

JADE: OCCURRENCE AND METASOMATIC ORIGIN

¹HARLOW, G. E. and ²SORENSEN, S. S. ¹American Museum of Natural History, New York, NY, U.S.A.;

²Smithsonian Institution, Washington, DC, U.S.A.

The term jade, as used in geology and gemology, refers to two extremely tough, essentially monomineralic rocks used for carvings and gems. Amphibole jade is nephrite, a tremolite-actinolite [$\text{Ca}_2(\text{Mg,Fe})_5\text{Si}_8\text{O}_{22}(\text{OH})_2$] rock with a felted, microcrystalline habit, and pyroxene jade is jadeite [$\text{NaAlSi}_2\text{O}_6$] rock (jadeitite) which varies from micro- to macrocrystalline textures. Both rock types have received relatively little attention due to their scarcity, minor economic importance, and cryptic petrography. The geological interpretation of both jade types has been hindered by poor exposure and the occurrence of major jadeitite deposits in politically unstable countries. However, recent investigations show not only that the jades share some common geological characteristics, but both result from and record important Earth processes.

Nephrite is the more common and less valuable of the two jade types. Important deposits occur at the Polar, Kutcho, and Ogden Mtn. properties in northern British Columbia, Canada (Gabrielse, 1990); Kunlun Mtns., Xinjiang, China (see Webster, 1975); SW of Lake Baikal in the East Sayan Mtns., Siberia, Russia (Prokhor, 1991); near Cowell, South Australia (Flint and Dubowski, 1990); the Westland (Arahura River—Cooper, 1995), the Livingstone, Nelson, Otago, and South Westland fields on South Island, New Zealand (Beck, 1991); northeastern Taiwan (Wand, 1987); Jordansmuhl, Poland (Visser, 1946); in the Granite Mtns., Lander Co., Wyoming (Madson, 1978); and along the Noatak & Kobuk Rivers south of the Brooks Range in Alaska (Loney and Himmelberg, 1985). Many minor occurrences are associated with small ultramafics in ophiolite belts around the world, such as in the Western and Central Alps, central Brazil, and the ophiolite belts from California to Alaska.

Nephrite ranges from pure, white tremolite (“mutton-fat jade”) to dark green actinolite and occasionally black from Fe-actinolite or oxide / graphite pigment. Rarely nephrite can have an emerald-green color from Cr^{3+} in sodic-tremolite/actinolite. Staining to ochre colors from iron oxidation in weathering rinds of boulders is common. Minor coexisting minerals include diopside, garnet, magnetite, chromite, graphite, apatite, rutile, pyrite, datolite, vesuvianite, prehnite, talc, and titanite. Nephrite bodies result from contact and/or infiltration metasomatism of either dolomite by magmatic fluids or silicic rocks by serpentinite fluids. White nephrite is derived from siliceous metasomatism of dolomite by a

“granitic” body or its pneumatolytic / hydrothermal apophyses (e.g., Yurung-kash [White Jade River], Kunlun Mtns.). However, dolomite metasomatism can yield green to black jade if a source of iron is present, such as from mafic bodies, iron-stone (e.g., Cowell), etc. Other nephrites involve either metasomatism of silicic rocks in serpentinite (or serpentinite melange) by Ca-Mg-rich fluids or a blackwall-like boundary reaction between silicic rocks and CaMg-rich aqueous fluids from serpentinite (see Karpov *et al.* 1988; Suturen, 1986). Ca saturation is produced by clinopyroxene breakdown during maximum serpentinitization, however, in part, it may also be the result of decreasing P and increasing T upon fluids rising through (and with) serpentinite melange—see below. Conditions can range from the high T limit of greenschist-amphibolite facies (< 550 °C) in the dolomite-derived type to moderate (~400 °C for Fengtian nephrite, Taiwan; Yui *et al.*, 1988) to very low temperatures (~100 °C) in ophiolites; all occur at moderate to low pressure (<2kbar?). Supersaturation of interacting fluids or fluids and solids at low T appears to yield the fibrous-mat crystallizations characteristic of nephrite; alternatively some authors attribute the nephrite texture to recrystallization of metasomatic amphibole by subsequent shear deformation (e.g., Cooper, 1995) or replacement of serpentinite (e.g., O’Hanley, 1996). Botryoidal nephrite from northern California and appears to result from infiltration of serpentinite vein fluid into permeable graywacke blocks, reaction with the permeable matrix, and creation of little “cumulus cloud” structures (Harlow, unpublished data).

Jadeitite is rarer than nephrite and, when translucent, is the “precious” jade used in jewelry. The largest and most important deposit is the Hpakan-Tawmaw tract, Kachin State, northern Myanmar (Burma) and in conglomerates and alluvials derived from that source (Chhibber, 1934; Bender, 1983; Hughes *et al.*, in press). The important source of New World jade is in the middle Motagua Valley, Guatemala (Harlow, 1994). Relatively undeveloped deposits exist along Ketchpel River, Pay-Yer massif, Polar Urals (Morkovkina, 1960), and the Borus Mtns, West Sayan (Dobretsov, 1963) in Russia and Itmurundy, near Lake Balkhash, Kazakhstan (Dobretsov and Ponomareva, 1965). Other localities are along the Kotaki River, Niigata Pref., Japan (Chihara, 1971) and along Clear Creek in the New Idria serpentinite, San Benito Co., California (Coleman, 1961). Except for the Polar Urals occurrence, which is probably Devonian, jadeitite deposits are associated with post-Cretaceous geology.

Jadeitite is a very uncommon rock type restricted to primary occurrences in bodies of subduction-related serpentine along major fault zones. Pure jadeite jade is

white, "Imperial" emerald green is due to Cr^{3+} , leak-green from Fe^{2+} , blue-green from mixed Fe^{2+} and Fe^{3+} and mauve from Mn^{2+} . A new blue jadeite from Guatemala has not as yet been studied. Compositions range from Jd_{100} to omphacite usually with Ac_{5-10} . Jadeite occurs as veins (Myanmar, California) or tectonic blocks (Guatemala, Polar Urals) generally with surrounding albite, actinolite schist and a blackwall rind bounding serpentinite. Minerals coexisting with primary jadeite include sodic amphibole (eckermannite in Myanmar) or mica (phengite and/or paragonite in Guatemala) \pm albite, titanite, rutile, zircon, apatite, chromite, pyrite, and graphite—quartz is absent except in a single sample reported by Smith and Gendron (1997). Crystals of jadeite in jadeites are cryptically to rhythmically zoned, indicating crystallization from an aqueous fluid. Thus, most jadeites probably began as vein crystallizations, although a partial metasomatic replacement origin is difficult to rule out. The host serpentinite is either highly faulted or a melange and is always associated with a major fault which is usually a lateral fault on the wedge side of a fossilized convergent margin. Consequently fluid flow in faulted serpentinite and emplacement of serpentinite along faults active during subduction or collision are critical features to jadeite occurrences.

Jadeite is a high pressure mineral, but with $P_{\text{H}_2\text{O}} = P_{\text{total}}$ and no quartz, P is only $> 5-6$ kbar (reaction $\text{Jd} + \text{W} = \text{Anl}$) rather than $> 8-11$ kbar (reaction $\text{Jd} + \text{Qtz} = \text{Ab}$) for the low T environments (200 to 400 °C based on assemblages). Nevertheless, this represents substantial depth ($> 16 - 20$ km) for a fluid that deposits jadeite in serpentinite (serpentinizing peridotite) by rising through an accretionary wedge. Fluid inclusions and O/H isotopic systematics infer the predominance of a seawater-like fluid entrained during subduction rather than the product of dehydration of deep metamorphic minerals, at least for Guatemala (Johnson and Harlow, 1999). Trace element studies of jadeite from jadeites manifest considerable heterogeneity, suggesting diverse fluid trajectories for different jadeites in the same deposit, although overall trends suggest some deposits may be derived primarily from sediments (perhaps in Guatemala) while others may record a significant felsic-igneous component (perhaps Myanmar) (Sorensen and Harlow, 1998, 1999, and in prep.).

Jadeite formation requires devolatilization, primarily dewatering of sediments, within a subducting slab at depths down to the blueschist-to-eclogite transition. Such fluids will be enriched in components that are nearly saturated with jadeite (e.g., Manning, 1998). These fluids may become channelized through overlying serpentinitized peridotite (of unknown provenance) which

can diapirically rise along a fore-arc transform/lateral fault, which may be related to final oblique convergence of continental (Myanmar) or island arc (Guatemala) terrane. Crystallization of jadeite provides a focus for brittle fracture, fluid flow, and further deposition of jadeite during serpentinite diapirism and faulting. Fluid travels down P but up T. Fractionation by jadeite crystallization and decrease in P progressively enriches the diopside content in the rising fluid, so pyroxene crystallization trends to omphacite at crystal rims. Increased silica activity at shallower depths leads to the co-crystallization of albite + omphacite or diopside. Interaction of the fluid with tectonic blocks entrained in the host serpentinite can lead to jadeitization, or in the case of basaltic blocks, the formation of Fe-rich omphacites or omphacite-rich amphibolites. At the top of the system tremolite may saturate—with possible formation of nephrite. The diapiric rise of serpentine, perhaps enhanced by collision, exposes fossil jadeite, however the rapid uplift may also result in a short duration of exposure, explaining the paucity and young age of most jadeite deposits.

The formation of most nephrite and jadeite deposits records events at convergent margins that involve fluid interactions in and around serpentinizing peridotite at depths from perhaps > 50 km to the near surface. Preservation of the jade is a relatively rare event that may require special tectonic conditions and a limited range of peridotite hosts for jadeite and perhaps nephrite. Jades are thus unique probes of convergent margins and fluids derived from subduction zone devolatilization—profoundly interesting geologically as well as materially and archaeologically.

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