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## **Serpentinization of the Ronda Massif (Spain): structural control and fluid origin, a framework for metal mobility**

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## 1. Introduction

Serpentinization is a hydrothermal transformation of ultramafic rocks, such as the Sub-Continental Lithospheric Mantle (SCLM) which represents a reservoir of metals (e.g., Cu, Zn, Co, Ni, Cr, PGE, V, Ti, Au). During their exhumation, the mantle rocks are affected by various hydrothermal processes which can lead to economically viable metal deposits (e.g., seafloor massive sulfides; Patten *et al.*, 2022). Despite some works (Deschamps *et al.*, 2013; Lawley *et al.*, 2020), **the characteristics of metal mobilities during serpentinization still remain poorly constrained**, notably the related spatial scales. To address this issue, we have chosen a terrestrial example : the Ronda Massif (Spain). This massif is the largest remnant of SCLM in the world. It is partially serpentinized and is thus perfectly suitable to characterize metal mobilities at various scales (from the centimetre to the multi-kilometres scales). To date, **studies on the serpentinization of the Ronda peridotite remain scarce** (Pedrera *et al.*, 2016). Here we present the main serpentinization stages, then the structures along which serpentinization occurred and stable isotope data (*i.e.*, oxygen and hydrogen), as a pre-requisite to study metal mobilities.

## 2. Geological setting

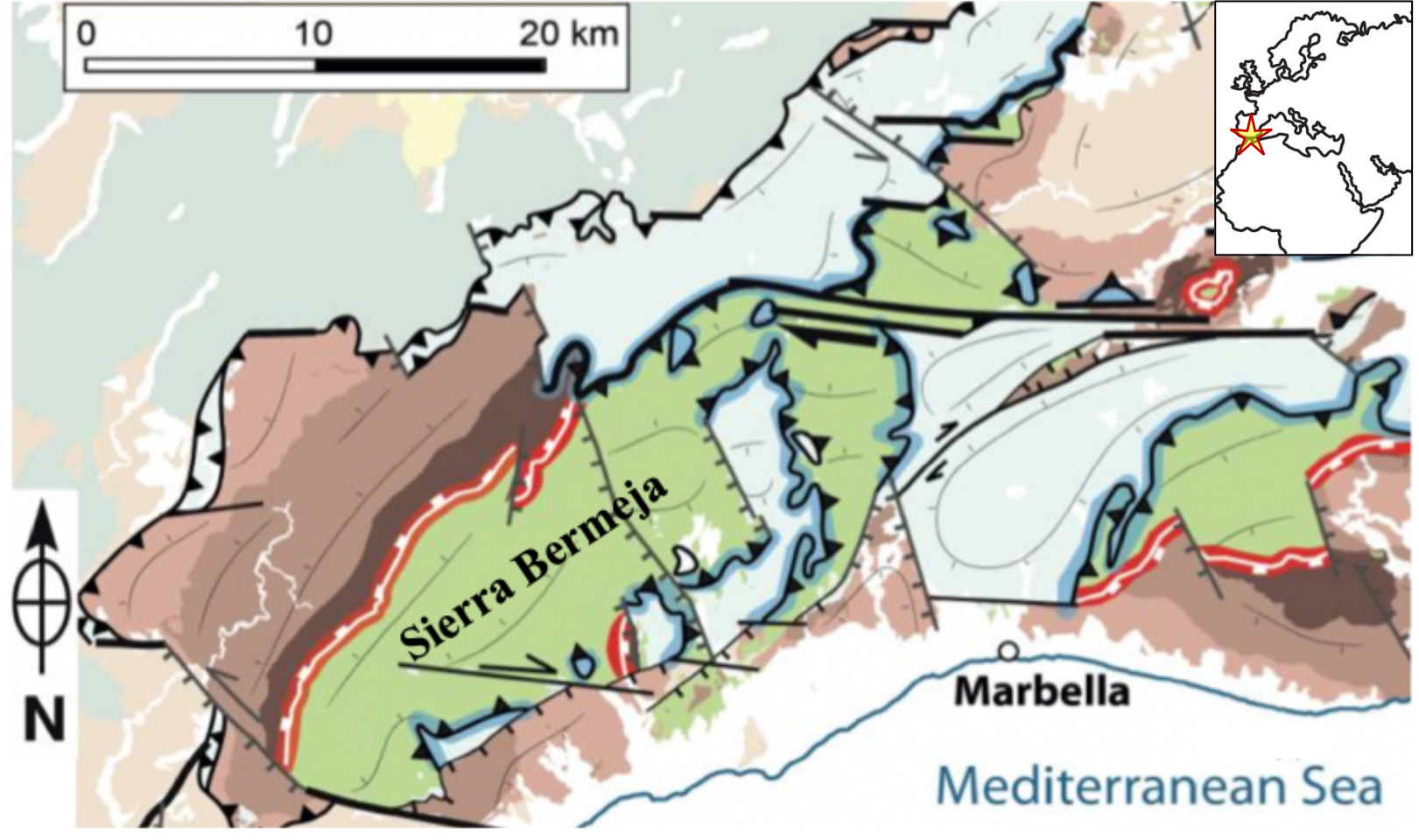
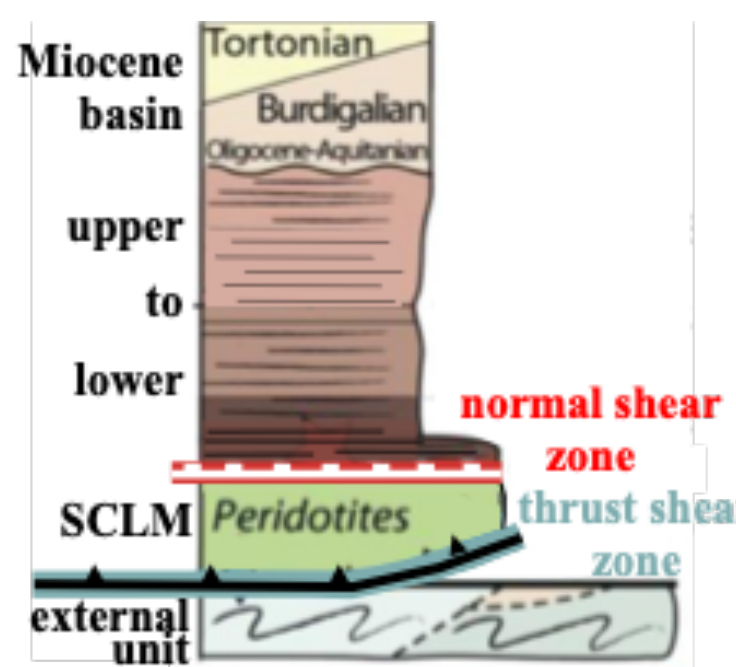
The Ronda Massif is located in the western Betic Cordilleras (Spain). This chain is the result of polyphase tectonics, starting from the oceanic openings during Mesozoic (Central Atlantic Ocean, Ligurian Tethys and Maghrebian Tethys), to Cenozoic convergence between Africa and Iberia plates.

The Ronda Massif is a paleolithosphere slice (*i.e.*, upper to lower crust with SCLM) exposed at the earth surface. However, the mechanisms and timing of this massif emplacement are still controversial.

To date, we retain 2 models :

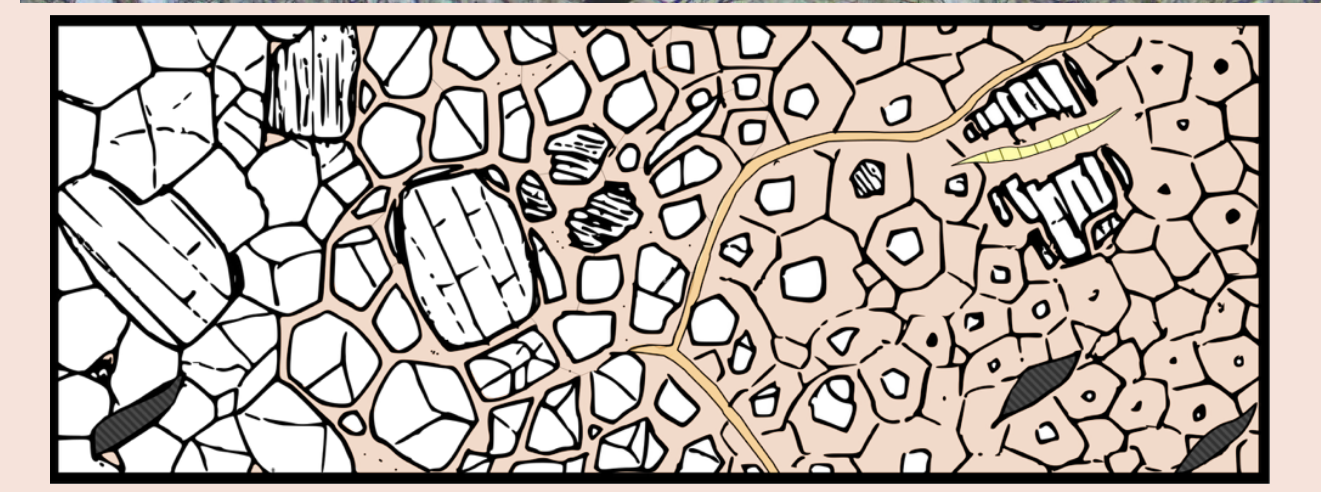
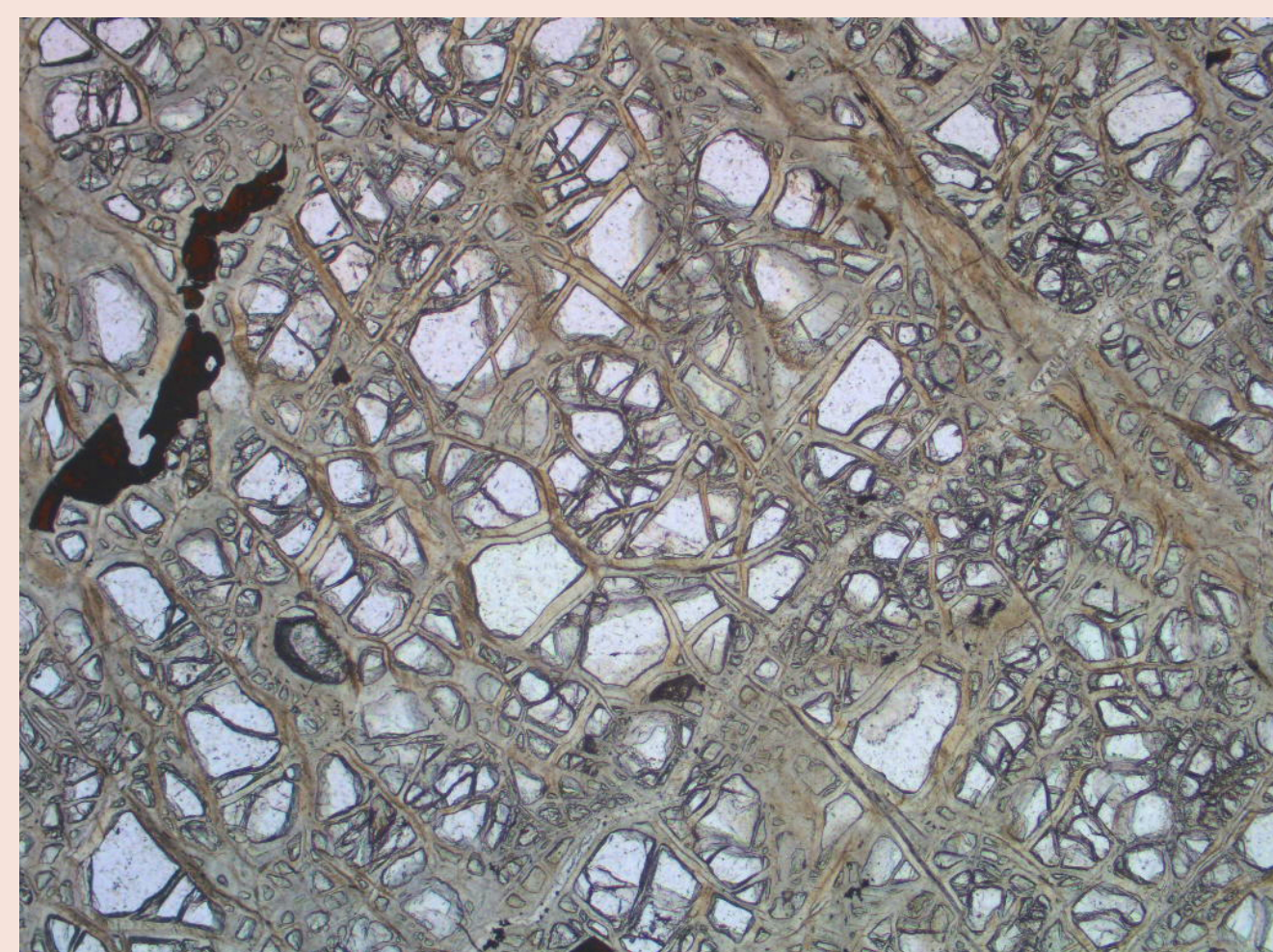
- i) transpressional emplacement (Mazzoli *et al.*, 2011),
- ii) back-arc rifting before thrusting (Frasca *et al.*, 2017).

The emplacement timing is approximated by dating differentiated felsic magmas that intruded the Ronda Massif between 19 and 22 Ma (U-Pb on zircon; Frasca *et al.*, 2017).



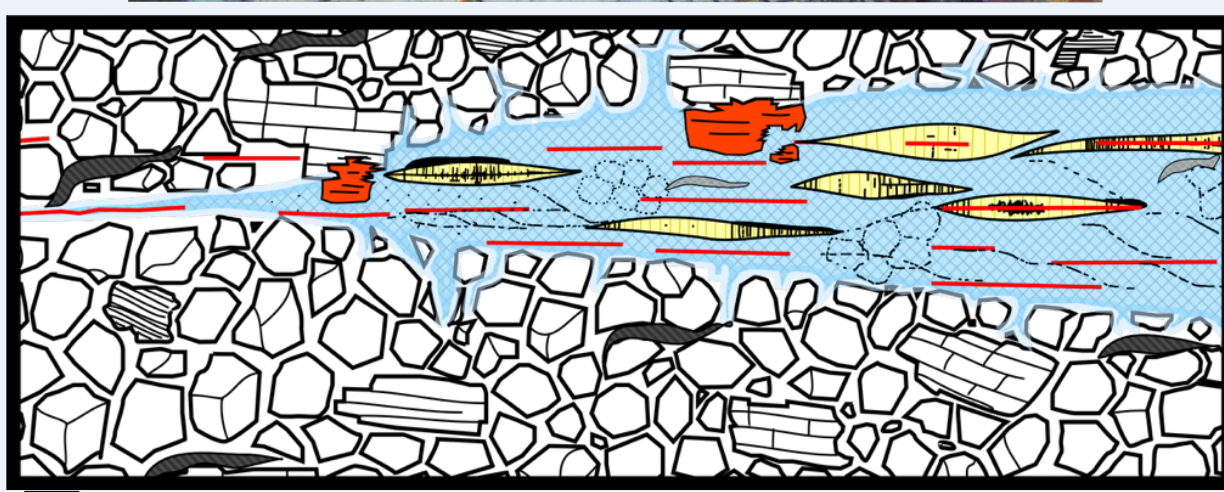
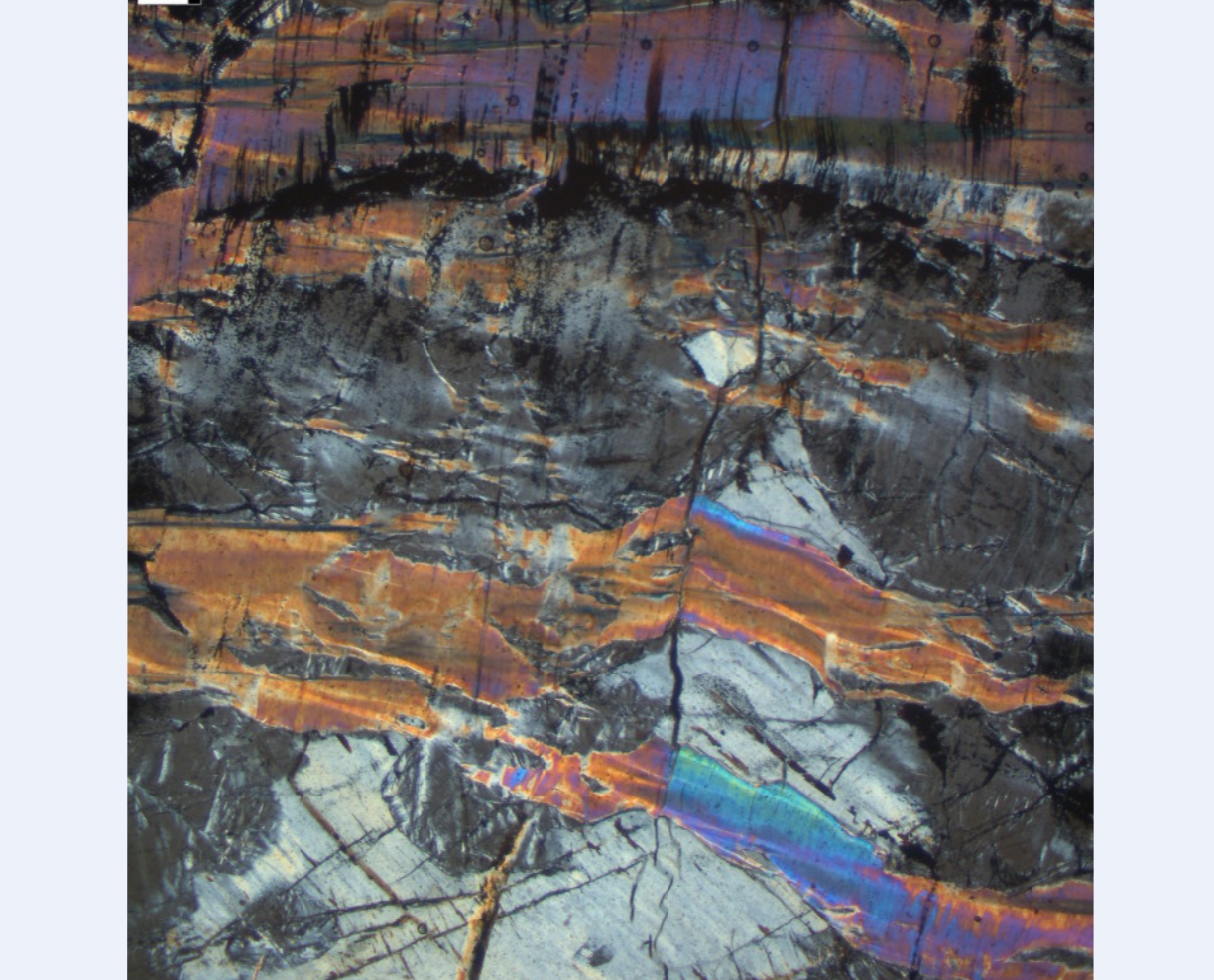
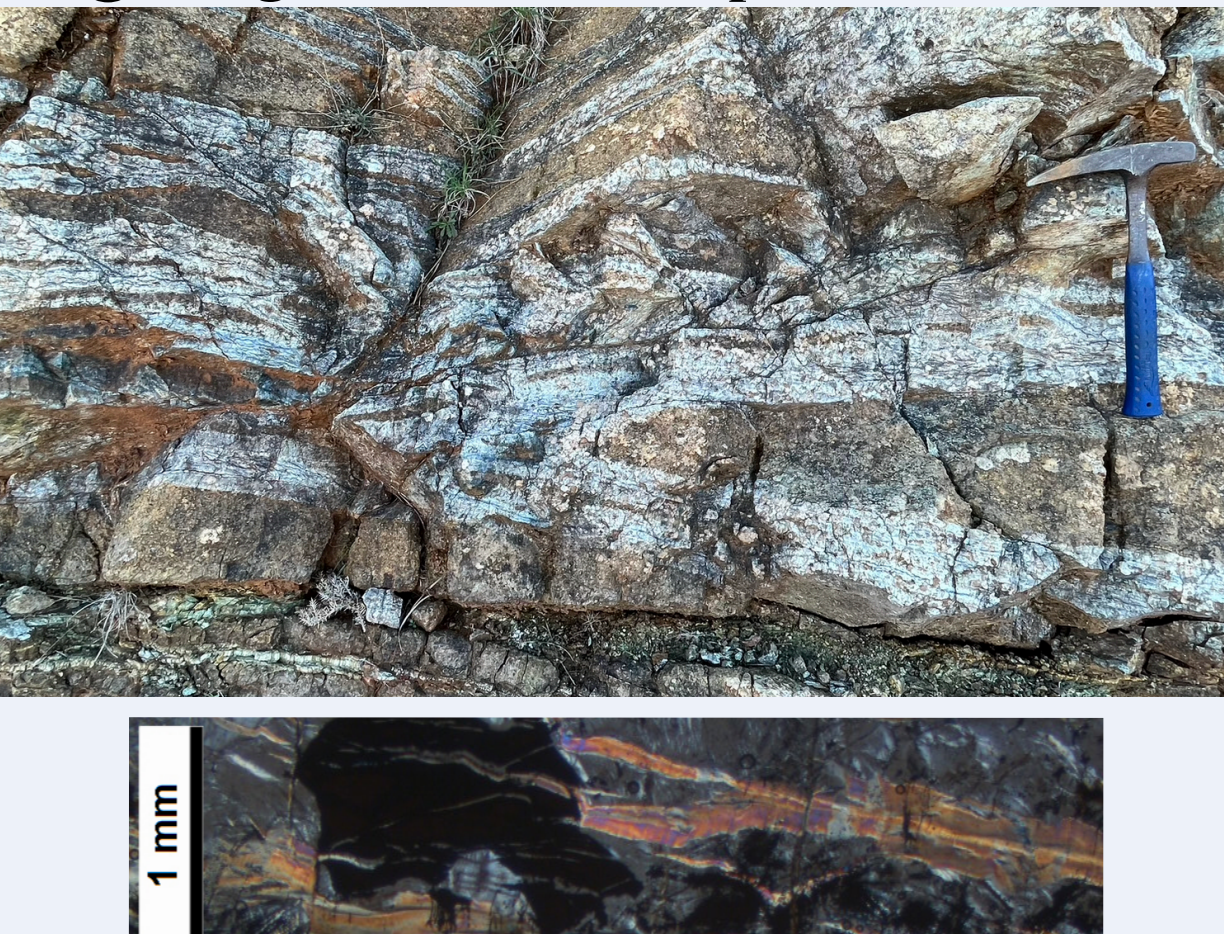
## 3. Three stages of serpentinization in the Ronda Massif

### Stage 1: pervasive mesh texture serpentinization



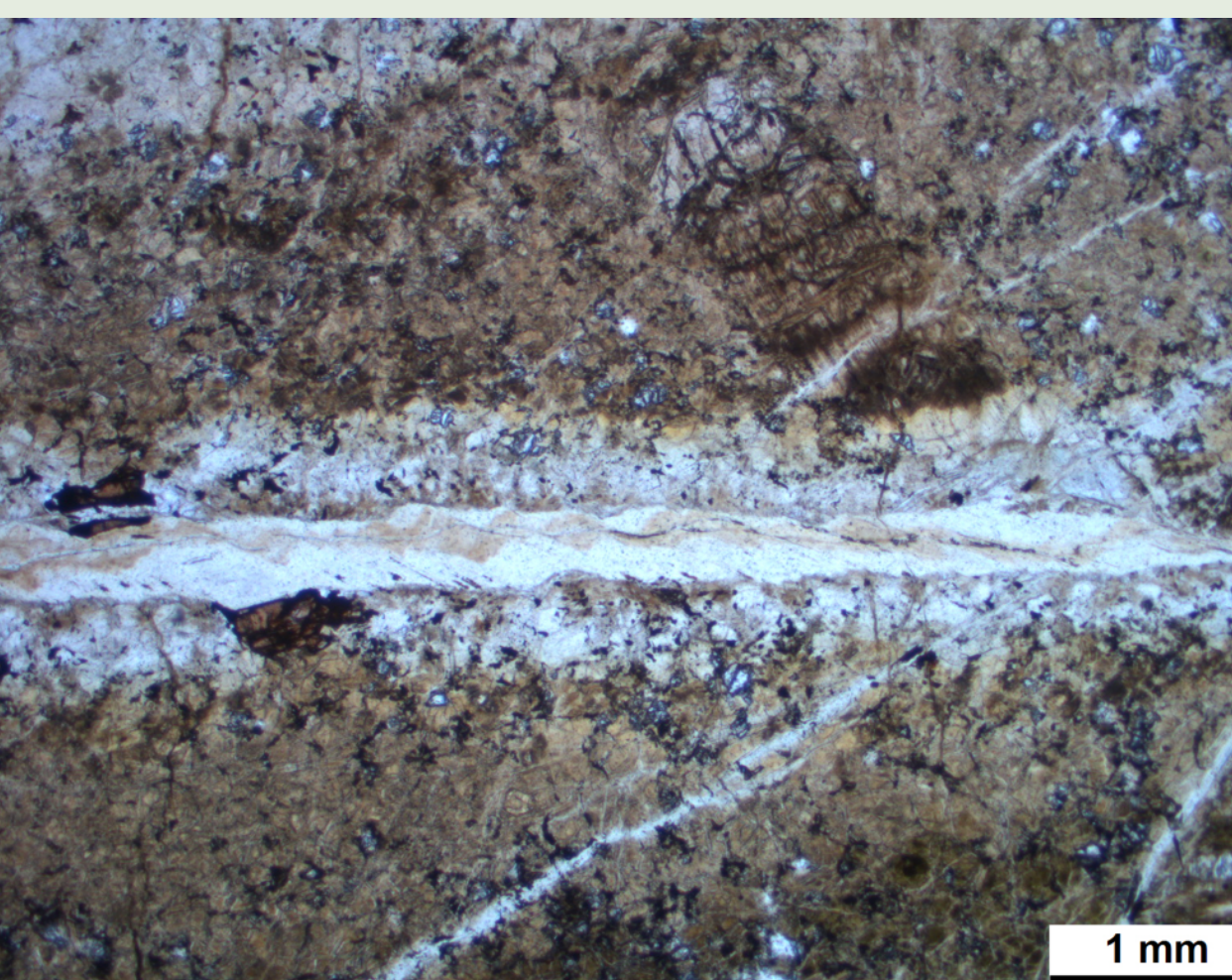
Peridotite: orthopyroxene, clinopyroxene, olivine, spinel. Serpentinized peridotite: liz 1 - mesh-texture + magnetite, channel of liz 1, chrysotile.

### Stage 2: corridor serpentinization



Peridotite: fracture, bastite, liz 2 - recrystallized, disseminated magnetite, serpentinized peridotite (stage 1). Serpentinized peridotite: magnetite veinlet, ferrichromite, chrysotile + magnetite, magnetite cluster.

### Stage 3: syn-serpentinization cataclasis



S&F: serpentinized peridotite (stage 1), crack-seal, polygonal serpentine, liz 3 - metasomatic halo, chrysotile + calcite comb.

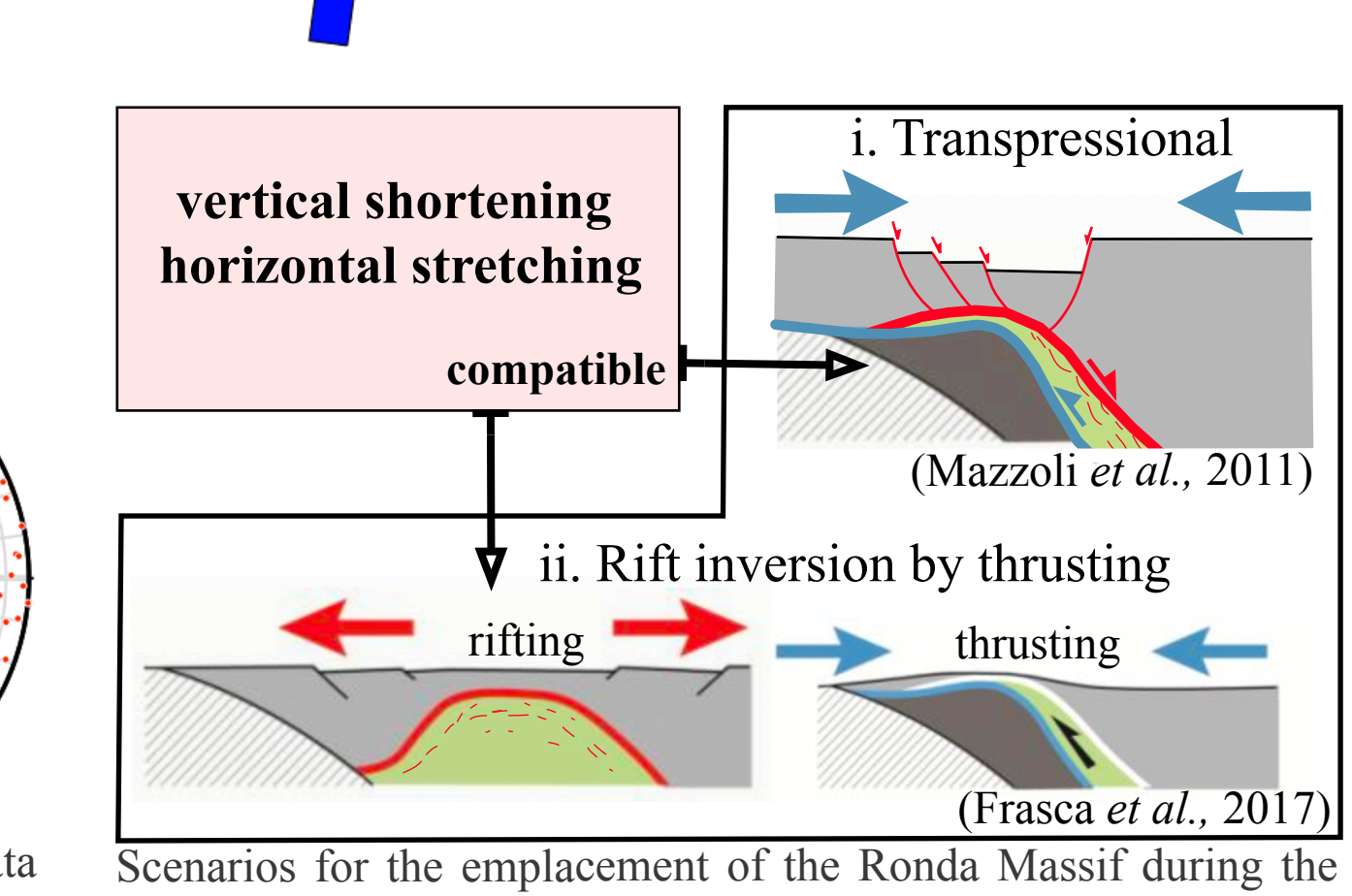
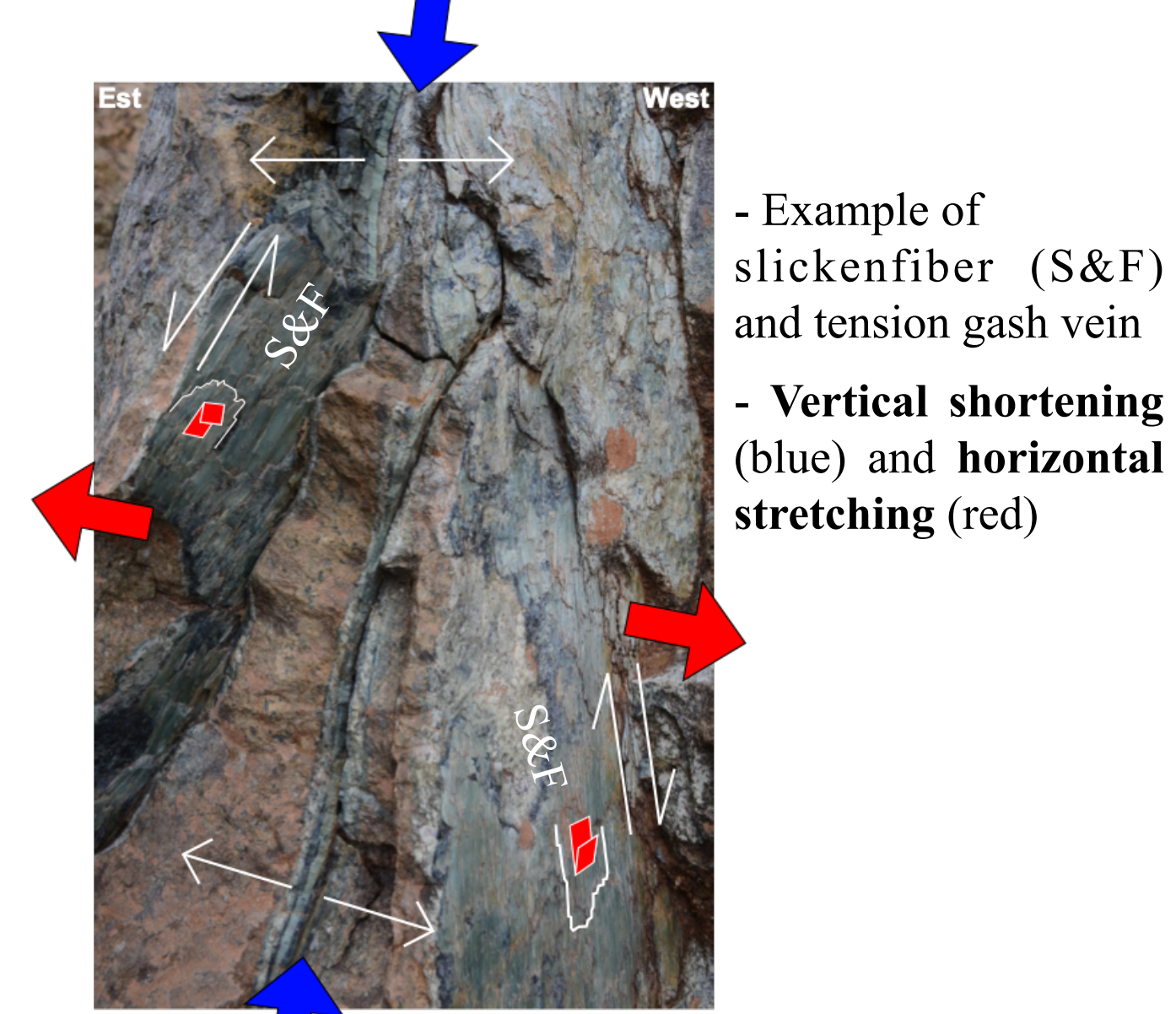
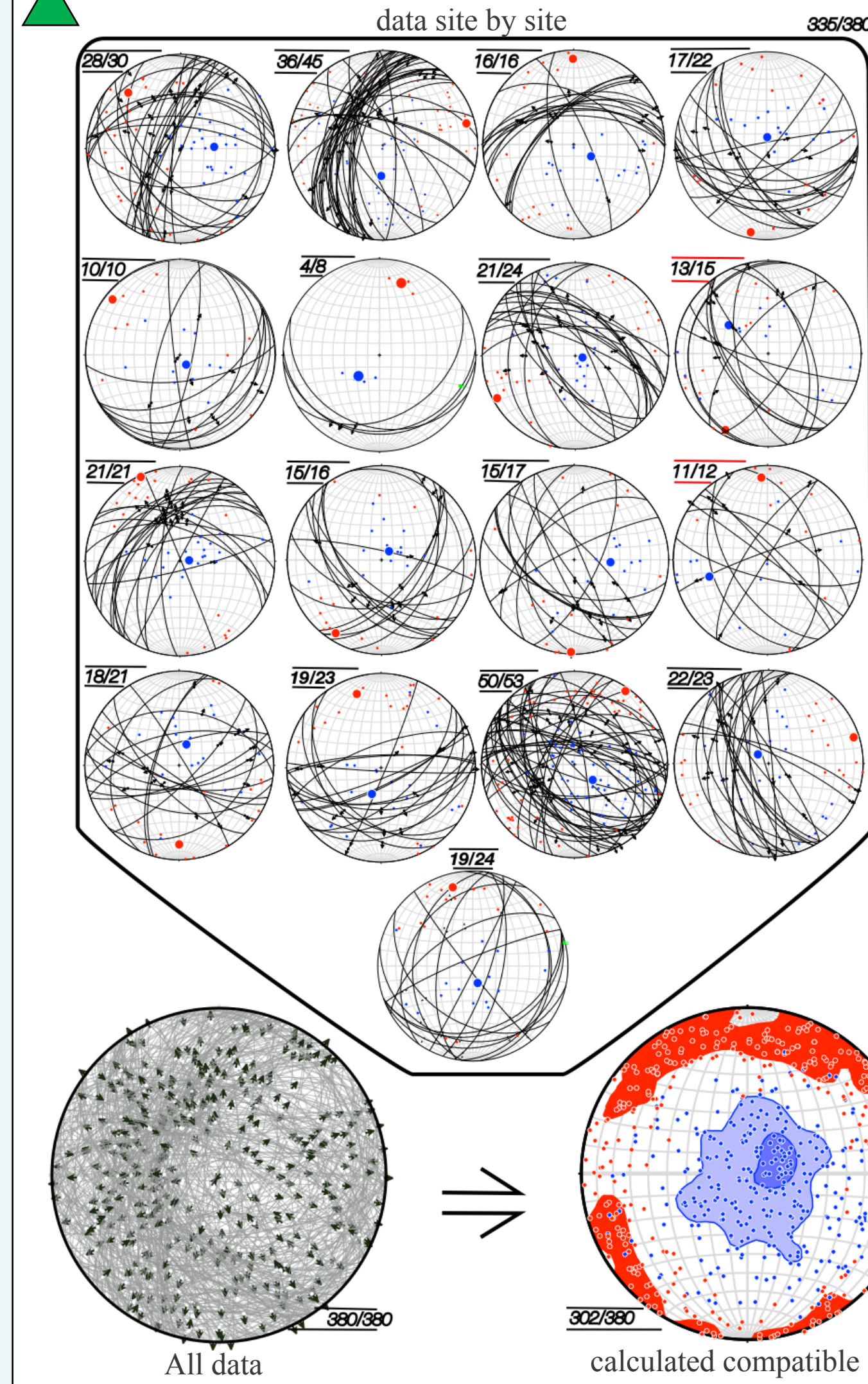
minerals	stages	stage 1	stage 2	stage 3	Other
serpentinized	Lizardite	liz 1 - mesh texture	liz 2	liz 3	
	Chrysotile		vein - fibrous		
	Bastite			vein - fibrous or crack-seal	
	Polygonal serp.				mgt 1 - disseminated, mgt 2 - veinlet, mgt 3 - cluster
	Magnetite				vein - comb, veinlet
Others carbonates	Calcite				
	Others carbonates				
Syn-serpentinization deformation	?	?			
Intrusions		mafic (183-131 Ma)		felsic (23 Ma)	

- Stage 1 is represented by pervasive serpentinization with variable rate in peridotite. The serpentinized peridotite appears brown and massive in the outcrop, and contains lizardite 1 in mesh texture with scarce magnetite.

- Stage 2 corresponds to localized serpentinization in multi-centimetre white corridors, with development of lizardite 2, bastite, chrysotile and abundant magnetite (veinlet, disseminated and cluster).

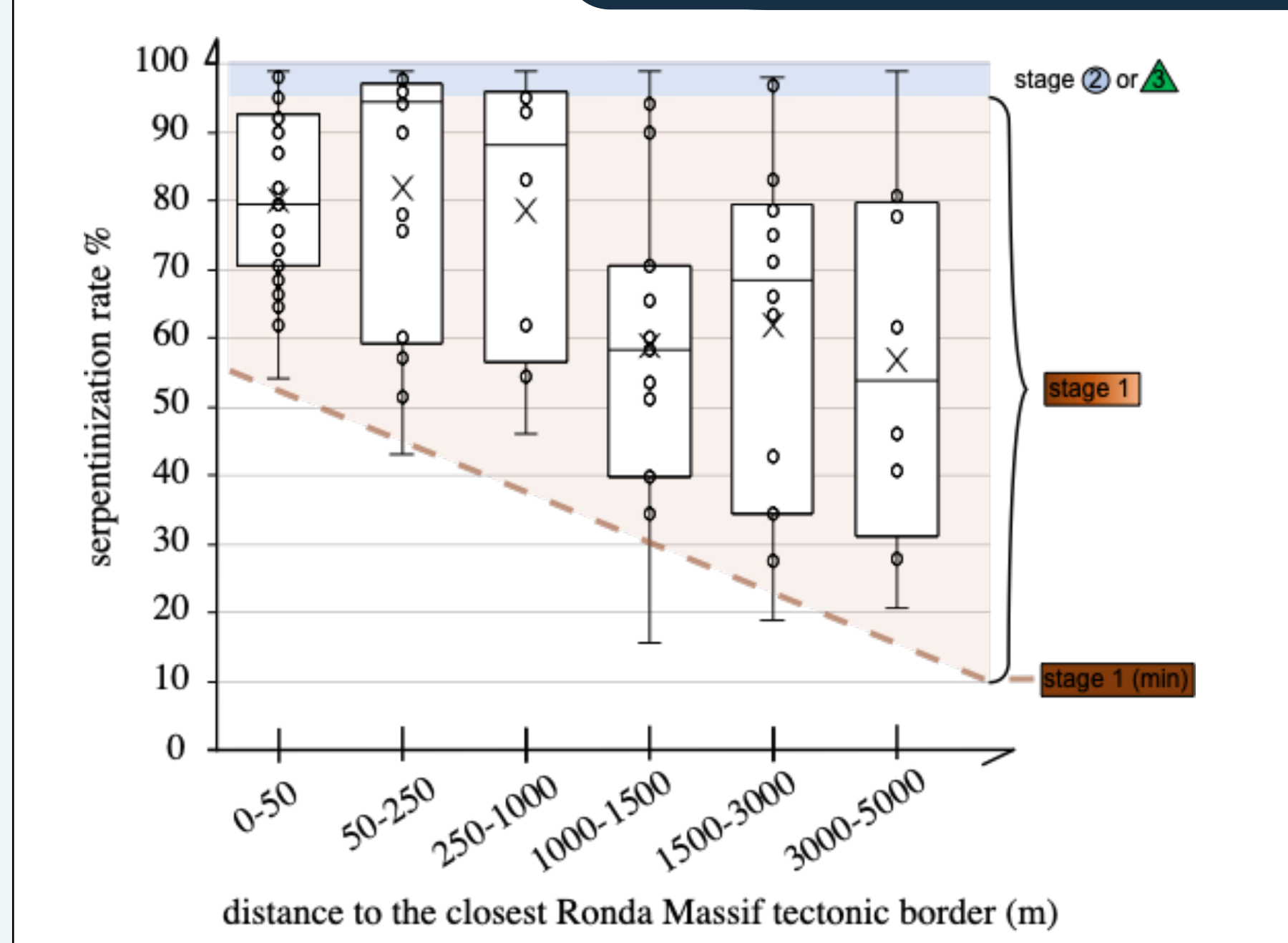
- Stage 3 is associated to cataclastic deformation, with shear zones and multi-millimetre green syn-tectonic fibrous veins. The veins contain polygonal serpentine and/or chrysotile, with lizardite 3, bastite and magnetite cluster in metasomatic halo.

## 4. Strain analysis during stage 3 serpentinization



- S&F (stage 3) measurements through the Ronda Massif on 17 sites.
- No obvious dominant trend in vein orientation is observed in whole massif, but all sites present a vertical shortening (blue) and horizontal stretching (red) similar site to site (with variable direction), compatible with extension.
- If we consider the whole massif as a single site, the multidirectional and horizontal stretching argues in favor of the pure flattening deformation mode (double boudinage?).
- Two tectonic models are compatible with the vertical shortening and horizontal stretching of stage 3 serpentinization: back-arc rifting (Frasca *et al.*, 2017) or transpressional emplacement (Mazzoli *et al.*, 2011)

## 5. Serpentinization rate at the scale of the massif



- Serpentinization rate is highly variable both at the outcrop and the massif scales.
- Serpentinization rate decreases near the peridotite tectonic border during stage 1.
- Other stages show high serpentinization rate.

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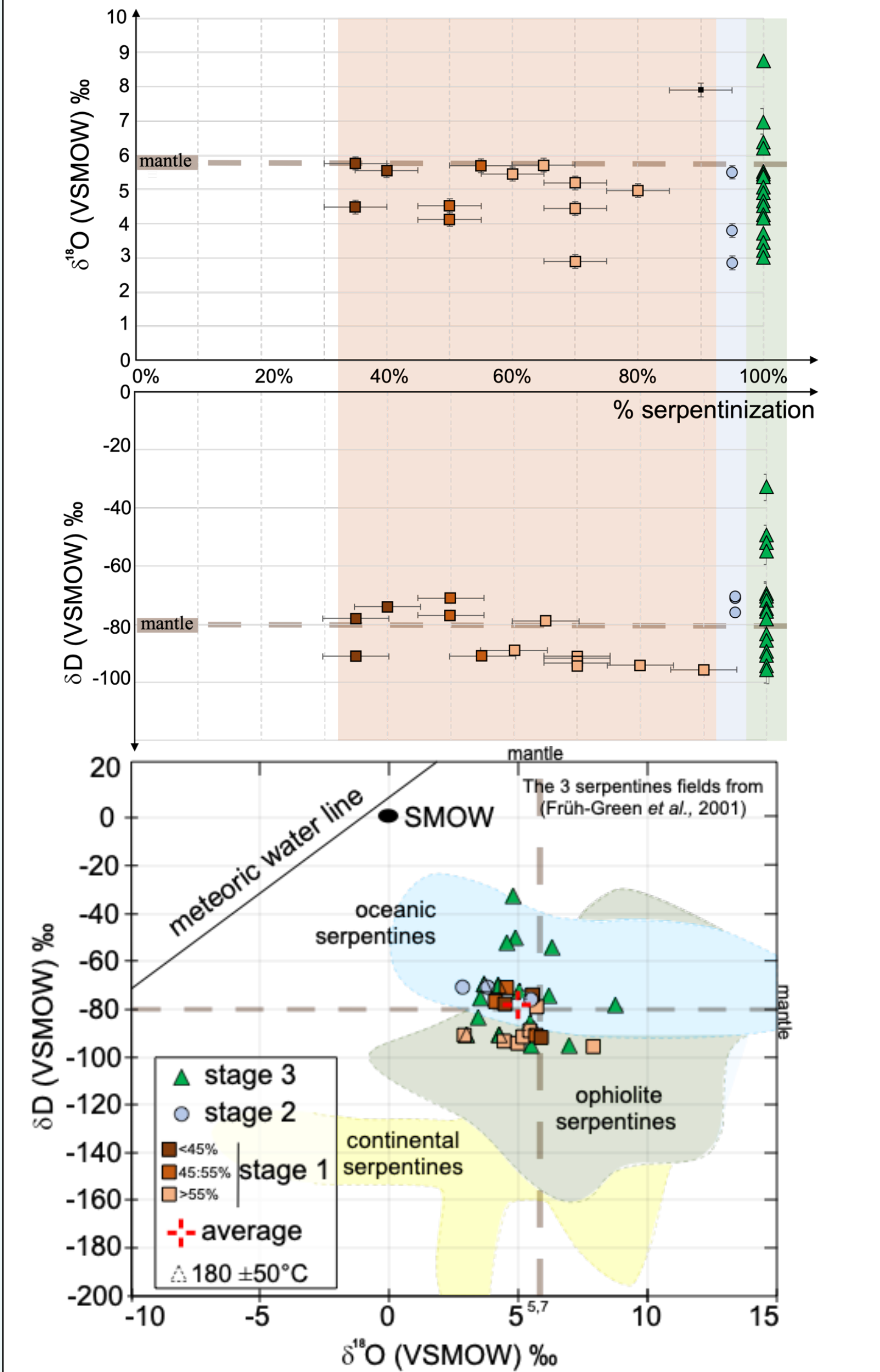
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## 6. Oxygen and hydrogen isotope compositions



- Stages 1 and 2 cluster near the intersection mean isotopic data. Stage 3 is scattered around the values of stages 1 and 2.
- There is no correlation between serpentinization rate and isotopic values.
- The  $\delta^{18}\text{O}$  and  $\delta\text{D}$  value of Ronda serpentinites are split between ophiolite and oceanic serpentines fields. Yet, the origin of the serpentinization fluid cannot be determined with certainty only based on the available data.
- Overall, the fairly comparable isotopic compositions plead for a continuum of serpentinization, and relatively similar fluid-rock interaction conditions (low fluid/rock ratio, variable temperatures).
- Isotopic data from two pairs of stage 3 serpentine-magnetite intergrowth suggest a temperature of equilibrium of  $180 \pm 50^\circ\text{C}$ , using the fractionation factor of Früh-Green *et al.*, (1996)

## 7. Conclusion

The peridotite of Ronda Massif has undergone three stages of serpentinization.

- Stage 1 corresponds to pervasive serpentinization more efficient near the outer contour of the massif than in the centre. It is marked by mesh texture lizardite 1.
- Though being widespread through the Massif, stage 2 consists of discrete cm-long corridors of lizardite 2, chrysotile and magnetite.
- Stage 3 is marked by polygonal serpentine veins which lie within cataclastic zones at temperatures around  $180 \pm 50^\circ\text{C}$  during the Oligo-Miocene. The cataclastic deformation is characterized by multi-directional horizontal stretching and vertical shortening, compatible with two tectonic scenarios.

The three serpentinization stages display comparable isotopic signatures with average  $\delta^{18}\text{O} \sim +5\%$  and  $\delta\text{D} \sim -79\%$ . Globally, both mineralogical and isotopic data suggest that stages 1 to 3 likely occurred during a unique, syn-tectonic, serpentinization event.