

Water contrast between Precambrian and Phanerozoic continental lower crust in eastern China

Xiao-Zhi Yang,^{1,2} Etienne Deloule,² Qun-Ke Xia,¹ Qi-Cheng Fan,³ and Min Feng¹

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[1] The presence of water, even in small amounts, in the continental lower crust may play a critical role in its physical and chemical properties and behavior. However, the environment and evolution of water in the deep crust remain poorly constrained. Investigation of water, dissolved as H-related point defects in minerals of lower crustal granulites, may provide clues to clarify this issue. The analyzed and compiled water data of nominally anhydrous clinopyroxene (cpx), orthopyroxene (opx), and plagioclase (plag) in lower crustal granulites from Hannuoba, Nushan, and Daoxian in eastern China reveal significant contrast in water contents (ppm H₂O by weight) between Precambrian and Phanerozoic samples, e.g., 200–2330 versus 275–720 ppm for cpx, 140–1875 versus 60–185 ppm for opx, 145–900 versus 65–345 ppm for plag, and 155–1120 versus 165–360 ppm for the bulk concentrations. Our data show consistently higher water contents in the Precambrian granulites, implying a more hydrous lower crust in the Precambrian than in the Phanerozoic. Such a difference may reflect variable water contents in the original melts, indicating higher water contents in the Precambrian upper mantle or a plume source for that part of the Precambrian lower crust.

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1. Introduction

[2] The continental lower crust, as the interface between the upper and middle continental crusts and upper mantle, is of critical importance in the tectonic evolution of the continents and in geochemical models of the bulk Earth. The lower crust consists predominately of granulites, and granulite xenoliths brought to the surface by basaltic volcanism and granulite terrains exposed to the surface by tectonic displacements provide direct insight into the composition and nature of present and/or ancient deep crust [Rudnick, 1992; Rudnick and Fountain, 1995]. Studies performed on these samples, combined with the constraints from seismic velocity data, suggest that the lower crust is dominated by mafic assemblages [e.g., Rudnick and Fountain, 1995].

[3] Granulites are composed mainly of nominally anhydrous minerals (NAMs): clinopyroxene (cpx), orthopyroxene (opx), and plagioclase (plag), and the lower crust is thus traditionally considered “dry.” Nevertheless, Xia *et al.* [2006] showed that granulite minerals may contain a significant amount of water in the form of structural OH.

Water may fundamentally influence several physical and chemical properties of the lower crust, such as the rheology, electrical conductivity, and melting behavior. Surprisingly, despite significant analytical progress in the determination of water in NAMs [e.g., Keppler and Smyth, 2006], the distribution and especially the evolution of water in the continental lower crust are still poorly known, and only reports of water in upper and middle crusts and in igneous feldspars and very few data on lower crustal minerals have been published [Johnson, 2006, and references therein]. Here, we report water content of the main constitutive phases in mafic lower crustal granulites of different forming ages from eastern China. Combining new data with those of our former study [Xia *et al.*, 2006], we discriminate water concentrations of Precambrian and Phanerozoic continental lower crust in eastern China, with the aim of understanding a possible time-dependent distribution of water in the lower crust.

2. Geological Background and Samples

[4] The North China Craton (NCC) is one of the world’s oldest continental nuclei, with crustal remnants older than 3.8 Ga [Liu *et al.*, 1992]. It is bounded to the north by the late Paleozoic–early Mesozoic Central Asian Orogenic Belt and is separated in the south from the Yangtze Craton by the Qinling-Dabie and Su-Lu high- to ultrahigh-pressure metamorphic belts. The NCC is made up largely of Archean to early Paleoproterozoic basement [Zhao *et al.*, 2001]. On the basis of differences in geology and tectonic and metamorphic pressure-temperature-time history, the craton can be

¹CAS Key Laboratory of Crust-Mantle Materials and Environments, School of Earth and Space Sciences, University of Science and Technology of China, Hefei, China.

²Centre de Recherches Pétrographiques et Géochimiques, Centre National de la Recherches Scientifique, Vandoeuvre-les-Nancy, France.

³Institute of Geology, China Earthquake Administration, Beijing, China.

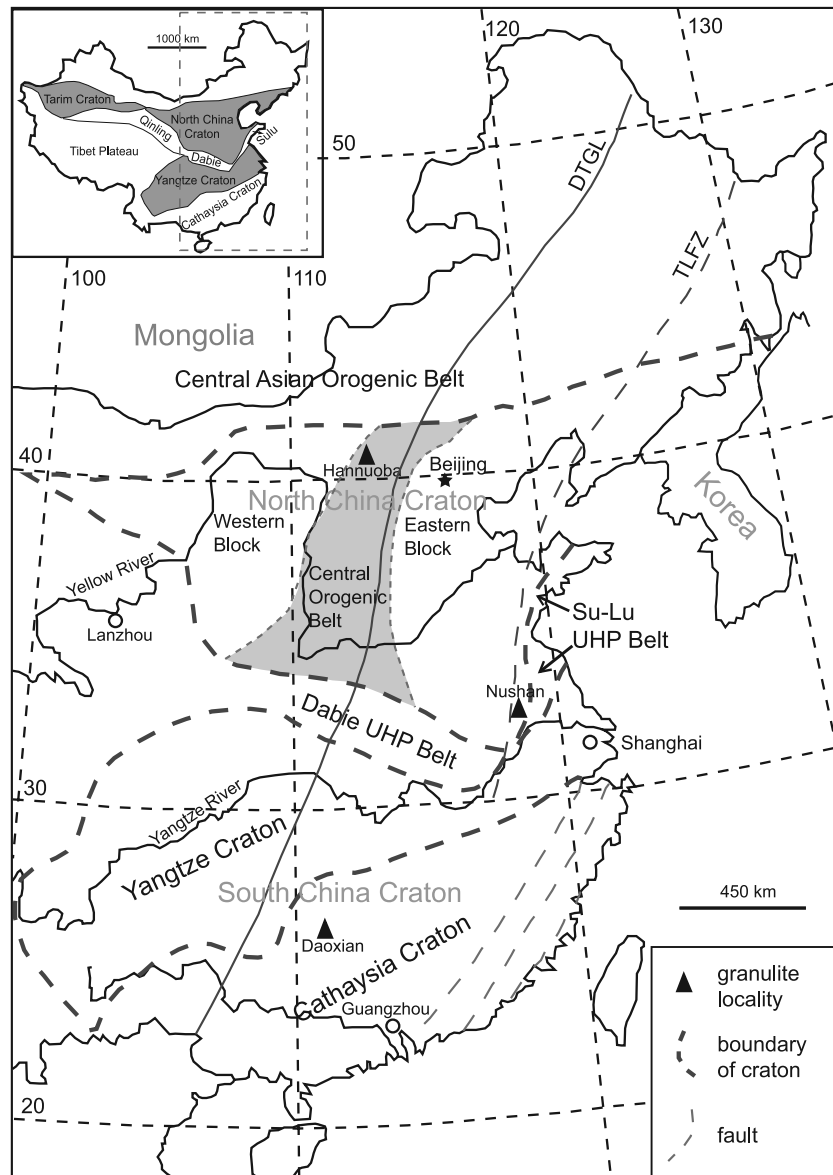


Figure 1. Locations of granulite samples in eastern China. DTGL is Daxing'anling-Taihangshan Gravity Lineament; TLFZ is Tan-Lu Fault Zone. Geological map of the Hannuoba region is given in the auxiliary material.

divided into the Eastern and Western blocks and the Central Orogenic Belt (Figure 1). The base of the Eastern and Western blocks is dominated by late Archean tonalitic, trondhjemitic, and granodioritic gneiss domes surrounded by minor supracrustal rocks, while the Central Orogenic Belt consists of late Archean amphibolites and granulites, together with some granite-greenstone terrains. The collision between the Eastern and Western blocks at ~ 1.8 Ga led to the formation of the Central Orogenic Belt, representing the final amalgamation of the NCC [Zhao *et al.*, 2001]. The NCC experienced widespread tectonothermal reactivation during the late Mesozoic and Cenozoic, and at least 80–140 km of the Archean lithosphere have been removed from the base [Griffin *et al.*, 1998; Menzies *et al.*, 1993].

[5] The South China Craton (SCC) is composed of the Yangtze Craton and the Cathaysia Craton (Figure 1), formed

by a collage amalgamation between these two cratons during the Grenvillian-age orogeny [Chen *et al.*, 1991; Li *et al.*, 2002; Shu and Charvet, 1996]. The Yangtze Craton is another Archean continental nucleus in China with basement ages >3.2 Ga, as indicated by Nd and Hf model ages and sensitive high-resolution ion microprobe (SHRIMP) zircon U-Pb ages [Gao *et al.*, 1999; Qiu *et al.*, 2000; Zhang *et al.*, 2006; Zheng *et al.*, 2006]; by contrast, the Cathaysia Craton is relatively younger compared to the NCC and the Yangtze Craton. The basement of this craton is dominantly Paleoproterozoic to Mesoproterozoic, with some local late Archean component [Chen and Jahn, 1998]. The exposed terrains in this craton are mainly sedimentary rocks, derived from variable time periods, and magmatic rocks dominated by Mesozoic granites. The most noticeable characteristic of

geology in the Cathaysia Craton is intensive and widespread Mesozoic magmatism [Li *et al.*, 2004; Li and Li, 2007].

[6] Hannuoba (Figure 1) is a distinctive locality in the north edge of the NCC where both lower crustal granulite xenoliths and terrains are present. Hannuoba granulite xenoliths were captured by Cenozoic basalts and resulted dominantly from magma underplating and subsequent fractional crystallization and metamorphism between 180 and 80 Ma as indicated by zircon U-Pb dating [Chen *et al.*, 2001; Fan *et al.*, 1998; Liu *et al.*, 2001; Wilde *et al.*, 2003]. Hannuoba granulite terrains have been interpreted in terms of an exposed lower crustal section [Zhai *et al.*, 2001], which underwent two important granulite-facies metamorphic events at 2.6–2.5 and 1.9–1.8 Ga and was then uplifted to the surface at ~1.8 Ga [e.g., Guo *et al.*, 2005; Zhai *et al.*, 2005]. Preservation of kelyphite, consisting of extremely fine-grained minerals (e.g., cpx + opx + plag) around fresh garnet core in the terrain granulites [Guo *et al.*, 2005, and references therein], implies that they experienced rapid decompression and rapid cooling and thus can preserve their source information in an efficient way [Rudnick, 1992].

[7] Daoxian in the Hunan Province lies at the north margin of the Cathaysia Craton (Figure 1). This region, as well as the adjacent Ningyuan area, is unique in the west Cathaysia Craton for the presence of abundant lower crust and mantle xenoliths. Daoxian granulite xenoliths were entrained by Mesozoic basalts, with their ages ranging from 150 to 130 Ma, determined by K-Ar and Ar-Ar methods [Guo *et al.*, 1996; Li *et al.*, 2004; Zhao *et al.*, 1998]. They were formed through accumulation of pyroxene and plagioclase from underplating mafic melts, followed by subsequent lower crustal metamorphism in multiple episodic periods. The Sm-Nd mineral isochron age is ~220 Ma [Guo *et al.*, 1996]; the SHRIMP U-Pb dating demonstrates that most zircons from Daoxian granulites have relatively young ages (200–280 Ma), although rare old (up to 850 Ma) zircons do exist [Dai *et al.*, 2008]. Therefore, the Daoxian granulites are believed to have formed in the Mesozoic in accordance with extensive Mesozoic magmatism in this area [Li *et al.*, 2004; Li and Li, 2007].

[8] The samples analyzed for this study include 8 xenolith and 10 terrain granulites from Hannuoba and 14 xenolith granulites from Daoxian (Table 1). They are characterized, in thin sections, by medium- to fine-grained granoblastic fabrics or heteroblastic and/or near-equigranular textures. Hypersthene is very common in all these samples; mineralogical banding composed of plag-rich and pyroxene-rich layers can be found in almost all of these samples. All these samples are two-pyroxene granulites, and their compositions range from dominantly mafic to less intermediate [Dai *et al.*, 2008; Liu *et al.*, 2001]. These suggest that they originate from igneous mafic cumulates subject to the lower crustal metamorphism, as proposed by Guo *et al.* [2005], Liu *et al.* [2001], and Dai *et al.* [2008]. These samples are all well preserved with no hydrous phases or observable alteration, except for some Hannuoba terrain granulites in which amphibole is found in minor amounts (<3%) (Table 1) and for Daoxian xenolith granulites in which alteration of opx into chlorite is often observed, but cpx are always very fresh [see also Dai *et al.*, 2008]. According to the age patterns, these samples are simply divided into Precambrian

(Hannuoba terrain granulites) and Phanerozoic (Hannuoba and Daoxian xenolith granulites) groups (Table 1).

[9] To obtain a more general comparison of water content, the water data on the Nushan xenolith granulites reported by Xia *et al.* [2006] were also compiled here. The Nushan xenolith granulites were entrained by Cenozoic basalts, but zircon U-Pb dating indicates mostly two episodes of ~2.5 Ga and ~1.9 Ga for their formation. This, coupled with trace element modeling, Sr-Nd isotope systematics, and similarities in seismic velocity and major element compositions, led Huang *et al.* [2004] to suggest that Nushan granulites were mainly derived from the late Archean crystalline basement with very weak, if any, effects from subsequent mafic underplating and only subordinately derived from the mafic layer newly accreted during the late Mesozoic and that they can be used as a proxy for early lower crust. These samples were allotted to the Precambrian group in this paper.

3. Analytical Methods

[10] Mineral compositions were determined by CAMECA SX50 and SX100 electron microprobes at the University Henri Poincaré in Nancy for the Hannuoba xenolith and terrain granulites and by a JEOL JXA-8100 superprobe at Nanjing University, China, for the Daoxian xenolith granulites, following similar conditions: 10 nA beam current, 15 kV accelerated voltage, and natural and synthetic standards, calibrated by Pouchou and Pichoir [1985] and atomic number, absorption, and fluorescence corrections, respectively. Two to three points (from core to rim) for each grain and three to five grains for each mineral in the same sample were analyzed. Densities of the minerals in the studied granulites were estimated from the proportion and the density of end-member minerals [Deer *et al.*, 1992]: Wo 2.98 g cm⁻³, En 3.21 g cm⁻³, Fs 3.96 g cm⁻³, An 2.76 g cm⁻³, Ab 2.55 g cm⁻³, and Or 2.63 g cm⁻³. The variation of the calculated density for a mineral is <3% between different samples from the same locality and <6% between different localities. For each suite of granulites, the average density of individual minerals was used in the calculation of the bulk water content.

[11] Fourier transform infrared (FTIR) measurements were conducted following Katayama *et al.* [2006] and Xia *et al.* [2006]. Infrared spectra were obtained at wave numbers from 650 to 6000 cm⁻¹ using a Nicolet 5700 FTIR spectrometer coupled with a Continuum microscope at the University of Science and Technology of China. The samples were measured by unpolarized radiation with an IR light source, a KBr beam-splitter, and a liquid nitrogen-cooled mercury-cadmium-tellurium narrowband, high-sensitivity detector. For each spectrum, 128 or 256 scans were accumulated at a 4 cm⁻¹ resolution. Optically clean, inclusion- and crack-free areas, usually centered in the core region of each grain, were selected for the measurements with apertures of 30 × 30 or 50 × 50 μm. A golden wire-grid polarizer was applied on some oriented crystals, and some large and fresh grains were selected for the H profile analysis. Accurate quantitative measurement of hydrogen species in anisotropic minerals requires the preparation of oriented single crystals and the use of polarized IR radiation [Libowitzky and Rossman, 1996]. However, performing

Table 1. Summary of Petrographic Features for Granulites From Eastern China^a

Samples	Model Mineralogy	Description
<i>Precambrian</i>		
Hannuoba terrain		
MJ9801	cpx30opx12plag30grt23mt2amp3	fine grain, near-equigranular texture
MJ9803	cpx30opx13plag55mt2	banded, fine grain
MJ9805	cpx30opx10plag40grt15mt5	banded, fine grain
MJ9806	cpx30opx7plag55mt5amp3	less banded, fine grain
MJ9807	cpx35opx10plag50mt5	banded, fine grain
MJ9808	cpx40opx7plag50mt3amp2	fine grain, near-equigranular texture
MJ9810	cpx45opx20plag25grt5mt3amp2	banded, fine grain
MJ9811	cpx35opx12plag45grt5mt3	fine grain, near-equigranular texture
SX-1	cpx25opx5plag50grt15mt3amp2	banded, fine grain (large grt grains)
SX-2	cpx28opx5plag40grt23mt3amp1	banded, fine grain
<i>Phanerozoic</i>		
Hannuoba xenolith		
WD9520	cpx45opx20plag35	banded, medium to coarse grain, near-equigranular texture
WD9522	cpx30opx50plag20	banded, medium grain, heteroblastic texture
WD9530	cpx45opx25plag30	banded, medium to coarse grain, near-equigranular texture
WD9532	cpx55opx25plag20	banded, medium grain, granoblastic, near-equigranular texture
WD9546	cpx55opx35plag10	less banded, medium grain, granoblastic, heteroblastic texture
DM9855	cpx30opx25plag45	banded, medium to coarse grain, near-equigranular texture
DM9871	cpx25opx10plag65	banded, medium grain, granoblastic, near-equigranular texture
HD71	cpx50opx35plag15	banded, medium grain, near-equigranular texture
Daoxian xenolith		
DX01	cpx40opx30plag30	medium to fine grain, near-equigranular texture
DX03	cpx35opx10plag54sp1	banded, medium to coarse grain
DX04	cpx20opx20plag60	banded, medium to fine grain
DX06	cpx30opx20plag49sp1	banded, medium to fine grain
DX10	cpx30opx25plag44sp1	banded, medium to fine grain
DX12	cpx25opx10plag64sp1	banded, medium to fine grain
DX13	cpx40opx19plag40sp1	banded, medium to coarse grain
DX19	cpx20opx15plag54sp1	banded, medium to coarse grain
DX20	cpx30opx15plag54sp1	banded, medium to fine grain
DX28	cpx35opx20plag45	less banded, fine grain
DX31	cpx65opx20plag14sp1	medium to fine grain, heteroblastic texture
DX34	cpx20opx10plag70	less banded, fine grain
DX40	cpx30opx10plag59sp1	less banded, coarse grain
DX44	cpx35opx20plag44sp1	banded, medium to coarse grain

^aAbbreviations are grt, garnet; amp, amphibole; sp, spinel; and mt, magnetite. Samples labeled MJ and SX in the Hannuoba terrain granulites are from Manjinggou and Xiwangshan at the Hannuoba region, respectively; Hannuoba granulite xenoliths are from Damaping at the Hannuoba region (see auxiliary material for the illustration of these localities).

such a treatment on fine-grained natural granulites is extremely difficult. And so here, where unpolarized determinations were made, we instead analyzed a significant number of individual grains (e.g., 8–25) of each mineral in the same sample, whose orientations are highly variable as revealed by our FTIR results (see section 4), and their average value was used to determine the water content, as were the values of *Grant et al.* [2007], *Katayama and Nakashima* [2003], *Katayama et al.* [2006], and *Xia et al.* [2005, 2006]. The possible effects from nonstructural OH/H₂O on some spectra (e.g., of garnet) were resolved by using the Peakfit V4.12 program (Jandel Scientific) based on a Gaussian function.

[12] Water contents were calculated by the modified form of the Beer-Lambert law:

$$\Delta = I \times c \times t \times \gamma,$$

where Δ is the integral absorption area (cm⁻¹) of absorption bands, I is the integral-specific absorption coefficient (ppm⁻¹ cm⁻²), c is the content of hydrogen species (ppm H₂O weight), t is the thickness of the section (cm), and γ is the orientation factor discussed by *Paterson* [1982]. In this

paper, the integral region was 2700 ~ 3800 cm⁻¹ with the integral-specific coefficient of 7.09 ppm⁻¹ cm⁻² for cpx, 14.84 ppm⁻¹ cm⁻² for opx, and 1.36 ppm⁻¹ cm⁻² for garnet from *Bell et al.* [1995] and 15.3 ppm⁻¹ cm⁻² for plagioclase from *Johnson and Rossman* [2003]. Thickness was measured with a digital micrometer and reported as an average of 30 ~ 40 measurements covering the whole section; the orientation factor of 1/3 was applied in the calculation for anisotropic cpx, opx, and plag, and a factor of 1 was applied for isotropic garnet [*Paterson*, 1982]. Baseline corrections were carried out with a spline fit method by points outside the OH-stretching region.

[13] Possible factors influencing the calculated results include the following.

[14] 1. Unpolarized light is the main uncertainty during the analysis, but it is estimated to be mostly less than 10% considering the treatment (averaging 8–25 individual grains with variable absorbance) [*Asimow et al.*, 2006; *Sambridge et al.*, 2008; *Kovács et al.*, 2008].

[15] 2. Another possible factor is baseline correction. The background could be treated as a flat curve along the trend of our spectra in most cases, and the difference between different baseline corrections, e.g., spline fit or polynomial

fit or slightly changing the points during the fitting, is usually <5%.

[16] 3. A third possible factor is the variation of sample thickness on the thin sections. On each section, 30–40 thickness measurements point out that variations are less than 6% in our samples.

[17] 4. Extinction coefficients may influence results. There are slight differences between cpx, opx, and garnet in our granulite samples and those used to determine the mineral-specific absorption coefficients [Bell *et al.*, 1995], but the variation is generally <8% in their compositions and densities, and it is even less than 2% for plag relative to those used by Johnson and Rossman [2003]. The error caused by the coefficients is therefore estimated to be <10%. The total uncertainty is estimated to be less than 30%.

4. Results

[18] Electron microprobe measurements show that the individual minerals are homogeneous for each sample (the averaged data are provided in the auxiliary material).¹ These results are very similar to those reported by Chen *et al.* [2001] and Liu *et al.* [2001] for the Hannuoba mafic xenolith granulites, by Fan *et al.* [2005] for the Hannuoba terrain granulites, and by Dai *et al.* [2008] for the Daoxian xenolith granulites.

[19] Following the protocol suggested by Xu *et al.* [1998], equilibrated pressure-temperature (P-T) conditions were calculated by the geobarometer of Wood [1974] for garnet-bearing samples and the two-pyroxene geothermometers of Wood and Banno [1973] and Wells [1977]. Pressures of xenoliths were estimated by using the geotherm established by Chen *et al.* [2001] in the Hannuoba region and by the P-T estimation of Dai *et al.* [2008] in the Daoxian region. The temperatures obtained by the two-pyroxene geothermometers of Wood and Banno [1973] and of Wells [1977] agree to within $\pm 50^\circ\text{C}$ for most samples, which is consistent with the calculation uncertainties. The estimated results are 780–860°C and 1.0–1.5 GPa for the Hannuoba terrain granulites, 860–920°C and 0.9–1.2 GPa for the Hannuoba granulite xenoliths, and 850–900°C and 0.9–1.2 GPa for the Daoxian granulites, so they are in good agreement with previous reports [Chen *et al.*, 2001; Dai *et al.*, 2008; Guo *et al.*, 2005; Liu *et al.*, 2001; Zhai *et al.*, 2005]. These P-T data indicate that the granulites were at equilibrium in the lower and lowermost crust beneath the Hannuoba and Daoxian regions (the estimated crust-mantle boundary is ~ 42 km at Hannuoba [Chen *et al.*, 2001] and ~ 40 to 45 km at Daoxian [Dai *et al.*, 2008]); the same conclusion was reached by Xia *et al.* [2006] for Nushan xenolith granulites.

[20] FTIR spectra (Figure 2) show that all the spectra of cpx, opx, plag, and garnet have several absorption bands in the range of 3000 to 3750 cm^{-1} , which can be divided into several different groups for each mineral. The different bands are common in all the samples, with the exception of high-absorption bands only found in some terrain granulites. The position and shape of these bands are similar to those reported for individual minerals [Bell *et al.*, 1995; Bell

and Rossman, 1992; Johnson and Rossman, 2004; Skogby *et al.*, 1990; Skogby and Rossman, 1989; Stalder and Skogby, 2002]. Slight differences may be associated with the chemical composition and crystal structure of the hosted phases. The relative absorbances of bands for anisotropic cpx, opx, or plag are variable for different grains even in the same sample, which are attributed to variable orientations of the grains with respect to the infrared beam direction and to possible water heterogeneity. Polarized analyses performed on some oriented grains show a significant dependence of the OH absorbance on the polarized orientation for these different bands (Figure 3), attesting that they result from the vibration of structural OH. Molecular H_2O may also occur in our plag based on the characteristic bands at ~ 3620 , ~ 3550 , and ~ 3440 cm^{-1} as reported by Johnson and Rossman [2004]. The 3420–3450 cm^{-1} band of garnet is out of the energy range of structural OH, usually 3500–3700 cm^{-1} , in previous studies on both natural and synthesized garnets, and is commonly ascribed to tiny fluid inclusions [Langer *et al.*, 1993; Rossman and Aines, 1991; Rossman *et al.*, 1989], and they are therefore removed from the calculation of water content by the Peakfit treatment; some spectra also display weak absorbance in the range of 3700–3800 cm^{-1} , which is probably an artifact due to the light source in the Nicolet instrument (G. Rossman, personal communication, 2004), and were also excluded from the calculation of water content.

[21] H profile analyses performed on selected pyroxene grains in each suite of granulites reveal very weak variations of OH absorbance from core to rim regions, ranging mostly from 5 to 10% and in rare cases a little higher up to $\sim 20\%$ (see auxiliary material). No apparent variations beyond the analytical uncertainty (30%) were found for H absorbances in large pyroxene grains in the granulites, implying the absence of significant exchange/diffusion loss of H between melts and minerals during their exhumation. The calculated average H_2O contents, as well as the compiled Nushan data from Xia *et al.* [2006], are presented in Table 2, and the OH content of garnet for individual grains in the Hannuoba terrain granulites is given in Table 3.

[22] The water contents are highly variable. They range on average from 275 to 720 ppm for cpx, 60 to 185 ppm for opx, 65 to 205 ppm for plag, and 165 to 355 ppm for bulk rock in the Hannuoba xenolith granulites; from 585 to 1480 ppm for cpx, 230 to 1875 ppm for opx, 175 to 895 ppm for plag, 290 to 620 ppm for garnet, and 405 to 1120 ppm for bulk rock in the Hannuoba terrain granulites; and from 285 to 500 ppm for cpx, 65 to 135 ppm for opx, 205 to 345 ppm for plag, and 200 to 360 ppm for bulk rock in the Daoxian xenolith granulites. These variations are roughly similar to those observed in the Nushan xenolith granulites [Xia *et al.*, 2006] (see also cited data in Table 2). OH content of garnet in the terrain samples demonstrates large variations, ranging from 0, with grains without any evident H-related IR absorption (Figure 2), to more than 1000 ppm (Table 3); similar variations were reported for garnet from the central Dabieshan eclogites by Xia *et al.* [2005] and for garnet from the skarn belt in Oak Hill and Willsboro, Adirondacks, by Johnson [2006]. The above mentioned variations of water content for either individual minerals, bulk contents, or different garnet grains are far beyond the estimated uncer-

¹Auxiliary materials are available in the HTML. doi:10.1029/2007JB005541.

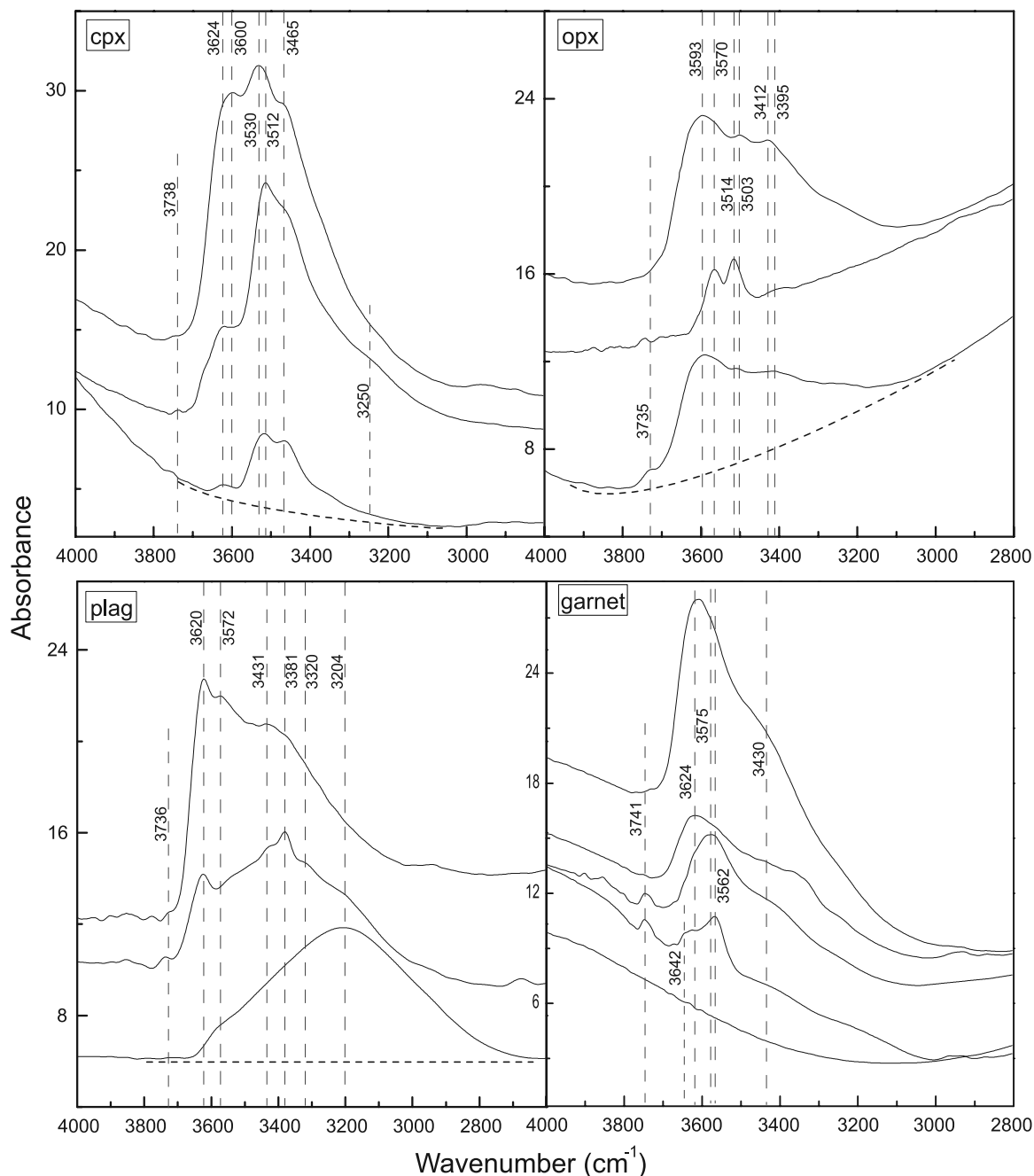


Figure 2. Representative Fourier transform infrared (FTIR) spectra of cpx, opx, plag, and garnet in the granulites. Dashed lines show where the baseline was taken by spine fit method; spectra were normalized to 1 cm thickness and offset for clarity.

tainty (30%), indicating heterogeneous distribution of water in the lower crust.

[23] Water contents of individual minerals and bulk rocks in the Hannuoba terrain granulites resemble those in the Nushan xenolith granulites [Xia *et al.*, 2006] (Table 2), consistent with similarities in their major/trace element compositions, formation ages, and other behaviors [Huang *et al.*, 2004], and they are remarkably higher than those in the Hannuoba and Daoxian xenolith granulites except for a few Nushan samples which have relatively lower water content (Figure 4) despite the large heterogeneities of water in these suites of granulites. Considering the age informa-

tion of these samples, the Precambrian granulites appear to have higher water contents than the Phanerozoic ones (Figure 4).

5. Preservation of Initial Water Content in the Lower Crust

[24] Whether deep-seated minerals brought to the surface can preserve their original water contents is an unresolved question. It is argued that some minerals can keep their initial OH contents [e.g., Bell *et al.*, 2004; Grant *et al.*, 2007; Peslier *et al.*, 2002], but there are also studies

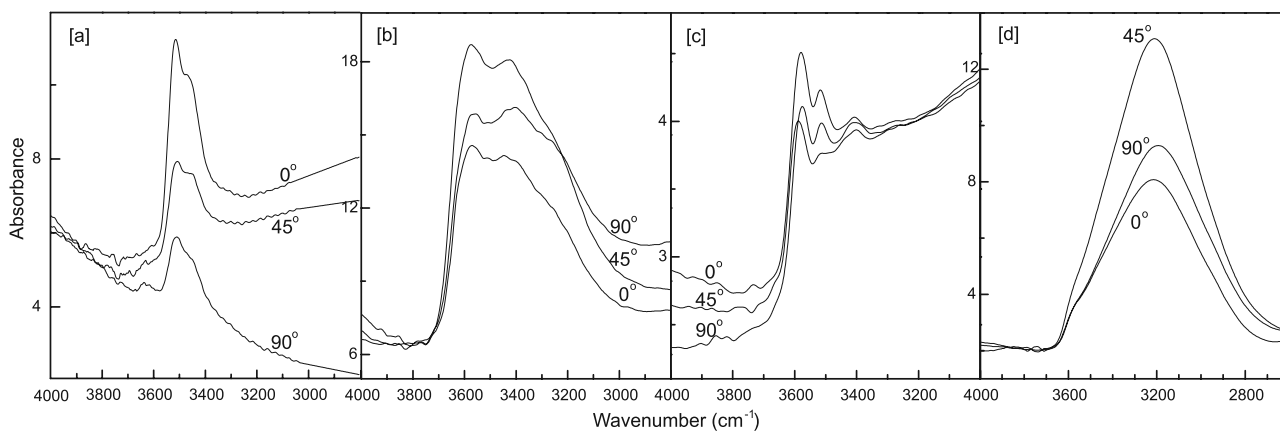


Figure 3. Representative polarized FTIR spectra of cpx, opx, and plag with polarization orientation: (a) cpx spectra from DM9855, (b) opx spectra of high water content from MJ9806, (c) opx spectra of low water content from DM9855, and (d) plag spectra from DM9855.

showing that the water content of minerals may be modified during eruption, especially by hydrogen diffusion and by exchange between crystals and fluids [e.g., *Ingrin and Skogby, 2000*].

[25] In our study, the measured H₂O data are interpreted in terms of original contents on the basis of the following characteristics.

[26] 1. Each of the phases in the same sample is chemically identical. No major element compositional zoning has been observed for the studied grains in these samples, and no rare Earth element (REE) compositional zoning has been observed in individual grains within selected Hannuoba xenolith and terrain and Nushan xenolith granulites revealed by in situ ion microprobe measurements [*Yang et al., 2007*].

[27] 2. The FTIR measurements were usually conducted in the core region of clean, crack- and inclusion-free grains of relatively large size. It is therefore inferred that the loss of H in these areas by diffusion during the exhumation would be very weak [*Peslier and Luhr, 2006*].

[28] 3. Profile analyses on many pyroxene grains in all the granulites show that the H-related IR absorption is mostly homogeneous between their core and rim regions [*Xia et al., 2006; this study*], indicating negligible variation of H content, possibly because of diffusional exchange.

[29] 4. The studied samples are usually very fresh, and the spectra used in the water calculation show no signal of any evident hydrous phases, which would produce sharp bands in the region of $>3660\text{ cm}^{-1}$. In this case, there is no evident interference from other H-bearing phases or any exchange of H between them.

[30] 5. The hydrogen isotopic measurements by ion microprobe for both profile analyses across mineral grains and the average compositions of individual minerals in the selected Hannuoba xenolith and terrain and Nushan xenolith granulites also favor the preservation of their initial hydrogen information [*Yang et al., 2007*].

6. Partitioning of Water Between Lower Crustal Phases

[31] The partitioning of water between lower crustal granulite mineral pairs, e.g., cpx-opx, plag-cpx, and plag-opx are shown in Figures 5a–5c. Roughly, these mineral

pairs display positive relationships, although some samples deviate obviously from the trends (e.g., cpx-opx in Figure 5a). The partition coefficient of water between cpx and opx varies in the range of 0.5 to 10.2, with an average of 3.2; the coefficients are variable between different geological localities, e.g., ~ 6 for the Hannuoba xenolith granulites, ~ 1 for the Hannuoba terrain granulites, ~ 2.5 for the Nushan xenolith granulites, and ~ 4 for the Daoxian xenolith granulites (Table 2). Similar variations can also be observed for the plag-cpx and plag-opx pairs (Figures 5b and 5c). These may reflect the dependence on geological environments as argued by *Skogby et al.* [1990].

[32] Although the lack of data on water partitioning between plagioclase and pyroxenes makes it hard for a quantitative comparison with our data, available studies on natural and synthesized mantle samples have documented that the equilibrium partition coefficient of water between cpx and opx, $D_{\text{cpx/opx}}^{\text{water}}$, is about 1.9–2.3 [e.g., *Aubaud et al., 2004; Bell and Rossman, 1992; Bell et al., 2004; Grant et al., 2007; Hauri et al., 2006; Koga et al., 2003; Peslier et al., 2002*]. The values measured in our samples (in particular, Nushan and Daoxian granulites) (Figure 5) are similar to those mentioned above. Deviation from the equilibrium trend may be ascribed to water loss from individual grains/minerals during granulite-facies metamorphism (e.g., via mineral degassing after crystallization or water loss from the original mantle melts [*Yang et al., 2007*]). These processes could certainly modify the initial water content of minerals inherited from their original melts or even the water content in the melts and therefore produce the observed disequilibrium. However, there are also several other scenarios which can result in such disequilibrium: (1) the equilibrium could not be acquired under the lower crustal P-T conditions, (2) the water content of lower crustal minerals was not inherited from the mantle source where they originated, or (3) closed-system redistribution of H between coexisting minerals altered their partitioning as a function of the different mineralogical composition (e.g., plagioclase-rich versus pyroxene-rich samples).

[33] The possibility exists that the equilibrium partition coefficient between mantle-derived pyroxenes should not be used for crustal rocks because of the difference in chemical composition and crystal structure (e.g., rich in

Table 2. Water Content of Main Constitutive Minerals in the Granulites From Eastern China^a

Sample	Thickness (cm)	cpx	opx	plag	grt	Bulk
<i>Precambrian</i>						
Hannuoba terrain						
MJ9801	0.016	1480	1875	895	560	1120
MJ9803	0.021	665	310	265	-	405
MJ9805	0.011	1250	1480	580	-	795
MJ9806	0.017	820	1325	795	-	855
MJ9807	0.024	780	306	274	-	480
MJ9808	0.016	585	620	325	-	470
MJ9810	0.022	1175	885	345	430	875
MJ9811	0.019	1100	365	245	620	615
SX-1	0.020	1365	1285	445	291	725
SX-2	0.019	885	230	175	430	465
Nushan xenolith						
04NS1	0.025	-	290	460	-	435
04NS5	0.033	2330	665	725	-	970
04NS8	0.032	2030	590	710	-	790
04NS9	0.024	215	445	365	-	325
04NS11	0.029	-	465	450	-	455
04NS12	0.021	200	160	145	-	155
04NS13	0.026	-	140	290	-	260
04NS14	0.038	-	1270	900	-	950
04NS15	0.023	1245	550	565	-	645
04NS16	0.021	2330	525	820	-	870
<i>Phanerozoic</i>						
Hannuoba xenolith						
WD9520	0.019	440	65	180	-	275
WD9522	0.019	600	185	135	-	300
WD9530	0.011	470	140	205	-	310
WD9532	0.021	480	70	85	-	300
WD9546	0.015	570	90	140	-	355
DM9855	0.014	275	135	100	-	165
DM9871	0.023	720	70	90	-	260
HD71	0.026	470	60	65	-	265
Daoxian xenolith						
DX01	0.023	445	110	350	-	310
DX03	0.017	285	70	205	-	220
DX04	0.020	335	65	205	-	200
DX06	0.016	390	90	295	-	280
DX10	0.016	345	90	345	-	270
DX12	0.022	435	120	265	-	295
DX13	0.022	310	110	290	-	260
DX19	0.016	430	140	305	-	315
DX20	0.023	425	85	250	-	280
DX28	0.018	435	135	260	-	295
DX31	0.023	285	80	225	-	235
DX34	0.015	350	85	275	-	270
DX40	0.013	500	70	340	-	360
DX44	0.015	370	135	330	-	300

^aWater contents were rounded to the nearest 5 ppm (H₂O by weight). Nushan data are referred to Xia *et al.* [2006] and are calculated by the same method used in this paper for comparison. Dash indicates not present. The thickness is an average of 30 ~ 40 measurements covering the whole section (see text).

Fe in granulites versus Mg in peridotites), which may greatly influence the incorporation of H [e.g., Skogby and Rossman, 1989; Stalder, 2004]. In principle, a greater range of substitutions of trivalent and tetravalent ions, even of large size such as OH, may be accommodated by the structure of Fe-rich granulite-borne pyroxenes than by the Mg-rich pyroxene from mantle xenoliths. In fact, the mechanisms of H incorporation into minerals may be different between lower crustal and mantle P-T conditions, as recently proposed on the basis of experiments on Al-rich orthopyroxene [Mierdel *et al.*, 2007]. Further investigations are necessary

for a better knowledge of the partitioning of water between lower crustal assemblages.

7. Implications for the Water Content in the Lower Crust

[34] Precambrian granulites, on average, contain more water than the Phanerozoic granulites by a factor of 2–3 or even higher (Figure 4). If they actually preserved their initial water content, as discussed in section 6, it follows that the continental lower crust of eastern China was more hydrous in the Precambrian than in the Phanerozoic era. The higher water contents in the Precambrian lower crust may have profound influences on many physical properties of lower crustal materials, such as lowering the rheological strength and melting temperatures at depth and/or modifying the seismic velocity, even on the mechanisms of crustal growth.

[35] The strong contrast in water content between the Precambrian and Phanerozoic lower crust of eastern China can be explained in the following terms.

[36] 1. While the possibility of pressure, or difference in equilibration depth, affecting the solubility of OH in minerals may to some extent influence the water content, it cannot make a large contribution to the contrast observed in the studied rocks. Granulites equilibrated at about 0.7 to 1.5 GPa, and within this pressure range, possible variations of OH content caused by pressure (e.g., <15% for cpx and <30% for opx [Rauch and Keppler, 2002; Bromiley *et al.*, 2004; Mierdel *et al.*, 2007]) are far smaller than those observed in the samples (Table 2 and Figure 4).

[37] 2. There is no evidence that Precambrian reequilibrated granulites with mantle melts and increased OH contents were affected by mantle melts [Huang *et al.*, 2004; Zhai *et al.*, 2005]. Furthermore, the ability for melt to percolate within a rock matrix is controlled by the dihedral angle (θ) between solid and melt, and for $\theta > 60^\circ$, small melt fractions cannot percolate [Waff and Bulau, 1979]; θ between lower crustal assemblages and melt is usually larger than 60° (e.g., θ is 98° between cpx and melt) and is 76° between opx and melt [Toramaru and Fujii, 1986]. Thus, melt percolation through the lower crust is unlikely as is rehydration of the lower crust by mantle melts.

Table 3. Water Content of Garnet in the Hannuoba Terrain Granulites

	Analysis									
	1	2	3	4	5	6	7	8	9	10
MJ9801	982	1114	949	787	287	354	882	1337	933	618
	140	89	143	237	362	105	439	281		
MJ9810	635	569	953	558	1477	955	1132	1253		
MJ9811	490	1243	229	794	761	523	285			
SX-1 ^a	62	167	124	142	191	24	140	206	60	157
	54	147	95	68	142	90	156	175	63	173
	297	322	365	358	209	581	165	79	133	408
	174	556	211	349	151					
SX-2	481	199	336	406	654	584	273	552	404	392

^aNearly 40 grains in sample SX-1 were analyzed because garnet is especially abundant and fresh in it; some grains in these samples actually contain no water (see text), which were not illustrated here.

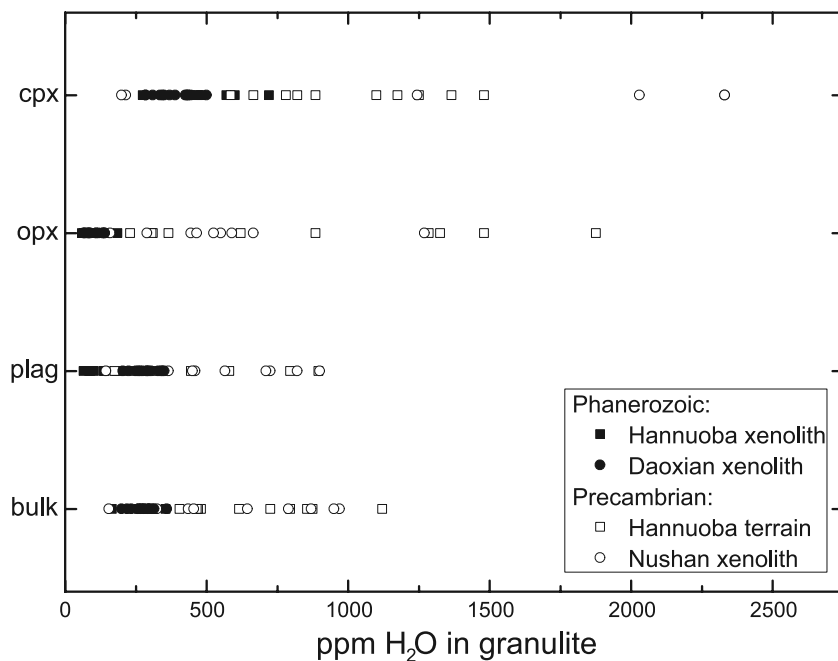


Figure 4. Water content of cpx, opx, plag, and bulk values in the granulites from eastern China.

[38] 3. During dehydration of the Phanerozoic granulites via heating and partial melting from an underplated mantle, fractional crystallization prior to and/or partial melting after the formation of these granulites might have lowered the OH contents of crustal rocks. It is suggested that the incompatible behavior of H₂O during melting and crystallization may be comparable to that of cerium [e.g., *Michael, 1995*, and references therein] and that large-ion lithophile element (LILE) and light REE (LREE) patterns could be

used to infer H₂O loss besides tracing melting process. However, if the initial water contents in Precambrian and Phanerozoic granulites (or their original melts) were similar, relatively high degrees of dehydration are required to produce the measured compositions. The extent of fractional crystallization for the Hannuoba xenolith granulites has been inferred to be low to medium (5–40% [*Liu et al., 2001*]) and consistency in REE patterns in individual minerals between the Hannuoba xenolith, Nushan xenolith,

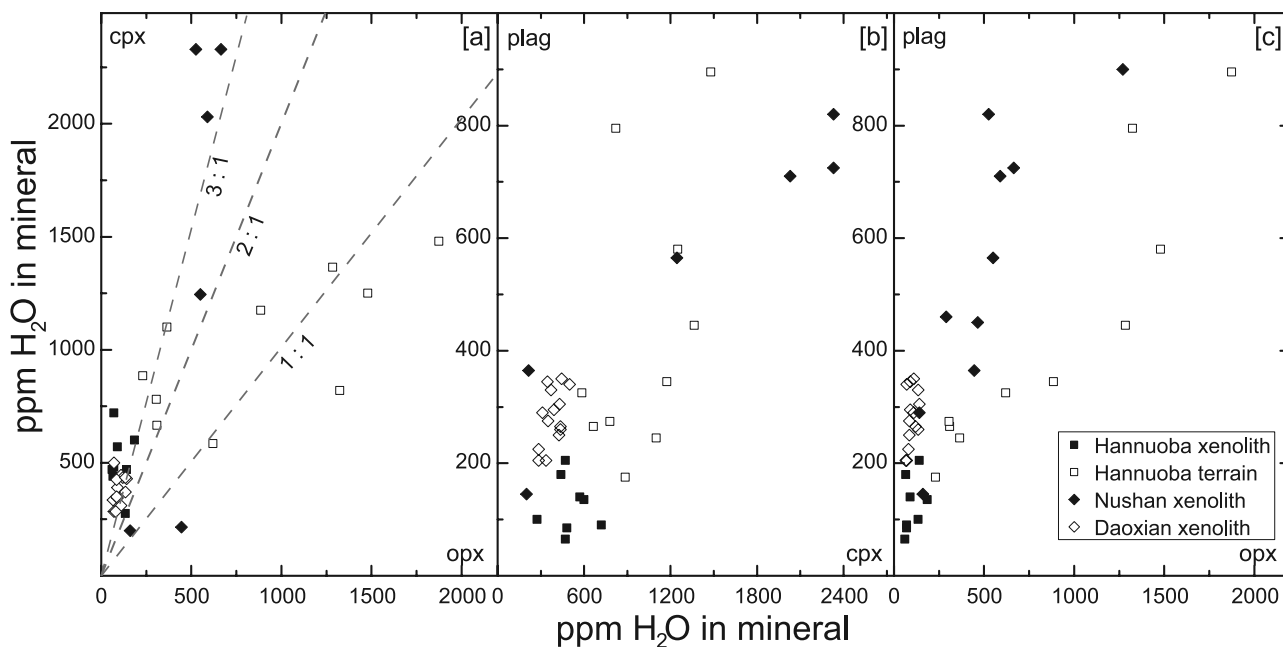


Figure 5. Partitioning of water between lower crustal granulite minerals of eastern China. Three dashed gray lines in terms of 1:1, 2:1, and 3:1 partitioning of water between lower crustal granulite mineral pairs (a) cpx-opx, (b) plag-cpx, and (c) plag-opx were drawn for reference.

and Hannuoba terrain granulites [Yang *et al.*, 2007]; undepleted LREE and LILE concentrations in bulk rocks of Hannuoba [Liu *et al.*, 2001] and Daoxian xenolith granulites [Dai *et al.*, 2008]; and the absence of simple correlations between Mg # values (index of partial melting) and Ce contents for pyroxenes in the Hannuoba xenoliths (see auxiliary material) and for bulk compositions in the Daoxian xenoliths [Dai *et al.*, 2008] do not support extensive partial melting after their formation.

[39] 4. It is possible that the heat provided by underplating melts induced significant H loss, e.g., through dehydration, in the Phanerozoic lower crust, but such thermal events did not produce any visible partial melting of the granulites (e.g., the above discussed point 3). In this case, the dehydration loss of H in the Phanerozoic granulites would be evidently larger than in the Precambrian ones. Nonetheless, the estimated difference in the extent of dehydration from their H isotopic data, mainly in the manner of H₂ loss, between the Hannuoba xenolith granulites and the Hannuoba terrain and Nushan xenolith granulites is on the first order of only about 10% (assuming they derived from mantle melts with similar δD of -80% [Yang *et al.*, 2007]), which would provide no way of accounting for the observed large difference in their water contents if their original concentrations were similar. This possibility is thus excluded.

[40] 5. Percolation of fluids dominated by CO₂ was suggested by Newton *et al.* [1980] for the formation of granulites, and such percolation would effectively remove most of the water without changing major/trace elements markedly. The effects of CO₂ on granulite-facies metamorphism have been debated, as it was argued recently that CO₂ probably plays a consequential rather than causal role in the genesis of granulites [Cesare *et al.*, 2005]. On the other hand, a pervasive percolation of CO₂ in the lower crust is in conflict with the observed intergrain $\delta^{18}O$ heterogeneity, up to 2–3‰, in intragrain homogenous samples even in <1 cm scale; such microscale variations would be erased by the fluids [Yang, 2008; see also Valley and O'Neil, 1984]. And furthermore, if granulites were really involved with CO₂ for their genesis (e.g., influx of CO₂ produces the lower water content in granulites), it would be difficult to imagine that only the Phanerozoic granulites were markedly influenced by CO₂ to lower their water contents relative to the Precambrian granulites. This possibility is therefore not favored.

[41] 6. Secondary metasomatism by melts/fluids, responsible for the formation of amphibole in the Hannuoba terrain granulites, may play some role in buffering/increasing the water content of the coexisting cpx, opx, and plag. However, it has been suggested that the formation of secondary hydrous amphibole through later alterations or metasomatism consumes nearly all of the water available in the fluid phase [Andrut *et al.*, 2003] or even in the coexisting NAMs [Peslier *et al.*, 2002]. In the former case the H content in the NAMs will remain unmodified, while in the latter case they can be notably lowered, e.g., via closed-system H redistribution. In addition, the REE patterns of mineral grains in the Hannuoba terrain samples resemble those in the Hannuoba and Nushan xenolith granulites, and no extreme variations in (La/Yb)_N ratios of individual minerals can be observed between them,

implying that these grains were not modified by later alteration or metasomatism [Yang *et al.*, 2007]. Finally, no hydrous phases occurring in the Nushan xenolith granulites show higher water contents.

[42] 7. For the case of water contrast being inherited from their original melts/protoliths, if the melts derived from the upper mantle, the water content of the upper mantle may have been higher in the Precambrian than in the Phanerozoic, which was then inherited by the lower crust formed from them. It is interesting to note that if the water content of the lower crust decreased from Proterozoic to Phanerozoic era, this could explain the large dispersion of water content observed for the Nushan granulites, which resided in the lower crust during this time interval. That is, the Nushan granulites may represent a mixture of Precambrian and newly formed Phanerozoic lower crust [Huang *et al.*, 2004]. In contrast, water in the Hannuoba terrain granulites could be preserved from late reequilibration because of its early exhumation.

[43] In summary, our data suggest that the Precambrian continental lower crust in eastern China was more hydrous than the Phanerozoic one and that the contrast in water contents may relate ultimately to the difference of water content in the original melts/protoliths. This may indicate that the ancient upper mantle in China was more hydrous, in agreement with the hypothesis that the upper mantle was more hydrous in the Precambrian than in the Phanerozoic [e.g., Stone *et al.*, 1997]. Several other implications from our data include the following: If the granulites formed during mantle upwelling and the source of upwelling was the deep mantle, our results would make a real difference between the upper and lower mantle degassing. Alternatively, if formation of the early lower crust was related to the occurrence of superplumes, as proposed by Condie [2004], and buildup of the NCC was also related to a plume, as suggested by Zhao *et al.* [2001], our results indicate that these plume-related melts were rich in water. So if superplumes accounted for the growth of the early lower crust in the NCC, the Precambrian upper mantle was not necessarily H₂O richer than the Phanerozoic upper mantle. Future research on the lower crustal granulites may shed light into which one of these hypotheses is correct.

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E. Deloule, Centre de Recherches Pétrographiques et Géochimiques, Centre National de la Recherches Scientifique, BP 20, Vandoeuvre-les-Nancy CEDEX, F-54501 France.

Q.-C. Fan, Institute of Geology, China Earthquake Administration, Beijing 10029, China.

M. Feng, Q.-K. Xia, and X.-Z. Yang (corresponding author), CAS Key Laboratory of Crust-Mantle Materials and Environments, School of Earth and Space Sciences, University of Science and Technology of China, Hefei 230026, China. (qkxia@ustc.edu.cn)