https://doi.org/10.3799/dqkx.2019.231

超高压变质岩中柯石英的产出和保存机制

刘鹏雷，章军锋，金振民

中国地质大学地球科学学院，湖北武汉 430074

摘 要：了解柯石英的产出并制约其保存机制对于深入认识超高压变质岩的形成和演化具有重要的启示意义．早期的研究发现超高压变质岩中的柯石英主要以包裹体的形式产在刚性寄主矿物中，而粒间柯石英之前仅在苏鲁仰口的超高压双矿物榴辉岩中有过发现．目前提出的柯石英保存机制主要包括以下两种：涉及"构造超压"的"高压釜"模型和较干的变质演化环境．新近报道的大别山甘家岭超高压变沉积岩中的粒间柯石英和白云石中的大量柯石英包裹体肯定了较干的变质演化环境而削弱了传统的"高压釜"模型在保存柯石英方面所起的作用．

关键词：大别山；超高压；白云石；粒间柯石英；构造超压；岩石学．

中图分类号： P581 **文章编号：** 1000－2383(2019)12－4028－06 **收稿日期：**2019－08－19

Occurrences and Preservation Mechanisms of Coesite in Ultrahigh-Pressure Metamorphic Rocks

Liu Penglei, Zhang Junfeng, Jin Zhenmin

School of Earth Sciences, *China University of Geosciences*, *Wuhan* 430074, *China*

Abstract: Insights into the occurrences and preservation mechanisms of coesite bear important implications for the formation and evolution of ultrahigh-pressure (UHP) metamorphic rocks. Early researches reveal that coesite usually appears as inclusions in strong host minerals in UHP rocks. Thus far, interstitial coesite has only been found in the UHP two-mineral eclogite from Yangkou, Sulu orogen. Two major mechanisms have been proposed for the preservation of coesite: the "pressure-vessel" model involving "tectonic overpressure" and dry metamorphic environment. Interstitial coesite and abundant coesite inclusions in dolomite recently discovered in a UHP metasedimentary rock from the Ganjialing area in Dabieshan highlight the role of dry metamorphic environment and undermine the importance of "pressure-vessel" model in preserving coesite.

Key words: Dabieshan; UHP; dolomite; interstitial coesite; tectonic overpressure; petrology.

0 引言

柯石英是石英的高压相，前者比后者密度大10％左右．该矿物最早由Coes(1953)通过高温高压实验合成，其随后在陨石撞击坑(Chao *et al.*, 1960)和幔源的榴辉岩捕掳体(Smyth, 1977)中被发现并命名．石英－柯石英的相变 P-T 曲线具有非常小的 dP/dT 斜率，在正常的俯冲带地温梯度条件下，柯石英的稳定压力高于 2.6～2.7 GPa(Bohlen and Boettcher, 1982)．基于西阿尔卑斯Dora-Maira Massif白片岩中发现的柯石英，Chopin(1984)第一次证明陆壳能够俯冲至80 km以下的地幔深度并由此

基金项目：国家重点基础研究发展计划项目(No.2015CB856101).

作者简介：刘鹏雷(1988－)，男，特聘副教授，主要从事高压－超高压变质岩石学研究．ORCID：0000-0002-8560-5169. E-mail：liupengleiincug@aliyun.com

引用格式：刘鹏雷，章军锋，金振民，2019．超高压变质岩中柯石英的产出和保存机制．地球科学，44(12):4028－4033.

引申出超高压变质作用和大陆深俯冲的概念.

1 超高压变质中柯石英的产出

作为超高压变质作用的一种关键性标型矿物,柯石英一般以包裹体的形式产在刚性矿物中(如石榴子石和锆石中;Liu and Liou,2011;Liou *et al.*,2012).沿颗粒边界和/或裂隙,柯石英包裹体一般部分或完全被细粒的石英集合体取代.因为柯石英的晶体结构更加致密,所以当柯石英包裹体退变为石英时会引起体积膨胀从而在包裹体内部形成所谓的"构造超压"(寄主矿物和内部包裹体所承受压力之差;Gillet *et al.*,1984).当"构造超压"超过寄主矿物的抗张强度时,就会围绕柯石英包裹体在寄主矿物内形成放射状裂纹(图1a).需要强调说明的是,放射状裂纹往往与较大的柯石英包裹体紧密伴生,当柯石英包裹体足够小时(≤13 μm),其周围往往缺失放射状裂纹(Schönig *et al.*,2019).

柯石英包裹体在弱相矿物如白云石中也有报道(Schertl and Okay,1994;Zhang and Liou,1996;Lü *et al.*,2014;Liu *et al.*,2015),但是数量非常有限.不同于常见的刚性寄主矿物如石榴子石等,白云石中的柯石英包裹体周围普遍缺失放射状裂纹(图1b~1f).这是因为白云石易发育三组极好解理,而沿解理面和/或解理面所对应的晶面发生滑移可以很好地调节由柯石英退变引起的体应变增量,从而不利于放射状裂纹形成(Schertl and Okay,1994).粒间柯石英在超高压变质岩中更加罕见,之前仅在中国苏鲁青岛仰口的超高压榴辉岩中有过报道(Liou and Zhang,1996;叶凯等,1996).仰口榴辉岩中的粒间柯石英产在刚性矿物石榴子石和绿辉石颗粒之间,寄主岩石经历了明显的榴辉岩相剪切变形,无角闪岩相等退变质作用叠加且缺乏含水矿物如多硅白云母等,反映了一种干燥的变质演化环境(Liou and Zhang,1996;叶凯等,1996;Wang *et al.*,2018).最近,Yang *et al.*(2014a,2014b,2016)报道了仰口榴辉岩中发育的构造角砾岩和碎裂岩,并认为其中的粒间柯石英等超高压矿物形成于地震诱发的瞬时局部超高压变质环境.

2 超高压变质岩中柯石英的保存机制

超高压变质岩中柯石英的保存机制历来是众所关注的一个焦点问题.基于柯石英的产出形式,目前提出的关于柯石英的保存机制主要分为两种.第一种为"高压釜"(pressure-vessel)模型,即考虑到刚性寄主矿物具有较强的抗张强度,柯石英在退变为石英的过程中寄主矿物可将包裹体所承受的压力缓冲到柯石英-石英转换边界附近,通过形成"构造超压"阻止柯石英包裹体进一步退变(Gillet *et al.*,1984;van der Molen and van Roermund,1986;Perrillat *et al.*,2003;Guiraud and Powell,2006).第二种机制主要是基于仰口榴辉岩中发现粒间柯石英提出的,该机制从反应动力学的角度强调干的变质环境对柯石英保存的意义,即流体活动的缺失可以降低柯石英的退变速率,从而有利于柯石英保存(Liou and Zhang,1996;叶凯等,1996).Liu *et al.*(2017)新近在大别山超高压变质带的一类富碳酸盐的变沉积岩中发现了三粒粒间柯石英(图2),同时在该类岩石的白云石中发现了大量的柯石英包裹体(图1),这些发现为超高压变质岩中柯石英的保存机制提供了新的重要制约.

早期发现的柯石英包裹体主要产在刚性矿物如石榴子石和锆石中,故传统的"高压釜"模型得到了广泛认可,不过这一模型无法解释弱相矿物白云石中大量柯石英包裹体的保存(图1b~1f).高温高压变形实验研究表明,当剪切应力存在时,由刚性物质围限的弱相物质内部应力场和应变场一般并不均匀,局部弱相物质的稳定性受控于最大主应力而非平均应力或静岩压力,即局部存在显著的粒间"构造超压"(Green,1972;Hirth and Tullis,1994;Zhou *et al.*,2005;Richter *et al.*,2016).仰口榴辉岩中的粒间柯石英产在刚性矿物石榴子石和绿辉石颗粒之间,同时寄主岩石经历了榴辉岩相剪切变形(Liou and Zhang,1996;Wang *et al.*,2018),因此仰口榴辉岩内也许存在粒间"构造超压".粒间"构造超压"新近再次被提出用于解释某些高压-超高压矿物相的产出(Richter *et al.*,2016),其在仰口粒间柯石英的保存方面也可能起着一定作用.甘家岭变沉积岩中的粒间柯石英产在弱相矿物白云石和磷灰石颗粒之间(图2),同时寄主岩石无明显变形记录(Liu *et al.*,2017),故其保存不能用粒间"构造超压"进行解释.因此,超高压变质岩中柯石英的保存可

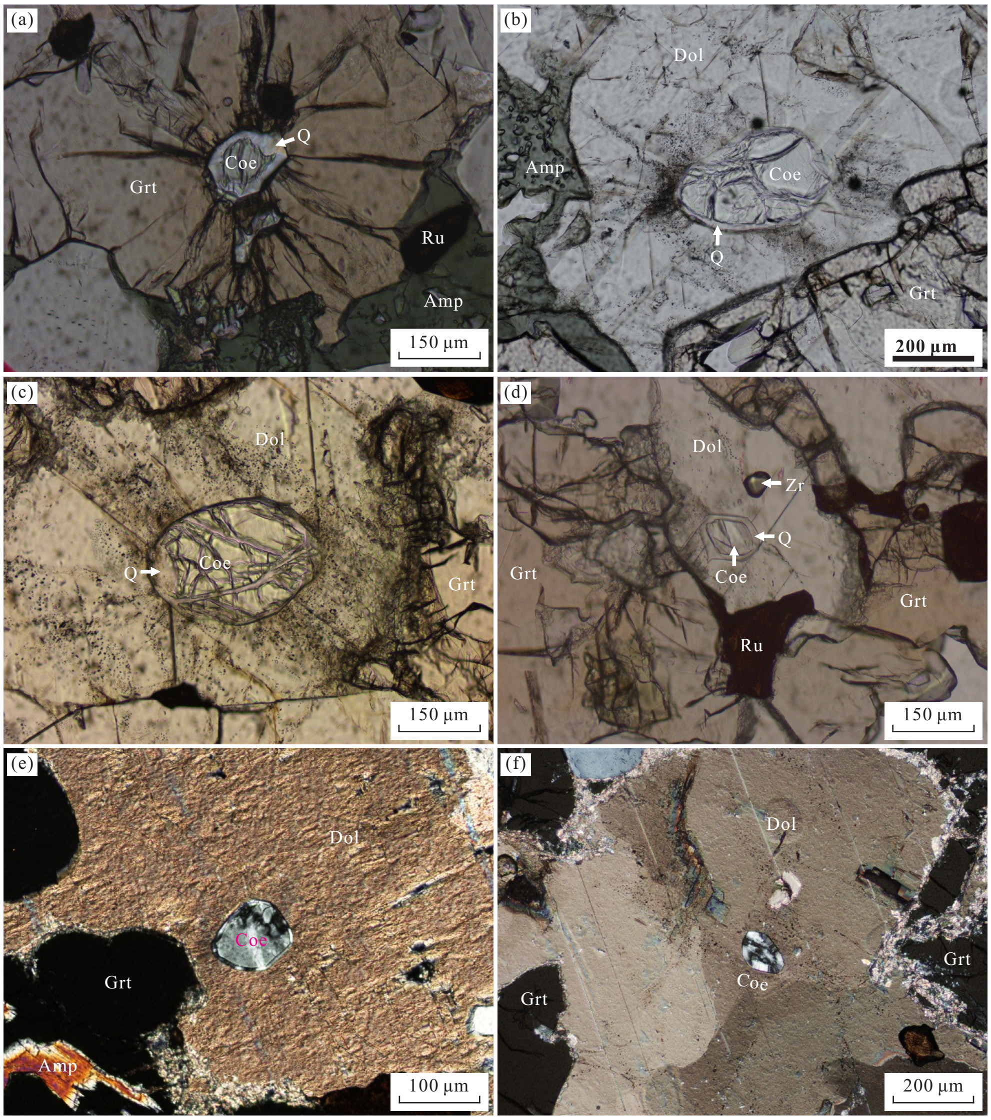

图1 大别山甘家岭富碳酸盐变沉积岩中的柯石英包裹体

Fig.1 Coesite inclusions in the Ganjialing carbonate-rich metasedimentary rock from Dabieshan

a.石榴子石中的柯石英包裹体,周围发育发射状裂纹;b~f.白云石中的柯石英包裹体,周围缺失放射状裂纹;所有的柯石英包裹体沿颗粒边界和/或裂隙均不同程度地被细粒石英集合体取代;a~d.单偏光;e、f.正交光;Amp.角闪石;Coe.柯石英;Dol.白云石;Grt.石榴子石;Q.石英;Ru.金红石;Zr.锆石;据Liu *et al.*(2017)

能和反应动力学过程具有更加紧密的联系.

从反应动力学的角度进行定义,柯石英的退变程度=退变速率×退变时间,而退变速率又同温度和流体活度呈正比关系.柯石英退变动力学实验研究表明,在名义上缺水且温度高于375 ℃的条件下,一颗100 μm大小(该粒度在超高压变质岩中具有代表性)的柯石英完全退变为石英仅需不超过一百万年的时间(Mosenfelder and Bohlen,1997;Mosenfelder *et al.*,2005;Perrillat *et al.*,2003;Lathe *et al.*,2005).地质年代学的研究结果表明,折返中的超高压地体从进入石英稳定域开始直到角闪岩相(500~600 ℃)退变质阶段至少要历经几百万年的时间(Hermann and Rubatto,2014).因此,柯石英的保存需要重点考虑退变速率而非退变时间,而影响退变速率的因素中又需要重点考虑流体活度而非温度.具体来讲,超高压变质岩中柯石英保存的局部流体环境要比上述实验条件更加干燥.仰口含粒间柯石英的榴辉岩没有经历角闪岩相等退变质作用的叠加改造,同时缺乏含水矿物如多硅白云母,故流体活动的缺失可以很好地解释仰口榴辉岩中粒间柯石英的保存(Liou and Zhang,1996;叶凯等,1996;Wang *et al.*,2018).甘家岭含粒间柯石英的变

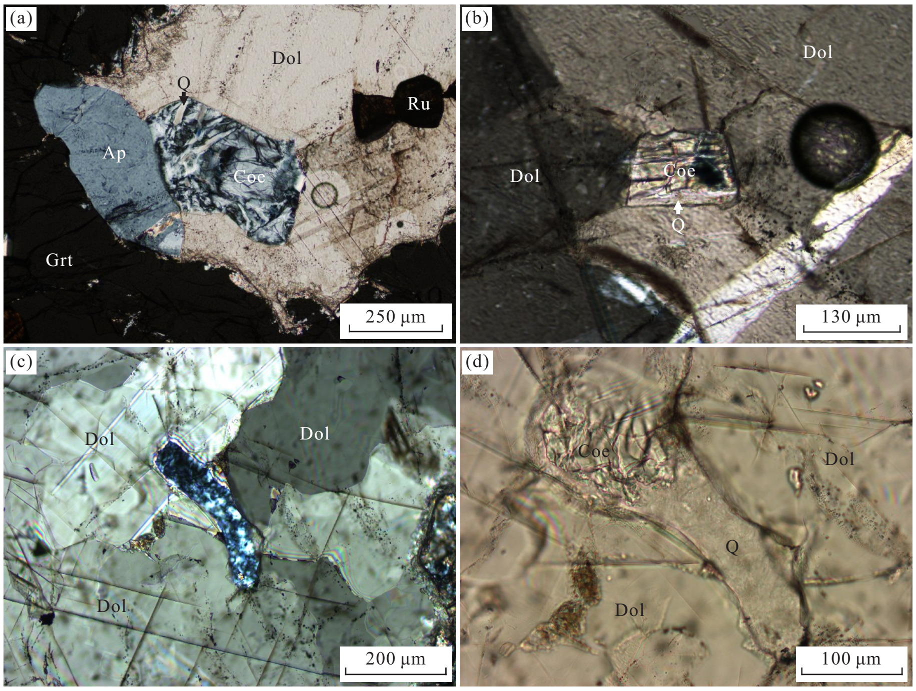

图 2　大别山甘家岭富碳酸盐变沉积岩中的粒间柯石英

Fig.2　Interstitial coesite in the Ganjialing carbonate-rich metasedimentary rock from Dabieshan

a.两粒白云石和磷灰石之间的粒间柯石英；b.两粒白云石之间的粒间柯石英；c、d.四粒白云石之间的粒间柯石英；a～c.正交光；d.单偏光；Ap.磷灰石；修改自 Liu *et al*.(2017)

沉积岩经历了一定程度的角闪岩退变质作用(Liu *et al*.,2017)，故基质中的大多数柯石英已完全退变为石英，而少数粒间柯石英的保存可能和周围矿物差异体应变引起的局部密闭环境有关(图 2).不同于寄主矿物石榴子石，白云石中的柯石英包裹体周围普遍缺乏放射状裂纹(图 1b～1f).这意味着基质中的流体很难渗透到白云石的柯石英包裹体中，从而有利于柯石英包裹体的保存.

除了基质中的自由水外，柯石英本身的结构水含量也会极大地影响柯石英的退变速率(Lathe *et al*.,2005；刘卫平等，2018).值得进一步强调说明的是，前人还未考虑过寄主矿物中的结构水对柯石英包裹体退变过程的影响.以石榴子石为例，名义上不含水的矿物中可以含有一定量的结构水(盛英明等，2005)，同时结构水含量往往随压力升高而增加(Lu and Keppler，1997；Withers *et al*.，1998；Katayama *et al*.，2006).因此，石榴子石在折返过程中会出溶结构水，结构水出溶的时间以及由此形成的自由流体的去向可能会影响柯石英包裹体的保存.不同于石榴子石，白云石中基本上不含任何结构水(Liu *et al*.,2017).考虑到白云石中的柯石英包裹体周围也不发育放射状裂纹，那么从反应动力学即流体来源的角度进行理解，白云石相对于石榴子石应该是一种可以更好地保存柯石英包裹体的寄主矿物.

3　结语

制约柯石英的保存机制对于认识超高压变质岩的形成和演化具有重要的启示意义.基于新近报道的大别山甘家岭超高压变沉积岩中的粒间柯石英和白云石中的大量柯石英包裹体可以推测，反应动力学即较干的变质演化环境在保存柯石英方面可能起到了更为关键的作用，传统的"高压釜"模型在保存柯石英方面可能也起着一定作用，但其重要性不如反应动力学机制.

致谢：感谢两位匿名评审人的认真审阅和提出的宝贵意见.

References

Bohlen, S. R., Boettcher, A. L., 1982. The Quartz-Coesite Transformation: A Pressure Determination and the Effects of Other Components. *Journal of Geophysical Research*, 87(B8):7073－7078.

Chao, E. T. C., Shoemaker, E. M., Madsen, B. M., 1960. First Natural Occurrence of Coesite. *Science*, 132(3421): 220—222. https://doi.org/10.1126/science.132.3421.220

Chopin, C., 1984. Coesite and Pure Pyrope in High‑Grade Blueschists of the Western Alps: A First Record and Some Consequences. *Contributions to Mineralogy and Petrology*, 86(2): 107—118.

Coes, L., 1953. A New Dense Crystalline Silica. *Science*, 118(3057): 131—132.

Gillet, P., Ingrin, J., Chopin, C., 1984. Coesite in Subducted Continental Crust: *P*-*T* History Deduced from an Elastic Model. *Earth and Planetary Science Letters*, 70(2): 426—436.

Green, H. W., 1972. Metastable Growth of Coesite in Highly Strained Quartz. *Journal of Geophysical Research*, 77(14): 2478—2482.

Guiraud, M., Powell, R., 2006. *P*-*V*-*T* Relationships and Mineral Equilibria in Inclusions in Minerals. *Earth and Planetary Science Letters*, 244(3—4): 683—694. https://doi.org/10.1016/j.epsl.2006.02.021

Hermann, J., Rubatto, D., 2014. Subduction of Continental Crust to Mantle Depth: Geochemistry of Ultrahigh‑Pressure Rocks. *Treatise on Geochemistry*, 4: 309—340.

Hirth, G., Tullis, J., 1994. The Brittle-Plastic Transition in Experimentally Deformed Quartz Aggregates. *Journal of Geophysical Research*, 99(B6): 11731—11747.

Katayama, I., Nakashima, S., Yurimoto, H., 2006. Water Content in Natural Eclogite and Implication for Water Transport into the Deep Upper Mantle. *Lithos*, 86(3—4): 245—259.

Lathe, C., Koch-Müller, M., Wirth, R., et al., 2005. The Influence of OH in Coesite on the Kinetics of the Coesite‑Quartz Phase Transition. *American Mineralogist*, 90(1): 36—43. https://doi.org/10.2138/am.2005.1662

Liou, J. G., Zhang, R. Y., 1996. Occurrences of Intergranular Coesite in Ultrahigh‑P Rocks from the Sulu Region, Eastern China: Implications for Lack of Fluid during Exhumation. *American Mineralogist*, 81(9—10): 1217—1221.

Liou, J. G., Zhang, R. Y., Liu, F. L., et al., 2012. Mineralogy, Petrology, U‑Pb Geochronology, and Geologic Evolution of the Dabie-Sulu Classic Ultrahigh-Pressure Metamorphic Terrane, East-Central China. *American Mineralogist*, 97(10): 1533—1543. https://doi.org/10.2138/am.2012.4169

Liu, F. L., Liou, J. G., 2011. Zircon as the Best Mineral for P-T-Time History of UHP Metamorphism: A Review on Mineral Inclusions and U-Pb SHRIMP Ages of Zircons from the Dabie‑Sulu UHP Rocks. *Journal of Asian Earth Sciences*, 40(1): 1—39.

Liu, P. L., Massonne, H. J., Zhang, J. F., et al., 2017. Intergranular Coesite and Coesite Inclusions in Dolomite from the Dabie Shan: Constraints on the Preservation of Coesite in UHP Rocks. *Terra Nova*, 29(3): 154—161.

Liu, P. L., Wu, Y., Chen, Y., et al., 2015. UHP Impure Marbles from the Dabie Mountains: Metamorphic Evolution and Carbon Cycling in Continental Subduction Zones. *Lithos*, 212—215: 280—297.

Liu, W. P., Wu, X. L., Zhang, X. L., et al., 2018. Micro-FTIR Analysis and First‑Principle Calculation of Structural Water in Coesite from NAMs. *Earth Science*, 43(5): 1474—1480 (in Chinese with English abstract).

Lu, R., Keppler, H., 1997. Water Solubility in Pyrope to 100 kbar. *Contributions to Mineralogy and Petrology*, 129(1): 35—42.

Lü, Z., Zhang, L. F., Chen, Z. Y., 2014. Jadeite- and Dolomite-Bearing Coesite Eclogite from Western Tianshan, NW China. *European Journal of Mineralogy*, 26(2): 245—256.

Mosenfelder, J. L., Bohlen, S. R., 1997. Kinetics of the Coesite to Quartz Transformation. *Earth and Planetary Science Letters*, 153(1—2): 133—147.

Mosenfelder, J. L., Schertl, H. P., Smyth, J. R., et al., 2005. Factors in the Preservation of Coesite: The Importance of Fluid Infiltration. *American Mineralogist*, 90(5—6): 779—789.

Perrillat, J. P., Daniel, I., Lardeaux, J. M., et al., 2003. Kinetics of the Coesite-Quartz Transition: Application to the Exhumation of Ultrahigh-Pressure Rocks. *Journal of Petrology*, 44(4): 773—788. https://doi.org/10.1093/petrology/44.4.773

Richter, B., Stünitz, H., Heilbronner, R., 2016. Stresses and Pressures at the Quartz‑to‑Coesite Phase Transformation in Shear Deformation Experiments. *Journal of Geophysical Research: Solid Earth*, 121(11): 8015—8033.

Schertl, H. P., Okay, A. I., 1994. A Coesite Inclusion in Dolomite in Dabie Shan, China: Petrological and Rheological Significance. *European Journal of Mineralogy*, 6(6): 995—1000.

Schönig, J., von Eynatten, H., Meinhold, G., et al., 2019. Diamond and Coesite Inclusions in Detrital Garnet of the Saxonian Erzgebirge, Germany. *Geology*, 47(8): 715—718.

Sheng, Y. M., Xia, Q. K., Hao, Y. D., et al., 2005. Water in UHP Eclogites at Shuanghe, Dabieshan: Micro‑FTIR Analysis. *Earth Science*, 30(6): 673—684 (in Chinese with English abstract).

Smyth, J.R., 1977. Quartz Pseudomorphs after Coesite. *American Mineralogist*, 62:828－830.

van der Molen, I., van Roermund, H.L.M., 1986. The Pressure Path of Solid Inclusions in Minerals: The Retention of Coesite Inclusions during Uplift. *Lithos*, 19(3－4): 317－324.

Wang, L., Wang, S.J., Brown, M., et al., 2018. On the Survival of Intergranular Coesite in UHP Eclogite. *Journal of Metamorphic Geology*, 36:173－194.

Withers, A.C., Wood, B.J., Carrol, M.R., 1998. The OH Content of Pyrope at High Pressure. *Chemical Geology*, 147 (1－2):161－171.

Yang, J.J., Fan, Z.F., Yu, C., et al., 2014a. Coseismic Formation of Eclogite Facies Cataclasite Dykes at Yangkou in the Chinese Su-Lu UHP Metamorphic Belt. *Journal of Metamorphic Geology*, 32:937－960.

Yang, J.J., Huang, M.X., Wu, Q.Y., et al., 2014b. Coesite-Bearing Eclogite Breccia: Implication for Coseismic Ultrahigh-Pressure Metamorphism and the Rate of the Process. *Contributions to Mineralogy and Petrology*, 167(6): 1013－1030.

Yang, J.J., Zhang, H.R., Chen, A.P., et al., 2016. Petrological Evidence for Shock-Induced High-P Metamorphism in a Gabbro. *Journal of Metamorphic Geology*, 35(2): 121－140.

Ye, K., Hirajima, T., Ishiwatari, A., et al., 1996. Significance of Interstitial Coesite in Eclogite from Yangkou, Qingdao City, Eastern Shandong Province. *Chinese Science Bulletin*, 41(15):1047－1048(in Chinese).

Zhang, R.Y., Liou, J.G., 1996. Coesite Inclusions in Dolomite from Eclogite in the Southern Dabie Mountains, China: The Significance of Carbonate Minerals in UHPM Rocks. *American Mineralogist*, 81(1－2):181－186.

Zhou, Y.S., He, C.R., Song, J., et al., 2005. An Experiment Study of Quartz-Coesite Transition at Differential Stress. *Chinese Science Bulletin*, 50(5):446－451.

附中文参考文献

刘卫平，吴秀玲，张晓玲，等，2018. NAMs柯石英中结构水的红外光谱和第一性原理计算. 地球科学，43(5)：1474－1480.

盛英明，夏群科，郝艳东，等，2005. 大别山双河超高压榴辉岩中的水：微区红外光谱分析. 地球科学，30(6)：673－684.

叶凯，平岛崇男，石渡明，等，1996. 青岛仰口榴辉岩中粒间柯石英的发现及其意义. 科学通报，41(15)：1047－1048.