Pressure-depth relationships of the Roop Lakes Stock and Keno Hill Ag-Pb-Zn veins

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ABSTRACT

Key mineral assemblages help determine pressure, temperature and depth of emplacement for mineralized veins of the Keno Hill district, as well as for local Cretaceous pluton emplacement. New electron microprobe analyses are presented on samples collected in the field, enabling further characterization of the hydrothermal and plutonic regimes. Staurolite-garnet-albite-biotite schist along the margins of the Cretaceous Roop Lakes stock record contact metamorphic conditions, averaging 518°C and 3450 bar. To the west, hydrothermal veins of the Keno Hill district containing pyrite-pyrrhotite-sphalerite-arsenopyrite, indicate hydrothermal conditions of approximately 400°C and 1500 bar. Lithostatic conditions for the pluton, and likely hydrostatic conditions for the veins, are interpreted to indicate a similar depth of emplacement for the two systems, near 10-13 km below the surface.

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INTRODUCTION

The Roop Lakes stock (Roots, 1997; also known as the Mayo Lake pluton, Boyle 1965; Green, 1971) is the largest exposed granitic body of the Tombstone Plutonic Suite. It occurs at the eastern extremity of the west-trending string of plutons spanning 220 km across central Yukon. The stock is elliptical in shape, measuring 8 km wide and 20 km long (Fig. 1). The granitic body features a coarse porphyritic core and a medium to fine-grained margin. As with many of the plutons from the Tombstone Suite (*e.g.*, Poulsen *et al.*, 1997), the Roop Lakes stock has a well-developed contact metamorphic aureole, overprinting the tectonic fabric. Contact metamorphic minerals such as andalusite and staurolite place upper and lower limits, respectively, on pressure (*e.g.*, Lynch, 1989a,b). However, acquisition of new electron microprobe data on selected minerals, combined with mineral equilibrium data and software (TWEEQ, Berman 1991), allow for a quantitative determination of pressure and temperature. Similarly, in the veins of the Keno Hill district (Fig. 1), the key assemblage of sphalerite-pyrite-pyrrhotite-arsenopyrite is a useful barometer/thermometer as described from other districts by Lynch and Mengel (1995) and Lentz (2002). Although sphalerite and pyrite are widespread, pyrrhotite is restricted to the central portion of the vein system between Keno Hill and Galena Hill, and is one of the diagnostic minerals in the definition of separate broad mineral zones (Lynch, 1989a,b). Previous determinations of pressures for the vein systems were made from CO_2-bearing fluid inclusions (Lynch, 1989b), and temperatures have been established from fluid inclusions, as well as from tetrahedrite composition (Sack *et al.*, 2003). These data provide a basis for comparison with the results presented here. Although methods for determining temperature in vein systems are relatively common, the means for pressure determinations are rare, and the assemblage of coexisting sphalerite-pyrite-pyrrhotite-arsenopyrite provides an opportunity to determine pressure and temperature. Furthermore, establishing pressures for the Mayo Lake Pluton and the Keno Hill vein system will contribute to investigating possible links between pluton emplacement and hydrothermal circulation. To this end, a basic understanding of the differences between hydrostatic and lithostatic pressure-depth relationships are required, and presented in the discussion.

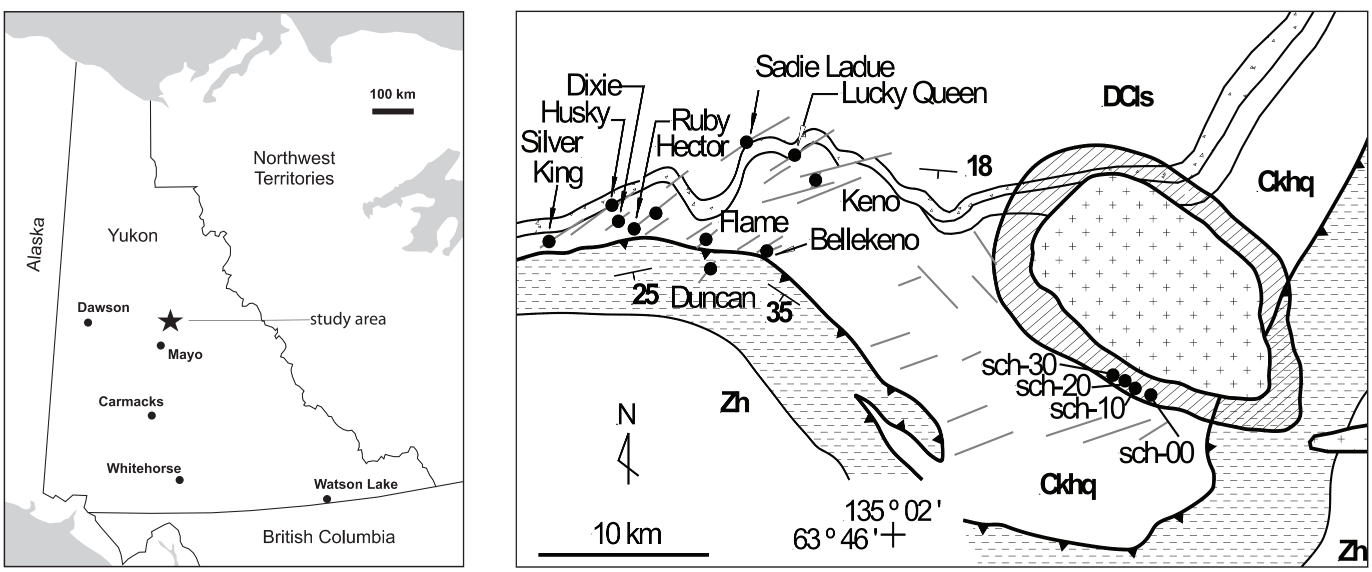


Figure 1. *Location map of sample sites from the Keno Hill district and from the margin of Roop Lakes stock. Thick grey lines are fracture systems and fault planes containing hydrothermal assemblages and mineralization. Stratigraphy includes the Devonian-Carboniferous Lower Schist unit (DCls); the graphitic Keno Hill Quartzite of Carboniferous age (Ckhq); as well as Neoproterozoic to Cambrian units of the Hyland Group (Zh) including the Upper Schist unit patterned with the horizontal dashed motif. Units dip moderately to the south and the Robert Service thrust bounds the top of the Keno Hill Quartzite. The Late Cretaceous Roop Lakes granitic pluton is a prominent crosscutting feature to the east and has a well-developed contact metamorphic aureole, shown here with the diagonal ruled pattern.*

GEOLOGIC SETTING

Comprehensive descriptions of the regional geologic setting are contained in bulletin form by Murphy (1997) and Roots (1997), each of which include an extensive bibliography of previous work. The veins in both the Keno Hill district and the Roop Lakes stock crosscut, and are largely contained within, the Mississippian Keno Hill Quartzite unit (KHQ), which extends east-west for approximately 220 km along the northern edge of the Selwyn Basin (Tempelman-Kluit, 1970; Mortensen and Thompson, 1990; Gordey and Anderson, 1993). The region has been affected by late Jurassic to middle Cretaceous deformation, metamorphism and igneous activity (Roots, 1997). Strata dip generally south as a result of northerly thrusting (Murphy, 1997). The KHQ may be as much as 1 km thick where affected by imbrication and structural thickening. Lithologically the KHQ includes dark graphitic quartzite, calcareous quartzite, schist, graphitic phyllite and minor limestone, as well as tuffaceous metavolcanic rocks (Roots, 1997; Lynch, 2006). Granitic bodies of the Tombstone Plutonic Suite (*e.g.,* Anderson, 1987) intrude the KHQ and include the Roop Lakes stock, which has been dated at 92.8 ± 0.5 Ma (Roots, 1997).

Mineralized veins of the Keno Hill district are described in a GSC Bulletin by Boyle (1965), and in a thesis by Lynch (1989b). Veins are controlled by a district-wide series of northeast-trending fractures and faults contained primarily, but not uniquely, within the KHQ and Triassic diorite sills.

CONTACT METAMORPHISM

Contact metamorphism forms a broad halo around the Roop Lakes stock, extending for as much as 1-2 km beyond the contact exposed at surface. Mineral growths associated with contact metamorphism are more strongly expressed in schist and graphitic schist units between quartzite beds of the KHQ. Contact metamorphism is zoned away from the stock and is also influenced by host lithology. Sillimanite-schist occurs in immediate contact with the chilled margin of the stock comprising medium to fine-grained equigranular granodiorite. Sillimanite occurs in medium-grained bundles with fine prismatic needles aligned along the rock fabric. The rock is light coloured and bleached of graphite. In contrast to this, andalusite-schist is black and graphitic, occurring further outboard from the stock. Andalusite is coarse grained; crystals are randomly oriented and the porphyroblasts give the rock a distinct knobby texture. Alkali-rich bedded units, on the other hand, contain a more diverse mineralogical assemblage featuring garnet-staurolite schist with associated plagioclase, biotite and muscovite. Traces of ilmenite are also present. Micas are medium to coarse and have a weak preferential orientation, whereas garnet and staurolite porphyroblasts clearly overgrow the older rock fabric and appear to be largely post-kinematic with regards to deformation.

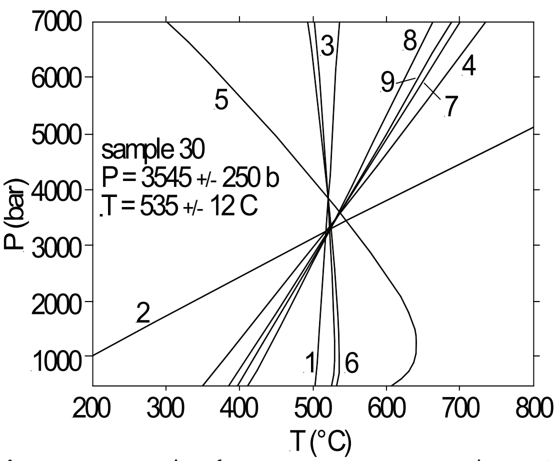
Staurolite-garnet schist was sampled at four different locations along the southwest margin of the stock for petrographic and electron microprobe analysis. Mineralogical data are presented in Table 1. The assemblage of garnet-staurolite-plagioclase-biotite-muscovite-quartz is ideal for metamorphic pressure-temperature determinations. Mineral equilibria data and software from Berman (1991; TWEEQ) was used to establish converging pressure-temperature intercepts for three independent reactions within the available mineral assemblage (Fig. 2). Results are shown in Figures 2 and 3. Pressure is estimated at between 2950-3830 bar, averaging 3440 ± 470 bar. Temperature is estimated at between 505° and 540°C, averaging 518° ± 22°C. These results occur near the upper stability limit of co-existing andalusite-sillimanite.

HYDROTHERMAL VEINS

In the Keno Hill district, mineralized veins are dominated by galena-sphalerite-tetrahedrite-pyrite, in a gangue of siderite and quartz. A number of accessory minerals are present and assemblages change, as well as the mineral compositions, according to position in the district (Lynch, 1989a,b). The full paragenesis is described in Boyle (1965) and Lynch (1989a,b). Pyrrhotite is an accessory mineral, which is restricted to the central portion of the regionally zoned hydrothermal system, including the Duncan, Flame and Moth veins situated between Keno Hill and Galena Hill. The presence of pyrrhotite defines the central mineral zone. Here, pyrrhotite is closely intergrown with the dominant sulphide assemblage of galena-sphalerite-pyrite-tetrahedrite, in addition to common arsenopyrite (Fig. 4). In general, pyrite and pyrrhotite may occur together under ideal conditions of temperature and sulphur fugacity. However, pyrrhotite is preferentially developed at higher temperatures, or when the sulphur content of mineralizing fluids diminishes. In the presence of pyrite and pyrrhotite, the iron content of sphalerite is pressure-dependant (*e.g.,* Scott, 1983; Lynch and Mengel, 1995), whereas the As content of arsenopyrite is dependant on

Table 1. *Electron-microprobe data from metamorphic aureole. Values in wt%, averaged from five or more determinations.*

SAMPLE	SIO_2	TIO_2	AL_2O_3	FEO	MNO	MGO	CAO	NA_2O	K_2O	BAO	SRO	TOTAL
biotite-00	33.80	1.48	18.45	21.31	0.03	8.23	0.19	0.18	8.45	0.09	-	92.81
biotite-10	33.52	1.53	18.35	20.92	0.04	8.45	0.03	0.18	9.22	0.15	-	92.99
biotite-20	33.53	1.53	18.16	20.87	0.03	8.29	0.04	0.13	9.06	0.13	-	92.38
biotite-30	33.57	1.47	18.15	21.45	0.04	8.27	0.04	0.12	9.17	0.12	-	93.00
muscovite-00	45.63	0.27	33.92	1.17	0.00	0.72	0.04	1.12	9.76	0.27	-	93.18
muscovite-10	45.93	0.42	33.71	1.13	0.02	0.76	0.03	1.15	9.72	0.25	-	93.43
muscovite-20	45.65	0.25	33.36	1.16	0.04	0.75	0.02	1.15	9.75	0.34	-	92.79
muscovite-30	44.83	0.23	34.78	0.99	0.03	0.40	0.03	1.46	9.51	0.32	-	92.79
staurolite-00	33.37	1.46	18.16	21.45	0.03	8.51	0.16	0.11	8.47	0.16	-	92.55
staurolite-10	26.99	0.56	51.68	14.13	0.06	1.35	0.02	0.00	0.01	0.07	-	95.26
staurolite-20	27.27	0.51	51.79	14.04	0.10	1.36	0.02	0.00	0.00	0.05	-	95.63
staurolite-30	41.59	0.23	30.28	6.35	0.02	2.71	0.03	0.80	8.11	0.17	-	90.53
plagioclase-00	59.87	-	24.12	0.20	-	-	6.06	7.99	0.13	0.09	0.11	98.57
plagioclase-10	59.14	-	25.14	0.08	-	-	6.98	7.44	0.14	0.13	0.26	99.32
plagioclase-20	60.97	-	23.99	0.21	-	-	5.51	8.24	0.07	0.12	0.14	99.26
plagioclase-30	58.36	-	25.14	0.28	-	-	7.13	7.21	0.13	0.12	0.07	98.46
garnet-00	37.17	0.06	20.58	34.61	5.03	1.42	2.42	0.00	0.00	-	-	101.30
garnet-10	36.70	0.05	20.46	35.09	4.31	1.51	2.39	0.01	0.00	-	-	100.54
garnet-20	36.84	0.06	20.42	35.36	3.85	1.55	2.38	0.01	0.00	-	-	100.52
garnet-30	36.84	0.07	20.34	34.92	4.18	1.50	2.44	0.01	0.00	-	-	100.34
ilmenite-10	1.16	50.96	1.32	45.62	0.77	0.41	0.07	-	-	-	-	100.66
ilmenite-20	0.57	52.35	0.66	46.00	0.27	0.15	0.04	-	-	-	-	100.37
ilmenite-30	1.98	49.91	1.27	46.08	0.69	0.39	0.17	-	-	-	-	100.79



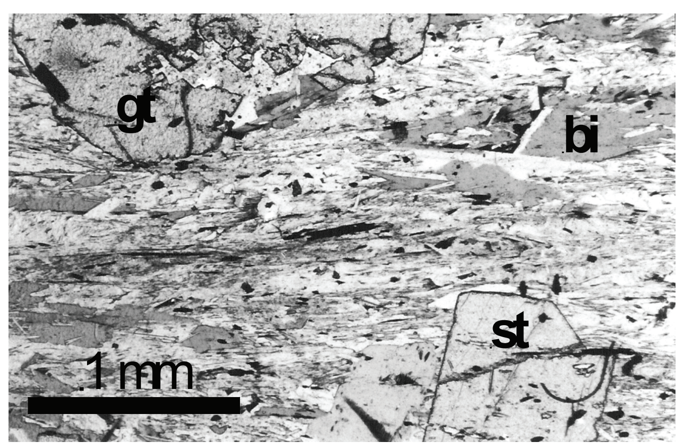


Figure 2. *Example of pressure-temperature determination for staurolite-garnet schist in metamorphic halo of the Roop Lakes pluton. Series of equations here comprise three independent reactions, with best estimate equilibria indicating a pressure of 3514 ± 230 bar and 533° ± 11°C. Determinations were made using TWEEQ software and thermodynamic database of Berman (1991). Photomicrograph in plane polarized light displays staurolite and garnet porphyroblasts surrounded by, and overgrowing, a matrix of quartz, biotite and muscovite, with minor plagioclase. Reaction mineral abbreviations from Berman (1991).*

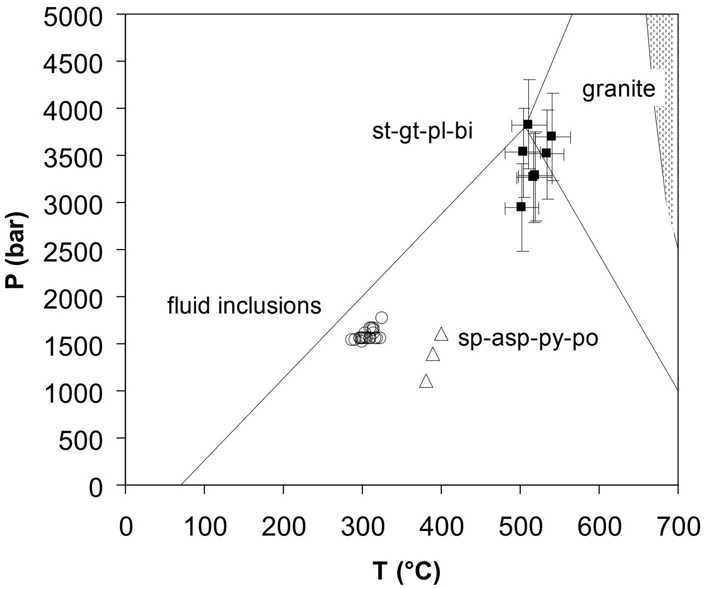


Figure 3. *Pressure-temperature plot of data from Keno Hill district and metamorphic halo along margin of Roop Lakes pluton; staurolite-garnet schist (black squares) determinations occupy higher pressure and temperature domain approaching granite solidus; fluid inclusion determinations from paragenetically early vein quartz in the mining district (Lynch, 1989), shown as open circles; coexisting pyrite-pyrrhotite-sphalerite-arsenopyrite shown as open triangles. py = pyrite, sp = sphalerite, gt = garnet, asp = arsenopyrite, po = pyrrhotite, st = staurolite.*

temperature (Sharp *et al.*, 1985). A total of 156 spots on sphalerite were analysed in three samples, averaging 18.2 mole % FeS at Flame and Moth and 19.0 mole % FeS at Duncan (Fig. 5). These values translate to pressures of approximately 1.1 and 1.6 kilobar, respectively. Arsenopyrite thermometry from these samples is reported in Sack *et al.* (2003), indicating temperatures between 389° and 408°C (Fig. 5).

DISCUSSION AND CONCLUSIONS

This paper provides the first quantitative determinations of pressure and temperature for contact metamorphism along the Roop Lakes stock specifically, or for plutons of the Tombstone Suite in general. Pressure and temperature determinations on the other hand, have been made for mineralized veins using fluid inclusion techniques (Lynch, 1989b), as well as from tetrahedrite composition (Sack *et al.*, 2003). Results from veins and metamorphism are plotted together on the pressure-temperature graph of Figure 3. Fluid inclusion pressure determinations were obtained only from quartz which is early in the vein paragenesis relative to vein carbonate minerals. Quartz fluid-inclusion pressures overlap those from the sphalerite barometer, which together span 1100-1800 bar. Arsenopyrite temperatures are similar to those from tetrahedrite determinations (Sack *et al.*, 2003), which at near 400°C, are significantly higher than temperature

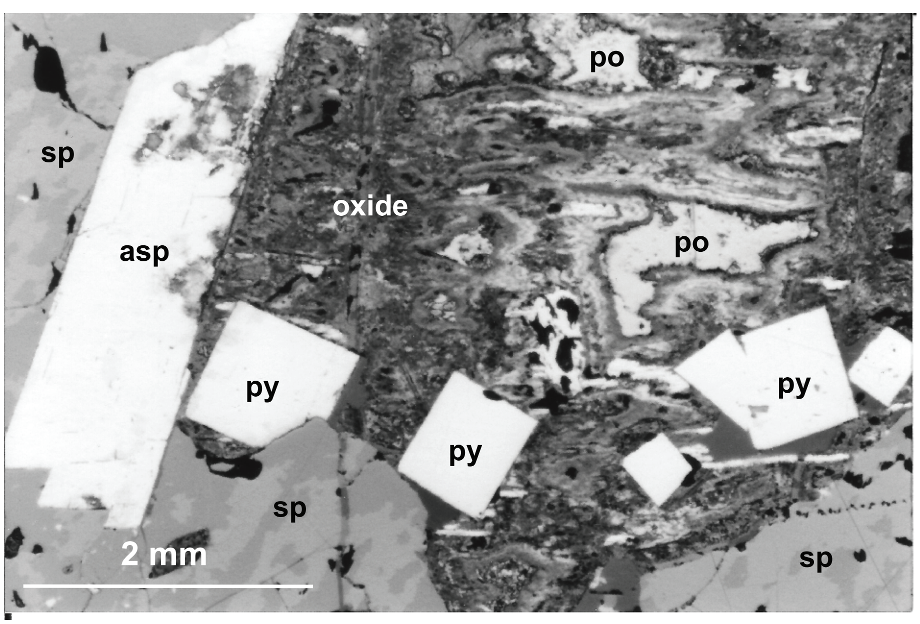


Figure 4. *Reflected-light petrographic photograph of co-existing pyrite (py), sphalerite (sp), arsenopyrite (asp) and pyrrhotite (po); proportion of pyrrhotite is oxidized (oxide).*

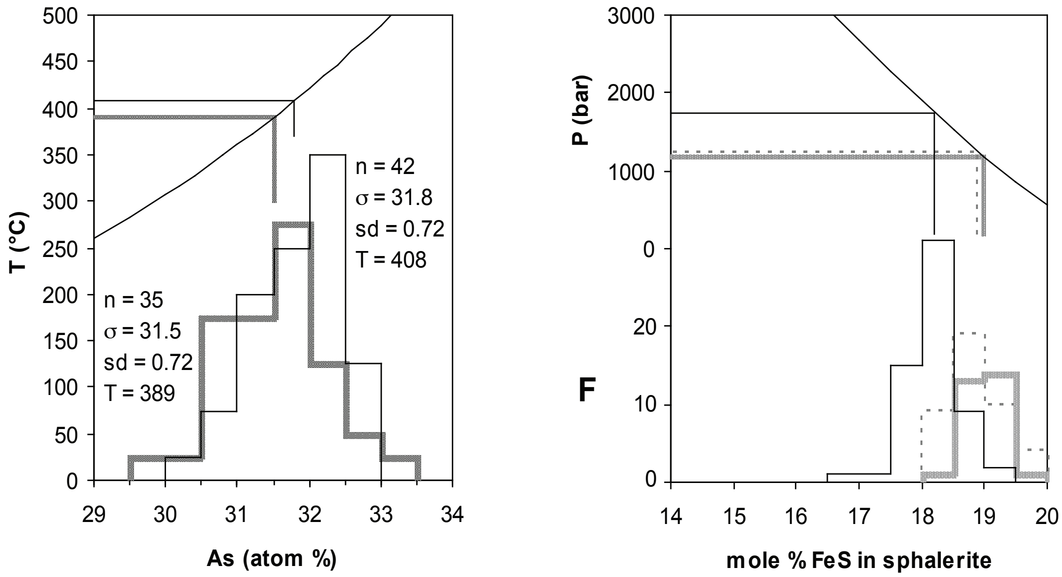


__Figure 5.__ Histogram of microprobe analyses for arsenopyrite and sphalerite from Flame-Moth and Duncan veins in central Keno Hill district, from samples with co-existing sphalerite-arsenopyrite-pyrite-pyrrhotite.

determinations from fluid inclusions within quartz (Fig. 3) which are nearer to 300°C. Pressure and temperature determinations from contact metamorphism are significantly higher, near 3440 bar and 518°C.

Although there is a large difference between the absolute pressure of contact metamorphism and the pressure of the hydrothermal veins, there is no discrepancy once converted to depth, while taking into account differences in lithostatic versus hydrostatic gradients. Contact metamorphism occurs under lithostatic conditions whereas hydrothermal circulation takes place largely under hydrostatic conditions. At similar depths, hydrostatic pressures and lithostatic pressures are separated by a factor of three, approximately. Metamorphic minerals support the weight of the rock column, whereas hydrothermal fluids in pore space or along an open fault system support the weight of the water column. Observations from deep boreholes at several locations worldwide indicate that hydrostatic pore pressures typically persist to depths of as much as 12 km in the upper crust (Zoback and Townend, 2001). Transient overpressures in hydrothermal systems may increase up to a maximum of approximately 80% of the lithostatic pressure, at which point brecciation and pressure release will occur. However, hydrothermal pressures more typically approximate 37% of lithostatic pressure. Taking into account coexisting hydrostatic and lithostatic conditions, the depth for the Roop Lakes stock and the veins of the Keno Hill district during sphalerite precipitation is estimated at approximately 10-13 km (Fig. 6).

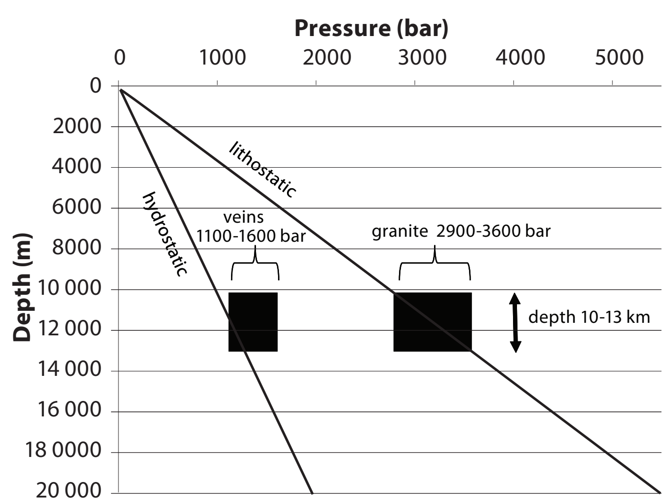


__Figure 6.__ Interpreted pressure-depth plot for hydrostatic and lithostatic profiles for veins and metamorphism in Keno Hill district and Roop Lakes stock.

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