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# Temporal changes in diamond formation by subduction through Earth history: thermal modeling, seismology, & petrology evidence

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## Introduction

Lithospheric diamonds and sublithospheric diamonds both contain evidence for the recycling of surficial components that have equilibrated at low temperatures in ocean floor hydrothermal systems. The known way to inject these materials into diamond-forming regions of the mantle is the oceanic lithosphere or "slab" subduction of plate tectonics. Both diamond types have thus formed by variants of slab subduction that may have differed in depth and style over geologic time.

## Sublithospheric diamonds

In the current plate tectonic regime, thermal modeling, petrology, and seismology (Shirey et al. 2021) show that cold slabs avoid the devolatilization occurring with normal arc and wedge subduction and carry some of their volatiles into the deep upper mantle, mantle transition zone, and uppermost lower mantle. Crust near the slab surface devolatilizes by melting at these depths when it intersects its carbonated solidus (Shirey, et al. 2024; Thomson, et al. 2016; Walter, et al. 2022). Mantle that is deeper and colder towards the slab interior will devolatilize later because it has to heat up to melt or re-crystallize 'dryer' mineral assemblages (Shirey, et al. 2024; Shirey, et al. 2021; Walter, et al. 2022). Fluids in cracks and faults will become diamond-forming as they react with enclosing mantle rocks (Shirey, et al. 2021). Diamonds formed in this way will record deformation produced by mantle convection, trap mantle minerals reacting with diamond-forming fluids, and can become lodged beneath mantle keels by diapiric uprise (e.g. Timmerman, et al. 2023). Sublithospheric diamonds are the prime natural samples we have from modern deep mantle geodynamics.

## Comparison of lithospheric vs sublithospheric diamonds

Lithospheric diamonds, stored in static ancient continental keels, lack the connection to the type of deep geodynamic regime that is evident from sublithospheric diamonds. A comparison between the two diamond types can lead to a geologic model for lithospheric diamond formation in the ancient past. Lithospheric diamonds are different from sublithospheric diamonds in critical ways: 1) much higher average N content including heavy $\delta^{15}$N (Stachel, et al. 2022), 2) older ages extending into the Paleoarchean (Smit et al. 2022), 3) inclusion assemblages indicating formation at lower pressure, 4) lack of certain internal deformation features, and 5) having sulfide inclusions some with MIF S isotopic compositions (Farquhar, et al. 2002).

## Nitrogen in the slab

Nitrogen content is critical to relating lithospheric diamonds to a lithospheric diamond subduction model. Nitrogen occurs in clays and sediments at the slab surface or uppermost crust (Bebout, et al. 2016). For sublithospheric diamonds derived from supercritical aqueous fluids/melts or carbonatitic liquids, their low nitrogen content occurs because they crystallized from low nitrogen fluids produced once nitrogen has been largely devolatilized (Bebout, et al. 2016; Li and Keppler 2014), from rocks deeper in the slab where nitrogen is scarce (e.g. Mikhail and Howell 2016), or from equilibration with a phase that has a high affinity for nitrogen (Rustioni, et al. 2024; Smith and Kopylova 2014). For lithospheric diamonds, the converse is true —their high nitrogen content is evidence that diamond-forming fluids are much richer in nitrogen. This basic fact leads to a clear constraint on Archean subduction and continental craton assembly.

## Lithospheric diamonds —the most important continental growth indicator?

To produce lithospheric diamonds with higher N content, their fluids would have to have been derived from the surface of warmer slabs, since this is where nitrogen resides. Such devolatilization from slab surfaces and of warmer slabs occurs shallower than 300 km and releases fluids into the mantle wedge when one exists. At these depths, under normal island arc or continental arc settings, the mantle wedge is too oxidizing to promote diamond crystallization. Furthermore, any magmas formed will be basalts unable to transport diamonds without dissolving them. To explain the high nitrogen content of most lithospheric diamonds, we propose a setting where subduction occurs against the dipping edge of a subcontinental mantle keel and that this condition is a requirement so that they can crystallize from nitrogen-rich fluids. This setting allows for mantle-wedge-free transfer of diamond-forming fluids from the subducting plate to the *hanging wall* of the reducing and nascent subcontinental mantle keel. Such settings have been proposed for the formation of Mesoarchean diamonds in the Kimberley Block of the Kaapvaal Craton (Shirey, et al. 2013) and the Phanerozoic fibrous diamonds of the Slave Craton (Weiss, et al. 2015) among others. The existence and location of high nitrogen, lithospheric diamonds thus become indicators of slab subduction directly against the continental mantle keel. As such, they are better *fossils* of Archean and Proterozoic mantle geodynamics than detrital zircons or TTGs which must be viewed through the lens of crustal differentiation.

## Implications for temporal changes in subduction and blueschist preservation

A gradual temporal change from shallow, keel-adjacent, mantle-wedge-poor subduction that produced lithospheric diamonds starting in the Mesoarchean (e.g. Shirey and Richardson 2011) to cold and deep subduction that produced sublithospheric diamonds in the Paleozoic (Timmerman, et al. 2023) has recently been proposed to have started in the in the late Paleoproterozoic (e.g. Zhang, et al. 2024). This temporal change is consistent with many geologic features that have been proposed for the Archean: an early stagnant lid and a buoyant Archean oceanic lithosphere (Foley 2018); shallow formation of the subcontinental lithospheric mantle (Stachel, et al. 1998); advective thickening of the cratonic keel (Jordan 1988; Pearson, et al. 2021); slab-imbrication accompanying lithospheric thickening (Timmerman, et al. 2022); the diamond endowment of portions of mantle keels; and the anomalously diamond-rich nature of ancient eclogites (Taylor, et al. 2000).

More importantly, keel-adjacent, mantle-wedge-absent subduction that is part of the advective lithosphere thickening process would likely not preserve blueshists in the geologic record. The absence of blueschists greater than 1 Ga has been extensively promoted as the key indicator that subduction started late in Earth history (e.g. Stern 2018). Yet, the youth age of blueschists and paucity of > 1Ga blueschist occurrences could be explained by preservation bias. Low T– high P terrains of the type that host blueschists are found today only at young, non-cratonic continent edges where the lithosphere is thin (Brown and Johnson 2019). The eclogite found in continental mantle keels, while likely minor (Schulze 1989) is wide-spread and generally thought to be ancient incorporated oceanic slab crust (Jacob 2004). But some of the eclogite could be the ancient blueschist from keel-adjacent, mantle-wedge-absent subduction that was incorporated during advective thickening of the lithosphere. Proterozoic to Archean cratonic lithosphere has been thickened substantially to >200 km in a time frame that roughly follows the ages (Brown & Johnson 2019) of crustal metamorphic terranes. Lithospheric diamonds then, are our best indicator that modern-style plate tectonics started on Earth at least in the Mesoarchean.

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