DIAMONDS FROM THE DEEP
WINDOWS INTO SCIENTIFIC RESEARCH

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What Have Diamond Ages Taught Us?

The mantle below the oldest crustal rocks of Earth's continents has been attached to the crust since the time the crust formed. This fact is known from isotopic age dating, and it generally means that three billion-year-old crust will be underlain by three billion-year-old mantle. Welded together with the stable continental crust as a unit known as a craton (see detail below), this mantle—known as the subcontinental lithospheric mantle—has been isolated from mantle convection for billions of years. This lithospheric mantle is recognized as an important carbon reservoir, is where the majority of diamonds are stored in the earth, and has been the source of nearly all age-dated diamonds.

The subcontinental lithospheric mantle was depleted of volatiles like carbon and water during its initial formation by the igneous processes of melt generation and migration. Later subduction from ocean basins away from and below the continents carried carbonate and water in altered ocean floor rock to great depths in the mantle where it warmed up, melted, and/or released fluid. Over time the lithospheric mantle became gradually re-enriched in carbon and water by the infiltration of these fluids and melts. With the use of diamond age determinations, we are dating these re-enrichment processes because diamonds grow from these fluids and melts, thereby giving us a glimpse of ancient geodynamic processes.

The story of how and why diamonds become stored in the lithospheric mantle has only emerged in the last 35 years as techniques to determine diamond ages have been developed (see Spring 2019 Diamonds from the Deep). This edition focuses on the geologic lessons that have been learned from diamond ages. We examine the large-scale tectonic processes that have created lithospheric diamonds. These diamonds have become a key way to look at continent evolution and carbon cycling between the crust and mantle over the past 3.5 billion years (figure 1).

Diamonds, Their Ages, Cratons, and Continent Evolution

A worldwide association between the most ancient and stable portions of continents—cratons—and diamond occurrences has long been known (e.g., Kennedy, 1964; Clifford, 1966; Gurney and Switzer, 1973; Boyd and Gurney, 1986).

Gems & Gemology, Vol. 56, No. 4, pp. 534–541.

Even though early work recognized the association of diamonds with ancient cratons of at least 1.5 Ga age (Kennedy, 1964; Clifford, 1966), common usage of the term craton evolved to refer simply to portions of Earth's continental crust that have long-term stability. Such portions presently show exceptionally little earthquake activity, no recent rifting or mountain building, and may contain rocks that range in age from as young as 1 billion years to as old as 4 billion years (Pearson et al., in press, 2021). However, just because such regions are now stable diamond storehouses does not mean that they always were so. Indeed, diamond dating allows us to look at just how continent collision or deep mantle upwelling processes—the antithesis of geologic stability—can create diamonds in the first place.

This updated definition of the term craton uses teleseismic (meaning from distant earthquakes across the globe) studies to establish the thickness of the stable lithospheric mantle that lies below the continental crust. Its thickness is established through fast seismic shear wave speeds in global seismic velocity models. In the updated definition, cratons are regions of the earth's continental crust that are underlain by 150–200 km of lithospheric mantle as a keel providing long-term stability since at least 1 Ga. Using this updated definition, around 63% of exposed continental crust and 18% of Earth's surface are cratons.

The first harzburgitic-garnet-inclusion-based diamond ages—which were more than 3 billion years old—proved that diamonds originate in continental mantle and that it too must be very old in order to store them (Richardson et al., 1984). These old ages, along with the strong spatial association of diamond occurrences with old continental crust and the high pressure/temperature conditions of diamonds and their host rocks, all led to the understanding that diamonds form and reside in the subcontinental lithospheric mantle (e.g., Boyd et al., 1985; Boyd and Gurney, 1986; Haggerty, 1986).

Diamonds have formed through nearly all of Earth's history, in distinct episodes that can often be linked to larger-scale tectonic processes (Richardson et al., 2004; Shirey and Richardson, 2011; Howell et al., 2020) and are likely forming today. Diamonds, and their ages, are the ideal time-resolved samples that can provide an overview of continent formation and evolution from deep in the mantle well below the crust (the crust-mantle boundary is typically around 40 km). A classic example is how the creation, assembly, and modification of the Kaapvaal-Zimbabwe craton in southern Africa is reflected in the age, chemistry, and geographic dis-

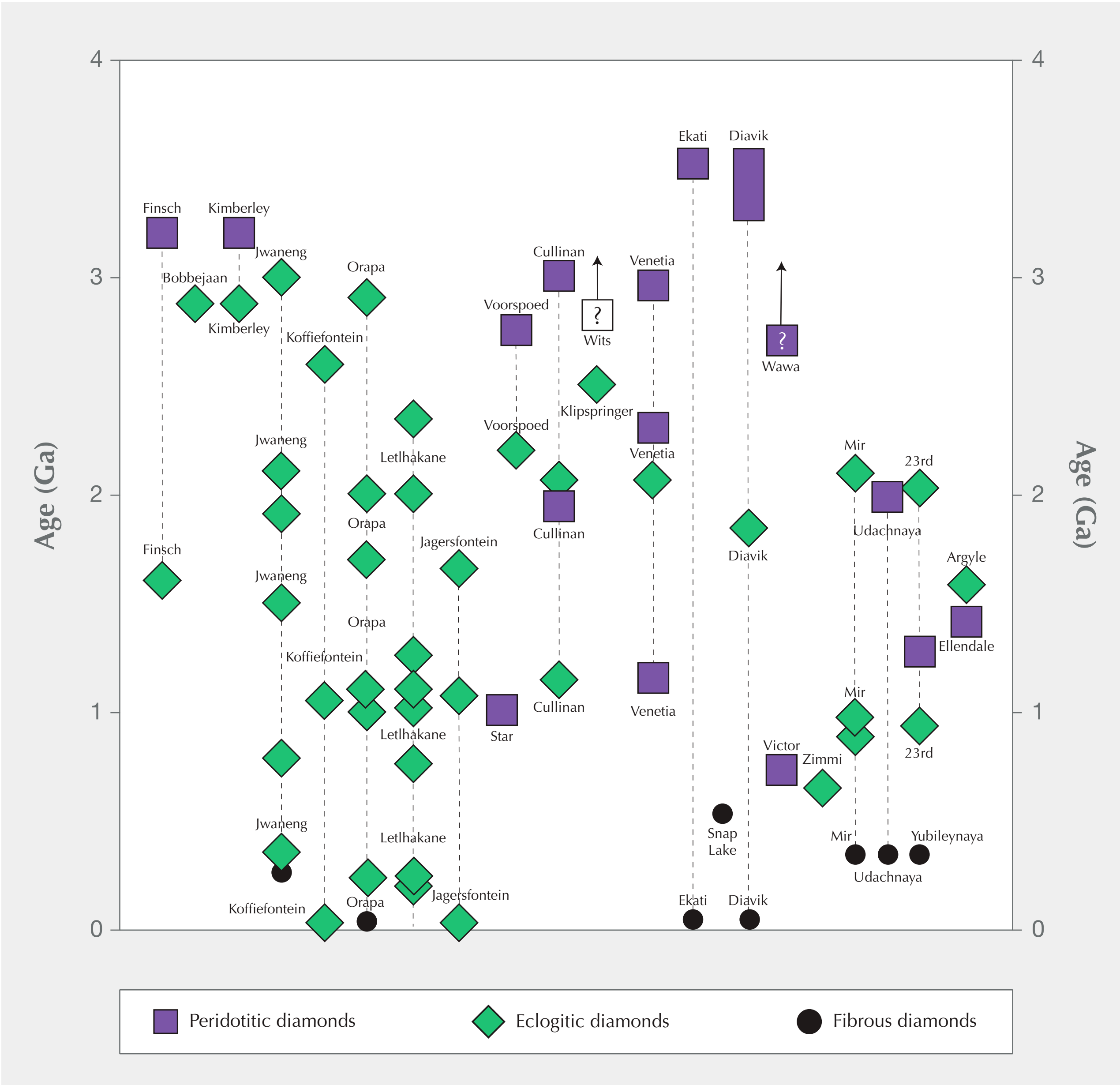


Figure 1. Age plot for all the diamond mines that have supplied enough diamonds on which to do age studies. This diagram summarizes all the known diamond growth events through time. Diamond mines typically have more than one age, may have both eclogitic and peridotitic diamonds, and may use different isotopic dating methods (Rb-Sr, Sm-Nd, Re-Os; see Spring 2019 Diamonds from the Deep). Diamond formation is associated with large-scale tectonic processes and has become a key way to look at continent evolution and carbon cycling between the crust and mantle over the past 3.5 billion years. Diamonds that occur in the Wawa and Witwatersrand conglomerates are undated, but minimum ages are given based on conglomerate age. Modified and updated from Howell et al. (2020).

tribution of multiple generations of diamonds formed and stored in its lithospheric mantle (Shirey et al., 2002, 2004).

Diamonds and Formation of the First Continents

The formation of the first continents involved the production of melt or magma in an Earth hotter than today's Earth. Direct melting of the mantle produced the earliest basaltic and komatiitic crust, leaving behind a buoyant residue. Subsequent remelting of this basalt was necessary to produce the silica-rich, granite-like rocks, termed felsic, that are hallmarks of the continental crust. The surface exposures of igneous rock on continents are composed of at least 50% high-silica rock, yet when basalt melts, less than

1/5 of the volume of melt is felsic. Therefore the amount of initial basalt that was available must have been huge and the amount of buoyant, depleted mantle even more huge—perhaps up to 10–20× the volume of granite. It is some of this abundant buoyant mantle residue that is thought to have become trapped underneath the crust to become nascent continental mantle. Where diamond ages play a role in the story is in using the oldest ages to understand how and when the buoyant mantle was produced and collected.

Active debate among research scientists about the stabilization of the thick buoyant continental mantle compares some form of horizontal tectonic processes—similar to modern subduction and accretion—to vertical tectonic processes that are similar to the upwelling of mantle plumes that occur beneath ocean islands like Hawaii and Iceland today. Both geodynamic scenarios would generate the abundant basaltic melt needed to eventually make the continental crust, but each scenario has different implications for the styles of early mantle convection, the release of Earth's excess heat, and the recycling of constituents from Earth's hydrosphere.

The oldest known diamonds to inform us about these earliest craton formation processes are the 3.5 Ga diamonds from the Diavik and Ekati mines on the Slave craton (Westerlund et al., 2006; Aulbach et al., 2009). Compositions of high-Ni sulfide inclusions related to mantle peridotite in Ekati diamonds are best explained by some surface material being recycled back into the mantle (Westerlund et al., 2006). However, diamond evidence for the lack of atmospherically modified sulfur isotopes (Cartigny et al., 2009) and the presence of very depleted peridotites deep in the continental mantle here suggest that the continental lithosphere was assembled in a way that did not involve substantial surface material. To accommodate these complexities and evidence from the overlying crust that can be explained by localized subduction, a hybrid model of localized subduction-like melting at the craton margin followed by plume-upwelling and underplating has been proposed (Aulbach et al., 2019). Is this subduction similar to modern plate tectonics, while an even earlier vertical upwelling regime is waning, as Aulbach et al. (2019) has suggested? Only future research can resolve the question.

Diamonds and Evidence for the Onset of Modern Plate Tectonics (Wilson Cycle)

The global database for diamond ages from all studies shows that prior to 3.1 Ga, only peridotitic diamonds formed, whereas after 3.0 Ga, eclogitic diamonds became prevalent (figure 1). Shirey and Richardson (2011) suggested that the prevalence of eclogitic diamonds after 3.0 Ga resulted from the capture of eclogite and diamond-forming fluids in mantle lithosphere via subduction and continental collision. From this observation and early continental assembly patterns, they suggested that the evident continental collision was preceded by rifting and comprised the first full cycle of ocean basin opening and closure, known as a Wilson Cycle, starting at about 3.2 Ga. The significance of identifying the earliest Wilson Cycle is that it is the form of plate tectonics we have today.

The regional pattern of diamond ages and the inclusion types seen in the Kaapvaal-Zimbabwe craton (figure 2) support the operation of the Wilson Cycle because they suggest that a piece of ocean floor was underthrust westward beneath the extant continental mantle as an ocean basin closed. When this underthrusting occurred, fluids transported by hydrated and carbonated oceanic crust were released into the overlying continental mantle crystallizing the predominant diamond type, the 2.9 billion-year-old eclogitic sulfide bearing diamonds found in diamond mines west of the suture between the two cratonic blocks (Kimberley, Jwaneng, and Orapa; Richardson et al., 2001, 2004; Shirey et al., 2013; figure 2). This mantle geologic history is in full agreement with the crustal magmatic history of the two cratonic blocks, because diamond ages have permitted us to correlate the geologic processes happening in the mantle with those that were happening in the crust at the same time.

Diamonds and Continent Growth at Their Margins: Subduction and Mountain Building

There are many examples worldwide where diamond formation is associated not just with old cratons (e.g., diamond formation in old enriched lithosphere; Richardson et al., 1984) but rather with deformed regions known as mobile belts, produced during continent collision. These mobile belts are zones of intense deformation in the crust that result from crustal thickening—a process known as orogeny that forms mountain chains around the world such as the Appalachians or the Himalayas. In the older mobile belts, the mountains have since been worn away by billions of years of erosion, and diamonds give us a look at the preserved mantle in the root zone of mountain belts that would not otherwise be seen.

The best example of a diamond deposit associated with collisional mountain building is the Argyle mine in Australia, where "subduction along the Kimberley craton edge generated the world's biggest diamond deposit" (Stachel et al., 2018). The Argyle mine has been a famous supplier of pink and red diamonds (Shigley et al., 2001) and, over its three-decade life, was known for its exceptionally high diamond abundances (Rayner et al., 2018). Argyle occurs within the Proterozoic Halls Creek orogen (1.92–1.83 Ga; Hancock and Rutland, 1984). The Argyle eclogitic diamonds formed "shortly" after continent collision, at 1580 ± 30 Ma (Richardson, 1986), likely within Archean mantle (Luguet et al., 2009). After their formation, the diamonds resided in the high-temperature, high-deformation region near the base of the lithosphere (figure 3). This region near the convecting mantle provided the ideal conditions to im-

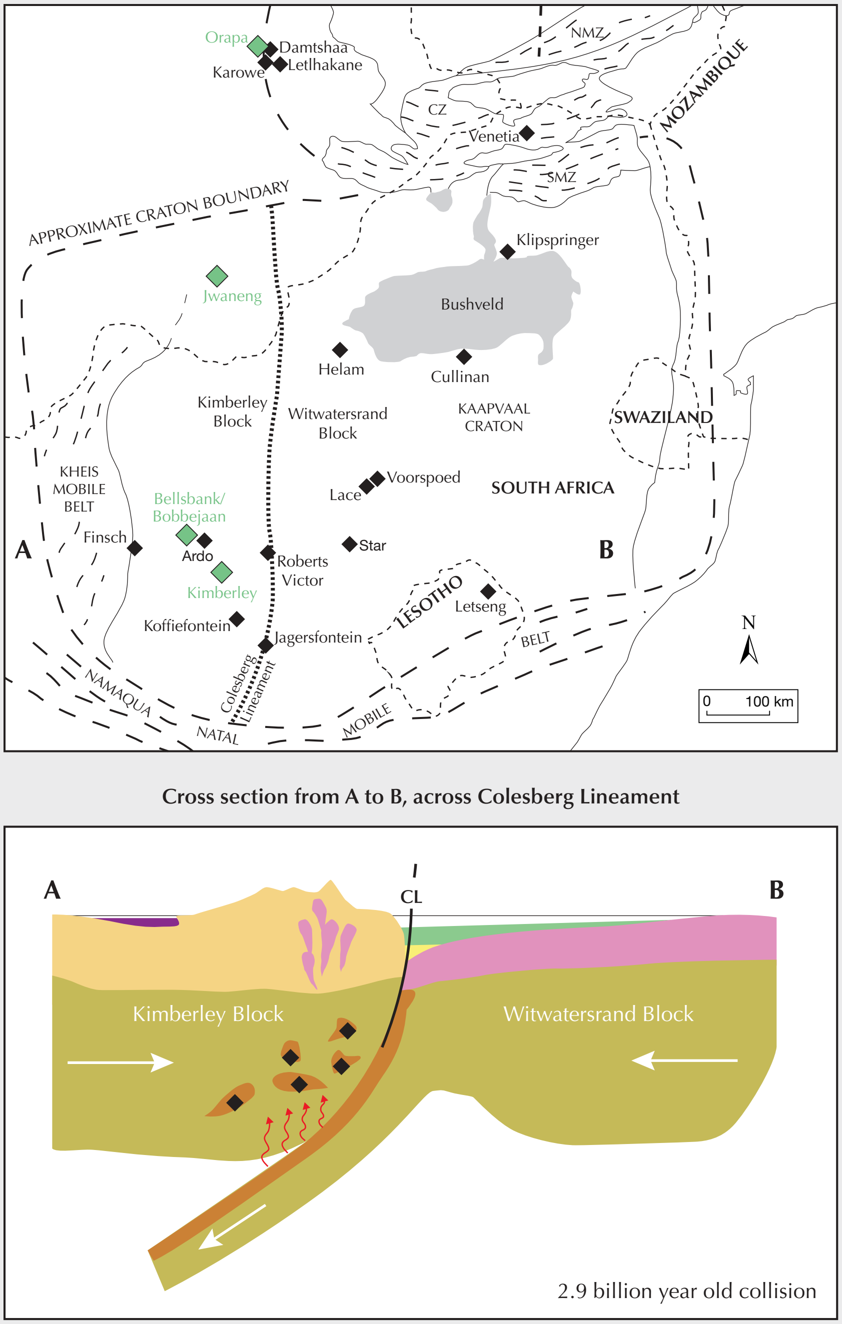


Figure 2. In the Kaapvaal craton (boundary shown by dashed line), some diamond formation occurred during continental collision. The top panel shows the Bellsbank/Bobbejaan, Kimberley, Jwaneng, and Orapa diamond localities (green), all with abundant to common 2.9 Ga diamonds. Diamonds of this age are thought to be derived from fluids (small squiggly arrows) associated with westward subduction along the Colesberg Lineament (CL), as shown in the lower panel (Shirey et al., 2013). The mantle is shown in olive, and the crust is in shades of pink, buff, and brown. Bold arrows show the direction of continental collision.

part strain to some of the diamonds resulting in the platelet degradation that causes their pink and brown colors (Stachel et al., 2018; Eaton-Magaña et al., 2019).

There are many other worldwide diamond localities that have allowed us to link diamond formation to collisional processes along the edge of an ancient continent. In Siberia, for example, lherzolitic and eclogitic diamonds formed in association with orogenesis related to the 1.8–1.2 Ga Angara and Akitkan orogens (Cherepanova and Artemieva, 2015, and references therein). In West Africa, diamonds from Zimmi formed at ~650 Ma (Smit et al., 2016) due to subduction and collision along the Rokelide orogen on the SW margin of the Man craton (700–550 Ma; Lytwyn et al., 2006). Other examples occur at the margins

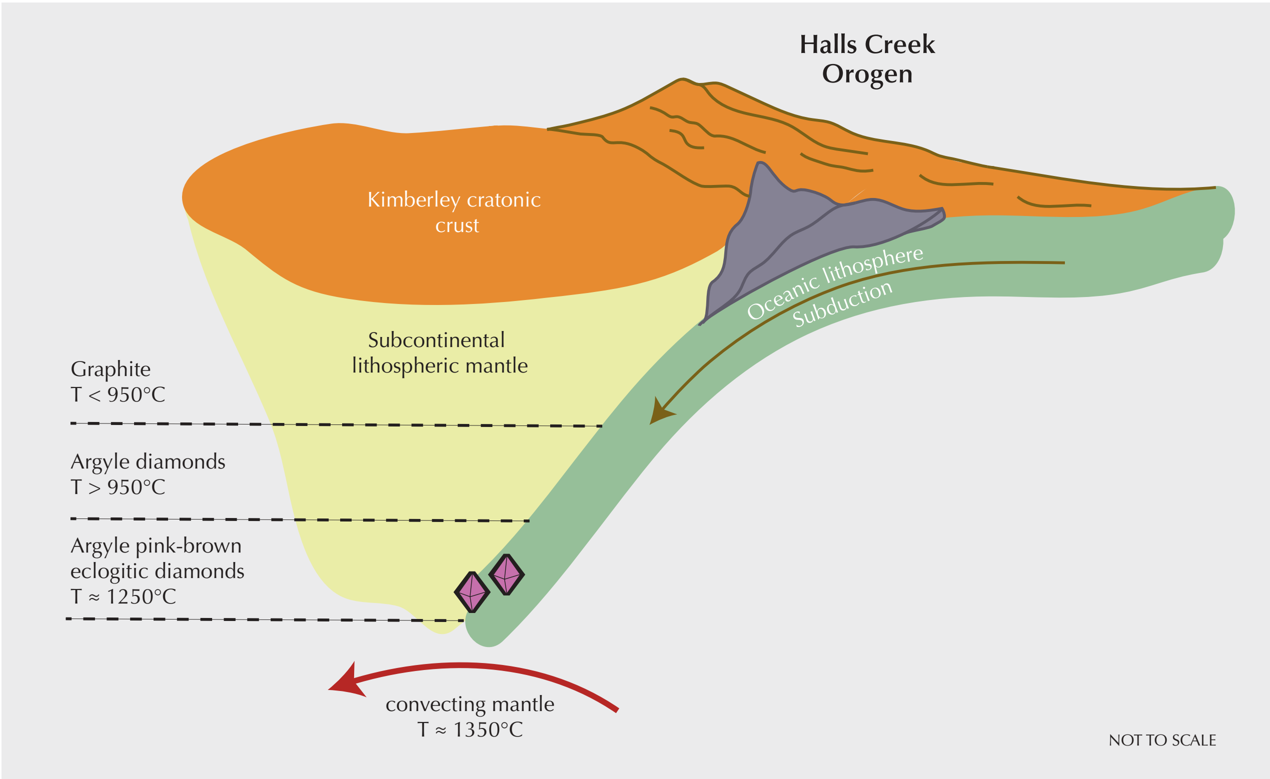


Figure 3. Formation of the pink-brown eclogitic diamonds at Argyle—the world's largest diamond deposit. After their formation, Argyle pink-brown diamonds resided in the high-temperature, high-deformation region near the base of the lithosphere (Viljoen, 2002; Stachel et al., 2018), which provided the ideal conditions to strain the diamonds, induce platelet degradation, and produce their pink and brown colors.

of the Slave (Canada), Kaapvaal (southern Africa), and Wyoming (United States) cratons.

A typical feature of diamonds forming in these mobile belts seems to be the existence of lithospheric mantle caught up in the collision process. An interesting and essential geologic question is whether the diamonds are older diamonds that survived in the lithospheric mantle through tectonic reworking, or diamonds forming at the time of deformation from inherited older carbon, or diamonds formed from carbon newly introduced into the continental mantle during deformation. Similarly, as researchers we want to know if there is mantle newly added during the collision process or whether much older mantle is involved. Answers to these questions cannot be obtained without the age constraints from diamond dating. In the end, incorporation of craton-margin areas to diamond exploration targets has expanded the limits suggested by Clifford (1966) and will continue to contribute to the finding of new economic diamond deposits.

What Do Diamond Ages Show Us About Where Diamonds Are Forming Today?

There is no reason to think that diamonds aren't still forming right now. Based on our knowledge of the age association of diamonds with global plate tectonic processes, we can make a few predictions about where diamonds might be forming today. Most of Earth's mantle is at the right pressure and temperature conditions for diamond formation as long as carbon-bearing fluids and melts are reduced enough to keep carbon from combining with oxygen—the most abundant element in the mantle.

Active subduction zones are obvious candidates for the mobilization of carbon into either the lithospheric or sublithospheric diamond-forming regions of the deeper Earth (figure 4). In oceanic subduction settings, conditions are often too oxidizing to be diamond friendly. The thermal paths of the hotter subducting slabs dictate that they may lose their water and carbon to island arc volcanism at conditions too oxidizing for diamonds to form. Additionally, at these relatively shallow depths, the only magmas available for transport of diamonds to the surface are basalts (not kimberlites) that will be destructive to any diamonds since they are too oxidizing, and/or diamonds may be graphitized due to slow eruption. In other words, diamonds might be forming at depth in normal oceanic subduction zones today, but we may never see them survive to the earth's surface.

Diamonds with relatively young ages have come from two geologic settings, suggesting that these are settings where diamonds may be forming today.

The first is in continental arcs where subduction can impinge directly against the base of the subcontinental mantle keel or can transfer fluids from the slab to the base of the continental mantle keel without triggering diamond-destroying basaltic magmatism. This is the process discussed above to produce many of the 2.9 Ga Kaapvaal diamonds and some of the other continent margin diamonds. Recent work has shown that only 200 million years ago, eastward subduction of the Farallon slab under the Slave craton released diamond-forming fluids that produced thick, fibrous diamond overgrowths on preexisting 3.5 and 1.8 billion-year-old monocrystalline diamonds (Weiss et al., 2015). Today, the best chance for diamond formation are the few places where subduction occurs against lithospheric mantle, despite the amount of subduction taking place around the margins of the Pacific Ocean. Diamond formation may be continuing today along the western margin of North America, where the Farallon/Juan de Fuca plates are being subducted eastward. Another possible environment is where the Nazca plate is being subducted below South America.

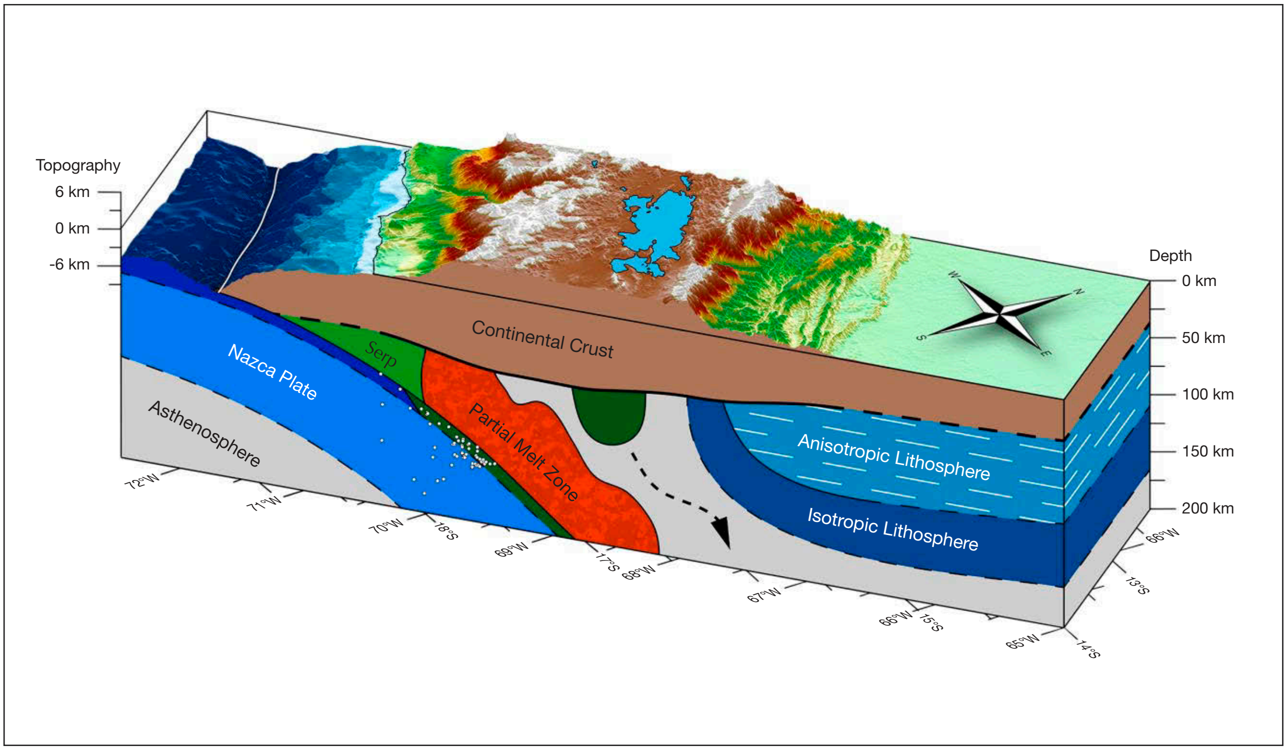
A second geological environment where we might find diamonds forming today is at the deeper reaches of subduction of oceanic lithosphere. We have evidence for diamonds forming between 400 and 700 km due to the deep subduction of cold slabs, which has carried carbon and volatiles into the transition zone and lower mantle. In this environment, the famous CLIPPIR (Smith et al., 2016, 2017) and type IIb blue diamonds (Smith et al., 2018) have crystallized from the mantle portion of the slab, whereas other diamonds have crystallized from carbonated oceanic crust (Walter et al., 2011; Regier et al., 2020).

Although modern diamond formation may be taking place in these regions, there is no definitive way for us to prove it without access to the diamonds. We need to wait for kimberlite or lamproite to erupt through the lithosphere and bring diamonds and their associated mantle rocks to the surface.

Diamonds forming in sublithospheric regions (300–700 km) have an additional complication in that they first need to be brought to shallower regions that can be sampled by kimberlites and lamproites. This is thought to happen through either mantle convection or upwelling plumes, which may take millions of years.

Since the last kimberlitic eruption was around 10,000 years ago (see Summer 2019 Diamonds from the Deep), we may have a long wait!

Figure 4. Geologic block diagram interpreted from seismic data showing modern-day subduction against the South American continental lithosphere, forming the Andes Mountains. Although diamonds could theoretically be forming in the mantle wedge anywhere between a depth of 160 and 300 km, local mantle conditions should also be reducing enough for elemental carbon to survive without being converted to carbon dioxide. Reproduced from Ward et al. (2016), with permission from John Wiley and Sons.



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