Colored gemstones of metamorphic origin: Progress report in understanding how they crystallize at depth in East Africa, the Hindu Kush, Pamir Mountains, and the Middle-Urals Ring Structure

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Two problems

It is difficult to reconcile the existence of deposits of transparent gems of metamorphic origin with the observation attributed to Robert Boyle (1627–1691) that the best crystals grow in cavities. A problem arises for the gem-rich areas in East Africa, the Urals, the Hindu Kush, Pamirs and elsewhere because cavities do not exist at the depths where regional metamorphism occurs.

In the absence of actual cavities, we might seek regions at depth where the constraining pressure is somehow regionally reduced. But such circumstances are also absent from metamorphic terrains.

To be clear, isolated 3–D spots or groups of spots with low pressure do exist and may indeed contribute to gem-formation. Low pressure spots at Merelani where tanzanite crystallized in association with boudins are a clear example (Olivier, 2008). But localized spots such as furnished by boudins or at the apexes of tight folds are only contributing factors. As a matter of scale — cm vs. km — they throw no light on the existence of extended metamorphic terrains (in East Africa, the Urals...) that host multiple gem deposits formed at depth.

There is another problem too: all the colored gemstones in a given region crystallized within one particular short-lived window of time. In East Africa, for example, all the gems crystallized approximately 550 million years ago.

Elements of a solution

The pressure at any depth in the Earth is essentially fixed, but this is not necessarily true for temperature.

An increase in temperature at depth would allow certain minerals to crystallize higher in the Earth, hence under lower constraining pressure, hence, in some cases, as gems.

A rise in temperature leading to the formation of gems under metamorphic conditions cannot, however, be achieved by familiar sources of heat such as volcanism or igneous intrusions. For whereas volcanism and igneous intrusions are common, gem-producing regions are rare.

Thus, for the gem-rich areas in East Africa, for example, it is necessary to identify a source of heat that was active. c.550 million years ago *but not before that time and not after*.

A candidate-source of heat available for the formation of metamorphic gems is furnished by thrust faults whereby thick sheets of rock, thrust one over another, produce temperature inversions that place hot rocks from deep in the Earth on top of cooler rocks from closer to the surface; Figure 1.

Such temperature inversions are locally augmented by transient frictional heat whose magnitude is determined by the types of rocks and the thickness and temperature of the thrust sheets (Fritz, *et al*., 2009).

Heat was dispersed *upward* into overlying rocks *though only temporarily*, producing elevated temperatures at unusually shallow depths. Certain minerals were then “tricked” into crystallizing higher in the Earth than usual, hence with better quality crystallization. And in East Africa, the Urals, Himalayas, Hindu Kush, Pamirs, and presumably elsewhere, the time of thrusting and the time of gem formation are correlated.

Such scenarios, along with secondary contributing factors such as faults, the formation of boudins, or the production of temperature-lowering fluxes, provide circumstances that might allow high-quality crystallization at depth throughout a sizable region.

But we are confronted with the fact that large thrusts, which characterize continent-to-continent collisions, are not uncommon. And, to repeat, gem-rich regions are rare. So there must be differences between large-scale thrusting in general and those particular large-scale thrusts (in East Africa, the Urals...) that actually lead to the formation of gems.

One difference may be the thickness of individual thrust sheets, and another difference would be their initial temperature (see Fritz, *et al*., 2009).

Another difference, potentially affecting heat production, is the distance inland from the collision zone. For, as has been shown for the India–Eurasia (Hindu Kush, Pamirs) convergence (Figure 2), the initial subduction of coastal sediments causes a “temporary acceleration in subduction rates” by a factor of >2, a phenomenon responsible for additional frictional heat, and thought to be “a common feature at the final stage of continental assembly” (Zhou *et al*. 2024). The incoming plate sprints at the end of its marathon!

Yet this is not the last word for, as can be observed (Figure 2), gems are preferentially formed at the passive edges of the “target” continent in places where the incoming plate encounters a circular plug of resistant rock, which is the case, as I have long argued in East Africa, the Hindu Kush, Pamirs and the Middle Urals Ring Structure (Saul, 2014, 2016, 2017, 2022, 2023; Burba, 1991, 2003a, 2003b). In such places thrusting over the resistant plug is much like that of sandpapering over a knot.

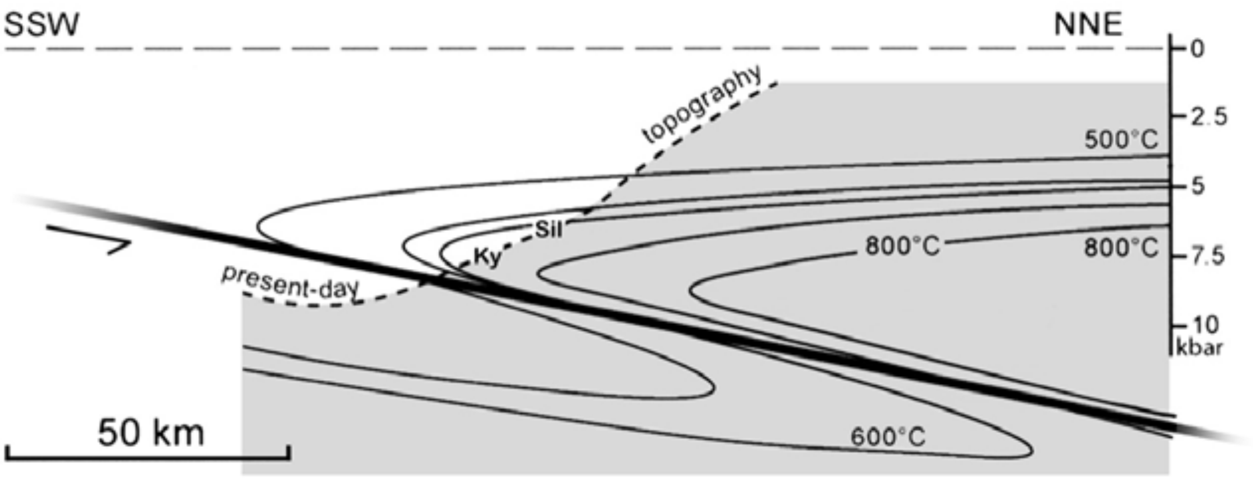

Figure 1: Thermal profile along the Himalayas in central Nepal. A thrust fault (thick line) caused overlying rocks to be metamorphosed at higher temperatures than those below. This allowed minerals to crystallize higher in the Earth than is usual, hence with less constraining pressure. “Sil” indicates sillimanite and “Ky”, below it, indicates kyanite, which normally crystallizes above sillimanite. Adapted from Le Fort (1975). Similar profiles for East Africa or the Urals were not available for this study.

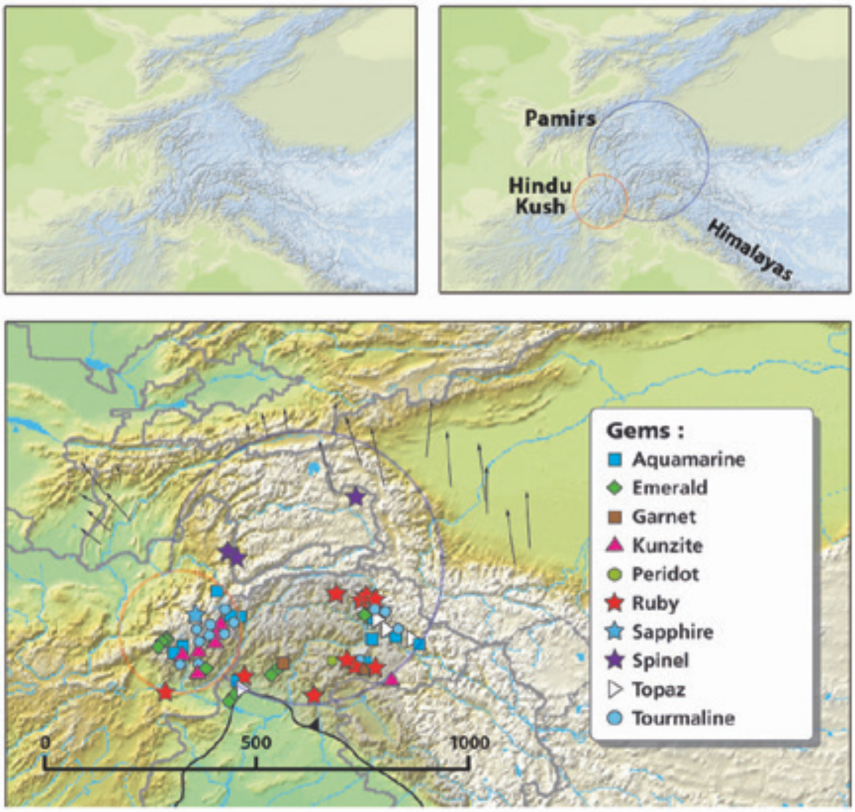

Figure 2: Gemstone locality map of the Hindu Kush and the Pamirs, both of which have faint circular outlines.

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