



Editor: Evan M. Smith

## Deep-Focus Earthquakes: The Heartbeat of a Diamond Factory?

The geological landscape around us evolves so slowly that it can appear static, but the rigid tectonic plates that make up the outer layer of our planet drift across its surface over time. Interactions between plates result in large-scale bumping, grinding, and breaking of rocks that we feel as earthquakes. Some earthquakes originate from *below* the rigid outer layer of plates, even from depths greater than about 300 km where rocks are expected to be under too much confining pressure to break by brittle failure. Instead of being related to multiple plates jostling together, these deep earthquakes are always associated with cold, lone plates that have sunken down into the warmer convecting mantle through the process of subduction. The nature and cause of these so-called deep-focus earthquakes remain poorly understood, but recent research suggests they might have something to do with the growth of top-quality gem diamonds.

As a sinking or subducting plate, also colloquially called a “slab,” descends into the mantle, the pressure and temperature increase. Changing conditions can cause some minerals to melt or undergo phase changes that release water. Recent slab modeling shows that the measured depths of deep-focus earthquakes coincide with the depth where melts and fluids should be released from some slabs, especially those that are relatively cold to begin with (Shirey et al., 2021). The release of melts and fluids at depths beyond 300 km potentially serves to trigger these deep-focus earthquakes. Shirey et al. (2021) also linked this earthquake activity to the formation of sublithospheric or

super-deep diamonds, which have been connected with subducted material and both carbonatitic melts and hydrous fluids in previous studies (Walter et al., 2008; Harte, 2010; Pearson et al., 2014; Smith et al., 2016, 2018; Thomson et al., 2016b; Smith and Nestola, 2021). Here we will explore the connection between deep-focus earthquakes and the growth of diamonds—specifically the variety known as CLIPPIR diamonds (Cullinan-like, Large, Inclusion-Poor, Pure, Irregular, and Resorbed) that make up many of the type II diamonds in the gem market (Smith et al., 2016, 2017).

### Deep-Focus Earthquakes

An earthquake in the crust is caused by a sudden brittle failure of rock, often along a preexisting, large-scale fracture where two plates meet, called a *fault*. Tectonic plates move at a pace of a few centimeters per year, about the same rate our fingernails grow, but the motion is not smooth and continuous at the boundaries between plates. Friction along faults resists the motion. Stresses build up until they cause sudden brittle failure and movement that can shake Earth’s interior and surface. The vibrations or seismic activity can cause serious damage to buildings and infrastructure, or they can be so slight that they are only detected with sensitive instruments called *seismometers*.

Scientists have been recording earthquake activity for more than a century, with increasing degrees of sophistication, accumulating a tremendous amount of data. With multiple seismometers recording the same earthquake, it is possible to calculate where it originated within the earth. The location in the earth where an earthquake starts is called the *hypocenter*, while the location directly above it at the surface is called the *epicenter*. When mapped out over time, earthquakes near the surface trace out faults, marking the boundaries between mobile tectonic plates.

There is also important information conveyed by the depth of earthquake hypocenters. Figure 1A shows a his-

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togram of the depth of earthquakes worldwide, revealing two humps or modes in the data. The first and most prominent mode peaks within the uppermost 100 km and drops off exponentially with depth (Frohlich, 2006). These shallower earthquakes are associated with movements along faults between tectonic plates, especially where plates push together, at subduction zones and continental collisions (figure 1B). Deeper earthquakes, plotted all the way down to 700 km in figure 1A, are associated with subducting plates and record their activity as they sink into the mantle.

Initially, earthquake activity coincides with dehydration and the release of fluids from sediment and crust in a subducting slab. Seismicity tapers off sharply down to a depth of 300 km, and it is expected that dehydration and loss of volatiles from the slab are largely complete by this point. There should be no further earthquakes as the slab continues to descend into the mantle. For this reason, the deep-focus earthquakes below about 300 km that peak in a second mode at 500–600 km are anomalous (figure 1A).

Deep-focus earthquakes are a subject of active research. Several ideas have been proposed to explain them. One of the proposed mechanisms is that subducting slabs contain hydrous minerals in their interior from previous interaction with seawater at the surface, which eventually break down as the slab warms up, releasing water and promoting brittle failure within the slab (Omori et al., 2004). This idea is singled out here because it ties in with the modeling

work by Shirey et al. (2021), who refined the idea and connected it with recent observations from CLIPPIR (~type IIa) and type IIb diamonds.

## A Primer in Plate Tectonics

It is clear that deep-focus earthquakes are linked with subduction, so it is important to clarify some of the concepts of plate tectonics before moving further. The rigid outer layer of the earth that makes up the plates in figure 1B is called the *lithosphere*, and it rides on the weak and plastic (but not molten) rock beneath the lithosphere, shown simply as white space under the plates. The lithosphere is an open-faced sandwich of two components, with the crust on top and a portion of rigid mantle rock beneath it. The bottom of the lithosphere or plate is a mechanical boundary where the mantle rocks transition from rigid and brittle to weak and plastic. The weak and flowing mantle beneath the lithosphere is sometimes specified as the sublithospheric mantle or convecting mantle, which extends all the way down to the outer core at 2900 km.

There are two very different kinds of lithosphere. Continents, including their underwater continental shelf extensions, are made of continental lithosphere, whereas ocean floors are made of oceanic lithosphere (figure 1B). Continental lithosphere is thicker, more buoyant, and relatively stable through geologic time. Oceanic lithosphere is thinner, denser, and has a relatively finite life cycle.

Figure 1. Earthquake depth distribution and overview of plate boundaries. A: Depth distribution of earthquakes worldwide (note the logarithmic scale). Most “regular” earthquakes occur at depths shallower than 200 km, and the frequency decreases with depth. Earthquakes deeper than about 300 km stray from this pattern, and there is an anomalous mode of activity around 500–600 km. The histogram shows magnitude 5 and greater earthquakes for a 40-year period (1964–2004) in the EHB (Engdahl-van der Hilst-Buland) catalog (Engdahl et al., 1998). B: A simplified schematic cross section of the earth, showing interactions between tectonic plates. Most earthquake activity occurs by interactions between these rigid plates near the surface, especially where plates push together, at subduction zones and continental collisions. Deeper earthquakes are spatially associated with subducted plates and must occur by a different mechanism that remains poorly understood.

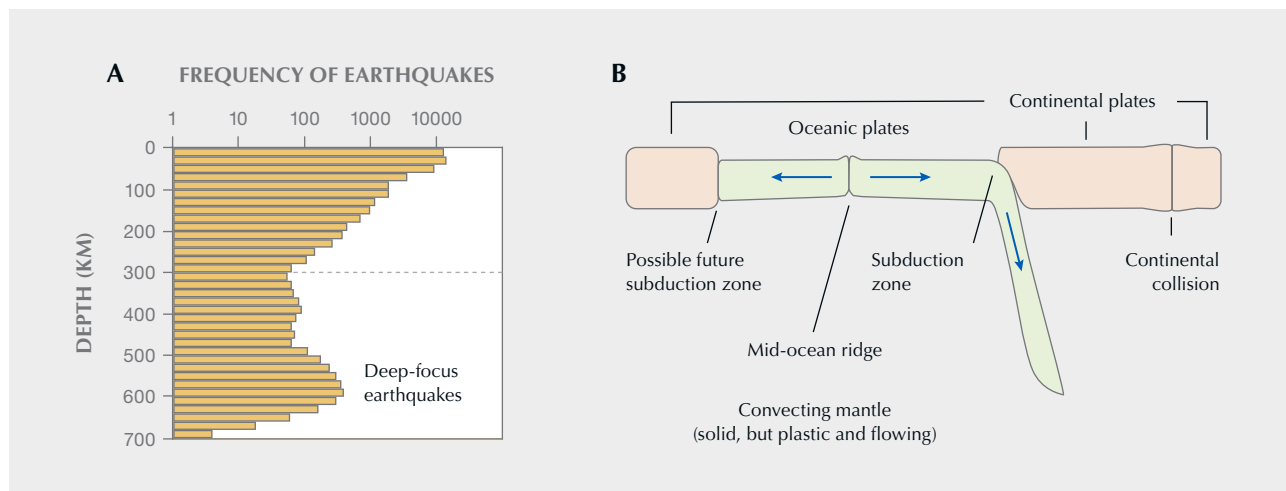




Figure 2. These large type IIa diamonds are good examples of CLIPPIR diamonds, which are the kind of top gem-quality diamonds produced in the sublithospheric mantle, potentially in association with deep earthquakes. The diamonds shown are from the Letšeng mine in Lesotho and range from 14 to 91 ct. Note the irregular morphologies, including surfaces that are both broken and substantially resorbed. Photo by Robert Weldon/GIA; courtesy of Gem Diamonds Ltd.

Oceanic lithosphere is created almost continuously at the spreading centers of mid-ocean ridges. On either side of a ridge, the plates gradually spread apart. Eventually, in 20 to 200 million years, the oceanic lithosphere bends and sinks down into the convecting mantle, a process called *subduction* (figure 1B). The creation and subduction of oceanic lithosphere are ongoing. The rate of spreading at mid-ocean ridges and convergence at subduction zones often differs and is not necessarily balanced in the same ocean basin, so oceans are dynamic regions that can open and grow or shrink and close. The opening of the Atlantic Ocean, for example, is facilitated by the creation of new oceanic lithosphere along the mid-Atlantic ridge. There is currently no subduction of oceanic lithosphere around the Atlantic's perimeter. The Pacific Ocean, however, is almost completely surrounded by subduction zones where oceanic lithosphere is subducting down into the mantle and fueling arc volcanoes that make up the Pacific Ring of Fire.

Nearly all the oceanic lithosphere on Earth is younger than about 200 million years old. Modern-style plate tectonics is thought to have been operating for about the past 3 billion years (Earth is 4.5 billion years old) (Shirey and Richardson, 2011). Over this time, several oceans have opened and closed (Wilson, 1966) along with the assembly and breakup of various continental configurations, such as the supercontinent Pangaea.

### Super-Deep Diamond Factories

Hundreds of kilometers down inside the earth, where subducting slabs reach perhaps 360–750 km, there may be blossoming domains of diamond growth. Most mined diamonds are thought to originate from shallower depths within the continental lithosphere at about 150–200 km, but some (estimated to be approximately 2%) originate from below the continental lithosphere. These are known as *sublithospheric* or *super-deep* diamonds. Despite being a relatively rare mineral, diamond can form in multiple different ways. The variables that lead to different kinds of diamond include the host rock type, the composition of the diamond forming fluid, how carbon resides in the fluid and surrounding mantle, and the pressure and temperature conditions. Individual diamond deposits at the surface often contain several distinct populations that can be recognized by studying mineral inclusions or other features, such as their morphology, internal growth history, nitrogen content and aggregation, and carbon isotopic composition (e.g., Stachel and Harris, 2008).

The study of sublithospheric diamonds over the past few decades has been dominated by small (usually <1 ct), generally non-gem quality diamonds from the Juina region of Brazil and various other localities worldwide (see reviews by Stachel et al., 2005; Kaminsky, 2012; Harte and Hudson, 2013; Smith and Nestola, 2021). In the past few years, however, it has been discovered that the prevalence

of sublithospheric diamonds is greater than previously thought and includes some of the largest and highest-quality gem diamonds (Smith et al., 2016, 2017, 2018). Diamonds such as the exquisite type IIa (containing no detectable nitrogen by FTIR) gems from the Letšeng mine (figure 2) are now recognized to belong to the sublithospheric variety termed CLIPPIR diamonds. These are argued to account for most of the type IIa diamonds in the gem marketplace, amounting to about 1% of diamonds (Smith et al., 2017). Similarly, rare type IIb diamonds (boron-bearing), which can be blue in color, have also been shown to be sublithospheric (Smith et al., 2018).

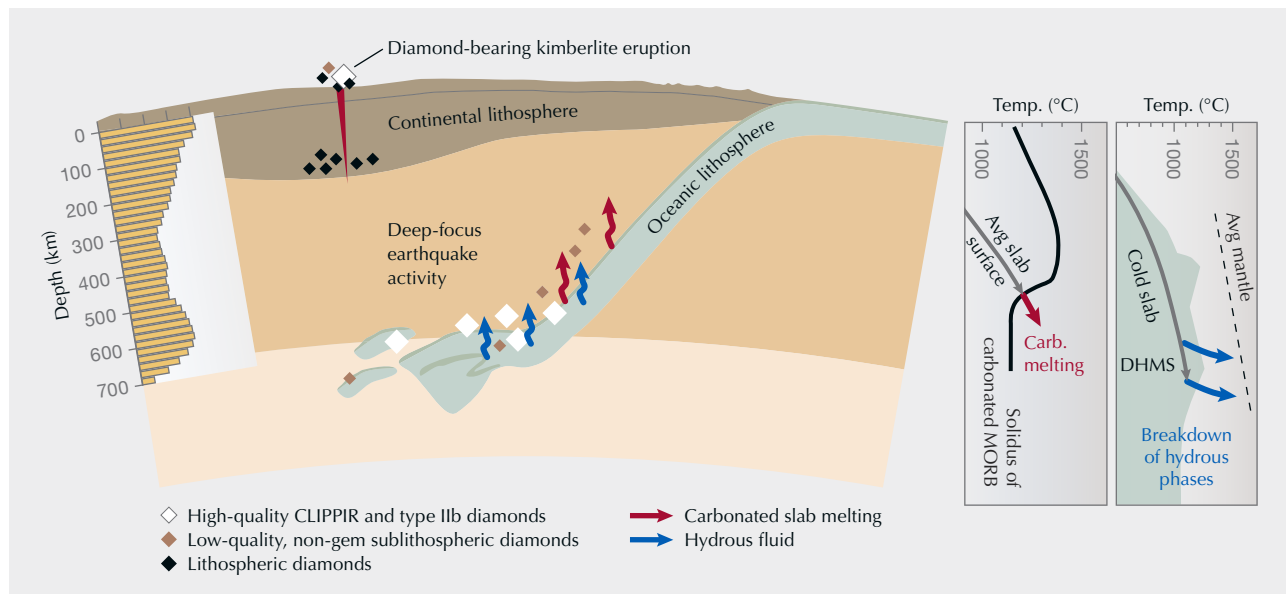
A connection to subducted oceanic lithosphere is an emerging theme common to many sublithospheric diamonds, based mainly on the composition of mineral inclusions (Walter et al., 2008, 2011; Bulanova et al., 2010; Burnham et al., 2015; Ickert et al., 2015; Seitz et al., 2018; Smith et al., 2018; Thomson et al., 2016a). CLIPPIR and type IIb diamonds have also been linked to subducted slabs and to serpentinized peridotite in the mantle portion of slabs in particular. Serpentinization is a complex series of reactions between water and rock, resulting in the formation of hydrous (water-bearing) minerals such as serpentine

from normally anhydrous minerals such as olivine. The strongest piece of evidence for this connection between diamonds and serpentinites comes from measurements of iron isotopes in inclusions trapped in CLIPPIR diamonds (Smith et al., 2021). The iron in these inclusions has an isotopic signature produced during serpentinization reactions between seawater and the ocean floor. In order for this signature to be trapped in CLIPPIR diamonds, deeply subducted serpentinized oceanic lithosphere must have contributed to their formation. In a sense, subducting slabs are like conveyor belts feeding raw materials down to hidden super-deep diamond factories at 360–750 km depths. Exactly how these diamonds make their way upward to shallower depths where they can be swept up to the surface in volcanic eruptions of kimberlite magma remains an open question, however (figure 3).

### Earthquakes and Diamond-Forming Fluid

Slabs gradually warm up as they subduct into the mantle. The temperature change with depth is called a *geotherm*. About half of Earth's subducting slabs trace out warmer pathways, while the remainder are colder, depending on the

Figure 3. Mantle cross section showing a relatively cool subducting slab, with an inset histogram of earthquake frequency (from figure 1). Profiles on the right show the slab surface and interior temperature during subduction. Where the slab surface temperature intersects the solidus of carbonated mid-ocean ridge basalt (MORB), partial melting may occur (red arrows). At the far right, a cold slab interior remains within the dense hydrous magnesium silicates (DHMS) stability field until the slab stalls and warms up, causing the breakdown of these hydrous phases and the release of hydrous fluid (blue arrows). Large white and smaller brown diamond symbols signify the growth of high-quality gem diamonds (CLIPPIR and type IIb) and low-quality, generally non-gem sublithospheric diamonds, respectively. Poorly understood mechanisms transport some diamonds upward where they can be swept up in kimberlite eruptions and mixed with common lithospheric diamonds (small black diamond symbols). Modified from Smith and Nestola (2021) with carbonated MORB solidus from Thomson et al. (2016b) and DHMS stability field from Harte (2010).



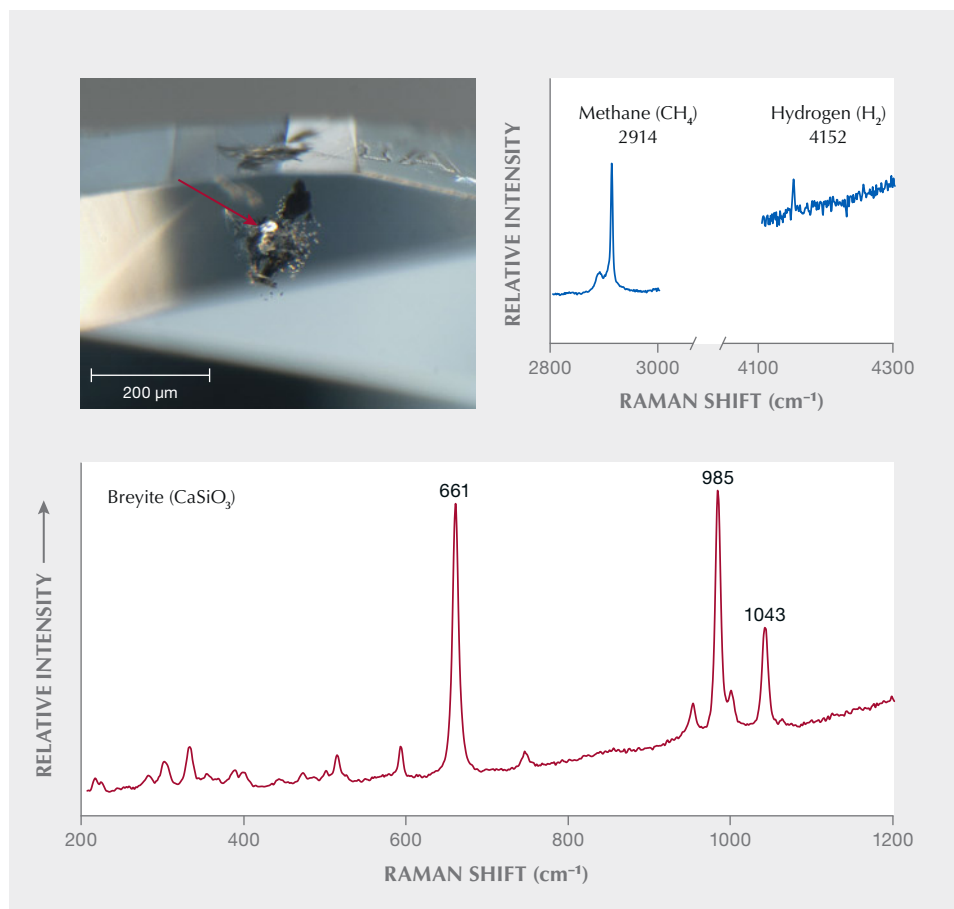


Figure 4. Evidence of hydrous fluid presence during diamond growth. This inclusion of breyite (photomicrograph and bottom Raman spectrum) within a blue type IIb diamond is interpreted to have been trapped as  $\text{CaSiO}_3$  perovskite, which has inverted to a lower-pressure mineral form during exhumation from the mantle, originating from a depth greater than 360 km. Raman spectroscopy also reveals peaks associated with methane and molecular hydrogen (top right spectrum), which are present as a thin fluid layer trapped at the interface between the solid inclusion and the host diamond. Photomicrograph by E.M. Smith; field of view 0.65 mm.

age of the slab and the speed at which it subducts. Warmer slabs generally lack deep earthquakes, which appear to be unique to colder slabs. Shirey et al. (2021) examined slabs around the world and modeled their temperature change with depth as they heat up during subduction into the mantle. They also made a careful comparison between earthquake locations, slab geotherms, and the expected mineralogy and phase changes within slab rocks. Overlaying the slab geotherms onto phase diagrams helps to illustrate where water-bearing phases break down and release fluid, such as the relatively well-accepted loss of most water from warm slabs at relatively shallow depths (<200 km). This is the activity that generates melt and fuels arc volcanoes such as those of the Pacific Ring of Fire. Cold slabs, however, can partially bypass this shallow dewatering process and transport a budget of carbonate and water to depths beyond 300 km, where its later release can cause deep-focus earthquakes (figure 3).

The cold slabs can be thought of as having a carbonated crust component and a hydrated/serpentinized mantle peridotite component that lies shielded beneath the crust, toward the interior of the slab. The deep release of carbonatitic melt and hydrous fluid from each component, respectively, is shown in the two depth profiles in figure 3. The carbonated crust (mid-ocean ridge basalt, or MORB) of the slab surface will intersect a deep depression in its solidus,

the curve describing the beginning of melting, meaning it exceeds the melting temperature. Beyond this point, carbonate melting (red arrows) is expected to occur within the top/crustal portion of the slab.

For hydrated/serpentinized mantle peridotite inside the slab, its stability also depends on temperature. If it remains cool, the serpentine can metamorphose into higher-pressure water-bearing minerals called *dense hydrous magnesium silicates* (DHMS) rather than breaking down. DHMS phases are a good vehicle for transporting water, with some carrying as much as 10% or more water by weight. The geotherm for the interior of cold slabs remains in the DHMS stability field far beyond a depth of 300 km (far right in figure 3). The slab in figure 3 is shown deflecting as it reaches the top of the lower mantle (at 660 km), where there is a change in mantle density and deformability. As the slab stalls and warms up, DHMS phases break down to form minerals that carry much less water, thereby causing water release (blue arrows in figure 3). These are the mechanisms proposed to trigger not only deep-focus earthquakes but also super-deep diamond growth (Shirey et al., 2021).

Inclusions in the smaller, lower-quality varieties of sublithospheric diamonds often show evidence of growth from carbonatitic melts derived from slabs (Walter et al., 2008), but hydrous/aqueous fluids have also been implicated for some samples (Wirth et al., 2007; Pearson et al., 2014; Palot

et al., 2016). Serpentinite in subducting slabs can be relatively enriched in boron, meaning that the eventual breakdown of hydrous minerals from serpentinized peridotite can release boron-bearing hydrous fluid, which has been linked with the formation of type IIb (boron-bearing) diamonds (Smith et al., 2018). Figure 4 shows a calcium silicate (breyite) inclusion with methane and hydrogen in a type IIb diamond. The original mineral inclusion may have been relatively hydrogen-rich upon trapping because it crystallized from, or was exposed to, hydrous fluids. Subducted serpentinized peridotite is also a key ingredient for CLIPPIR diamond growth, on the basis of recent iron isotope measurements (Smith et al., 2021).

### Broken Diamonds

Evidence of natural deformation and breakage in diamond is not uncommon. For example, this evidence can be in the form of plastic deformation lines or internally fractured diamond overgrown by new layers of pristine diamond. Features such as these attest to the occasional turbulent conditions in the mantle, even before diamonds are picked up and scrambled by kimberlite eruptions. Little is known about the circumstances responsible for these features.

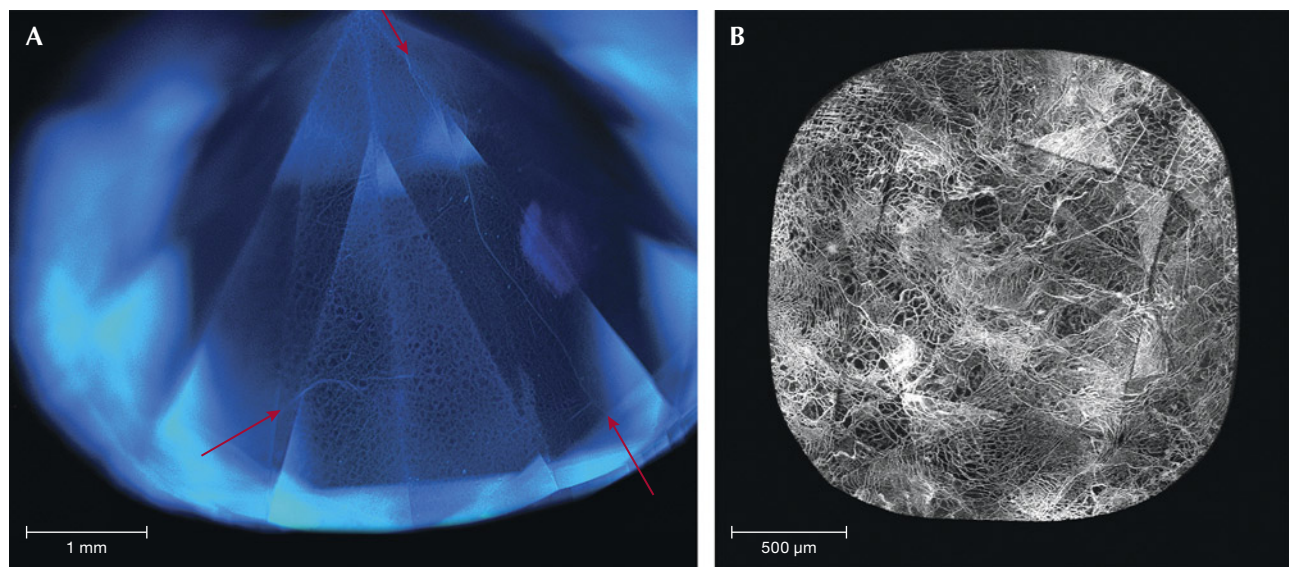
Sublithospheric diamonds in particular bear evidence of deformation and breakage, typically having irregular morphologies with broken and resorbed surfaces. CLIPPIR diamonds, which can reach thousands of carats (including the 3,106 ct Cullinan), often have surfaces that appear to

be broken (figure 2). Some of those broken surfaces on large diamonds have high degrees of resorption or chemical dissolution, to an extent that would consume any small diamonds nearby (Gurney and Helmstaedt, 2012). For this reason, such extreme resorption is unlikely to be associated with volcanic transport in a kimberlite where smaller diamond crystals survive. This indicates that the resorption, and in turn some of the breakage of large CLIPPIR diamonds, occurred early in the diamond's history.

In addition to diamond breakage, some sublithospheric diamonds have internal evidence of more subdued brittle fractures that have healed rather than separated (figure 5). Network-like patterns of dislocations inside these diamonds often conform with the healed fractures rather than being cross-cut by them, suggesting the deformation and fracturing was followed by a protracted period of annealing in the mantle to allow the network pattern to develop. Again, this points to sublithospheric diamond deformation and breakage that is not due to kimberlite activity.

If fluid and melt release from deeply subducted slabs causes both deep-focus earthquakes and diamond growth, it is worth considering how diamonds might be affected by earthquakes. Breakage and other signs of deformation could potentially be related to diamond growth in a dynamic setting punctuated by deep-focus earthquakes. Obviously, more research is needed to decipher the natural deformation history of diamonds. Nevertheless, it is interesting to speculate on a possible connection between diamond breakage and deep-focus earthquakes.

*Figure 5. Evidence of the incredibly dynamic setting in which these diamonds form. A: Deep-UV luminescence image of a type IIa diamond with irregular blue lines (see arrows) that may be healed fractures lying within a typical dislocation network pattern. Image by E.M. Smith; field of view 5.92 mm. B: Cathodoluminescence image of a type IIb diamond with an irregular dislocation network pattern that encloses several long straight segments, reaching up to 600  $\mu\text{m}$ , interpreted as healed segments of brittle fracture/cleavage within an otherwise plastically deformed and annealed diamond. Image by E.M. Smith; field of view 2.39 mm.*



## Scientific Significance

Subduction is a fundamental aspect of plate tectonics that is driven by Earth's internal heat engine—the means by which heat escapes from the mantle and core. It forces us to consider plate tectonics not just as a system of plates at Earth's surface but also as a process that involves the exchange of material between the surface and the deeper convecting mantle over time (figure 1B). During its time at the seafloor, oceanic lithosphere interacts with seawater over many millions of years. Water can circulate into fractures and react with the basaltic and peridotitic rocks that make up the oceanic lithosphere. As the aged and modified oceanic plates subduct, they now carry sediments, pore fluids, altered oceanic crust, and serpentinized peridotite along for the ride.

The sediments, water, and carbonate in the upper portion of the slab may be stripped off at shallower depths in the subduction zone (<200 km) where they fuel arc volcanoes, but some carbonated crust and serpentinized peridotite can be transported deeper. Deep-focus earthquakes and diamonds may be a product of some slabs, namely those that have remained cooler during subduction, carry-

ing a budget of carbonate in altered ocean crust and hydrous minerals in serpentinized peridotite down to 300 to 700 km. The deep cycling of carbon and water has a big impact on the behavior of Earth's interior, how it moves and melts.

These large-scale processes are relevant for the evolution of the atmosphere, the distribution of water at the surface, and the formation of continents over geological time. All of these parts of the dynamic earth are connected. Despite the proven 1 to 3 billion-year-old ages of many gem diamonds that come from the lithosphere, there is no reason that diamonds cannot be forming in the present. If diamonds and deep earthquakes are truly related, as described by Shirey et al. (2021), the implication is that modern-day earthquakes herald the formation of new diamonds. In this sense, subduction drives a sort of modern diamond factory—one that has the potential to produce some of the largest and most valuable diamonds known (including type IIa and type IIb diamonds). Diamonds and earthquakes, while fascinating in their own right, are two of the most powerful tools we have to unravel the inner workings of our planet.

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