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DESCRIPTIVE, GRADE, AND TONNAGE MODELS FOR MOLYBDENUM-TUNGSTEN GREISEN DEPOSITS

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ABSTRACT

Molybdenum-tungsten greisen deposits are present in extensional rift zones in thick continental plates and are associated with acid (SiO_2 >73–75 weight percent), commonly weakly alkaline (K_2O+Na_2O >8.24 weight percent) and mainly potassium-rich ($K_2O:Na_2O$ >1), large, multiple-phase granite stocks, batholiths, and cupolas of varied morphology. The deposits range in age from Proterozoic to Mesozoic.

Molybdenum-tungsten greisen bodies are confined to apical lobes of plutons and adjacent rocks. They may form pods, veins, pipes, breccias, sheeted veins and stockworks (veinlets). They are commonly found together with other deposits of rare metals, as well as with polymetallic base-metal deposits.

Greisenization is the principal alteration process, and is usually associated with (from lower to upper levels) microclinization, albitization, sericitization and adularization. Greisens are present as assemblages of quartz, muscovite, topaz, fluorite and rarely zinnwaldite or lepidolite. The greisenization process may form solid greisen bodies or greisen veins, pipes or breccias close to the roof of mineralized plutons.

Morphology of these deposits varies from stockworks through vein-stockworks, stockwork-veins, and, at the deepest levels, to vein ore bodies. Most deposits contain molybdenum and tungsten, and less commonly, bismuth and tin. Molybdenite, wolframite, scheelite, cassiterite and bismuthinite are the primary ore minerals, together with pyrite, chalcopyrite, sphalerite, and galena.

Comparison of molybdenum-tungsten greisen and molybdenum porphyry deposits demonstrates that greisens are characterized by a plutonic, rather than a volcano-plutonic environment, and probably formed at deeper levels than most porphyry deposits.

Molybdenum-tungsten greisen deposits are characterized by negative gravity anomalies and positive aureoles of molybdenum, tungsten, bismuth, tin, copper and lead. Metal ratios and the outcrop area of ore-bearing plutons may help predict the size and depth of erosion of newly-discovered deposits.

Each molybdenum-tungsten greisen deposit represents a different level of emplacement. Taken together, they define a composite greisen column, which may be represented by distinct grade and tonnage models. Proximal deposits (Type 1) have a mean tonnage of 0.43 million mt and a mean grade of 0.17 weight percent Mo. Distal deposits (Type 2) have a mean tonnage of 40 million mt and a mean grade of 0.081 weight percent Mo.

INTRODUCTION

This report is intended to be consistent with previous occurrence and grade-tonnage models published by the U.S. Geological Survey (Cox and Singer, 1986; Bliss, 1992). The purpose is to provide a viable model that can be used to characterize molybdenum- and tungsten-rich greisen deposits, and to predict the size and quality of undiscovered deposits. It is a description, and is not meant to be part of a formal classification system, nor to discriminate absolutely molybdenum-tungsten greisens from other greisen deposits, such as those of tin (Menzie and Reed, 1986; Reed, 1986). Deposits included in this model have distinct grade and tonnage characteristics. Appendix A presents this material in abbreviated form, in the style of past deposit models (Cox and Singer, 1986).

Greisen deposits are one of the most important sources of rare metals, and contain a large part of the world's mineable reserves of tungsten, tin, beryllium, and molybdenum, and significant resources of tantalum, niobium and rare-earth elements (REE) (Shcherba, 1970, Rundquist and Denisenko, 1986b).

Molybdenum-tungsten greisen deposits are present in rare metal provinces, predominantly in Asia (fig. 1). Countries, with important molybdenum-tungsten greisen deposits include the former Soviet Union (Kazakhstan, Russia), China, Canada, and Mongolia, where significant reserves of tungsten and molybdenum are associated with Paleozoic (Hercynian, Mississippian–Permian) and Mesozoic (Cimmerian, Triassic–Jurassic) plate movements. In these countries, this type of deposit is a leading source of molybdenum and tungsten. Proterozoic molybdenum-tungsten greisen deposits have been discovered in the last two decades in the northern and southeastern parts of Europe in the Baltic and Ukrainian shields. In addition, molybdenum-tungsten greisen deposits and occurrences are known in Australia (Blanchard, 1947), Austria (Göd and Koller, 1989), Argentina (De Brodkorb, 1986), Finland (Vokes, 1978), France (Bouladon, 1989), Italy (Zuffardi, 1989), Norway (Bugge, 1978), Portugal (Thadeu, 1986, 1989), Republic of Korea (Gallagher, 1963, 1968), and Ukraine (Metalidi and others, 1986). Molybdenum-tungsten greisen deposits are essentially unknown in the tin-tungsten greisen provinces of Europe (Erzgebirge-Krusné Hory) and southeast Asia, and are rare in the Americas.

Figure 1 near here

More such deposits may also exist in North America, Greenland, and northwest Africa because their geologic features are similar to those in the major regions of molybdenum-tungsten greisen deposits in Asia. Molybdenum-tungsten greisen deposits are compound (Mo-W-Bi-Sn) and usually contain at least two recoverable metals. These deposits are found in the same districts with rare metal deposits (Ta, Nb, Be).

Greisens have been recognized and investigated for hundreds years, since the time of Agricola in the 16th century (Smirnov, 1965; Scherba, 1970; Rundquist and others, 1971). Greisens have been classified and subdivided by Smirnov (1965). We use the terms greisen and greisenization in the sense of Shcherba (1968, 1970) and Burt (1981), who stated that greisen deposits are the result of the ore-forming process, greisenization. Greisens themselves may constitute the ores, as well as any other rocks in which the ore constituents were deposited. Ore is found as disseminated minerals in greisenized granites, pegmatites, and aplites, as massive greisen bodies in the apical parts of granite plutons (endogreisen), as quartz veins, as sheeted veins and veinlets (stockwork) with greisen envelopes, and (or) as greisenized skarn and other adjacent rocks (exogreisen). Scherba (1970) suggested that some quartz veins, quartz-topaz veins and associated quartz-feldspar replacement veins, which contain ores of rare metals in a many deposits, have been formed at upper levels by deposition of surplus products of the greisenization process and, for that reason, should be assigned to the greisen class.

The deposits may be subdivided into proximal deposits (Type 1), and distal deposits (Type 2). These two subgroups are characterized by significantly different tonnage and grade distributions. The grade and tonnage models of molybdenum-tungsten greisen deposits presented in this study include 28 deposits (tables 1, 2) and are the result of translation of papers, books, and other materials, together with data compilation, comparison, selection and analysis. Previous grade and tonnage information about deposits in the former Soviet Union can be found in Laznicka (1976) and Sutulov (1978). Most of the deposits, especially the smaller ones, have been mined (Bamford, Changsu, Kingsgate, Preissac, Taehwa, Wolfram Camp, Wonban). Several of the largest are presently being mined (Eastern Kounrad, Xihuashan, Mt. Pleasant), and others have only estimates of ore resources (Ackley group, Bainazar, Batistau, Dzhida, Kara Oba, Koktenkol, Nebelstein, South Dzhaur, Upper Kairakty, Verbinskoe, Yugodzir). However, many are incompletely described, especially those in the former Soviet Union, China, Republic of Korea, and Australia. Nevertheless, the information available permits construction of useful models.

Table 1 near here

Table 2 near here

GEOLOGIC ENVIRONMENT

Molybdenum-tungsten greisen deposits are recognized in Archean to Hercynian plates and confined to areas of thick, stable continental crust. They may been formed in the closing stages of a subsequent within-plate orogeny (Kazakhstan) or in association with isolated, anorogenic granite fields (Australia, Canada, China, Republic of Korea, Mongolia, and Russia).

Molybdenum-tungsten greisen deposits in Kazakhstan are found near the boundaries between Hercynian basins and the Caledonian plate (Pokalov, 1972). These deposits were formed at about 290–320 Ma, shortly after the closing of the Hercynian basin system. In other cases (Australia, Canada, China, Republic of Korea, Mongolia, Russia), ore-bearing granites were intruded long after the last period of geotectonic development. In Russia (western Transbaikalia, Dzhida), for example, lower Jurassic molybdenum-bearing granites were emplaced in rocks of Baikalian (Proterozoic) and Caledonian deformation. In China (Xihuashan, Shizhuyuan) Cretaceous Yanshanian granites intruded Cambrian and Devonian rocks of the Southern China plate (Liu Nailong, 1992). In all cases, the geological environment of molybdenum-tungsten greisen deposits is that of the extensional rift zones in continental plates described by Sillitoe (1980), and the apparent difference in tectonic setting is primarily the interval of time between the last major orogenic activity and the intrusion of ore-bearing granites and mineral deposition.

Molybdenum-tungsten greisen deposits in Kazakhstan are present in areas with crustal thicknesses ranging from 37 to 55 km, with most examples between 44 and 55 km (Akylbekov and Belov, 1987). They are characterized by local and regional negative gravity anomalies (Dukhovskiy, 1980). This setting is similar to the environment of Climax, Urad-Henderson, Mt. Emmons and other large molybdenite deposits in the Western Cordillera (Smith, 1978; White and others, 1980).

Rock Types

Molybdenum-tungsten greisen deposits are associated with highly differentiated multiphase intrusions, which range in area of outcrop from a few km^2 to a few thousand km^2. Dukhovskiy and others (1975) showed that ore-bearing plutons are characterized by numerous distinct cupolas and lobes, and are dominated by late-stage magmatic rocks, whereas barren plutons have flat roofs and rare small lobes, and are dominated by early-stage magmatic rocks. Most of deposits are found above the roots, or feeder zones of plutons.

Plutons are primarily one- or two-mica granite and, rarely, associated granodiorite (Lacorne, Preissac). Textures range from coarse-grained in the earliest phases to fine-grained, equigranular, porphyritic or granite porphyry in the latest phases. Fine-grained granites commonly form lenses subparallel to contacts of coarse-, medium-grained granite plutons, as well as apophyses extending out from the plutons. These represent the most likely environment of mineral deposition. The plutons consist of multiple intrusive phases and are accompanied by pegmatites, aplites and multiple stage inter- and post-mineral dikes, which range from acid (granite porphyry) to alkaline (lamprophyre) composition.

Whole-rock chemical analyses (table 3) indicate, that the most significant geochemical signatures of granites are high contents of SiO_2 (>73–75 weight percent), low CaO (<1.0 weight percent), $K_2O:Na_2O > 1$, and variable but generally high F content. The granites are characterized by variable ferrous:ferric ratios and levels of alumina saturation. Apparently, plutons that are the source for molybdenum-tungsten greisens may belong to the magnetite series or to the ilmenite series (Ishihara, 1977), as well as to the I-type or to the S-type. Unfortunately, isotopic data for molybdenum-bearing granites are rare (Pokalov, 1985, Suvorova and others, 1990) and it is difficult to accurately classify most of them with respect to I, S or A-types (Hutchison, 1982). Most plutons display a lack of assimilation and hybridization, and thus exhibit a relatively narrow range of composition (Serykh, 1972). In contrast to tin-specialized granites (Taylor, 1979), plutons associated with molybdenum-tungsten greisens do not appear to be characterized by high concentrations of molybdenum or tungsten (Pokalov, 1984a).

<u>**Table 3 near here**</u>

Age Range

Ages of molybdenum-tungsten greisens vary from 2650 Ma to 148 Ma (table 2). The most significant molybdenum-tungsten greisen deposits were formed in two main periods: Hercynian in Australia, Austria, Canada, Kazakhstan, Norway, and Cimmerian in China, Mongolia, Republic of Korea(?), and Russia. Some Proterozoic deposits are also known in Canada, Finland, Norway, Russia, and Ukraine. Molybdenum-tungsten greisen deposits younger than 100 Ma are not known. Figure 2 shows that the large, distal deposits were formed during all three major metallogenic epochs, and have been preserved until the present day.

<u>**Figure 2 near here**</u>

Depositional Environment

Ore bodies are located exclusively in or over the apical lobes or slopes of plutons or in adjacent metasedimentary or metavolcanic rocks, and can be found above the granite roof to 1.5–2 km and below the granite roof to 200–500 m.

Associated Deposit Types

Molybdenum-tungsten ore bodies may be accompanied by Zn-Cu or Zn-Pb polymetallic veins (most deposits), sub-economic mineralization of tin in greisen zones (Kara Oba, Mt. Pleasant), and (or) tantalum and niobium mineralization in the deeper levels (Verbinskoe, Xihuashan). In the same regions or districts there could also be tungsten greisens and veins (Ackley group, Changsu, Dzhida, Eastern Kounrad), porphyry copper deposits (Eastern Kounrad) and polymetallic skarns (Batistau). Mo-W pipes of Australia are accompanied by minor Sn pipes in endocontact zones, and by Cu- or Ag-Pb-Zn pipes in the vicinity of the exocontact zone. Rare-metal occurrences are known near the margins of districts, such as Be-Ta-Sn in K-metasomatized rocks (Verbinskoe) and REE-Ta-Nb-Sn-Zr in alkali granites (Central Kazakhstan) (Abdarachmanov, 1981; Akylbekov and Belov, 1987).

Carbonate host rocks may contain tungsten or polymetallic skarns, which accompany molybdenum-tungsten greisen deposits. In this case, the rare-metal ores are supposed by Shcherba (1970) to be products of greisenization that is superimposed on earlier skarns. The best examples are Shizhuyuan in China (Lin Chuanxian, 1987, Liu Nailong, 1992) and Koktenkol in Kazakhstan, where wolframite-molybdenite (cassiterite) ore in greisen gives way upward to scheelite-bismuthinite-cassiterite skarn ore (table 4) and wolframite-molybdenite stockworks are represented by scheelite skarns in carbonate rocks (Pokalov, 1977).

Table 4 near here

These relationships suggest that most molybdenum-tungsten greisen deposits are part of complex districts, and that the associated skarn and vein deposits that may be part of these districts may be good exploration guides and may also help to estimate the level of erosion. We agree with Kamilli and Ganster (1995) that all hydrothermal rare-metal deposits share a characteristic association with highly-evolved silicic magmas; they differ primarily in their metallogeny and level of emplacement.

DEPOSIT DESCRIPTION

Alteration

Greisens may demonstrate different assemblages (tables 5a and 5b), from simple and weak (quartz, quartz-muscovite) to complex and pervasive (quartz-muscovite-topaz-fluorite-zinnwaldite). Weak alteration occurs in the deeper parts of plutons and deposits, such as Ackley group or Nebelstein, and here greisen may be accompanied by albitized and microclinized rock. Complex and pervasive alteration occurs most often near the roofs of ore-bearing plutons as in Bainazar, Kara-Oba, Verbinskoe, Wolfram Camp or Yugodzir. Higher in the system, greisen alteration becomes weaker and silicified and sericitized rocks may be found.

Tables 5a, 5b near here

In many cases, molybdenum-tungsten greisen deposits occur as a complicated system throughout the greisen column with one or more types of morphology, and in individual deposits are represented by:

- greisenized granite (pegmatite, aplite) + greisen veins or quartz veins with greisen envelops (Ackley group (fig. 3–13), Akchatau (fig. 3–6), Changsu, Drammen, Knaben (fig. 3–12), Matasvaara, Taehwa, Xihiashan (fig. 3–11));
- massive greisen bodies (lens-shaped) + quartz veins (Bainazar (fig. 3–5), Verbinskoe (fig. 3–4), Yugodzir (fig. 3–9));
- greisenized granite + quartz veins + quartz veinlets or stockworks in hornfels (Batistau, Eastern Kounrad (fig. 3–8), Kara Oba (fig. 3–1), Koktenkol (fig. 3–2), Dzhaur (fig. 3–3), Dzhida, Lobash) and
- greisenized granite + greisen + skarn (Dzhaur (fig. 3–3), Koktenkol, Upper Kairakty, Shizhuyuan (fig. 3–7)).

Bainazar pluton (Kazakhstan), with a horizontal cross-section (although unexposed) of more than 1000 km^2, is a particular example, where individual lobes control the positions of the Bainazar, Batistau and Dzhaur deposits and numerous other occurrences. These represent practically the entire greisen column within a single district.

The various alteration zones of a greisen system in a well developed molybdenum-tungsten greisen deposit are more commonly found superimposed on one another than found as separate individual types.

Figure 3 near here

Morphology

Molybdenum-tungsten greisen deposits may be represented by several different morphologic types. From deep to shallow levels, they include pods, veins, pipes, breccias, sheeted veins, and stockworks (veinlets). These morphologic types may be present in endocontact zones or exocontact zones. Pods, veins, pipes, and breccias most commonly appear in the endocontact zone; sheeted veins and veinlets or stockworks are in the exocontact zone. In adjacent rocks the widths of veins decrease, for example, from 13 mm (Eastern Kounrad) to 1.3 mm (Batistau) (Burmistrov and others, 1990), and their density increases relatively from 7 to 14 units/m^3, and the vein type changes to veinlets or stockwork. Common ratios between volumes of ore hosted in the plutonic lobes and in the adjacent rocks are 1:5–1:10 in the case of stockwork morphology. Stockworks may be present within 100–150 m below the pluton roof in the endocontact zone and within 1500 m above the roof in the exocontact zone. Morphologically there is a complete gradation from typical stockwork deposits (Bainazar, Upper Kairakty, Dzhaur) through vein-stockwork (Bainazar) to stockwork-vein (Kara Oba), and, at the deepest levels, to vein ore bodies of Akchatau (Beskin and others, 1973; Yefimov and others, 1990) or Eastern Kounrad (fig. 3). In the last case, stockworks are developed locally around the veins, although, some believe that this may be an example of second-generation (veinlets) mineralization superposed on veins, caused by a hidden pluton (Bolshakov and others, 1970; Beskin and others, 1973).

The superposition of different morphologic types in well developed molybdenum-tungsten greisen deposits is present more commonly than individual morphologic types.

Commodities

Molybdenum in the greisen deposits may be a major metal or a minor commodity with other metals, such as tungsten. As a rule, either molybdenum or tungsten is the byproduct of the other. Other commodities, such as bismuth and tin, are rare. Fourteen percent of the tungsten deposits in the world are of Mo-W type (Rundquist and Denisenko, 1986b). In some cases, molybdenum is a major commodity in greisen deposits (Kazakhstan); in others, the major component is tungsten (China, Republic of Korea, Australia), and some of these deposits are among the largest tungsten deposits in the world. The Mo/W ratio may vary from around 10–15 (Eastern Kounrad) to 0.5–0.1 (Upper Kairakty).

The zonal relations between molybdenum, tungsten and other components are complex in these deposits. High contents of molybdenum are typical of the vein-stockwork ores of the proximal exo- and endocontact zones, giving way, with distance from the pluton, to stockwork ores poorer in molybdenum (in the exocontact zone) and vein ores (in the endocontact zone). At the same time, the highest contents of tungsten are concentrated in the upper horizons and flanks of deposits or districts. In vein deposits, areal separation between tungsten and molybdenum ores is sometimes present, and W- and Mo-bearing veins may form separate ore bodies (Kara Oba, Taehwa), or separate deposits (Dzhida, Eastern Kounrad). In the stockwork type (Bainazar, Batistau, Kairakty, Kara Oba, Koktenkol, Mt. Mulgine, Mt. Pleasant), molybdenum and tungsten ores may be present around separate centers.

The degree of separation of mineralized centers is greatest in exocontact zones of large lateral and vertical extent. In some cases, where the exocontact zone reaches 500–1500 m in width, the contained tungsten may be as much as ten times greater than the molybdenum (Kairakty, Mt. Mulgine-T). Because of incomplete tungsten tonnage and grade data for greisen deposits in Russia, Kazakhstan, China and Korea, it is not possible to present a tungsten grade distribution for the molybdenum-tungsten greisen deposit model, but existing data show that some of these deposits may reach billions of tons ore with WO_3 grades of 0.1–0.2 percent. For example, in the Upper Kairakty deposit, a deep deposit contains 150–170 thousand mt with a Mo grade of 0.08–0.12 percent, with negligible W, whereas a higher mineralization center contains 1600–1800 million mt with a WO_3 grade of 0.1–0.2 percent, and negligible Mo. The Batistau deposit contains 200–250 million mt of Mo and 800–900 million mt of W, with the grades similar to Upper Kairakty (Pokalov, 1984, and author's estimate). At Upper Kairakty, a W-bearing stockwork is present approximately 1500 m above the pluton; at Batistau, the stockwork is about 500 m above the pluton. The amount of tungsten in these deposits is at least an order of magnitude larger than in previously-known deposits like Mt. Pleasant, Logtung (Menzie and others, 1992) and Baid al Jamalah (Kamilli and others, 1993).

Molybdenite or wolframite may be the primary ore mineral (Australian pipes, Akchatau, Bainazar, Kara Oba, Eastern Kounrad, Mt. Pleasant, Taehwa, Xihuashan, Yugodzir), but, at higher levels, wolframite is commonly replaced by scheelite (Batistau, Dzhaur, Koktenkol, Upper Kairakty), which is a major mineral in the upper levels of the exocontact zone. Scheelite in the ore column may be more prominent in the presence of calcareous volcano-sedimentary rocks (Dzhaur, Mt. Mulgine) or limestone (Koktenkol, Shizhuyuan) (fig. 3–7).

Relations between molybdenum and tin are even more equivocal. As already stated, molybdenum is rare in known Sn-W greisen deposits, although there are a few examples (<1 percent of deposits) (Rundquist and Denisenko, 1986a) of subeconomic molybdenum-bearing tin-tungsten greisen deposits, such as Borralhya (Thadeu, 1986) in Portugal, and in the Erzgebirge (Baumann, 1970, Tischendorf, 1973) in Central Europe. A new discovery of subeconomic molybdenum mineralization in quartz-muscovite greisen in Austria, Nebelstein, (Göd and Koller, 1989; Koller and others, 1991), is characterized by the apparent complete absence of tin and tungsten. Nevertheless, tin is a rare accessory in molybdenum-tungsten deposits, and in Climax-type molybdenum deposits, tin appears only in trace amounts (Westra and Keith, 1981). In cases where tin is present in molybdenum-tungsten greisen deposits in economic or subeconomic amounts, cassiterite is found commonly in separate mineralogical stages and greisen assemblages (Mt. Pleasant) (Kooiman and others, 1986; Samson, 1990), and as a rule at significant distances laterally or vertically from molybdenum ore (Kara Oba, Shizhuyuan). At Shizhuyuan (Lin Chuanxian, 1987; Liu Nailong, 1992) different parts of the deposit contain different proportions of W, Mo, Bi and Sn and grade into one another from the greisenized roof of the pluton to skarn in the exocontact zone (table 4, fig. 3).

The nature of rare metal distribution in molybdenum-tungsten greisen deposits is not well understood. It is clear that, the closer the average crustal concentrations of those elements are to that of molybdenum (for example, tungsten), the more frequently those elements are present together in the ores (Rundquist and Denisenko, 1986a,b). The observed variations in W/Mo ratio, probably depend on oxygen fugacity in the hydrothermal system and associated igneous rocks (Stemprok, 1974; Candela and Bouton, 1990; Kamilli and others, 1993). Molybdenum and tin are likely to occur in distinct blocks of the crust (Taylor, 1979; Rundquist and Denisenko, 1986b), or be associated with different types of granite—tin and tungsten in ilmenite and (or) S-type granites, and molybdenum, copper, zinc, and lead in magnetite and(or) I-type granites (White and others, 1977), although this typology is not supposed by some authors to be generally applicable (Tuach and Strong, 1986).

To summarize, molybdenum-tungsten greisen deposits, especially distal ones, are likely to be complex rather than monometallic.

COMPARISON OF PORPHYRY AND GREISEN DEPOSITS

Some authors (Mutschler and others, 1981; Westra and Keith, 1981) would probably suggest that the molybdenum-tungsten greisen deposit type includes the giant deposits of the Colorado molybdenum belt, such as Climax, or Urad-Henderson. Indeed, Burt (1981) used the term "porphyry-greisen deposits". Beyond question, these deposits have some features of the greisen type, including a similar geotectonic position in continental rift zones, evidence of the formation of greisen in the early and late stages, and a complex metallogeny, which may contain tungsten and tin.

Characteristics of greisen and porphyry deposits are contrasted in Table 6. First of all, Climax-type ore deposition is confined to well-developed volcano-magmatic complexes that commonly include intrusive, subvolcanic and volcanic rocks; that is, in the shallow subvolcanic zone (Roedder, 1971; Hall and others, 1974; Wallace and others, 1978; Ludington, 1986; Singer and others, 1986). Greisen deposits are connected with magmatic systems that include the main plutonic body, porphyry apophyses, and dikes. Greisen deposits are confined to plutonic rocks or to hornfels in the exocontact zone. In the case of Climax-type porphyry deposits, the genetic relation between ore and granites is clearly indicated by relative positions of different molybdenum ore bodies above specific granitic stocks (White and others, 1981). In the case of molybdenum-tungsten greisen, Pokalov (1984b) established a genetic relation between ore and various stages of intrusion, using relations between different stages of mineralization (molybdenum, tungsten) and intra mineral dikes.

Table 6 near here

Molybdenum-tungsten greisen deposits seem to form at greater depths than porphyry deposits, at the depth of the "underlying batholithic chamber" (Mutschler and others, 1981) or "plutonic porphyry deposits" (Clark, 1972; Woodcock and Hollister, 1978). Strong (1985) noted that the group of Mo deposits in the Colorado mineral belt "provides a younger, less deeply eroded, analog of the European Hercynian and other more typically mineralized granite terrains". This contrast in depth could help explain the differences, including pluton sizes and morphology, alteration types and mineralogy, temperatures, deposit morphology and chemical components. Even though greisen and Climax-type deposits have many similar features, porphyry molybdenum deposits were not incorporated into the greisen model. Nevertheless, it may be difficult to draw a boundary between these two types, and some examples of molybdenum-tungsten greisen deposits (Mt. Pleasant) and sub-economic occurrences (St. George batholith) (Lentz and others 1988), are characterized by features of both types of deposits.

EXPLORATION GUIDES

General prospecting guides include extensional zones where crustal thickness is more than 40–45 km. Regional negative gravity anomalies, that may represent felsic plutons are also indicative. General analysis of geologic (petrologic and petrochemical) data, combined with the results of regional geophysical surveys, can lead to the delineation of potential targets.

Experience in exploration for this type of deposit in different countries shows that subsequent field work must include geochemical surveys (rock, soil or stream sediments), detailed gravimetric measurements, and aeromagnetic surveys. These methods usually detect the ore-bearing granites, particularly hidden plutons or their cupolas. Local negative gravity and positive magnetic anomalies may outline unexposed plutons, the specific characteristics of roof morphology (lobes), and variations in the thickness of granites (roots). Zonal dispersion of lead, zinc and copper from one side and molybdenum, tungsten, tin and bismuth from the other indicates the polarity, or symmetry of the metallized system. Separation of tungsten and molybdenum within a district, with tungsten dominant, might be the sign of an unexposed, compound mineral deposit.

The discovery of the unexposed Neuf Juors leucogranite cupola with tungsten-molybdenum mineralization in greisens at depths of 50–100 m in the Massif Central (France), was based on this concept-oriented exploration (Burnol, 1986), and demonstrates the potential in seemingly well-investigated regions, where detailed knowledge of the geological environment is available.

EXPLANATION OF GRADE AND TONNAGE MODELS

Molybdenum-tungsten greisen deposits present a complex variety of characteristics, with much variation with respect to morphology, alteration assemblage, and relationship to plutonic centers. In addition, they exhibit a wide range of tonnage (0.014–600 million mt) and Mo grade (0.01 percent–0.472 percent) (table 2, fig. 4). The standard deviation of the logarithm of tonnage (1.27) is larger than most of the models compiled previously. For example the standard deviation of the logarithm of tonnage for the Climax Mo model of Singer and others (1986) is 0.50. This observation, combined with the fact that tonnage and grade have a significant correlation (R = 0.55), suggests that this distribution may represent a mixed population of deposits.

Figure 4 near here

Comparison of the main characteristics of molybdenum-tungsten greisen deposits, as tabulated in Tables 2, 3, and 5 allows us to separate these deposits into two groups. The deposits can be subdivided on the basis of geology, mineralogy, alteration assemblage, morphology, and position relative to the plutonic center.

The first type, which we call proximal molybdenum-tungsten greisen deposits, are present within and along the margins of plutons, and are distinctly smaller than the deposits of the second type, which are more distant from plutonic centers, and which we call distal molybdenum-tungsten greisen deposits.

Proximal deposits (Type 1) are associated with eroded batholiths of more than 300–500 km^2. Morphologically these deposits are represented by pods, veins, and pipes, and alteration assemblages are typical greisenized granite. The deposits are consistently associated with pegmatites and aplites within the host pluton, which is typically a coarse-grained granite. They are chiefly deposits of molybdenum, and, more rarely, two commodities (tungsten as wolframite).

Distal deposits (Type 2) are associated with smaller, poorly exposed or unexposed plutons of less than 150–100 km^2. Morphology of the deposits includes combinations of veins and sheeted veins, massive bodies and dominant or ubiquitous veinlets or stockwork. Alteration assemblages vary widely. Many of these deposits are associated with apophyses of larger plutons, and are present in hornfels. Others are emplaced within fine-grained granite sheets that are marginal to coarser-grained plutons. These deposits commonly contain Mo, W, and, less commonly, a third element, Bi or Sn. Tungsten may be found as wolframite and (or) scheelite.

When the deposits are subdivided in this way, their grade and tonnage distributions exhibit more appropriate statistics, and the two groups appear to be significantly different. Correlation coefficients for tonnage and grade are smaller, and no longer significant (proximal, r=0.36; distal, r=0.33). The separate distributions have standard deviations of the logarithm of tonnage of 0.84 (proximal) and 0.75 (distal). Comparison of tonnage shows significant differences between the two distributions at the 99 percent level on the Fisher PISD (95886.718) and Scheffe F-test (6.21) and comparison of Mo grade shows significant differences at the 95 percent level on the Fisher PISD (0.101) and Scheffe F-test (3.746) . All these statistics support division of the data into two groups. Scatter plots and conventional cumulative histograms of the two grade and tonnage models are shown in figure 5.

Figure 5 near here

Some deposits (Eastern Kounrad and Verbinskoe) may occupy an intermediate position. But the relation between these deposits and host plutons is not clear. Geophysical and geologic data show that they might be connected with unexposed plutons (Metalidi and others, 1986; Voynovski and Kotlyar, 1988; Beskin and others, 1973; Bolshakov and others, 1970) and, in this case, they should be assigned to the distal subtype. It is most likely that there is no clear boundary between these two types of deposit. It is clear, however, that the tonnage of proximal deposits is practically independent of degree of erosion, if the exposed area of ore-bearing granites is more than 100 km^2. Conversely, the tonnage of distal deposits is inversely related to the amount of erosion of massifs as expressed by outcrop area, and the largest deposits are higher in the column, and connected with unexposed plutons. Figure 6, constructed directly from data in Table 2, portrays these relationships graphically.

Figure 6 near here

CONCLUSIONS

- Molybdenum-tungsten greisen is a distinct type of mineral deposit, apparently confined to granitic plutons in extensional rift zones in Proterozoic, Hercynian and Cimmerian continental plates, and primarily found in areas with thick crust in Asia.
- Molybdenum-tungsten greisen deposits exhibit different morphologies, including vein and stockwork, which are found exclusively in or over the apical lobes or slopes of plutons; molybdenum is accompanied by tungsten in major deposits.
- Although molybdenum-tungsten greisen deposits have many similarities with Climax-type deposits, they seem to form at greater depths, in a mostly plutonic environment. This may alter the current classifications of molybdenum, molybdenum-tungsten, and tungsten deposits.
- The deposits may be subdivided into proximal deposits (Type 1), and distal deposits (Type 2). These two subgroups are characterized by significantly different tonnage and grade distributions.
- The tonnage of molybdenum-tungsten greisen deposits is inversely correlated to the exposed area of ore-bearing granites, so the largest deposits are connected with unexposed plutons.

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Appendix A

Model 16A

DESCRIPTIVE MODEL OF MOLYBDENUM GREISEN DEPOSITS

APPROXIMATE SYNONYMS

Molybdenite in greisens, quartz-, quartz-muscovite veins, sheeted veins and veinlets, often with wolframite (scheelite).

DESCRIPTION

Fine- to coarse-grained molybdenite, molybdenite and wolframite (scheelite) in greisenized granites, massive greisen bodies, quartz veins and veinlets in greisen and greisenized adjacent rocks in the endocontact zone (endogreisen) and exocontact zone (exogreisen) of granites and alaskites.

GENERAL REFERENCES

Burt (1981), Pokalov (1984), Shcherba (1968, 1970).

GEOLOGICAL ENVIRONMENT

Extensional zones in continental rifts.

Rock Types

Granites with 73-75 percent SiO_2, K_2O>Na_2O (1.1-2.5), Al_2O_3 >12.5-13 percent, low CaO (<1.0), variations in F content, lack of contamination process, non specialized. Multiphase hypabyssal plutons (10-1000 km^2) with apophyses, inter-mineral and post-mineral dikes.

Age Range

Proterozoic (1,000-2,650 Ma), Hercynian (292-348 Ma), Cimmerian (140-210 Ma).

Depositional Environment

Apical lobes of multiphase plutons and adjacent rocks.

Tectonic Setting

Endocontact and exocontact zones of batholiths, stocks, and cupolas.

Associated Deposit Types

Tungsten (wolframite, scheelite), tin (cassiterite) in greisen and quartz veins in the upper level of the same deposits or in the same districts; sub economic lead-zinc occurrences in the flanks of the same deposits or districts; tantalum, niobium and beryllium deposits in the alkali granite or potassium or sodium metasomatites in the same districts or zones.

DEPOSIT DESCRIPTION

Mineralogy

Molybdenite, wolframite, scheelite, bismuthinite, cassiterite;

Quartz, muscovite, fluorite, topaz, K-feldspar, lepidolite, zinnwaldite.

Texture/Structure

In lodes, bedded greisen, veins, sheeted veins and veinlets or stockworks; pods, foliated masses, coarse, medium, fine-scales, disseminated.

Alteration

Greisenization, albitization, microclinization, silicification, sericitization.

Ore Controls

Lobes of granite plutons, system of fractures, chemistry of adjacent rocks.

Weathering

In arid climates, the oxygenated and leached zones are 10–60 m below surface, and molybdenum grade may decrease as much as 70 percent.

EXPLORATION GUIDES

Geochemical Signatures

-primary anomalies of Mo, W, Sn, Bi, Ag, Li, Zn, Pb.

-secondary anomalies in soil, stream sediments and plants of Mo, W, Sn, Bi, Cu, Zn and Ag.

-elevated Re in molybdenite, >50 ppm.

Geophysical Signatures

Thick crust (>40 km), regional and local gravity anomalies with positive electric anomalies (halo of pyrite mineralization surrounds bodies); distinct U/Th as well as magnetic anomalies in close proximity to the greisen.

EXAMPLES

Koktenkol, Akchatau, Bainazar, Kazakhstan	(Shcherba, 1960; Pokalov, 1964; 1972)
Yugodzir, Mongolia	(Bobrov, 1962; 1974)
Wolfram Camp, Australia (Australian pipes group)	(Blanchard, 1947; McLeod, 1965; Plimer, 1974; 1975)
Mt. Pleasant, Canada	(Kooiman, 1986; Petruk, 1973)

GRADE AND TONNAGE MODEL OF MOLYBDENUM GREISEN DEPOSITS

COMMENTS There is significant correlation between grades and tonnage in the mixed population (R=0.55); there is no significant correlation in subgroups: Type 1 (R=0.36) or in Type 2 (R=0.33).

Type 1. Proximal deposits

Deposit	Country	Abbrev.
Ackley group	Canada	AG
Bamford	Australia	BD
Changsu	Korea	CS
Drammen	Norway	DN
Kingsgate	Australia	KG
Knaben	Norway	KN
Lacorne	Canada	LN
Matasvaara	Finland	MR
Nebelstein	Austria	NN
Preissac	Canada	PC
Taehwa	Korea	TH
Wolfram Camp	Australia	WC
Wonban	Australia	WN

Type 2. Distal deposits

Deposit	Country	Abbrev.
Batistau	Kazakhstan	BT
Bainazar	Kazakhstan	BR
Dzhaur	Kazakhstan	DR
Dzhida	Russia	DD
Eastern Kounrad	Kazakhstan	EK
Kara-Oba	Kazakhstan	KO
Kairakty	Kazakhstan	KT
Koktenkol	Kazakhstan	KL
Lobash	Russia	LH
Mt. Pleasant	Canada	MP
Mt. Mulgine/H	Australia	MMH
Mt. Mulgine/T	Australia	MMT
Verbinskoe	Ukraine	VK
Xihuashan	China	XN
Yugodzir	Mongolia	YR

List of molybdenum-tungsten greisen deposits   Table 1

Type 1. Proximal deposits

#	Deposit	Country	Abbr.	References
1	Ackley group	Canada	AG	Kirkham and others, 1982; Tuach, 1984, Tuach and Strong, 1986; Whalen 1980, 1983
2	Bamford	Australia	BD	Blanchard, 1947; McLeod, 1965; Plimer, 1974, 1975
3	Changsu	Korea	CS	Gallagher, 1963, 1968
4	Drammen	Norway	DN	Bugge, 1978; Ihlen, and Martinsen, 1986
5	Kingsgate	Australia	KG	Blanchard,1947; McLeod, 1965; Plimer, 1974, 1975
6	Knaben	Norway	KN	Bugge, 1978; Schneider, 1963
7	Lacorne	Canada	LN	Kirkham and others, 1982; Schneider, 1963
8	Matasvaara	Finland	MR	Vokes , 1978
9	Nebelstein	Austria	NN	Göd and Koller, 1989; Koller and others 1991
10	Preissac	Canada	PC	Kirkham, 1982; Schneider, 1963
11	Taehwa	Korea	TH	Gallaher, 1963, 1968
12	Wolfram Camp	Australia	WC	Blanchard, 1947; McLeod, 1965; Plimer, 1974, 1975
13	Wonban	Australia	WN	Blanchard, 1947; McLeod, 1965; Plimer, 1974, 1975

Type 2. Distal deposits

#	Deposit	Country	Abbr.	References
1	Batistau	Kazakhstan	BT	Ivanov and others, 1966; Ivanov, 1968, 1969;
2	Bainazar	Kazakhstan	BR	Konoplyanzev, 1959
3	Dzhaur	Kazakhstan	DR	Belov and others, 1986
4	Dzhida	Russia	DD	Korolev, and others 1969; Korzhinskiy, and others 1988; Shapenko, 1982
5	Eastern Kounrad	Kazakhstan	EK	Bolshakov and others, 1970; Gavrikova and Bakhteev, 1965
6	Kara-Oba	Kazakhstan	KO	Akylbekov and others, 1982
7	Kairakty	Kazakhstan	KT	Korolev and others, 1969; Valkov, 1988
8	Koktenkol	Kazakhstan	KL	Pavlov and Yashkhin, 1970; Pavlov and others, 1970
9	Lobash	Russia	LH	Pokalov and Semenova, 1993
10	Mt. Pleasant	Canada	MP	Kooiman and others, 1986; Petruk, 1973
11	Mt. Mulgine/H	Australia	MMH	Kwak and others, 1986
12	Mt. Mulgine/T	Australia	MMT	Kwak and others, 1986
13	Verbinskoe	Ukraine	VK	Metalidi and others, 1986
14	Xihuashan	China	XN	Liu Nailong, 1992; McLeod 1979
15	Yugodzir	Mongolia	YR	Bobrov, 1962; Ivanova and others, 1977

* For Kazakhstan ore deposits common references are Shcherba, 1960; Krylov and Lee, 1962; Pokalov, 1964, 1972,1977, 1984a, Pokalov and Orlov, 1973

Parameters of molybdenum-tungsten greisen deposits — Table 2

Type 1. Proximal deposits

Deposit	Commodities	Tonnage (thousand of metric tons)	Mo % weight percent	WO_3 % weight percent	Morphology	Deposit control	Host rocks	Texture	Pluton outcrop area (sq. km)	Age, Ma
Ackley group	Mo, Sn-W	113.4	0.31	0.0x	flat pods	endocontact	granite	medium, coarse-gr	2,700	338
Bamford	W-Mo	72	0.14	>1	pipes	endocontact	adamellite	medium-gr, porphyritic	>1,000	340(?)
Chansu	Mo	852	0.118	-	veins	endocontact	granite	n/d	>1,000	150(?)
Drammen	Mo	200	0.118	-	veins	endocontact	granite	coarse-gr, porphyritic	300	284
Kingsgate	W-Mo	54	0.37	>1	pipes	endocontact	adamellite	medium-gr porphyritic	>1,000	340(?)
Knaben	Mo	14,036	0.112	-	veins	endocontact	granite	n/d	>1,000(?)	1,600
Lacome	Mo-Bi	4,064	0.203	-	veins	endocontact	granite	n/d	500	2,650
Matasvaara	Mo	1,154	0.083	-	veins	exocontact (?)	granite	n/d	>1,000(?)	2,700
Nebelstein	Mo	370**	0.025**	-	veins	endocontact	granite	fine, medium-gr	1,000	311
Preissac	Mo-Bi	3,238	0.169	-	veins	endocontact	granite	n/d	500	2,650
Taehwa	Mo-W, Cu, Ag, Au	254	0.472	2	veins	exocontact	granite	n/d	>1,000	150(?)
Wolfram Camp	W-Mo	716	0.27	>1	pipes	endocontact	adamellite	medium, coarse-gr, porphyritic	>1,000	280
Wonban	W-Mo	14	0.39	>1	pipes	endocontact	adamellite	coarse-gr	>1,000	280

Type 2. Distal deposits

Deposit	Commodities	Tonnage (thousand of metric tons)	Mo % weight percent	WO_3 % weight percent	Morphology	Deposit control	Host rocks	Texture	Pluton outcrop area (sq. km)	Age, Ma
Batistau	Mo-W	213,400**	0.07**	0.1**	stockwork	exocontact	granite	fine-gr	unexposed	292
Bainasar	Mo-W	17,500**	0.07**	0.2**	stockwork	exocontact	granite	fine-gr	6	292
Dzhaur	Mo-W	17,000**	0.07**	0.2**	stockwork	exocontact	granite	n/d	unexposed	292
Dzhida	Mo, W	14,400**	0.2**	0.2**	stockwork	endo-exocontact	granite	fine, medium-gr	2	180
Eastern Kounrad	Mo, W	5,760**	0.3**	0.02	veins, stockwork	endocontact	granite	medium-gr, porphyritic	144	292
Kara-Oba	Mo-W-Sn-Bi	200,000**	0.07**	0.2**	veins, stockwork	endo-exocontact	granite	coarse-fine-gr	1.2	292
Kairakty	W-Mo	150,000**	0.05**	0.1**	stockwork	exocontact	granite	n/d	unexposed	292
Koktenkol	Mo-W-Bi	600,000**	0.07**	0.01**	stockwork	exo-endocontact	granite	coarse, fine-gr	0.15	292
Lobash	Mo	350,000	0.04	0.01	stockwork	exo-endocontact	granite	porphyritic	unexposed	1,440
Mt.Pleasant	Mo-W-Bi, Sn	45,040	0.118	0.21	stockwork	exo-endocontact	granite	fine-gr	unexposed	330
Mt. Mulgine/H	W-Mo	1,000	0.472	0.6	veins	endocontact	granite	n/d	0.1	n/d
Mt. Mulgine/T	W-Mo-Ag-Au	12,000	0.04	0.19	sheeted veins	exocontact	granite	n/d	0.1	n/d
Verbinskoe	Mo-Bi, Sn	21,600	0.148	-	sheeted veins	endocontact	granite	coarse-, fine-gr	120	1,470
Xihuashan	W-Mo-Bi-Sn	35,000***	0.01	0.21	sheeted veins	endo-exocontact	granite	medium-gr , porphyritic	19	148
Yugodzir	Mo-W	90,000**	0.2**	0.3**	solid bodies	endo-exocontact	granite	fine-gr	2.5	210

* Data for molybdenum ore only; ** authors' estimate; *** adopted from McLeod, 1979, with authors' estimate; - not present;

Representative analyses of molybdenum-tungsten greisen-bearing granites — Table 3

Type 1. Proximal deposits

Phases	Deposit	Rock	Texture	SiO_2	TiO_2	Al_2O_3	Fe_2O_3	FeO	MnO	MgO	CaO	Na_2O	K_2O	P_2O_5	H_2O +	H_2O-	S	F	Type*	Series**
Latest	Ackley group	aplite	fine-gr	76.36	0.08	12.30	0.44	0.24	0.03	0.03	0.2	3.33	5.77	0.00	0.21	-	0.01	n/d	I(A)	mgt
Middle	Ackley group	granite	medium-gr	74.75	0.31	12.87	0.78	0.81	0.07	0.35	0.60	3.62	5.08	0.00	0.46	-	0.01	n/d	I(A)	mgt
	Nebelstein	granite	medium-gr	73.60	0.26	14.08	1.83	n/d	0.04	0.44	1.08	2.75	4.89	0.17	0.92	-	n/d	0.156	S	n/d
	Nebelstein	granite	medium-gr	75.54	0.09	13.78	0.96	n/d	0.03	0.14	0.59	3.15	4.72	0.10	0.69	-	n/d	0.089	S	n/d
	Nebelstein	granite	medium-gr	75.15	0.08	13.62	1.71	n/d	0.01	0.09	0.46	2.82	4.87	0.11	0.91	-	n/d	0.075	S	n/d
Earliest	Ackley group	granite	coarse-gr	73.89	0.26	12.98	0.89	0.67	0.03	0.21	0.92	3.34	5.26	0.06	1.52	-	0.01	n/d	I(A)	mgt
	Wolfram Camp	adamellite	coarse-gr	75.73	0.05	12.26	0.17	1.13	0.08	0.23	0.76	2.08	5.16	0.02	1.53	-	n/d	n/d	S	ilm

References: Ackley group - Whalen, 1980; Nebelstein - Göd and Koller, 1989; Wolfram Camp - Plimer, 1974;

Type 2. Distal deposits

Phases	Deposit	Rock	Texture	SiO_2	TiO_2	Al_2O_3	Fe_2O_3	FeO	MnO	MgO	CaO	Na_2O	K_2O	P_2O_5	H_2O +	H_2O-	S	F	Type*	Series**
Latest	Akchatau	granite	fine-gr	75.10	0.09	12.96	1.72	0.62	0.03	0.13	0.57	2.74	4.52	0.00	-	0.53	n/d	n/d	S	mgt
	Kara-Oba	granite	fine-gr	76.68	0.07	12.22	0.97	0.85	0.01	0.22	0.81	2.08	3.82	0.03	-	0.20	n/d	n/d	S	mgt
	Eastern Kounrad	granite	fine-gr	75.87	0.13	13.27	0.80	0.93	0.13	0.21	0.44	3.23	4.55	0.06	-	0.16	n/d	n/d	S	mgt
	Mt. Pleasant	granite	fine-gr	75.70	0.04	12.90	0.30	1.20	0.03	0.13	0.79	3.50	4.98	0.02	n/d	n/d	0.01	0.48	I(A)	ilm
	Xihuashan	granite	medium-, coarse-gr	76.19	0.1	12.69	0.27	1.17	0.04	0.15	0.7	3.3	4.65	0.14	n/d	n/d	-	-	I	ilm
Middle	Akchatau	granite	medium-gr	76.03	0.31	12.08	1.00	0.73	0.07	0.59	1.09	3.32	3.69	0.18	-	0.35	n/d	n/d	I	mgt
	Koktenkol	granite	medium-gr	74.09	0.21	13.48	0.91	0.51	0.01	0.48	1.09	4.12	4.70	0.07	-	0.07	n/d	n/d	I	mgt
	Kara-Oba	granite	medium-gr	75.87	0.11	13.33	0.44	1.18	0.04	0.19	0.91	3.17	3.86	0.02	-	0.13	n/d	n/d	S	ilm
	Eastern Kounrad	granite	medium-gr	75.42	0.18	13.51	1.00	0.67	0.06	0.34	0.68	3.28	4.39	0.04	-	0.14	n/d	n/d	S	mgt
	Xihuashan	granite	porphyritic	74.11	0.15	13.25	0.45	1.5	0.04	0.39	1.08	3.28	4.63	0.13	n/d	n/d	-	-	I	ilm
Earliest	Akchatau	granite	coarse-gr	74.31	0.22	13.06	1.19	1.17	0.10	0.92	1.08	2.74	3.96	0.19	-	0.30	n/d	n/d	S	mgt
	Dzhida	granite	coarse-gr	74.75	0.12	13.09	0.69	0.25	0.04	0.15	0.83	3.60	4.70	0.00	1.22	0.09	n/d	0.44	I	mgt
	Eastern Kounrad	granite	coarse-gr	72.31	0.34	14.21	1.39	0.91	0.19	0.49	1.23	3.73	4.52	0.22	-	0.41	n/d	n/d	I	mgt
	Verbinskoe	granite	coarse-gr	73.47	0.02	13.36	0.60	2.38	0.08	0.81	0.35	3.00	4.70	0.09	-	-	0.06	0.08	S	ilm

References: Akchatau, Dzhida, Eastern Kounrad, Kara-Oba - Pokalov, 1972; Mt. Pleasant - Kooiman and others, 1986; Xihuashan - Tanelli, 1982; Verbinskoe - Buchinskaya and Nechaev, 1989; *Rocks with $Al_2O_3/CaO+Na_2O+K_2O$ (mol) > 1.1 - are S-type; rocks with $Al_2O_3/CaO+Na_2O+K_2O$ (mol) < 1.1 - are I-type. **Rocks with $Fe^{3+}/Fe^{3+}+Fe^{2+}$ (atomic) > 0.31 are magnetite (mgt) series; rocks with $Fe^{3+}/Fe^{3+}+Fe^{2+}$ (atomic) < 0.31 are ilmenite (ilm) series.

Zoning of the Shizhuyuan deposit*

Table 4

Rock	Alteration zoning	Minerals	Grade (wt. %, relative %, in bold)					Principal Commodities
			W	Mo	Sn	Bi	Be	
Carbonate beds	Marble Skarnized marble	Cassiterite, stannite, taafeite, chrysoberyl, spinel	-	-	0.26 **79**	-	0.07 **21**	**Sn-Be**
	Skarn	Scheelite, bismuthinite	0.0267 **8**	-	0.186 **58**	0.11 **34**	-	**Sn-Bi-W**
Contact	Stockwork greisen Complex skarn	Wolframite, scheelite, bismuthinite, molybdenite, cassiterite	0.632 **63**	0.121 **12**	0.093 **9**	0.152 **16**	-	**W-Bi-Mo-Sn**
Granite	Planar greisen	Wolframite, molybdenite, cassiterite, bismuthinite, beryl	0.353 **49**	0.163 **22**	0.070 **9**	0.056 **8**	0.085 **12**	**W-Mo-Be-Sn-Bi**

*Adopted from Liu Nailong, 1992, with additions

Mineralogy and alteration assemblages of molybdenum-tungsten greisen deposits — Table 5a

Type 1. Proximal deposits

Deposit	Ore minerals	Gangue minerals	Secondary minerals	Ore texture	Alteration	Greisenization
Ackley group	molybdenite	cassiterite, wolframite, sphalerite, chalcopyrite, pyrrhotite	quartz, K-feldspar, muscovite, carbonate, barite, topaz, fluorite	erratically distributed coarse, fine-gr rosettes, dissemination, pods and fracture fillings	silicification, greisenization, sericitization	quartz-muscovite, quartz-topaz, fluorite
Bamford	molybdenite, wolframite, native bismuth	bismuthinite, pyrite, pyrrhotite, chalcopyrite	quartz, muscovite, topaz, fluorite, tourmaline	plates, fine-coarse-gr	greisenization, sericitization	quartz, quartz-muscovite
Changsu	molybdenite	chalcopyrite	quartz, muscovite, pink orthoclase and scant fluorite, biotite	foliated masses (to 21 kg), flakes scales	greisenization(?)	quartz-muscovite-fluorite
Drammen	molybdenite	pyrite, sphalerite, galena	quartz, topaz, fluorite, sericite	n/d	greisenization, albitization, sericitization	quartz, quartz-topaz
Kingsgate	molybdenite, wolframite, native bismuth	bismuthinite, pyrite, pyrrhotite, chalcopyrite	quartz, muscovite, topaz, fluorite, tourmaline	plates, fine-coarse-gr	greisenization, sericitization	quartz, quartz-muscovite
Knaben	molybdenite	sulfides	mica, quartz, feldspar	in the quartz lode, highly mineralized fissures in granite, Mo-impregnated granite, brecciated vein mass	silicification, greisenization (?)	quartz-muscovite
Lacorne	molybdenite	pyrite, chalcopyrite, bismuthinite, native bismuth, scheelite	quartz, muscovite, tourmaline, fluorite, apatite, calcite, feldspar	dissemination, irregular scales or flakes, fine impregnation	greisenization(?)	quartz-muscovite(?)
Matasvaara	molybdenite	pyrite, pyrrhotite, chalcopyrite, sphalerite, galena	n/d	scales, accumulations in the spaces, dissemination	silicification, potash alteration	
Nebelstein	molybdenite	magnetite, pyrite, pyrrhotite, chalcopyrite	quartz, muscovite, fluorite, apatite, monazite	disseminated mineralization (under discussion)	greisenization,	quartz-muscovite
Preissac	molybdenite	pyrite, chalcopyrite, bismuthinite, native bismuth, scheelite	quartz, muscovite, tourmaline, fluorite, apatite, calcite, feldspar	dissemination, irregular scales or flakes, fine impregnation	greisenization (?)	quartz-muscovite(?)
Taehwa	molybdenite, wolframite,	chalcopyrite, pyrite, scheelite, gold, silver(?)	quartz, muscovite, orthoclase	disseminated in foliated masses, as scales and plates (6 cm)	greisenization (?)	quartz-muscovite
Wolfram Camp	molybdenite, wolframite, native bismuth	bismuthinite, pyrite, pyrrhotite, chalcopyrite	quartz, muscovite, topaz, fluorite, tourmaline	plates, fine, coarse-scale	greisenization, sericitization	quartz, quartz-muscovite
Wonban	molybdenite, wolframite, native bismuth	bismuthinite, pyrite, pyrrhotite, chalcopyrite	quartz, muscovite, topaz, fluorite, tourmaline	plates, fine, coarse-scale	greisenization, sericitization	quartz, quartz-muscovite

Mineralogy and alteration assemblages of molybdenum-tungsten greisen deposits — Table 5b

Type 2. Distal deposits

Deposit	Ore minerals	Gangue minerals	Secondary minerals	Ore texture	Alteration	Greisenization
Batistau	molybdenite, scheelite (minor wolframite)	pyrite, chalcopyrite, sphalerite, galena	quartz, fluorite, feldspar	fine, medium-scale	hornfels, silicification, greisenization	quartz-muscovite, quartz-muscovite-fluorite
Bainazar	molybdenite, wolframite (minor scheelite)	pyrite, bismuthinite, chalcopyrite,	quartz, muscovite, topaz, fluorite, beryl	fine, medium-scale	greisenization, hornfels, sericitization	quartz-muscovite-topaz
Dzhaur	molybdenite, wolframite, scheelite	pyrite	quartz, muscovite, feldspar	fine, medium-scale	greisenization, epidotization, amphibolization	quartz, quartz-muscovite
Dzhida	molybdenite	gubnerite, scheelite, pyrite, sphalerite, chalcopyrite	quartz, fluorite, muscovite, topaz	dissemination, small pockets in greisen	greisenization, skarn	quartz, quartz-muscovite
Eastern Kounrad	molybdenite, wolframite	pyrite, wolframite, sphalerite, chalcopyrite, bornite, galena, bismuthinite	albite, microcline, muscovite, fluorite	fine, medium-scale	greisenization	quartz-muscovite, quartz-feldspar
Kara-Oba	molybdenite, wolframite , cassiterite, bismuthinite	pyrite, chalcopyrite, galena, beryl	quartz, muscovite, fluorite, topaz, feldspar	fine, medium-scale	greisenization, hornfels, feldspathisation, sericitization	quartz, quartz-muscovite, muscovite, quartz-topaz-fluorite
Kairakty	molybdenite, scheelite	pyrite, wolframite, bismuth, chalcopyrite, galena	quartz, muscovite, sericite, fluorite	fine, medium-scale	greisenization, hornfels	quartz-muscovite
Koktenkol	molybdenite, wolframite, scheelite	bismuthinite, pyrite, chalcopyrite	quartz, muscovite, fluorite, feldspar	fine, medium-scale	greisenization	quartz-muscovite-fluorite
Lobash	molybdenite	pyrite, chalcopyrite, pirrhotite, sphalerite, galena, scheelite, bornite	quartz, minor-epidote, muscovite-sericite, fluorite, tourmaline, carbonate;	coarse, medium and fine scaled, less dissemination	biotitization, hornfels, muscovatization, sericitization greisenization, propylitization	quartz-muscovite
Mt. Pleasant	molybdenite, wolframite	arsenopyrite, bismuthinite, bismuth, cassiterite	quartz, topaz, biotite, lepidolite, chlorite, K feldspar, sericite, fluorite	dissemination, coarse-scale	greisenization, potassic, propylitization(chlorite-sericite)	quartz-topaz-sericite-fluorite, quartz-biotite-chlorite-topaz, quartz-topaz, quartz-chlorite-mica
Mt. Mulgine/H	scheelite, molybdenite	chalcopyrite	quartz, fluorite	dissemination, sheeted veins	greisenization	quartz-muscovite, fluorite
Mt. Mulgine/T	scheelite, molybdenite	bismuth, bismuthinite, tetrahedrite, gold	quartz, fluorite	dissemination, sheeted veins	greisenization	quartz-muscovite, fluorite
Verbinskoe	molybdenite, cassiterite, bismuthinite	sphalerite, galena, argentite, chalcopyrite;	quartz, zinnwaldite, topaz, muscovite, fluorite, sericite	dissemination, coarse-scale	greisenization, albitization	quartz-muscovite-zinnwaldite-fluorite
Xihuashan	wolframite, cassiterite, molybdenite, native bismuth	bismuthinite, scheelite, chalcopyrite, bornite, pyrite, tantalo-columbite, datolite, bertrandite;	quartz, potash feldspar, fluorite, beryl, calcite, lithium muscovite, zinnwaldite, biotite, topaz	n/d	greisenization, silicification, microclinization and albitization	mica rich, quartz rich, normal and greisenized granite
Yugodzir	molybdenite, wolframite	scheelite, sulfides(Cu, Pb, Zn), magnetite, bismuth	quartz, muscovite, zinnwaldite, lepidolite, tourmaline, fluorite, beryl, topaz	dissemination, massive and drusy texture	greisenization, hornfels	quartz-muscovite, quartz-topaz, quartz-beryl-fluorite-muscovite

Comparison of Climax Mo porphyry and molybdenum-tungsten greisen deposit types — Table 6

Characteristics	Porphyry (Volcanic)*	Greisen (Plutonic)
	Geological Environment	
Tectonic setting	Mainly extentional zones in cratons, but found far from continental margins in areas of thick crust(?), and late in the cycles	Extentional zones in cratons (45-49 km)
Rock types	Granite-rhyolite, rhyolite porphyry and (or) granite-porphyry plugs)	Coarse-, to fine-gr granites, adamellites and inter post-ore dikes
Chemistry, fingeprinters	SiO_2>75%, F>0.3%, K>Na	SiO_2=73-77%, F=0.03-0.3%, K>Na
Textures	Porphyry with fine- to medium-gr aplitic groundmass	Coarse- to fine -gr, rare porphyries massive granite
Depositional environment	Multistage hypabyssal (epizonal) intrusions (volcanic)	Multistage intrusions (plutonic)
Size	1-10 sq. km, vertical extend 2 km or more	10-1000 sq. km, vertical extend 8-10 km
Morphology	Stocks, plugs	Batholiths, stocks, cupolas
Associated deposit types	Ag-base-metal veins, fluospar deposits	W, Sn veins, W veinlets, Cu-Pb-Zn veins and skarns with the same commodities
	Deposit description	
Mineralogy	Molybdenite, fluorite, wolframite	Molybdenite, wolframite (veins), scheelite (veinlets)
Texture/Structure	In veinlets and fractures; minor dissemination, breccias	Coarse-fine scale in veins and veinlets, dissemination in greisen
Alteration	Q and Q-Kfld veining; upper phyllic and propylitic zones; halo of rhodochrosite, rhodonite, spessartine garnet; minor greisen veins below ore body	Greisenization, silicification, Q, Q-Mu, Q-Kfld veining
Ore control	Stockwork ore zone draped over small, <1 sq. km stocks multiple phases of intrusion and mineralization are highly favorable	Cupolas and slopes of plutons, endocontact- and exocontact zones, over root part (most thickness), usually one phase connected with last stage of intrusion
Commodities	Mo, less W	Mo, Mo-W, W-Mo, W-Mo-(Bi-Sn)
Mo/W(tonnage)	>100	10-0.1
Vertical extend	To 600-1600 m (porphyry/adjacent rocks-1:1)	To 1500-2000 m above the plutons' roof, and 200-500 m below (granites/adjacent rocks-1:5-10)
Morphology	Stockworks	Pods, veins, sheeted veins, stockworks
Deposition depth	From 0.6 to 3.6 km	From 2.5 to 5 km

*Adopted from Ludington, 1986, with additions

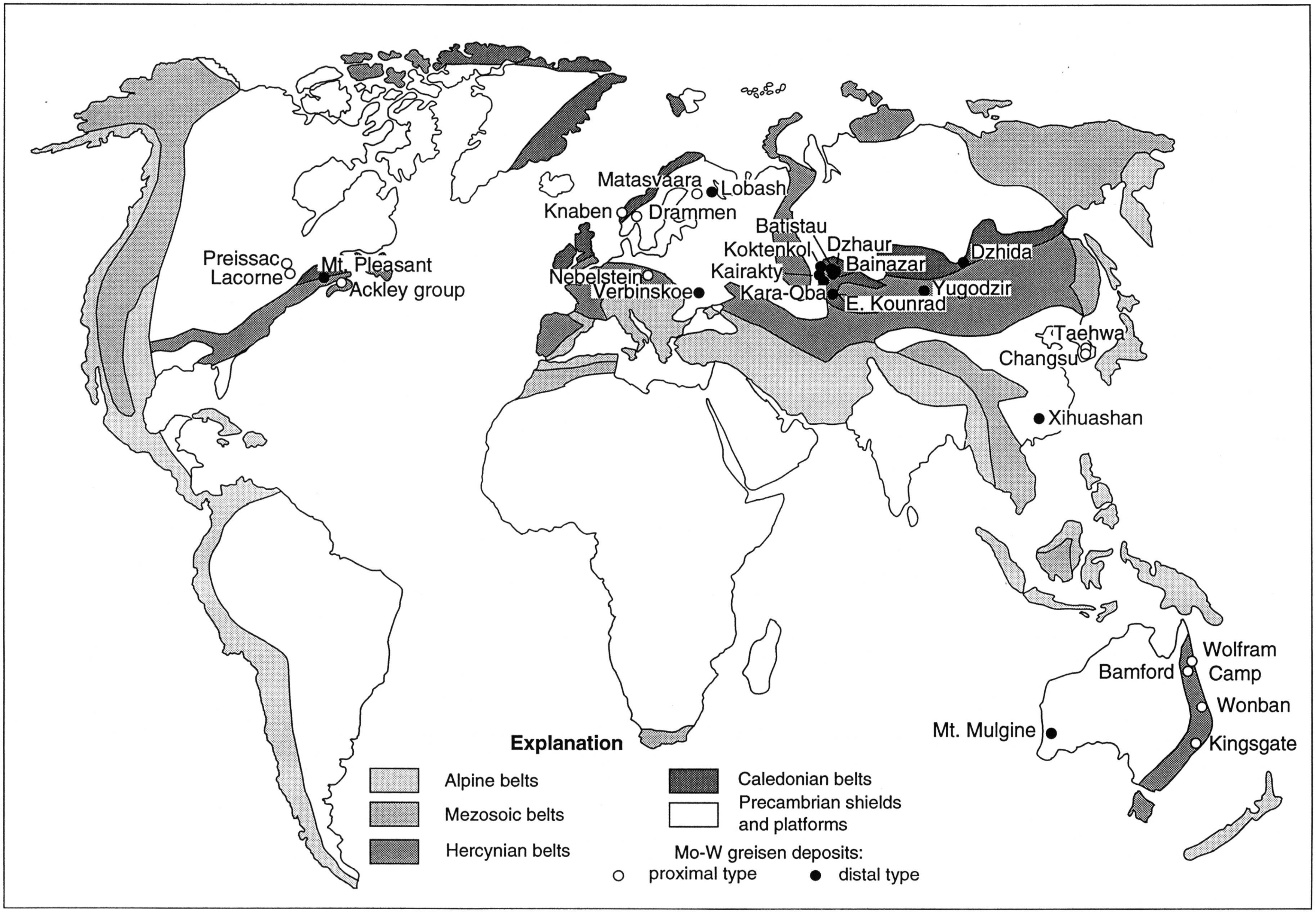

Figure 1. World distribution of molybdenum-tungsten greisen deposits

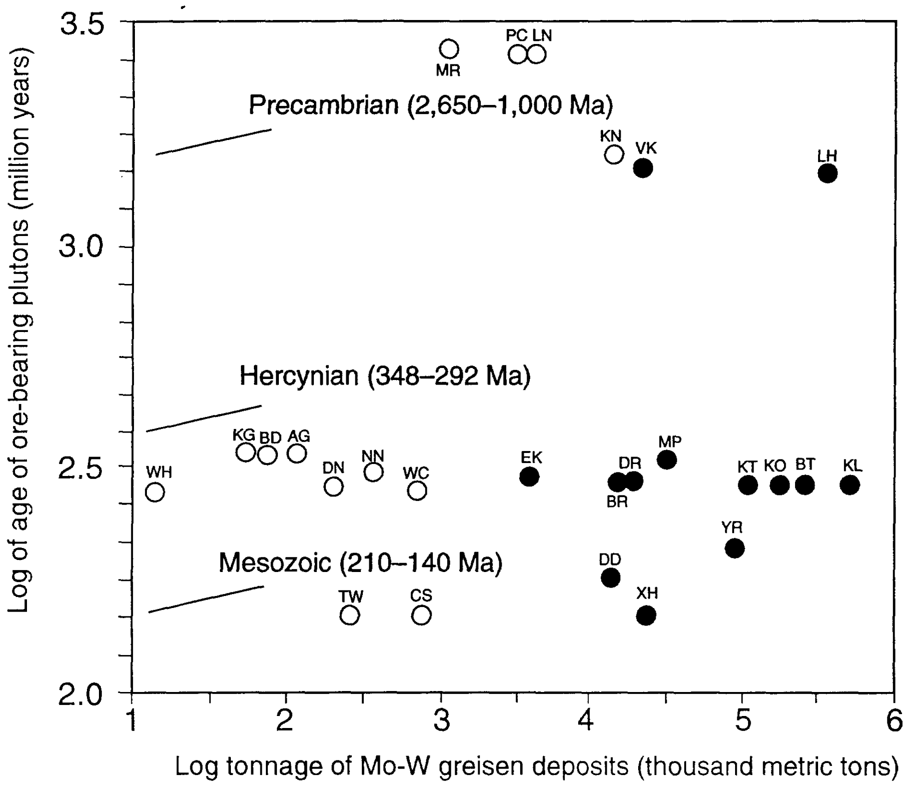

Figure 2. Relations between age of ore-bearing plutons and tonnage of molybdenum-tungsten proximal (white) and distal (black) greisen deposits

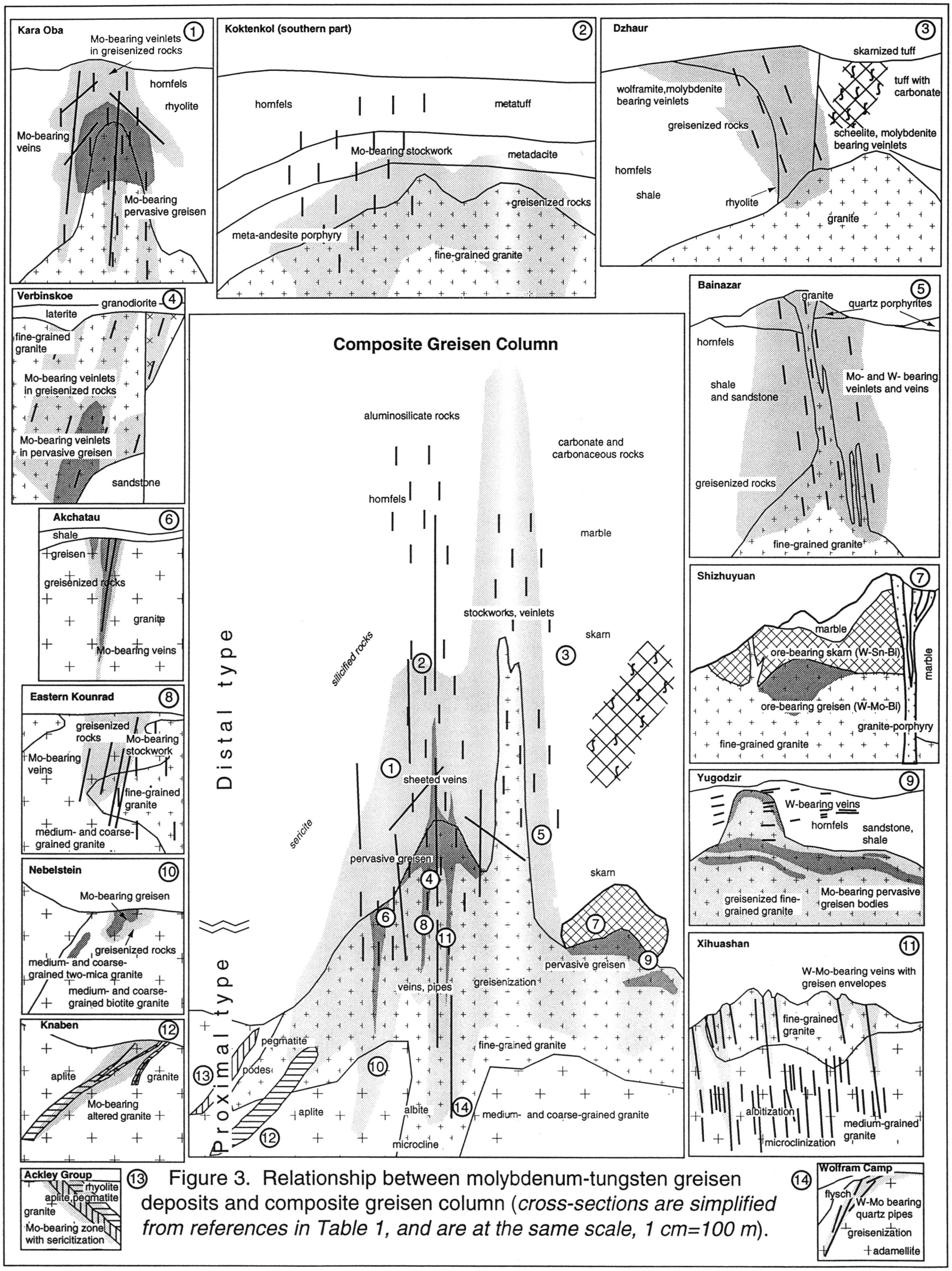

Figure 3. Relationship between molybdenum-tungsten greisen deposits and composite greisen column (*cross-sections are simplified from references in Table 1, and are at the same scale, 1 cm=100 m*).

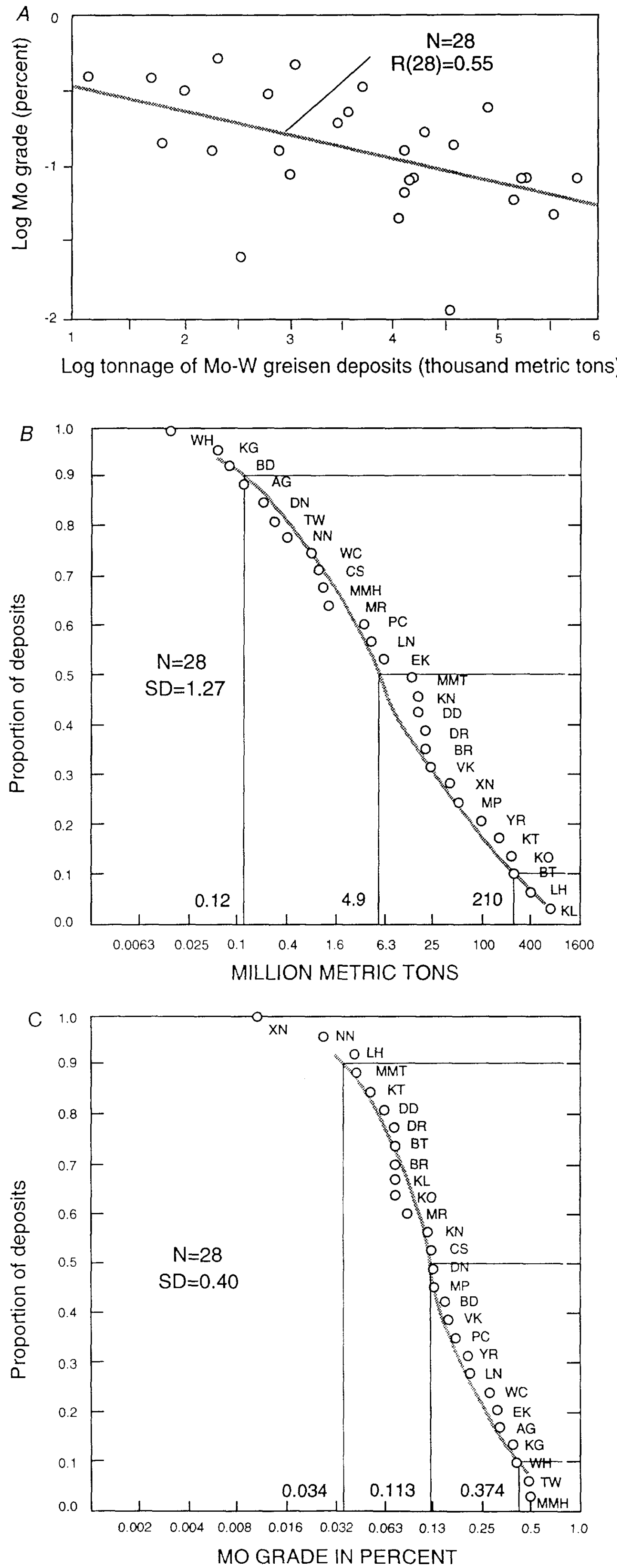

Figure 4 . Grade and tonnage model of molybdenum-tungsten greisen deposits. Plotting conventions as in Cox and Singer (1986). Abbreviations of deposit names from Table 1.

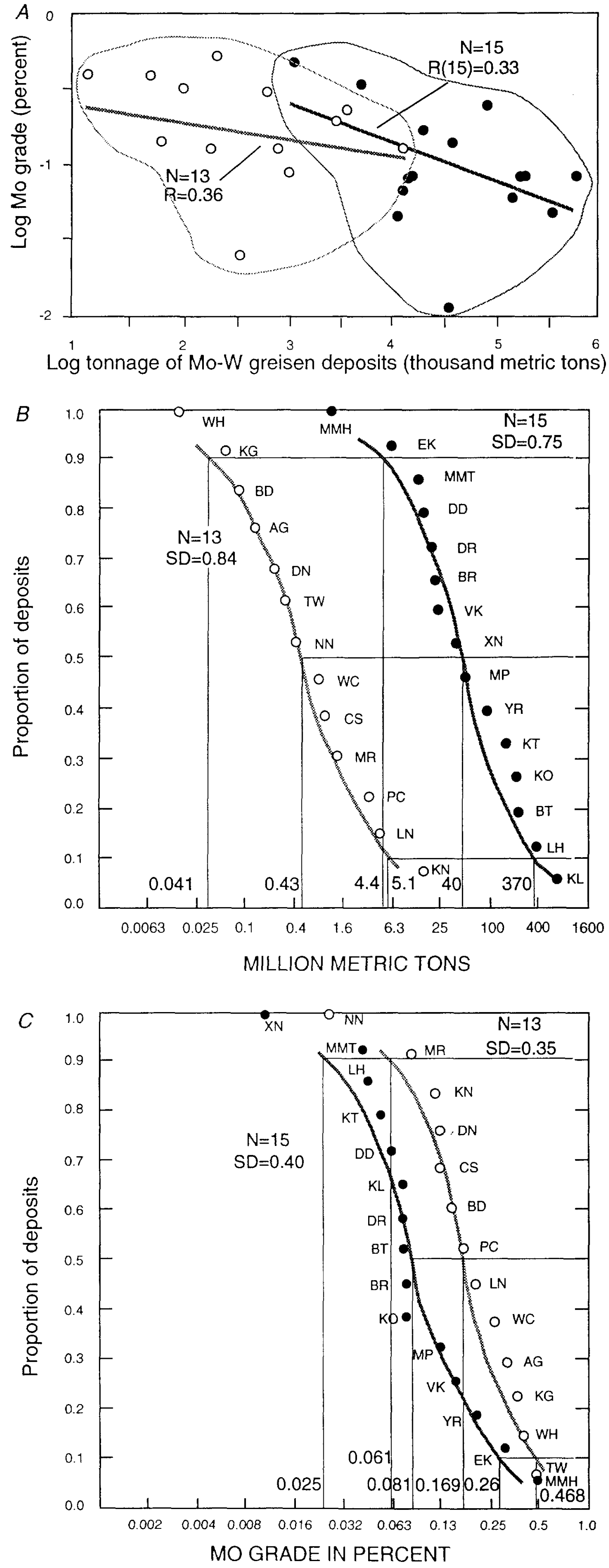

Figure 5 . Grade and tonnage models of proximal (Type 1, •) and distal (Type 2, ○) molybdenum-tungsten greisen deposits. Plotting conventions as in Cox and Singer (1986). Abbreviations of deposit names from Table 1.

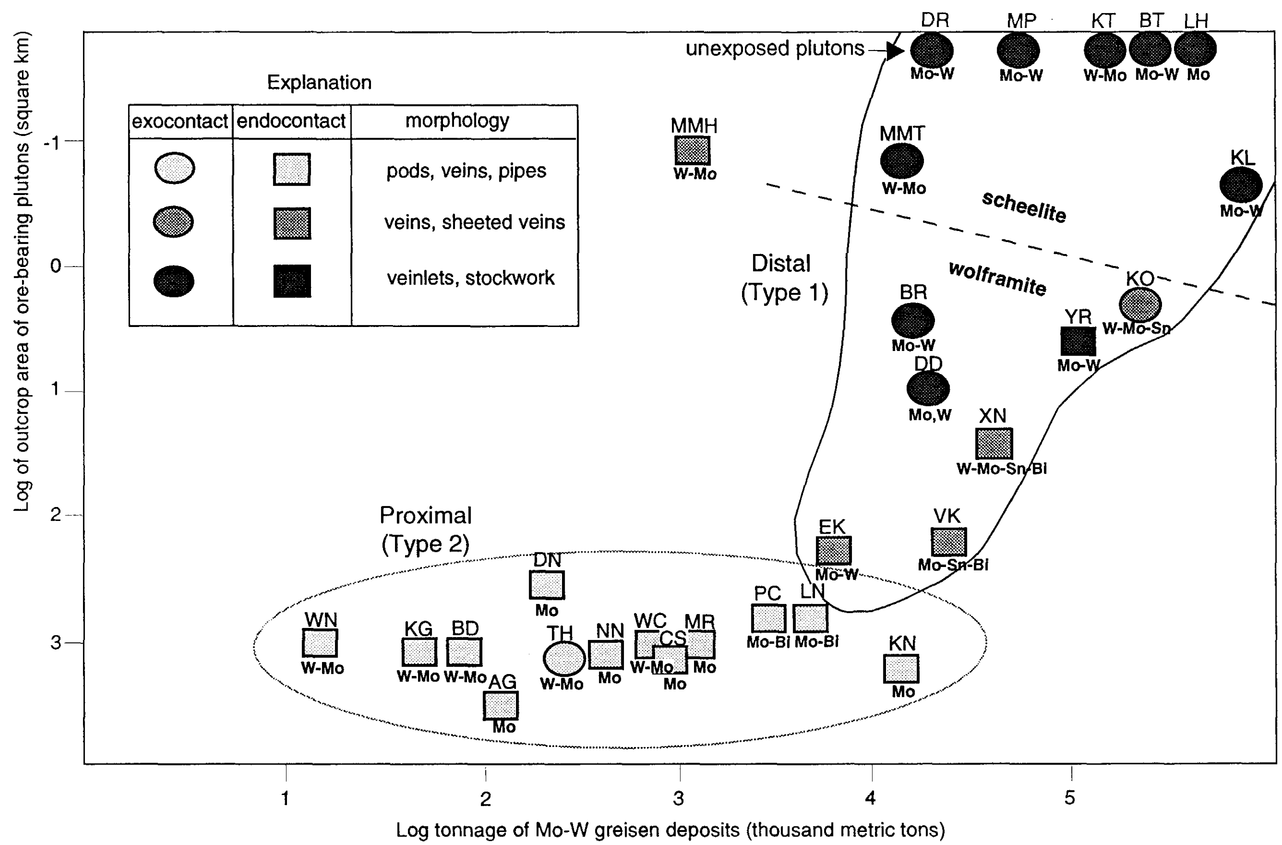

Figure 6. Relationship between tonnage, outcrop area of associated plutons, morphology and commodities for molybdenum-tungsten greisen deposits. Abbreviations of deposit names from Table 1.