Characterisation of a garnet population from the Sikkim Himalaya: insights into the rates and mechanisms of porphyroblast crystallisation

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(1) Motivation

The Sikkim Himalaya (Fig. 1.1) provides us with an outstanding natural laboratory in which to study fundamental processes associated with metamorphic mineral growth. We use a garnet-grade metapelite (Fig. 2.1) from Sikkim in order to address the following questions:

- Was garnet growth **interface-controlled or diffusion-controlled**?
- Were there significant deviations from **equilibrium** conditions during garnet crysallisation?
- Can **rates of metamorphism** be constrained using diffusion modelling?

We address these points by integrating (2) a characterisation of the bulk rock garnet distribution, (3) compositional variations within the garnet population and (4) forward modelling of the sizes and compositions of the population using an equilibrium crystallisation model.

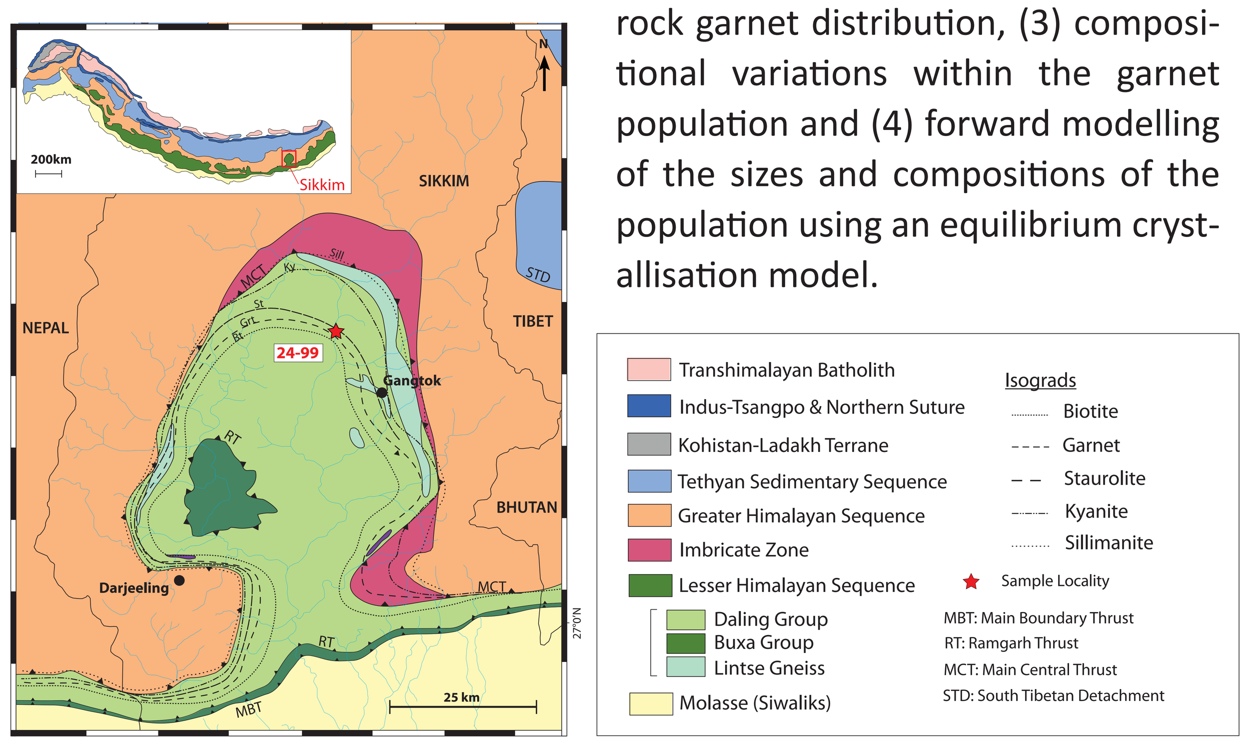
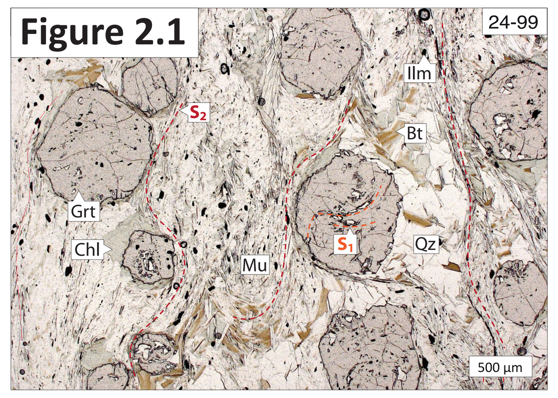


Figure 1.1 - Regional geological map of the Sikkim Himalaya, and its position within the Himalayan orogen (inset). Sample locality highlighted.

(2) Sample characterisation

grt + pl + mu + chl + bt + qz + ilm + gph + tur



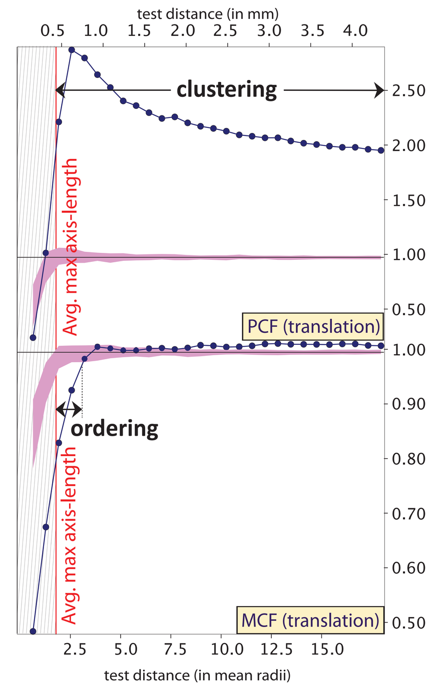


Figure 2.3 - Reduce3D (Hirsch, 2011) textural statistics. Clustering of crystal centres at > 0.44 mm. Smaller than average grain radii at <0.7 mm.

High-resolution µ-computed tomography:

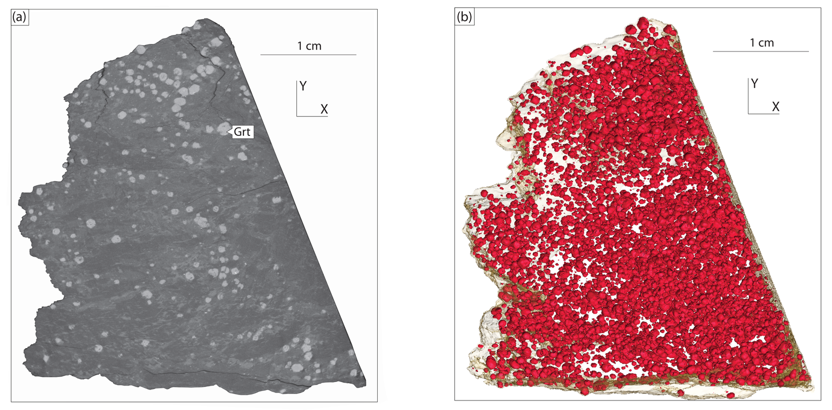


Figure 2.2 - X-ray attenuation image of sample 24-99 and corresponding prismatic volume of 24-99 analyzed by XR-µCT. X-Y view of the surface-rendered scanning volume illustrating the size, shape and spatial distribution of garnet.

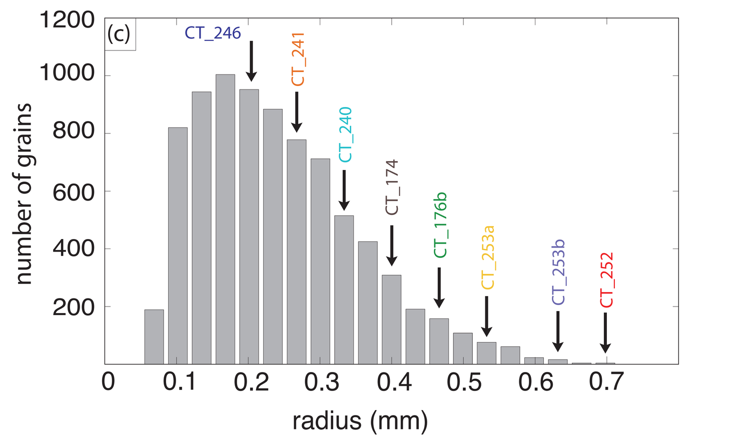


Figure 2.4 - Crystal size distribution (CSD) as determined from segmented XR-µCT. Black arrows highlight size classes from which garnets have been isolated and analysed in detail.

(3) Observed garnet zoning

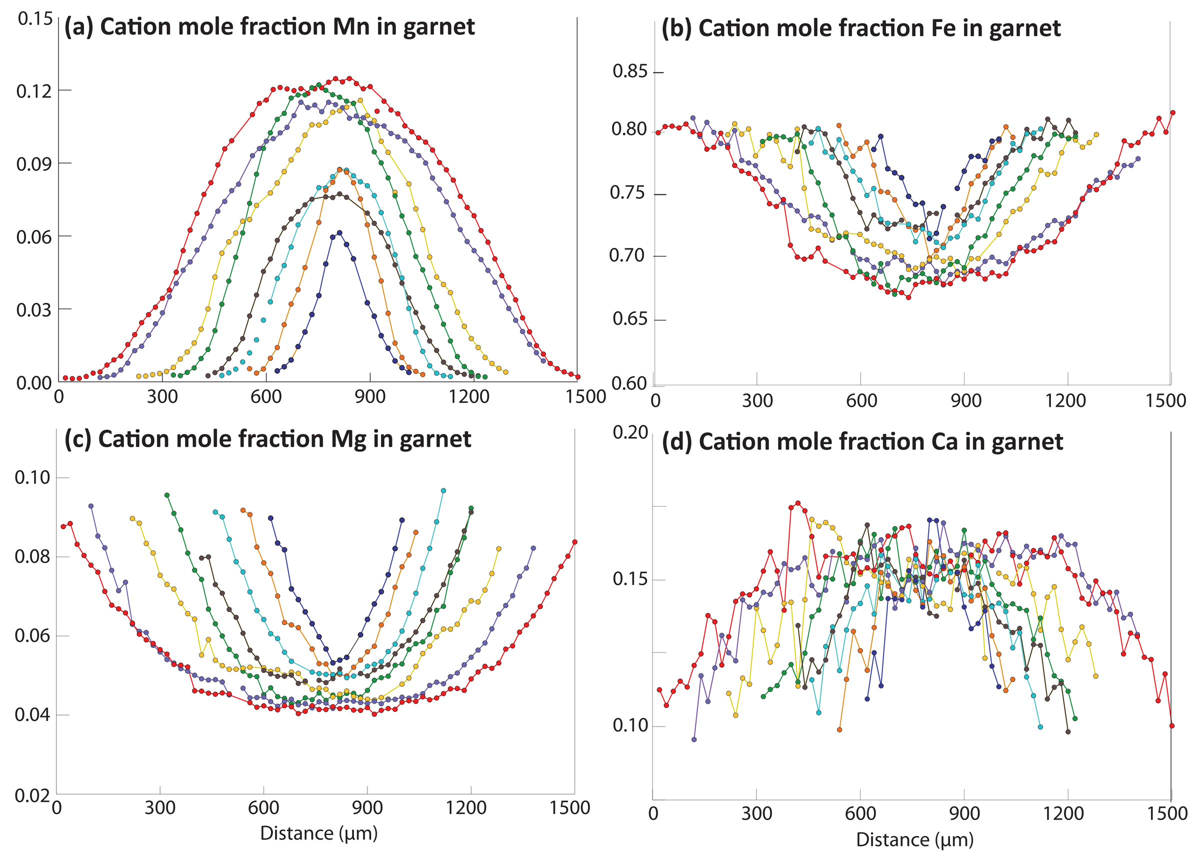


Figure 3.1 - Garnet compositional line profiles through compositional cores of grains that are representative of the sample 24-99 CSD.

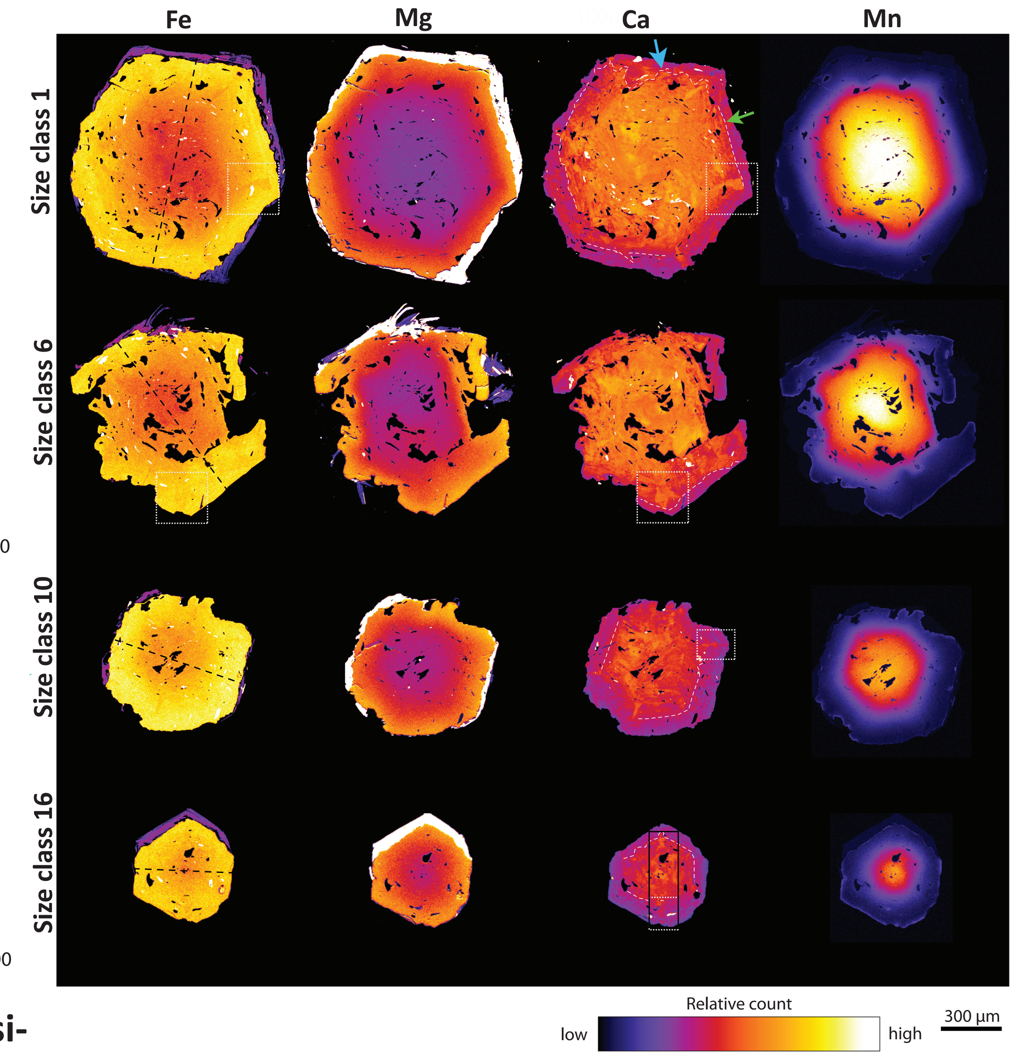


Figure 3.2 - X-ray maps of representative garnet crystal sizes. Flame structures highlighted by dotted boxes, Ca discontinuity marked by dashed white line.

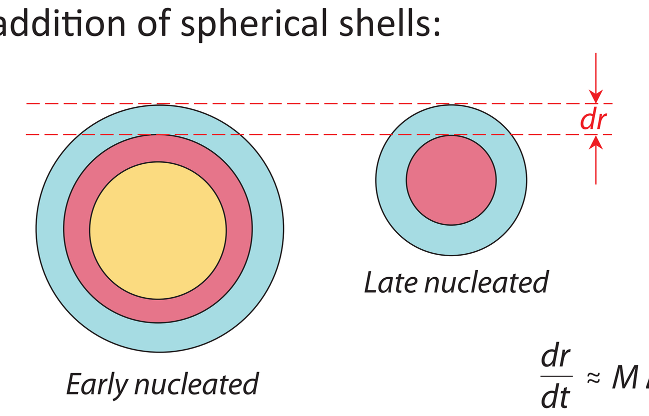
- Systematic core-rim zoning of whole population.
- Progressive core composition change from large to small crystals.
- Steepening of compositional gradients from large to small grains, prounounced in Mg.
- Short wavelength Ca-oscillations, overprinted on broad core-to-rim decrease.
- All compositions appear to retain primary compositional signatures, with little diffusional modification .

(4) Modelled garnet chemistry

Theria_G (Gaidies et al, 2008) simulates **nucleation and growth of garnet population** by considering:

- **equilibrium thermodynamics**
- **multi-component diffusion**
- **chemical fractionation**

Garnet growth is simulated assuming a **size-independent radial growth rate**, as the sucessive addition of spherical shells:



$$\frac{dr}{dt} \approx M\,\Delta G_v$$

Figure 4.1, right - (a) ***P-T*** **phase equilibria for bulk composition below, with observed assemblage highlighted in red.** Incipient garnet growth < 10°C from garnet-in curve **(b) Best-fit P-T path and evolving garnet-in contour as growth and fractionation proceeds along P-T path.**

SiO_2	TiO_2	Al_2O_3	Fe_2O_3	MnO	MgO	CaO	Na_2O	K_2O	LOI
64.9	0.6	18.73	6.44	0.05	1.89	0.55	0.87	3.60	2.36

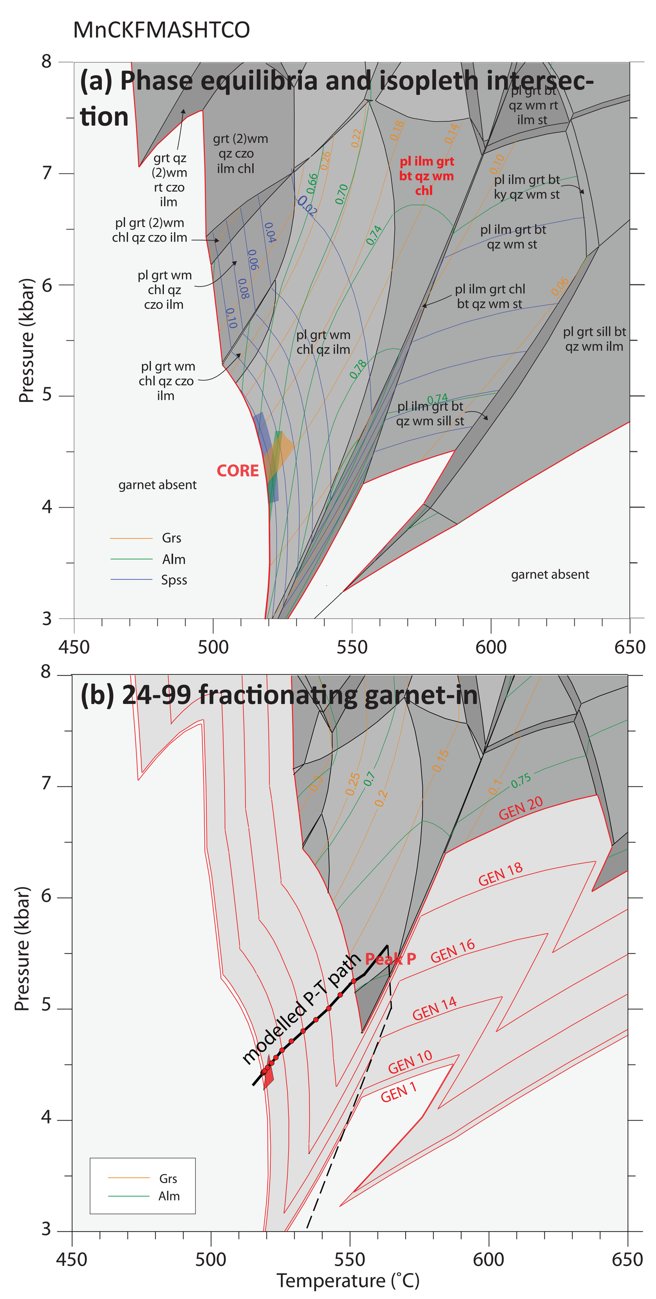


Figure 4.2, below - Modelled increase in radius and volume of largest simulated garnet crystal. Also plotted are the temperatures at which each successive size class nucleates.

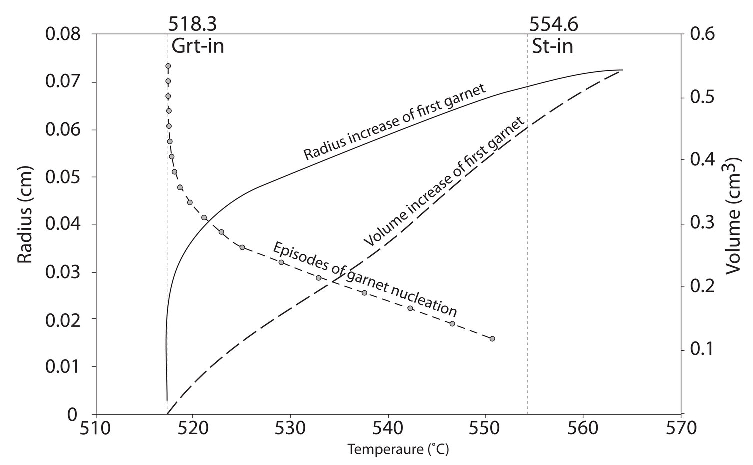
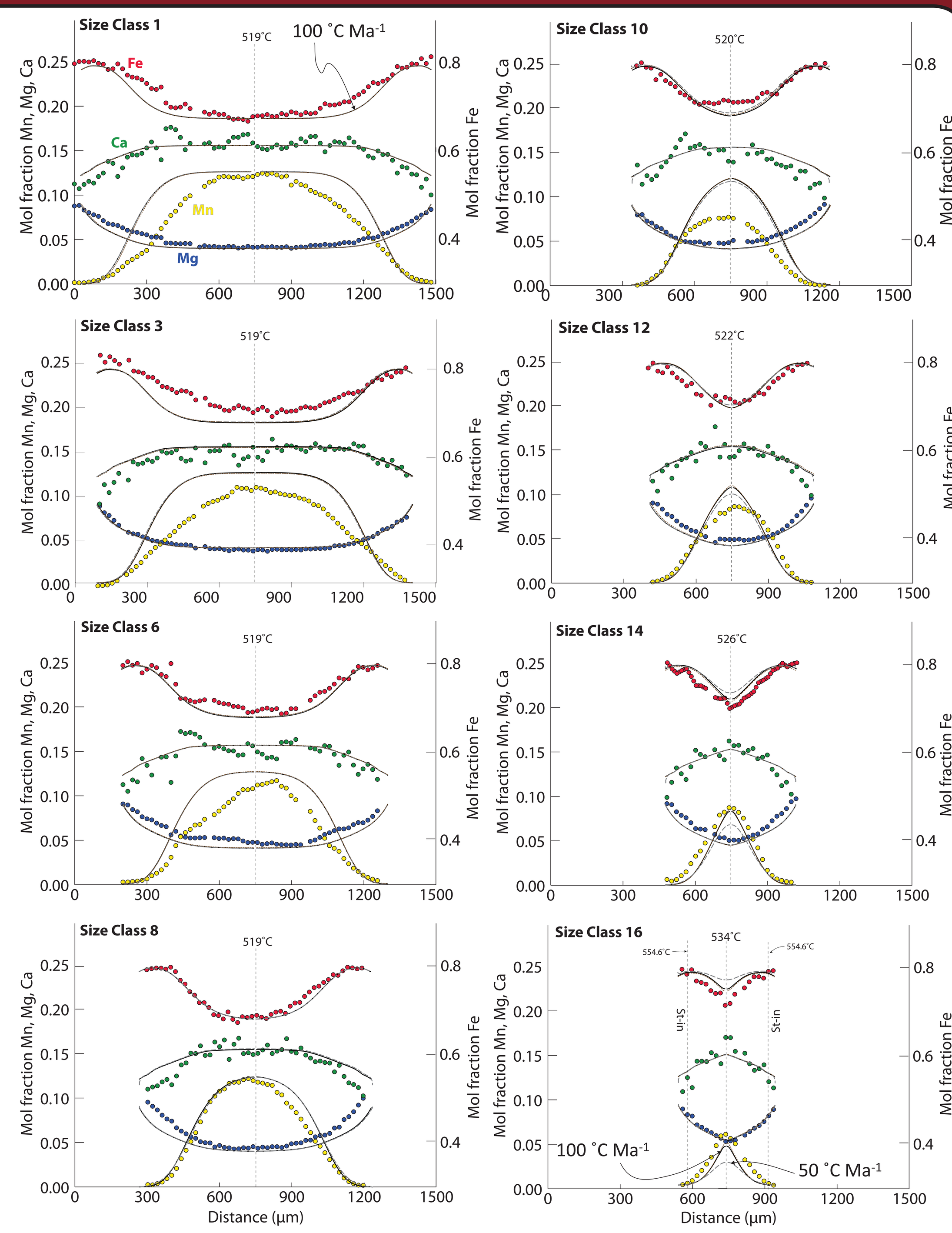


Figure 4.3, right - Results of major end-member THERIA_G modelling along P-T path above, for garnet compositional profiles displayed in Fig. 3.1.

- Best fit *P-T* path (Fig. 4.1b) with heating rates of 100°C Ma^{-1}. These rates are consistent with Lu-Hf garnet geochronology by Anczkiewicz *et al.*
- Rim compositions & crystal sizes predicted.
- Core composions are within error for all but size class 10 and 12.
- Excellent fit in smallest size classes 14 and 16.
- Gradient discrepany in size classes 1–6 for Mn



(5) Implications

As a consequence of very **rapid rates of prograde metamorphism** in the Sikkim Himalaya, in-excess of 100 °C/Ma, the primary compositional zoning within all garnets of a population has been preserved. This zonation yields the following implications:

A. Visually significant core discrepancies between model and observed compositions equate to **< 10°C temperature overstep** for nucleation (Fig. 5.1).

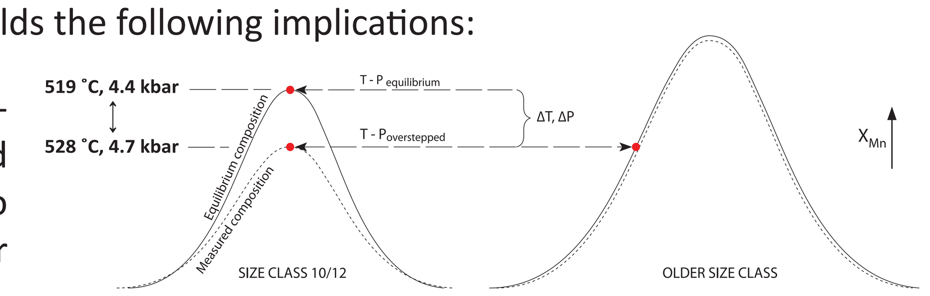


Figure 5.1

B. The whole population **crystallised as a succession of approximately equilibrated states**, as evidenced by ability to accurately forward model compositions and sizes of garnet with an equilibrium model.

C. Radial rate of growth progressively decreases through the crystallisation interval, resulting from increases in the interfacial term, *σ*, and decreases in the interface curvature, *R*, with increasing *P–T* according to:

$$\frac{dr}{dt} = M\left(\Delta G_v - \frac{2\sigma}{R}\right)$$

D. Diffusion may be the rate-limiting step at lengthscales < 0.7 mm, as indicated by Reduce3D results. If this is the case, diffusion-control cannot have been significant enough to dramatically affect observed compositions. However since this system is so well equilibrated, it is difficult to distinguish the true contrbutions of interface- and diffusion-control. Notable evidence for disequlibrium may only exist in the Ca-oscillations observed in compositional profiles.

(6) Selected references

Gaidies, F., De Capitani, C. and Abart, R., 2008. THERIA_G: a software program to numerically model prograde garnet growth. Contributions to Mineralogy and Petrology, 155(5), pp.657-671.

Hirsch, D.M., 2011. Reduce3D: A tool for three-dimensional spatial statistical analysis of crystals. Geosphere, 7(3), pp.724-732.

Anczkiewicz, R., Chakraborty, S., Dasgupta, S., Mukhopadhyay, D. and Kołtonik, K., 2014. Timing, duration and inversion of prograde Barrovian metamorphism constrained by high resolution Lu–Hf garnet dating: A case study from the Sikkim Himalaya, NE India. Earth and Planetary Science Letters, 407, pp.70-81.