Geologic Structure of the Greens Creek Mine Area, Southeastern Alaska

By John M. Proffett

Chapter 7 of

Geology, Geochemistry, and Genesis of the Greens Creek Massive Sulfide Deposit, Admiralty Island, Southeastern Alaska

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Contents

Figures

Plates

[on CD–ROM]

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Introduction

This chapter discusses the surface and subsurface structural geology of the Greens Creek mine and surrounding area. It is based on detailed geologic mapping of selected mine workings at a scale of 1 inch = 20 feet and 1 inch = 40 feet, and of surface outcrops at 1 inch = 200 feet and 1 inch = 40 feet (J.M. Proffett, written commun., 1987, 1997, 1998, 1999, 2000, 2001, 2002). The mapping was supplemented with detailed logging of drill core at various scales. In addition to field work by the writer, drill logs and underground maps by numerous Greens Creek geologists have been essential to developing the present understanding of the geologic structure. Work by others on various aspects of the structural and regional geology at Greens Creek, including Brian Martin, Thomas Crafford, Klaus Triebel, Paul Lindberg, Norman Duke, Kerry Lear, Andrew West, Brian Erikson, Peter Powers, and Christian Schrader, have also been helpful.

Greens Creek geology is extremely complicated due to complex structure and a wide variety of metaigneous and metasedimentary rock units, many of which have undergone hydrothermal alteration. Regionally, the rock units can be divided into a Late Triassic (and younger?) age group and a Paleozoic (and older?) age group. The ore at the Greens Creek mine lies mostly near the base of the Triassic rocks. The earliest structures (S1 and S1.5) are known only from the older rocks and do not affect the ores. Three major folding-cleavage-forming events (F2–S2, F3–S3, and F4–S4) overprint the Upper Triassic rocks and ore, as well as older rocks (fig. 1). Major ductile shear zones, between F2 and F3 in age, occur above and below the ore zone, and one or more periods of brittle faulting, involving at least three sets of faults, postdate the youngest (F4) folding event. Understanding this complex geology is essential not only for directing exploration and interpreting results for resource estimates and mine planning, but also for planning and interpreting work directed toward understanding the genesis of the Greens Creek ore deposit. This paper will begin with a brief review of rock units, which is essential to understanding the discussion of structures that follows.

Rock Units and Their Distribution

Rock units, as defined regionally (Loney, 1964; Lathram and others, 1965; Muffler, 1967), have been used somewhat differently from those used for more detailed geologic work in the mine and vicinity. Regional units are discussed first, followed by a discussion of mine units and how they may correlate with regional units. More detailed discussions of rock units are provided in chapters 2, 4, and 6 of this volume.

Regional Rock Units

The Greens Creek region is underlain by several Paleozoic and Upper Triassic metasedimentary and metavolcanic rock units. Upper Jurassic to Lower Cretaceous metasedimentary and metavolcanic rock units are known to the north and east (Lathram and others, 1965). Paleozoic rocks are separated from Upper Triassic rocks by what appears to be a major unconformity (Lathram and others, 1965; Brew and Karl, 1988). Mafic and ultramafic intrusive rocks also are present in the mine area.

Paleozoic Rocks

A sequence of dark gray, graphitic, quartz-mica schists (fig. 2*A*) and interlayered white, pale yellow to pale green quartz-muscovite schists (fig. 2*B*) is exposed along Hawk Inlet and for a variable distance inland. Rare marble units interlayered with these rocks in the north part of Hawk Inlet have yielded conodonts of Late Devonian age (collected by Russ Franklin and Duane Olsen; identified by Anita Harris, chap. 11). Calcite marble on the ridge east of Hawk Inlet has yielded a Devonian or Silurian megafossil (Brew and Ford, 1985) and is probably part of this sequence. These rocks were called the Retreat Group by Lathram and others (1965).

Metacherts and siliceous metasedimentary rocks of Late Devonian to Early Permian age, assigned to the Cannery Formation, occur on southern Admiralty Island and adjacent areas (Muffler, 1967; Jones and others, 1981). Early Permian megafossils southwest of Eagle Peak (3 miles northeast of the Greens Creek mine) indicate the presence of Cannery Formation partial equivalents there (Lathram and others, 1965).

Stratigraphy and structure in these older rocks are not well understood in the Greens Creek area, and it is not known whether or not the “Retreat Group” and the Cannery Formation in the Greens Creek area belong to the same sequence. Clasts of the deformed and metamorphosed Paleozoic rocks occur in Triassic conglomerates at Greens Creek (fig. 2*C*)

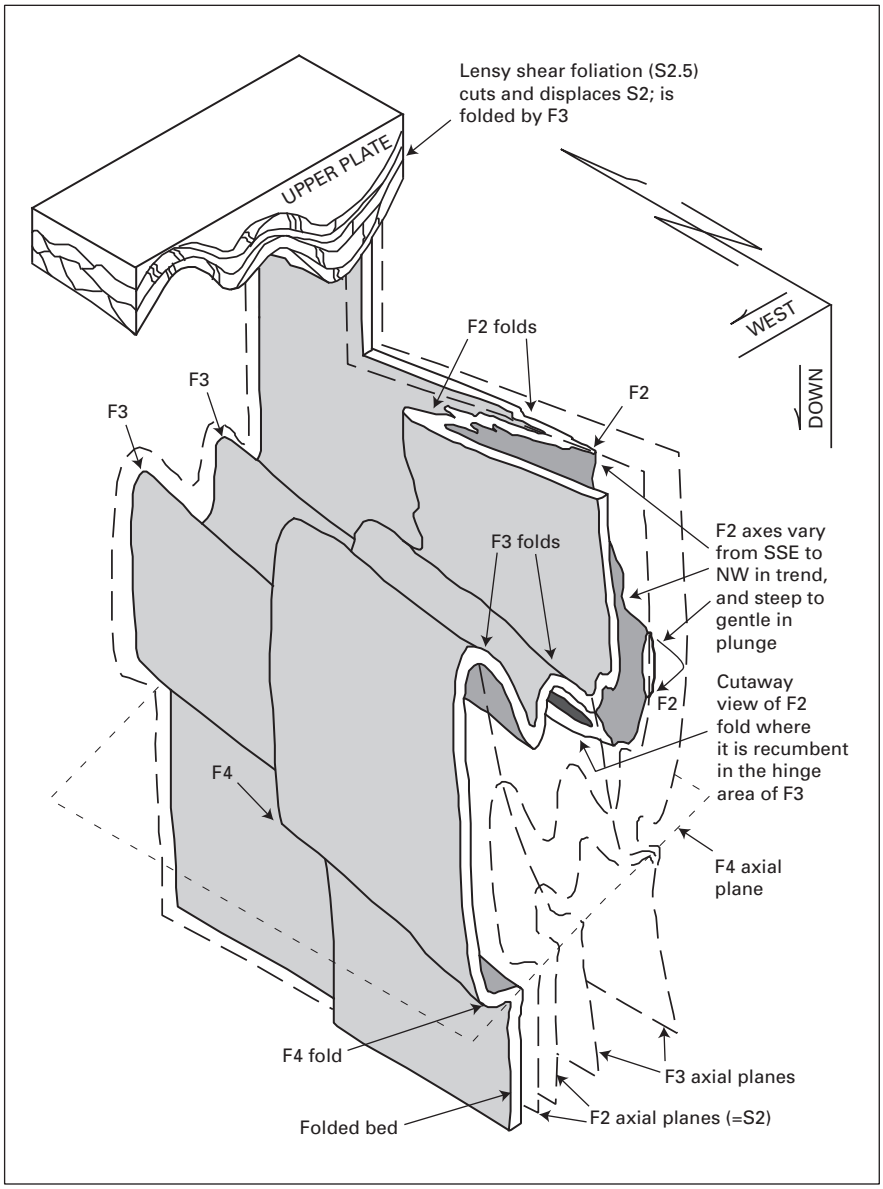


Figure 1. Diagrammatic 3-dimensional sketch showing relationships between the different stages of ductile deformation at the Greens Creek mine.

and near Young Bay. $^{40}Ar/^{39}Ar$ cooling ages of about 265 m.y. on metamorphic white mica and hornblende from the Paleozoic rocks of Admiralty Island (Haeussler and others, 1999) indicate a deformational and metamorphic event prior to late middle Permian time.

Triassic Rocks

The Upper Triassic Hyd Group of Admiralty Island and vicinity consists of locally derived conglomerate and sedimentary breccia, black slaty, calcareous, and dolomitic argillite, limestone, dolomite, and metabasalt. The conglomerate and sedimentary breccia (fig. 2*C*) are near or at the base of the section in most areas near Greens Creek. The overlying argillite section, which contains the Greens Creek orebodies near its base, has yielded conodonts of late Carnian to earliest Norian age (chap. 11). Metabasalts on Gallagher Ridge, just south of the Greens Creek mine, conformably overlie argillite, contain late Carnian to earliest Norian conodonts (chap. 11), and have a U/Pb isochron age of 218 ±16 Ma and a Sm/Nd age of 215±95 Ma (chap. 11). Argillite with *Monotis subcircularis*, a late Norian pelecypod, reported from farther south on Admiralty Island (Loney, 1964; Lathram and others, 1965), indicates that the Hyd Group includes rocks younger than those dated in the mine area.

Jurassic and Cretaceous

Sedimentary rocks with Late Jurassic and Early Cretaceous fossils and interbedded volcanic rocks (the Seymour Canal Formation) occur in a belt along the east side of Admiralty Island, 4 miles northeast of Greens Creek (Loney, 1964; Lathram and others, 1965; Cohen and Lundberg, 1993). Rocks along the southwestern side of this belt, nearest to Greens Creek, consist mainly of dark gray slate and slaty graywacke. Contacts between the Seymour Canal Formation and the Triassic rocks were not observed during this study. However, Barker (1957) indicates that observed contacts between these units appear conformable (Barker's Barlow Cove Formation is apparently partly equivalent to the Triassic Hyd Group and his Symonds Formation (abandoned by Lathram and others, 1965) is equivalent to the Seymour Canal Formation). Fossils suggest a significant nondepositional hiatus between the Hyd Group and the Seymour Canal Formation. Structures observed during this study in the Hyd Group and in the lower part of the Seymour Canal Formation are similar, which is interpreted to suggest that a major metamorphic or deformational event did not occur during this hiatus.

Intrusive Rocks

Intrusive rocks include middle Cretaceous quartz diorite plutons 11 to 15 miles east of Greens Creek (Haeussler, 1992) and ultramafic and mafic rocks near the Greens Creek mine and to the northwest. The ultramafic and mafic rocks are of uncertain age, but fragments of some of them in basal Hyd Group conglomerates at Greens Creek indicate that they are at least in part older than Upper Triassic Hyd Group and therefore are at least in part older than ore.

Rock Units of the Greens Creek Mine Area

Rock units in the mine area are briefly summarized here for use in the following discussion. More detailed descriptions can be found in chapter 6 of this volume. The units are grouped according to whether they are stratigraphically below or above the ore horizon. Those stratigraphically below the ore horizon include deformed and metamorphosed ultramafic and mafic rocks and their intensely altered, deformed, and metamorphosed equivalents, which comprise a group collectively referred to as "phyllites." Conglomerate and sedimentary breccia, with clasts of the mafic and ultramafic rocks and of phyllites, lie above these rocks and below the ore horizon. Rocks stratigraphically above the ore horizon are argillites, metabasalts, and minor metagabbros of the Upper Triassic Hyd Group and slaty siltstones and lithic sandstones that are either part of the Hyd Group or part of a younger unit.

Graphitic Quartz Mica Schist (Retreat? Group)

Outcrops of graphitic quartz mica schist and phyllite are in the northern part of the Bruin Creek area, near the 1350 portal, just east of the mouth of Gallagher Creek, and in a few other localities (pl. 7–1). These are highly deformed, commonly graphitic, quartz-rich metasedimentary rocks that resemble the Paleozoic rocks referred to as "Retreat Group" (Lathram and others, 1965) along Hawk Inlet. In the mine area, these rocks lie structurally below the altered mafic rocks discussed herein, but in the Bruin Creek area they locally lie structurally above these rocks, though below the conglomerate and sedimentary breccia (pl. 7–1).

Ultramafic Rocks

Ultramafic rocks include serpentinite (±chlorite) (SC), and its hydrothermally altered, deformed equivalent, carbonate (magnesite, ankerite or dolomite)-±mariposite-±chlorite-±talc(?)-±quartz-±leucoxene phyllite.

Mafic Rocks

Most mafic rocks are strongly altered and deformed, but where alteration and deformation are least intense, relict textures generally indicate the rock is gabbro (DG). Relict textures indicative of basalt are generally rare to absent within the phyllites of the mine area. However, if basalts had been present, their textures may have been destroyed because of the finer grain size. Altered, deformed equivalents of the mafic rocks, in order of increasing alteration intensity, are chloritic rock or phyllite (CR), chlorite-sericite-±quartz-pyrite-±carbonate-leucoxene phyllite (SPc), sericite-quartz-±carbonate-pyrite-±leucoxene phyllite (SP), and siliceous rock (SR, essentially alteration silica with pyrite, ±minor sericite). Phyllites representing the most intense alteration are most commonly found stratigraphically directly below the ore. These rocks are discussed in more detail in chapter 6 of this volume.

Conglomerate/Breccia

A unit of strongly deformed conglomerate and sedimentary breccia is commonly present at the top of the phyllites. Coarse sandstone is present locally and may be bedded (fig. 2*C*). West of Gallagher Creek (16675N, 17150E, pl. 7–1) conglomerate and coarse sandstone are interbedded with the lower part of the argillite unit. Throughout the mine area clasts mostly consist of various metamorphic rocks of types found in the Paleozoic section and of altered, deformed, and metamorphosed mafic and ultramafic rocks, like those they overlie. Due to the intense deformation, it is not always certain whether the altered mafic/ultramafic clasts were altered before or after becoming clasts. In a few exposures, however, such as west of Gallagher Creek (16788N, 17193E, pl. 7–1), the presence of carbonate-mariposite-quartz (probable altered ultramafic) clasts adjacent to serpentine clasts in a serpentine-rich clastic matrix suggests at least some alteration took place before deposition of the conglomerate. Except for the presence of clasts, the conglomerates closely resemble sericitic phyllites and siliceous rock of the underlying "phyllites" and when clasts are difficult to see, these rocks are usually mapped as

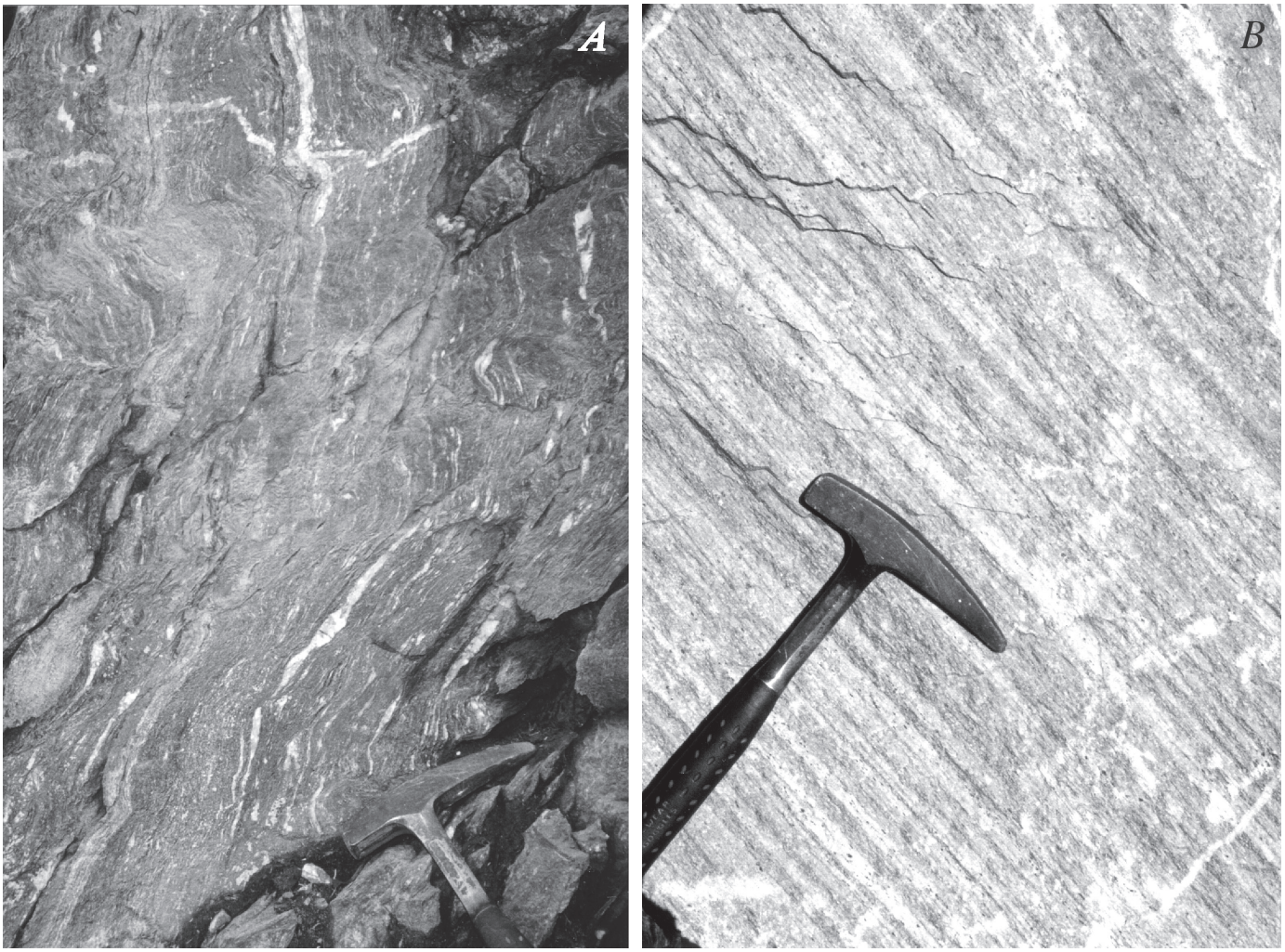


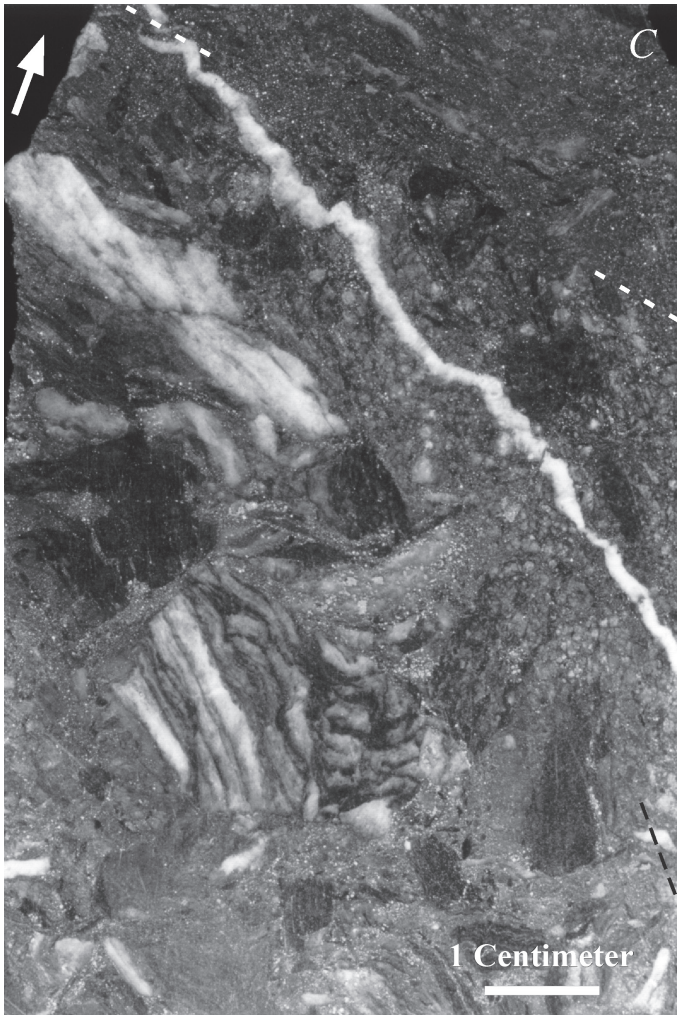
Figure 2 (above and facing page). Photographs of Greens Creek rocks. *A*, Graphitic quartz-mica phyllite or schist of Paleozoic Retreat(?) Group, 3.4 mile "B" road, 3.6 miles (5.9 km) west-northwest of Greens Creek mine. White to pale gray lenses are mainly highly deformed vein quartz of predeformation origin. *B*, White to pale greenish quartz-muscovite schist of Retreat(?) Group, Pit 7, "A" road, 6.5 miles (10.5 km) northwest of Greens Creek mine. White layers are mainly quartz; gray (actually greenish) is muscovite. *C*, Angular pebble conglomerate with faintly bedded sandstone in upper right. White dashes show contact between conglomerate and sandstone and are parallel to bedding; black dashes show orientation of S2. Some fragments contain a preconglomerate foliation and metamorphic segregation at various angles to each other and to S2, and some fragments contain preconglomerate quartz veins. Matrix and sandstone largely pyritized. From 720 ore access (17250N, 20300E, 718-foot elevation), looking N. 27 W., with up indicated by white arrow in upper left.

part of the phyllite package. However, the presence of Paleozoic metamorphic clasts indicates that they are probably part of the conglomerate unit near the base of the Upper Triassic Hyd Group.

Clasts of mafic and ultramafic metaintrusive rocks and of their phyllitic altered equivalents in the conglomerate indicate that at least some mafic and ultramafic rocks are of pre-Hyd age, older than Greens Creek ore, and may not be related to the Hyd basalts. Alternatively, they may, at least in part, have been emplaced early in a protracted igneous episode that included later ore deposition and still later Hyd basalts.

Argillites and Mafic Rocks

Most ore occurs in the basal part of the argillite unit of the Upper Triassic Hyd Group. The main lithologies in this unit are black to dark gray, slaty argillite (SA) and gray to brown, dolomitic and calcareous, massive argillite (MA). Massive argillite occurs in beds that vary from about 2 cm to 20 cm (rarely up to a meter) thick. They are characterized by abundant white ladder veins or "lightning veins" (fig. 3*A*). Some massive argillite beds mainly consist of fine dark silica, but it is not known if this is primary chert or the result of silicification of carbonate beds.



Massive argillite beds are generally separated by interbeds of slaty argillite and occur in sequences up to tens of meters thick (for example, fig. 4). Sequences of slaty argillite with few or no massive argillite beds are also common and seem to become more abundant in the upper part of the section. Locally minor, thinly laminated, pale gray to pinkish chert is associated with the ore horizon (for example, fig. 5).

Conodonts from two localities near the base of the argillite in the mine have yielded Late Triassic ages with possible ranges from late Carnian through about middle Norian (chap. 11). Two samples, one from the mine and one from Big Sore Creek, from argillite farther from the phyllite contact (presumably higher in the section?) have yielded possible age ranges of late Carnian through earliest Norian (chap. 11). Conodonts from a limestone bed at the phyllite/argillite contact west of Gallagher Creek are also latest Carnian through earliest Norian (chap. 11).

On Gallagher Ridge south of the Greens Creek mine, a sequence of Hyd metabasalts overlies typical argillite in conformable depositional contact. Conodonts from limestone interbedded with the lowermost two or three flows also are of late Carnian through earliest Norian age. Gabbro sills in the underlying argillite may be related to feeders for the flows and are discussed further in chapter 12.

Graphitic Slates and Sericitic Slaty Sediments

Above the Greens Creek mine, a sequence of metasedimentary rocks of uncertain correlation with other rock units in the area overlies a major low-angle ductile shear zone (see pl. 7–1; shear zone described in “Geologic Structure” section). Although these rocks are strongly deformed, a few graded beds suggest they are mostly right-side-up. The lowermost part of the sequence consists of black to pale gray, graphitic, slaty sedimentary rocks with rare beds of calcareous or dolomitic argillite a few centimeters thick. Some of the calcareous or dolomitic beds have lightning veins, and the sequence somewhat resembles parts of the argillite sequence above the orebodies. However, sequences with abundant massive argillite beds, such as are common above the ore, have never been observed in this upper sequence. Upwards in the section, the few beds of massive argillite are absent, and the rocks resemble argillite above the orebodies even less. The graphitic slaty sedimentary rocks are overlain by greenish to pale gray, sericitic, slaty rocks. These consist of siltstones and lithic sandstones that are commonly well bedded and which may locally be interbedded with rocks similar to those of the underlying graphitic unit. A few beds are very fine grained and siliceous, but it has not been determined if these are primary cherts or silicified siltstones. Rare dolomitic beds are also present.

More than 20 samples of calcareous and dolomitic beds from the graphitic slaty sedimentary unit and the sericitic slaty sedimentary unit were sampled for conodonts, but all were barren (chap. 11). Possibilities for correlation of these two units are: (1) They represent an upper part of the Upper Triassic Hyd Group well above the ore horizon; (2) they may correlate with parts of the Upper Jurassic and Lower Cretaceous Seymour Canal Formation, which they somewhat resemble, except for the slightly stronger deformation, alteration, and metamorphism; or (3) they may be part of an unrecognized post-Hyd unit.

Geologic Structure

Structural features are described in the following subsections from oldest to youngest; the younger structures have had important effects on the distribution and orientation of older structures. Northwest-trending strike-slip faults are the youngest features and divide the area into several major blocks. The best known blocks are those on each side of the Maki fault; structure and stratigraphy are readily correlated across the fault (pl. 7–1). Other blocks occur within and southwest from the Gallagher fault system, southwest of the mine (pl. 7–1). In addition, all blocks are further subdivided by major low-angle ductile shear zones of post-F2, pre-F3 age. The best known is the “Upper Shear Zone” above the mine workings, which separates the geology within the mine (“Mine Plate” or footwall of Upper Shear Zone) from the geology exposed on the surface along Big Sore Ridge (“Upper Plate” or hanging wall of Upper Shear Zone) above the mine (pl. 7–2A, B). Also, a less well known “Lower Shear Zone” lies below the mine workings; the footwall rocks (“Lower Plate”) are poorly known (pl. 7–2A, B).

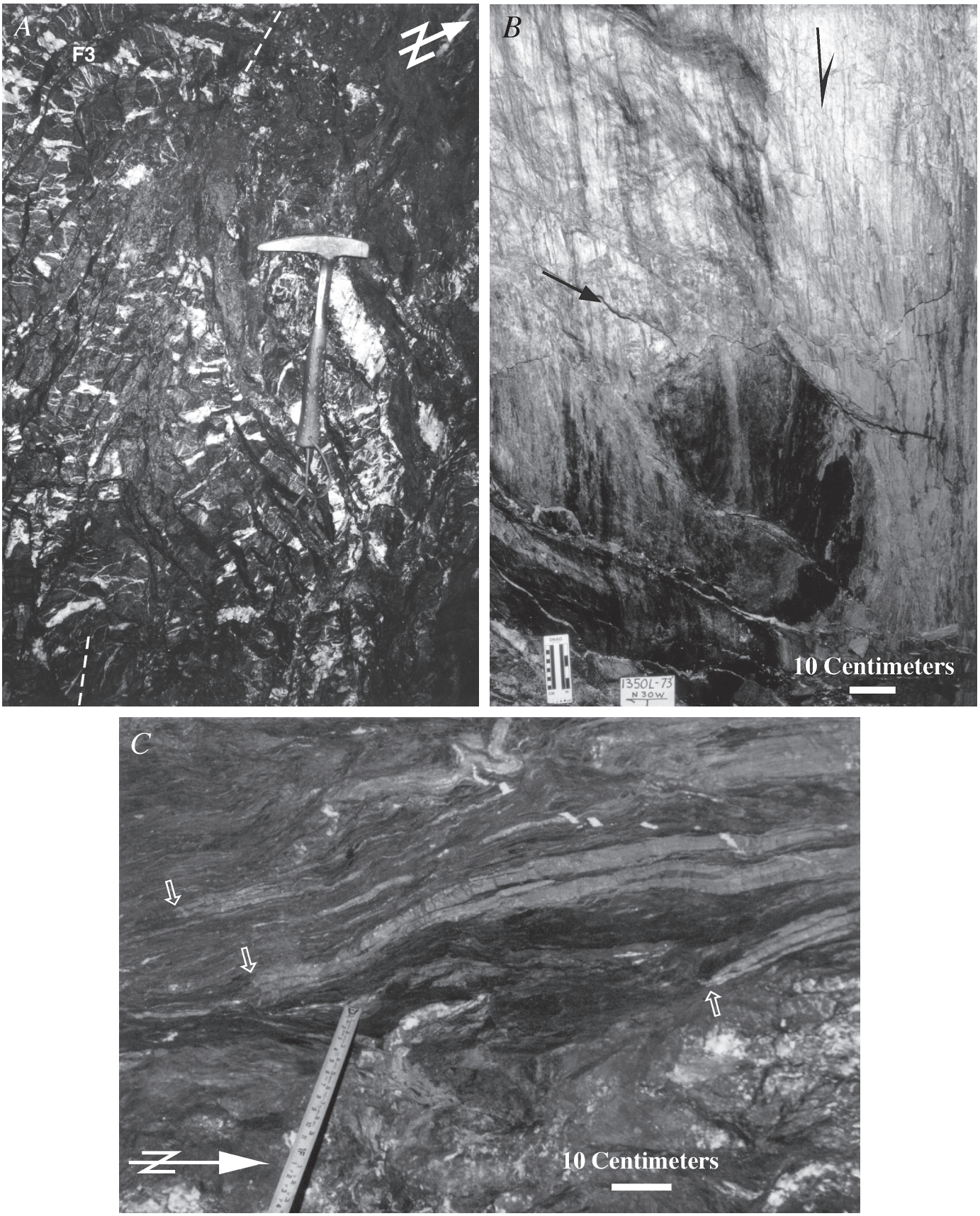

A
F3
B
10 Centimeters
1350L-73
N 30W
C
10 Centimeters

Figure 3 (facing page). Photographs of F2 related structures in the Greens Creek mine. *A*, Tight F2 fold in massive argillite beds, looking down plunge (N. 58 W., 67°). F2 axial plane (white dashed lines) and axial planar S2 foliation in slaty interbeds are slightly refolded by F3. Ladder veins are at a high angle to S2 and are not folded by F2, even in the tight F2 hinge zone, but are folded by the small F3 fold. 580 ore access, 17450N, 20355E, 584-foot elevation. *B*, S2 foliation plane, showing L2 (half-barbed arrow) and small F4 folds (full arrow). 1350 tunnel, 73 feet from portal, northeast rib, looking N. 60 E. (20085N, 19995E, 1,365-foot elevation). *C*, Layers of massive sulfides (lighter colored bands in upper half of photograph) in slaty argillite, tightly folded by F2 (open arrows point to hinges). Strong, penetrative S2 is subparallel to the tightly folded layers, and many S2 planes appear to have accommodated shearing. Lower part of photograph is massive argillite. 344S stope, view of back, looking up (16905N, 20392E, 360-foot elevation).

Pre-Hyd Group Deformation (S1 and S1.5)

Pre-Hyd Group deformation is represented by foliation in metamorphic clasts in the conglomerate/sedimentary breccia unit (fig. 2*C*), and by foliations observed in outcrops of the graphitic quartz mica schists and phyllites correlated with the Retreat(?) Group (see section "Rock Units of the Greens Creek Mine Area"). The most common type of early foliation, in outcrops and in clasts, is a prominent metamorphic, segregation-type layering, in which quartz-rich layers, 1–10 mm thick, alternate with thinner, gray to black, sericitic layers. This layering is here referred to as S1.5. Although S2 foliation (described in the following subsection) overprints this layering and is commonly parallel to the layering, outcrops can be found in which S2 is at an angle to the layering, and the layers are folded by F2. Rare outcrops can also be found (pl. 7–1, 23880N, 18820E) in which the layering is truncated at the basal contact of the conglomerate/sedimentary breccia unit. In conglomerate, the metamorphic layering is restricted to clasts, is of different orientations in different clasts, and is truncated by the conglomerate matrix (fig. 2*C*). Clasts, metamorphic layering within clasts, and conglomerate matrix are all overprinted by S2 foliation (fig. 2*C*).

Within the quartz-rich layers of the graphitic sericitic schists and phyllites, a relict foliation at an angle to the layering can be observed locally (pl. 7–1, just east of the mouth of Gallagher Creek, and in the Bruin Creek area). This relict foliation, here referred to as S1, is defined by grain size, grain shape, and by white to dark gray colored layers, in quartz and associated carbonate. Rarely, micas are parallel to this relict foliation, but in most rocks mica has been reoriented parallel to S2 or S1.5.

Muscovite that defines S1 or S1.5 is commonly coarser grained than that which defines S2 or younger foliations (fig. 2*B*). Layers rich in leucoxene, carbonate, chlorite, or other silicates may define S1.5 or S1 in mafic and ultramafic rocks.

It is likely that S1.5 and possibly S1 were formed as part of the Permian metamorphic event documented by the 265-m.y. cooling ages reported by Haeussler and others (1999). This event likely involved structural features other than these foliations but has not yet been studied in detail in the Greens Creek area.

F2 Folding and S2 Foliation

F2 folding at Greens Creek and related S2 foliation represent the oldest deformation known to have affected rocks of the Upper Triassic Hyd Group and overprint all older rocks. Folding and foliation that appear to be similar to F2 and S2 at Greens Creek, with regard to its characteristics and age relationships, are well developed in the surrounding region, extending at least from Hawk Inlet to Young Bay. At Young Bay the folding and related foliation overprint Hyd Group rocks as well as rocks of at least the lower part of the Upper Jurassic to Lower Cretaceous Seymour Canal Formation. Therefore, this deformation is tentatively considered to be an early phase of the middle Cretaceous deformation that occurred in a belt along the east margin of the Alexander terrane in southeastern Alaska (Haeussler and others, 1999).

F2 folds in the Greens Creek mine area are extremely tight and are isoclinal in many places (figs. 3*A*, 3*C*, 4, 5). S2, which is axial planar to these folds, is very strongly developed and is usually penetrative. In most of the phyllites, S2 is the dominant structural fabric (for example, see fig. 10*C*) and S2 is also well developed in most argillites. A lineation, L2, is common on S2 planes. In metasedimentary rocks, L2 is commonly a color streaking due to S2-bedding intersections and, in these cases, is essentially parallel to F2 fold axes. In phyllites, L2 is commonly a color streaking or, in some cases, is defined by small, hard ridges and grooves (fig. 3*B*). L2 in phyllites is commonly, but not always, subparallel to fold axes. L2 may be the result of the intersection of S2 with various features in the phyllite, such as altered relict primary mineral grains, fragments, or small veinlets, that have been elongated subparallel to fold axes or flattened subparallel to axial planes during deformation.

F2 folds have highly variable orientations, at least partly because they have been strongly refolded by F3 folds. F2 axial planes and S2 planes generally strike north-northwest and dip steeply on the east limbs of F3 synforms, dip gently in most F3 hinge zones, and dip gently to moderately easterly on west limbs of F3 synforms (fig. 1). With the effects of F3 folding removed, it appears that the average S2 orientation would have dipped moderately to the southwest. F2 axes also vary greatly in orientation within the refolded F2 axial planes (fig. 6). In most of the Mine Plate, F2 axes, L2, and bedding-S2 intersections (pl. 7–3, 7–4) plunge mostly steeply where S2 is steep, and have a northeast-southwest to west-northwest–east-southeast orientation where S2 dips gently. There are many exceptions, however, and many F2, L2, and bedding-S2 intersections also plunge gently northerly or southerly. In the Upper Plate, F2 orientation is also

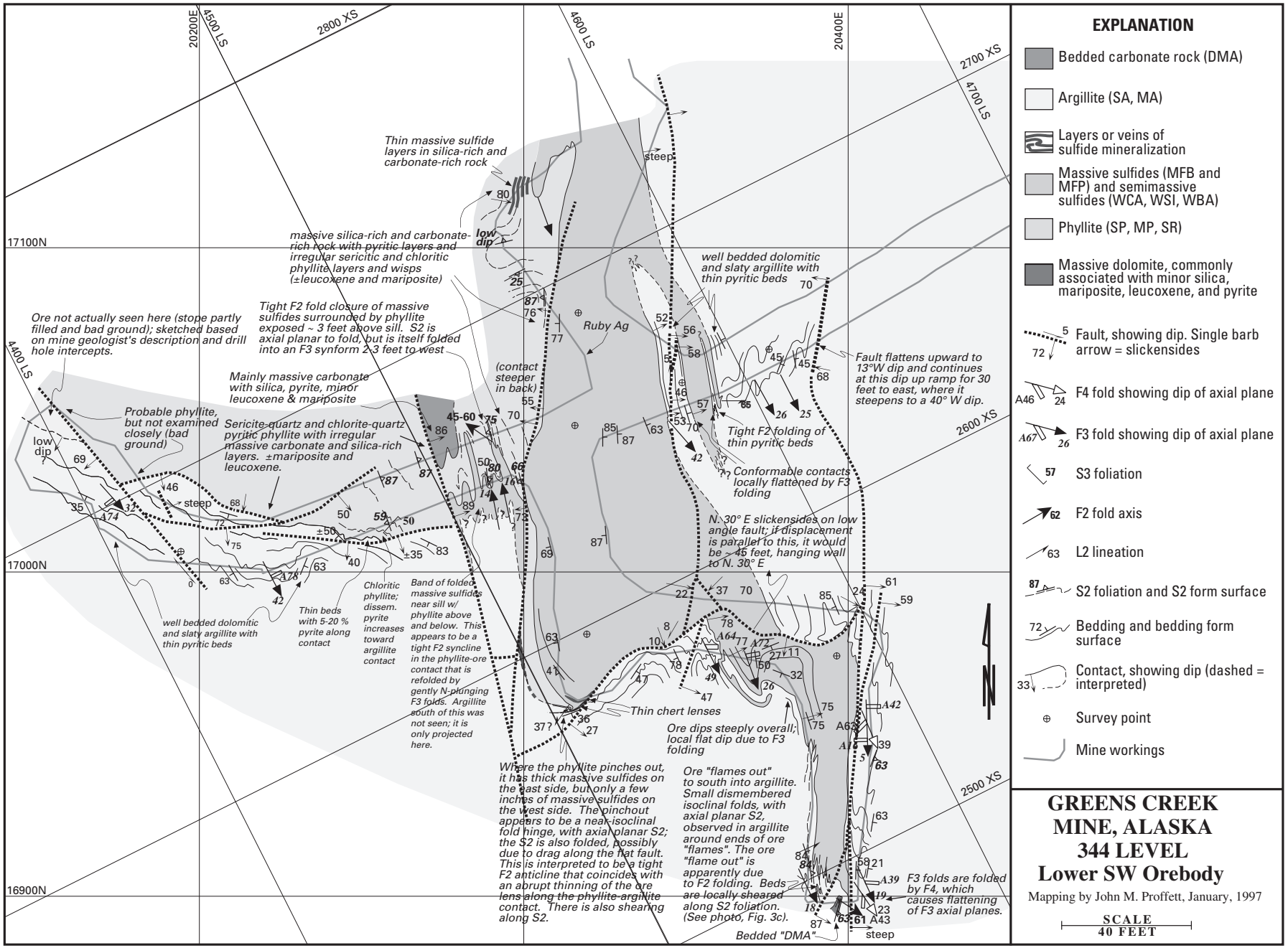


Figure 4. Map of 344 stope and 350 ore access crosscut (344–354-foot mine elevation).

highly variable (pl. 7–3), but here F2 has a tendency to trend south-southeast at gentle to moderate plunges, especially in the southern part of the area.

The variability of measured axial orientations is also reflected in direct observations of F2 folds in outcrops and mine workings. Axes are observed to bend more than 60 degrees across a few feet of mine workings.

Although much of the variability of F2 axis orientations is due to refolding by F3, observations suggest that some variability may be due to causes other than later folding. Possible causes are F2 folding of previously deformed rocks, possibly the result of pre-F2 folding or faulting that is not yet understood, or nonhomogeneous deformation, resulting in amplitude variations along fold axes. Nonhomogeneity is not uncommon in strong deformation, such as F2.

In phyllites, S2 is defined by oriented sheet silicates and, in some cases, by layers or lenses rich in quartz and(or) carbonates that alternate with layers rich in sheet silicates. Generally, minerals that define S2 are finer grained than those that define S1.

Most massive argillite beds have white ladder veins of quartz and calcite ("lightning veins"). Generally these are oriented at a high angle to S2 but are parallel to, or within a few tens of degrees of, F2. They have not been observed to be folded by F2, but are folded by F3 (fig. 3*A*). The veins are interpreted to have formed as tension fractures more or less perpendicular to the lengthening direction that was perpendicular to F2 shortening.

In mine workings many F2 folds have been mapped that have amplitudes of up to several tens of feet, and in some cases up to 200 feet (fig. 5). Based on correlation between various workings and drill holes, larger F2 folds with up to several hundred feet amplitude are interpreted. In the eastern and northern parts of the mine, most F2 anticlines (that is, folds with phyllite cores and argillite outer parts) close southward and have long eastern limbs and short western limbs (when viewed looking downward where the F2 folds are exposed on steep east limbs of F3 synforms; see figs. 7, 8). Overall, with F3 unfolded, it appears this zone would have been the overturned lower limb of a major, inclined, south- or southeast-closing F2 anticline, with older rocks above and to the west (fig. 8). The hinge and west (right-side-up) limb of this anticline is mostly truncated upward by the Upper Shear Zone, but parts of the west limb are exposed just below the Upper Shear Zone east of the mouth of Gallagher Creek (pl. 7–1, ~18800N., 17300E.).

Several F2 folds, with geometries consistent with location on the overturned lower limb of a major F2 anticline, cross through the West orebody (see pl. 7–4 for orebody locations). Their axes can be traced southwestward through the north part of the Central West orebody (fig. 7) to where they are displaced 1,750 feet northwestward across the Maki fault to the Northwest West orebody. They trend southward through the Northwest West orebody, where they bend to the southeast and, at the south end of this orebody, are again cut by the Maki fault and displaced southeast back to the south part of the Central West orebody (fig. 6). Here they trend southeast, and as they are followed southeastward, they again bend to the south (fig. 6).

The Upper Southwest and Lower Southwest orebodies appear to be situated on a large F2 anticline (pl. 7–2A). The eastern part of the Lower Southwest orebody is mostly on the steep east limb of the anticline (fig. 4) and flat-lying ore is on the west limb. The Upper Southwest orebody consists of several tight anticlines within the hinge zone of the main anticline (fig. 5) that have been refolded by F3. These anticlines appear to define an overall axial zone that plunges moderately to the south.

In surface exposures above the Upper Shear Zone, most F2 anticlines also appear to close to the south, but with long west limbs and short east limbs, and with older rocks apparently exposed below and to the east. Overall, this area appears to be on the upright lower limb of a major, inclined, F2 syncline, with older rocks below. The hinge zone of this major F2 syncline is exposed west of Gallagher Creek (pl. 7–1, 7–3, ~ 17650N, 15000E).

Where examined in detail, beds are sometimes found to end abruptly at S2 planes, especially in areas of strongest F2 deformation. Apparently, cleavage plane shearing has taken place, but it is not certain if this was part of the F2 deformation process or related to the S2.5 ductile shearing event that followed (described below).

Ductile Shear Zones (S2.5)

Upper Shear Zone

The Upper Shear Zone is a major ductile shear zone exposed above the uppermost mine workings, on the surface, and in several drill holes (pl. 7–1, 7–2A,7–2B). This zone dips gently and separates the geology of the mine (Mine Plate) from the somewhat different geology exposed on the surface above (Upper Plate).

The shear zone is tens to several hundred feet thick, and rocks within this zone are overprinted by a strong shear foliation (fig. 9). Immediately below the zone in the mine area are mafic and ultramafic rocks and their altered equivalents, mostly phyllites consisting of carbonates and sheet silicate. Rocks immediately above the zone are black graphitic slates and slaty argillites with rare carbonate or siliceous massive argillite interbeds. In parts of the shear zone, shear-foliated equivalents of rocks above and below can be recognized, but intensely shear-foliated rocks of uncertain origin also are present within the shear zone. These latter rocks consist of quartz and(or) carbonate with minor sericite and other sheet silicates (qsc unit—see pl. 7–1, 7–2A,7–2B; fig. 9). The protoliths for the quartz-rich rocks probably were siliceous metasedimentary rocks and(or) phyllites, and the protoliths for the carbonate-rich rocks probably were altered ultramafic and mafic rocks.

The shear foliation consists of slightly undulating, bifurcating, thin, discrete layers rich in sheet silicates, that separate thin, lens-shaped layers relatively rich in quartz and(or)

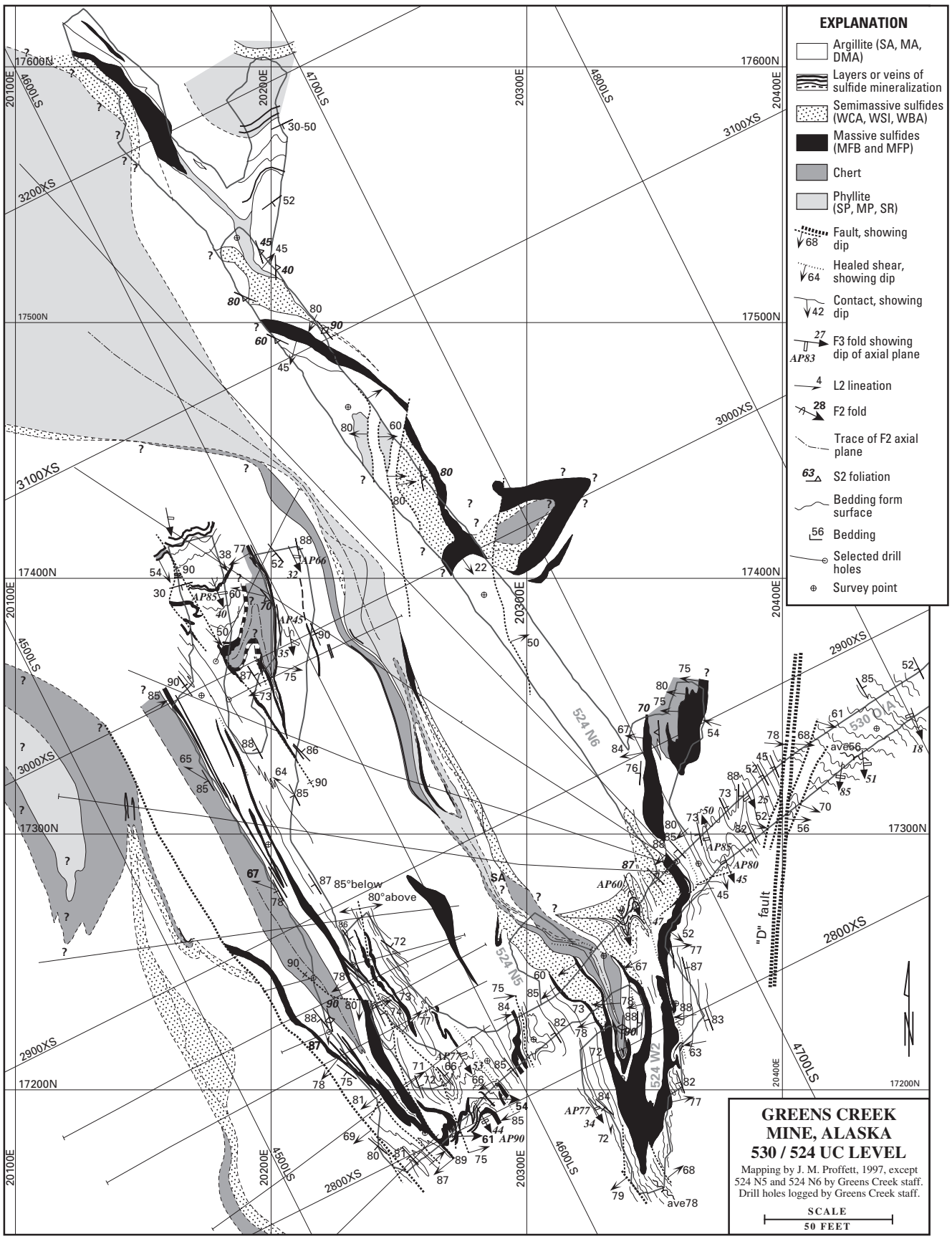


Figure 5. Map of 524 stope and 530 ore access crosscut (524–532-foot mine elevation).

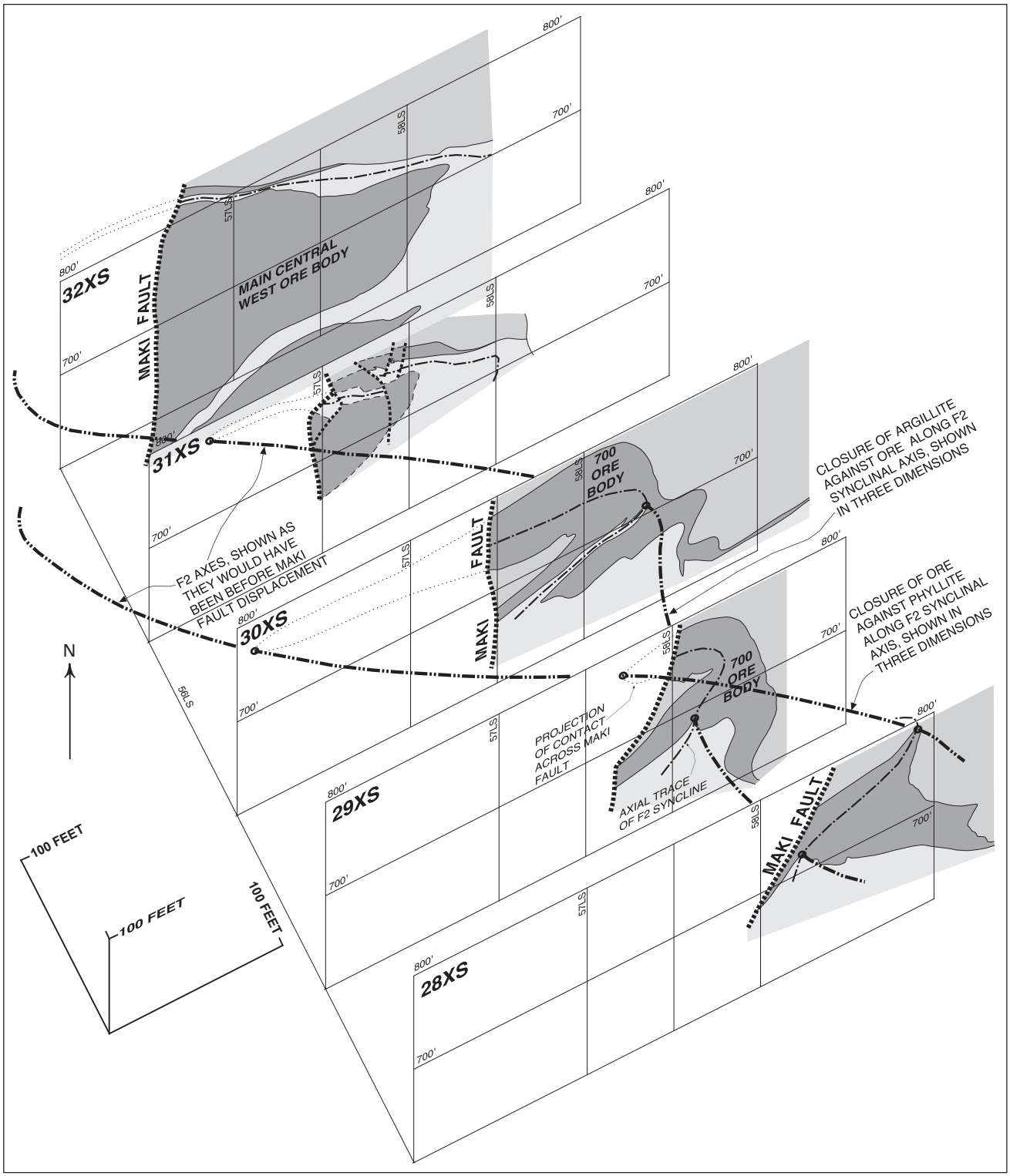


Figure 6. Fence section, looking north and down at 60°, showing variation in orientation of F2 axes in West orebody between 28XS to 32XS. The axial trace of the uppermost F2 fold is shown as a dot-dash line on each section. F2 fold axes for this fold are shown in three dimensions as they would have projected across both sides of the Maki fault, as double-dot-dash lines connecting the sections, one showing the hinge for the argillite/ore contact, and one showing the hinge for the ore/phyllite contact. The ore horizon is interpreted as thickest on the east limb of this F2 fold south of 31XS, resulting in the 700 orebody, and as thicker on the west limb of the fold north of 31XS, resulting in the main Central West orebody. The shape of orebodies on the sections appears flattened because of the perspective resulting from the view looking down at a 60° angle (compare the center section, 30XS, with the same area on pl. 7–2A (in CD), which shows a slightly more detailed interpretation).

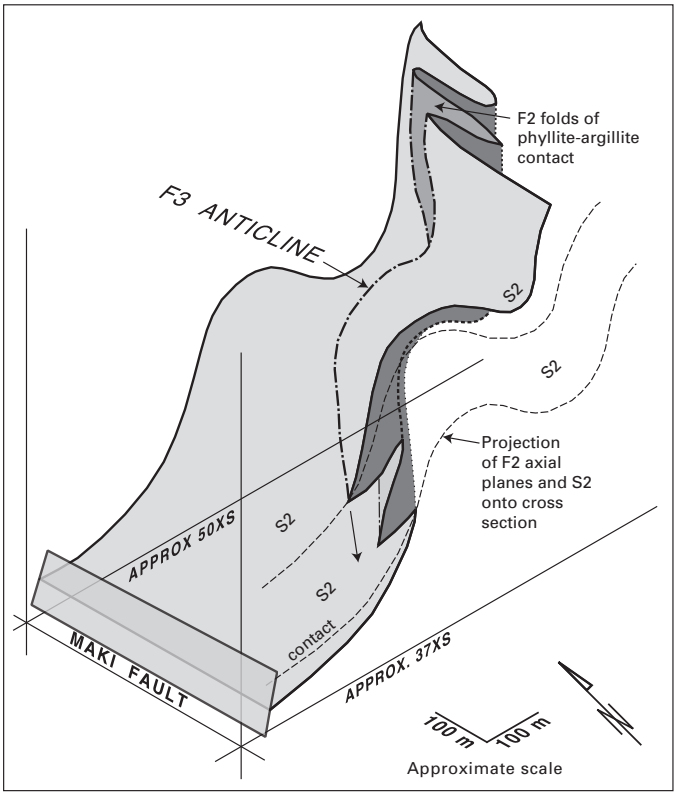


Figure 7. Three-dimensional sketch of northern part of Central West orebody, diagrammatically showing interpretation of F2 folds refolded by F3, east of Maki fault.

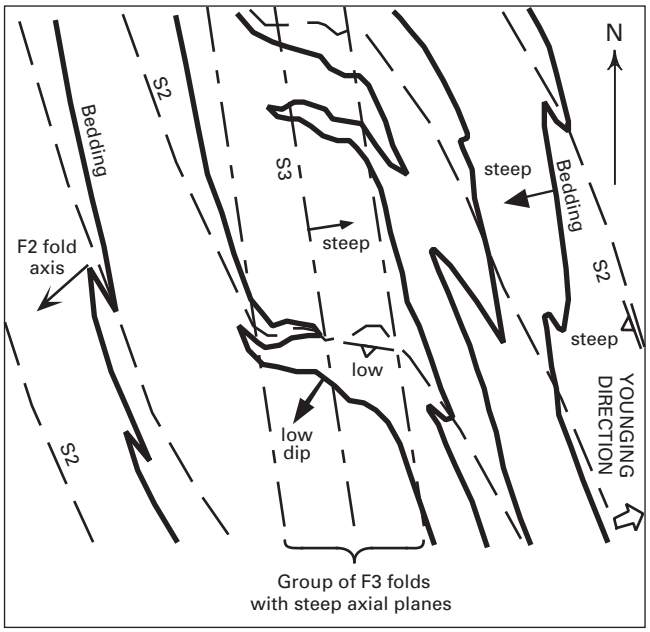


Figure 8. Diagrammatic plan view, showing relationships between bedding, F2/S2, and F3/S3 in the main part of the Mine Plate. South-closing F2 folds (which are anticlines here) have short west limbs and long east limbs. Bedding and S2 are locally folded by groups of F3 folds with axial planar S3.

carbonates (fig. 9). A stretching or mineral lineation (L2.5) is usually present on shear foliation surfaces, and the quartz/carbonate-rich lenses between shear-foliation planes are elongate parallel to the lineation. The lenses are thus ribbonlike, with length to width to thickness ratios of as much as 50:10:1.

Shear foliation (S2.5) postdates F2 and predates F3; it displaces and deforms S2 foliation but is folded by F3.

Zones of breccia, or partly brecciated wall rock, are present along the shear zone (pl. 7–2A,7–2B) and are overprinted by the shear foliation. Therefore, it appears that the shear zone began as a brittle fault zone, which became ductile with time.

Direction and amount of displacement across the Upper Shear Zone are uncertain. Although some generalized stratigraphic units can be matched across the shear zone, complex F2 structure and limited exposures have precluded establishment of a satisfactory match. Displacement direction is likely in the direction of the shear lineation previously described, which in most outcrops measured trends E–W to WNW–ESE. Rare megascopic shear-sense indicators suggest top-to-the-west (fig. 9*A*) as does limited petrographic work (fig. 9B), but more work is needed. Effects on shear sense indicators of F3 and of other postshearing deformations are still being evaluated. Top-to-the-west displacement would be consistent with the apparent younging directions in the Mine Plate and Upper Plate (pl. 7–2A).

Klaus Shear

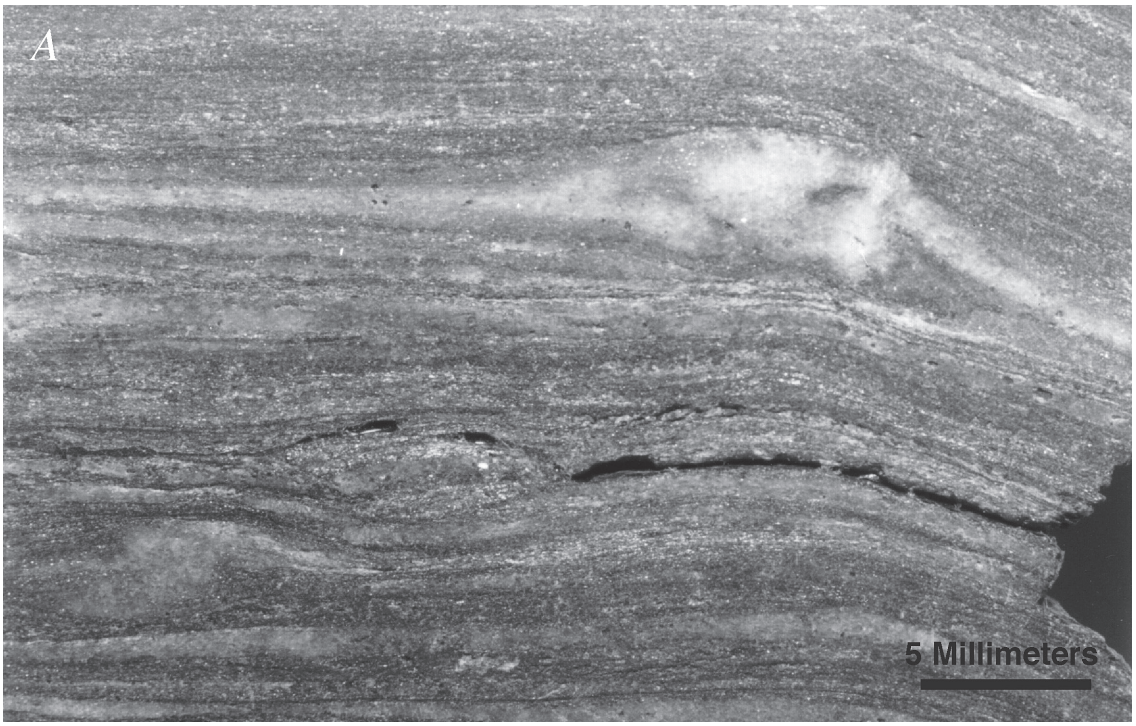
The Klaus shear, first noted by Klaus Triebel (written commun., 1992), is a low-angle healed fault that displaces the argillite/phyllite contact in the east part of the mine (pl. 7–2A). A displacement of a few hundred feet of hanging wall northwest has been estimated by Lindberg (P.A. Lindberg, written commun., 1994). This shear zone appears to correlate with one mapped in the 1350 tunnel (J.M. Proffett, written commun., 1987), which is associated with ductile shear foliation and is folded by F3. The Klaus shear could, therefore, be part of the same deformational event as the Upper Shear Zone.

Lower Shear Zone

Evidence for another shear zone has been found in a few deep drill holes below the mine (pl. 7–2A, 7–2B). In most holes, argillite is juxtaposed against underlying phyllites. Ductile shearing fabrics similar to those in the Upper Shear Zone occur in the Lower Shear Zone, as do zones of breccia and partly brecciated wall rock that are overprinted by shear foliation.

Possible F2.5 Folds (?)

A few folds have been found that appear to fold S2 but are overprinted and transected by S3. These are not common, but their age relationships suggest they could be related to the ductile shearing event.



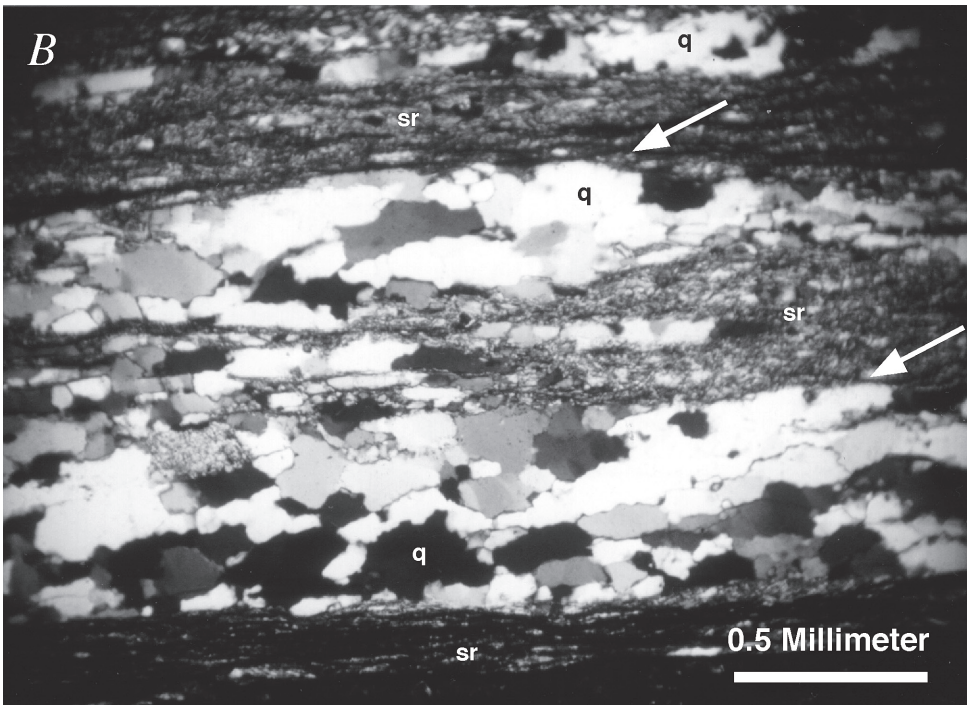


Figure 9. *A*, Photograph of shear foliated quartz-sericite-(carbonate) phyllite (a mylonite), showing asymmetric tails on quartz pods that suggest top-to-the-west sense of shear. *B*, Thin section of *A*, crossed polarizers, showing preferred orientations of flattened quartz grains (white arrows) oblique to shear foliation (which is parallel to bottom and top edges of photograph), also indicating top-to-the-west sense of shear (Simpson and Schmid, 1983; Lister and Snoke, 1984). Quartz-rich lenses indicated by "q," sericite-rich areas by "sr." Top of both photographs is top in the field; both photographs looking south; view is of a plane cut perpendicular to foliation (S2.5) and parallel to lineation (L2.5); location: 18681N, 21137E, surface, 1,952-foot elevation.

F3 Folding and S3 Foliation

F3 folds are generally tight to open upright folds and are the most common and obvious folds in the mine (fig. 10*A*, *B*). They clearly fold S2 as well as bedding and shear foliation and are refolded by F4 (fig. 10*C*). Where not affected by post-F3 structural events, F3 axial surfaces generally strike north-northwest in the northern and eastern part of the area, gradually bend to an approximate north-south strike farther south, and to a south-southwest to southwest strike in the southwest part of the area (pl. 7–5). Most axial surfaces dip moderately to steeply eastward throughout the area. There are many local exceptions to these general trends. Where refolded by F4, the F3 axial surfaces commonly dip gently eastward overall (fig. 1). Locally, axial surfaces dip near vertically, or steeply west, which could also be due to F4 refolding.

F3 fold axes generally plunge gently to the south in the plane of the axial surface, but locally they plunge gently northward (pl. 7–5). In rare cases, they plunge quite steeply north or south. In the 530 Ore Access in the Upper Southwest orebody, F3 changes from a 50°N plunge to a 45°S plunge across a 15-foot-wide crosscut (fig. 5). This could be due to bedding that was previously deformed rather than to refolding of F3.

F3 synforms generally have steeply dipping east limbs (fig. 10*A*) and moderately east dipping west limbs. The mine area includes several large-scale F3 folds with wavelengths of several hundred feet. Hinge zones of these larger scale folds are characterized by numerous smaller scale F3 folds (fig. 10*B*) with wavelengths and amplitudes of a few inches to a few feet. These smaller scale folds are less common on the limbs of the larger scale folds. Most of the upper east part of the mine is on the east limb of a large synform (see pl. 7–2A), with an antiform and another synform west of this. Much of the Upper Southwest orebody is in an F3 antiformal hinge zone with abundant smaller scale folds, and the eastern part of the Lower Southwest orebody is on the west limb of this same anticline (pl. 7–2A).

S3 foliation is axial planar to F3 folds, is usually spaced, and usually crenulates S2 (fig. 10*B*). In some areas it is not developed, especially in massive rocks such as massive argillite. It is most strongly developed in rocks that have abundant fine sheet silicates, such as many of the phyllites and some of the slaty argillites. In a few areas, S3 can be very strongly developed, especially where F3 hinge zones occur in rocks with abundant fine sheet silicates, locally causing complete reorientation of S2. In such areas, it is possible to distinguish S3 from S2 only by mapping the structures into an area where the S3 overprinting is less strong. L3 is a crenulation lineation, generally consisting of small-scale (millimeter scale) folding of S2 foliation planes (fig. 3*B*).

In general, F2 folds tend to change in orientation irregularly through the mine and on the surface from a roughly southwest trend in the north to a more or less south-southeast trend in the south, whereas F3 folds appear to do the opposite (pl. 7–3, 7–4, 7–5).

S3 Shear Zones

Apparent displacement of older structures or rock units is commonly observed across certain S3 foliation planes. In most cases apparent displacements are only a few centimeters, and many of these could be the result of rock dissolution along cleavage planes. Others are on the scale of mine workings and can locally displace ore and other rock units several feet. At the northern end of the map (pl. 7–1 and 7–5, 24300N, 17900E) the Upper Shear Zone and rock units above and below are displaced by a north-northwest-trending shear zone that is parallel to strongly developed S3. Where exposed, this shear zone forms the contact between graphitic sericitic phyllite to the southwest and carbonate-altered ultramafic rock to the northeast. The contact zone consists of several centimeters of sericitic phyllite, strongly foliated parallel to S3, but no late fault gouge. The vertical component of displacement of the Upper Shear Zone by this S3 shear zone (which is the minimum possible displacement) is 300–400 feet, northeast-side-down. The net direction and total amount of displacement are not known.

F4 Folding

F4 folds and axial planar S4 cleavage are locally developed throughout the mine and surface (fig. 10*C*). They are abundant in certain areas near the 1350 portal and in the upper part of Big Sore Ridge (pl. 7–5).

F4 folds, which are usually open, have axial planes that generally dip gently southerly and axes that plunge southwest to south (pl. 7–5). They are commonly nearly coaxial with F3, but F4 axial planes generally are at high angles to F3 axial planes (fig. 1). Where F4 and F3 occur together, F3 axial planes are folded by F4 folds (fig. 10*C*), and the folded F3 axial planes commonly are flattened to an overall gentle east dip. S4 cleavage is only locally developed and is either a spaced fracture cleavage or a crenulation cleavage.

The nearly coaxial orientation of F3 and F4 folds suggests they may be related to the same period of deformation. However, the age relationships and differing orientations of these two fold sets is consistent throughout the mine area, as well as in other areas, such as along the access road (2.5 mi "B" road) just east of Hawk Inlet. In the 1350 tunnel (450 feet southeast of portal), where F4 refolds F3, a quartz vein cuts an F3 axial plane without being folded by F3, but is folded by F4 (fig. 10*C*). Therefore, these two periods of folding were separated by a fracturing and veining event.

Brittle Faults

Low-Angle Faults

Small, gently dipping faults occur in several parts of the mine. Many of these are healed by white quartz and calcite vein material, and some have been refractured and have dark clay gouge. Other faults consist mainly of clay gouge. These

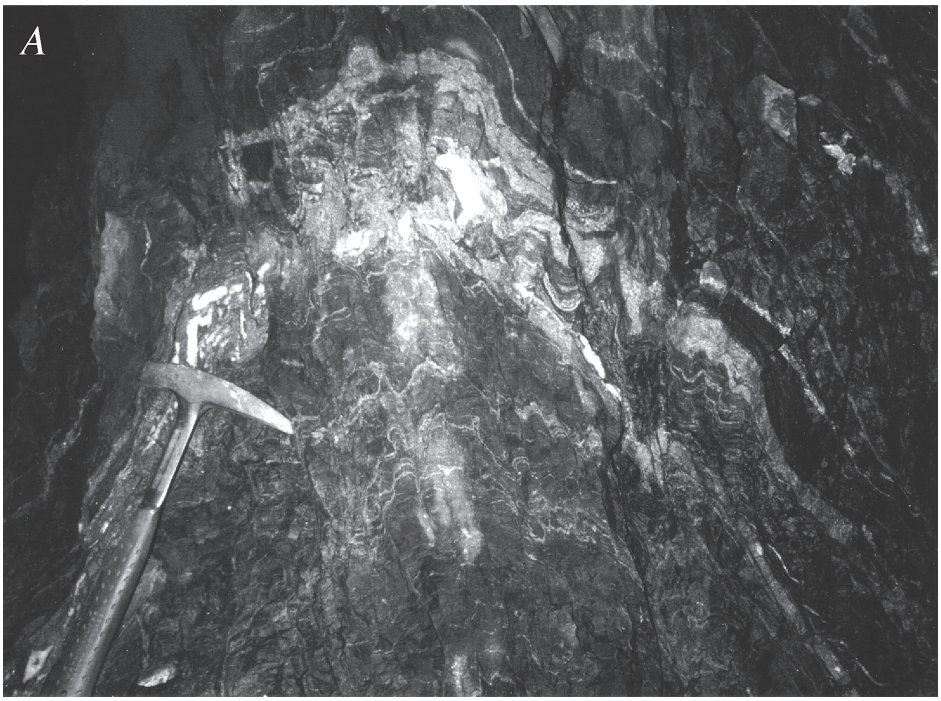
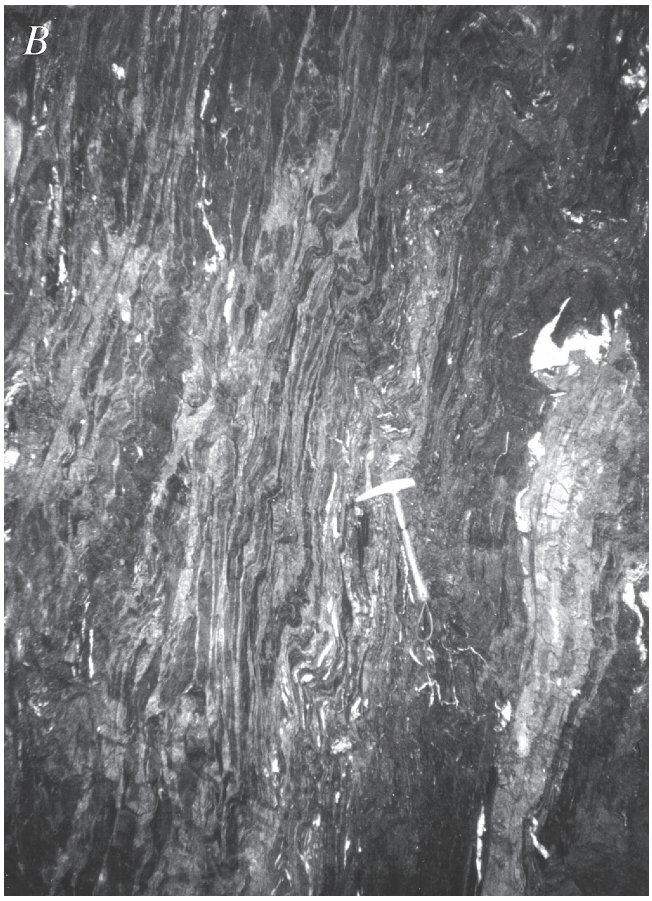
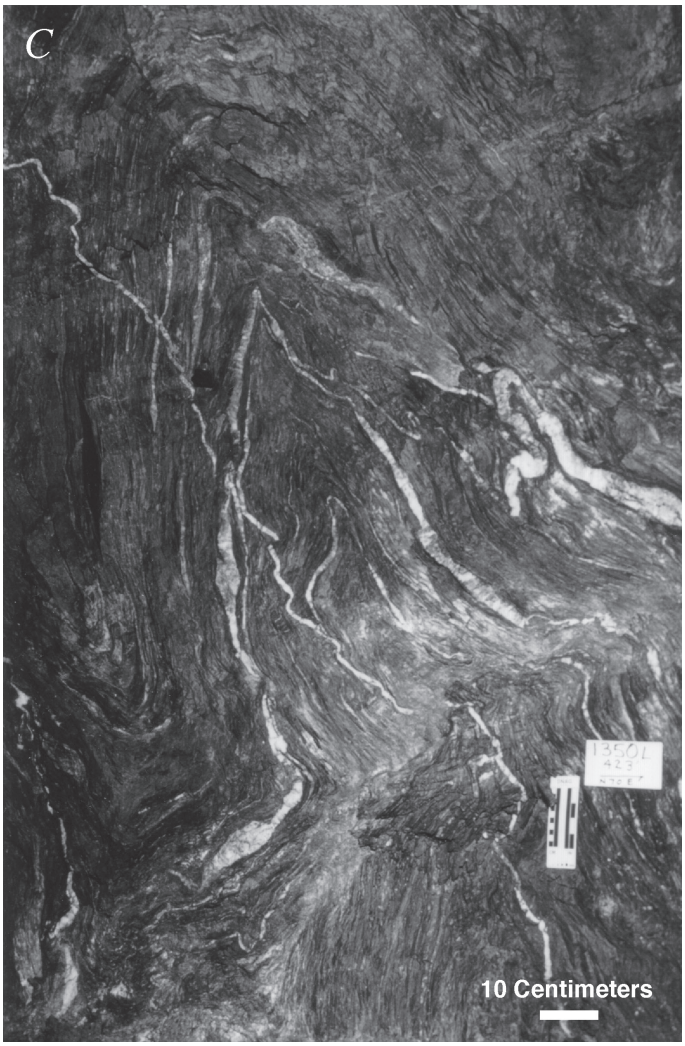


Figure 10. Photographs. *A*, Steeply west-dipping beds of argillite, with massive sulfide layers, on the east limb of a large-scale F3 synform. Note that bedding is flattened only where crossed by rare F3 folds, such as along hammer handle and 1 foot left of hammer. 580E stope, looking north-northwest (17520N, 20395E, 580-foot elevation). *B*, Cherty argillite with massive base-metal sulfide layers and pyritic beds, folded in an F3 antiform. Note spaced S3 cleavage parallel to axial plane. 580E stope looking north-northwest (17502N, 20385E, 580-foot elevation). *C*, S2, and quartz veins parallel to S2, in tan phyllite, folded by F3 and refolded by F4. Note later quartz vein that cuts across F3 axial plane without being folded, but which is folded by F4. 1350 tunnel at 423 feet from portal, NE rib, looking N. 20 W., up plunge (19912N, 20275E, 1,407-foot elevation).





low-angle faults truncate F3 folds, but their relationship to F4 folds has not been established. Many seem to be closely related to strike-slip faults (described below) and may represent bends in strike-slip fault planes or connecting faults between different strike-slip faults. None of these faults are known to have large displacement. For example, the fault shown in figure 4 appears to have about 45 feet of north-northeast displacement of the hanging wall.

Northwest-Striking Right-Slip Faults

The most important brittle faults in the mine area are northwest-striking right-slip faults. These dip steeply, generally to the southwest. The best known is the Maki fault, which separates the east and west parts of the mine (pl. 7–1, 7–4). This fault was defined by T.C. Crafford (written commun., 1986), and an estimate of about 1,800 feet of right slip was made by P.A. Lindberg (written commun., 1994). Correlation of axes of large F2 folds and thickened ore in the Central West ore zone east of the fault with similar structures and thickening in the Northwest West ore zone on the west indicates 1,755 feet (535 meters) of right slip, with 110 feet (34 meters) of west-side-up slip, closely confirming Lindberg's estimate.

The Maki fault consists of several strands within a zone nearly 200 m wide in the southern part of the mine. Northward, the strands merge to a zone about 10 m wide in the north part of the mine. The fault strands consist mainly of soft, sheared, clay-rich gouge and breccia. The Maki fault is also exposed on the surface above and southeast of the mine and can be traced across the district as a prominent topographic lineament.

The Gallagher fault in the Gallagher Creek area west of the mine (see pl. 7–1) is similar to the Maki fault. It consists of at least two main branches, referred to as the East Gallagher fault and the Middle Gallagher fault (P.A. Lindberg, written commun., 1998). Each branch may have up to a few hundred feet of displacement. Topographic lineaments and mapping to the north (for example, T.C. Crafford, written commun., 1987) suggest that another northwest-trending right-slip fault may occur to the northeast of the mine, northeast of Big Sore Creek.

North-Northeast-Trending Left-Slip Faults

Steep, north- to northeast-trending faults with left slip occur in a few areas of the mine. Like the northwest-trending strike-slip faults, these also have brittle clay gouges and breccias. An example is the "D" fault in the Southwest orebody area (fig. 5), which has tens of feet of displacement. Several such faults occur on the surface near the headwaters of Gallagher Creek (pl. 7–1). These have from a few feet to about 250 feet of left slip, with a possible north-side-down component. Some strands displace branches of the Middle Gallagher fault, but it is possible that the left-slip faults are displaced by the East Gallagher fault. Another set of northeast-trending faults, possibly with left slip and north-side-down displacement, are interpreted to cut the rocks west of the Maki fault about 1,700 feet south of the 1350 portal (see pl. 7–1) based on drill-hole intercepts and surface outcrop patterns.

The similarity of gouges on northwest-trending right-slip faults and northeast-trending left-slip faults, and the apparent mutual crosscutting relationship between the two sets, suggest that they are related. They may be a complementary set, and would indicate regional north-south shortening. Haeussler (1992) found similar relationships and came to similar conclusions in the Seymour Canal Formation rocks to the east.

Relationship Between Ore and Structure

Ore minerals replace matrix and clasts in conglomerate, which contains clasts in which S1.5 is truncated by the conglomerate matrix, and base-metal-bearing veins cut the conglomerate. Mineralization is therefore younger than S1.5. Orebodies are clearly folded by F2 and overprinted by S2 foliation. The S2 foliation near F2 hinges is sometimes refracted where it passes from slaty host rocks into ore, but S2 is not well developed in ore except where ore contains patches of sheet silicates. Many sulfide-bearing veinlets in sericitic phyllite and siliceous rock adjacent to ore are also folded by F2 and overprinted by S2. Sericite and chlorite of the phyllite, which are part of the alteration halo of the ore, are strongly recrystallized and reoriented along S2, and these minerals along with the quartz, carbonate, and sulfides of the phyllite are in many cases segregated along S2 foliation planes. Thus, the mineralization predated F2 events.

Small tension fractures related to F2 folding, or in some cases F3 folding, commonly cut the ore. These may be filled with various ore minerals, such as chalcopyrite, bornite, galena, silver-sulfosalts, or electrum, which apparently formed by remobilization of certain ore elements during deformation (see also chap. 9).

Essentially all alteration minerals, especially sheet silicates, have been strongly affected by S2 deformation and probably recrystallized during related greenschist facies metamorphism. In F2 hinge zones, such as most of the Upper Southwest orebody, most ore appears to have been largely recrystallized. Even in the least-deformed, least-recrystallized ore on the limbs of F2 folds, such as in much of the Lower Southwest orebody, most primary ore components have been modified, though up to 30 percent of the ore components appear to retain primary textures, mineralogy, and trace-element distributions (chap. 9). The age of gangue and ore mineral recrystallization and other modification is tentatively considered to be middle Cretaceous, based on the tentative age assignment of F2 (previously discussed).

In addition to effects on the ore itself, the intense nature of F2 deformation makes the original overall geometry of the Greens Creek deposit extremely difficult to decipher. To

arrive at even a rudimentary understanding of the distribution of such features as possible syndepositional faults or feeders, location of intrusive or volcanic units, sedimentary facies distribution, original mineral or alteration zoning, or other features that might be of interest would require detailed understanding of all F2 and younger structure, as well as stratigraphic younging directions. Such a study would require very careful lithologic and structural mapping and analysis of essentially all workings in the mine and of most available drill core.

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