JADE: its tectonic formation, geochemistry, and archaeology in East Asia – in reverse order

Gina L. Barnes

East Asian jade

Traditionally, the highest prized jade in China is “mutton fat” jade, a white nephrite. In 1990, it cost US$3,000 per ounce. Since 1784, however, a jadeite from Myanmar (Burma) called “imperial green jade” began to be exported and has gained great popularity in China. Before then, only nephrite was known in China especially that from Khotan (Hetian) of Silk Road fame in the southern Tarim Basin of western China. The only source of jadeite in East Asia is from the Jade Coast in Niigata prefecture of Japan and known as “Itoigawa jade”; however, it was not distributed to China – only as far as Korea.

Jade for working is mostly collected as cobbles from riverbeds or beaches. Hetian nephrite from Khotan is mostly collected from the White Jade River, while Itoigawa jadeite from Niigata is collected from the Hime River emptying onto the “Jade Coast” in the Japan Sea.

Both kinds of jade are metamorphic minerals. Nephrite is a hydrous calcic amphibole [$Ca_2Mg_5Si_8O_{22}(OH)_2$], while jadeite is a non-hydrous sodic pyroxene [$NaAlSi_2O_6$]. Although nephrite is tougher than jadeite because of its fibrous (asbestiform) nature, it is slightly softer (at Mohs 6–6.5) than jadeite (Mohs 6–7). The toughness and hardness of these jades respectively have required special forming techniques: they can be flaked like normal stone tools but only grossly. To shape them, they are usually cut using a “flexible string” (maybe leather or bamboo) together with an abrasive, usually quartz sand. Cutting slabs of nephrite in prehistoric China led to most artefacts being flat or flat-sided. They could then be rounded off by grinding with abrasive, and features could be applied by flexible string, as the wedge-shaped notches in early Hongshan jades illustrate (Figure 1).

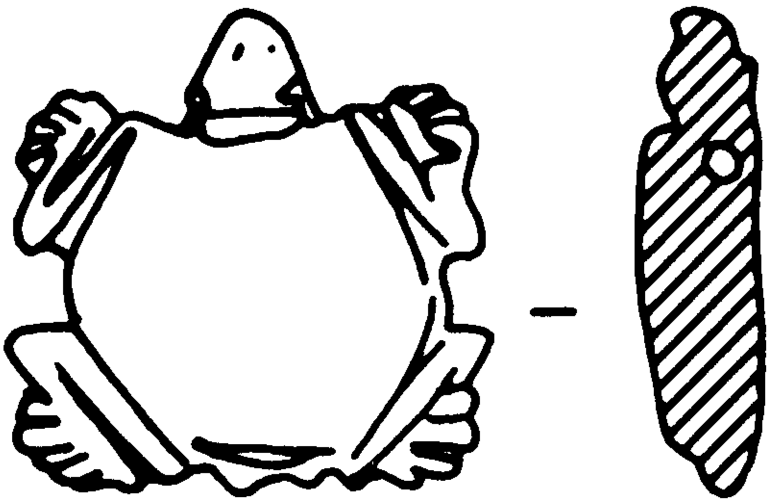

Figure 1 **Hongshan jade turtle totem, from the Hongshan culture of northeastern China (ca. 4500–2800 BC) [after Barnes 2015]**

Towards the end of the Neolithic period in China, fine engraving techniques were developed. Scanning electron microscopy (SEM) by Margaret Sax of the British Museum showed that each line was composed of fine tool notches as the line was created pushing forwards rather than drawing the tool across the jade. The tool used might have been quartz in the form of flint or chert – a harder material at Mohs 7 than nephrite. Today drills as fine as dentist drills are used to shape and incise the fine details of Chinese jades.

The earliest jade use in the world is currently known from north-eastern China in the Neolithic Xinglongwa culture, 8000–7000BC. Nephrite was used to make slit earrings, among other artefacts. The same area developed into the Hongshan culture, 4600–2800BC, which has given us unique shapes and styles of jades, especially what are called "pig dragons", but also flared tubes, cloud-shaped ornaments, etc. These are often rounded, bevelled, and finely incised, while flexible string forming is known from turtle totems. The apex of Neolithic jade-working was the Liangzhu culture in the 3rd millennium BC. In the region of the Shanghai delta, jade workshops are known to have produced flat *bi* disks and jade *cong* tubes with square outer walls but circular core. Both these forms occasionally have fine designs engraved on them, most notably the beast & man with headdress motif.

Jade was used extensively in burials in early historic China, in the Zhou to Han periods between 700–100BC. It was thought that they preserved the body, hence the creation of jade suits and the placing of jade pieces on all the orifices of the body to keep in the spirit. Jade ornaments and artefacts were symbols of power, ritual, morality, wealth, and immortality. In historic times, the 5 Virtues of Jade were constituted as:

- Smoothness = the virtue of humanity;
- Translucence = the virtue of justice;
- Sound = the virtue of wisdom;
- Hardness = the virtue of courage; and
- Purity = the virtue of honesty.

In Japan and Korea, jade usage was somewhat different. Itoigawa jadeite was utilized in Japan from Jomon times, particularly in the 1st millennium BC. The ornaments of these hunter-gatherer-horticulturalists consisted of slit earrings and pebble pendants. In the Kofun period of state formation (250–645AD), curved beads became an important insignia of the elite, and the curved bead (*magatama*), bronze mirror and sword comprise the imperial regalia of the Japanese emperor. The Korean Peninsula has sources of nephrite, but they were not intensively exploited. Instead, amazonite (a meta-feldspar called microcline) was primarily used in the Neolithic and Bronze Ages. However, during the Silla period (300–668AD) of state formation, curved beads made of Itoigawa jade were used in royal crowns; whether the raw materials or the finished beads were imported is not yet confirmed – maybe both.

Jade geochemistry

Both jadeite and nephrite are metamorphic minerals; however, they generally formed not from pressure/temperature metamorphism but from metasomatism, i.e., they are solid-solution minerals that precipitated from *fluids*. Solid-solution minerals exhibit a continuous distribution of exchangeable elements, and their variable chemical constitutions form different minerals within that distributional range.

Nephrite belongs to the Tremolite-Actinolite-Ferroactinolite (T-A-F) solid solution series, which has as its basic elements Ca, Si, O and H, with the addition of either Mg, or Fe. Pure nephrite jade is the mineral tremolite [$Ca_2Mg_5Si_8(OH)_2$]. Replacement of Mg by Fe leads to the formation of actinolite [$Ca_2[Mg,Fe)_5Si_8(OH)_2$] and ferro-actinolite [$Ca_2Fe_5Si_8(OH)_2$]. "The idealized actinolite chemical formula, is rarely encountered with natural samples. There are generally appreciable amounts of Al^{3+}, Fe^{3+}, Mn, Cr, and Na" (Mustard 1992:345). In fact, it is difficult to find pure end members as well, so that most Chinese nephrites can be classed as tremolite-actinolite.

The Ca-Mg-Fe solid solution chemistry has other outcomes besides the T-A-F series - from anthophyllite [$Mg_1Si_8O_{22}(OH)_2$] through Cummingtonite [$(Mg,Fe)_7Si_8O_{22}(OH)_2$] to Grunerite [$Fe_1Si_8O_{22}(OH)_2$]. Again, these minerals are rarely pure, with other elements as named above substituted for Mg and Fe. The fact that there are two different solid solution series for the same elements means that depending on availability of elements in different liquid mixtures, up to six different minerals may form, giving nephrite chemical relatives that might occur with it as neighbours in geological settings.

Looking at tremolite alone, the mineral may consist of major elements of over 1% each (that are represented in the ideal chemical formula: Si, Mg, Ca, H, O), minor elements of between 0.1–1% (Fe, Na, Mn), and trace elements of less than 0.1% (F, Al, K, Cl, T). These elements were reported for an Italian tremolite of 98% purity. Despite such possible variability in minor and trace elements even in almost pure jade, however, Chinese studies of archaeological nephrite were not able to identify sources because the chemical compositions were so similar. Isotopic analyses of the artefacts could assist in nephrite sourcing, but there is no comparative collection from jade sources as yet.

Jadeite is much more complicated than nephrite as it belongs to a solid solution that is continually graded among several different minerals. The nearest relatives of jadeite [$NaAlSi_2O_6$] are omphacite [$(Ca,Na)(Mg,Fe,Al)Si_2O_6$] and aegirine [$NaFe^{3+}Si_2O_6$]. Their relatives are Aegirine-augite, augite and other Ca-Fe-Mg pyroxenes: orthoferrosilite, eulite, ferro-hypersthene, hypersthene, bronzite, enstatite, diopside, salite, ferrosalite, ferroaugite, and hedenbergite. Thus again, several minerals can precipitate from the same solution if the elements are temporally or spatially differentiated, and jadeite might coexist with some of these minerals as neighbours in a geological deposit. Moreover, jadeites are rarely pure: most have some diopside (Ca,Mg) molecules or augite group minerals [$(Ca,Na)(Mg,Fe,Al,Ti)(Si,Al)_2O_6$] in them (Harlow 2012).

Given the variety of minerals that can occur and be found together in geological settings, it is necessary to distinguish rock from mineral. Nephrite, a term well used in the archaeological literature, is not a valid mineral name according to the IMA (International Mineralogical Association). The mineral instead should be referred to as tremolite or tremolite-actinolite and the rock it occurs in (possibly together with other minerals such as actinolite or ferro-actinolite) can be called nephrite. Jadeite, on the other hand, is a mineral that occurs in the rock called jadeitite, defined as at least 90 vol% pyroxene AND that pyroxene contains 90%wt jadeite. Thus, a jadeitite may be composed of, e.g., Jade Jd100–Jd80 +Aegirine1-10, with an omphacite overgrowth and some presence of diopside.

Pseudo-jades include up to forty other rocks and minerals that masquerade as jades in the archaeological record. Some of the more common are: serpentine, prehnite, aventurine quartz, grossular garnet, chrysoprase, and dolomite marble. How does one identify true jade? Scientifically, x-ray diffraction and Raman spectroscopy are used. One study on Lantian jade (Wang, Gan & Zhao 2012) discovered that the rock was lizardite jade, a variety of serpentinite rock that consisted of the minerals calcite and lizardite with traces of talc, dolomite and tremolite.

Petrogenesis

There are two host rocks from which the jade rocks and minerals are formed through metamorphism, limestone, which is loaded with calcite [$CaCO_3$], and mantle rock (peridotite, lherzolite, dunite or hartzburgite) that contains varying amounts of olivine [$(Mg,Fe)_2SiO_4$]. Each of these host rocks can undergo metasomatism or P/T metamorphism (Figure 2). In addition, one mineral, albite, can undergo P/T metamorphism to produce jadeite + quartz, complicating the picture.

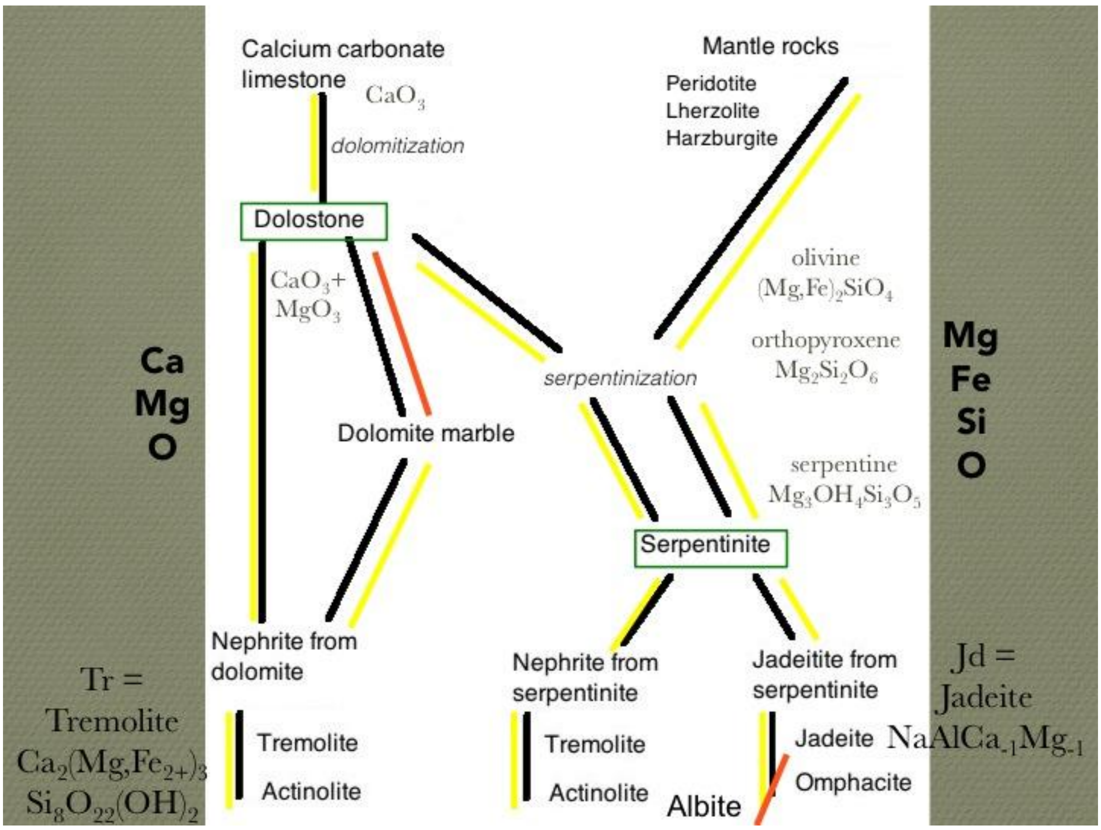

Figure 2 Schematic representation of jade petrology from host rocks of limestone and mantle rocks via metasomatism and vein crystallization (yellow lines) and P/T metamorphism (orange lines) [© Barnes 2015]

- Limestone can be turned into dolostone (a rock) through the substitution of Mg for Ca; the main mineral being dolomite [$MgCO_3$]. This can be acted on

directly by fluids to produce nephrite and its constituent minerals tremolite and actinolite or it can be P/T metamorphosed into dolomitic marble and then acted on by fluids to produce nephrite and its constituent minerals tremolite and actinolite.
- Dolostone can also be serpentinized through metasomatism, resulting in serpentinite, which can further be metasomatized into nephrite and its constituent minerals tremolite and actinolite.
- Starting with mantle rocks, these can be metasomatized and serpentinized into serpentinite, then further metasomatized into jadeitite and its constituent minerals jadeite and omphacite.

Thus, we have three different routes for the formation of nephrite – directly from dolostone, via dolomitic marble, and via serpentinite – and we have two different routes for the formation of jadeite – from mantle rocks via serpentinization and from solid-state recrystallization of albite.

The process by which metasomatism produces the jade minerals is not completely known. Was there a "ready fluid", or did it gain elements during circulation? Were the elements drawn from country rock or present in seawater, or meteoric water?

Geological settings

True jades are associated with subduction zones. Nephrite commonly occurs in ophiolites – slices of the ocean floor that formed in back-arc basins and have been emplaced on land during the final stages of subduction and ocean closure. The co-occurrences of nephrite sources and ophiolite locations around the world have been mapped by Harlow (2014). Two types of nephrite are distinguished: that formed from dolomite (dolostone) and that from serpentinite; however, whether that serpentinite came from metasomatized dolostone or mantle rock is not stated/known. The geographical correlation maps show that for Chinese nephrite, there are fifteen known locations for jade from carbonate (especially from the Altun belt south of the Tarim Basin, which is 1100km long), and seven locations for jade from serpentinite.

In contrast, the occurrences of jadeitite around the world correlate with metamorphic rocks of blueschist facies in subduction zones, within or separate from ophiolites. Jadeitite forms in subduction zones where the dehydration of the downgoing oceanic crust releases fluids into the overlying mantle, serpentinizing the peridotite into serpentinite and further formation of jadeitite. Three case studies in Myanmar, Japan and Guatemala demonstrate that jadeitite is formed in veins in association with several other surrounding minerals in zoned layers within serpentinite.

The geological maps for the East Asian region shows that the orogenic zones containing ophiolites and blueschist facies rocks are concentrated in the Central Asian Orogenic Belt between the North China craton and the Siberian Craton in the paleo-Tethys region. Also, examination of granite masses across China, which indicate prior subduction zones, are highly represented in the south-east and north-west. The jades from the northern Hongshan culture have been sourced to an outcrop in the eastern Manchurian Basin, and those from southern Liangzhu are sourced to the nearby Meitian deposit. The latter were discovered to match by comparing the formation dates of the jade in the artefacts and in the source. Thus it seems that the

Hetian jade sources at Khotan were not employed during the Neolithic but were developed later with the Silk Road trade.

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