4 Whither terrane boundary of Southern Granulite Terrain? A deeper level simile to the Himalayan Crustal Extrusion model

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The Southern Granulite Terrain (SGT) occupies the central position in a number of Gondwana reconstructions and hence has attracted a large number of scientists who have worked towards understanding it tectonic architecture. Over last three decades they have generated enough data to put reasonable constraints on models for its tectonic evolution.

Chronologically, some of the important observations and models relevant to tectonics of the SGT are given below:

1. **'Fermor Line' as a fundamental boundary:**
   Fermor (1936) first suggested that the charnockitic terrains of Peninsular India (EG and SGT combined) form a mobile belt adjacent to the Dharwar craton and that the boundary between the high-grade and low-grade terrains - known as the "Fermor line" - represents a fundamental crustal boundary along which there must have been considerable vertical displacement. The area south of 'Fermor Line' is popularly known as the Southern Granulite Terrain (SGT)
2. **SGT as lower level exposure of a continuous crustal domain involving Dharwar Craton (DC):**
   In the mid-1960s, it became clear that the boundary between the charnockite and gneiss is transitional in nature and that charnockites south of the "Fermor Line" represent metasomatized equivalents of a variety of crustal protoliths of the Dharwar craton (Pichamuthu, 1965; Subrahmanian, 1967). Thus, the DC and the SGT form a continuous crustal domain in which the SGT represents the lower crustal exposures of the DC (Pichamuthu, 1965; Nautial, 1966; Shackleton, 1976).
3. **Identification of trans-continental lineaments from LANDSAT imageries:**
   In the year 1980 Landsat imagery interpretation brought out two major trans-continental shear zones alogn two major lineaments in the SGT (Drury and Holt, 1980). These are, (i) in the north the Palghat Cauvery Shear Zone (PCSZ) along the E-W trending Palghat-Cauvery Lineament and (ii) in the south the Achankovil Shear Zone (ASZ) along the NW-SE trending Achankovil Lineament.
4. **Support for trans-continental lineaments as Fundamental crustal boundaries:**
   Follow-up works revealed discontinuitites of the metamorphic P-T estimates, Nd-model ages and Rb-Sr mineral ages across the PCSZ and the ASZ (Drury et al., 1984; Harris and Santosh, 1993; Harris et al., 1994). Consequently, the PCSZ came to be known as a major lithospheric boundary. Some of the geophysical data, notably bouguer anomaly data, though done much earlier to this work were re-interpreted supporting this tectonic model. The identification of Pan-African charnockite in Kerala by Choudhury et al. (1992) gave a major boost to the acceptability of this tectonic model that the PCSZ marks a fundamental crustal boundary as the charnockites north of this lineament were demonstrably Late Archean in age. For about two decades this tectonic model involving the PSCZ as a fundamental crustal

boundary became much well entrenched in all geological and tectonic models. Accordingly, many Gondwana reconstruction models also used this tectonic interpretation. A major handicap for this model had been the lack of field map based data to support it.

5. **Vasundhara Project of the GSI (GSI, 1994): beginning of modern thinking on SGT:**
   In 1994 the Geological Survey of India, under Project Vasundhara, brought out a series of multi-layered thematic maps highlighting field-based lithostratigraphic data. These maps did not quite support the model of fundamental boundary along the PCSZ and provided a base of all subsequent works in the area.
6. **A challenge to satellite-based interpretations for tectonic architecture of SGT: the proposal of a new tectonic boundary, the KKPTSZ**
   The model that Palghat Cauvery Lineament marks a fundamental crustal boundary was questioned by Ghosh (1999) and Ghosh et al. (2004) based on corridor mapping across these shear zones, compilation of many 1:50,000 scale maps of Geological Survey of India and a series of high-quality U-Pb zircon dates. They proposed that the Dharwar craton extends further south of the Palghat Cauvery Lineament at least till a 'V' shaped shear zone, named as the Karur-Kambam-Painavu-Trichur Shear Zone (KKPTSZ). Area further south of the KKPTSZ represents either a pericratonic basin to the Dharwar craton or a separate terrane. The main tenets of model by Ghosh et al. (2004) are as below:
   a. Charnockites in the SGT do not constitute orthogneiss plutons and so they are not stratigraphic units. They are the deeper level metasomatic variants of different upper crustal rocks. On this point charnockitization is simile to lateritization processes in the surface. The boundary between charnockite massifs and granitic gneisses though appear as very pronounced features in satellite imageries, mostly run across lithostratigraphic boundaries and structural trends. The tectonic model of Drury et al. (1984) based mainly on the interpretation of satellite imageries in which tectonic grains were shown parallel to the charnockite-gneiss boundaries was thus not tenable.
   b. The Archearn TTG gneisses of the Dharwar craton extend across the Palghat Cauvery Lineament at least till the Kodaikanal Hills in the south. The area further south, known as the Madurai Province is occupied mainly by paragneisses and younger granites and their charnockitized variants. Though some remnants of basement gneiss are possible, the rocks are much deformed and hybridized by later partial melting and intrusion.
   c. The Achankovil Lineament also does not represent a terrane boundary. It marks an attenuated limb of a large regional fold defined by folding of quartzite and calc-silicate bands in the paragneiss and metasediments.

7. **Strengthening of the idea of the KKPTSZ:**
   A number of workers who worked in the SGT since the model of Ghosh (1999) and produced large number of high-quality laboratory and field based data on metamorphism, U-Pb zircon geochronology, Hf-isotope data on zircons etc. have provided further credence to the model. Prominent among them are reports of Late Archean granitoid from the Palni Hills (Pravsa et al., 2012, Brandt et al., 2014 and Bhattacheryya et al., 2014).

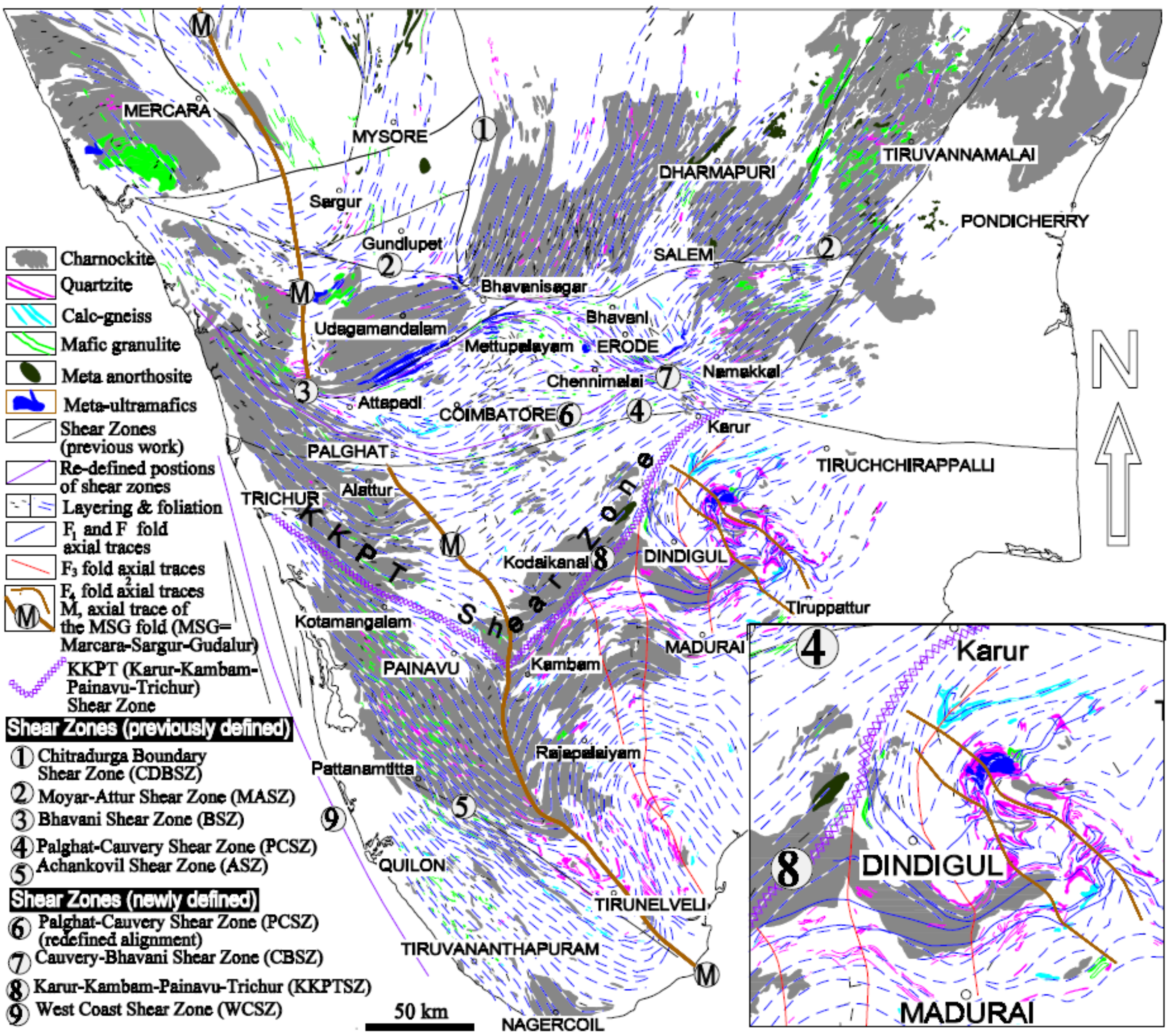

Figure showing important structural elements in the SGT and trend of structural grains drawn on the basis of strikes of quartzite, calc-silicate and amphibolites bands.

8. **Proposal for modification of the KKPTSZ: a continental collision boundary along the Kambam UHT belt:**

   A modification to the model of Ghosh (1999) has now come up (Brandt et al., 2014). While keeping the eastern side of the V-shaped KKPTSZ intact (i.e., Karur to Kambam sector), this new model has proposed that from Kambam the KKPTSZ instead of swerving in the NW-SE direction as Ghosh et al. (2004) have proposed, takes a due south turn till the Achankovil Lineament. This new alignment is named by them as the Kambam Ultra High Temperature Belt (Kambam UHT belt). The main tenets of this new tectonic model are as below:

   a. The Kambam UHT belt is about a 40 km wide zone marking presence of high-pressure ultra-high temperature metamorphism with clock-wise PT path. This belt has been interpreted to mark a fundamental collisional crustal boundary.
   b. The area west of this Kambam UHT belt, named Western Madurai Block, is a terrane composed of late-Neoarchaean (2.53–2.46 Ga) subduction-related, magnesian charno-enderbites, which were reworked in the early-Palaeoproterozoic during granulite facies metamorphism and partial melting .
   c. The area to the east of the Kambam UHT Belt, named as the Eastern Madurai Block, is dominated by a vast supracrustal sequence, which was deposited on a late-Palaeoproterozoic (1.74–1.62 Ga) basement of magnesian charnockites

and Hbl-Bt gneisses that formed through reworking of underlying Archaean rocks.

9. A critique to model of collision zone along Kambam UHT:

While this new model of Brandt et al. (2004) has made a significant contribution in identifying a HP-UHT belt in the Madurai Block, if suffers from a fundamental inadequacy in identification of possible basement rocks in either side of the newly proposed Kambam UHT Belt occurring south of the KKPTSZ.

a. In the West Madurai Block, the continuation of Archean basement south of the KKPTSZ is based on zircon dating of a single migmatitic charnockite that yielded a number of near-concordant clusters of U-Pb dates at 2.45 Ga, 850 Ma, 750 Ma, 600 Ma and 550 Ma. The 2.45 Ga date is taken as representing the basement age, assuming that the migmatitic charnockite represents a basement that suffered many later thermal events. This assumption is in suspect. As pointed out by Ghosh (1999) is area is dominated by paragneiss, though intense deformation and charnockitization makes it difficult to easily identify rock features in field. Though presence of a remobilized basement is a possibility, the large spread of near concordant dates from the sample is suggestive that they are possibly detrital zircons of charnockitized paragneiss.
b. Similarly, the interpretation of the Paleoproteorozic basement (~1.7 Ga) in the Eastern Madurai Block south of the KKPTSZ is based on analyses of a single migmatitic Hbl-Bt gneiss that yielded a large discordant spread on a line joining ~1.74 Ga and ~780 Ma with a younger spread on the Concordia ranging from 800 Ma and 500 Ma. Again, as pointed out by Ghosh (1999) the area is dominated by paragneiss and the large spread of discordant dates might as well indicate detrital zircon dates. Interpreting the 1.74 Ga date as the protolith age of a migmatitic Hbl-Bt gneiss is in suspect.

The interpretation of basement rock in a poly-deformed and poly metamorphic area dominated by paragneiss is very critical and need to be supported by convincing field-based data. A very strong single cluster on the Concordia is a good hint. Analyses of large number of samples from these rocks along with Hf-isotope data would likely clarify be able to clarify whether the rocks are remobilized basement or paragneiss.

10. Southern Granulite Terrain as deeper level simile to Himalayan Crustal Extrusion model:

Any tectonic model of the SGT should take into account of the following important parameters:

a. The TTG gneisses of the Dharwar craton extends at least as far south as the KKPTSZ.
b. Though ~550 Ma high-grade metamorphism is quite common in the SGT south of the Palghat Cauvery Lineament, older metamorphic and magmatic imprints are also recorded.
c. The area south of the KKPTSZ is dominated by paragneiss with younger intrusive and their charnockitized equivalents. Very widely varying U-Pb zircon dates along with Hf-isotope data that are coming out in large numbers these days, give credence to the idea that protolith from which these metasediments derived are widely varying and includes reworked basements.

d. As pointed out in 4a, charnockites in the SGT are metasomatic equivalents of older rocks and do not have any lithostratigraphic bearing. South of the KKPTSZ, though difficult, these older rocks are identifiable as paragneiss or granitic intrusives into paragneiss. 'Charnockitization front' is identifiable is identifiable in many cases at the boundary of the charnockite massifs and lower ground of paragneiss. Quartzite bands at high angle to such fronts continue from paragneiss into the charnockite massifs where gneiss banding is parallel to such lithostratigraphic layering. Such strong field criteria should get precedence over sophisticated geochemical criteria in deciding magmatic versus metasomatic origin of charnockites.
e. Charnockite superimposed planer penetrative fabric both in the KKPTSZ and in the ASZ. At least one phase of charnockitization occurred post 550 Ma, likely in between short time span of 530 Ma and 528 Ma (Ghosh, 1999). In the KKPTSZ ~570 Ma is affected by shearing while in the ASZ ~550 Ma granite show weak fabric development. It is thus possible that movement along the KKPTSZ and ASZ were broadly coeval, though much detail structural and geochronological work is needed.
f. Though the SGT warrants serious structural analyses to establish kinematics of the shear zones proposed, structural discordance across the eastern arm of the KKPTSZ was brought out by Ghosh (2004) mainly with the help of compilation of 1:50,000 maps of the Geological Survey of India. In the western arm of the KKPTSZ, the structural discordance is not evident as the structural trends are subparallel across the KKPTSZ in the western part.
g. Structural trends defined by quartzite bands and calc-silicate rocks in the area south of the KKPTSZ indicate that the Achankovil Lineament is an attenuated limb of a large scale fold, which might have been sheared.
h. There exists a nearly N-S trending High Pressure- Ultra High Temperature metamorphic belt, the Kambam UHT Belt along the mid-part of the paragneiss area south of the KKPTSZ.
i. Both KKPTSZ and the ASZ were active during Neoproterozoic time. Ghosh (1999) pointed out that charnockitization occurred in between 548 Ma and 528 Ma, with a likelyhood that it occurred in between 530 Ma and 528 Ma. Charnockite superimposed penetrative shear fabric both in the KKPTSZ and in the ASZ. Although the KKPTSZ could have been activated a number of times, one phase of activation was post 570 Ma. Similarly, movements along ASZ were pre 548 Ma. Thus, a broad coeval movement along the KKPTSZ and the ASZ is a possibility.
j. Poly-phase Neoproterozoic metamorphism for the SGT has been shown by Braun et al. (2007) by analyses of monazite inclusions in garnet and other minerals. Such dates range between 950 Ma and 480 Ma. This agrees with a number of different Neoprotezoic thermal events recorded by other workers. Certainly, lower crust of the SGT was fertile in terms of heat source for a very long time, either continuously or in phases.

With the constraints placed by above parameters, a strong simile of the SGT with the Crustal Extrusion model of the Himalayan collision tectonics cannot be missed, though the SGT is exposed at much deeper level than the Himalaya.

In the Himalaya, south to north the major lithostratigraphic units are: (i) the low to medium grade metamorphic of the Lesser Himalaya, (ii) the High-grade rocks with in situ partial melting in the Higher Himalaya, (iii) the low to medium grade metasediments of the Southen Tibetian Detachment Belt (Tethian sediments), (iv) the Indus-Tsangpo Ophiolite belt marking the collisional front of the Indian Plate, (v) Trans-Himalayan Granites and other rocks of the Asian Plate. The boundary marking the Lesser Himalaya and the Higher Himalaya is called the Main Central Thrust (MCT) while the boundary between the Higher Himalaya and the Tethian sediments is called the Southern Tibetan Detachment Shear (STDS). The emplacement of high-grade rocks of the Higher Himalaya interspaced between low- to medium grade rocks on both north and south is famously explained by Crustal Extrusion model whereby subducted Indian Plate under the Asian Plate suffered higher grade of metamorphism and has undergone partial melting because of delamination and high radiogenic elements in the rocks providing heat required. The buoyant partially melted rocks of the Indian Plate underneath the Asian Plate were pushed up as a crustal extrusion due to channel flow and were emplaced as Higher Himalayan rocks in between two prominent shear zones, the STDS and the MCT (with analogy of squeezing out of toothpaste from tubes). While MCT has a reverse slip movement, the STDS has normal slip movement, possibly triggered by gravitational collapse.

In the SGT, the Dharwar craton extends at least as far south as the KKPTSZ. This southern part of the Dharwar craton is comparable with the Indian Plate defined by Lesser Himalayan sequence in the Himalaya, though presently exposed at much deeper level than the Lesser Himalaya. The paragneiss dominated Madurai Block south of the KKPTSZ till the Achankovil Lineament is comparable with the Higher Himalyan sequence in the Himalaya, which exposes much higher grade metamorphic rocks than the bounding lithostratigraphic units. The paragneisses south of the Achankovil Lineament are of lesser metamorphic grade than the paragneisses north of it, just as the lower grade Tethyan metasediments north of the STDS in the Himalaya. The Achankovil Lineament itself appears as an attenuated limb of a large scale regional structure (Ghosh, 2004). It could represent a zone of gravitational collapse similar to the STDS in the Himalaya. In such a deeper level crustal extrusion due to channel flow model, the actual collisional front of the SGT should lie somewhere south of the Indian Peninsula. Table 1 shows the comparable lithostratigraphic and tectonic features of the SGT and the Himalaya based on development by crustal extrusion due to channel flow:

Features in the Himalaya (South to North)	Deeper level comparable feature in the SGT (North to South)
Lesser Himalaya	Area north of the KKPTSZ
Main Central Thrust (MCT)	Karur Kambam Painavu Trichur Shear Zone (KKPTSZ)
Higher Himalaya (higher grade metamorphism than bounding units)	Area in between the KKPTSZ and Achankovil Lineament (higher grade metamorphism than bounding units)
Southern Tibetan Detachment Shear (STDS)	Achankovil Shear Zone (ASZ)
Tethyan metasediments (lower grade of metamorphism)	Area south of the Achankovil Lineament (lower grade of metamorphism)
Collision front (Indus Tsangpo Suture Zone)	Area south of Indian peninsula
Asian Plate (Trans-Himalayan granites etc.)	

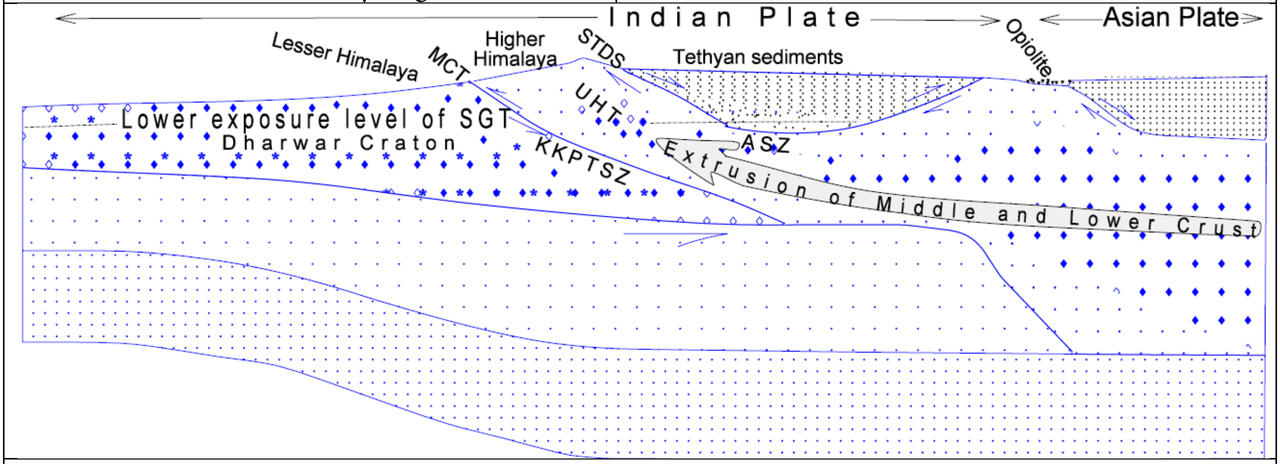

Figure showing Crustal extrusion by Channel Flow as applicable to Himalaya and to the SGT (at a deeper level): MCT= Main Central Thrust (zone of compression); STDS: Southern Tibetan Detachment Shear (zone of extension); KKPTSZ: Karur Kambam Painavu Trichur Shear Zone (Ghosh et al., 2004): ASZ= Achankovil Shear Zone: UHT= Kambam Ultra High Temperature Belt (Brandt, et al., 2014)

11. Applicability of the deeper level crustal extrusion model in the SGT:
The strongest argument for channel flow crustal extrusion model for the SGT comes from broadly coeval movement and metamorphic inversions at bounding surfaces (KKPTSZ and ASZ) with highest grade of rocks in the middle showing intense partial melting. A deeper level crustal extrusion model for the SGT explains some of the vexed problems of the area.

a. The occurrence of higher grade of metamorphic rocks in the area bounded by the KKPTSZ and Achankovil Lineament. This part represents partially molten deeper level equivalent of the Indian plate that has been extruded up due to channel flow and emplaced in between lithostratigraphic units of lower metamorphic grade.

b. Movements along the KKPTSZ and ASZ were possibly coeval (point 10e). A coeval movement along bounding shear zones is a necessity for crustal extrusion model.

c. Occurrence of HP-UHT rocks along the Kambam UHT Belt is explained by crustal extrusion due to channel flow where by being viscous a domain may extrude up more than the other parts depending on proportion of melts and constraints placed by bounding surfaces. The Kambam UHT Belt have extruded higher up more than the bounding areas.

d. Presence of a large number of different U-Pb concordant ages of zircons from the area south of the KKPTSZ with Hf-isotopes indicating different source characteristics is explained as they are essentially detrital zircons in the frontal parts of the collision zone. In the Higher Himalayan sequence also there exist a range of detrital zircon ages which do not have analog plutons in the Indian Plate.
e. Absence of ophiolite of Neoproterozoic age in the SGT is explained by the fact that any collisional front might have been present off the limit of Indian peninsula.

12. Tests for an deeper level Crustal Extrusion model for the SGT:

a. It is possible that the area between the KKPTSZ and the ASZ has some domains of basement protoliths, but they are expected to be thoroughly mauled by deformation and metamorphism as well as invaded by later melts. However, identification of such basement protoliths would provide important constraints on the evolution of the SGT.
b. A deeper level Crustal Extrusion model for the SGT would require constraints from timing and kinematics of the KKPTSZ and the Achankovil Lineament. They would need to reveal opposing kinematics but similar timing of movement (Jones et al., 2006). A crustal extrusion model as proposed here would require compressional shearing along the KKPTSZ and extensional shearing along the ASZ.
c. It is also needed to constrain the timing of the exhumation history of the paragneisses of the area between the KKPTSZ and the Achankovil Lineament. This can easily be done by U-Pb dating of different minerals like monazite, titanites, garnet, rutile, apatite etc. from a number of places. The exhumation histories from different blocks of the SGT would put good constraints on the model.

13. Conclusion:

Over the years and with efforts from a large number of workers we have certainly progressed a quite far in our understanding of the tectonics of the SGT. However, the area has suffered poly deformation and poly metamorphism at high grade conditions. It is perfectly OK even after all our sincere efforts; we fail to come up with a nice model.

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