Plate tectonic gemstones

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ABSTRACT

The gemstones jadeite and ruby generally form as a result of the plate tectonic processes subduction and collision. Jade made of jadeite (jadeitite) forms when supercritical fluids released from subducting oceanic crust condense in the overlying mantle wedge, 20–120 km deep in the Earth. Jadeitite deposits thus mark the location of exhumed fossil subduction zones. Ruby, the red gem variety of corundum, forms during amphibolite- and granulite-facies metamorphism or melting of mixed Al-rich and Si-poor protoliths, 10–40 km deep in the crust. Suitable conditions generally exist where passive-margin carbonates and shales are involved in continental collision. Most ruby deposits formed during Ediacaran-Cambrian (ca. 550 Ma) collisions that produced the East African–Antarctic orogen and the supercontinent Gondwana, or during Cenozoic collisions in south Asia. Ruby is thus a robust indicator of continental collision. As a result of these diagnostic properties, we propose the term "plate tectonic gemstones" (PTGs) for jadeitite and ruby. The PTGs are a new type of petrotectonic indicator that are mostly found in Neoproterozoic and younger rocks. The PTGs as petrotectonic indicators that form deep in the Earth have the added advantage that their record is unlikely to be obliterated by erosion, although the possibility of destruction via retrogression needs to be further assessed. Recognition of the PTGs links modern concepts of plate tectonics to economic gemstone deposits and ancient concepts of beauty, and may aid in exploration for new deposits.

INTRODUCTION

Any mineral or stone beautiful enough to be sought, mined, and sold for its beauty alone is a gemstone (Groat, 2012). The subclass of rocks and minerals that comprises gemstones—whether precious or semi-precious—has mostly been established since antiquity (a few new gemstones have been recognized more recently, for example tanzanite). Humans have sought and prized gemstones since thousands of years before the science of geology was established. Because gemstones are rare by definition, the geological conditions that produced them must have been exceptional. Thus, there is a confluence of economic, esthetic, and academic interest in gemstones. In this contribution we build on this common interest by exploring the plate tectonic significance of two gemstones, both of which are generally produced by plate tectonic processes: jadeitite and the gem variety of corundum, ruby. These gemstones are products of plate convergence, and reflect end-member processes of subduction and collision and thus different protoliths and thermal regimes. We summarize how jade—specifically the variety jadeite—is the characteristic beautiful product of normal oceanic lithosphere subduction and that rubies are the characteristic beautiful products of continental collision. We further explore what these "plate tectonic gemstones" (PTGs) can add to our understanding of the fundamental processes that produced them: "collision-type (A-type)" and "Pacific-type (B-type)" plate tectonic regimes (Maruyama et al., 1996; Liou et al., 2004).

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JADEITE: THE SUBDUCTION GEMSTONE

Jade is a term ascribed to two different materials with similar properties, toughness, and beauty that evolved in usage and significance from toolstones for axes, choppers, and hammers to one of the most highly revered gemstones in the world. As a tool, jade was employed during the Paleolithic (before 35,000 BCE) but was raised to high symbolic stature as a gemstone in proto-Chinese Hongshan and Liangzhu cultures by 3500 BCE, in the Jomón culture of Japan by 3000 BCE, and in Central America by the Olmec of the Early Formative period by at least 1500 BCE, and later in Mayan civilization. Both forms of jade, termed *yü* (玉) in China, are nearly monomineralic rocks: Jadeite jade (or jadeitite) consists predominantly of the pyroxene jadeite ($NaAlSi_2O_8$) and is hard jade (*ying yü*—硬玉), while nephrite jade is tremolite-actinolite [$Ca_2(Mg,Fe)_5Si_8O_{22}(OH)_2$] and is soft jade (*ruan yü*—軟玉). The term jade was derived from the Spanish *piedra de yjada* (loin stone) for talismans worn by the Aztec to ease abdominal pain, but was mistranslated to the word jade (Harlow et al., 2007). In New Zealand nephrite is sometimes called greenstone, a favorite material of the Maoris (their *pounamu*). Jadeitite is found in association with other high-pressure/low-temperature (H*P*-L*T*) metamorphic lithologies that are diagnostic of fossil subduction zones. This assemblage typically includes subducted oceanic crust transformed to blueschist (glaucophane metabasalt) and eclogite (Fig. 1), and mantle wedge material (serpentinized peridotite), typically as mélange matrix (Harlow et al., 2007). Such an assemblage probably represents an exhumed subduction channel (Vannucchi et al., 2012), in which buoyancy-driven return flow above the plate interface has brought subducted and mantle-wedge materials back to the surface. Jadeitites form in this environment at a wide range of depths, typically 20–60 km but occasionally as deep as 100 km (Fig. 2).

Of the two jade rocks, jadeitite is the actual subduction indicator. Jadeite, by virtue of its density (3.4 g cm^{-2}), is a high-pressure indicator, and thinking on its significance predates plate tectonic theory (e.g., Yoder, 1950a, 1950b; Miyashiro and Banno, 1958), but a rock essentially formed of jadeite is not simply interpreted as a metamorphic rock. With the realization that jadeitite is a precipitate or metasomatic replacement from hydrous fluids released during dehydration of subducted oceanic crust, the "jadeite problem" was resolved. High pressure in subduction zones enhances dissolved solute concentrations in hydrous fluids released from subducted materials, enriched in Na, Al, and Si, such that the primary saturated phase is jadeite (Manning 1998, 2004). These hydrous fluids are buoyant and flow up to infiltrate and react with the overlying mantle wedge sole, which itself becomes pervasively altered (Kimura et al., 2009), forming jadeitite veins. The occurrence of relict chromian spinel in many jadeitites further indicates reaction between jadeitite and host ultramafic rocks (Tsujimori and Harlow, 2012). Jadeitites thus serve as a proxy for the related mass transfer within a subduction zone at relatively shallow depths (<100 km).

Jadeitites form under *P-T* conditions that are somewhat hotter than expected for the subduction interface, even compared to hot subduction zones where young crust is subducted, for example beneath southwestern Japan (Fig. 2). This further suggests that jadeite forms in the warmer mantle wedge, above the subduction interface (Fig. 2). Jadeite deposits are found in the northern continents, especially North America and Eurasia, where 15 deposits are documented (Table DR1 in the GSA Data

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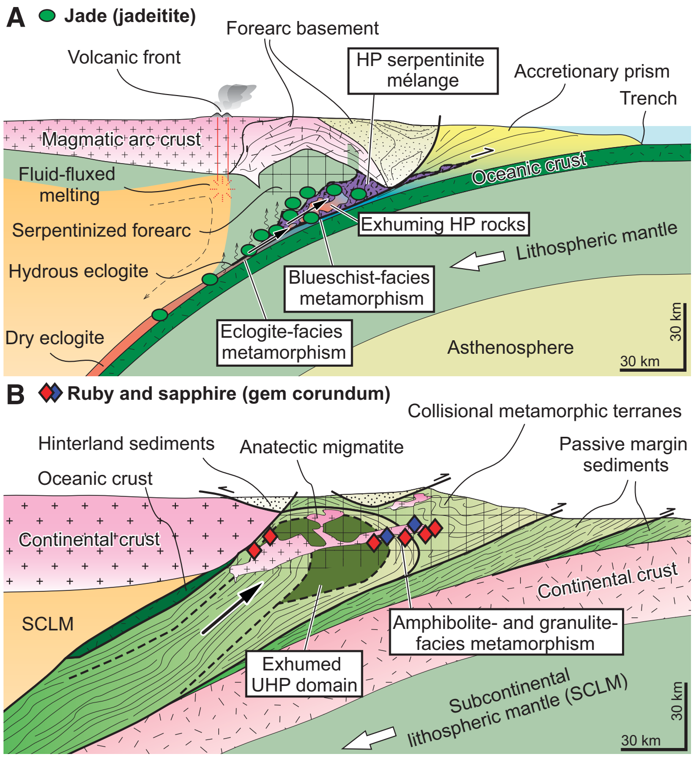

Figure 1. Cross sections showing characteristic tectonic environments where plate tectonic gemstones form. A: Pacific-type subduction zone (modified after Gerya, 2011), where jadeitite forms. B: Continental collision zone (after model R2 of Warren et al., 2008), where ruby forms. HP—high pressure; UHP—ultra-high pressure.

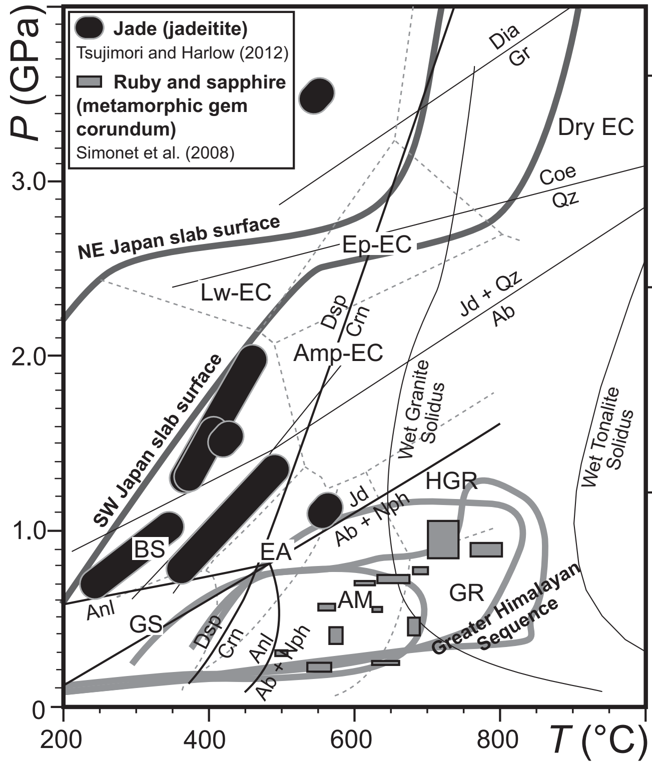

Figure 2. Pressure-temperature (*P-T*) diagram showing *P-T* conditions recorded by plate tectonic gemstones jadeite (rounded black symbols; Tsujimori and Harlow, 2012) and gem corundum (gray rectangles; Simonet et al., 2008). Thick, light gray lines show collision zone *P-T* paths, from Jamieson et al. (2006). Thick dark lines show modeled *P-T* paths (model D80 of Syracuse et al., 2010) for slab surfaces, both hot (southwestern Japan/Nankai) and cool (northeastern Japan/Tohoku) subduction zones. Mineral abbreviations: Ab—albite; Anl—analcime; Coe—coesite; Crn—corundum; Dia—diamond; Dsp—diaspore; Gr—graphite; Jd—jadeite; Nph—nepheline; Qz—quartz. Metamorphic facies: BS—blueschist; AM—amphibolite; Lw-EC—lawsonite eclogite; Ep-EC—epidote eclogite; Amp-EC—amphibole eclogite; Dry EC—dry eclogite; GS—greenschist; EA—epidote-amphibolite; GR—granulite; HGR—high-pressure granulite.

Repository[1]; Fig. 3). Another jadeite occurrence is found in New Guinea, part of the Gondwana fragment Australia. These deposits are entirely Phanerozoic (Fig. 4B), products of subduction leading to the formation of various accretionary orogens (Cawood et al., 2009).

In contrast to the clear plate tectonic signal of jadeite jade, nephrite jade does not form at H*P*-L*T* subduction-related conditions. One variety forms via contact metasomatism of dolomite with granitic rock and the other is associated with serpentinite in a supra-subduction setting (Harlow et al., 2007). In this latter case, nephrite forms by metasomatic reactions between peridotite/serpentinite and sedimentary rocks (greywacke or sandstone) during ophiolite emplacement or collision. Because of these differences, the compilation in Table DR1 and Figure 4B excludes nephrite jade.

RUBY: THE COLLISION GEMSTONE

There are two kinds of gem corundum (hexagonal Al_2O_3): ruby and sapphire. Rubies show intense red color due to substitution of Cr for Al; sapphires are gem corundum of all other colors, even pink. Ruby comes from *ruber*, Latin for red. The Mogok Valley in Upper Myanmar (Burma) was for centuries the source of the world's finest rubies, but in recent years very few good rubies have been found there. Ruby and sapphire are perhaps the world's most widely sold colored gemstones, accounting for approximately one-third of sales by value (Groat, 2012). They can command some of the highest prices paid for any gem: for example, a 8.62 ct Burmese ruby sold in 2006 for US$3,640,000 (Shor and Weldon, 2009).

Primary (non-alluvial) gem corundum deposits can be igneous or metamorphic. Igneous deposits are associated with silica-undersaturated lavas and dikes such as sapphire-bearing syenites in Kenya and alkali basalts from eastern Asia and Australia (Simonet et al., 2004; Graham et al., 2008). Fluid/melt inclusion studies on igneous gem corundums indicate that most formed in CO_2-rich syenitic melts. Because lavas and associated dikes with gem corundum erupt or are emplaced far from plate margins, these gemstones cannot be uniquely ascribed to plate tectonic processes. The responsible alkaline volcanism may reflect rifting and decompression melting that is a far-field effect of plate tectonics, but because we are not sure how close is the link between plate tectonics and igneous gem corundum, these are excluded from our PTG compilation (Table DR1; Fig. 4C).

Gem corundum of metamorphic origin are associated with continental collision zones and thus are plate tectonic indicators. In metamorphic deposits, gem corundum result from amphibolite- and granulite-facies metamorphism (Fig. 2) of mixed Al-rich and Si-poor protoliths. Metamorphic gem corundum also forms due to metasomatism accompanying reactions between aluminosilicate-rich rocks (granitoids, gneisses, migmatite) and silica-poor rocks (ultramafics, carbonates, evaporite, shale). Such deposits include ruby-bearing mafic granulites, ruby-bearing marbles, and ruby/sapphire-bearing gneisses and granulites. The third type of gem corundum deposits is associated with partial melting of Al-rich shale and Si-poor carbonate (Simonet et al., 2008). Suitable protoliths exist and *P-T* conditions develop where passive margins (with carbonates and shales) are subducted at continental collision zones (Fig. 1B). This type of gem corundum deposit is also considered to be a plate tectonic indicator.

[1]GSA Data Repository item 2013202, Table DR1 (plate tectonic gemstones: locations, host rocks, ages, and references), is available online at www.geosociety.org/pubs/ft2013.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, USA.

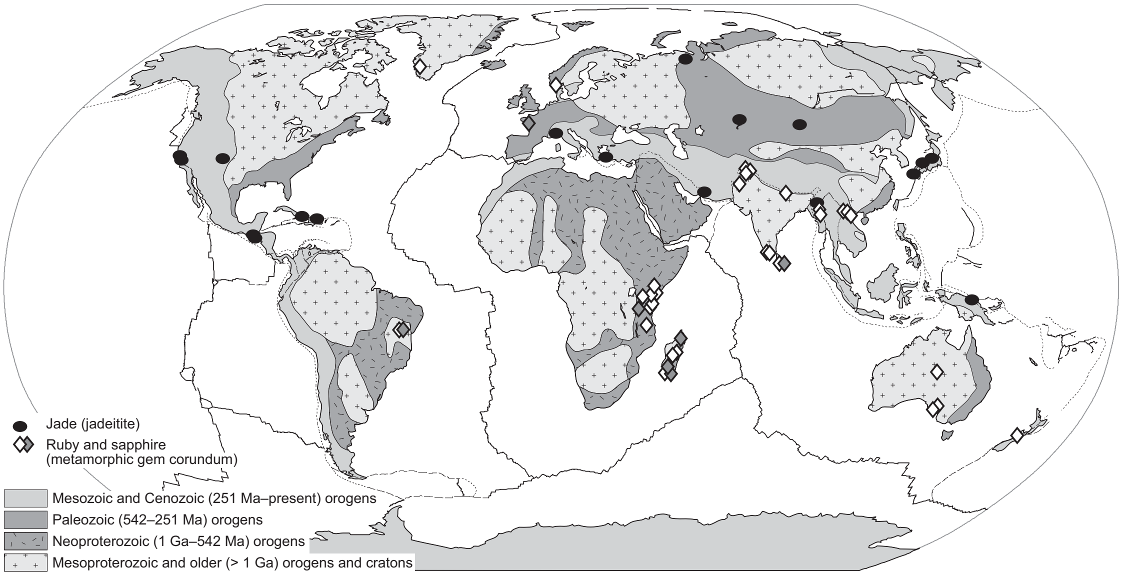

Figure 3. Locations of the plate tectonic gemstones jadeitite and ruby, superimposed on map showing continental crust ages from Tsujimori et al. (2006). Supporting information can be found in Table DR1 (see footnote 1).

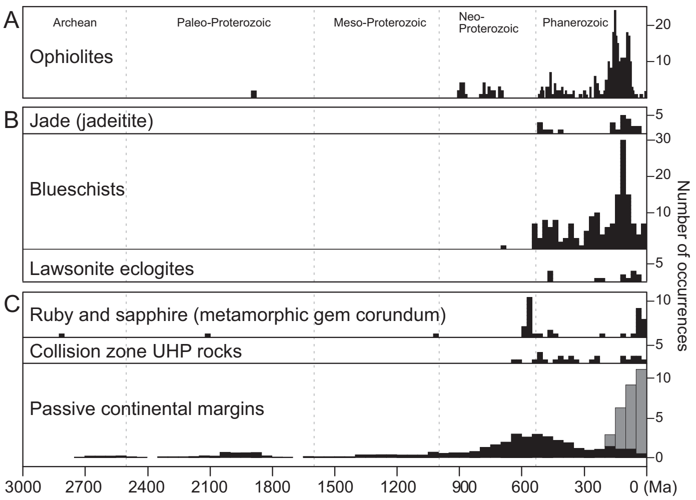

Figure 4. Histograms showing ages of preserved plate tectonic indicators (including plate tectonic gemstones; data from Table DR1 [see footnote 1]) for the last 3 b.y. of Earth history. A: Oceanic lithosphere (ophiolites). B: Subduction zone metamorphic products (jadeitites, blueschists, and lawsonite eclogites). C: Continental margins and collision zones (gem corundum, ultrahigh-pressure [UHP] metamorphic rocks, and passive continental margins). Vertical axis numbers represent aggregate data per bin, excepting the passive margins histogram, for which numbers correspond "aggregate length" per bin (× 10,000 km). Age distribution of ophiolites from Dilek (2003) for those up to 1040 Ma, plus the only convincing older ophiolite (1.95 Ga Jormua ophiolite, Finland) from Peltonen and Kontinen (2004). Age distributions of jadeites from Tsujimori and Harlow (2012); of blueschists from Maruyama et al. (1996); and of lawsonite eclogites from Tsujimori et al. (2006). Age distributions of UHP metamorphic belts from Liou et al. (2009); of metamorphic gem corundums from Table DR1; and of passive margins from Bradley (2008); note that gray bins represent modern passive margins.

Twenty (20) of the 38 gem corundum deposits listed in Table DR1 are Phanerozoic in age, 15 are Ediacaran. and only 3 are pre-Neoproterozoic (one each Mesoproterozoic, Paleoproterozoic, and Archean; Fig. 4). Most metamorphic and anatectic gem corundum deposits formed in association with major continental collisions, especially the Alpine-Himalayan (Cenozoic) and East Africa–Antarctic (Ediacaran-Cambrian) orogens. Ediacaran-Cambrian collisions produced gem corundum deposits in Africa, India, Madagascar, and Sri Lanka, whereas Cenozoic collisions produced deposits all over south Asia (Fig. 3).

DISCUSSION

PTGs represent a new set of petrotectonic indicators, rocks and minerals from which plate tectonic activity and tectonic settings can be inferred. The concept of petrotectonic assemblages was introduced by Dickinson (1972), who identified ophiolites and magmatic arcs as especially diagnostic. It is very useful to have multiple petrotectonic indicators, diagnostic minerals as well as assemblages. Minerals may be less equivocal than rock assemblages, if these can be uniquely ascribed to plate tectonic processes. Glaucophane metabasalt (blueschist) for example is universally acknowledged as a product of the plate tectonic process of subduction (Ernst, 2003); similarly, coesite- and/or diamond-bearing ultra-high-pressure (UHP) metamorphic rocks are accepted to manifest subduction of continental crust to at least 100 km deep (Maruyama et al., 1996). These two subduction indicators are restricted to Neoproterozoic and younger times (Figs. 4B and 4C), but the significance of this is again controversial. Perhaps the absence of these rocks from older crust reflects removal by erosion, or retrograde metamorphism, or a somewhat hotter Earth?

In this discussion, it is useful to have additional petrogenetic indicators such as the PTGs. Figure 4B compares the age distribution of jadeite with two other indicators of normal subduction, blueschist and lawsonite eclogite. There is a remarkable similarity between these three independent indicators, which are all limited to Neoproterozoic and younger rock sequences. Analogously, Figure 4C compares the distribution of metamorphic gem corundum with other indicators of continental collision, such as UHP metamorphic rocks. The distribution of passive continental margins (which are integral parts of the supercontinent cycle leading to continental collision) was traced by Bradley (2008) back to Archean times. The temporal distributions of gem corundum—with three exceptions—are limited to Neoproterozoic and younger time.

It is beyond the scope of this paper to explore in detail what the record of PTGs tells us about when plate tectonics began on Earth (Stern, 2007). It may be noteworthy that, because the PTGs are produced 0–120 km deep (Fig. 2), it is unlikely that the near absence of these prior to Ediacaran time is due to removal by erosion, as has been offered as an explanation for why other petrotectonic indicators such as ophiolites are not common in pre-Neoproterozoic rocks. Erosion of many kilometers of crust should expose PTGs if they had formed. We cannot be as confident that the PTG record has not been obscured by retrogression.

In addition to the utility of the PTGs as petrotectonic indicators, the recognition that jadeite and ruby were produced by specific plate tectonic processes provides useful insights in the search for new economic deposits. This recognition also provides important linkages between aesthetically pleasing natural materials and our understanding of how the solid Earth operates.

CONCLUSIONS

The well-known gemstones jadeitite and ruby are identified as plate tectonic petrotectonic indicators. Jadeitite is the subduction indicator whereas rubies manifest continental collision. These are the plate tectonic gemstones (PTGs). Most ruby deposits formed during Ediacaran-Cambrian (ca. 550 Ma) and Cenozoic (<65 Ma) collisions. The PTGs are a new class of petrotectonic indicators and they are particularly useful because they are unlikely to be obliterated by erosion. Identification of ruby and jadeitite as PTGs is intended to be illustrative and exemplary. There are probably many more examples of gemstones that are diagnostic of specific plate tectonic environments, and we encourage the effort to identify these and discuss their characteristic tectonic associations.

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REFERENCES CITED

Bradley, D.C., 2008, Passive margins through Earth history: Earth-Science Reviews, v. 91, p. 1–26, doi:10.1016/j.earscirev.2008.08.001.

Cawood, P.A., Kröner, A., Collins, W.J., Kusky, T.M., Mooney, W.D., and Windley, B.F., 2009, Accretionary orogens through Earth history, *in* Cawood, P.A., and Kröner, A., eds., Earth Accretionary Systems in Space and Time: Geological Society of London Special Publication 318, p. 1–36, doi:10.1144/SP318.1.

Dickinson, W.R., 1972, Evidence for plate-tectonic regimes in the rock record: American Journal of Science, v. 272, p. 551–576, doi:10.2475/ajs.272.7.551.

Dilek, Y., 2003, Ophiolite pulses, mantle plumes and orogeny, *in* Dilek, Y., and Robinson, P.T., eds., Ophiolites in Earth History: Geological Society of London Special Publication 218, p. 9–19.

Ernst, W.G., 2003, High-pressure and ultrahigh-pressure metamorphic belts—Subduction, re-crystallization, exhumation, and significance for ophiolite studies, *in* Dilek, Y., and Newcombe, S., eds., Ophiolite Concept and Evolution of Geological Thought: Geological Society of America Special Paper 373, p. 365–384.

Gerya, T.V., 2011, Future directions in subduction modeling: Journal of Geodynamics, v. 52, p. 344–378.

Graham, I., Sutherland, L., Zaw, K., Nechaev, V., and Khanchuk, A., 2008, Advances in our understanding of the gem corundum deposits of the West Pacific continental margins intraplate basaltic fields: Ore Geology Reviews, v. 34, p. 200–215, doi:10.1016/j.oregeorev.2008.04.006.

Groat, L.A., 2012, Gemstones: American Scientist, v. 100, p. 128–137.

Harlow, G.E., Sorensen, S.S., and Sisson, V.B., 2007, Jade, *in* Groat, L.A., ed., The Geology of Gem Deposits: Quebec, Mineralogical Association of Canada, Short Course Series, v. 37, p. 207–254.

Jamieson, R.A., Beaumont, C., Nguyen, M.H., and Grujic, D., 2006, Provenance of the Greater Himalayan Sequence and associated rocks: Predictions of channel flow models, *in* Law, R.D., Godin, L., and Searle, M.P., eds., Channel Flow, Ductile Extrusion, and Exhumation of Lower Mid-Crust in Continental Collision Zones: Geological Society of London Special Publication 268, p. 165–182.

Kimura, J., Hacker, B.R., van Keken, P.E., Kawabata, H., Yoshida, T., and Stern, R.J., 2009, Arc Basalt Simulator version 2, a simulation for slab dehydration and fluid-fluxed mantle melting for arc basalts: Modeling scheme and application: Geochemistry Geophysics Geosystems, v. 10, Q09004, doi:10.1029/2008GC002217.

Liou, J.G., Tsujimori, T., Zhang, R.Y., Katayama, I., and Maruyama, S., 2004, Global UHP metamorphism and continent subduction/collision: The Himalayan Model: International Geology Review, v. 46, p. 1–27, doi:10.2747/0020-6814.46.1.1.

Liou, J.G., Ernst, W.G., Zhang, R.Y., Tsujimori, T., and Jahn, B.M., 2009, Ultrahigh-pressure minerals and metamorphic terranes: The view from China: Journal of Asian Earth Sciences, v. 35, p. 199–231, doi:10.1016/j.jseaes.2008.10.012.

Manning, C.E., 1998, Fluid composition at the blueschist-eclogite transition in the model system Na_2O-MgO-Al_2O_3-SiO_2-H_2O-HCl: Schweizerische Mineralogische und Petrographische Mitteilungen, v. 78, p. 225–242.

Manning, C.E., 2004, The chemistry of subduction-zone fluids: Earth and Planetary Science Letters, v. 223, p. 1–16, doi:10.1016/j.epsl.2004.04.030.

Maruyama, S., Liou, J.G., and Terabayashi, M., 1996, Blueschists and eclogites of the world and their exhumation: International Geology Review, v. 38, p. 485–594, doi:10.1080/00206819709465347.

Miyashiro, A., and Banno, S., 1958, Nature of glaucophanitic metamorphism: American Journal of Science, v. 256, p. 97–110, doi:10.2475/ajs.256.2.97.

Peltonen, P., and Kontinen, A., 2004, The Jormua ophiolite: A mafic-ultramafic complex from an ancient ocean-continent transition zone, *in* Kusky, T., ed., Precambrian Ophiolites and Related Rocks: Amsterdam, Elsevier, p. 35–71.

Shor, R., and Weldon, R., 2009, Ruby and sapphire production and distribution: A quarter century of change: Gems and Gemology, v. 45, p. 236–259, doi:10.5741/GEMS.45.4.236.

Simonet, C., Paquette, J.L., Pin, C., Lasnier, B., and Fritsch, E., 2004, The Dusi (Garba Tula) sapphire deposit, Central Kenya—A unique Pan-African corundum-bearing monzonite: Journal of African Earth Sciences, v. 38, p. 401–410, doi:10.1016/j.jafrearsci.2004.02.002.

Simonet, C., Fritsch, E., and Lasnier, B., 2008, A classification of gem corundum deposits aimed towards gem exploration: Ore Geology Reviews, v. 34, p. 127–133, doi:10.1016/j.oregeorev.2007.09.002.

Stern, R.J., 2007, When did plate tectonics begin? Theoretical and empirical considerations: Chinese Bulletin of Science, v. 52, p. 578–591, doi:10.1007/s11434-007-0073-8.

Syracuse, E.M., van Keken, P.E., and Abers, G.A., 2010, The global range of subduction zone thermal models: Physics of the Earth and Planetary Interiors, v. 183, p. 73–90, doi:10.1016/j.pepi.2010.02.004.

Tsujimori, T., and Harlow, G.E., 2012, Petrogenetic relationships between jadeitite and associated high-pressure and low-temperature metamorphic rocks in worldwide jadeitite localities: A review: European Journal of Mineralogy, v. 24, p. 371–390, doi:10.1127/0935-1221/2012/0024-2193.

Tsujimori, T., Sisson, V.B., Liou, J.G., Harlow, G.E., and Sorensen, S.S., 2006, Very low-temperature record in subduction process: A review of worldwide lawsonite eclogites: Lithos, v. 92, p. 609–624, doi:10.1016/j.lithos.2006.03.054.

Vannucchi, P., Sage, F., Morgan, J.P., Remitte, F., and Collot, J.-Y., 2012, Toward a dynamic concept of the subduction channel at erosive convergent margins with implications for interplate material transfer: Geochemistry Geophysics Geosystems, v. 13, Q02003, doi:10.1029/2011GC003846.

Warren, C.J., Beaumont, C., and Jamieson, R.A., 2008, Deep subduction and rapid exhumation: Role of crustal strength and strain weakening in continental subduction and ultrahigh-pressure rock exhumation: Tectonics, v. 27, TC6002, doi:10.1029/2008TC002292.

Yoder, H.S., Jr., 1950a, The jadeite problem; Part I: American Journal of Science, v. 248, p. 225–248, doi:10.2475/ajs.248.4.225.

Yoder, H.S., Jr., 1950b, The jadeite problem; Part II: American Journal of Science, v. 248, p. 312–334, doi:10.2475/ajs.248.5.312.

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ERRATUM to this article

The authors would like to correct the formula for pyroxene jadeite; it should be $NaAlSi_2O_6$.