NOTE

Sulfur isotopic ratios of ore deposits associated with Mesozoic felsic magmatism in South Korea, with special reference to gold-silver deposits

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Isotopic composition is determined for ore sulfur from seventeen Au-Ag, six W-Mo and one fluorite deposits in the southern Korean Peninsula. The age of ore formation ranges from pre-Cambrian to Cretaceous. Together with the data available in the literature, the following characteristics are recognized: 1) most $\delta^{34}\text{S}$ values fall in the narrow range of +2 to +7‰, 2) no systematic variations are observed among the deposits of different geologic environments and with different workable metals, and 3) exceptional negative $\delta^{34}\text{S}$ values are observed in some deposits located in and near the Taebaegsan area. Pre-dominance of ore sulfur with positive $\delta^{34}\text{S}$ values suggests the biogenic sulfur-poor nature of constituent sedimentary rocks in the Korean continental crust.

INTRODUCTION

The regional variation of isotopic compositions of ore sulfur is of great interest from the viewpoint of material source and formation mechanism of hydrothermal mineral deposits. Moreover, the recent discovery of parallelism between sulfur isotopic compositions of granitoid and genetically related ores, established in the Japanese Island Arc by Sasaki and Ishihara (1979, 1980), stimulates the study on the regional variation of isotope ratios of ore sulfur in other granitic terrains than the Japanese Islands.

In the southern Korean Peninsula, Jurassic and Cretaceous granitic rocks, called Daebo and Bulgugsa series, respectively, are widespread besides pre-Cambrian granitic gneisses (Reedman and Um, 1975). According to Ishihara *et al.* (1981), the former in general belongs to ilmenite series defined by Ishihara (1977), while the latter to magnetite series, although the Daebo granitic rocks tend to change gradually into magnetite series toward the north (Shimazaki

et al., 1981). There are many hydrothermal mineral deposits in the southern Korean Peninsula associated with those granitic activities. Recent age dating data revealed that some productive W-Mo and base metal deposits are formed in Cretaceous time (Kim, 1971a; Fletcher and Rundle, 1977; Farrar *et al.*, 1978; Yun and Silberman, 1979; Sato *et al.*, 1981a; Kaneoka *et al.*, 1983; Shibata *et al.*, 1983; So *et al.*, 1983a). The formation age, however, of Au-Ag and some W-Mo deposits is still controversial. Based on similar distribution patterns and general trends between Au-Ag veins and the Daebo granitic rocks, many Au-Ag deposits, especially those known as the Korean type Au deposits, are considered to have been formed in Jurassic time genetically related to the Daebo activity (e.g. Kim, 1971b; Lee, 1981). Some Au-Ag and W-Mo deposits are even believed to have been formed in pre-Cambrian (see the compilation by Lee, 1981).

Several papers reported the isotopic composition of ore sulfur in base metal and W-Mo deposits (Kim and Nakai, 1980, 1982; Sato *et*

are given in the $\delta^{34}\text{S}$ value as defined by:

$$\delta^{34}\text{S}(\text{‰}) = \left[\frac{(^{34}\text{S}/^{32}\text{S})_{\text{sample}}}{(^{34}\text{S}/^{32}\text{S})_{\text{standard}}} - 1 \right] \times 1000$$

The standard is troilite sulfur from the Canyon Diablo meteorite. The uncertainty in $\delta^{34}\text{S}$ values is less than $\pm 0.2\text{‰}$ in most cases.

RESULTS AND DISCUSSION

Sulfur isotope data obtained are summarized in Table 1, and plotted in Fig. 1. The $\delta^{34}\text{S}$ values show rather wide variation from -0.5 to $+15.4\text{‰}$, but about 80% of the values fall in a narrow range of $+2$ to $+7\text{‰}$. As clearly shown in Fig. 1, the isotopic ratios of ore sulfur from the deposits of the same type which are located close to each other, are nearly identical. For example, the value $+9.6\text{‰}$ for the Geunwang deposit (A), a kind of satellite one around the famous, large Mugug deposit (B), is close to the value $+8.5\text{‰}$ for the latter. The ore sulfur from the Cheonbo (C), Seogyo (D) and Namchang (E) deposits reveals values around $+6$ to $+7\text{‰}$, similar to each other. These three deposits are closely associated with Jurassic pegmatite dikes.

In the Gyeolseong mining area (H), two adits, namely the Main and Geodo adits, were once operated. The appearance of the ores from the Main adit is quartz-rich and poor in other minerals, whereas those from the Geodo adit are abundant in sulfide and carbonate minerals. Under the microscope, however, the mineral assemblage in the ores from both adits is essentially the same. Sulfur isotopic compositions were measured separately on the composites of the ores from these adits, and were confirmed to be identical with each other. The values for the Geumjeong (P) and Dadeuk (Q) deposits are also very close to each other. In this case, however, the type of the deposits is quite different, that is, the gold mineralization of the former occurs in a pre-Cambrian alaskite (quartz - K-feldspar) dike and that of the latter in usual quartz veins. The Ssangjeon (V) and Ogbang (W) W-Mo deposits are situated closely, and have relatively light ore sulfur. These fea-

tures on the isotopic compositions of ore sulfur, are recognized also by Sato *et al.* (1981b), who applied almost the same procedure as the present study to the samples from 22 hydrothermal Cu-Zn-Pb and W-Mo deposits in South Korea.

The opaque minerals observed in the composite samples are also listed in Table 1. As in the case of $\delta^{34}\text{S}$ values, mineral assemblages are almost identical among the Au-Ag deposits situated closely to each other. For example, the assemblage pyrite-arsenopyrite predominates in the deposits located in the northern parts (mines A to H and P-Q), while pyrite only or pyrite with sporadic pyrrhotite or arsenopyrite predominates in the south (mines I to O). This mineral assemblage change may be related to the general trend of $\delta^{34}\text{S}$ values of the Au-Ag deposits from the north to the south, that is, heavier in the north as $+9.6\text{‰}$ and lighter in the south as $+2.3\text{‰}$. Pyrrhotite is observed in some Au-Ag deposits. The FeS contents of sphalerites from these deposits, however, are less than twenty mole per cent, demonstrating that pyrrhotite occurs sporadically in the deposits, not being equilibrated with sphalerite (Mizuta *et al.*, 1984). The presence of pyrrhotite could not be taken as the evidence of relatively reducing environments achieved at the time of mineral precipitation in these deposits. Thus it is quite difficult to estimate the redox environments, and also to estimate ionic species of sulfur, in the hydrothermal solutions responsible for these Au-Ag deposits.

A heavy isotopic composition of sulfur, $+15.4\text{‰}$, from the Jinrag fluorite deposit (X) is worthy of note. The deposit is of replacement type in limestone and granite gneiss. The occurrence of chalcedonic quartz in the deposit suggests shallow formation at lower temperatures, just like many other fluorite deposits in South Korea (Shimazaki *et al.*, 1981). In Japan, this type of deposits is known as the Hiraiwa type, and their distribution is restricted to the regions where ilmenite series granitoids prevail (Sato, 1980). Unfortunately no sulfur isotope data are available on the fluorite deposits in

Table 1. Sulfur isotope composition of composite samples from South Korean Au-Ag, W-Mo and F deposits

Name of mine	No. of specimens	$\delta^{34}\text{S}$ (‰)	Ore minerals observed	Ore formation age
<i>Au-Ag</i>				
A Geumwang	9	+9.6	py, aspy, sp, cp, acth, moly	
B Mugug	6	8.5	py, cp, aspy, sp	Cretaceous*
C Cheonbo	4	6.2	py, aspy, cp, gn, moly	Jurassic*
D Seogyo	9	5.8	py, aspy, cp, gn, elec	Jurassic*
E Namchang	12	7.0	aspy, py, gn	Jurassic*
F Samgwang	13	3.6	aspy, sp, gn, cp, py	
G Gubong	14	5.9	po, gn, sp, py, aspy, elec	
H Gyeolseong	7, 6	5.7, 5.2	py, gn, cp, sp, po, aspy	
I Imcheon	11	4.4	py, sp, cp, gn, acth	Cretaceous*
J Jeonjuil	10	4.9	py, acth	
K Deogon	13	5.4	py, gn, sp, cp, elec, aspy	Cretaceous**
L Yanghang	3	3.1	py, sp, cp, gn, po, elec	Cretaceous*
M Baekjin	7	5.3	py, sp, gn, cp, aspy	
N Gwangyang	6	2.3	cp, py, sp, po, gn	Cretaceous**
O Sanggeum	6	3.7	py, sp, cp, moly	Cretaceous**
P Geumjeong	26	4.8	py, cp, aspy, po	pre-Cambrian*
Q Dadeuk	6	4.6	sp, gn, py, cp, aspy	
<i>W-Mo</i>				
R Garisan	8	2.1	py, cp, sp, gn, po, wolf, nabi	
S Daehwa	13	4.2	cp, py, po, sp, moly, wolf	Cretaceous***
T Cheongyang	15	4.7	cp, py, po, sp, moly, wolf, nabi	
U Jangsu	7	4.3	moly, cp, sp, nabi	
V Ssangjeon	9	1.0	py, aspy	
W Ogbang	4	-0.5	po, py, cp	
<i>F</i>				
X Jinrag	3	15.4	py, cp, po, sp	

Abbreviations acth: acanthite, aspy: arsenopyrite, cp: chalcopyrite, elec: electrum, gn: galena, moly: molybdenite, nabi: native bismuth, po: pyrrhotite, py: pyrite, sp: sphalerite, wolf: wolframite

* Shimazaki *et al.* (unpublished data).

** Estimated from geological evidences.

*** Kaneoka *et al.* (1983), Shibata *et al.* (1983) and So *et al.* (1983c).

Japan and Korea for comparison. The large positive $\delta^{34}\text{S}$ value for the Jinrag deposit, could be explained only assuming the participation of sulfate sulfur in the extraction and/or transportation process of sulfur by the hydrothermal solution.

All the data obtained by the present study and by Sato *et al.* (1981b), are plotted together in Fig. 2 and histograms of $\delta^{34}\text{S}$ values are given in Fig. 3. These figures demonstrate the following characteristics of ore sulfur in the southern Korean Peninsula: 1) although some exceptions are present, most $\delta^{34}\text{S}$ values fall in the narrow range of +2 to +7‰, and 2) no systematic variations are observed among the deposits of different geologic environments, and with dif-

ferent workable metals.

As shown in Fig. 1, the Bulgugsa granitic rocks are distributed mainly in and around the Gyeongsang Basin. No isotopic variations, however, are recognized among ore sulfur from the deposits in and out of the Basin (Fig. 3). In addition, the present data confirm that some deposits associated with the Jurassic ilmenite series granitic rocks have ore sulfur with positive isotopic values. The sulfur isotope systematics established in Japan by Sasaki and Ishihara (1979, 1980) might not be applicable to the southern Korean Peninsula. A more acceptable explanation, however, is to assume rock sulfur with positive isotopic values for the Jurassic ilmenite series granitic rocks in South Korea.

Fig. 2. $\delta^{34}\text{S}$ values in per mil for ore sulfur from the representative deposits in South Korea. Data are taken from this study (24 deposits) and Sato *et al.* (1981b) (22 deposits).

As has been mentioned by Sasaki and Ishihara (1979), the crustal sulfur may have remarkably heavy isotopic values in continental regions. The ilmenite series granitic rocks in such regions do not necessarily have negative $\delta^{34}\text{S}$ values. Further works on whole rock sulfur of the Korean granitic rocks are indispensable to discuss the genetical relation between the ore and rock sulfur.

The sulfur isotope data on individual sulfide minerals from some base metal and W-Mo deposits are given in several previous works (Kim and Nakai, 1980, 1982; So and Shelton, 1983; So *et al.*, 1983a,b,c, 1984). Throughout all data available to date, including those on composite samples and individual minerals, it is remarkable that only a few deposits in South Korea have ore sulfur with negative $\delta^{34}\text{S}$ values. They include the Ogbang W-Mo (W: -0.5‰), Shinyemi Zn-Pb-Mo (-1.4‰ ; Sato *et al.*, 1981b), Geodo Cu-Fe (-0.3‰ ; Sato *et al.*, 1981b) and Youngduck Zn-Pb (-2.0 to -2.5‰ ; Kim and Nakai,

Fig. 3. Histograms of isotopic compositions of ore sulfur from 46 representative deposits in South Korea, compiled from Fig. 2. Dotted boxes show the deposits present in the Cretaceous Gyeongsang Basin.

1980). It is noteworthy that these deposits locate near the northeastern end of the southern Korean Peninsula, known as the Taebaegsan area. In the Sambo Zn-Pb deposit, significantly light sulfide sulfur, -4.0 to -12.1‰ of $\delta^{34}\text{S}$ values, is reported by Kim and Nakai (1980) and So *et al.* (1984). According to them, however, associated barite has heavy sulfur, $+14.7$ to $+19.5\text{‰}$, and the average isotopic composition of sulfur precipitated in the deposit is estimated to be about $+5\text{‰}$ (Kim and Nakai, 1980).

As has already been noted by Sasaki and Ishihara (1979, 1980), the isotopic trend of ore and rock sulfur for ilmenite series granitic rocks in Japan, could be explained by the incorporation of crustal sulfur enriched in ^{32}S . Predominance of ore sulfur with positive $\delta^{34}\text{S}$ values in South Korea, suggests a scarcity of clastic sediments with biogenic sulfur in the Korean con-

tinental crust. Limited distribution of deposits with isotopically light ore sulfur just mentioned, may indicate the variation of constituent sedimentary rocks in the basement.

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