported to have a weight of 0.6 carats (Anglo Swiss Resources Inc., personal communication). Less clear stones may be cut "en cabochon" (an unfaceted, domed, smoothly polished stone). The largest cabochon from this property weights 1.5 carat (Anglo Swiss Resources Inc., personal communication). Wight (1999) reports that cordierite cut in cabochons from these occurrences display asterism (stars).

Constraints on the Origin

Peak metamorphic conditions are represented by garnet-hornblende-quartz-plagioclase and cordierite-sapphirine-corundum-garnet-plagioclase and shown approximately on Figure 6. Relative topology of the high temperature equilibria shown on Figure 6 is correct, however, reactions make take place at slightly lower temperatures. Until the problems highlighted by Gunter (1977), Skippen and Gunter (1996) and Lal (1997) are addressed the temperatures shown on Figure 8 are approximate.

These assemblages are consistent with peak metamorphic conditions in excess of 900°C and 9 kilobars, but slightly higher than those reported by Spear and Parrish (1996). This temperature is a maximum temperature for cordierite stability in the study area, and possibly corresponds to the highest temperature metamorphic rocks ever reported in British Columbia. Geothermometry of garnet-biotite pairs confirms post-peak reequilibration at

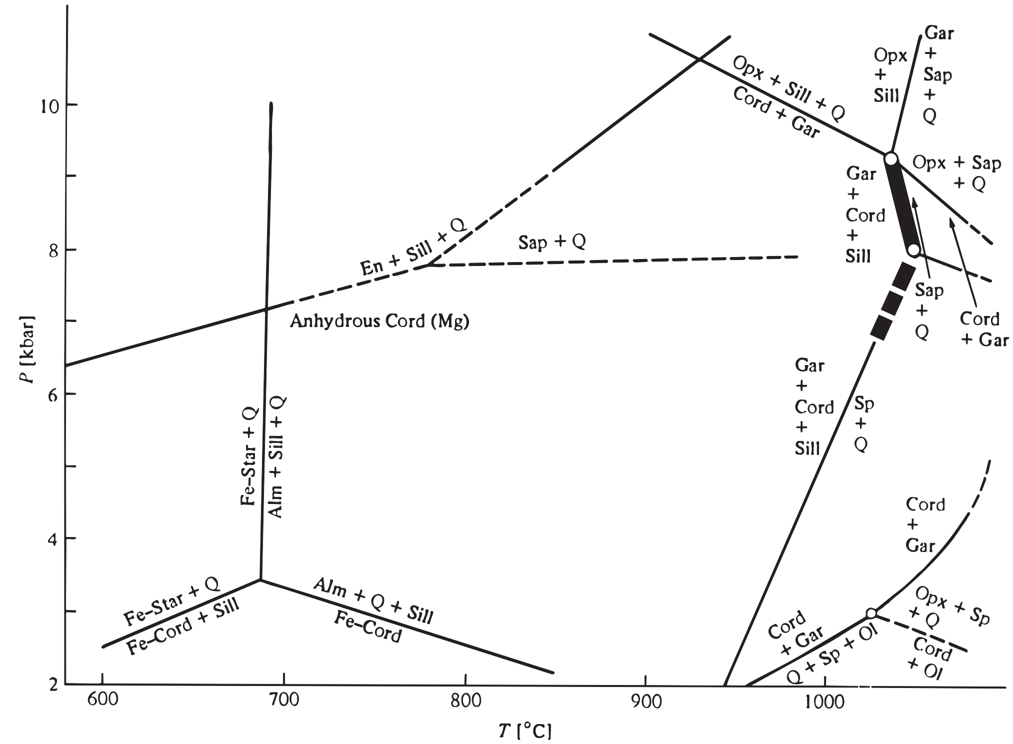

Figure 6. Equilibria involving cordierite in granulite facies (after Muller and Saxena, 1977). Opx; orthopyroxene; Sap: sapphirine; Q: quartz, Cord: cordierite; Gar: garnet; Sill: sillimanite, Sp: spinel; Ol: olivine, En: enstatite. Prograde and retrograde assemblages are shown by heavy solid and heavy doted lines respectively. P total = PH_2O, however PH_2O<P total above 900^{o}C.

the deposit scale, previously documented on the regional scale by Spear and Parrish (1996). Based solely on the spatial association of iolite with pegmatite, quartz veins and coarse biotite selvages , we can say that anthophyllite lithologies are an important ore control and that gem-quality cordierite is metasomatic or pegmatite-related. Abundant alteration and replacement of coarse euhedral cordierite crystals suggest a retrograde reequilibraion.

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