Effects of experimental aqueous alteration on the abundances of argon-rich noble gases in the Ningqiang carbonaceous chondrite

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Abstract–Ar-rich noble gases, the so-called “subsolar” noble gases, are a major component of heavy primordial noble gases in unequilibrated ordinary chondrites and some classes of anhydrous carbonaceous chondrites, whereas they are almost absent in hydrous carbonaceous chondrites that suffered extensive aqueous alteration. To understand the effects of aqueous alteration on the abundance of Ar-rich noble gases, we performed an aqueous alteration experiments on the Ningqiang type 3 carbonaceous chondrite that consists entirely of anhydrous minerals and contains Ar-rich noble gases. Powdered samples and deionized neutral water were kept at 200 °C for 10 and 20 days, respectively. Mineralogical analyses show that, during the 10-day alteration, serpentine and hematite formed at the expense of olivine, low-Ca pyroxene, and sulfide. Noble gas analyses show that the 10-day alteration of natural Ningqiang removed 79% of the primordial 36Ar, 68% of the 84Kr, and 60% of the 132Xe, but only 45% of the 4He and 53% of the primordial 20Ne. Calculated elemental ratios of the noble gases removed during the 10-day alteration are in the range of those of Ar-rich noble gases. These results indicate that Ar-rich noble gases are located in materials that are very susceptible to aqueous alteration. In contrast, heavy primordial noble gases remaining in the altered samples are close to Q gas in elemental and isotope compositions. This indicates that phase Q is much more resistant to aqueous alteration than the host phases of Ar-rich noble gases. In the 20-day sample, the mineralogical and noble gas signatures are basically similar to those of the 10-day sample, indicating that the loss of Ar-rich noble gases was completed within the 10-day alteration. Our results suggest that almost all of the Ar-rich noble gases were lost from primitive asteroids during early, low-temperature aqueous alteration.

INTRODUCTION

Primordial noble gases, which were incorporated into meteorites during their formation, include three components: exotic, Q, and Ar-rich noble gases. Exotic noble gases reside in presolar carriers. Light primordial noble gases are dominated by the exotic gases (e.g., HL gases in presolar diamonds) (Lewis et al. 1987). Heavy noble gases are composed mainly of Q and Ar-rich noble gases, and exotic gases are minor (HL+P3 gases are only 5.3% of all 132Xe in Orgueil CI chondrite; Ott 2002). Q gas is located in phase Q (Lewis et al. 1975) that is still unidentified but probably represents absorption sites (Wacker 1986) on carbonaceous materials (Ott et al. 1981) mainly represented in the fine-grained matrix and rims around chondrules of unequilibrated meteorites (Nakamura et al. 1999; Vogel et al. 2003). The elemental composition of Q gas shows a relatively small range: 40 to 120 for 36Ar/132Xe and 0.5 to 1.3 for 84Kr/132Xe (Busemann et al. 2000).

Ar-rich noble gases are characterized by the high 36Ar/132Xe and 84Kr/132Xe ratios relative to Q gas (Wacker and Marti 1983); up to 2660 for 36Ar/132Xe and up to 10 for 84Kr/132Xe (Crabb and Anders 1981). Ar-rich noble gases in enstatite chondrites are especially called “subsolar” noble gases (Crabb and Anders 1981). Ar-rich noble gases are found in meteorites that consist predominantly of anhydrous minerals: some classes of anhydrous carbonaceous chondrites (Miura et al. 2001), unequilibrated ordinary chondrites...
Ar-rich noble gases in carbonaceous and unequilibrated ordinary chondrites are located in materials that are dissolved by HF/HCl acid treatment. Schelhaas et al. (1990) found that Ar-rich noble gases are lost from some unequilibrated ordinary chondrites during deep etching, since they could not detect the gases that have high $^{36}\text{Ar}/^{132}\text{Xe}$ and $^{84}\text{Kr}/^{132}\text{Xe}$ ratios in the HF/HCl-resistant residues. It was reported that Ar-rich noble gases in a dark inclusion and its host of the carbonaceous chondrite Ningqiang were removed by light HF/HCl etching that corresponds to the removal of approximately 1 $\mu$m of mineral surface (Nakamura et al. 2003b). The loss of Ar-rich noble gases was accompanied by loss of amorphous rim coatings around fine-grained olivines and pyroxenes, suggesting that Ar-rich gases are located in the amorphous rims. In contrast to Ar-rich noble gases in carbonaceous and unequilibrated ordinary chondrites, those in enstatite chondrites are located in enstatite (e.g., Okazaki 1999) and those in ureilites are located in diamonds (Göbel et al. 1978). Therefore, it is unclear whether Ar-rich noble gases in carbonaceous and ordinary chondrites and those in enstatite chondrites and ureilites have the same origin.

Ningqiang is a type 3 carbonaceous chondrite that consists entirely of anhydrous minerals. It contains chondrules up to 3 mm in size embedded in a fine-grained olivine-rich matrix. Chemically, Ningqiang is an ungrouped carbonaceous chondrite because of low abundances of refractory lithophile elements (Rubin et al. 1988), but it has some similarities to oxidized CV3 chondrites in respect to petrologic, oxygen isotopic, and thermoluminescence characteristics (Rubin et al. 1988; Kallemeyn 1996; Mayeda et al. 1988; Guimon et al. 1995; Weisberg et al. 1996). This chondrite contains Ar-rich noble gases as well as Q and HL gases (Eugster et al. 1993; Scherer and Schultz 2000; Nakamura et al. 2003b).

The absence of Ar-rich noble gases in hydrated chondrites and their presence in anhydrous chondrites suggest that the abundance of Ar-rich gases relates to the degree of aqueous alteration. In this study, we have experimentally examined the effects of aqueous alteration on the abundances of Ar-rich noble gases in Ningqiang and found that the alteration drastically changes the noble gas abundances.

**EXPERIMENTAL METHOD AND ANALYTICAL PROCEDURES**

A bulk Ningqiang sample weighing 300 mg was crushed into micrometer-size small particles and loaded into a Teflon vessel together with 10 g deionized neutral liquid water. The Teflon vessel was encapsulated into the stainless steel pressurized vessel. The sample and the water were kept at 200 °C. The internal water vapor pressure is estimated to be about 15 atms. After 10 days, the vessel was opened to recover half of the sample (150 mg); the remaining part of the sample (150 mg) was soaked for another 10 days.

A natural (untreated) Ningqiang sample and the two altered ones soaked for 10 and 20 days were analyzed for mineralogy and noble gases. The bulk mineral compositions before and after the experimental alteration were determined by the powder X-ray diffraction (powder XRD) method with the Rigaku RAD-II A at Kyushu University. Each sample (approximately 130 mg) was mounted on a glass plate and exposed to CuK$\alpha$ ($\lambda = 1.542 \text{Å}$). In order to obtain X-ray diffraction patterns with sufficiently high resolution to distinguish the changes in mineral composition during experimental aqueous alteration, the powder XRD analyses were obtained at diffraction angle intervals of $0.01^\circ$. These analyses took about 15 hours. The samples used in these analyses were recovered for the noble gases measurements. In addition, altered samples were further analyzed by synchrotron radiation X-ray diffraction (SR-XRD) method to confirm the presence of phyllosilicate. A small aggregate (~100 $\mu$m in size) of the altered sample was mounted on a thin glass fiber, 5 $\mu$m in diameter, set in a Gandolfi camera, and then exposed to synchrotron radiation X-rays ($\lambda = 2.161 \pm 0.001 \text{Å}$) at the Photon Factory Institute of Material Structure Science, High Energy Accelerator Research Organization, Tsukuba, Japan (Nakamura et al. 2003a).

The concentrations and isotopic ratios of noble gases in the natural and altered samples were determined with a mass spectrometer (modified MM5400) at Kyushu University. The detailed experimental configurations of the mass spectrometer were described in Nakamura et al. (2003b). Noble gases in natural and altered samples were extracted by stepwise heating in a Mo crucible at temperature steps of 300, 700, 1000, 1300, and 1850 °C for 20 min each. The heating step at 300 °C was performed to remove adsorbed atmospheric noble gases. In fact, Ar and Xe, released at 300 °C from natural and experimentally altered samples, have isotopic ratios close to air (300 °C fractions in Tables A1 to A8; all appendix tables are available online at http://meteoritics.org/Online%20Supplements.htm) and thus Ar, Kr, and Xe released at 300 °C are not considered in the following discussion. All of the samples, except for the 10-day sample #2, He and Ne extracted at 300 °C consist largely of non-atmospheric components on the basis of their isotopic compositions. All parts of the concentrations of He and Ne of noble gases released at 300 °C are added to the 700 °C fractions.

The stepped pyrolysis was performed on three aliquots (each one weighing about 10 mg) prepared from the 10-day and 20-day samples, respectively (three aliquots from each
sample) in order to confirm the homogeneity of noble gas elemental and isotopic compositions in the powdered samples. For the natural Ningqiang sample, a two-step extraction first at 300 °C followed by a melting step at 1850 °C was carried out on five aliquots (about 2 mg each) and the stepped pyrolysis analysis was performed on a 23.2 mg aliquot. The concentrations of 4He, 20Ne, 84Kr, and 132Xe, in each aliquot prepared from the natural, 10-day, and 20-day altered samples, deviate much less from each other than the differences between the different sample types. However, in the 10-day sample #1, there is a larger amount of Ar than in other 10-day samples #2 and #3 (Table A5). This could not be explained by inhomogeneity between aliquots because this excess was much larger than the variation of Ar concentrations detected in both natural and 20-day samples. This can only be accounted for if, in the sample #1, there are particular phases that absorb or incorporate atmospheric noble gases. Therefore, the concentrations and isotopic ratios of Ar in 10-day sample #1 are not taken into consideration below.

The concentrations of noble gases in 10-day and 20-day samples are expressed per gram of natural sample because the changes of sample mass were below 1% of sample mass through the 20-day aqueous alteration experiment. To calculate the proportions of primordial (subscript “pri”) and cosmogenic components of neon and argon, the following 21Ne/22Ne and 38Ar/36Ar ratios were used. The ratios of the primordial component were assumed to be 0.024 (Ne-A) (Alaerts et al. 1980) and 0.188 (Ar-Q) (Busemann et al. 2000) and those of the cosmogenic component were 0.94 (maximum 21Ne/22Ne value in natural and experimental altered sample) and 1.5 for 21Ne/22Ne and 38Ar/36Ar, respectively. In calculations of Ar-rich and Q abundances, the 36Ar/132Xe ratios of Ar-rich and Q gases were assumed to be 382 (calculated ratio of noble gases lost during 10-day alteration which would otherwise have been released at 1000 °C in stepped pyrolysis) and 74 (ratio of gases remaining in the 10-day sample and gases released at 1850 °C during stepped pyrolysis of the 10-day sample), respectively. The concentrations of Ar-rich noble gases decrease by 4%, and those of Q gas increase by 16% if assumed 36Ar/132Xe ratios of Ar-rich noble gases increase by 20%. The measured 84Kr/132Xe ratios of noble gases in Ningqiang have higher uncertainties than those of 36Ar/132Xe ratios, thus not 84Kr/132Xe ratios but 36Ar/132Xe ratios are used for calculation of abundances of Ar-rich and Q gases.

RESULTS AND DISCUSSION

Changes of Mineral Composition During Experimental Aqueous Alteration

The results of the powder XRD analyses of natural, 10-day, and 20-day altered samples are shown in Fig. 1. The result of natural Ningqiang sample shows that the natural sample consists mainly of olivine, low-Ca pyroxene, magnetite, pyrrhotite, and troilite, among which olivine is the most dominant phase (Fig. 1a). This result is consistent with the mineralogical composition of Ningqiang obtained by modal analyses by Wang (1988).

The 10-day sample consists mainly of a phyllosilicate, probably serpentine, with a basal spacing of 7.28 Å, olivine, low-Ca pyroxene, and magnetite (Fig. 1b). The presence of the 001 basal reflection at 7.28 Å and the 021 prism reflection around 4.6 Å both in the 10-day and 20-day samples confirms that the phyllosilicate is serpentine (Figs. 2a and 2b). In Fig. 1b, diffraction intensities from olivine and low-Ca pyroxene are lower than those in the natural sample. No reflections from pyrrhotite and troilite were detected. These results indicate that olivine, low-Ca pyroxene, pyrrhotite, and troilite were decomposed during 10-day alteration. No intensity change is observed for the diffraction at 1.48 Å, which is assigned only to magnetite, indicating that magnetite content does not change during 10-day alteration (Fig. 1b). The presence of reflections at 7.28 Å and 2.70 Å in the 10-day sample indicates that serpentine and hematite, respectively, were formed during alteration (Fig 1b), because these reflections are not detected in the natural sample.

The 20-day sample has a mineralogical composition basically similar to that of the 10-day sample, but shows some changes in the relative mineral abundances (Fig. 1c). The relative abundances of olivine decrease from 0.6 (10-day sample) to 0.3 (20-day sample) compared to that in the natural sample based on the integrated intensity of the diffraction 2.80 Å. Similarly, the relative abundances of low-Ca pyroxene decrease from 0.7 (10-day sample) to 0.6 (20-day sample) based on the integrated intensity of the 3.17 Å reflection. The decreases indicate that the decomposition of olivine and low-Ca pyroxene proceeds with time. On the other hand, the diffraction intensity of hematite at 2.70 Å is higher in the 20-day sample than in the 10-day sample. This indicates that the hematite content increases with time. The diffraction intensity of magnetite at 1.48 Å is equivalent between 10-day and 20-day samples, indicating that the magnetite content is constant during alteration. The diffraction at 3.50 Å is observed in the 20-day sample, but not seen in the 10-day sample. This indicates that anhydrite formed during the second half of the 20-day alteration. The formation of calcium sulfate by experimental aqueous alteration was also reported in previous work done for Allende (Brearley and Duke 1998), but in this case it was gypsum. Calcium sulfates such as anhydrite and gypsum are common in CI chondrites (Fredriksson and Kerridge 1988).

Effects of Aqueous Alteration on the Abundances of Noble Gases

The results of the noble gas analyses of natural, 10-day, and 20-day sample are shown in Tables A1 to A8. The concentrations and isotopic ratios of noble gases in the natural
Ningqiang sample are comparable to published data (Eugster et al. 1993; Scherer and Schultz 2000; Nakamura et al. 2003b). The (36Ar)_{pri}/^{132}Xe, 84Kr/^{132}Xe, and (20Ne)_{pri}/^{132}Xe ratios in the natural Ningqiang sample are 208, 1.7 and 2.7, respectively (Fig. 3 for (36Ar)_{pri}/^{132}Xe and 84Kr/^{132}Xe). The result of stepped pyrolysis reveals that the noble gases released at around 1000 °C have higher (36Ar)_{pri}/^{132}Xe ratios (257) than those released at other temperatures and total noble gases in Ningqiang. The elemental ratio is in the range of Ar-rich noble gases contained in enstatite chondrites (Crabb and Anders 1981; Patzer and Schultz 2002) and ureilites (Göbel et al. 1978; Wacker 1986; Goodrich et al. 1987) and indicates that heavy noble gases of the 1000 °C fraction are dominated by Ar-rich noble gases. On the other hand, the noble gases released at 1300 °C and 1850 °C have lower (36Ar)_{pri}/^{132}Xe ratios than those released at 1000 °C. These elemental ratios are in the range of Q gas (Wieler et al. 1991; Busemann et al. 2000), indicating that Q gas is a major component in heavy noble gases released at 1300 °C and 1850 °C.

Experimental aqueous alteration using neutral water has markedly reduced the noble gas concentration in Ningqiang. Relative abundances of the primordial noble gases remaining in and lost from the sample during the 10-day alteration are shown in Fig. 4. It is noteworthy that the 10-day alteration at 200 °C with neutral water removed 79%, 68%, and 60% of (36Ar)_{pri}, 84Kr, and 132Xe, respectively, compared to the natural Ningqiang sample. This indicates that the decomposed minerals had contained larger part of Ar, Kr, and Xe than those remaining in the 10-day sample. The noble gas

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Fig. 1. The powder XRD patterns in a range of diffraction angles (2θ) from 5 to 80° that show changes of bulk mineralogical compositions during aqueous alteration of Ningqiang. a) Natural sample. b) Sample altered for 10 days. c) Sample altered for 20 days.
elemental ratios also changed during the 10-day alteration. The \((^{36}\text{Ar})_{\text{pri}}/^{132}\text{Xe}\) and \((^{84}\text{Kr})/^{132}\text{Xe}\) ratios were reduced to 110 and 1.4, respectively (Fig. 3), whereas \((^{20}\text{Ne})_{\text{pri}}/^{132}\text{Xe}\) increased up to 3.6 in the sample after 10-day alteration. These elemental ratios are almost identical to the typical values of Q gas (Busemann et al. 2000) and thus indicate that the noble gases remaining in the 10-day sample are enriched in Q gas. This is consistent with the previous work done for Allende, in which Q gas is remaining in the experimental altered samples (Nakasyo et al. 2000).

Calculated \((^{36}\text{Ar})_{\text{pri}}/^{132}\text{Xe}\) and \((^{84}\text{Kr})/^{132}\text{Xe}\) ratios of the noble gases removed during the 10-day alteration are 234 and 1.9, respectively (Fig. 3). These values are higher than those of natural Ningqiang and in the range of the Ar-rich noble
gases. The results indicate that the noble gases removed by the 10-day alteration are mostly Ar-rich noble gases. This suggests that the host phases of Ar-rich noble gases in Ningqiang, soluble in light HF/HCl reported by Nakamura et al. (2003b), are altered even by neutral water for 10 days. The results from the 10-day sample lead to the conclusion that the Ar-rich noble gases are located in sites that are susceptible to the weak aqueous alteration by neutral water, even for 10 days, and that phase Q is much more resistant to aqueous alteration than the host phases of Ar-rich noble gases. These conclusions are consistent with the fact that chondrites that have experienced aqueous alteration, such as CI, CM, and Tagish Lake types, do not have Ar-rich noble gases, although they contain large amounts of Q gas (e.g., Nakamura et al. 1999; Nakamura et al. 2003a).

A significant change in the compositions of primordial
Noble gases in the Ningqiang carbonaceous chondrite

A noble gas was not found between 10-day and 20-day alteration. In the 20-day sample, the concentrations of $^{36}\text{Ar}_{\text{pri}}$ and $^{132}\text{Xe}$ reduced by 16% and 39%, respectively, compared to the natural Ningqiang sample. These concentrations are almost identical to those of the 10-day sample. This suggests that Ar-rich and Q gases were lost within first 10 days of experimental aqueous alteration at 200 °C. Figures 5a and 5b show the changes of concentrations of $^{36}\text{Ar}_{\text{pri}}$ and $^{132}\text{Xe}$, respectively, during alteration. These figures indicate that for both Ar and Xe, first 10-day alteration removed the major part of Ar-rich noble gases. The remaining gas is dominated by Q gas.

Krypton and xenon isotopic ratios are essentially identical between natural and altered samples within experimental uncertainties, except for a depletion of $^{129}\text{Xe}$ in the altered samples (Tables A6 and A8). This suggests that the Ar-rich noble gases in Ningqiang have Kr and Xe isotopic compositions similar to the gases trapped in sites resistant to aqueous alteration such as the phase Q. $^{129}\text{Xe}$ is made up of both primordial and radiogenic components, of which radiogenic $^{129}\text{Xe}$ is a decay product of $^{129}\text{I}$ with a half-life of 17 Myr. The $^{129}\text{Xe}/^{132}\text{Xe}$ ratios of noble gases remaining in the 10-day altered samples were close to those of primordial noble gases, which indicates that the major part of radiogenic $^{129}\text{Xe}$ were lost during the 10-day alteration.

The concentration of $^{21}\text{Ne}$, dominated by the cosmogenic component, decreases during aqueous alteration. The abundances of $^{21}\text{Ne}$ of the 10-day and 20-day samples are 80% and 60% of $^{21}\text{Ne}$ in the natural sample, respectively, and correlate with the abundances of olivine and low-Ca pyroxene. The results indicate that cosmogenic $^{21}\text{Ne}$ in olivine and low-Ca pyroxene was removed when olivine and pyroxene, which are distributed uniformly in the Ningqiang meteorite, were transformed to phyllosilicate. Therefore, $^{21}\text{Ne}$ concentrations in the experimentally altered samples could be a measure of the extent of the aqueous alteration reactions. As

Fig. 5. Changes of concentrations of $^{36}\text{Ar}_{\text{pri}}$ (a) and $^{132}\text{Xe}$ (b) remaining in the sample during aqueous alteration. In both $^{36}\text{Ar}_{\text{pri}}$ and Xe, almost all Ar-rich noble gases are removed within first 10 days of alteration, and hardly any changes take place during the second half of the 20-day alteration. The remaining gas is dominated by Q gas.
The alteration proceeds, the concentrations of primordial noble gases such as Ar-rich noble gases and Q gas decrease much more than those of $^{21}$Ne. The proportion of Q gas lost during the experimental aqueous alteration to those in the natural Ningqiang is consistent with that of the result by Nakasyo et al. (2000). These results suggest that even low degrees of aqueous alteration remove great amounts of primordial noble gases, which exist in specific phases that are easily influenced by aqueous alteration. The decrease of $^3$He/$^4$He ratios between the 10-day and 20-day aqueous alteration (Tables A5 and A7) can be ascribed to a loss of the cosmogenic component with high $^3$He/$^4$He ratios and remaining of primordial component with low $^3$He/$^4$He ratios.

Radiogenic $^{40}$Ar and $^{129}$Xe were lost during the 10-day alteration, which removed 97% and 67% of $^{40}$Ar and $^{129}$Xe, respectively, compared to the natural Ningqiang sample (Tables A3 and A5 for $^{40}$Ar). This suggests that the host phases of $^{40}$Ar and $^{129}$Xe are more affected by aqueous alteration than that of Ar-rich noble gases, because the larger part of radiogenic noble gases is lost by early periods of aqueous alteration compared with those of the primordial noble gases. This result leads us to conclude that not only thermal metamorphism but also aqueous alteration effectively resets radiometric ages.

### Atmospheric Noble Gases Incorporated into Secondary-Formed Mineral Phases

The concentration of $^{40}$Ar in the 20-day sample is over four times larger than that in the 10-day sample (Fig. 6). The concentration of $^{40}$Ar released at 700–1000 °C increases by one order magnitude compared with those in the 10-day sample. The $(^{36}$Ar)$_{pri}$/132Xe and $^{84}$Kr/132Xe ratios of noble gases released at 700 °C are shifted toward atmospheric ratios (Fig. 7). In order to remove the effect of the atmospheric noble gases, a correction was made. In the correction, we assumed that excess $^{40}$Ar in the 20-day sample is a contribution from atmospheric noble gases with elemental and isotopic ratios compiled in Ozima and Podosek (2002). The corrected elemental ratios of the 700 °C fraction of the 20-day sample are 139.6 for $^{36}$Ar/132Xe and 3.5 for $^{84}$Kr/132Xe. These ratios are lower than those of non-corrected ratios, but higher than those in the 10-day sample. This indicates that the excess noble gases are fractionated relative to the atmosphere to have low Ar/Xe and Kr/Xe ratios. These results suggested that the enrichment of $^{40}$Ar in the 20-day sample could be accounted for by absorption or incorporation of the heavy gas-enriched fractionated atmosphere into some phases such as anhydrite or hematite that formed during experimental aqueous alteration.

### Possible Host Phases and the Origin of Ar-Rich Noble Gases

The $(^{36}$Ar)$_{pri}$/132Xe ratio of Ar-rich noble gases of Ningqiang is similar to that of enstatite chondrites (Crabb and Anders 1981) and ureilites (e.g. Göbel et al. 1978; Wacker 1986). However, the release temperatures of Ar-rich noble gases in Ningqiang during the stepped pyrolysis are quite different from those in enstatite chondrites and ureilites. The release temperatures of the Ar-rich noble gases are below 1000 °C for Ningqiang and above 1200 °C for enstatite chondrites and ureilites (Göbel et al. 1978; Okazaki 1999). The difference in the release temperatures of Ar-rich noble gases probably reflects difference in their host phases. The host phases of Ar-rich noble gases are most likely enstatites for enstatite chondrites (Crabb and Anders 1981), and diamonds for ureilite (Göbel et al. 1978). Thus, the host phase...
Fig. 7. Noble gas elemental compositions of released gases during the stepped pyrolysis of natural and the 20-day altered sample. The numbers near the data points refer to the release temperature in °C. The elemental ratios of Ar-rich (South Oman), Q gas, and atmosphere are from Crabb and Anders (1982), Busemann et al. (2000), and Ozima and Podosek (2002), respectively.

Fig. 8. Changes of $^{20}\text{Ne}_{\text{pri}}/^{36}\text{Ar}_{\text{pri}}$ and $^{84}\text{Kr}/^{36}\text{Ar}_{\text{pri}}$ ratios during experimental aqueous alteration. Main figure shows a part of bottom right figure. Two lines coming from Q gas in the main figure show mixing lines connecting to solar and the atmospheric noble gas, respectively. The 20-day altered sample has elemental ratios close to the 10-day sample. The $^{20}\text{Ne}_{\text{pri}}/^{36}\text{Ar}_{\text{pri}}$ and $^{84}\text{Kr}/^{36}\text{Ar}_{\text{pri}}$ ratios of bulk Y-790992 (CO3), which contains Ar-rich noble gases, are plotted here. The elemental ratios of Y-790992, Q gas, solar, and the atmosphere are from Nagao and Matsuda (1986), Busemann et al. (2000), Wieler (2002), and Ozima and Podosek (2002), respectively. In this figure, the elemental ratios of noble gases released during experimental aqueous alteration plotted outside of the areas defined by solar, Q, and atmosphere, declaring that the released noble gases from Ningqiang during experimental aqueous alteration are not a mixture of these components.
of Ar-rich noble gases in Ningqiang is possibly different from those in enstatite chondrites and ureilites. Busemann et al. (2003) proposed that subsolar noble gas in the EH5 chondrite St. Mark’s consists of a tiny amount of solar gases plus usual Q and atmospheric noble gases. Figure 8 shows the \((20\text{Ne})_{\text{pri}}/(36\text{Ar})_{\text{pri}}\) and \(84\text{Kr}/(36\text{Ar})_{\text{pri}}\) ratios of noble gases lost from and remaining in the Ningqiang samples during experimental aqueous alteration. The elemental ratio of noble gases lost is plotted outside the field defined by the mixing of solar, Q, and atmospheric noble gases and thus the noble gases are not a mixture of these three components. In addition, the elemental ratios of the noble gas lost are close to those of Ar-rich noble gases found in a dark inclusion of Ningqiang (Nakamura et al. 2003) and Y-790992 (Nagao and Matsuda 1986). The release temperatures of the subsolar noble gas in St. Mark’s are higher than those of Ar-rich gases in Ningqiang: the former is 1000 °C or higher, while the latter is 1000 °C or lower. The differences in the elemental ratios and the release temperatures suggest that Ar-rich noble gases in Ningqiang differ from subsolar noble gas in St. Mark’s in their origin and host phase.

**CONCLUSIONS**

Our results, obtained from analyses of natural, 10-day, and 20-day altered Ningqiang samples suggest that Ar-rich noble gases are lost from their host phases during the 10-day aqueous alteration by neutral water at 200 °C. The Ar-rich noble gases are possible to locate in the amorphous matter coating around in fine-grained olivine and pyroxene in Ningqiang because amorphous matters are very sensitive to aqueous alteration. The Ar-rich noble gases in Ningqiang are different from the subsolar noble gas in an enstatite chondrite St. Mark’s in respect of their host phases and elemental ratios. In contrast to Ar-rich noble gases, Q gas was remaining in the 10-day altered sample. This indicates that phase Q is not affected by aqueous alteration as the host phases of Ar-rich noble gases. Our results suggest that, in the primitive hydrous asteroids, the loss of major portion of heavy primordial noble gases might have taken place during low-temperature aqueous alteration.

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