Geology and Geochemistry of the Dashuigou Tellurium Deposit, Western Sichuan, China

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Abstract

The Dashuigou tellurium deposit, located on the western margin of the Yangtze platform, is unique. The deposit is hosted by Triassic metabasalt 50 to 80 meters thick. The orebodies occur as a group of NNE-striking parallel veins. Mineralization developed in three stages: Stage I—pyrrhotite-pyrite, Stage II—tetradymite, and Stage III—chalcopyrite-pyrite. Stage II is the principal tellurium mineralization stage and the tellurium-bearing minerals are mainly tetradymite, tsumoite, tellurbismuth, joseite, calaverite, stuetzite, and native tellurium. The general ore grade of the tellurium in Stage II ranges from 0.2 to 5 wt%, and it reaches 15 to 25 wt% for the massive ores. The dominant gangue minerals are calcite and dolomite, with minor biotite, muscovite, albite, quartz, and chlorite.

Fluid-inclusion studies of calcite, dolomite, and quartz from Stages I, II, and III yield homogenization temperatures of 356° to 260° C (mean = 320° C), 295° to 198° C (mean = 240°), and 235° to 152° C (mean = 170° C), respectively. Salinities of primary fluid inclusions in all three stages are 1.5 to 5.8 wt% NaCl equivalent, 9 to 15.2 wt% NaCl equivalent, and 2.8 to 3.0 wt% NaCl equivalent, respectively.

Isotopic studies show that δ34S values of sulfides range from -2.2 to +2.8 per mil. δ13C values of calcites and dolomites in the ore veins range from -5.3 to -7.42 per mil, and δ18O values range from +10.9 to +13.1 per mil, which are quite different from the δ13C values of +1.0 to +2.8 per mil and δ18O values of +16.8 to +28.5 per mil for the calcites from the Triassic carbonates in the deposit. The δD and δ18O values of muscovite and quartz were measured to be -61 to -54 per mil and +9.9 to +13.0 per mil, respectively. Values of δ18Owater computed from fluid-inclusion trapping temperatures are +3.9 and +7 per mil.

A date of 93 Ma was obtained through measurement of muscovite from the No. 12 ore vein. Sulfur-, oxygen-, carbon-, and hydrogen-isotope data indicate that the ore-forming substances of the Dashuigou tellurium deposit were derived from deep-seated sources, and the mineralizations probably are associated with Late Mesozoic alkaline or alkaline granitic magmatism. The estimated sulfur fugacities (fS) are 10^{16.7} for Stage I and 10^{-14} to 10^{-15.5} for Stage II, whereas the tellurium fugacities (fTe) are 10^{-15} to 10^{-14} and 10^{-11.2} to 10^{-10.5}, respectively.

Introduction

The DASHUIGOU tellurium deposit is located in Shimian County in western Sichuan Province, at 29° 10'17" N. Lat. and 102° 11'06" E. Long. It is a mountainous area, ranging in elevation from 1200 to 4000 meters. The deposit is 30 km west of the Shimian county town, and is accessible by road, which makes transport convenient. Before the deposit was confirmed, local peasants had mined sulfur there for more than a decade. At that time, tellurium-rich ore was discarded as waste. At the end of 1991, analysis by Ye Zhengming indicated that the tellurium and bismuth contents of the waste material were quite high. Dashigou then was determined to be a tellurium-dominated deposit as a result of further study by Yang Baichuan (Chen Yuchuan et al., 1993), and reserves of...
tellurium metal in a small part of the deposit now have been assessed at 1000 tons.

Tellurium is a dispersed element, with a Clarke of 0.0006 ppm, 0.001 ppm, 0.52 ppm, and 0.16 ppm for crust, upper mantle, lower mantle, core, and earth, respectively (Li Tong, 1976). Tellurium usually is dispersed and rarely forms its own independent deposits. After the Dashuigou tellurium deposit was reported (Cao Zhimin and Luo Yaonan, 1993; Chen Yuchuan et al., 1993), many studies on the deposit have been performed. During this period, gold also was confirmed to be one of the ore-forming elements (Luo Yaonan et al., 1994). Studies of the ores show that gold, silver, and selenium can be recovered as byproducts (Mao Jingwen et al., 1995b). Yin Jianzhao and Zhou Jianxong (1994) provided a preliminary description of the major ore minerals and gangue minerals from the mine. The physicochemical characteristics and sulfur-isotopic measurements for tetradymite, a predominant ore-forming mineral, were provided by Mao Jingwen et al. (1995a).

With regard to the genesis of the Dashuigou tellurium deposit, Mao Jingwen et al. (1994) proposed that the mineralization is associated with magmatism, as a result of their studies of the sulfur isotopes of tetradymite and pyrrhotite. On the basis of further study, Luo Yaonan et al. (1994) suggested that the tellurium deposit is related to Early Yanshanian granitic magmatism. Yin Jianzhao and Zhou Jianxong (1994) observed that the deposit is a sedimentary-reworked type one; i.e., tellurium and other ore-forming elements, originally enriched in the host rock, were mobilized during Yanshanian tectonic movements and then were deposited in fissures. Mao Jingwen et al. (1995b) speculated that Yanshanian alkaline magmatism possibly is responsible for the tellurium mineralization.

This paper describes the geology, mineralogy, geochemistry, fluid inclusions, and isotopes of the tellurium deposit in detail. It then attempts to ascertain the physicochemical conditions of its formation and proposes a metallogenic model.

Regional Geologic Setting

The Dashuigou tellurium deposit is located in the middle part of the Luding-Mianning regional ductile shear belt on the western margin of the Yangtze platform. The basement of the western Yangtze platform is a Precambrian metamorphic complex, consisting of Early Proterozoic amphibolites and hornblende-plagioclase gneisses, Middle Proterozoic low-grade greenschists, and Sinian continental volcanic rocks, coarse-grained elastic rocks, and carbonate rocks and evaporites. In the western marginal region, the Upper Ordovician, Devonian, Carboniferous and Lower-Middle Triassic sequences are mostly absent. But the stratigraphic sequence in the Shimian depression in the northern part of the platform is relatively continuous and consists of continental elastic rocks and carbonates (Bureau of Geology, 1974). Permian continental basalt (the Emeishan basalt) occurs extensively in the western marginal region of the Yangtze platform, covering an area of around 300,000 km$^2$ with an average thickness of 2,149 meters (Zhang Yunxiang et al., 1988; Liu Zhaoji et al., 1986). Because the Shimian district lies on the northern margin of the eruptive region, the basalt there ranges from 0 to 300 meters deep (Bureau of Geology, 1974).

The Pre-Triassic regional structures are characterized by NE-trending faults accompanied by multiphase magmatic intrusions and eruptions, including Late Proterozoic granitoids associated with tungsten-tin deposits and Hercynian mafic-ultramafic rocks associated with vanadic and titanite-magnetite deposits (Shen Su and Jing Mingxia, 1986). A group of extensional NNE-striking faults and compressional-ductile shears originated during Indosinian-Yanshanian tecto-movement starting at the end of the Triassic Period, accompanied by intrusions of granitic and syenitic magmas (Shen Su and Jing Mingxia, 1986).

Geology of the Deposit

Geologic setting

The Precambrian basement and the Devonian, Permian, and Triassic covers crop out in the vicinity of the Dashuigou tellurium deposit. The cover rocks have been transformed into sandy slate, phyllite, schist, and marble as a result of regional metamorphism. Four magmatic episodes have been recognized—i.e., Hercynian mafic rocks, Permian basalt, Triassic mafic metavolcanic rocks, and Yanshanian...
quartz diorite, granite, and aegirine-amphibole syenite. The main structural element in the Dashuigou area is the Wanbahe dome, consisting of Triassic slate interbedded with marble and the NNE and NNW sets of faults that cut through it. The Triassic mafic metavolcanic rocks cropping out as a circle in the Wanbahe dome are intercalated between thick-layered massive marbles, and are characterized by high enrichments in bismuth and tellurium. The Dashuigou tellurium deposit lies on the northern side of the basalt (Fig. 1).

The only rocks that crop out in the vicinity of the Dashuigou tellurium deposit are Triassic
marble and metabasalt (Fig. 2). The marble is composed of thick-layered white units alternating with dark- and white-striped layers. The actual host rock for tellurium mineralization—the metabasalt—is 50 to 80 meters thick and is intercalated between marbles (Fig. 2). A layer of fine-grained lava breccia occurs at the base in contact with the marble. The metabasalt shows marked layering, indicative of polycyclic eruptions, and is both vesicular and amygdaloidal. Because of the regional metamorphism, actinolite, chlorite, clinozoisite, ilmenite, and hematite are developed in the metabasalt and have an oriented fabric. Large crystals of biotite are developed along some interlayers. Chemical analysis indicates that the metabasalt contains SiO₂ = 46.09 wt% and Na₂O = 2.17 wt% on average, with K₂O/Na₂O ratios ranging from 0.04 to 0.18, and is enriched in cobalt, nickel, chromium, scandium, vanadium, copper, and strontium. Chemical analysis indicates that the metabasalt contains SiO₂ = 46.09 wt% and Na₂O = 2.17 wt% on average, with K₂O/Na₂O ratios ranging from 0.04 to 0.18, and is enriched in cobalt, nickel, chromium, scandium, vanadium, copper, and strontium. Chemical analysis indicates that the metabasalt contains SiO₂ = 46.09 wt% and Na₂O = 2.17 wt% on average, with K₂O/Na₂O ratios ranging from 0.04 to 0.18, and is enriched in cobalt, nickel, chromium, scandium, vanadium, copper, and strontium. Chemical analysis indicates that the metabasalt contains SiO₂ = 46.09 wt% and Na₂O = 2.17 wt% on average, with K₂O/Na₂O ratios ranging from 0.04 to 0.18, and is enriched in cobalt, nickel, chromium, scandium, vanadium, copper, and strontium. Chemical analysis indicates that the metabasalt contains SiO₂ = 46.09 wt% and Na₂O = 2.17 wt% on average, with K₂O/Na₂O ratios ranging from 0.04 to 0.18, and is enriched in cobalt, nickel, chromium, scandium, vanadium, copper, and strontium. Chemical analysis indicates that the metabasalt contains SiO₂ = 46.09 wt% and Na₂O = 2.17 wt% on average, with K₂O/Na₂O ratios ranging from 0.04 to 0.18, and is enriched in cobalt, nickel, chromium, scandium, vanadium, copper, and strontium.

**Ore veins**

The 13 ore veins discovered thus far in the Dashuigou tellurium deposit occur in the metabasalt, filling NE-striking fractures. Once the ore veins reach the interface between the volcanic rocks and the marble, they disappear immediately (Fig. 2).

Tellurium ore veins (Fig. 2) strike between N5°E and N30°E, roughly parallel to one another, and dip at angles of 50° to 75° to the west. The main ore veins frequently have several branches at their right sides, which show an inverse λ-like shape.

Mineralization of the Dashuigou tellurium deposit is recognized to have occurred in three stages: pyrrhotite-pyrite (Stage I), tetradymite (Stage II), and pyrite-chalcopyrite (Stage III). Stage-I mineralization is the most widely distributed in the deposit, accounting for the major parts of the 13 ore veins. The dominant ore minerals are pyrrhotite and pyrite. The pyrite occurs as enormous cubic and pyrhotite crystals ranging from 1 to 10 cm in diameter, embedded in medium- to coarse-grained pyrrhotite aggregates. Networks of gel-like pyrite and fine-grained pyrite are developed along the fractures in pyrrhotite crystals (Fig. 3A). Interstitial chalcopyrite and native gold fill openings among pyrrhotite and pyrite crystals and transect pyrrhotite and pyrite along the fractures. The major metallic minerals crystallized in the sequence—pyrrhotite, megacryst pyrite, gel-like pyrite, chalcopyrite, and native gold. Gangue minerals of Stage I—dolomite, biotite, actinolite, chlorite, olivine, tourmaline, and quartz—generally exhibit massive structures.

Stage-II ores are composed mainly of tetradymite with minor tsumoite, joseite, tellurbismuth, native tellurium, native gold, stuetzite, native bismuth, pyrrhotite, chalcopyrite, and sphalerite. The dominant gangue minerals are dolomite and calcite, with minor albite, muscovite, and quartz. In a few ore veins, such as a branch of the No. 12 ore vein, the muscovite content can reach 20 to 40 wt%. Radial spherical muscovite aggregates, and nested-radial tourmaline aggregates in diameters ranging from 2 to 10 cm, can be seen in the No. 12 main ore vein and its branches. Stage II is the predominant tellurium mineralization stage in the deposit. The tellurium ore types in the stage comprise massive ore, which consists almost entirely of large crystals of tetradymite (Fig. 3B), and disseminated ores consisting of pyrrhotite-dolomite aggregates with interstitial disseminated tetradymite, tsumoite, and other metallic minerals or dolomite aggregates, as well as interstitial disseminated tetradymite and other tellurium-bearing minerals.

Stage-II ore veins are developed spatially in newly opened fractures along the pyrrhotite-pyrite ore veins. Generally speaking, most ore veins of Stage II penetrate into both sides of Stage-I ore veins (Fig. 4) or cut through the pyrrhotite-pyrite ore and contain enclaves of the latter (Fig. 3C). Because Stage-I mineralization is controlled by tension fractures, both breccia ores and host rock breccias in ore veins occur frequently. A group of compressional-shearing fractures is responsible for Stage-II mineralization. The tellurium ore veins occur not only at one side or both sides of Stage-I ore veins, but also in a series of massive tellurium ore lenses, which are more than 10 meters long, several meters thick, and right-laterally arranged in the ore veins.

Graphic structure (Fig. 3D), consisting of pyrrhotite, tetradymite, and other tellurides, is developed extensively along the contact zones between the ores of the two stages, where
Fig. 3. Photomicrographs at the Dashugou tellurium deposit, all taken in plane-polarized light. A. Net-like pyrite aggregate along fissures in the pyrrhotite crystals. B. Pure massive tetradymite ore. C. Telluride ore (white) cutting through pyrrhotite (grey). D. Graphic structure consisting of worm-like pyrrhotites and tellurides (dark grey) and tetradymites (grey). E. Thread-like telluride veins in pyrrhotite ore (grey). F. Pyrrhotites showing wavy extinction structure.

The early-stage pyrrhotite and chalcopyrite assemblages are strongly altered by the late-stage hydrothermal solution. Complicated metallic mineral assemblages—including tetradymite, tsumoite, tellurbismuth, joseite, calaverite, stuetzite, and native tellurium—occur between the contact zones, and are replaced by almost pure tetradymite aggregates away from
the contact zones. Tellurium mineralization is developed as thread-like networks in the pyrrhotite-pyrite ores (Fig. 3E) at the other side away from the zones.

Stage-III mineralization occurs as veinlets and thread-like stockworks composed of pyrite, chalcopyrite, and quartz, which are superimposed either on the two ores of Stages I and II or on the surrounding metabasalts. Stage III is characterized by copper and gold mineralization, and their gold grade ranges from 3 to 15 g/t (Mao Jingwen et al., 1994).

The last mineralization is represented by auriferous quartz veins that are randomly distributed near the ore veins. Luo Yaonan et al. (1994) indicated that the gold content ranges from 0.004 to 21.38 g/t, and that the tellurium content ranges from 0.04 to 0.89 g/t.

Alterations

Wallrock alteration around both pyrrhotite-pyrite ore veins and tetrasydymite veins is remarkable, and frequently zoned. Alteration around Stage-I ore veins is characterized by intense biotitization. The alteration is zoned outward from the veins as follows: (1) coarse-grained biotite (5 to 10 cm wide), dominated by large-sheet biotite with interstitial fine-grained quartz, calcite, and minor ilmenite, apatite, pyrite, and sphalerite; (2) coarse-grained actinolite-calcite-epidote, in which actinolite 8 to 15 mm long forms a framework, with interstitial calcite, epidote, plagioclase, biotite, and clinozoisite, and opaque minerals of ilmenite, pyrrhotite, and chalcopyrite; (3) fine-grained biotite-feldspar, composed mainly of fine-grained biotite, quartz, calcite, plagioclase, muscovite, ilmenite, and minor pyrite; (4) quartz-biotite-actinolite, in which fine-grained quartz, biotite, and chlorite occur as interstitial minerals among actinolite; and (5) chlorite-actinolite of the metabasalt. It should be emphasized that the second alteration zone in the zoning occurs sporadically.

Alteration around Stage-II ore veins is characterized by a large amount of muscovite and sericite. Alteration zones, from the veins outward, are: (1) fine-grained calcite-muscovite dominated by muscovite and calcite, with minor quartz, tourmaline, fluorite, hematite, and pyrite; (2) quartz-sericite-calcite, mainly composed of calcite, with some quartz, sericite, and chlorite, as well as opaque hematite; (3) calcite-quartz-chlorite, composed mainly of chlorite, with minor sericite, quartz, calcite, and opaque hematite, chalcopyrite, and pyrite; and (4) metabasalt.

In addition, albite-quartz sericitization clearly occurs beside some small veins, such as pyrite-chalcopyrite-quartz ore veins and pyrite-pyrrhotite-bearing quartz-tourmaline veins. Large crystals of actinolite are distributed around the quartz stockwork, regardless of whether they are auriferous.

Mineralogy of vein systems

Thirty-three kinds of metallic and gangue minerals have been identified from the Dashuigou tellurium deposit, in three paragenetic stages (Fig. 5).

Pyrite. The stoichiometric composition of normative pyrite is Fe 46.55 and S 53.45 wt%. Pyrite in the Dashuigou tellurium deposit has an average composition of Fe 48.24 and S 51.73 wt%. It can be seen clearly that its sulfur content is lower than the normative stoichiometric composition of pyrite. Pyrite in the Dashuigou deposit is characterized by a low nickel content (4.9 to 25 ppm) and a high cobalt content (912 to 5800 ppm); the Co/Ni ratios range from 56 to 651.7. Moreover, pyrite in the Dashuigou tellurium deposit is enriched in tellurium (5 to 27 ppm), gold (2.5 to 4.1 g/t), and silver (5.2 to 13 g/t), with the Au/Ag ratios ranging from 0.28 to 0.79.

Pyrrhotite. Two types of pyrrhotite, monoclinic and rhombic, coexist in a mosaic intergrowth. In some places, pyrrhotite crystals are deformed, so that they show wavy extinction (Fig. 3F), and gel-like pyrite occurs in fissures within them. Components of pyrrhotite are Fe
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Fig. 5. Variations of minerals in different metallogenic stages.
DASHUIGOU TELLURIUM DEPOSIT, CHINA

FIG. 6. Compositions of carbonates on a CaCO₃-FeCO₃-MgCO₃ diagram.

57.95 to 62.61 wt% and S 33.72 to 38.47 wt%.
In comparison with pyrite, pyrrhotite has low Co/Ni ratios, which range from 0.07 to 2.90 (1.18 on average). Its Au content varies from 3.2 to 4.6 g/t (3.9 g/t on average), whereas its Te content is 6.3 to 3910 ppm (444 ppm on average). Most samples contain over 0.2 wt% of copper, 0.68 wt% at most.

Tetradymite. Tetradymite is the most important tellurium-bearing mineral in the Dashuigou deposit. It forms either massive ore in coarsely crystallized layers or disseminated and breccia ores in medium- and medium-coarse layers interstitial among dolomite and calcite aggregates. The layer tetradymite exhibits well-developed cleavage along the (0001) crystal face. The chemical composition of tetradymite in the Dashuigou deposit is Bi 57.65 to 58.62 wt%, Te 35.20 to 36.40 wt%, and S 4.59 to 5.36 wt% (Mao Jingwen et al., 1995b). Contents of some trace elements in tetradymite are Ag 230-340 ppm, Se 160-280 ppm, Fe 310-2800 ppm, Sb 100-280 ppm, and Au 1.4-10.7 g/t (Mao Jingwen et al., 1995b).

Tsumoite. Tsumoite occurs only in contacts between tellurium ore veins and pyrite-pyrrhotite ore veins. The microprobe analyses indicate that the tellurium content of tsumoite is 35.58-37.54 wt% and that of Bi is 61.50-62.20 wt%. Contents of some important trace elements of tsumoite are: S (0.01-0.87 ppm), Fe (0.03-0.11 ppm), Cu (0.04-0.23 ppm), Ni (0.02-0.14 ppm), and Zn (0.06-0.11 ppm).

Carbonates. Carbonates are the principal gangue minerals in both the ore veins and altered rocks. Several tens of samples have been analyzed by electron microprobe and the results are presented in Figure 6. The carbonates are composed mainly of dolomite, calcite, minor siderite, and a solid solution between siderite and magnesite. The dolomite commonly contains 7 to 26 wt% siderite molecules. The calcite contains more than 90 mole percent CaCO₃. In general, the ratio of dolomite to calcite from the ore veins is higher than that from the surrounding altered rocks.

Plagioclase. Plagioclase occurs mainly in the altered rocks beside the ore veins, in addition to
small amounts in the ore veins. The plagioclase in the altered rocks and that in the pyrite-
pyrrhotite ore veins share similar compositions
and are mainly oligoclase with 25 to 29% of the
An component. The plagioclase from the tellu-
rium ore veins coexists with muscovite and is
albite with an An content ranging from 0 to 3%.

Biotite. Biotite is one of the most important
alteration minerals, often occurring in the form
of aggregates. Biotites gradually decrease in
amount and become finer in grain size away
from the ore veins. The pleochroism of biotite is
Ng—dark yellow and Nm = Np—pale yellow.
The results for 20 samples analyzed by the
electron microprobe indicate that the biotites in
different alteration zones are almost identical.
Fe/(Fe + Mg) ratios of biotite vary from 0.42 to
0.58, suggesting that these biotites belong to
the transitional series between siderophyllite
and eastonite. As a result of systematic analyses
for biotite from the alteration zones beside one
of the ore veins, it has been discovered that,
although Fe/(Fe+Mg) ratios for biotite in dif­
ferent zones change slightly, the Al
values increase gradually from the inner zones out­
ward (Fig. 7). Al in biotite crystal lattice
replaces Si in T-fields, so that the silicon
content of the biotite decreases from the ore
veins outward, and aluminum contents change
inversely.

Muscovite. Muscovite is one of the minor
gangue minerals in most tellurium ore veins,
and is dominant in a few ore veins. A minor
amount of muscovite also occurs in the pyrite-
pyrrhotite ore veins. A large amount of mus-
covite occurs as medium- to fine-grained flakes
or fine-grained aggregates in altered rocks asso-
ciated with tellurium mineralization. Muscovi­
te in the tellurium ore veins is light green
and is characterized by a scarcity of manganese
and iron. Potassium ions (K+) in muscovite are
replaced by sodium ions (Na+). Muscovite con-
tains 3.13 to 4.29 wt% Na2O and 4.12 to 4.36
wt% K2O, with Na/K ratios ranging from 1.07
to 1.58. Muscovites from the No. 10 ore vein
and related alteration zones have been analyzed
systematically; the results suggest that the
atomic numbers of both iron and magnesium
(Fig. 8) increase synchronously from the ore
veins to the host rocks.

Amphibole. Amphibole, dark green in color, is
relatively abundant in the altered rocks around
the ore veins because the host rock is meta-
basalt. In Leake’s classification diagram for
calcic amphibole (Leake, 1978), microprobe
analyses show that the amphiboles from the
altered rock are tschermakite and that those
from metabasalt are ferro-tschermakite.

Chlorite. Chlorite also is extensively dis-
tributed in the Dashuigou tellurium deposit.
The chlorite compositions are projected
into two groups based on their Fe2+/ (Fe2++Mg2++Mn2+) ratio vs. silicon atomic num-
ber. The first group of chlorites occurs in the
altered host rocks beside the tellurium ore
veins, with Fe2+/ (Fe2++Mg2++Mn2+) ratios from
0.656 to 0.663 and silicon atomic numbers from
2.75 to 2.84. The second category of chlorites
occurs in the pyrrhotite-pyrite ore veins
and related altered rocks, with Fe2+/ (Fe2++

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Fig. 7. Al atom vs. Fe/(Fe+Mg) ratios for biotites. Legend: 1 = biotites; 2 = feldspar-quartz-biotite rock; 3 = biotite-
chlorite rock. Arrows indicate direction outward from the ore veins.
Mg\textsuperscript{2+}+Mn\textsuperscript{2+}) ratios ranging from 0.491 to 0.523 and silicon atomic numbers from 2.63 to 2.67. Projections of microprobe analyses indicate that they belong to ripidolite and dumasite, respectively.

**Geochemistry**

Major components, trace elements, and rare-earth elements (REE) for typical ores, altered rocks, and host rocks have been analyzed via plasma emission spectrometry, plasma mass spectrometry, X-ray fluorescence spectrometry, and routine chemical analyses. All analyses were performed in the National Research Center of Geoanalysis.

**Ore geochemistry**

Both Stage-I and Stage-II ores are major ore types in the Dashuigou deposit. The former type is mined mainly for sulfur and copper. Ore grades of this type for the ore-forming elements are: Cu 0.12–1.32 wt%, Te 5.4–445 ppm, Se 1.2–3.4 ppm, Au 0.08–0.24 g/t, Ag 0.15–4.0 g/t, and S 30–45 wt%. Contents of tellurium and selenium in the ores show a positive correlation. Massive sulfide ores contain <1.5 wt% CO\textsubscript{2}, but CO\textsubscript{2} contents reach 4.25 to 42.98 wt% for ores enriched in carbonates. The Stage-I ores are relatively enriched in zinc and poor in lead, with Zn/(Pb+Zn) ratios of 0.75 to 0.95.

Stage-II ores contain the following grades of metals: Te 0.2 to 10 wt%, massive tetradymite ore 15 to 25 wt%, Se 100 to 130 ppm, Au 2.1 to 82 g/t, and Ag 148 to 266 g/t. As tetradymite is the dominant metallic mineral, tellurium shows an obviously positive correlation with bismuth in Stage-I ore, with a correlation coefficient of 0.9. Both the lead and antimony contents of the ores are lower than 300 ppm; neither antimony nor lead tellurides have yet been found.
Chondrite-normalized patterns (Fig. 9) of transitional elements of the two types of ores indicate that they are quite similar to each other, and are characterized by depletion of chromium and nickel and enrichment in copper. In comparison, the metabasalt in the deposit is relatively enriched in titanium and zinc and is depleted in nickel.

**Geochemistry of altered rocks**

With increasing distance from the pyrrhotite-pyrite veins, the Na\(_2\)O contents in each alteration zone vary from 3.55 through 2.34 to 1.42 wt%, K\(_2\)O from 1.74 to 0.39 wt%, FeO from 8.33 through 9.72 to 12 wt%, MgO from 6.33 through 7.26 to 8.76 wt%; but TiO\(_2\) contents are relatively constant, ranging from 1.58 to 1.76 wt%. Thus it can be seen that during alteration, the sodium and potassium components move outward from the mineralization system, whereas iron and magnesium move to the mineralization system from the host rocks. Because the contents of transitional elements in each alteration zone are similar to each other, they share almost the same chondrite-normalized patterns.

Although there is clear alteration zoning around the ore veins, REE in the altered rocks do not change significantly during the alteration of the host rock (metabasalt). Outward from the ore veins, the total REE amounts of the altered rocks in different zones increase (Fig. 10) and the La/Yb ratios tend to rise as well. The La/Yb ratios are relatively higher in the rocks enriched in carbonates. HREE contents are relatively higher in biotites closely neighboring the ore veins, and the La/Yb ratios reach 3.89.

Compositional variations of the alteration zoning centered on the tetradymite ore veins are characterized by removal of carbonates during the mineralization process. From ore veins to the surrounding altered rocks, CO\(_2\) contents vary from 25.28 to 10.26 wt%, CaO from 24.61 to 8.75 wt%, and SiO\(_2\) from 0.69 to 42.85 wt%. K\(_2\)O contents reach 3.89 wt% in the muscovitization zones near the ore veins and decrease to 0.68 wt% in the farthest zones. Perhaps, owing to the apparently lower mineralization temperatures of Stage II, the REE patterns of the alteration zoning basically retain the features of the metabasalt (Fig. 11). Because of the different mineral assemblages of the samples and different proportions of the mineral phases, the total REE amount of the altered rocks varies slightly, and their chondrite-normalized patterns exhibit a slight depletion of enrichment of europium (Fig. 11). However, there are, on the whole, no apparent variation trends.
Fluid-Inclusion Studies

Doubly polished sections—approximately 0.3 to 0.5 mm thick—of calcite, quartz, and dolomite from Stage-I, Stage-II, and Stage-III ores were used for fluid-inclusion study. Most samples used for study were collected from underground occurrences. Microthermometric measurements were made using a Clamax gas-flow heating-freezing stage. Temperatures of homogenization (Th) and ice melting have stan-
dard errors of ±1.0° and ±2° C, respectively. Salinity data are based on freezing-point depression in the system H₂O NaCl (Potter et al., 1978).

Fluid inclusions are not very common in most samples and are considered to be both primary and secondary in origin. Primary inclusions occur either individually or as randomly oriented clusters, whereas secondary inclusions tend to be arranged in oriented clusters. Most inclusions are two-phase liquid and vapor, consisting of 10 to 30% vapor, which homogenizes into the liquid phase. A few inclusions in Stage II are CO₂-bearing inclusions with 25 to 95% CO₂. Rare three-phase inclusions of liquid-vapor-solid (halite) occur within Stage-II and Stage-III calcite; the inclusions range in size from 2 to 29 μm.

The results of heating and freezing experiments are depicted in Figures 12 and 13. Homogenization temperatures of primary inclusions in Stage-I quartz and calcite range from 260° to 356° C, with a peak of 320° C (Fig. 12A). Secondary inclusions in Stage-I quartz and dolomite vary from 185° to 260° C with a peak of 210° C (Fig. 12A). Stage-II primary inclusions of calcite and dolomite range from 198° to 295° C, with a peak of 240° C (Fig. 12B). Temperatures of primary inclusions in Stage III range from 152° to 235° C, with a peak of 170° C (Fig. 12C).

Freezing-point depressions for primary inclusions in Stages I, II, and III exhibit different ranges of values. Salinities of Stage-I fluids range from 1.5 to 5.8 wt% NaCl equiv (Fig. 13A), whereas those of Stage II range from 1.5 to 5.8 wt% NaCl equiv (Fig. 13B). Salinities of halite-bearing inclusions reach 20 to 25 wt% NaCl equiv, and those of Stage II range from 2.8 to 3 wt% NaCl equiv.

**Isotope Studies**

We measured the sulfur-isotope compositions of sulfide minerals; the carbon- and oxygen-isotope compositions of calcite, quartz, and dolomite; the hydrogen- and oxygen-isotope compositions of muscovite; and the formation age by the ³⁹Ar-⁴⁰Ar method, in order to elucidate the origin and history of hydrothermal fluids and their ore constituents. All of the stable-isotope analyses were performed in the Stable Isotope Laboratory of the Institute of Mineral Deposits, Chinese Academy of Geological Sciences. The analytical methods and standard errors of each method have been explained by Ding Tiping et al. (1988). ³⁹Ar-⁴⁰Ar analyses were performed in the
Institute of Geology, Chinese Academy of Geological Sciences. The analyzed process and standard errors have been reported by Fu Yunlian et al. (1987).

**40Ar-39Ar dates**

One sample of muscovite (GF-36) collected from the No. 12 ore vein was used to determine the 40Ar-39Ar age. The ore consists of muscovite, tetradymite, dolomite, and calcite, and shows a mosaic structure under the microscope. The spectrum of dates calculated from 40Ar-39Ar ratios of gas fractions released by incremental heating of neutron-irradiated muscovite are shown in Figure 14. The plateau of the mineral dates is well established, which suggests that the argon system has not been disturbed. The average plateau age of the muscovite is 92.10 ± 1.06 Ma calculated from the gas fractions released between 400° and 1400°. The temperature of 720° to 1170° C gas fractions of the muscovite indicate a date of 94.1 ± 1.0 Ma.

The measured 40Ar-39Ar and 39Ar-36Ar ratios of incremental gas fractions from the muscovite under 720° to 1170° C fit a straight line (Fig. 15), and an isochron age of 93.70 ± 3.44 Ma is obtained. The intercept (40Ar-36Ar) of the isochron (399.02) suggests that there is a small amount of excess radiogenic 40Ar in the muscovite lattice. Because the excess 40Ar is not enough to affect the calculation for date, an age of 92 to 93 Ma represents the time of mineralization.

**Sulfur isotopes**

Sulfur isotope analyses were performed on 22 samples from Stage I and on 10 samples from Stage II. The δ34S values in Stage I range from -0.6 to +1.7 per mil for pyrite and from -2.2 to +2.2 per mil for pyrrhotite. The δ34S values for tetradymite range from -0.5 to +2.1 per mil. All δ34S values occur in a narrow range (−2.2 to +2.8 per mil), corresponding to a normal distribution with a peak of +0.5 per mil (Fig. 16).

**Carbon and oxygen isotopes of carbonates**

Carbon- and oxygen-isotope analyses were performed on 13 samples of dolomite and calcite from ore veins and 4 samples from Triassic marble. The δ13C and δ18O values (Fig. 17) for ore veins range from -5.3 to -7.4 per mil and from +10.9 to +13.1 per mil (SMOW), respectively. Using the carbonate-water fractionation curve of O’Neil et al. (1969), the δ18O values of fluid in equilibrium with calcite at 280° to 210° C (trapping temperature of Stage I and II) were calculated at between +2.1 and +7.1 per mil (SMOW). The δ13C and δ18O values for the Triassic marble range from +1.0 to 2.8 per mil and from 16.8 to +28.5 per mil (SMOW), respectively.

**Hydrogen and oxygen isotopes**

Hydrogen- and oxygen-isotope analyses were carried out on three samples of muscovite and one quartz sample from Stage II. The δD values range from +9.9 to +13.0 per mil, respectively. Using the muscovite-water fractionation curve of O’Neil et al. (1969) and the quartz-water fractionation curve of Clayton et al. (1972), the δ18O values of fluid in equilibrium with muscovite and quartz (at fluid inclusion trapping temperatures of Stage II) were estimated to be between +3.9 and +7.0 per mil (SMOW).
Fig. 14. Spectrum of dates calculated from $^{40}\text{Ar}^{39}\text{Ar}$ ratios of gas fractions released by incremental heating of neutron-irradiated muscovite.

**Discussion and Conclusions**

*A new type of ore deposit*

Tellurium, being a dispersed element, tends to be disseminated via geological and metallogenic processes. It frequently occurs as a byproduct in ore deposits—for instance, in gold-tellurium deposits, such as at Cripple Creek, Colorado (Thompson et al., 1985), Emperor, Fiji (Ahmad et al., 1987), and Dongping, China (Song Guanxiang, 1991); in hydrothermal copper-bearing sulfide deposits, such
as Qibaoshan, China (He Siwei and Sun Minyun, 1986) and Dabaoshan, China (Li Yuwei, 1994); and in copper-nickel sulfide deposits, such as Jinchuan, China (Li Yuwei, 1994). Tellurium in these deposits commonly occurs as calaverite, copper-bearing telluride assemblages, and nickel-bearing telluride assemblages. The tellurium grade in most ore deposits is not higher than 100 ppm. However, tellurium-bearing minerals occur mostly in tellurium-bismuth mineral assemblages, and the tellurium grade attains 0.5 to 25 wt% in the Dashuigou tellurium deposit. Hence Dashuigou must be considered a tellurium-dominated deposit, and it is at present a unique world example (Chen Yuchuan et al., 1993).

Although Dashuigou is a tellurium-dominated deposit, it also is enriched in bismuth, gold, silver, and selenium, which can be recovered as byproducts. Thus its mineralization characteristics can be compared with some tellurium-bearing gold-silver deposits—such as Qibaoshan, China (He Siwei and Sun Minyun, 1986) and Dabaoshan, China (Li Yuwei, 1994); and in copper-nickel sulfide deposits, such as Jinchuan, China (Li Yuwei, 1994). Tellurium in these deposits commonly occurs as calaverite, copper-bearing telluride assemblages, and nickel-bearing telluride assemblages. The tellurium grade in most ore deposits is not higher than 100 ppm. However, tellurium-bearing minerals occur mostly in tellurium-bismuth mineral assemblages, and the tellurium grade attains 0.5 to 25 wt% in the Dashuigou tellurium deposit. Hence Dashuigou must be considered a tellurium-dominated deposit, and it is at present a unique world example (Chen Yuchuan et al., 1993).

Our heating and freezing data for fluid inclusions show that hydrothermal mineralization in the Dashuigou tellurium deposit occurred in the temperature range of 170° to 360° C with changeable salinities (Fig. 18). Within Stage-I mineralization, the temperature ranged from 360° to 260° C, with low salinities of 1.5 to 5.8 wt% NaCl equiv. Stage-II mineralization is characterized by middle-level temperatures, ranging from 295° to 198° C, and high salinities of 9 to 15.2 wt% NaCl equiv. Stage-III mineralization was a low-temperature and low-salinity event (Fig. 18). The data indicate that the fluid temperatures decrease from Cu-S mineralization, through Te-Bi-Se-Au-Ag mineralization, to Au (Cu) mineralization and that Te-Bi-Se-Au-Ag mineralization occurred as a result of high-salinity hydrothermal solutions.

Utilizing CO$_2$ density geobarometry, the confining pressure for dolomite and quartz from the ore veins was estimated to be $756 \times 10^5$ Pa (Luo Yaonan et al., 1994). Taking the geopressure gradient to be $263 \times 10^5$ Pa/km, the indicated crystallization depth of the minerals is 2.70 to 3.05 km.

Sulfur and tellurium fugacities of the main mineralization stages of the Dashuigou tellurium deposit can be measured approximately on the $f_S$ vs $f_T$ diagram (Fig. 19) from Afifi et al. (1988). An equilibrium diagram at 200° C (Fig. 19) is adopted here for the sake of discussion, considering that the Dashuigou deposit is an epithermal ore deposit. As the most important coexisting mineral pair of Stage I, pyrrhotite and pyrite were deposited mainly depending on the sulfur fugacity, and their equilibrium $f_S$ is read to be $10^{-16.7}$ (Fig. 19). Because there are no tellurides or native mercury in this stage, their $f_T$ of formation should be below the equilibrium line for the reaction pair of altaite and galena, approaching $10^{-14}$ to $10^{-15}$. Hematite, hessite, and tellurbismuth, as well as magnetite, stuetzite, and tetradymite, are present in Stage II. Therefore, the $f_S$ and $f_T$ are confined to a relatively small trapezoid (Fig. 19), and the Prasolovskoye Au-Ag-Te-Se deposit in Russia (So et al., 1995)—all of which are considered to be mesothermal or epithermal ore deposits associated with alkaline complexes.
Fig. 17. The $\delta^{13}$C vs $\delta^{18}$O diagram of carbonates. Legend: 1 = calcites and dolomites from ore veins; 2 = calcites from Triassic marble.

Fig. 18. Homogenization temperature (Th) vs salinity diagram for primary fluid inclusions in the main mineralization stages. Note that the darkened triangles represent Stage-I mineralization, open triangles Stage-II, and open circles Stage-III.
Sources of ore-forming materials

Although the Triassic metabasalts are the host rocks for mineralization in the Dashuigou tellurium deposit, the mineralization is characterized by an enrichment in silica, alkalis, and carbonates. Gangue minerals in the ore veins are dominated by carbonates (including dolomite, calcite, siderite, and magnesite), with minor biotite, muscovite, albite, oligoclase, quartz, and tourmaline. Alteration zoning of biotite-quartz-oligoclase-chlorite-epidote-actinolite and muscovite-quartz-albite-calcite-actinolite assemblages are developed around pyrrhotite-pyrite veins and tetradymite ore veins, respectively. K/Na ratios vary from 4.74 to 3, 12, 0.16, and 0.06 from the ore veins through the alteration zoning to the original host rock; Mg/Fe ratios vary from 0.94 to 0.74, 0.65, and 0.48 from the ore veins outward. The features above reflect an infiltration metasomatism of alkaline-rich mineralizing hydrothermal fluids outward. A hydrothermal fluid enriched in CO₂ and alkali-silicic components suggests that it was related genetically to alkaline or alkali-granitic magmatism.

The sulfur content in pyrite from the Dashuigou tellurium deposit appears to be lower than normal. This sulfur-poor characteristic suggests that the mineralization fluids are related to magmatism. Cui Yanhe (1993) generalized that pyrite from syngenetic deposits has a higher sulfur content than the standard composition, but that from hydrothermal deposits associated with magmatism contains lower amounts. Co/Ni ratios of pyrite are used frequently to recognize metallogenic environments (for example, Davidson, 1962; Dike and Hutchison, 1979). Song Xuexin and Zhang Jingkai (1986) demonstrated that, in China, a Co/Ni ratio for pyrite of less than 1 indicates a genetic environment of syngenetic deposits, a ratio of 1.1 to 23.5 indicates skarn and porphyry deposits, and of 1.2 to 32, hydrothermal deposits associated with magmatism. For the Dashuigou tellurium deposit, the Co/Ni ratios of pyrite range from 56 to 652, which suggests a deep source of mineralizing fluids.

The δ¹⁸O values of fluids, ranging from +2.1 to +7.1 per mil (SMOW), are lighter than expected for the isotopic composition of magmatic fluids (+5.5 to +9.5 per mil) (Ohmoto,
Unlike the $\delta^{18}O$ values, the $\delta D$ values of ore-forming fluids range from -61 to -54 per mil and overlap a field of the typical composition of magmatic ore-forming fluids (-80 to -40 per mil). It is possible that the ore-forming fluids were derived mainly from a magmatic source and were mixed with minor meteoric water.

The $\delta^{34}S$ values of sulfides in the Dashuigou tellurium deposit range from -2.2 to +2.8 per mil, with a mean value of 0.5 percent. This almost overlaps the 0 to +2 per mil range assigned to magmatic sulfur (Ohmoto, 1986; Taylor, 1986).

The $\delta^{13}C-\delta^{16}O$ diagram of carbonates (Fig. 17) shows that the $\delta^{13}C$ values overlap the range of -6 to -9 per mil (Faure, 1986) known to be typical of magmatic fluids. The $\delta^{18}O$ values are slightly heavier than those of magma. The $\delta^{34}C$ and $\delta^{18}O$ values of the Triassic marbles in the Dashuigou tellurium deposits are quite different from those of the ores.

**Genetic model for Dashuigou tellurium mineralization**

Because gold, silver, bismuth, and cerium can be recovered as byproducts from the Dashuigou tellurium ores, the deposit may be classed among the gold-tellurium (silver) mineralizations enriched in tellurium. In this case, it can be compared with gold-tellurium or polymetallic gold-tellurium deposits, such as Emperor, Fiji (Ahmad et al., 1987), and Dongping, China (Song Guanxiang, 1991). Most gold-tellurium deposits throughout the world are associated genetically with alkaline magmatic rocks (Zhang Zhaochong and Li Zhaonai, 1994). The following model for the genesis of the Dashuigou tellurium deposit is compatible with all available geological and geochemical data.

The west margin of the Yangtze platform experienced rifting during Permian to Triassic times. Subsequently, the rift was closed and the Songfan-Ganzi foldbelt formed, since the Jingshajiang plate was subducted beneath the Yangtze plate during Middle and Late Mesozoic time (Luo Yaonan et al., 1982). During this period (140 to 80 Ma), alkaline granite intrusions and syenite-leucite intrusions were emplaced. The nearest syenite stocks are known to be 7 to 8 km apart from the Dashuigou tellurium deposit. A recent geophysical study (Panxi Geological Team, 1993) has revealed that there is a concealed granite and syenite stock beneath the Wanbahe dome. The tellurium mineralization in the Dashuigou deposit is dated at 93 Ma by the $^{39}Ar-^{40}Ar$ method. Furthermore, more and more REE deposits genetically associated with syenite stocks have been found in the past 10 years along the western margin of the Yangtze platform.

The western margin of the Yangtze platform is a special belt for enrichment in rare and dispersed metallic elements. Not only the Dashuigou tellurium-dominated deposit, but also the Lanmunchang thallium-dominated deposit occurs, and several cerium and germanium-dominated mineralizations have been discovered in the belt. Moreover, tellurium has been known to exist as an accompanying element in many deposits, such as the Liwu VMS copper-zinc deposit (Mao Jingwen et al., 1995c), the Bajintazi gold deposit (a ductile shear-type gold deposit), the Yanyuan-Muli porphyry copper deposits, and others. We can imagine that the upper mantle and/or the lower crust in the belt are enriched in tellurium-, thallium-, cerium-, and germanium-dispersed elements and that some favorable environments exist for enrichment in this group of elements.

The ductile shear zones acted as channels for ascending hydrothermal fluids connected with alkaline magmatic activity. Triassic basic metavolcanic rocks are favorable to telluride mineralization. An alteration halo developed as a result of strongly contrasting chemical compositions between fluids and the host rocks.

Although transported for long distances from their source, the C, S, O, and H isotopes of hydrothermal fluids did not change substantially. Mineralization originated in three stages, the first two being the most important. The temperature and $f^s$ gradually decreased, and the $f^s$ and $f^{T}$ increased from Stage I to Stage II. Hydrothermal fluids of Stage I were enriched in S, Cu, and Fe; of Stage II in Te, Bi, Se, Ag, and Au; and of Stage III in gold.

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