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Oxygen Isotope Study on the Wolf River Batholith, Wisconsin in U.S.A.

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ABSTRACT : Oxygen isotope compositions have been determined for the granitic and the related rocks from the Wolf River Batholith, Wisconsin in U.S.A. Plutons which belong to the differentiation trend are almost identical in oxygen isotope fractionation, and plutons of undifferential sequences also show oxygen isotope compositions similar to each other, which show little isotope fractionations at high temperature range. In oxygen isotope composition, the country rocks (the Penokean plutonic rocks), which is higher by 1~2 permil than the batholith are improbable source of the batholith. However, the assimilation of parent magma of lower $\delta^{18}O$ values than the batholith with the Penokean plutonic rocks might have produced the batholith.

Key words : oxygen isotope, granitic rocks.

INTRODUCTION

The oxygen isotope compositions in igneous and metamorphic rocks are important geochemical parameters which may indicate their genesis. The oxygen isotope composition of whole rock samples has been used to identify the source material of rocks such as S-type granite vs. I-type granite (O'Neil and Chappell, 1977) and orthogneiss vs. paragneiss (Shieh *et al.*, 1976).

In this research oxygen isotope study was carried out on the Wolf River Batholith in Wisconsin, U.S.A., which is one of the main exposed Precambrian anorogenic granitic bodies. Since the petrochemistry of The Wolf River batholith was studied by Anderson (1975, 1980) and Anderson and Cullers (1978), in this work special emphasis was placed on the characterization of oxygen isotope composition of the batholith and the elucidation of the genetic relationships between the batholith and older surrounding country rocks based on oxygen isotope composition.

GEOLOGICAL BACKGROUND

Rock types intruded by the Wolf River Batholith are various and most are not older than 1.85 Ga (Fig. 1; Van Schmus, 1973; Van Schmus *et al.*, 1975b; Anderson, 1980). Many of western and northern parts of the batholith consist of synorogenic, calc-alkaline suite of metavolcanic and plutonic and associated metasedimentary rocks representing Penokean Orogeny (1.80~1.90 Ga). Along the southern margin, an Archean migmatite-gneiss terrain is intruded by the batholith in restricted areas (Van Schmus and Anderson, 1977). Eastern and southern parts are composed of Paleozoic rocks-mainly Cambrian sandstones and Ordovician limestones, dolomite, sandstone and shale (Dutton and Bradly, 1970). During the close of the Ordovician Period, and in the succeeding Silurian and Devonian Periods, Wisconsin is believed to have remained sub-

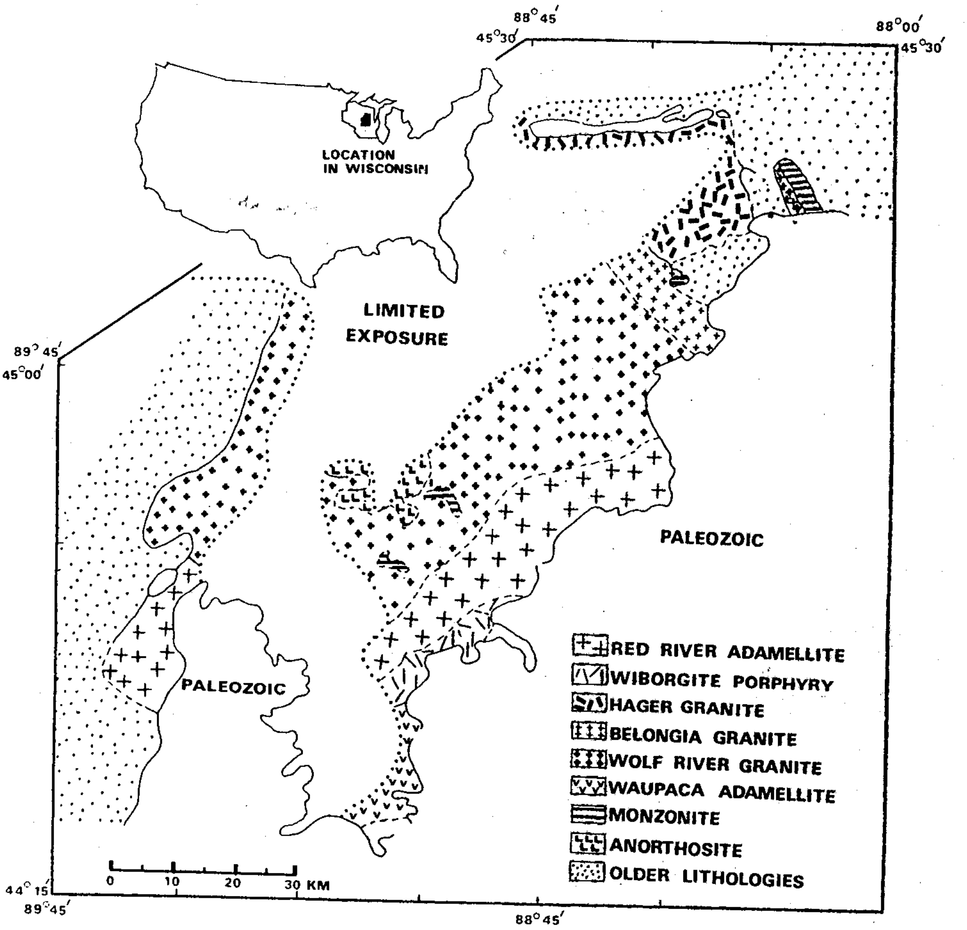

Fig. 1. Geological map of the Wolf River Batholith.

merged beneath the sea (LaBerge, 1986). Following geological informations are mostly from Anderson (1975, 1980) and Anderson and Cullers (1978).

The massive, unmetamorphosed anorogenic nature of the batholith contrasts strongly with the synorogenic metamorphosed character of the older surrounding rocks. At the margin of the batholith (especially along the western and northeastern borders), the regional structure becomes concordant with steepening of dip, attesting to the forceful nature of the intrusion. However, the intrusion has had no interaction with the surrounding rocks in the form of migmatization or hydrothermal activity, and the thermal effects on the pre-existing lower amphibolite grade (Penokean) are minimal.

The Wolf River Batholith consists of eleven plutons which are largely composed of biotite-granite and biotite-hornblende adamellite with minor occurrences of quartz syenite, older anorthosite and iron-rich pyroxene-olivine monzonite. Granitic plutons are the Waupaca Adamellite, the Wolf River Granite, the Wiborgite Porphyry, the Red River Adamellite, the Belongia Granite, the Hager Granites, the Hager Feldspar Porphyry, and the Hager Syenite.

Wolf River granite

This granite is red in color and is coarse-grained. Large (1~3 cm), ovoid and subhedral alkali feldspar is sporadically mantled with plagioclase (only 3~10% of the large alkali feldspar are mantled). Other minerals include quartz, interstitial plagioclase ($An_{15\sim20}$), biotite, hornblende, and accessory apatite, zircon, allanite, ilmenite, magnetite, sphene, and fluorite. Locally within the pluton, modal quartz content drops from a range of 25 to 35% to a low of 8% with a higher portion of feldspars, total mafic content, and an increase of hornblende over biotite. It is only these low-quartz portions of the Wolf River Granite (the Wolf River Granite cumulate) that have coarse grunerite as a subsolidus retrograde mineral, replacing hornblende.

Belongia Granites

These granites occur on the northeast margin of the Wolf River Granite and have a broad gradational contact (2~3 km) with the Wolf River Granite. The gradation consists of a northward modal decrease in hornblende relative to biotite, a decrease in total mafic-mineral content, and an increase in quartz. Accessary minerals are zircon, apatite, allanite and Fe-Ti oxides.

Wiborgite Porphyry

With the Waupaca Adamellite, this unit exhibits typical rapakivi texture. In phenocrysts, alkali feldspar cores are mantled with plagioclase. Other minerals occurring as phenocrysts are plagioclase ($An_{17\text{-}24}$), quartz, biotite, and hornblende. The matrix includes the above minerals plus sphene, allanite, zircon and apatite.

Red River Adamellite

The unit contains 1 to 20% phenocryst, generally unaltered perthitic alkali feldspar with subordinate amount of plagioclase, and quartz. The medium-grained matrix is composed of these minerals plus biotite±hornblende, ilmenite±magnetite, sphene, allanite, apatite, zircon, and fluorite.

Waupaca Adamellite

This pluton is the classical rapakivi granite. Approximately 70 to 80% of the coarse, ovoid alkali feldspar is heavily mantled with plagioclase ($An_{15\sim24}$). Alkali feldspars are perthite and string lamellae of albite (An_{04}) and patches of oligoclase ($An_{15\sim18}$). Accessory minerals include apatite, zircon, ilmenite, allanite, sphene, and fluorite.

Hager granite, Feldspar Porphyry and Syenite

This complex occurs in the northern portion of the batholith and has not been investigated thoroughly in this study, because its exposure is very poor and preliminary oxygen isotope analyses on three whole rock samples showed compositions similar to other plutons.

Monzonite

Four monzonite bodies occur, two as large blocks near the anorthosite and surrounded by the batholith (the Belongia Granites) and the Penokean plutonic rocks. The monzonites from the four isolated occurrences are indistinguishable in mineralogy. The monzonites are coarse-grained (0.3~1.5 cm) equigranular assemblage of subhedral plagioclase ($An_{20\sim37}$), alkali feldspar, mafic silicates (fayalite, ferroaugite-hedenbergite, hornblende and biotite), interstitial fluorite with apatite, zircon, ilmenite, and magnetite.

Anorthosite

This is located in the central part of the batholith. Plagioclase ($An_{45\sim55}$) is very coarse-grained (1~20 cm). Interstitial to the plagioclase are orthopyroxene, clinopyroxene, Fe-Ti oxide and apatite. The anorthosite is compositionally similar to that reported in other labradorite-type massif anorthosite (Green *et al.*, 1974; Emslie, 1978), except in its K/Rb ratio.

The sequence of emplacement as inferred by contact relationships, from the oldest to the youngest, is the Wolf River Granite, the Wiborgite Porphyry and the Red River Adamellite. The relation of the Waupaca Adamellite to the others is unknown. Since major and trace element trends overlap in many cases, these plutons were categorized as undifferentiated intrusive sequences and were proposed to be products of successive partial fusion of tonalitic to granodioritic material.

The low silica portions of the Wolf River Granite are considered to be cumulates of a fractional crystallization process, which produced high-SiO_2 content granite units, the Belongia Granites, from the undifferentiated Wolf River Granite. The Belongia Fine Granite is considered to be the extreme end of differentiation.

Anorthosite are commonly associated with pyroxene-olivine bearing monzonite or other members of the charnockite suite, and several of these complexes contain younger rapakivi granite and adamellite prompting discussion on cogenesis (Green *et al.*, 1974; Simmons and Hanson, 1974; Emslie, 1978). The common spatial association between anorthosite, monzonite and rapakivi granite may suggest that all three rock types may be comagmatic, as well as cogenetic, and related by a single process such as differentiation or fusion. Anderson (1980) and Anderson and Cullers (1978) examined the detailed mineralogical and geochemical characteristics of these units in the Wolf River Batholith. They concluded that even though there are some basic similarities, because of significant differences among them, they could not relate all three by a single, simple fusion or fractional crystallization process. All have the same fractionated REE pattern showing a moderate depletion in heavy REE. The monzonite overlaps compositionally with low-silica portion of the Wolf River Granite. However, unlike the monzonite and the anorthosite, the granites have hydrous mafic mineral assemblages. And the monzonite, the intermediate member of this suite, is uniquely high in Ba and REE, and is exceptionally iron rich, and has the highest Fe, Fe/Mn, Mn, total alkali, Ba, Eu, and Ba/Sr. However, they suggested that the anorthosite may be related to the monzonite alone by fractional crystallization with the monzonite representing more fractionated melt; 75~85% fractionation from anorthosite having typical mineralogy could generate the observed trace element abundance of the monzonite by fractional crystallization.

A large portion of the batholith is an intrusive sequence from the older rapakivi granite (the Wolf River Granite) to the younger adamellite (the Red River Adamellite), which implies progressive fusion or increasing degrees of crustal contamination. But in the evaluation of possible sources of these granitic rocks, crustal contamination has been rejected as a main mechanism, because of the rarity of foreign inclusions in the batholith. Using the compositions of the undifferentiated intrusives to model the gross compositional and mineralogical character of source which could have equilibrated with these melts, the predicted source is intermediate in composition probably similar to such rocks as tonalite, granodiorite and andesite. Excluded as potential sources are mantle rocks, metabasalts, amphibolites and felsic crustal rocks (Anderson, 1980; Anderson and Cullers, 1978).

A model for the evolutionary history of the batholith has been constructed as follows by Anderson (1980). The batholith has a partial fusion origin from tonalitic and granodioritic source material at a depth of 27~35 km. These granitic plutons intruded into the upper crust at depths less than 3.8 km, and crystallized at temperatures between 640~790℃ and under internally buffered oxygen fugacities subparallel to, and slightly below, the QFM buffer curve. The monzonite body last equilibrated at pressures ranging from 5.6~8.7 kb (21~32 km), and at the temperature and oxygen fugacity of approximately 900℃ and 10~13.4 bars respectively, implying that anorthosite-monzonite suite may have been the heat source necessary for melting.

Interestingly the terrain of Penokean age which surrounds the batholith is characterized by tonalite and granodiorite. Also, Sr data of Penokean plutonic rocks (Initial $^{87}Sr/^{86}Sr=0.7021$, $^{87}Rb/^{86}Sr<0.8$; Van Schmus *et al.*, 1975a) can yield initial ratio observed in the Wolf River Batholith (0.7048±0017; Van Schmus *et al.*, 1975a).

ANALYTICAL METHODS

Thirty-two whole rock samples were prepared by grinding in the agate mortar, and quartz from seventy-two samples were separated by hand-picking under the binocular. Cold hydrofluoric acid was used to dissolve away feldspars for fine-grained quartz.

The sample preparation and the isotope analysis were carried out in the stable isotope laboratory in the Purdue University. The extraction of oxygen from silicate was performed by reacting with BrF_5 at 650~670℃ in nickel reaction vessels (Clayton and Mayeda, 1963). CO_2 gas was obtained from oxygen by combustion with a resistance-heated graphite rod (Taylor and Epstein, 1962). The mass spectrometer used was a 60°, single-focusing, double collecting Nuclide 3-60 RMS.

The data are presented in terms of the δ-notation and values are reported in permil (parts per thousand).

$$\delta=(R_{sample}/R_{standard}-1)\times10^3\ \text{permil}$$

In this expression R is the ratio of $^{18}O/^{16}O$. The standard used for reporting isotope compositions is SMOW (Standard Mean Ocean Water) and the analytical error in this research is 0.3 permil.

ANALYTICAL RESULTS OF OXYGEN ISOTOPE

$\delta^{18}O_{Q(quartz)}$ and $\delta^{18}O_{WR(whole\ rock)}$ values throughout the entire batholith are fairly uniform and vary within 3 permil (Table 1 and Fig. 2, 3). $\delta^{18}O_Q$ ranges from 6.4 to 8.9 permil with the average being 7.9 for 74 samples. the $\delta^{18}O_{WR}$ ranges from 5.7 to 8.0 permil with average being 7.0 for 32 samples. All the granitic rocks, except the Waupaca Adamellite and the monzonite, show an even narrower range of about two permil (6.6~8.9 for quartz and 6.4~8.0 for whole rock). Excepting these plutons, other plutons are similar in isotope composition and the largest difference is only 0.5 permil for quartz (between the Wolf River Granite and the Belongia coarse Granite). The Waupaca Adamellite is lower than others by about one permil (6.4~7.9 for quartz and 5.7~7.4 for whole rock).

No differences were observed in isotope composition between samples collected from the contact zone adjacent to country rocks and samples collected far inside the batholith. The Wolf River Batholith belongs to the low end of so-called normal granite (Taylor, 1978).

$\delta^{18}O_Q$ values of the Penokean plutonic rocks range from 8.5 to 10.1 permil with the average of 9.3 permil, and $\delta^{18}O_{WR}$ values range from 7.9 to 9.2 with the average of 8.6, which are higher by 1~2 permil than those of the granitic rocks of the batholith.

RELATIONSHIP BETWEEN PLUTON UNITS

Units of Differentiation Trend

Even though the fractionations between melt and minerals are still not well known from experiment, it has been shown by studies of natural systems that fractional or equilibrium crystallization of primary magma cannot of itself produce any major changes in the oxygen isotope compositions resulting from the later fractionations between silicate melts and minerals (e.g. Taylor, 1978; Taylor and Sheppard, 1986).

Plutons which fit the fractional crystallization trend described above are well presented in the Wolf River Batholith. The Wolf River Granite, the cumulate portion of the Wolf River Granite,

Table 1. Oxygen isotope composition of the Wolf River Batholith

Pluton	Sample	WR	Q	Sample	WR	Q	Sample	WR	Q
Wolf River Granite	CL3A		7.3	1315		8.1	DR8	6.8	7.4
	1215	7.6	7.8	1311		8.2	1510		8.8
	1211		8.2	1306		8.1	1511		7.7
	1214		7.3	1516		8.5	1504		8.3
	W27		7.4	1517		8.0	1015		8.0
	1204		8.3	VSGR6	6.9		1016		7.6
	1203		8.5	8L	6.9		1017		7.9
	1242		7.8	GR36A	7.1		1018		7.6
	1403		8.3	W23-1		8.2	1112		8.1
	1406		7.9						
Wolf River Granite cumulate	GR6	7.2	8.1	GR4A		7.2	TG11A		7.5
	GR34	7.0	7.2	DR15	7.2		HT30	7.0	7.5
	GR24A	7.2	8.0						
Wiborgite Porphyry	1210		8.2	CL30		8.0	XS1		7.1
	TG17B		8.6	GR36B	7.0	7.6			
	1202		7.3	1239		7.7			
Red River Adamellite	TG11B	6.6	7.2	1213		8.5	1320		8.3
	CL16		8.0	1224		8.3	1321		7.4
	GR3	7.8	8.8	1228		8.3	1322		7.9
	SP24	7.6		1230		7.5	1509		8.7
	XW1	6.8	8.2	1232		8.4	1001		7.2
	1114		8.5	1301		8.1	1002		8.0
	1115			1319		7.5	1004		8.4
Waupaca Adamellite	TG38	7.0	6.7	1105		7.0	1108	5.7	7.4
	WP5A	5.7	6.4	1106		6.6	11M	6.4	
	XW4B	6.4	7.0	1107	7.4	7.9			
Belongia (Fine)	12ATC	6.5	7.9	1632		7.5	1709-2		8.4
Granites	73M	7.8		1633	6.4	7.5	1710		7.3
	58M	8.0	8.9	1520		7.9	1709-1		8.3
(Coarse)	83AT	7.1	7.4	1631		8.6			
Hager Granite	50M	7.7		72M	6.9				
Monzonite	92ATC	6.8		GR26A	6.3				
	GR17B	5.8		TM3	7.5				
Anorthosite	XS2	7.0		W22	7.5				
	W2	6.5		W5	6.9				
Penokean (SW)	1005	9.2	9.0	1009	8.8	8.5	1013		9.5
plutonic	1007		9.2	1012	7.9	9.0			
rocks (NE)	1533	8.4	9.4	1534		9.3	1537		10.1

WR : whole rock, Q : quartz.

and the Belongia Granites have been suggested as units belonging to the differentiation trend. Obviously as shown in Fig. 2, these units demonstrate very limited oxygen isotope fractionations, by only 0.5 permil (average) for quartz between the cumulate (7.5 on average) and the differentiated units, the Belongia coarse and fine Graites(8.0 on average). $\delta^{18}O_Q$ of the Belongia fine Granites, the most highly differentiated unit, is even lower than the Belongia coarse Granite by 0.4 permil on average and almost identical to that of the cumulate portions of the Wolf River Granite. The average $\delta^{18}O$ of quartz and whole rock of the Belongia Granites (coarse and fine) are 8.0 and 7.0 permil respectively, almost identical to the averages for the Wolf River Granite and the Wolf River Granite cumulate (7.9 for $\delta^{18}O_Q$ and 7.0 for $\delta^{18}O_{WR}$).

Undifferentiated Units

As shown in Fig. 2, $\delta^{18}O$ values of quartz as well as whole rock show almost identical values in three plutons, the Wolf River Granite, the Wiborgite Porphyry and the Red River Adamellite. The Waupaca Adamellite is slightly lower than the others by about 1 permil. The almost identical isotope compositions for these three plutons suggests their derivation from a homogeneous source material. The successive partial fusion of some common source material, as suggested by petrochemical studies (Anderson and Cullers, 1978; Anderson, 1980), agrees well with oxygen isotope data.

The temperature of fusion of source material is not known, but it must be higher than the 640~750℃ crystallization temperature range (Anderson, 1980) of the batholith. Following the same reasoning for the isotopic differentiation of silicate melt and minerals at even higher temperatures, partial fusion cannot itself produce any appreciable differences in isotope compositions, regardless of the order of fusion at such high temperatures. The Waupaca Adamellite is somewhat unique in that $\delta^{18}O$ of quartz and whole rock, and the SiO_2 content, are lower than other undifferentiated sequences. The Waupaca Adamellite might thus represent a slightly heterogeneous source material.

Monzonite and Anorthosite

The monzonite (5.8~7.5 permil, whole rock) and the anorthosite (6.5~7.5, whole rock) are very similar to the granitic rocks in oxygen isotope composition, especially to the Waupaca Adamellite (Fig. 2 and 3), which implies a possible comagmatic relation between them.

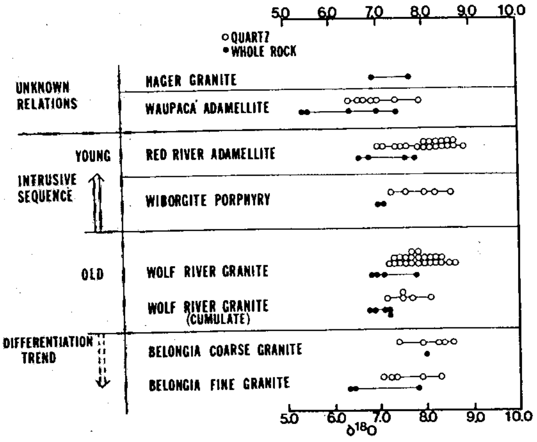

Fig. 2. Oxygen isotope composition of the Wolf River Batholith.

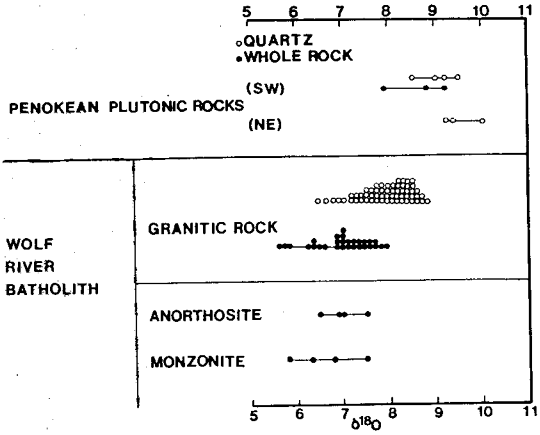

Fig. 3. Oxygen isotope composition of the Wolf River Batholith and the Penokean plutonic rocks.

However, a comagmatic relationship between the granitic rocks, monzonite and anorthosite is not supported by major and trace elements modeling (Anderson, 1980; Anderson and Cullers, 1978).

PETROGENESIS

For the discussion of petrogenesis, knowledge of pristine oxygen isotope composition is most important. Since Garlick and Epstein (1967) had pointed out the resistance of quartz to alteration, it has been confirmed and quartz has been used as an indicator mineral of original isotope composition especially under the condition of low temperature alteration (Shieh, 1983; Weis *et al.*, 1987). Since the hydrothermal alteration, reflected in high oxygen isotope composition in feldspar, is ubiquitous throughout the batholith (Kim, 1993), the isotope composition of quartz has been used to discuss the petrogenesis in this paper with that of the whole rock.

Petrogenesis of the Wolf River Batholith with regard to the Penokean plutonic rocks is discussed here based on the oxygen isotope composition, since the Penokean plutonic rocks have been suggested to be a possible source material of the batholith because: 1) the Penokean plutonic rocks are characterized by tonalitic and granodioritic composition, which has been suggested as a possible source material for the Wolf River Batholith by petrochemical modeling (Anderson, 1980; Anderson and Cullers, 1978), 2) Sr data of the Penokean plutonic rocks (initial $^{87}Sr/^{86}Sr=0.7021$, $^{87}Rb/^{86}Sr<0.8$) can yield the initial Sr ratio (0.7048) observed in the Wolf River Batholith (Van Schmus, 1975b), and 3) Nd isotope composition for the Penokean plutonic rock and the Wolf River Batholith show similar model TDM age of 2.3 Ga (Nelson and Depaolo, 1985) which represents the same mantle dissociation age.

The samples of the Penokean plutonic rocks were collected from two areas separated from each other by about 160 km. Three samples were from the northeastern margin, and four samples were from the southwestern margin of the batholith. $\delta^{18}O_Q$ values of the Penokean plutonic rocks range from 8.5 to 10.1 permil with the average of 9.3 permil, and $\delta^{18}O_{WR}$ values range from 7.9 to 9.2 with the average of 8.6. These ranges are generally higher than those of the Wolf River Batholith ($\delta^{18}O_Q$: 6.4~9.0, average 7.9, and $\delta^{18}O_{WR}$: 5.7~8.0, average 7.0), even though there is some overlap. Therefore it is not likely that the Penokean plutonic rocks produced granitic rocks of the Wolf River Batholith, because the oxygen isotope compositions of the former are higher by 1~2 permil both in $\delta^{18}O_Q$ and $\delta^{18}O_{WR}$.

Since direct genetic relationship between the Penokean plutonic rocks and the Wolf River batholith are not likely, the other explanation for the possible genetic relationship between the Penokean plutonic rocks and the Wolf River Batholith, based on the oxygen isotope composition data, is that the Penokean plutonic rocks were assimilated by the parent magma.

If parent magma of the Wolf River Batholith, of which the isotope composition were similar to or lower than the present values of the granitic rocks, and this parent magma assimilated the Penokean Plutonic rocks, then $\delta^{18}O$ values of the batholith which is intermediate between the parent magma and the Penokean plutonic rocks could be produced. In the case of the assimilation of country rocks, however, the original composition of the parent magma is not known. $\delta^{18}O_{WR}$ values of mantle rocks have been considered to be 5~6 permil (e.g. Taylor and Sheppard, 1986). These values are quite close to the lower end of the isotope composition range observed in granitic rock of the Wolf River Batholith. Also, $\delta^{18}O$ values of the northeastern part of the Penokean plutonic rocks are higher than the values of the batholith, suggesting the assimilation of the Penokean plutonic rocks by the mantle or lower crust source magma. Since $\delta^{18}O$ values of the primitive lower crust are not well known, if the primary magma originated from the lower crust having slightly higher $\delta^{18}O$ values than those postulated for the mantle, the assimilation seems more plausible. This model contradicts to the petrochemical model suggested by Anderson and Cullers (1978) and Anderson (1980), which denied the important role of assimilation in the production of the Wolf River Batholith.

CONCLUSIONS

1. Plutons which belong to the differentiation trend are almost identical in oxygen isotope compositions (the Wolf River Granite cumulate, $\delta^{18}O_Q$=7.5 on average; the Wolf River Granite, 8.0; the Belongia Granite, 8.0) because of the very small oxygen isotope fractionations between minerals and melts during crystallization at high temperature.

2. Plutons of undifferentiated sequences also show oxygen isotope compositions similar to each other (the Wolf River Granite (including the cumulate portion) $\delta^{18}O_Q$=7.8 permil on average; the Wiborgite Porphyry, 7.9; the Red River Adamellite, 8.1) due to very small isotopic fractionations during successive partial meltings.

3. Since the $\delta^{18}O_Q$ values of the Penokean plutonic rocks are higher by 1~2 permil than those of the Wolf River Batholith, their role as a source material of the batholith is improbable.

4. The assimilation of parent magma of lower $\delta^{18}O$ values than the batholith with country rocks could have produced the $\delta^{18}O$ values of the batholith, which, however, was denied by previous petrochemical modeling.

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미국 위스컨신주의 울프리버 저반에 대한 산소동위원소 연구

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요 약 : 미국 위스콘신주의 울프리버 저반의 산소동위원소의 조성을 분석한 결과, 분화계열에 속하는 심성암들 간의 산소동위원소 조성은 거의 유사한 경향을 보였으며, 미분화계열에 속하는 심성암체 간의 조성도 거의 유사한 경향을 보였다. 이는 고온에서의 극히 미약한 동위원소 분별작용을 보여주는 것이다. 주변 모암인 피노키안 심성암체의 산소동위원소 조성이 울프리버 저반보다 약 1-2 퍼밀이 높기 때문에 울프리버 저반의 근원 암으로 볼 수는 없으나, 울프리버 저반보다 약간 낮은 산소동위원소 조성을 갖는 근원 마그마가 존재하였다면, 이 마그마에 의한 주변 모암의 동화작용에 의해서 울프리버 저반의 산소동위원소조성의 생성이 가능한 것으로 판단된다.

핵심어 : 산소동위원소, 화강암.