MAPS, SECTIONS, AND STRUCTURE-CONTOUR DIAGRAMS SHOWING THE GEOLOGY AND GEOCHEMISTRY OF THE MOUAT NICKEL-COPPER PROSPECT, STILLWATER COMPLEX, STILLWATER COUNTY, MONTANA

By Michael L. Zientek, Walter J. Bawiec, Norman J Page,
U.S. Geological Survey

and

Roger W. Cooper, Department of Geology,
Lamar University, Beaumont, TX

ABSTRACT

Deposits of magmatic nickel-copper (Ni-Cu) sulfides are concentrated near the base of the Stillwater Complex, a Late Archean mafic to ultramafic layered intrusion exposed on the north edge of the Beartooth Mountains, Montana. Extensive drilling and limited underground development work by the Anaconda Minerals Company has delineated the sub-surface extent of one of these deposits, the Mouat Ni-Cu prospect or deposit. Structural interpretation shows that rocks of the Mountain View area of the Stillwater Complex are folded into a broad syncline which is inclined and cut by several generations of faults. The oldest faults strike northeast and have near vertical dips. These faults are cut by northwest-striking, near vertical faults showing left-lateral separation. Apparent separation on these faults are less than 500 ft. Two high-angle reverse faults, the Lake fault and the Bluebird thrust, truncate the Mouat deposit on the northeast and the southwest, respectively. Sulfide minerals that constitute this deposit are concentrated at the lower contact of the Stillwater Complex within the Basal series and within and adjacent to very discontinuous, irregularly shaped Stillwater-associated sills and dikes that intrude the metasedimentary rocks underlying the complex. The base of the Stillwater Complex shows considerable relief over short distances; as a result, the thickness of the Basal series ranges from 0 to 450 ft. However, there is no clear evidence that sulfides at the base of the complex pooled in depressions on the floor of the complex. Intensity of faulting and the discontinuous nature of the matrix-to-massive sulfide mineralization do not allow probabilistic tonnage and grade estimates to be made despite the density of drilling.

INTRODUCTION

The Mountain View area is one of several areas where conspicuous accumulations of sulfide occur near or at the base of the Stillwater Complex, a Late Archean layered ultramafic to mafic intrusion that crops out in southwestern Montana (fig. 1). Surface exposures of the Mouat deposit in the Mountain View area were discovered in 1886 and subsequently this area has been the focus of the most detailed evaluation of any of the Stillwater basal nickel-copper deposits (Page and others, 1985a). Early prospectors drove many adits in the vicinity of Verdigris Creek. Drilling programs were conducted by the Anaconda Minerals Company in 1937 (diamond drill holes (DDH) M-1 to M-11; Roby, 1949), 1966-1971 and 1977-1982 (DDH M-12 to M-22 and M-366-301 to M-395-329), and by the U.S. Bureau of Mines in 1939 (DDH A to H; Roby, 1949). Altogether, over 120,000 ft of core was drilled. Anaconda Minerals Company also drove a 1,547-ft exploration adit, the Mouat Tunnel, in 1970-1971.

These maps and sections document the salient geologic features of the Mouat nickel-copper prospect deposit. In addition, geochemical data for two of the section lines (C-C' and E-E; sheet 1) is shown to provide some insight into the complexity of the distribution of metal concentration in the deposit.

SOURCES OF INFORMATION AND METHODOLOGY

Prior to this investigation, numerous studies that have some bearing on the geology of this area were published. Studies dealing solely with the Mouat deposit or the Mountain View area include: Howland, 1933; Roby, 1949; Barker, 1971; Barker, 1975; Page and Simon, 1978; Miller and Adler, 1975; Drew and others, 1985; and Humphreys, 1983. Other studies that in part cover this area include those of Jackson, 1961; Page, 1977; Page, 1979; Page and Nokleberg, 1974, Peoples and others, 1954; Raedeke, 1982; Helz, 1985; Page and others, 1985b; and Zientek, 1983. However, none of these studies completely summarize the results of the drilling and underground exploration programs, particularly the work conducted between 1966 and 1971 when most of the drilling was done.

The majority of the holes collared in the 1966 to 1971 drilling program were drilled on 200-ft centers in an attempt to calculate ore reserves of this deposit (fig. 2, sheet 1). Holes on the 200-ft grid were assigned a six-digit diamond drill-hole name that is an abbreviation of the Montana south coordinates of the drill-hole collar. For example, a drill-hole whose collar coordinates were 237,915N and 132,946E is named M-379-329. The drilling grid was oriented parallel to the overall strike of the deposit, N. 50° E. The sections illustrated here are parallel and perpendicular to the grid lines and therefore are approximately oriented parallel and perpendicular to the strike of igneous layering in the Stillwater Complex.

During the course of this investigation, the surface exposures of the Basal series and the Stillwater-associated sills and dikes were remapped at scales ranging from 1:480 to 1:2400 and approximately 20,000 ft of drill core from 21 drill holes was relogged at a scale of 1:120 by two of the authors (Zientek and Cooper). This was essentially all the core that remained after a fire partially destroyed the core storage building in Butte in 1979.

The principal difficulty in working with rocks near the base of the Stillwater Complex is distinguishing lithologies. Previous investigators had extreme difficulty in differentiating fine-grained hornfels and fine-grained igneous rock and were unsuccessful in describing the mineralogical and textural variations of the medium-to-coarse-grained igneous rocks. Page (1979) showed that textures and mineralogy for these rocks are enhanced dramatically by etching sawn surfaces with concentrated hydrofluoric acid. An etching facility was constructed at the field office at Nye, Mont., and drill core was etched as necessary to identify lithologies, define contacts, and describe complex lithologic transitions. Samples were routinely etched every 10 ft downhole and the spacing decreased in zones of lithologic and structural complexity.

The new logs on these 21 drill holes were compared to the 1:240 logs previously made by N.J Page (written commun., 1980) and geologists of Anaconda Minerals Company at the time the holes were drilled. Very consistent correlations between the old and new logs allowed the geology for holes that were destroyed in the fire to be reinterpreted in light of information derived from the new logging and mapping. In addition, Drew and others (1985) recognized that patterns displayed by downhole Cu and Ni assay logs could be used to break out the major stratigraphic units; this information greatly facilitated the interpretation of the overall stratigraphy everywhere the old logs were ambiguous. Lithologic and stratigraphic units shown on the sections reflect those that show the greatest consistency between old and new logging.

Downhole distribution of visual estimates of volume percent sulfide in the rock and Cu and Ni grades are shown for sections C-C' (sheet 1). The volume-percent sulfide data were extracted from a computer database constructed from the drill logs. The Cu and Ni assay data represents whole rock analyses obtained by Anaconda on composite drill core samples. These samples were made by splitting the core, taking half of the core within the sample interval, and crushing and splitting it to get a sample for analysis.

The structure-contour diagrams and the perspective structure-contour diagrams (figs. 3-6, sheet 1) were generated utilizing the Interactive Surface Modeling program developed by Dynamic Graphics, Inc. of Berkeley, California. Artificial control points were added to the drill-hole data set as necessary so that the calculated grids and cross sections closely approximated the geologic map relations and the hand-drawn sections. The viewing angle on the perspective structure-contour diagrams is 40° above the horizontal. The numbers on the axis of figures 5 to 7 (sheet 1) represent the number of feet from the origin of the computer database grid (Attanasi and Bawiec, 1987; see figure on p. B6). The database grid is parallel to the drilling grid. The Montana south coordinates for the origin for the computer database grid are 234,545N and 130,825E.

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DESCRIPTION OF GEOLOGIC MAP UNITS

METAMORPHOSED SEDIMENTARY ROCKS

Metamorphosed sedimentary rocks make up the oldest unit in the map area; detrital zircons from this unit have yielded ages of approximately 3,200 Ma (Nunes and Tilton, 1971). These rocks experienced at least two, and perhaps three, episodes of folding prior to the intrusion of the Stillwater Complex (Page, 1977). These rocks were contact metamorphosed at the time the

Stillwater Complex was intruded; mineral assemblages for the metamorphosed sedimentary rocks in the Mountain View area are indicative of the pyroxene hornfels facies of metamorphism. Temperatures near the base of the Stillwater Complex at the time of crystallization and cooling of the complex may have been in excess of 825 °C; pressures probably were in the range of 2 to 3 kb (Labotka, 1985).

In the Mountain View area, two lithologies that compositionally correspond to mafic graywacke and Fe-Mg-Al-enriched shale have been recognized (Page and Zientek,1985). Both lithologies are characterized by presence of cordierite, biotite, plagioclase, and quartz; however, in the mafic graywacke, plagioclase, biotite and quartz are more abundant and quartz shows a relict detrital morphology. Accordingly, it is referred to as quartz-bearing hornfels. The mineralogy of the Fe-Mg-Al-enriched shale is dominated by cordierite and hypersthene; quartz, if present, forms anhedral grains filling interstices among other minerals. This lithology is referred to as cordierite-hypersthene hornfels.

The transition between these lithologies can be sharp, gradational over ten's of feet, or characterized by the presence of a transitional lithology in which almandine-rich garnet is a volumetrically important mineral. Southwest of the Verdigris fault, quartz-bearing hornfels occurs as a mappable unit directly beneath the cordierite-hypersthene hornfels. Northeast of this fault, the quartz-bearing hornfels is intercalated with the cordierite-hypersthene hornfels, the dominant lithology, and is not readily traced in the sub-surface. Therefore, it is not shown northeast of the Verdigris fault. Differences in contact relations suggest that the Verdigris fault may be an older structure that was reactivated during emplacement of the Stillwater Complex.

Blue metaquartzite also occurs sporadically within the metamorphosed sedimentary rocks as clasts and in thin, discontinuous layers. Its distribution is not shown on the maps and sections.

Despite the two or three episodes of folding and contact metamorphism, primary sedimentary features of the rocks are still evident. Features most commonly observed are fragmental textures and layering defined by changes in bulk composition, grain size, and/or mineralogy. The fragmental textures are present in both the quartz-bearing and cordierite hornfels. Detailed descriptions of the fragmental textures from the Mountain View area are given by Page and Koski (1973). Layering characteristics of these rocks are described by Page (1977).

SILLS AND DIKES ASSOCIATED WITH THE STILLWATER COMPLEX

Sills and dikes associated with the Stillwater Complex intrude the metamorphosed sedimentary rocks beneath the base of the Stillwater Complex in the Mountain View area (Zientek, 1983). On the basis of studies of Stillwater-associated sills and dikes in the Mountain View area and elsewhere along the base of the complex, Helz (1985) divided these sills and dikes into six compositional types: group 1 gabbronorite; group 2 high-Mg gabbronorite; group 3 mafic norite (metagabbronorite); group 4 high-Ti norite, group 5 norite, and group 6 olivine gabbro. Only compositional groups 1, 3, 4, and 5 occur in the Mountain View area. Excellent exposures of these rocks occur northeast of the Verdigris fault. Definitions of the compositional types can be found in Helz (1985); information on textures and pyroxene compositions are presented by Zientek (1983).

Unfortunately, all these compositional types cannot be distinguished in outcrop or drill core. Groups 1, 4, and 5 cannot be distiguished from one another; all contain similar proportions of plagioclase and mafic minerals and exhibit similar textures and grain size. As such, these rocks were mapped as diabase; where compositional data is available, compositional types are noted on the sections. Group 3 mafic norite is distinct from those types that were mapped as diabase and is shown as a distinct unit on the geologic map and sections. It was generally not possible to identify confidently sill or dike rocks in the metasedimentary rocks as either diabase or mafic norite on logs prepared by previous investigators; these intrusions are shown as undifferentiated norite on the geologic map and sections.

Group 1 sills and dikes are gabbronoritic diabases that exhibit ophitic, subophitic, and granular textures. Intrusions commonly have chilled contacts against the adjacent hornfels. Pyroxenes are the dominant ferromagnesian minerals with orthopyroxene more abundant than augite. Minor amounts of hornblende and biotite are present locally. A U-Pb date of 2712 ± 8 Ma has been obtained from zircons separated from the group 1 gabbronoritic diabase in DDH M-370-316 (W.R. Premo, written commun., 1987). The U-Pb zircon date of 2713 ± 3 Ma reported by Nunes (1981) from the Nye Basin area is most probably from a gabbronoritic diabase intrusion rather than from a chill of the complex.

Group 3 sills and dikes are referred to as mafic norites although they compositionally range from gabbronorite through melagabbronorite and melanorite to feldspathic orthopyroxenite. Sulfide minerals form a conspicuous part of the mineral assemblage of these rocks; disseminated (0 to 10 volume percent) and matrix sulfides (10 to 60 volume percent) occur commonly. Massive sulfide is usually associated with the group 3 sills and dikes either as accumulations near the margins of the intrusions or as dikelets proximal to the group 3 sill or dike. Orthopyroxene is the dominant silicate mineral in these rocks and usually displays a subhedral to euhedral, slightly skeletal morphology. Plagioclase usually forms anhedral grains interstitial to or poikilitically enclosing orthoproxene. Subordinate minerals include augite, olivine, hornblende, biotite, and quartz. Whole rock and rare-earth element (REE) compostions of many of these sills and dikes do not correspond to liquids; however, the presence of chilled margins on some of the sills and dikes and liquid-like REE patterns and abundances for some of the more gabbronoritic compositions indicate that at least some of these mafic-mineral-enriched rocks do approximate liquid compositions. A mafic norite dike exposed in the cliff exposures north of Verdigris Creek (Stop 4, locality 3 in Page and others, 1985b) has yielded a Nd-Sm date of 2661 ± 35 Ma (Snyder and others, 1987) and a U-Pb zircon date of 2707 ± 14 Ma (W.R. Premo; personal commun., 1989).

Group 4 sills and dikes are high-Ti noritic diabase. These rocks are characterized by subophitic to granular textures. Orthopyroxene is the dominant mafic phase; quartz is a common mineral that occurs interstitially to plagioclase and orthopyroxene. Opaque minerals (dominantly ilmenite) are a volumetrically important constituent of these rocks; TiO_2 of whole rock analyses ranges from 3 to 5 weight percent. A U-Pb date of 2711 ± 2 Ma has been obtained on zircons extracted from one of these intrusions intersected in DDH M-384-333 (W.R. Premo, written commun., 1987).

Group 5 sills and dikes are noritic diabases that compositionally appear to have crystallized from contaminated or hybrid magmas. Textures range from ophitic to granular. Orthopyroxene is the dominant mafic mineral. Quartz and augite are common accessory minerals. These rocks have not been dated radiometrically.

STILLWATER COMPLEX

The Stillwater Complex is a Late Archean ultramafic to mafic layered intrusion. Various dating techniques give ages that range from approximately 2,660 to 2,896 Ma; however an age of 2,700 Ma appears to be the best estimate of the age of intrusion (Lambert and others, 1985).

Layering in the Stillwater Complex can be defined on the basis of cumulus mineralogy, grain size, postcumulus mineralogy, and igneous lamination. However, the distribution of cumulus minerals is the most useful in mapping structures in the intrusion and in understanding its petrogenesis. As a result, the igneous rocks of the Stillwater Complex are best described utilizing cumulus nomenclature which simply means that the rocks are named according to the abundance of cumulus mineral present (Jackson, 1967; Irvine, 1982). A stratigraphy for the intrusion based on the cumulus mineralogy of the rocks has been devised; five major subdivisions (series) and 14 to 18 lesser subdivisions (zones) are present (Zientek and others, 1985).

In the area near the Mouat deposit in the Mountain View area only the Ultramafic and Basal series of the Stillwater Complex are present. Only the lower of the two zones of the Ultramafic series, the Peridotite zone, is present. In addition, the two zones recognized in the Basal series (Page, 1979) could not be broken out on the scale of the map and the sections. The units that appear on the geologic map are described in greater detail below.

Basal series

The Basal series of the Stillwater Complex in the Mountain View area consists dominantly of orthopyroxene-rich cumulates but noncumulus rocks, mafic pegmatoids, and contaminated rocks are present locally. Xenoliths of cordierite-hypersthene hornfels ranging from inches to tens of feet in diameter are common. In addition, disseminated to massive accumulations of magmatic sulfides are a characteristic feature of this unit. Detailed descriptions of the Basal series lithologies and aspects of the mineral or bulk sulfide chemistry can be found in Page (1979); Page and Simon (1978); Humphreys (1983); Barker (1971); Barker (1975); Raedeke (1982); and Zientek (1983).

Orthopyroxene, augite, inverted pigeonite, olivine, chromite, and plagioclase occur as cumulus minerals in the Basal series. Many combinations of these minerals have been recognized (Page, 1979; Zientek, 1983), but orthopyroxene cumulate is the dominant lithology. Orthopyroxene-olivine, orthopyroxene-augite, and orthopyroxene-plagioclase cumulates are also common.

Detailed studies of the internal stratigraphy of the Basal series have not resulted in a fine-scale subdivision of this unit. Individual cumulus layers appear to be laterally discontinuous or difficult to recognize from hole to hole. Textural relations in thin section and the appearance and disappearance of cumulus minerals in the stratigraphic section indicate several crystallization sequences are present in the Basal series (Page, 1979; Zientek, 1983). However, these partial crystallization sequences do not form cyclic units with enough lateral continuity to be mapped. Therefore, only the broadest of trends can be used to characterize the internal stratigraphy of this unit.

The following generalizations appear to apply to the Basal series of the Stillwater Complex wherever it has been observed in detail. First, multiphase cumulates are restricted to the lower portion of the unit; rocks that immediately underlie the contact with the Peridotite zone of the Ultramafic series are invariably orthopyroxene cumulates. Second, the proportion of magmatic sulfide generally increases towards the lower contact of the unit. Third, the textures of the cumulates change from bottom to top in the unit. Low in the unit, orthopyroxene is commonly skeletal whereas near the top of the Basal series, orthopyroxene commonly forms anhedral to euhedral, equant to prismatic crystals indistinguishable from cumulus pyroxene in the overlying Ultramafic series. Also, the cumulus minerals show a narrower range of grain size upsection and the rocks contain a lower proportion of intercumulus plagioclase. Fourth, segregations of fine-grained noncumulus mafic rock in the Basal series are most commonly found in the lower part of the unit.

Such differences between the upper and lower parts of the Basal series have served as a basis for subdividing it into a Basal bronzite zone and a Basal norite zone (Page, 1979; Zientek and others, 1985). Unfortunately, criteria to distinguish these two zones can only be recogized by detailed studies of core utilizing etching techniques and thin sections and are not routinely observed in logging. As a result, these two zones could not be shown on the sections.

Peridotite zone of the Ultramafic series

The Peridotite zone of the Ultramafic series of the Stillwater Complex is composed of a number of cyclic units in which olivine, bronzite, and chromite occur as cumulus minerals (Jackson, 1961; Raedeke and McCallum, 1984). An idealized cycle begins with olivine cumulate that contains accessory cumulus chromite. In some cycles, the chromite is concentrated into layers or seams. The olivine cumulate is overlain by olivine-bronzite cumulate and bronzite-olivine cumulate that are in turn overlain by bronzite cumulate. The proportion of cumulus olivine decreases and the proportion of cumulus bronzite increases upwards in the olivine-bronzite and bronzite-olivine cumulate layers. The contacts between the olivine cumulate, the bronzite-olivine cumulate, and the bronzite cumulate are gradational. The contact between the bronzite cumulate of one cycle and the olivine cumulate of the overlying cycle is sharp.

Cycles in the Peridotite zone rarely conform to this ideal. Many are incomplete; most commonly a new cycle began before all three cumulus layers in the underlying cycle formed. In some cases, the first layer in the new cycle is an olivine-bronzite cumulate instead of an olivine cumulate. In other cases, the middle layers of olivine and bronzite cumulates are poorly developed or absent. Despite these variations, the cyclic unit is a fundamental mappable unit in the Peridotite zone that serves to define the basic geometry and structure of this part of the complex.

Unfortunately, the original Anaconda logging was done before the utility of mapping cumulus layers was fully appreciated. Instead, the total mode was used to identify the lithology. The basic units therefore were harzburgite and bronzitite. Commonly, the harzburgite was divided into poikilitic and granular varieties that largely correspond to olivine cumulate and olivine-bronzite cumulate respectively. In general, bronzitite corresponds to bronzite cumulate. In practice, the correspondence is not good enough to map the cyclic units in detail. This largely results from generalization on the part of the early investigators (they did not realize the importance of the textural and modal variations in these rocks) rather than the units not being correlatable. In addition, considerable intervals at the beginning of the holes (typically in the Peridotite zone) were rotary drilled and only cuttings were available for inspection making detailed textural and modal descriptions difficult. Therefore only the least ambiguous features in this zone, hornfels xenoliths and chromite seams, are illustrated on the sections (sheet 2). On the geologic map (sheet 1), cyclic units are shown.

COARSE-GRAINED QUARTZ MONZONITE AND APLITE

A suite of silicic plutonic rocks including quartz monzonite, aplite, and hornblende quartz diorite crop out in the Mountain View area (Page and Nokleberg, 1974; Page and Nokleberg, 1972); however, in the map area for this study only the coarse-grained quartz monzonite and aplite are shown. Although elsewhere in the complex these rocks locally intrude the Basal series, in the Mouat Ni-Cu prospect area, they intrude only the metamorphosed sedimentary rocks and the Stillwater-associated sills and dikes.

The quartz monzonite exhibits relict xenomorphic to hypidiomorphic-granular, equigranular, and porphyritic textures. Overprinted on the igneous texture is one of metamorphic origin that consists of seriate grain boundaries in which muscovite, biotite, chlorite, quartz, and feldspar are recrystallized along feldspar-quartz grain contacts. Major minerals in this rock are plagioclase (0.5 to 2 cm long as phenocrysts; 0.075 to 0.3 mm grains in groundmass), potassium feldspar (0.3 to 1.5 cm long phenocrysts; 1-2 mm groundmass grains), and quartz (2-4 mm grains in clots 0.4 to 1 cm in diameter). Minor minerals are apatite, zircon, and oxide and sulfide minerals. Sericite, chlorite, and epidote are secondary minerals.

The aplite is a hypidiomorphic to xenomorphic fine- to medium-grained granular rock in which quartz, plagioclase, and microcline are the major minerals. Minor minerals are biotite, muscovite, epidote, zircon, apatite, and opaque minerals.

The ages of the coarse-grained quartz monzonite and the aplite were reported by Nunes and Tilton (1971). A three point regression on the zircon data for the coarse-grained quartz monzonite utilizing the new decay constants yields a date of 2,696 ± 9 Ma (J.L. Wooden, oral commun., 1987).

MAFIC INTRUSIVE ROCKS

Mafic sills and dikes showing intrusive relations indicating they are younger than all other Precambrian units exposed in the Stillwater Complex area are uncommon in the map area. Only one of these dikes has been mapped and its petrographic characteristics are not known. Petrographic descriptions of these rocks occurring elsewhere can be found in Page (1977) and Helz (1985).

QUATERNARY DEPOSITS

Quaternary deposits in the map area include landslide, colluvial, alluvial, and glacial deposits.

STRUCTURAL FEATURES

FOLDS

The penetrative deformation that affects the metasedimentary rocks in the vicinity of the Mouat deposit is described in detail in Page (1977) and is summarized briefly here. The layered metasedimentary rocks were folded into major and minor open folds whose fold axes now have a northeast trend and about a 60° NE. plunge (F_1). These folds were warped or refolded into broad open folds about axes that now have moderately plunging northwest axes (F_2). Associated with the layering folded by F_1 are a few tight intrafolial folds that can be interpreted as a phase of folding earlier than F_1. Two other styles of folds, asymmetric and broad discontinuous folds, are present but their relation to F_1 and F_2 are unknown. Only the broad open folds (F_1) are evident on the sections.

Page (1977) has shown that contouring of poles to cumulus layering (S_o) from the Mountain View area define a girdle oriented N. 43° E. and dipping 34° SE. The βs_o axis for this girdle fabric plunges 56°, N. 47° W. This axis probably represents the folding that resulted from compression of the Stillwater Complex and adjacent rocks between the Lake fault and the Bluebird thrust. This broad synclinal folding is evident in the sections (sheet 2), the structure-contour diagram of the contact between the Ultramafic and Basal series (fig. 4, sheet 1), and the maps of the underground workings of the Mouat chrome mine (Peoples and others, 1954).

FAULTS

Examination of the maps and sections reveals the metamorphosed sedimentary rocks and the rocks of the Stillwater Complex have been cut by at least five generations of faults. Unnamed faults are labelled 1 to 3 and A to Q on the maps and sections. Apparent separation on these structures within the Mouat Ni-Cu deposit are less than 500 ft. Examination of smaller scale maps of the Stillwater Complex (fig. 1) shows that the rocks in the Mouat Ni-Cu prospect area lie between the Bluebird thrust and the Lake fault and have been rotated relative to the rest of the complex (Jones and others, 1960; Page and Nokleberg, 1974). These faults have the greatest separation and truncate the Mouat deposit on the southwest and northeast.

Within the Mouat deposit (geologic map, sheet 1), the oldest fault, F, strikes northwest. It is offset by faults 1, 2, and 3 that strike northeast, have near vertical dips, and show left-lateral displacement. These faults are cut by northwest-trending faults that dip 50° to 60° to the southwest, and show left-lateral separation. The Hamslice fault and faults G, H, I, M, and N are examples of this generation of faulting. These faults are in turn cut by northwest-trending, near vertical faults showing left-lateral separation. Examples of these faults include faults A, B, C, D, E, and the Verdigris fault.

The Lake fault was intersected in several drill holes (M-393-328, M-393-334, M-394-332, M-395-327, and M-395-329, fig. 2, sheet 1) in the northeastern part of the deposit (section J-J', sheet 2). These intercepts, along with the exposure in the Monte Alto tunnel (Page and others, 1985b), show this fault trending approximately N. 80° E. and dipping 45° to 85° to the south.

GEOLOGIC FEATURES RELATED TO THE INTRUSION OF THE STILLWATER COMPLEX

Several general geologic features relevent to the intrusion of the Stillwater Complex are apparent despite the deformation and the difficulties in interpreting information collected by so many individuals over a twenty-year time span.

The amount of relief on the floor of the complex is one of the most apparent features. The thickness of the Basal series ranges from 0 to 450 ft thick. This variation in thickness is not a systematic increase from southwest to northeast as is the case in the overlying Peridotite zone (Jackson, 1968; Page and others, 1985b) but is related to antiforms and spires on the lower contact that may in part reflect the large open folds in the underlying metasedimentary rock. At this time, ponding of sulfide accumulations in depressions along the floor of the complex is not indicated.

The presence of numerous metasedimentary xenoliths, the largest over 800 ft in length, in both the Basal and Ultramafic series is also apparent. Studies of similar detail in the Nye Basin-Benbow, Chrome Lake, and Iron Mountain areas have identified metasedimentary xenoliths, but they are not as numerous and large, nor do they occur as commonly in the Peridotite zone as they do in the Mouat deposit.

The presence of the Stillwater-associated sills and dikes is restricted largely to the cordierite-hypersthene hornfels. Few of these intrusions are found in the quartz-bearing hornfels.

DISTRIBUTION OF SULFIDES AND METAL CONCENTRATION IN THE MOUAT NI-CU DEPOSIT

One of the principal reasons for attempting a detailed synthesis such as this is to identify features which may have some control on the deposition or localization of the immiscible sulfide magmas that crystallized to form the sulfide accumulations now seen. Variation in visual estimates of the volume-percent sulfide and the Cu and Ni concentrations are shown for two sections, C-C' and E-E' (sheet 1). The Cu and Ni concentrations represent whole rock analyses on composited intervals of drill core. The downhole covariation of Ni and Cu form patterns that reflect the silicate mineralogy and the sulfide abundance of the major lithologic units near the base of the intrusion and, in absense of direct lithologic observations, can be used to identify the units (Drew and others, 1985).

It appears on these sections (C-C', E-E', sheet 1) that sulfide minerals are concentrated at the lower contact of the Basal series with the metasedimentary rocks (for example DDH M-381-328) and within and adjacent to some of the Stillwater-associated sills and dikes (for example drill holes northeast of the Verdigris fault). However, sulfide minerals are not restricted to the Basal series but also occur as a trace constituency in the Peridotite zone of the Ultramafic series.

Within the Basal series, the sulfide minerals do not increase uniformly towards the lower contact with the metasedimentary rocks. There is a low sulfide interval several tens of feet thick that occurs immediately beneath the contact with the Ultramafic series. Abundant sulfide minerals appear abruptly beneath this interval; the Cu-Ni assay logs show an abrupt break at this point. Beneath this low sulfide interval, sulfide minerals generally increase towards the lower contact of the Basal series but with many reversals and discontinuities. The Cu-Ni assay logs show bulbous patterns of increasing and decreasing Cu and Ni concentrations; the low concentrations occasionally mark the position of hornfels xenoliths but in most instances there is no change in lithology. The increase in sulfide mineral abundance downhole is not reflected by higher whole rock Cu and Ni concentrations. This apparently results from changes in the proportions of pyrrhotite, pentlandite, and chalcopyrite as the total sulfide abundance increases; the proportion of pyrrhotite is higher in rocks containing a higher proportion of sulfide minerals. A high proportion of sulfide minerals and elevated Cu and Ni values extend several ten's of feet into the underlying metasedimentary rocks.

Examination of the sections show that most of the high concentrations of sulfide minerals and elevated Cu and Ni values occur within and adjacent to the group 3 mafic norite sills and dikes in the metamorphosed sedimentary rocks. Individual massive sulfide lens and pods have extremely limited continuity and rarely can be correlated between adjacent drill holes (Roby, 1949). Cu-rich sulfide mineral assembleges are associated with two of the thicker group 1 gabbronoritic diabase intrusions (DDH M-370-316 and M-384-333, section C-C', E-E'; sheet 1).

RESOURCE CONSIDERATIONS

As part of the investigation of the Mouat deposit, an estimate was made of the tonnage and grade of part of the explored part of the deposit (Attanasi and Bawiec, 1987); a generalized and modified version of the geological interpretation of the deposit presented here was used in these calculations.

The intensity of faulting and the very irregular shape and distribution of mineralized sills and dikes made it impossible to estimate a well behaved variogram. As a result, geostatistical methods could not be applied to quantify probabilistically the confidence attached to grade or tonnage estimates. Sulfide accumulations at the base of the Basal series showed the greatest continuity; therefore, the grade and tonnage computations concentrated on rock units near this contact. Data on both copper and nickel concentrations were analyzed and examined in 25-ft intervals above the base of the Basal series and below the Basal series into metasedimentary rocks using mining blocks 25 by 25 ft and 100 by 100 ft. Only two fault-bounded blocks contained sufficient information (number of drill holes or surface exposure of the contact) to credibly estimate grade-tonnage relationships. One fault-bounded block lying directly west of the Verdigris fault contains 17.1 to 22.3 million short tons of ore having an average grade of 0.5 percent combined copper and nickel. In a smaller fault-bounded block farther to the west, 2.4 to 5.3 million short tons of ore having an average grade of 0.5 percent combined copper and nickel is thought to be present. These numbers represent the tonnage and grade of only a small part of the explored deposit. The deepest parts of the deposit have not yet been explored.

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