GEOLOGICAL SURVEY OF CANADA
OPEN FILE 2123

Geology of the Epithermal Mount Skukum Gold Deposit, Yukon Territory

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1989

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Contribution to the Canada/Yukon Subsidiary Agreement on Mineral Resources 1985-1989 under the Canada/Yukon Economic Development Agreement

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SUMMARY

The Mount Skukum epithermal gold deposit consists of one major vein, the Cirque Zone, two smaller vein systems, the Brandy and Lake Zones, and a circular (in plan) gold-barren zone comprising alunite-rich alteration, all hosted by Eocene andesitic volcanic rocks of the Mount Skukum volcanic complex. The deposit is approximately 65 km southwest of Whitehorse, Yukon Territory. The geological reconstruction indicates that the Cirque vein opened by strike-slip movement on a fault structure, and that higher grades and thicknesses occurred where the fault refracted as it crossed a rhyolite dyke. The movement on this fault was probably caused by the same stresses that were responsible for the Brandy and Lake Zones. The Cirque Zone probably opened up more, and a wider vein formed, than in the Brandy and Lake Zones because in the Cirque Zone a rhyolite dyke was present, and the consequent refraction of the fault resulted in it having an orientation suitable for continued movement to cause a tabular opening to form. The strain ellipse associated with vein formation was oriented with its axis of maximum shortening north-northeast, its axis of maximum extension east-southeast, and its intermediate axis near-vertical. Brandy Vein 2 has the orientation of a tension vein, but on a more detailed scale it consists of many connected shear veins. The preferred interpretation of the structural and tectonic conditions that led to formation of the Brandy Zones is that the veins are hosted in Riedel shear fractures that developed in a zone of high strain and fracturing localized between the Tintina and Shakwak faults in Eocene time.

Alteration mineralogy and intensity are variable. Around the Cirque veins, alteration grades from potassic, through silicic, and phyllic, to chlorite-dominated propylitic. Around the Brandy and Lake veins, the alteration grades only from epidote-dominated propylitic to chlorite-dominated propylitic. In the Alunite Cap area, alteration mineralogy grades outward from massive alunite + silica, to pyrophyllite ± kaolinite, pyrophyllite ± silica, sericite, and finally to very weak chloritic-propylitic alteration. The texture and mineralogy of the alunite-silica alteration suggest it is the type thought to have formed, in other deposits, from magmatic volatiles. Its localization by synvolcanic caldera-margin faults supports a magmatic association. Gold mineralization is hosted in structures that are not related to volcanic activity, and may therefore be later than the alunite alteration, and unrelated to it.

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Purpose

This report presents the initial results of a Ph.D. study of the epithermal Mount Skukum gold deposit, Yukon Territory. It is a preliminary report of structural, stratigraphic and mineralogical relationships related to alteration and gold mineralization at the Mt Skukum deposit, together with a reinterpretation of available geological data, and is based on approximately two and a half months of mapping on surface, one month mapping underground, and one month logging drill core. The primary objectives of the Ph.D. research are to refine present knowledge of the geological setting of the deposit; to characterize, in detail, the mineralization; to define the transport and depositional conditions; and to delimit the source of precious metals.

Location and Mining History

The Mount Skukum mine lies within the Mount Skukum volcanic complex, in the Wheaton River district, approximately 65 km southwest of Whitehorse (Fig. 1). Exploration in the Wheaton River district began with the discovery of silver and antimony veins in 1893. AGIP Canada discovered the Mount Skukum vein deposit in 1981 by stream sediment sampling. Erickson Gold Mines Ltd. began underground development of the Cirque Zone in 1984. Proven reserves at that time were 148,980 tonnes of ore with average gold and silver grades of 24.98 g/t and 20.5 g/t, respectively (McDonald *et al.*, 1986). Production from the Cirque Zone began in February 1986 at an average rate of 300 tons (272 tonnes) per day. Development towards the more westerly Brandy zone began in 1986 and ore was produced from it for several months early in 1988. Development towards the Lake Zone began in 1987, but the ore shoots proved to be smaller than expected and were not mined.

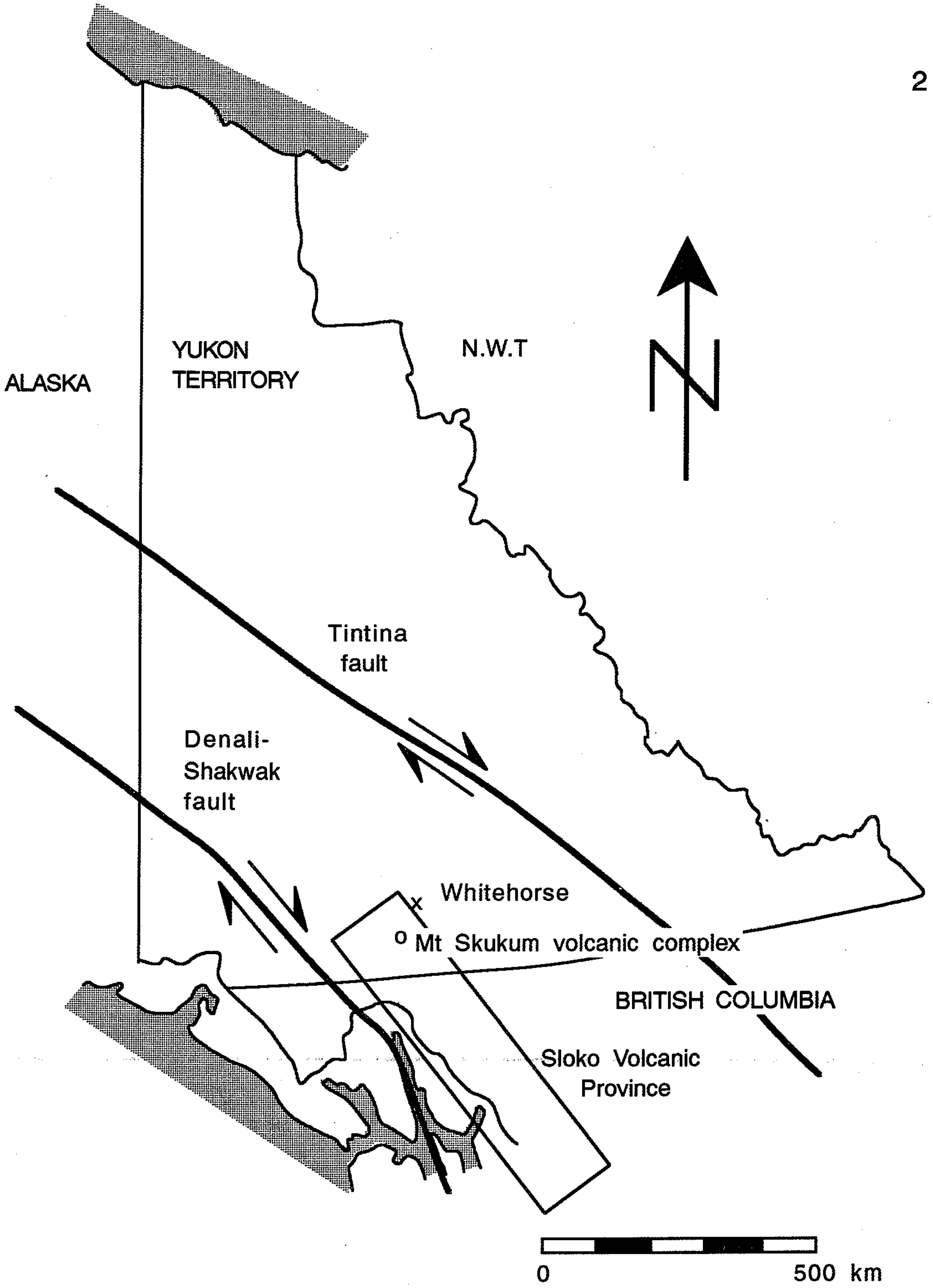


Figure 1. Location map of the Mt Skukum volcanic complex

Milling, mining, underground exploration, and development ended in the summer of 1988 owing to exhaustion of the ore reserves. The mine produced approximately 80,000 oz of gold in its brief lifetime.

Previous Work

M.J. Pride (née Smith) is engaged in a study of the overall geology of the Mount Skukum volcanic complex as part of a Ph.D. program (Smith, 1982, 1983; Pride 1985, 1986). B.W.R. McDonald, for his M.Sc., described the geology of the Mount Skukum deposit and studied the fluid inclusions and stable isotope geochemistry of the Cirque Zone (McDonald, 1987; McDonald *et al.*, 1986, McDonald and Godwin, 1986). D. Rucker carried out a fluid inclusion and oxygen isotope study of many of the silver-antimony veins in the Wheaton River district for his M.Sc. (Rucker, 1988), but did not examine the Mount Skukum deposit. Aurum Geological Consultants Inc. mapped all but the westernmost part of the Mount Skukum volcanic complex as part of a 1:50,000 scale mapping contract under the Canada - Yukon Economic Development Agreement (Doherty and Hart, 1988)

General Geology

The Mount Skukum volcanic complex underlies part of the Tagish Highlands physiographic region, which constitutes the boundary between the Intermontane Belt and the Coast Plutonic Belt (Holland, 1964). The complex is part of the Eocene Sloko Volcanic Province of southern Yukon and northern B.C. (Souther, 1977; Armstrong, 1988). The Sloko volcanic rocks are not correlative with the Mount Nansen, Carmacks, or Hutshi groups (Armstrong, 1988). The volcanic province formed in the last major magmatic episode in the Canadian Cordillera. This magmatism may have been related to an increase in the convergence rate between North America and the Farallon or Kula-Pacific plates, and may have ended because of a change in the relative motion of the ocean-floor plate and North America (Armstrong, 1988). In Middle to Late Eocene time the absolute motion of the Kula-Pacific plate changed from north-northeast to northwest, whereas the absolute motion of the North American plate remained west-southwestwards; thus their relative motion changed from northeastward subduction to northwestward transcurrent fault movement (Fig. 2, and Engebretson *et al.*, 1985). This change coresponded to a virtual cessation of subduction-related magmatism in Yukon and British Columbia (Armstrong, 1988). The magmatic front in Eocene time was about 250 km inland from the trench, and the Mt Skukum complex itself, approximately 300 km inland, assuming the trench was in the same location as it is today. The volcanic and intrusive rocks in the Mt Skukum volcanic complex are medium- to high-K calc-alkaline (McDonald, 1987), but are not shoshonitic.

The complex is preserved as a down-faulted block of intermediate to felsic volcanic rocks and derived sediments that lie unconformably on Cretaceous granitic rocks of the Coast Plutonic Complex, folded Jurassic sedimentary rocks, and Precambrian(?) Yukon Group metasedimentary rocks of the Yukon Crystalline Terrane, which is part of the Stikine Terrane (Fig. 3). The volcanic complex is elliptical in plan, and covers an area of about 140 sq km. Part of an andesitic stratovolcano forms the western and southern parts of the complex. The eastern part is dominated by felsic volcaniclastic rocks, in which a cauldron-subsidence

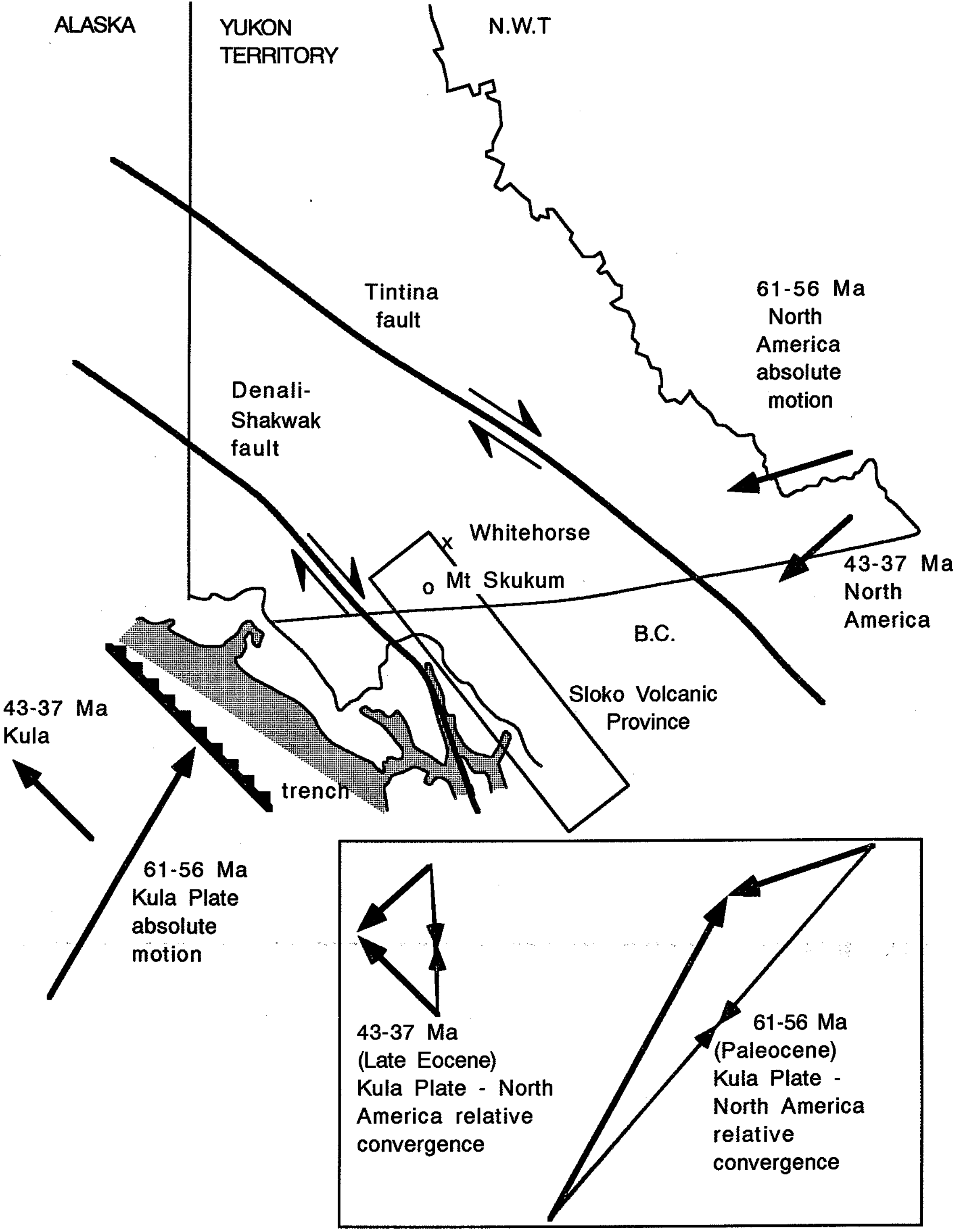


Figure 2. Plate tectonic map of the Yukon Territory showing Paleogene plate motions.

structure has been recognized (Pride, 1985, 1986). A quartz-feldspar - phyric rhyolite plug intruded the centre of the complex.

Gold mineralization at Mount Skukum is hosted in quartz-carbonate-sericite veins located in the mid-western part of the complex. The veins underlie Main Cirque, at the head of Butte Creek (Figs. 3 and 4). Mineralized veins cut most of the volcanic and hypabyssal rocks exposed in the deposit area, namely, andesite flows, rhyolite dykes, and a rhyolite ignimbrite, but some narrow intermediate dykes cut the veins. Multiple fracturing and filling is evident in all veins. Cockade and drusy textures, crustiform layering, colloform banding, and bladed calcite are common, all indicating open-space filling. Both adularia-sericite and quartz-alunite alteration are present in the Mount Skukum area, but the gold mineralization is associated only with the adularia-sericite - type alteration. The quartz-alunite - bearing assemblage occurs in the topographically-higher part of the system, forming the "Alunite Cap" area, but is barren. Silicified hydrothermal breccia, containing rounded silicified fragments that were probably hydraulically milled, occurs in the Alunite Cap area.

The vein systems in the Main Cirque area comprise three major, and many minor, north- to northeast-trending fault-hosted veins, with steep to vertical dips. The three major vein systems are the Cirque, Brandy and Lake Zones. The Cirque Zone, the largest of these, strikes about 035° and dips 80° east. The ore zone within the Cirque Zone was about 200 m long, extended 80 m down dip, and averaged 5 m wide. The ore zone was contained in a fault that is at least 1.5 km long, in an area where the fault changes strike as it transects a north-trending rhyolite dyke. The Brandy and Lake Zones are narrower, west-dipping vein

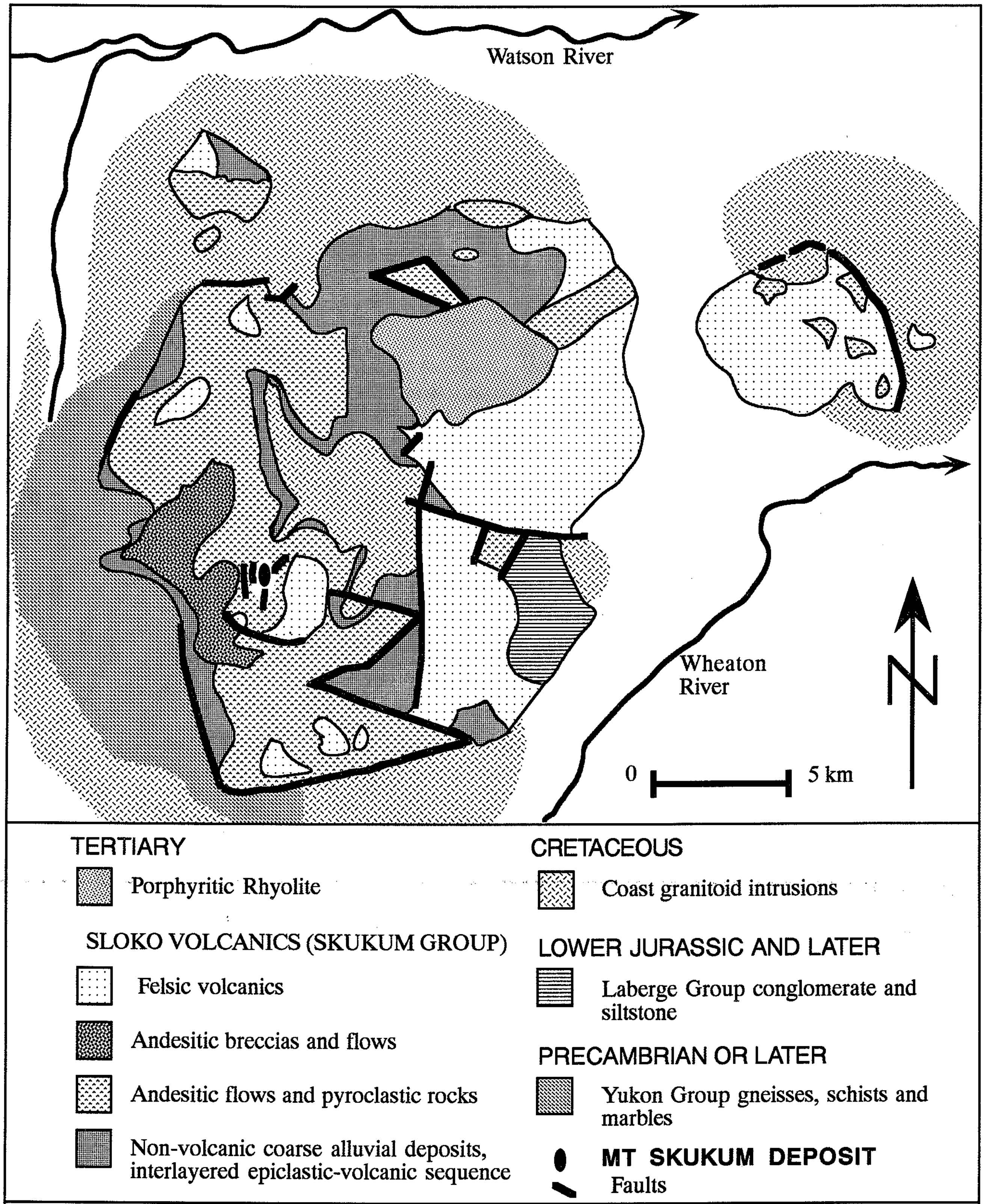
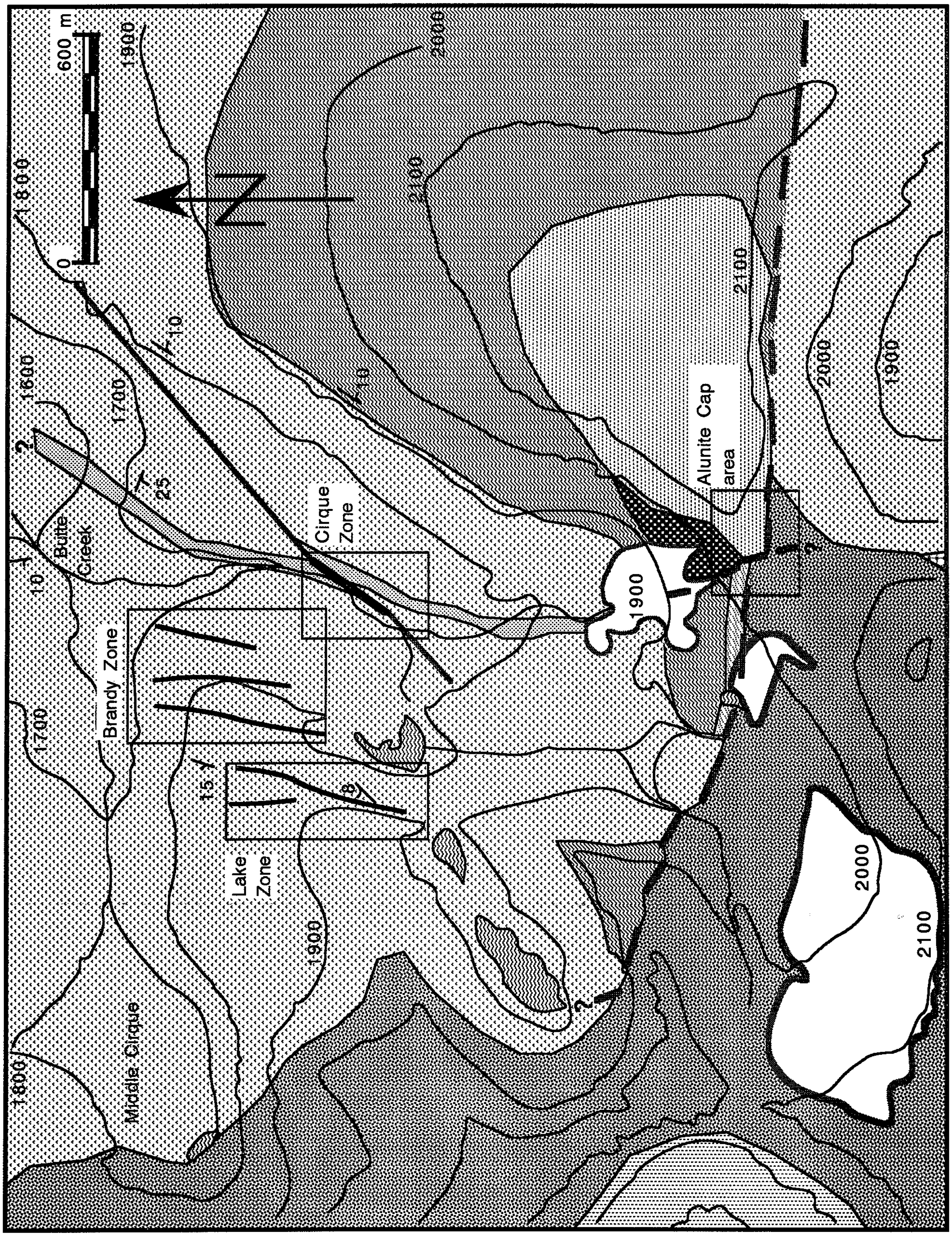


Figure 3. General geology of the Mt Skukum complex (after Pride 1986).

Figure 4. General geology of the Main Cirque area (on next page).

LEGEND

▒	Rhyolitic ignimbrite	Formation 4 (Pride 1986)
■	Mega-breccia / meso-breccia	
▨	Flow-banded rhyolite flows	
▧	Rhyolite breccia and lapilli tuff	
░	Massive rhyolite dyke and breccia dyke	
▓	Monolithic andesite breccia	Formation 5
▦	Heterolithic andesite breccia	
▩	Andesite flows , tuffs, block tuffs, and, lapilli tuffs	Formation 3
▥	Epiclastics	Formations 1 and 2
∿	Creeks	
◯	Snow fields and glaciers	
╱ ╱	Faults	
╱	Veins	
700	Contours in metres (contour interval 100 m)	


0
600 m
1800
1900
2000
2100
1600
1700
Butte Creek
25
10
Cirque Zone
Brandy Zone
Lake Zone
15
8
Middle Cirque
Alunite Cap area
1900
2000
2100
1900
2000
2100
1800

systems, lying, respectively, 300 to 600 m west of the Cirque vein, and ore-grade zones in them are approximately 100 m higher in elevation.

Results to Date

Stratigraphy and volcanic evolution of the Main Cirque area

The regional geology of the area within a few km radius of the mine has been mapped by the writer (Figs. 4 and 5). The geological history of the Main Cirque area interpreted from this mapping is generally similar to that proposed by McDonald (1987) and Doherty and Hart (1988), but differs from that of Pride (1986). Pride divided the volcanic stratigraphy into five informal "formations", and this subdivision is maintained here (Fig. 4). Formation 1 (the lowest) consists of clast- and matrix-supported pebble-boulder conglomerates and sandstones, lying unconformably on granodiorite. Formation 2 comprises felsic lapilli tuffs, block tuffs, and clast- and matrix-supported coarse conglomerates, and is locally gradational with Formation 1. Formation 3 consists of andesitic lava flows, andesitic breccia tuffs, and minor tuff and lapilli tuff, and is gradational from Formation 2. In the Main Cirque area Formation 4 is only a few hundred metres thick and comprises felsic block, lapilli tuff, flow-banded spherulitic and brecciated felsic flows and ignimbrite. However, in the northeastern part of the complex it is thicker and more variable. Pride (1986) defined Formation 5 as consisting mainly of heterolithic and monolithic andesitic breccia, but also included interlayered andesitic lava flows and pyroclastic rocks west of Main Cirque and south of Middle Cirque in Formation 5. Here, in agreement with McDonald (1987), these flows and pyroclastic rocks are included in

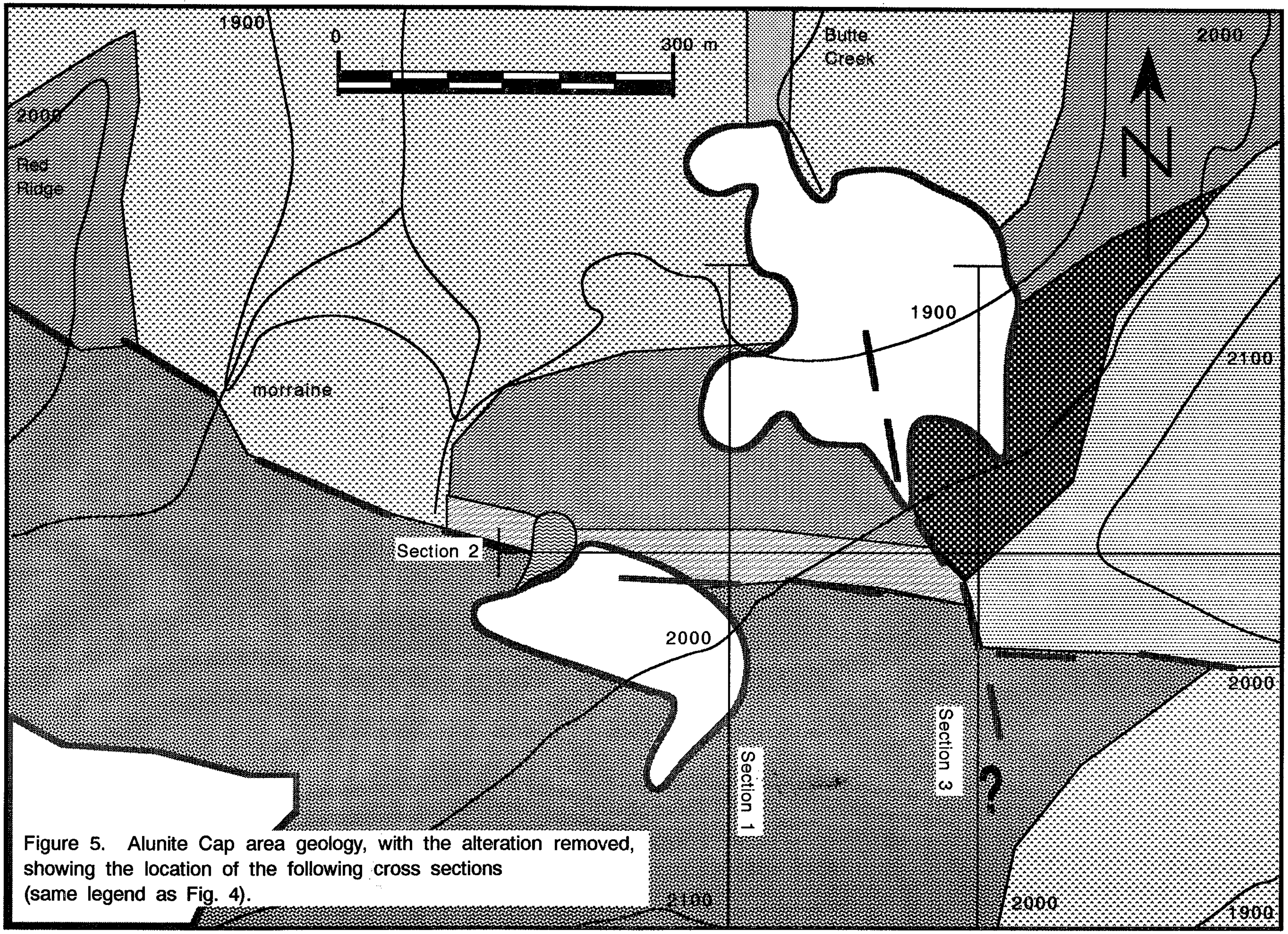


Figure 5. Alunite Cap area geology, with the alteration removed, showing the location of the following cross sections (same legend as Fig. 4).

Formation 3. The lower contact of Formation 5 is placed at the base of the heterolithic breccia, or, where it is absent, at the base of the monolithic breccia. Formation 3 coincides with Doherty and Hart's (1988) Cycle 3, Formation 5 with their Cycle 4, and Formation 4 with their Cycle 6. Cycle 5 of Doherty and Hart is only present in the eastern half of the volcanic complex, and is therefore absent in the Main Cirque area.

Pride (1986) stated that Formation 5 unconformably overlies 4. However, the author's mapping in the Alunite Cap area (see Map 1, back pocket, and Fig. 5) shows that, although felsic flows, lapilli tuff and ignimbrite of Formation 4 are lower in elevation than Formation 5, they are delimited by caldera-margin - type mesobreccias, and were down-dropped on caldera- or crater-bounding faults. It is concluded, therefore, that they were deposited after Formation 5.

In Middle Cirque and on the south and east sides of Mount Skukum, Formation 5 directly overlies Formation 3. In most exposures it is not clear if their contact is conformable. On the south side of Middle Cirque their contact is obviously an angular unconformity; however, flows and tuffs of Formation 3 there are nearly horizontal, and the steeply dipping contact probably represents the wall of the volcano's throat. At the south end of Main Cirque the contact relationship between Formations 3 and 5 is hidden by felsic volcanic rocks of Formation 4.

Formation 4, in Main Cirque, can be divided into upper and lower parts: the lower comprises flow-banded felsic flows, and felsic lapilli and breccia tuffs; and the upper contains a caldera-collapse breccia and a welded ignimbrite. The flow-banded felsic flows unconformably overlie andesitic flows and tuffs of Formation 3. They are, in turn, conformably overlain by felsic breccia and lapilli tuffs. The felsic flows and tuffs are bounded to the south by a steep, east-west - trending, undulose fault contact. South of this fault Formation 5 unconformably overlies Formation 3. The age of this fault is not clearly defined. Rocks of Formation 4 are not exposed south of this fault. The fault could be later than all volcanism, and felsic volcanic rocks of Formation 4 south of it eroded away. Conversely, it could be synvolcanic and the Formation 4 volcanics ponded against it. The undulose nature of the fault and its offset by a more clearly synvolcanic fault (described below) suggest that it was synvolcanic and may be a caldera margin fault, or the paleotopographic expression of one. The north-south cross-section of the south end of Main Cirque in Figure 6 illustrates the geological relationships described above.

The massive to flow-banded rhyolite exposed on Red Ridge, which is about 900 m west-northwest of the Alunite Cap area, has a gently southwest-dipping lower contact and overlies andesitic flows and lapilli tuffs of Formation 3. The southern contact of this rhyolite body, against monolithic andesite breccia of Formation 5, is sharp and nearly vertical. This vertical southern contact is thought to be the western extension of the east-west fault described above. No rhyolitic volcaniclastic rocks are exposed on Red Ridge, so it is not clear whether the rhyolite is intrusive or extrusive. The rhyolite body there could be the western extension of the rhyolite flows in the Alunite Cap area, or it could be a subvolcanic sill or laccolith.

Following deposition of the lower part of Formation 4, a north-trending synvolcanic fault formed, and mesobreccia to megabreccia, containing blocks of porphyritic andesite, andesite tuffs, conglomerate and flow-banded rhyolite, was deposited on the east side of this fault. This faulting and

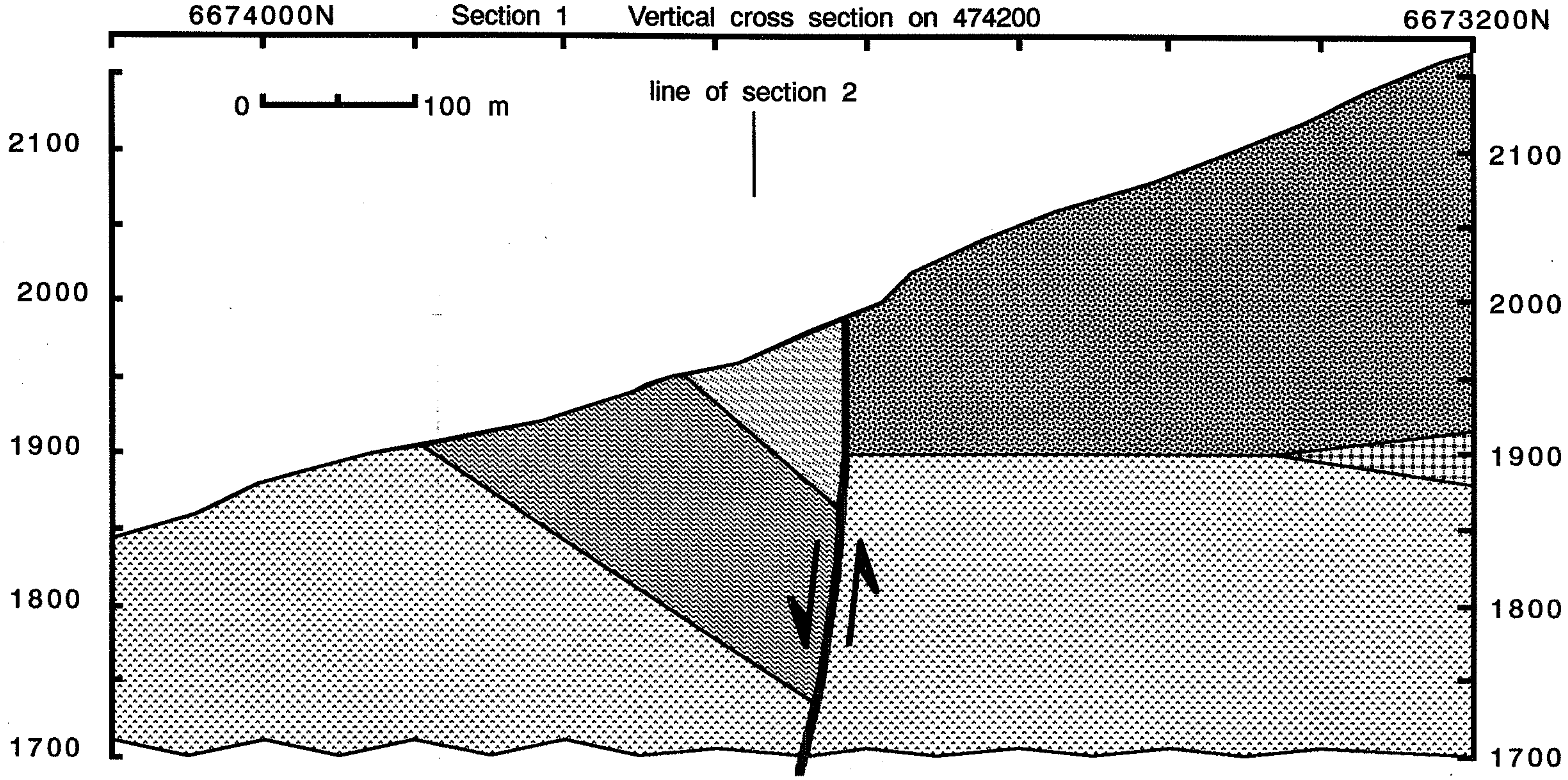


Figure 6. North - south cross section through the Alunite Cap area (looking east).

LEGEND

- ▒ Welded rhyolitic ignimbrite
- ▩ Mesobreccia
- ▒ Rhyolitic lapilli tuff
- ▒ Flow-banded rhyolite flows
- ▒ Monolithic andesite breccia
- ▦ Heterolithic andesite breccia
- ▒ Andesitic flows and tuffs
- / Fault

elevations are in metres
coordinates are UTM grid

deposition of the mesobreccia were followed by, and probably related to, eruption of the ignimbrite, which overlies the mesobreccia and the felsic flows of the lower part of Formation 4. Felsic breccia and lapilli tuffs of Formation 4 are not present beneath the ignimbrite, probably because they were eroded during its eruption. The east-west cross-section through the Alunite Cap area in Figure 7 shows the relationship of the mesobreccia and the north-trending fault.

The alteration and hydrothermal breccias of the Alunite Cap area are localized at the intersection of the two synvolcanic faults (see Map 1, in back pocket, and Figs. 7 and 8).

Structural Geology of the Brandy Zone

Presented in this section are the results of a detailed study of the structure of the Brandy veins. The structural analysis is based on structural measurements of vein-filled fractures and the orientation of slip lineations on the fracture walls, defined by underground mapping and drilling.

The Brandy veins are structurally controlled, and hosted in brittle fractures. Five closely-spaced, parallel zones of veining were defined during exploration, development and mining in the Brandy zone area, and were numbered BV1 through BV5, in order of discovery. BV2 was the only zone developed and mined, and thus the only one exposed for detailed mapping. Brandy Vein 2 was exposed underground for approximately 200 m of strike length, and over a vertical interval of about 50 m.

The objectives of this vein analysis are to: (1) define the geometry of the vein system; (2) determine the orientation and shape of the strain ellipsoid that describes the strain

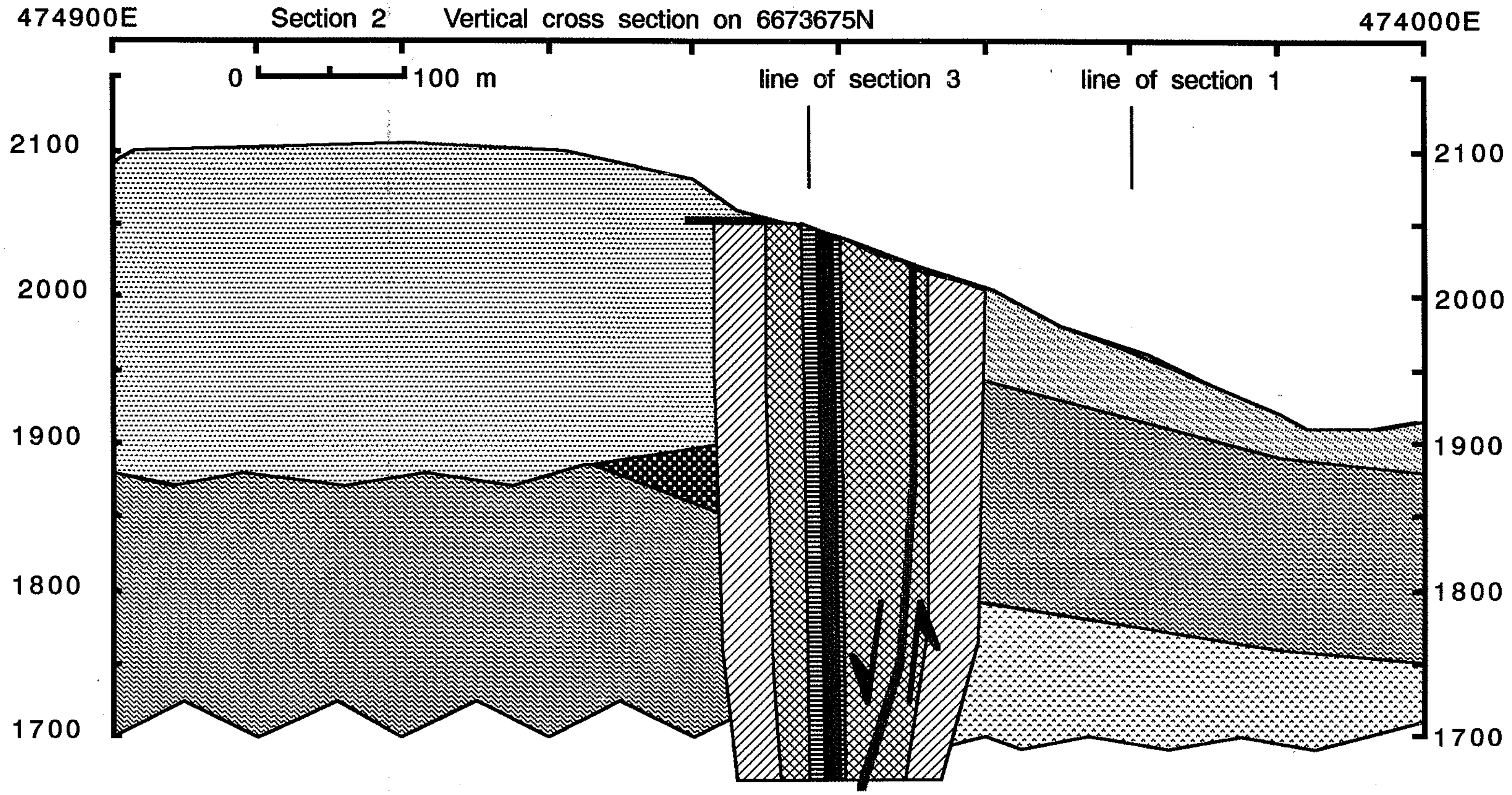


Figure 7. East - west cross section through the Alunite Cap area (looking south).

LEGEND

- ▒ Welded rhyolitic ignimbrite
- ▓ Mesobreccia
- ▒ Rhyolitic lapilli tuff
- ▒ Flow-banded rhyolite flows
- ▒ Andesitic flows and tuffs
- ▨ Serecitic alteration
- ▦ Pyrophyllite alteration
- ▤ Pyrophyllite + kaolinite
- ■ Alunite + silica
- ⬬ silica cap
- ▮ Fault

elevations are in metres
coordinates are UTM grid

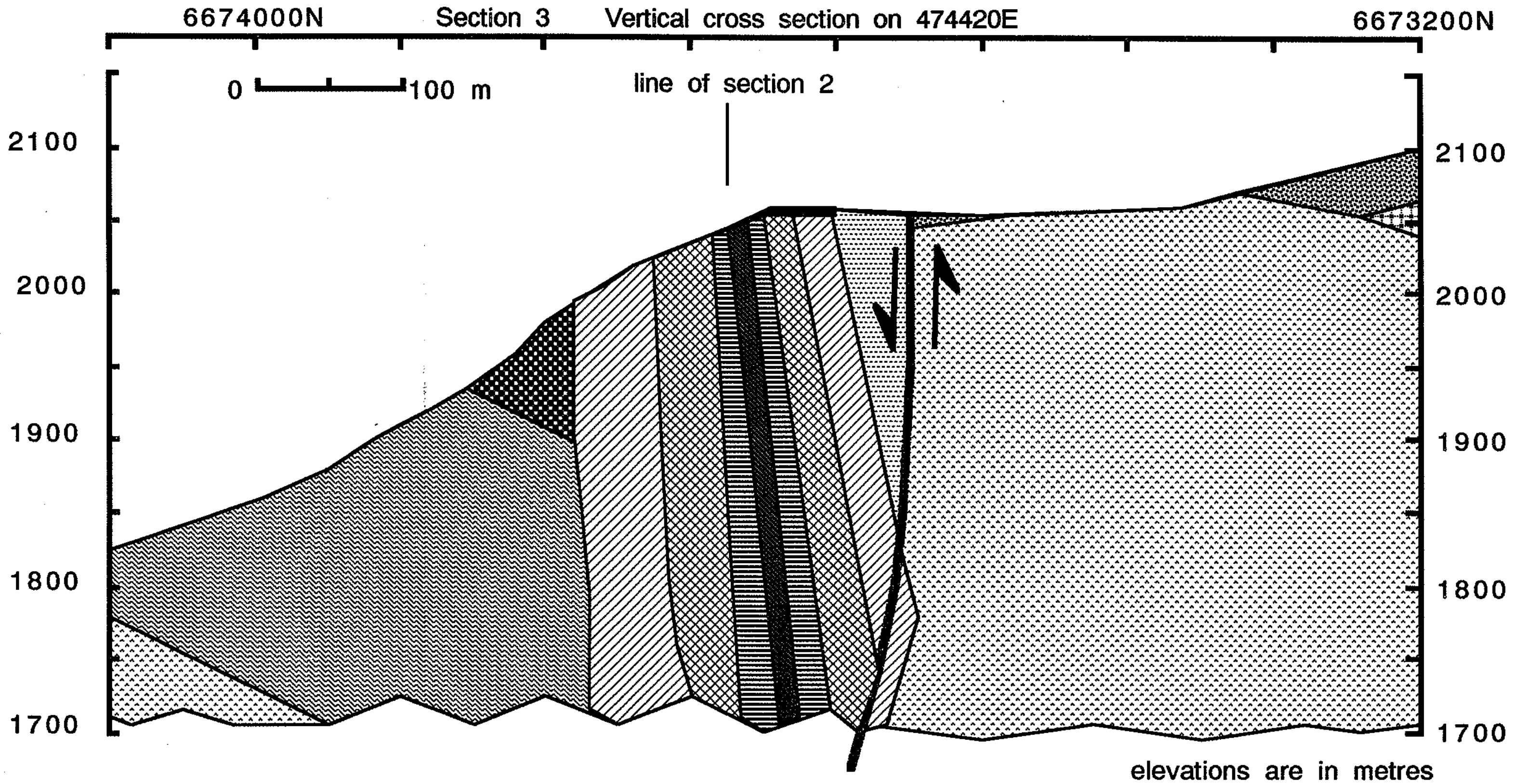


Figure 8. North - south cross section through the Alunite Cap area (looking east).

LEGEND

░	Welded rhyolitic ignimbrite	▒	Monolithic andesite breccia	▨	Serecitic alteration
▦	Mesobreccia	▦	Heterolithic andesite breccia	▩	Pyrophyllite alteration
░	Rhyolitic lapilli tuff	░	Andesitic flows and tuffs	▤	Pyrophyllite + kaolinite
▒	Flow-banded rhyolite flows	● silica cap	/ Fault	■	Alunite + silica

effected by movement on the vein-hosting fractures; and (3) determine the orientations of the stress axes for the stress field that caused the formation of the fractures and the pattern of movement in them.

Overall, BV2 strikes about 018°, and its dip varies between 70° and 55° to the west. Brandy Vein 2 is made up of a series of short, faceted veins, in some places joining in sharp, obtuse angles, or elsewhere disposed in an en echelon array. Some of the veins are curved. The nature of Brandy Vein 2 is shown on Map 2 (back pocket), which is a composite plan of three levels projected vertically onto one horizon. Slickensides are common on vein walls, indicating the veins are hosted by shear, not tension fractures.

Analysis of fractures

The poles to BV2 vein-filled fractures (Fig. 9A) cluster around four point maxima at 100/16, 082/22, 120/13 and 300/04 (Fig. 9B). It is inferred that the veins in the Brandy Zone system are hosted in four main sets of fractures, at 190/74, 172/68, 210/77 and 030/86, in order of decreasing abundance (Fig. 10).

From vein attitudes, the orientation and shape of the strain ellipsoid and the orientations of the stress axes can be estimated, assuming the veins formed by plane strain. Poles to fault planes should form a girdle defining a great circle (π circle) that contains s_1 and s_3, the pole to which (π pole) is s_2. The poles to the Brandy zone fractures do not clearly define a girdle, but the best-fit great circle through them is 336/12 and the pole to this, the orientation of s_2, estimated by this method, is 246/78 (Fig. 9A).

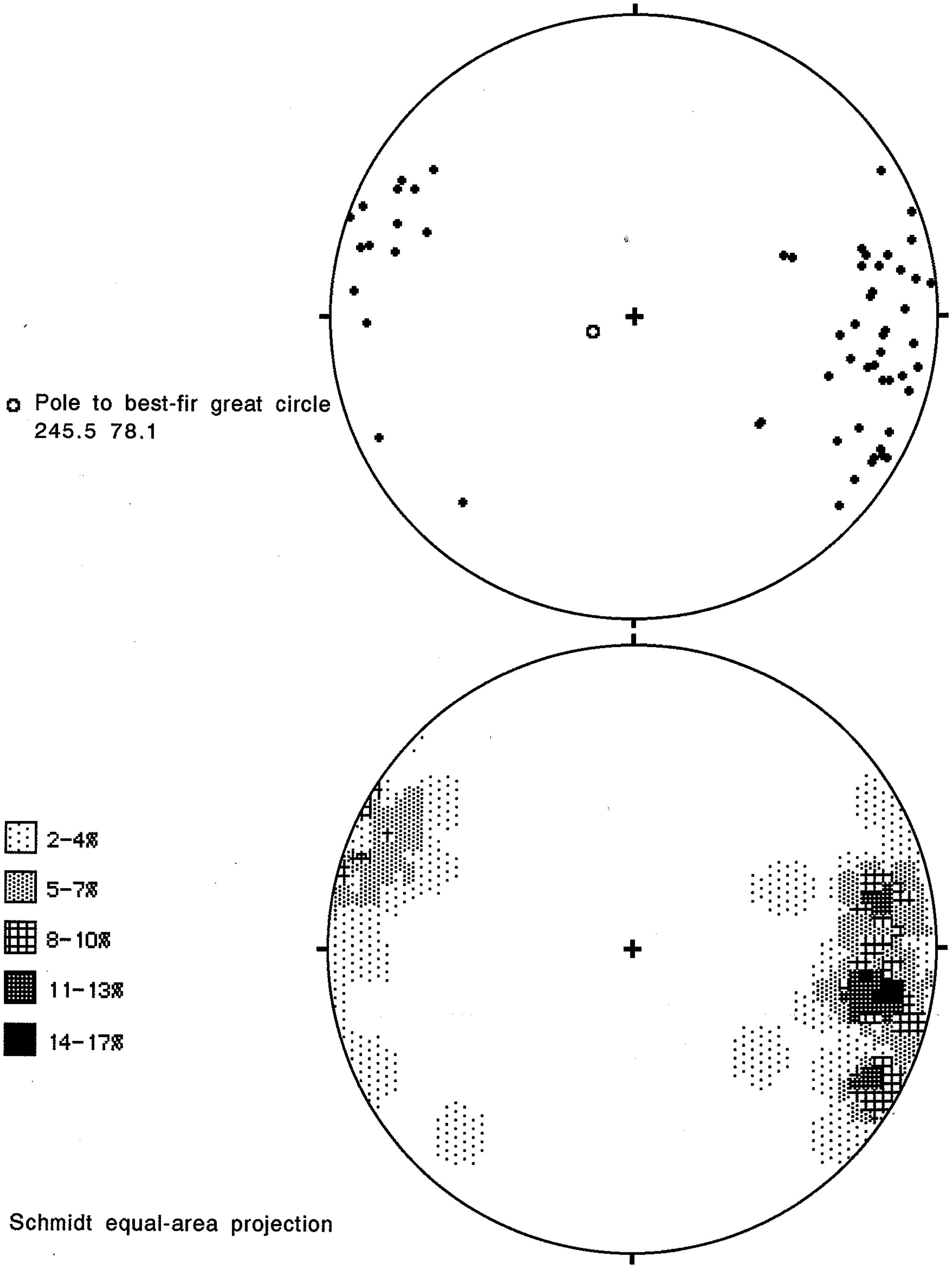


Figure 9. Stereonets of Brandy Zone shear veins. Top: poles to veins. Bottom: contoured per 1% area. N = 60.

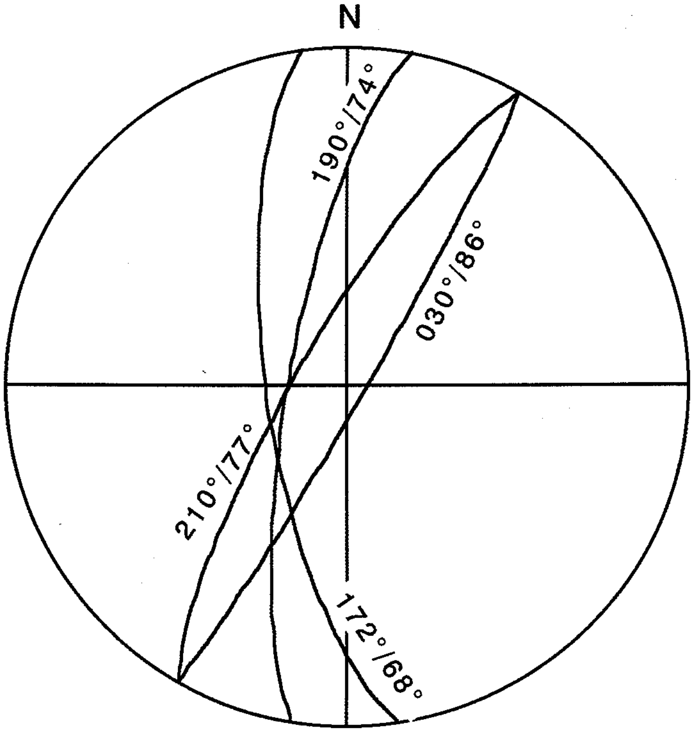


Figure 10. Stereonet showing an approximation of the four main veinlet sets comprising the Brandy Vein 2, based on maxima in Fig. 9B.

To check the interpretation above, the intersections of all the fracture planes were plotted in a "Beta diagram" (Fig. 11A) and the mean of the intersections calculated at 240/76. If the assumption of plane strain is correct, the intersections of all the fractures should form a point maximum (the β maximum), which corresponds to the orientation of s_2. However, rather than a single maximum, the fracture intersections are distributed in a girdle that has two large, equal maxima at 200/30 and 228/67, and two smaller maxima at 280/80 and 338/48 (Fig. 11B and 12). These maxima of vein intersections are close to the intersections of the planes corresponding to the maxima on the π plot (Fig. 9B and 10). The calculated mean Beta vector is between the two larger maxima. Geometrically, the β maximum should correspond to the π pole, but as noted by Phillips (1971, p. 68) in practice the "β axes are most satisfactorily located graphically from the π circle rather than directly from great circle intersections."

Analysis of lineations

All the lineations measured are slickensides on wall-rocks at the vein margins. Lineations (Fig. 13A) cluster around three point maxima (Fig. 13B), the largest one at 027/07, and the others at 002/18 and 341/23. The largest cluster of lineations coincides with the intersection of the planes corresponding to the two main maxima in the π diagram (Fig. 12), the 210/77 and 030/86 ones. The other two clusters of lineations are on the planes corresponding to the other two maxima in Figure 12. The best-fit great circle through the lineations is 222/26, and its pole is 132/64 (Fig. 14).

For faults formed under conditions of plane strain, slip

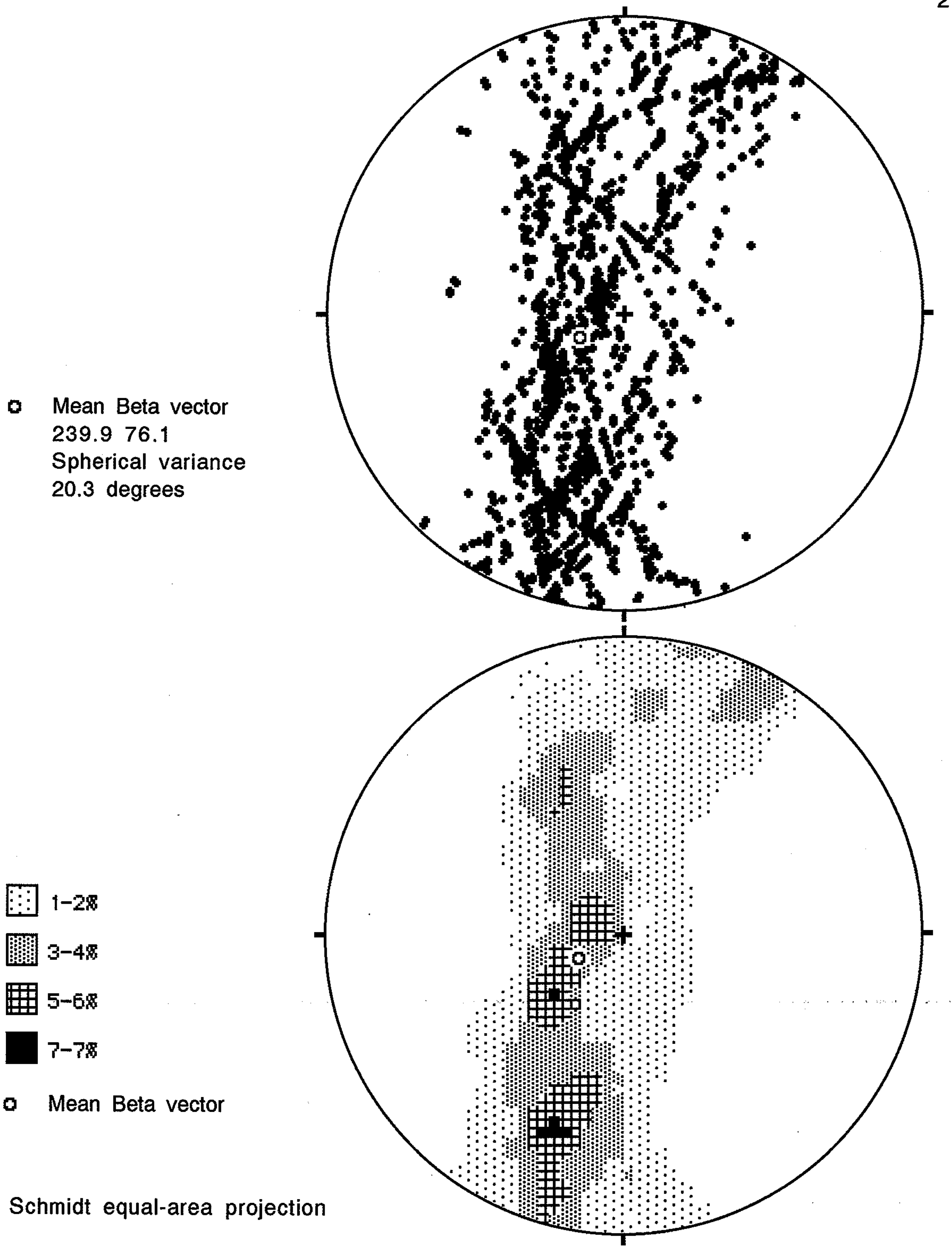


Figure 11. Stereonets of the lines of intersection of Brandy Zone shear veins, a Beta diagram. Top: intersection lines. Bottom: contoured per 1% area. N = 1768.

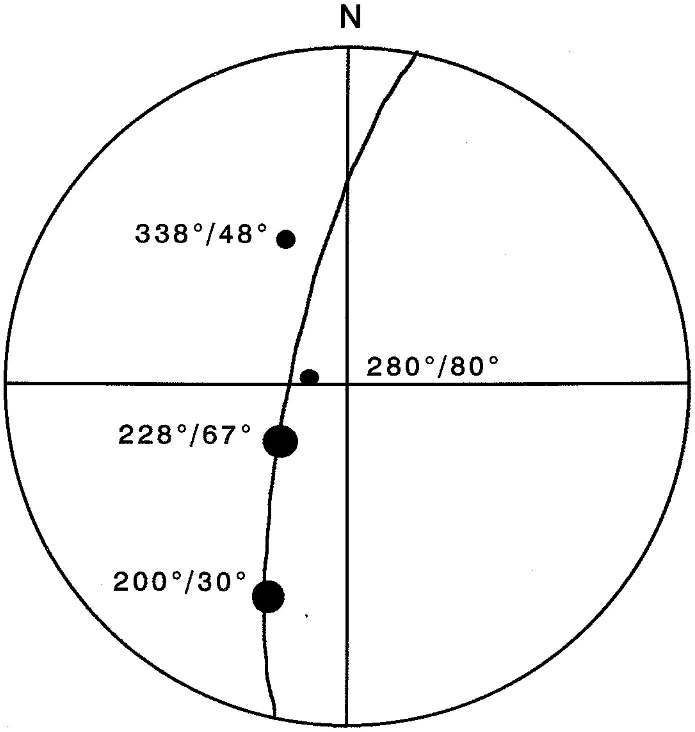


Figure 12. Stereonet showing the four major lines of intersection of Brandy veins, based on maxima in Fig. 11B.

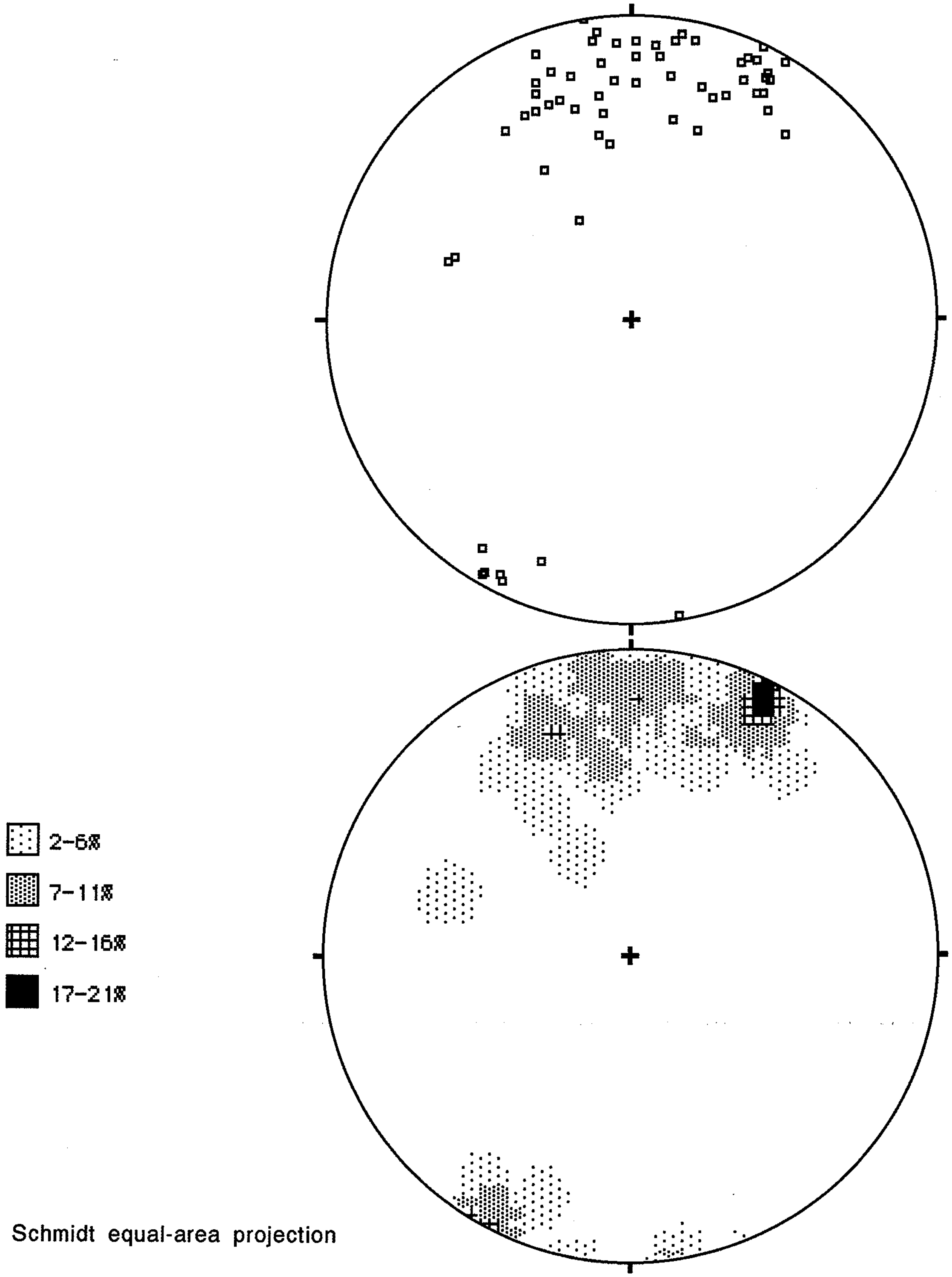


Figure 13. Stereonet of slip lineations on Brandy Zone vein walls. Top: lineations. Bottom: contoured per 1% area. N = 61.

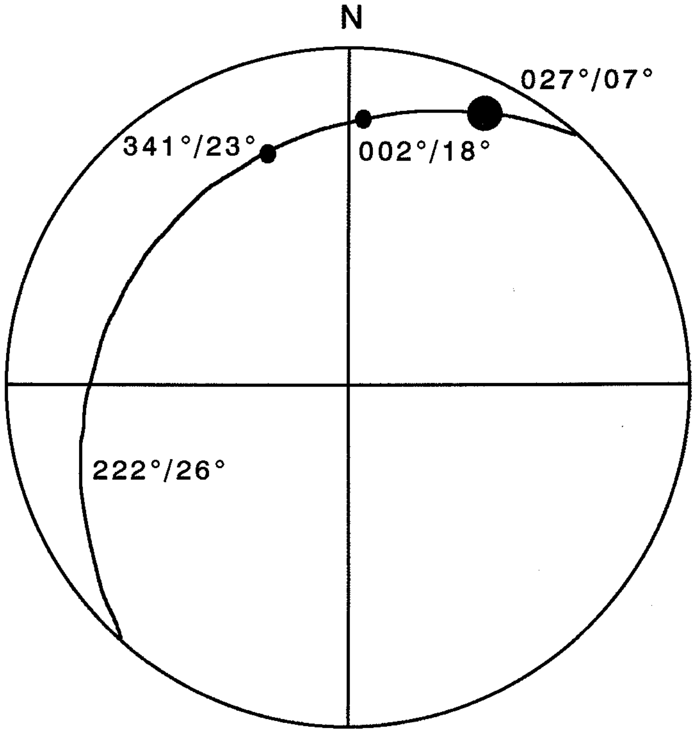


Figure 14. Stereonet showing the three maxima of slip lineations on Brandy vein walls, and a great circle through them.

lineations on conjugate faults should lie in the s_1 - s_3 plane, where it intersects the faults. The s_1 axis should bisect the two maxima of lineations corresponding to the intersections of the s_1 - s_3 plane with the conjugate faults. For the Brandy zone, the s_1 - s_3 plane should be the best-fit great circle through the lineations, 222/26, but there is a broad cluster of slip lineations covering about 60° of arc rather than two maxima. If the orientation of s_1 were estimated to fall in the middle of this cluster, it would be approximately 006/18. The s_2 axis should be the pole to the s_1 - s_3 plane, which for the Brandy zone would be 132/64. However, these estimates of strain axis orientations from lineation analysis are not the same as those from vein orientation analysis.

Discussion

The orientation of s_2 was determined by fracture analysis to be about 243/77, and by lineation analysis to be about 132/64. The s_1 - s_3 plane was determined by fracture analysis to be about 333/13, and by lineation analysis to be about 222/26. The inconsistency of estimates of the strain axes from fracture and lineation analyses indicates that the assumption of plane strain, upon which these analyses are based, is incorrect. Because there are more than two clusters of lineations and more than one cluster of fracture intersections, it is likely that the Brandy zone fracture sets developed in a three-dimensional strain field. The orientation of the strain axes in the case of three-dimensional strain can be estimated using Krantz's (1988) odd axis model.

In general three-dimensional strain there are three principal axes of extension: $\varepsilon_x > \varepsilon_y > \varepsilon_z$. One of these principal strain axes will have sign opposite to the other two, and this one is termed the odd axis. The other two principal strain axes are termed the intermediate axis and the similar axis (which is either ε_x or ε_z and has the same sign as the intermediate axis). For irrotational plane strain ε_y is zero, and the slip vectors are defined by the intersections of the conjugate faults and the $\varepsilon_x - \varepsilon_z$ plane. However, for general three-dimensional strain ε_y has an absolute magnitude greater than zero.

Provided none of the principal axes of extension is zero, a minimum of four sets of faults in orthorhombic symmetry are necessary to effect three-dimensional strain. Also, in the case of three-dimensional strain, none of the slip vectors will lie in any of the principal strain planes. Rather, the slip vector for each of the fault sets is the intersection of the fault plane and a second plane containing the pole to the fault plane and the odd axis (Fig. 15). In other words, the slip vector, fault pole and odd axis are coplanar. Because the odd axis lies in the plane of the fault pole and the slip vector for all fault plane orientations, it is possible to locate the odd axis by a stereonet construction. The plane containing each fault pole and associated slip vector can be represented as a great circle (GC in Fig. 15), and the common intersection of these great circles or their average intersection is the odd axis. Also, the poles to the great circles should cluster around the intermediate strain axis.

The intersections of all the great circles through the lineation and the pole to the fracture containing the lineation should ideally be a point maximum, but the Brandy zone data results in a girdle (Fig. 16A) that has a maximum at approximately 015/13 (Fig. 16B): this maximum is

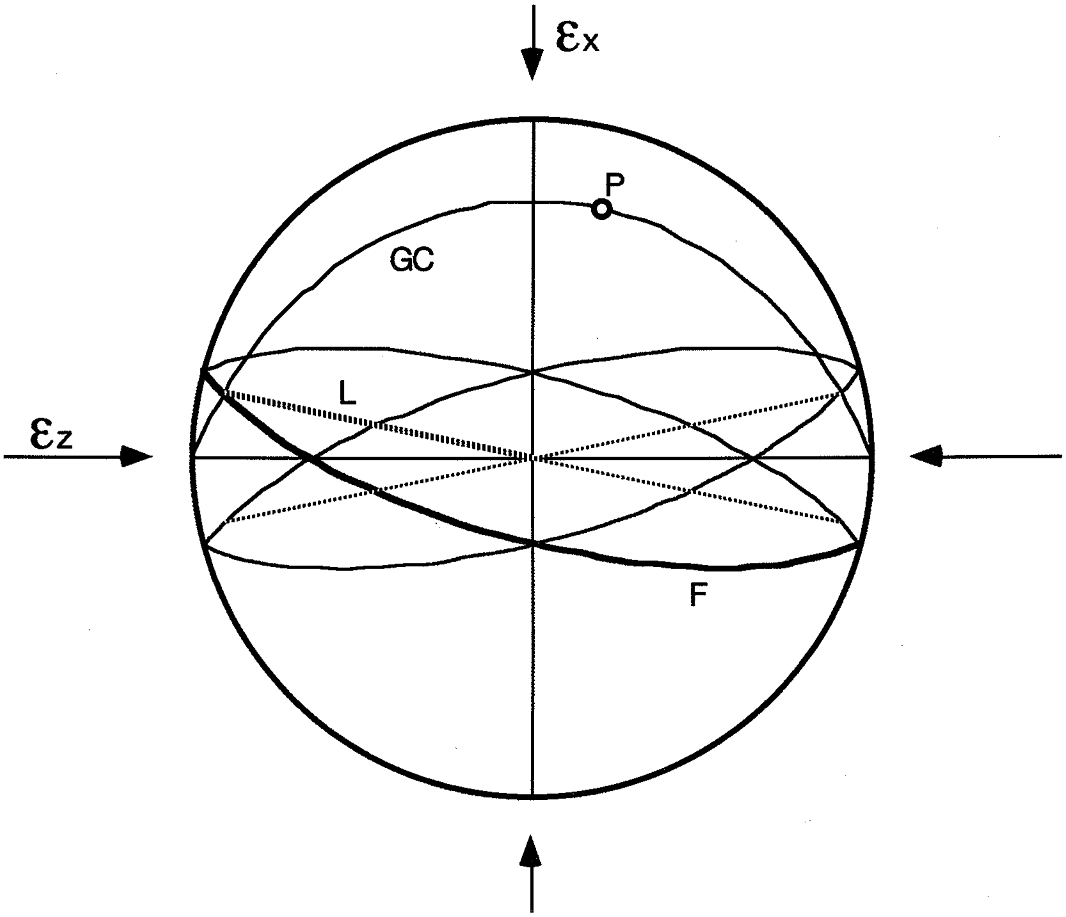


Figure 15. Stereonet of orthorhombic faults arranged in four sets (one heavy and 3 light solid arcs) symmetrical about the principal strain axes, and also showing slip lineations (one heavy and 3 light dotted lines).

F is one of the four faults.

P is the pole to F.

εx is the axis of maximum extension.

εz is the axis of minimum extension (maximum shortening).

L is the slip lineation on F.

GC is the great circle through εz, L, and P.

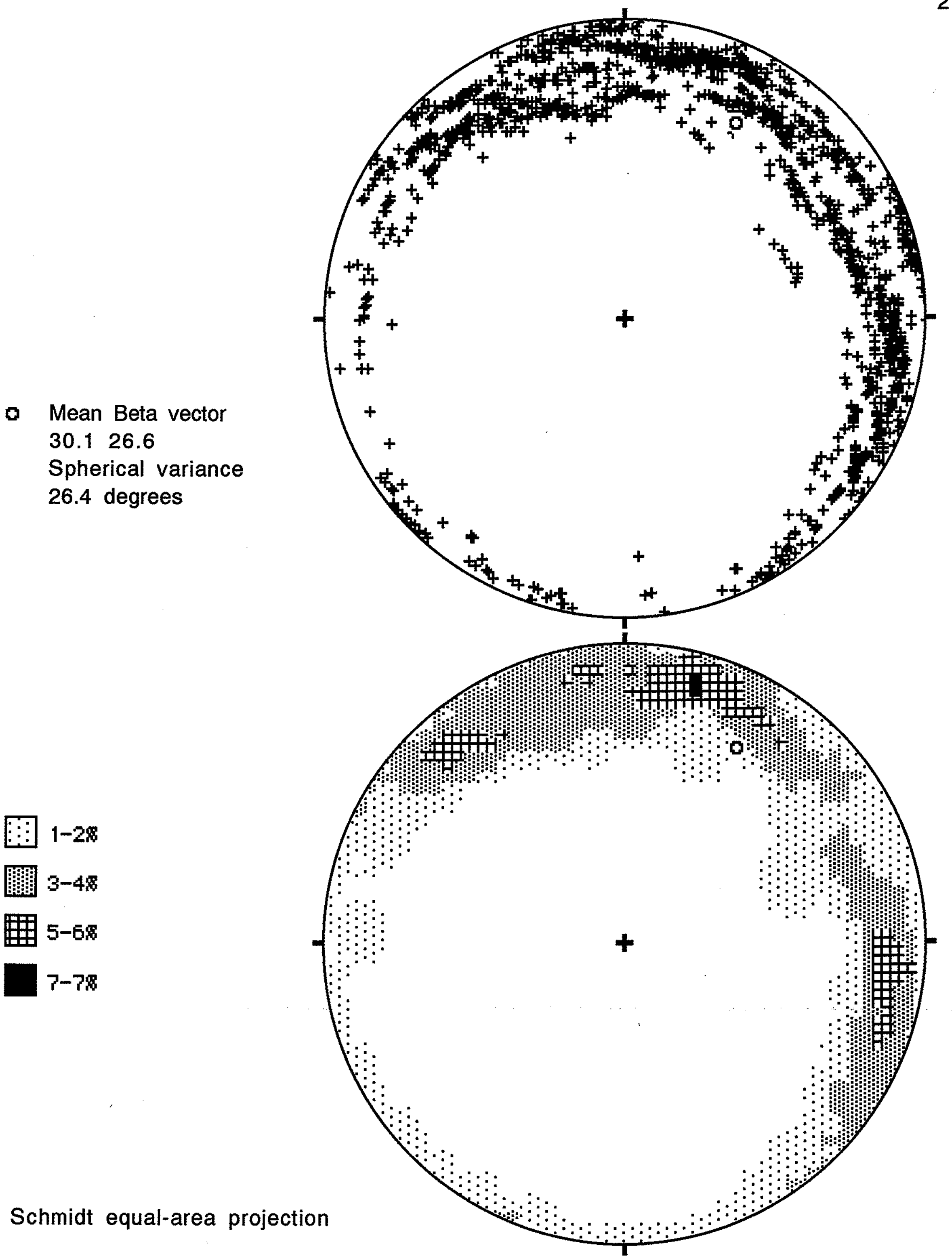


Figure 16. Stereonet construction for odd axis determination, showing the intersections of planes, where each plane contains the pole to a vein and the slip lineation on that plane's wall. The method is explained in the text and illustrated in Fig. 15. Top: lines of intersection. Bottom: contoured per 1% area. N = 1538.

interpreted as the odd axis. The other method to determine the odd axis is to plot the poles to the great circles, and to fit a plane through them; its pole should be the odd axis. Application of this second method to the Brandy zone data yields a cluster rather than a girdle of poles (Fig. 17A and 17B). A best-fit plane through this cluster of poles (Fig. 17A) results in an odd axis orientation of 018/29. An average of these two results could be calculated, but because of the potential error involved in estimating a great circle through a cluster of points, the result of the first method, 015/13, is considered the best estimate of the orientation of the odd principal strain axis.

The other two principal strain axes must lie in a plane perpendicular to the odd axis: that is, in the plane 105/77. There are two methods of estimating the other principal strain axes, each of which involves estimating one of them and solving geometrically for the other. The first method is to estimate two sets of great circles containing the lineation and the pole to the plane in which that lineation occurs, that intersect at the odd axis, and the similar axis should bisect the acute angle between them. The second method is to estimate the intermediate axis, which should bisect two equal maxima of poles to the same great circles, or coincide with one large maxima of these poles, and lie on the plane 105/77. Because the great circles do not form two obvious sets that intersect at the odd axis, whereas there is an obvious maximum of poles (Figs. 16 and 17), the second method is used here. The largest cluster of poles to the great circles is oriented at 245/72, and lies on the 105/77 plane (Fig. 17). This is interpreted as the intermediate axis. The similar axis is perpendicular to both the odd axis and the intermediate axis, and therefore is oriented at 119/13.

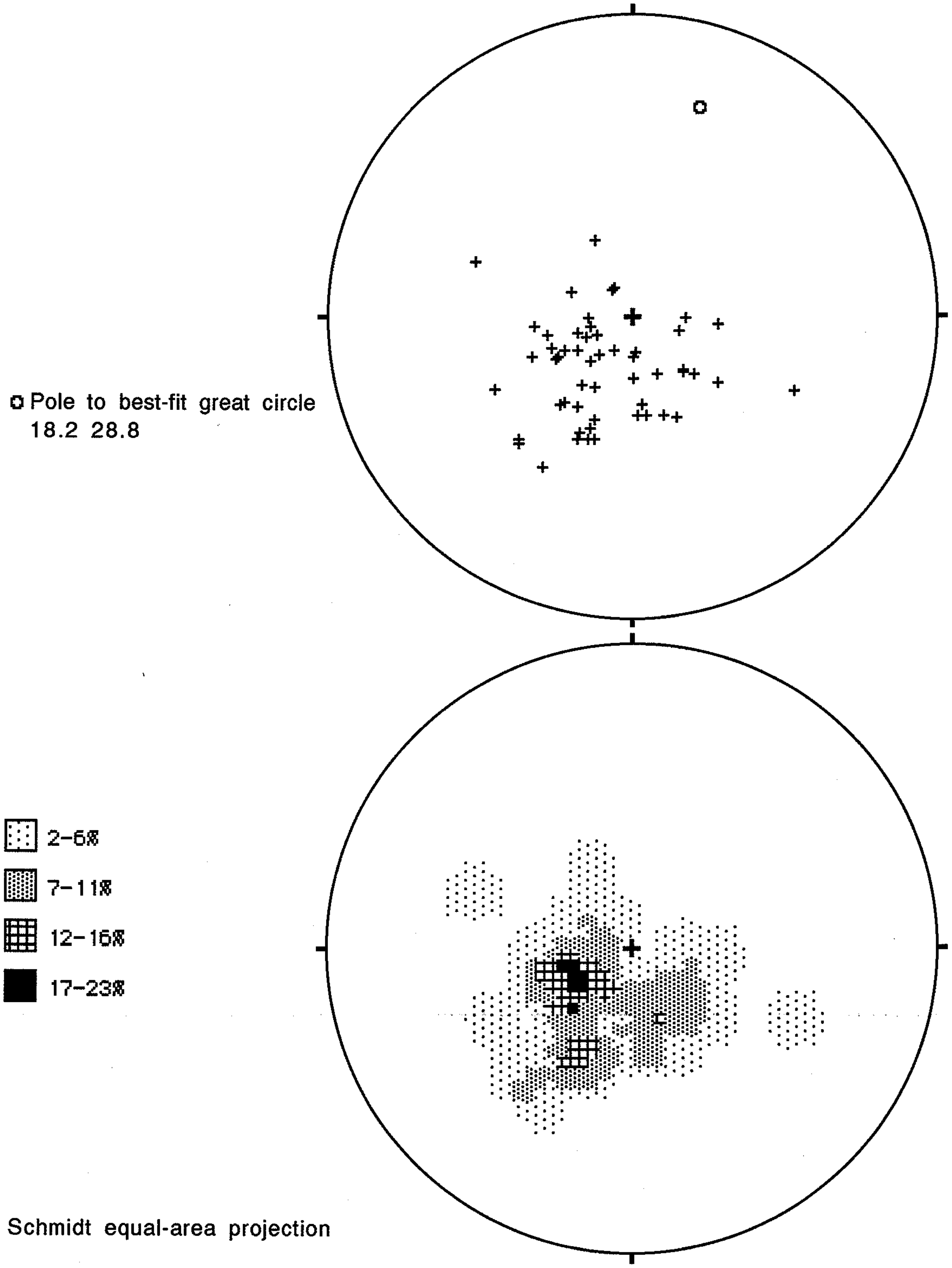


Figure 17. Stereonet construction for odd axis determination, showing the poles to planes, where each plane contains the pole to a vein and the slip lineation on that vein's wall. The method is explained in the text and illustrated in Fig. 15. Top: poles to planes. Bottom: contoured per 1% area. N = 56.

Whether the odd axis is the ε_x or ε_z axis is determined from other structural geological information. Shortening in the odd axis direction would mean that ε_z is the odd axis. Because slip lineations cluster around the shortening direction, and in the Brandy zone the lineations cluster near the odd axis, it is concluded that the odd axis for the Brandy zone was ε_z. The orientations of the three principal strain axes are shown on the stereonet in Figure 18 and a schematic diagram of the fractures that host the veins, in the block diagram, Figure 19. The ellipsoid that represents the strain associated with vein formation was oriented with its axis of maximum shortening north-northeast, its axis of maximum extension east-southeast, and its intermediate axis, which was also an axis of extension, near-vertical.

The ε_y - ε_z plane approximates the overall trend of BV2, 018/55-70. Because the overall attitude of this vein system is approximately perpendicular to ε_x it appears to have formed with the orientation of a tension vein. Thus, Brandy Vein 2 may have formed as a series of four connected sets of shear veins that had the general orientation (but not the form) of a tension vein. Curved veins could have formed where strain was transferred from one fracture set to another during fracture development.

McDonald *et al.* (1987) suggested that the morphology of Main Cirque, which contains the ore deposit, was controlled by high-angle normal faults that produced a step-like topography composed of three down-dropped blocks. They also suggested that the veins formed in the bounding faults between the down-dropped blocks, when they were reactivated as a result of resurgent doming. The three-dimensional strain analysis of the Brandy zone demonstrates, however, that strike-slip faulting, not normal faulting, was the predominant mechanism

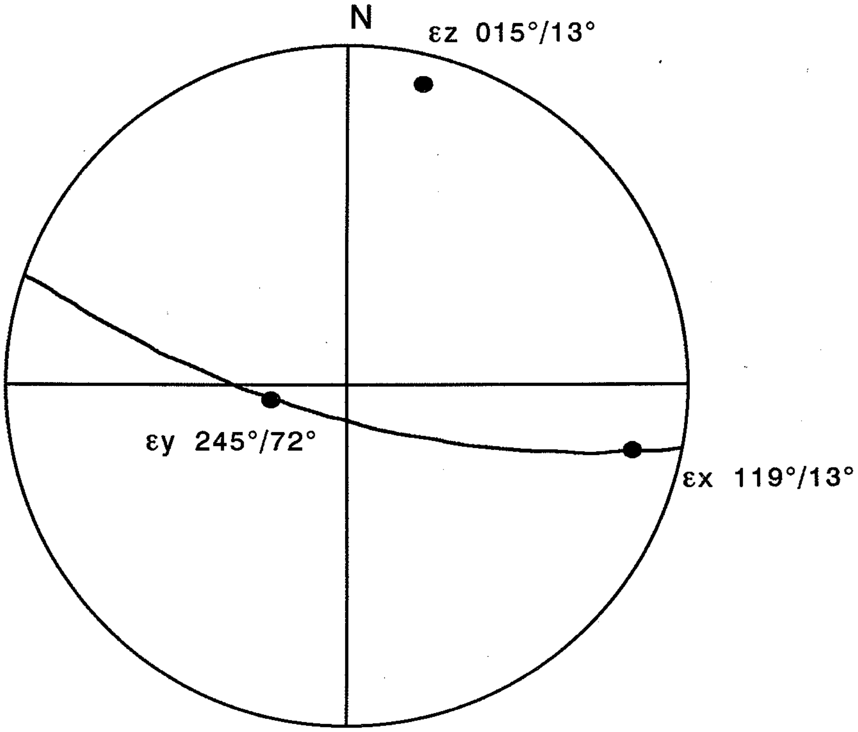


Figure 18. Stereonet showing the estimated principal strain axes during vein formation, based on anaylsis of veins and lineations in the Brandy Zone. The axes of extension are εx > εy > εz, where εz is negative, and, εx and εy are positive.

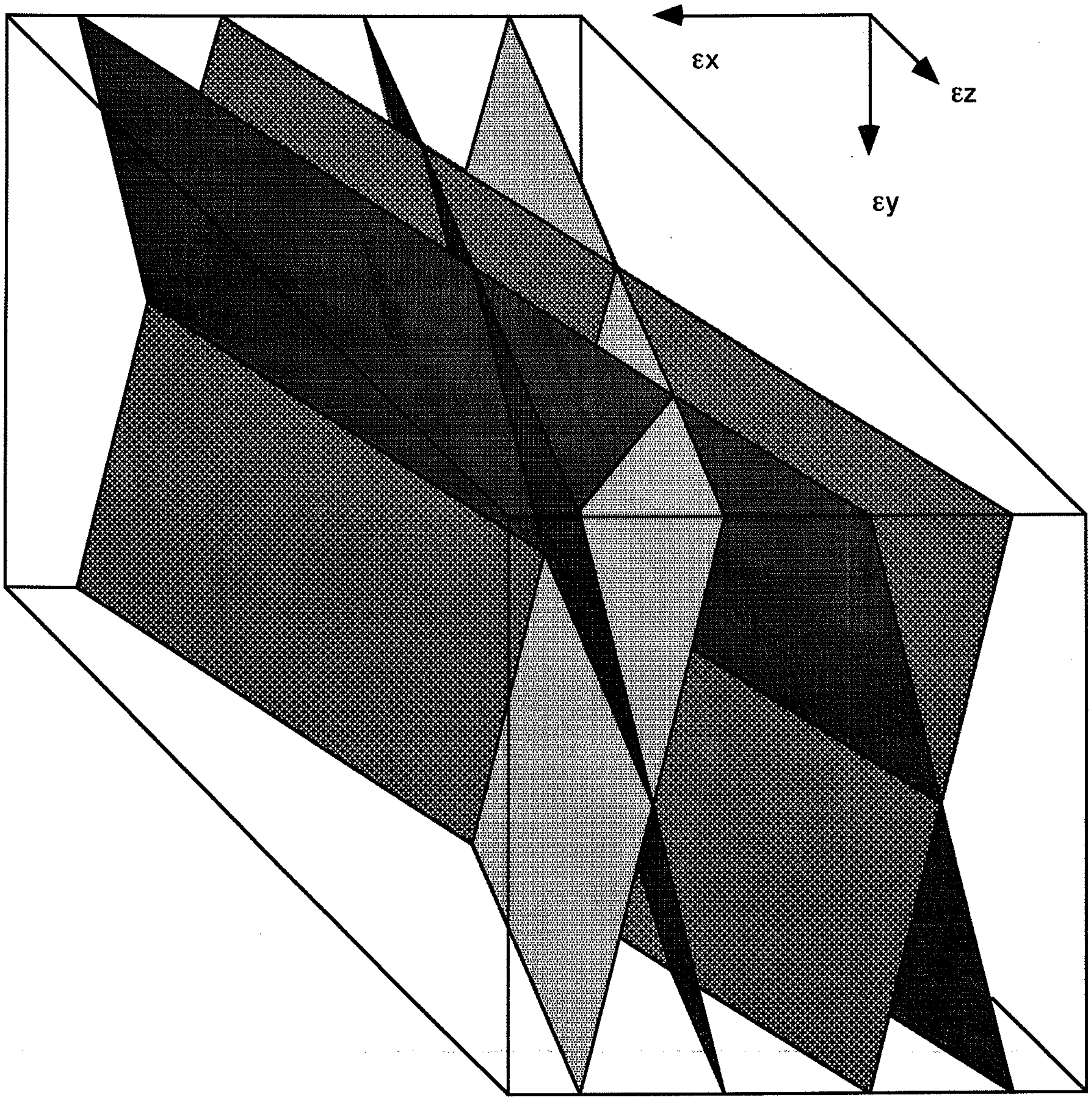


Figure 19. Schematic block diagram of four sets of faults in orthorhombic symmetry, in which the Brandy veins formed, and the principal strain (extension) axes that would have been responsible for their formation.

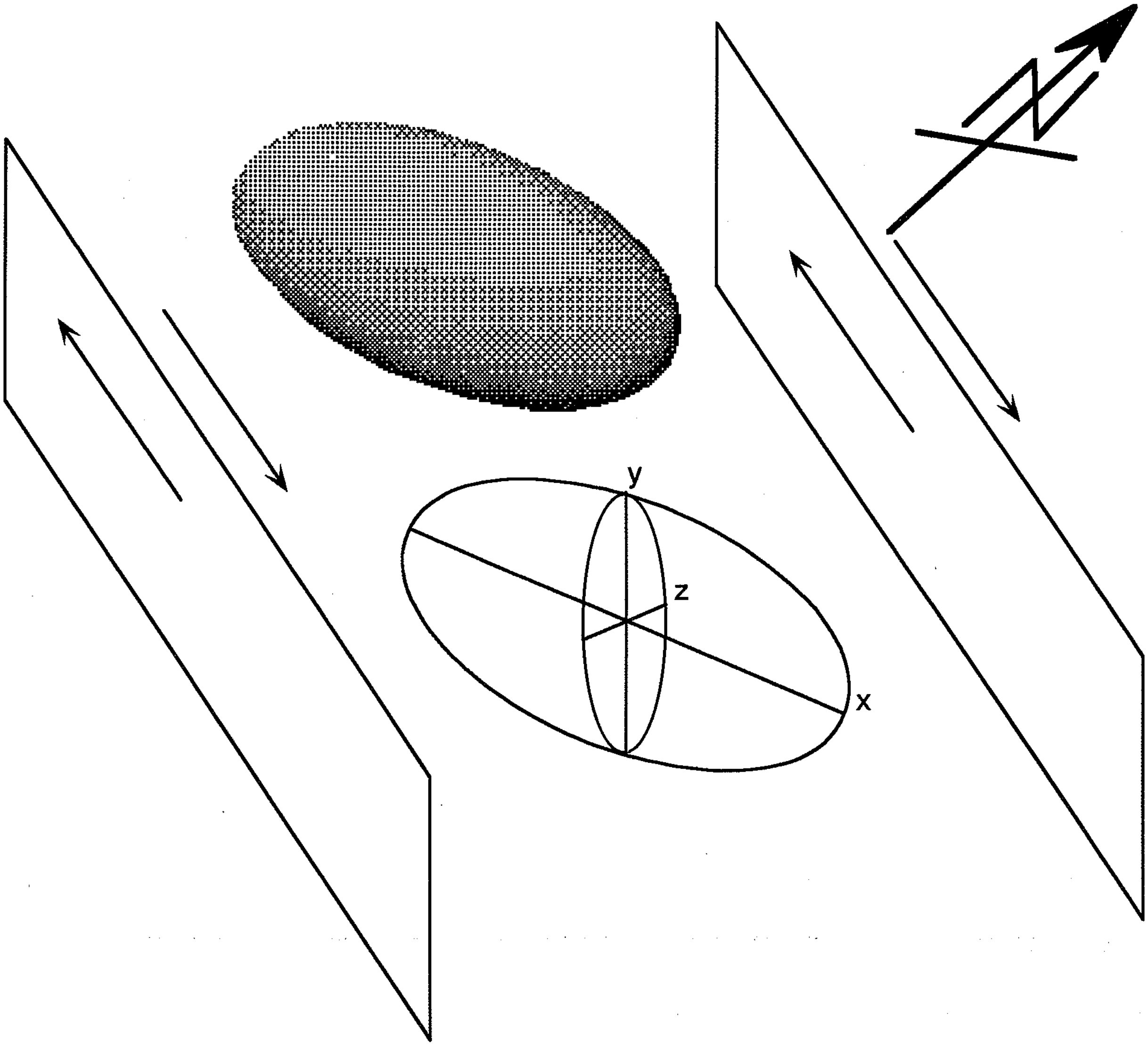


Figure 20. Strain ellipsoid orientation between two sub-parallel strike-slip faults.

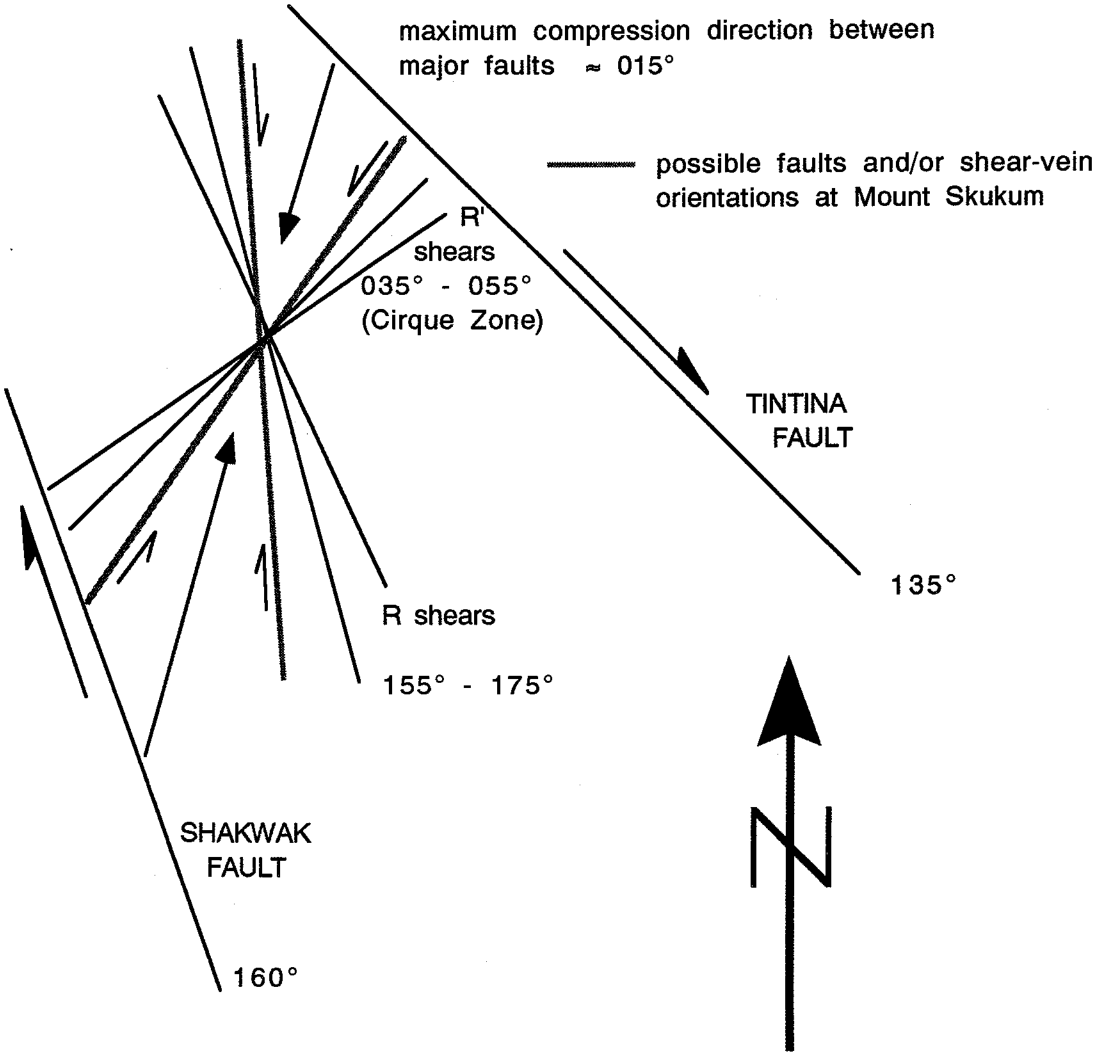


Figure 21. Model of the stress conditions responsible for formation of faults and/or shear-veins at Mount Skukum, as a result of stresses between the Shakwak and Tintina faults.

at the time of vein emplacement. This does not preclude the possibility that the vein-hosting faults originally formed as normal faults.

Strain having an orientation such as the one described above could have formed between two right-handed strike-slip faults. An approximation of the shape and orientation of the strain ellipsoid is shown in Figure 20. The preferred interpretation of the structural and tectonic conditions that led to formation of the Brandy Zone veins is that the veins are hosted in Riedel shear fractures that developed as a result of strain localized between the Tintina and Shakwak faults in Eocene time (Fig. 21). Unfortunately, it was impossible to obtain any reliable sense of shear data on the various vein sets that would confirm this interpretation. Dextral transcurrent faulting has been constrained to have occurred on the Tintina fault from Middle Cretaceous to Late Eocene or Oligocene times (Gabrielse, 1985), and on the Denali-Shakwak fault in the mid-Tertiary (Monger *et al.*, 1982). Although plate convergence rates and vectors changed between Eocene and Oligocene times (Fig. 2), and this probably resulted in the termination of the Eocene magmatic episode, the change in plate movement would not significantly affect the orientation of stresses in the zone lying between the Tintina and Shakwak faults. The axis of maximum compression, in a zone weakened by fracturing between the faults, should be at 45° to the faults (Casey, 1980). This orientation of s_1, inclined at 45° to the Tintina and Shakwak faults, would correspond to 010 to 015°, identical to the orientation of the major principal strain axis determined from the Brandy veins. Vein formation, therefore, may have been related to large-scale tectonics of the region, and not specifically to the volcanotectonic environment of the Mount Skukum Complex.

Structural Geology of the Cirque Zone

Structures in the Cirque Zone could not be mapped because mining there had been completed by the time this project was started. The following reconstruction of the geology of the Cirque zone is based on core logging and company records.

The Cirque Zone occurs in a fault that can be traced for more than 1.5 km across most of the eastern side of Main Cirque. The fault strikes approximately 055° and dips steeply to the east across most of the cirque, but, where it intersects a large north-trending rhyolite and rhyolite breccia dyke, its strike changes to about 035° and it dips 80° east (Fig. 4). The ore zone occurs in the fault only where the fault transects the dyke.

The sharp change of strike of the fault was likely the result of refraction because of the difference in mechanical properties between the andesite and rhyolite. The result of continued movement on any faceted or undulose fault is that parallelogram-shaped or lens-shaped prism-like openings form (Fig. 22). The apparent horizontal offset of the rhyolite dyke, by this fault, is sinistral. This offset could result from either sinistral or east-side-down normal movement on this fault. If the movement on the fault was normal, refraction of the fault in the rhyolite dyke would have resulted in a change in dip but no significant change in strike; but, the dip does not change significantly. Therefore movement on the fault is inferred to have been predominantly horizontal and sinistral. The result of continued movement on the fault was that the refracted part opened up into a parallelogram-shaped tabular body (Fig. 22). Sinistral horizontal movement on this fault and the observed refraction are consistent with the maximum principal stress

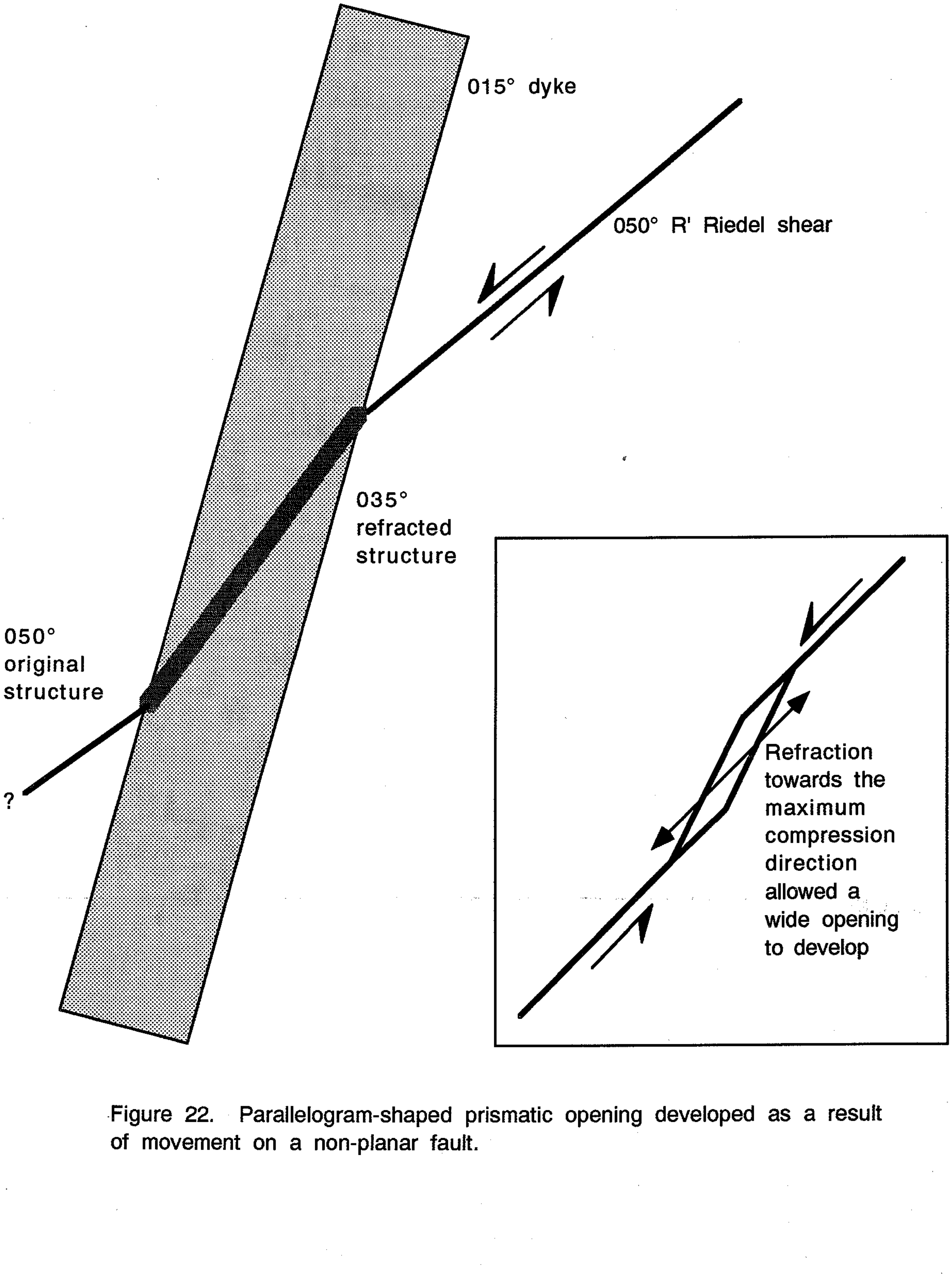


Figure 22. Parallelogram-shaped prismatic opening developed as a result of movement on a non-planar fault.

orientation of 015/13, as determined from the Brandy Zone. This fault can be classified as an R' Riedel shear (Fig. 21), assuming it was formed by the same stress conditions that controlled the orientation of the Brandy Zone.

The "Wheaton Lineament", which is a prominent, northeast-trending, 40 km-long lineation detected by remote sensing (Doherty and Hart, 1988), passes approximately 6 km east of the Cirque Zone. Doherty and Hart (1988, p. 51) comment: "The 'Wheaton Lineament' probably represents a deep-seated structure which was active during pre-Tertiary time and reactivated during post-Eocene time." The fault that hosted the Cirque Zone has approximately the same orientation as this lineament, and may also have been a reactivated deep-seated structure.

The Cirque Zone occurs in the refracted part of the fault where the rhyolite dyke is in the footwall of the fault. Cross-sections through the Cirque Zone have been assembled to show an expanded receeding oblique view of the Zone, as seen from the south (Map 3). A schematic diagram of the structural setting of the Cirque Zone (simplified from Map 3) is shown in Figure 23. The dyke - fault intersection plunges to the south, but ore grades do not persist below about 1635 m elevation. This apparent horizontal cut-off of ore grades could represent either a stratigraphic control on vein formation, or the deepest level at which boiling took place in the vein. The other side of the fault, where the dyke is in the hanging wall of the fault, and also the down-plunge extension of the dyke - fault intersection, could both represent significant exploration targets.

The Cirque Zone probably opened up more and a wider vein formed there than in the Brandy and Lake Zones because of a combination of two factors: first, in the Cirque Zone a

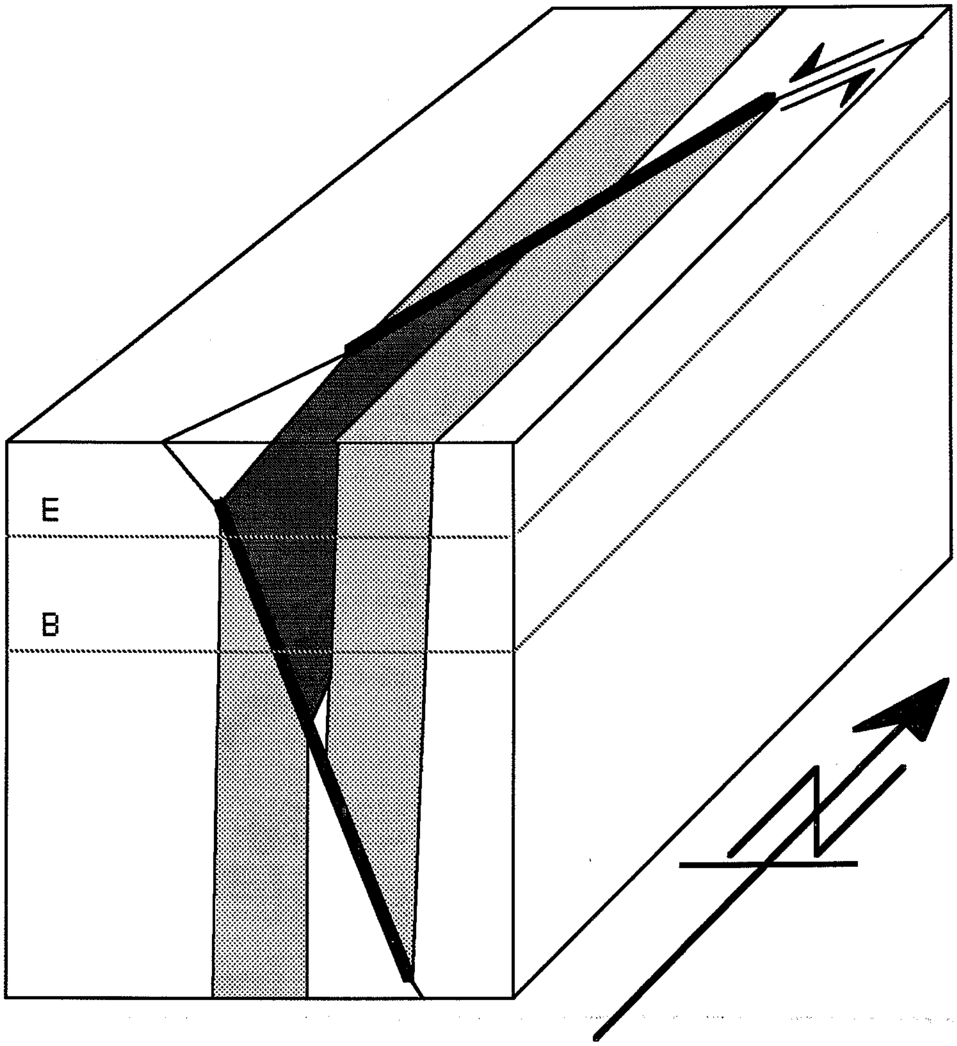


Figure 23. Schematic block diagram of the Cirque Zone.
B represents the base of the ore zone.
E represents the present erosion level.

rhyolite dyke was present, and the consequent refraction of a fault resulted in it having an orientation suitable for continued movement to cause an opening to form; and second, fault movement was sufficient to open a large space.

Alteration

McDonald (1987) suggested the following general zonation of alteration mineralogy developed around the veins at the Mount Skukum deposit:
1, potassic, characterized by adularia;
2, silicification accompanied by up to 5% pyrite;
3, phyllic, or sericitic; and
4, argillic, kaolinitic;
5, propylitic, consisting of chlorite, epidote, and calcite.

This general pattern of alteration was confirmed, in the case of the Cirque Zone, in this study. However, around the Brandy and Lake veins, the alteration grades only from epidote-dominated propylitic to chlorite-dominated propylitic. Therefore, although the alteration haloes around the Brandy and Lake veins are wider than those around the Cirque Zone, their mineralogy suggests less intense alteration. The alteration around the Cirque Zone could be less extensive because silicification, which is common around the Cirque veins but not around the others, isolated the wallrocks from the veins and thus limited the outward growth of alteration zones. Elevation could have been an important factor affecting the degree of alteration, and alteration could have been more intense deeper in the system. This second interpretation depends on the assumption that the relative position of the veins has not changed since vein emplacement. Also, alteration could be less intense in the Brandy and Lake Zones because they were smaller and less permeable hydrothermal conduits than the Cirque Zone, and therefore the wall-rocks interacted with less fluid.

In the Alunite Cap area, alteration mineralogy grades outward from massive alunite + silica, to pyrophyllite ± kaolinite, pyrophyllite ± silica, sericite, and finally to very weak chloritic-propylitic alteration (see Map 1, and Figs. 7 and 8). The alteration pipes shown in Figures 7 and 8 are simply vertical extensions of the concentric alteration zones mapped on surface. A more detailed examination of the drill holes through this zone will be done to confirm or reject this interpretation. The textures of the volcanic rocks are preserved in the outer, sericitic, zone of alteration, but are destroyed in the inner zones. The rock types and contacts mapped in the inner zones of alteration are extrapolated from the outer zone. Although on surface the alteration zones are not exactly centred on the intersection of the two faults, the fluids responsible for alteration probably were focused by the faults and only diverged from them near surface. If the interpretation of these faults as synvolcanic structures is correct, then it is likely the hydrothermal alteration was also synvolcanic, or at least very close temporally to volcanism.

Advanced argillic alteration caps occur elsewhere in both adularia-sericite - type and acid-sulphate - type epithermal deposits (Heald *et al.*, 1987). The argillic alteration associated with acid-sulphate - type gold mineralization is thought to have formed by disproportionation of magmatic SO_2, whereas the barren caps found above adularia-sericite vein deposits formed by oxidation of hydrogen sulphide separated from deep near-neutral brines during boiling (Heald *et al.*, 1987). The presence of pyrophyllite and the relatively coarse grain-size and massive texture of the alunite-silica alteration at Mount Skukum suggest that it is not the type of alteration that occurs above an adularia-sericite vein system, but is similar to that formed by disproportionation of SO_2 (R.H. Sillitoe, pers. comm., 1989).

The alunite alteration at Mount Skukum is localized by synvolcanic structures and may therefore be directly related to magmatism, whereas the gold mineralization is hosted in structures that are not related to volcanic activity, and may therefore be later.

Acknowledgements

I would like to thank Mount Skukum Gold Mining Corp. for their support of the project. The study has benefited from discussions with their geologists, especially B. McDonald and R. Basnett. I would also like to thank my supervisors at Queen's University, Dr. A.H. Clark and Dr. C.J. Hodgson, for their constructive and stimulating discussions and critical comments on the manuscript. This project is funded by the Canada - Yukon Mineral Development Agreement. I would like to thank Dr. W.D. Goodfellow, of the G.S.C., for establishing and funding this project, and for his valuable discussions. This work was partly supported by a scholarship from the Natural Sciences and Engineering Research Council of Canada.

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