On spreading modes and magma supply at slow and ultraslow mid-ocean ridges

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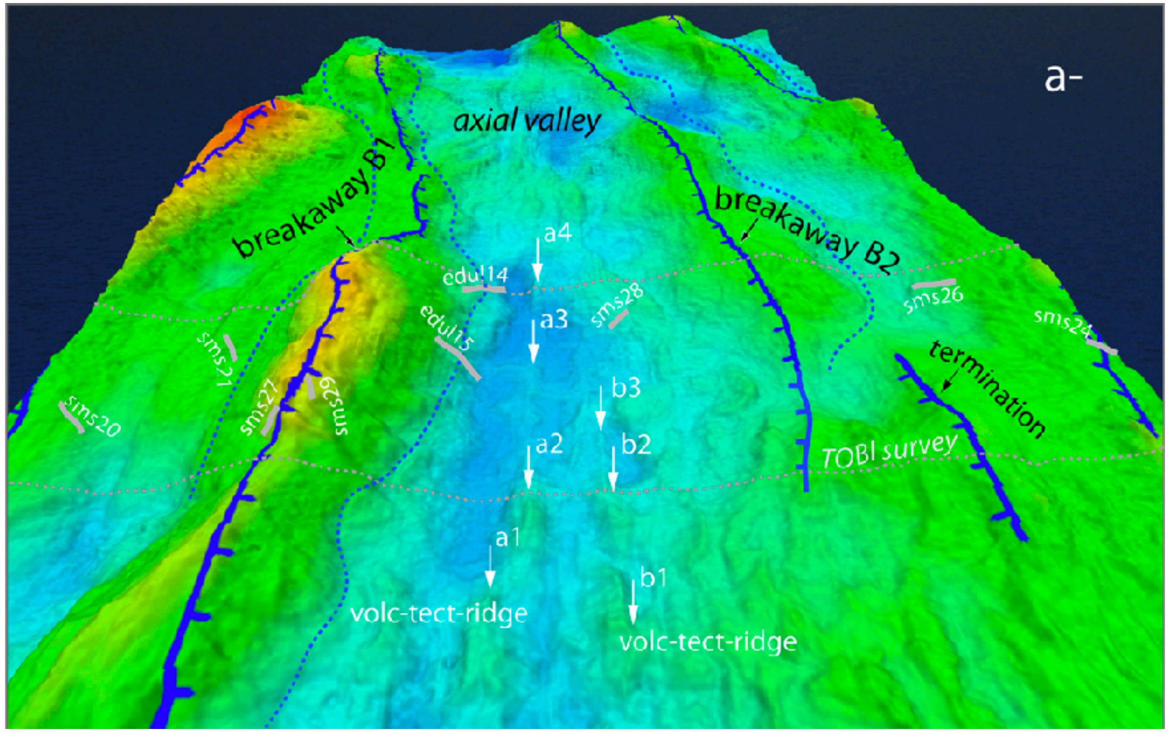
The availability of magma is a key to understand mid-ocean ridge tectonics, and specifically the distribution of the two contrasted spreading modes displayed at slow and ultraslow ridges (volcanically-dominated, and detachment fault-dominated). Magma has a triple role: building material for the newly accreted lithosphere, heat carrier, and strain localization agent.

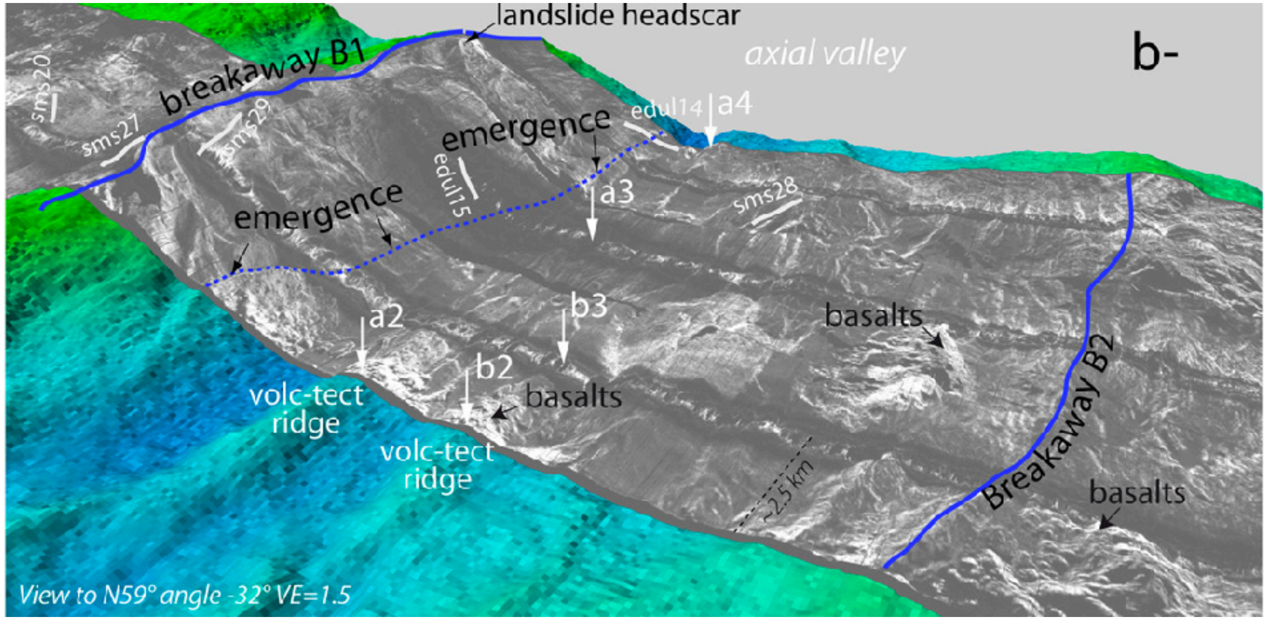
Because magma is highly mobile (through porosity, along permeability barriers, in fractures and dikes), it is likely that variations in magma supply to the ridge, in time and space, and variations in where this magma gets emplaced in the axial plate, cause a greater diversity of spreading modes, and of the resulting slow and ultraslow lithosphere composition and structure, than suggested by the first order dichotomy between volcanically-dominated and detachment-dominated spreading.

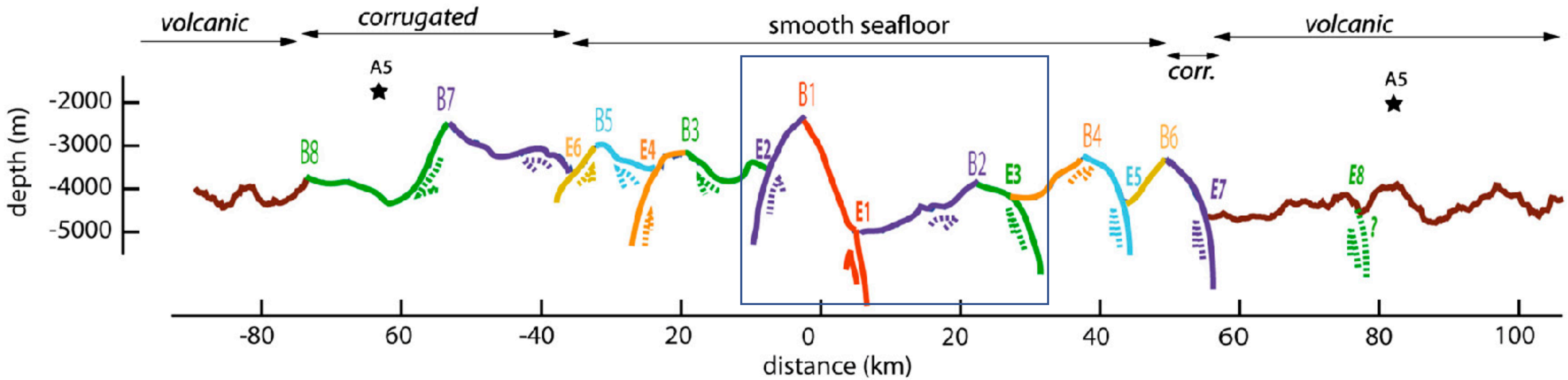
Several analogies can be made with distal divergent continental margins, where time and space variations in melt supply are increasingly recognized as key controls on the modes of transition to oceanic spreading.

In these slides, I illustrate a few of these points with figures from a recent paper about the eastern Southwest Indian Ridge (Cannat, Sauter et al., EPSL, 2019).

nearly amagmatic spreading corridor at 64°E





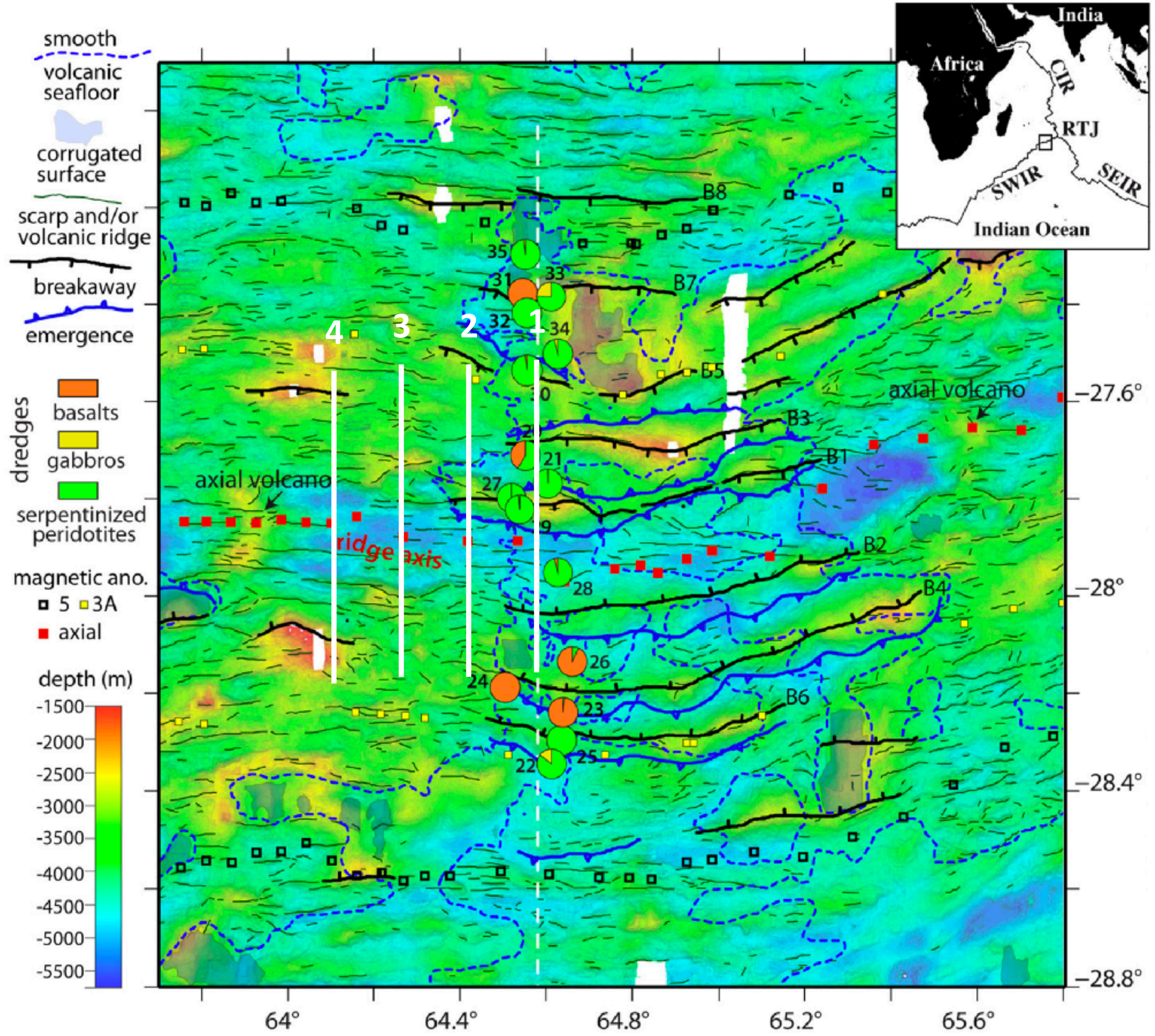


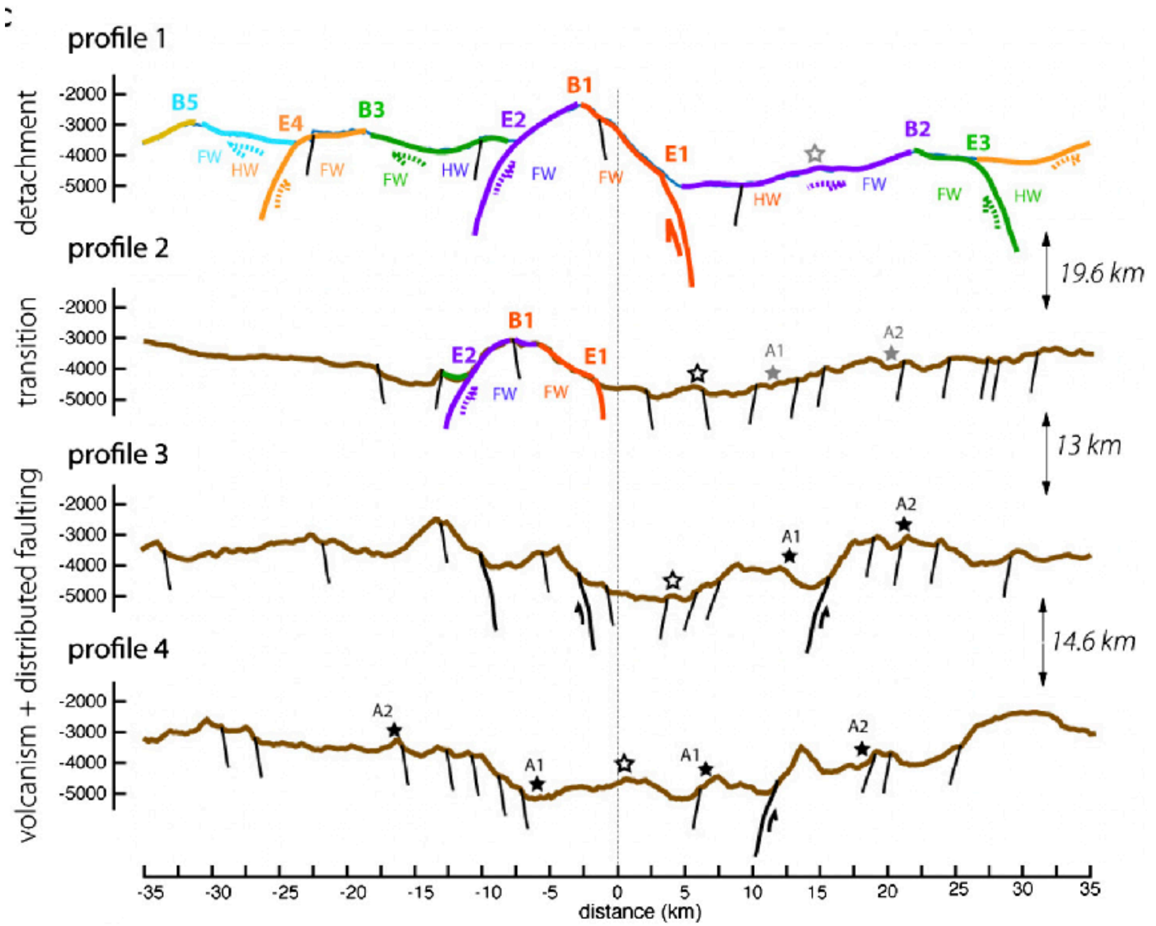
The part of the plate divergence that is not accommodated by magma emplaced as gabbros or basaltic dikes is taken up by normal faults that exhume upper mantle-derived rocks.

comments for slide 2:

In the upper left, we see, looking east, the bathymetry of the Southwest Indian Ridge at longitude 64°E in a region where spreading is at present almost amagmatic and therefore almost fully accommodated by faulting. The upper right panel shows seafloor reflectivity in the same region. Together these two images document the contrast between hummocky and reflective basaltic seafloor forming discrete volcanic ridges in the foreground, and the smooth topography and low reflectivity ultramafic seafloor (made of serpentinized mantle derived peridotites that have been exhumed by large offset normal faults).

The lower panel shows the proposed tectonic interpretation, with nearly amagmatic spreading prevailing over the formation of the most recent 100 km of seafloor, with the activation of several successive and antithetic normal faults (numbered from B6 to B1), each with a lifetime of up to 1.5 myrs. The presently active axial normal fault (B1) is represented in red in the cross-section. It forms the northern wall of the axial valley, with a 2500m-high relief.



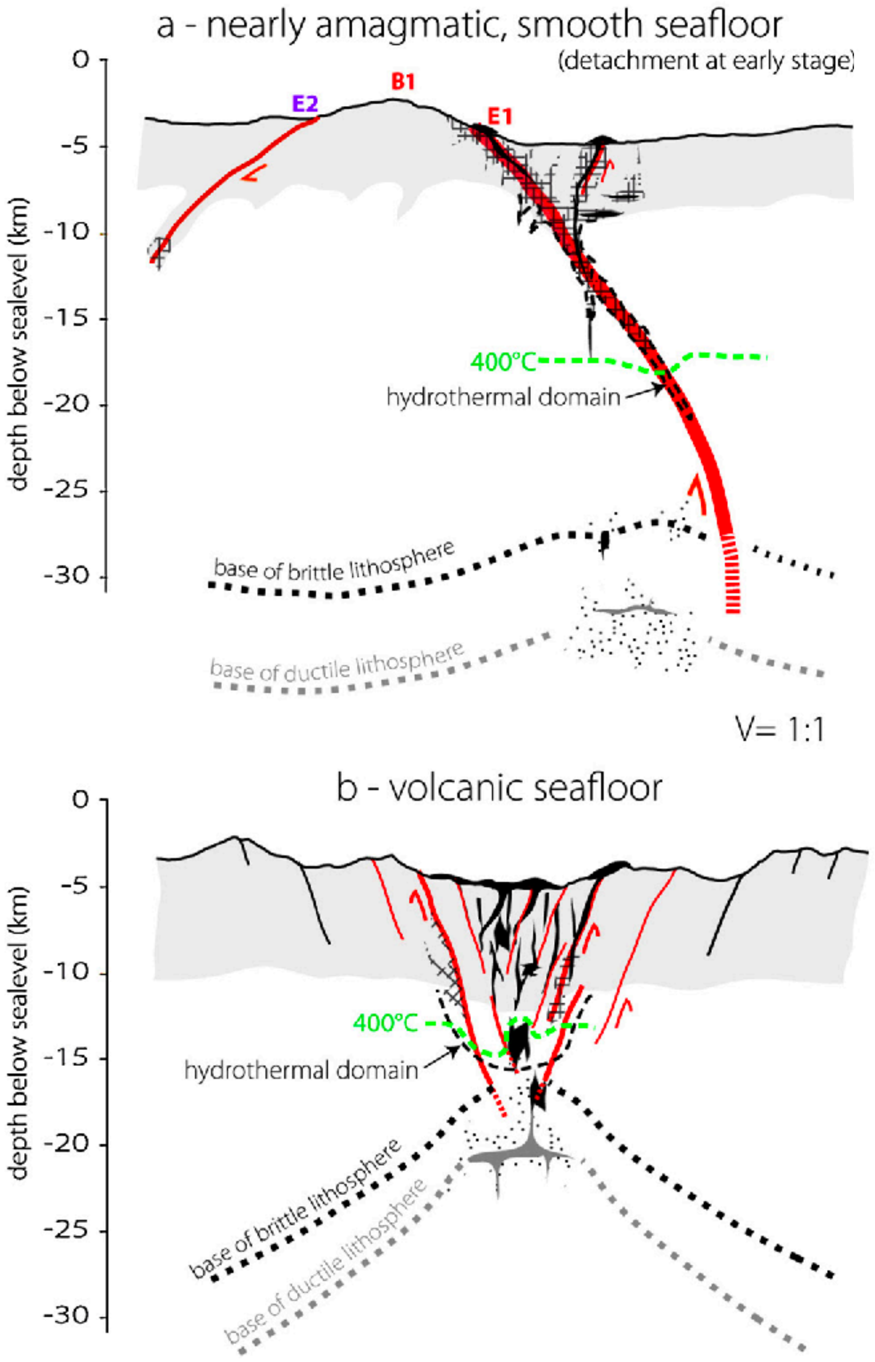


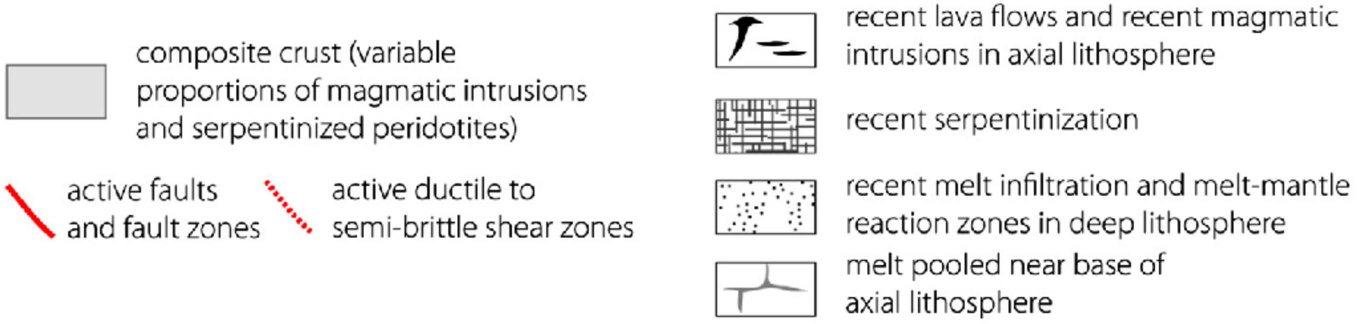
The transition from tectonically-dominated to magmatically-dominated spreading occurs along axis within 35 km

comments for slide 4:

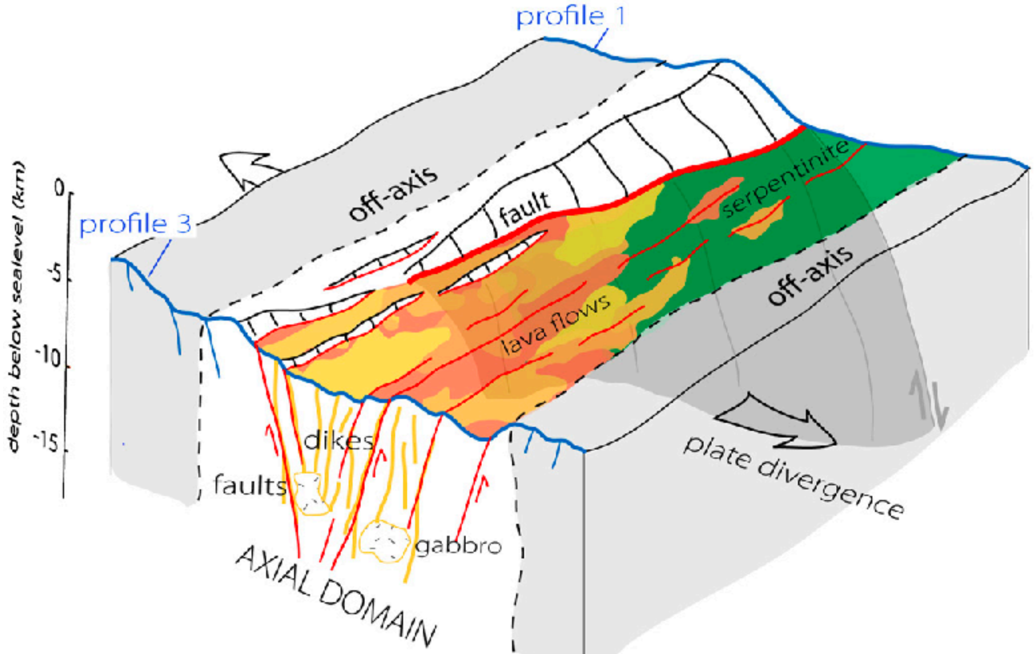
The map in the left panel shows the lateral extent of the breakaways for the proposed successive axial faults (in black), as well as their inferred emergence (in blue). The width of this fault-dominated spreading corridor has varied over time (up to 90 km along axis at the initiation of B4). It is bound on both sides by more magmatically active domains (volcanic seafloor). The sections in the right panel show that the transition from nearly amagmatic seafloor spreading (profile 1), with asymmetric faulting, to symmetrical faulting and magmatically active spreading (profiles 3 and 4), occurs along-axis in less than 35 km. The crossection in the previous slide extended further off-axis at the longitude of profile 1.

Nearly amagmatic spreading is uncommon, but it is a usefull an end-member to study the effect of magma on plate divergence processes.





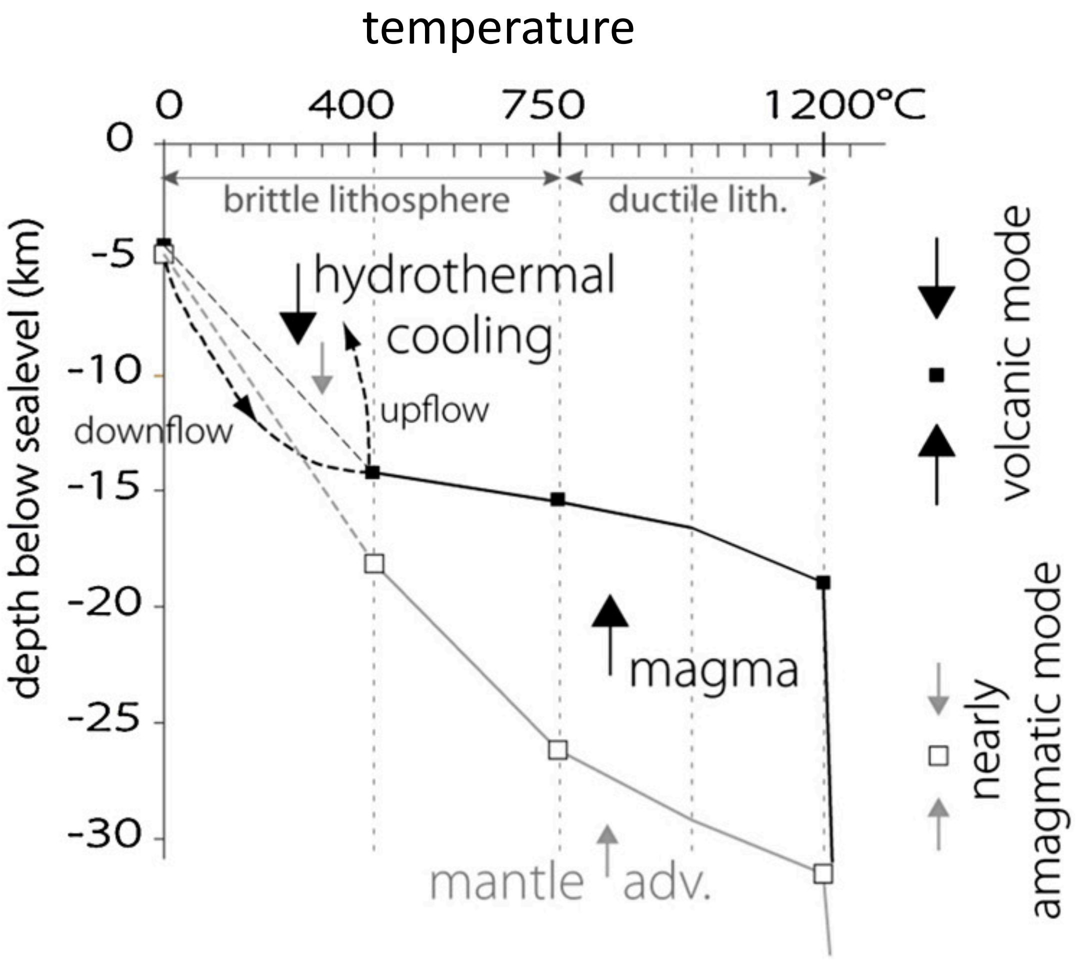
The transition from tectonically-dominated to magmatically-dominated spreading occurs along axis within 35 km



comments for slide 6:

Geological observations and published geophysical constraints (such as the depth of seismicity, references cited in Cannat et al., 2019) suggest that this transition from tectonically-dominated, to more magmatically active spreading involves a considerable change in the thermal structure of the axial region. The brittle lithosphere in the nearly amagmatic domains is 15 to 20 km-thick, and probably only around 10 km-thick in the more magmatic domains. Also, more melt is injected between the two plates in the magmatic case, reducing the need for faulting, and feeding heat to more robust hydrothermal systems. This results in very contrasted structure and composition for the new oceanic lithosphere.

The 3D sketch (lower right) shows that this change occurs progressively along-axis, faults taking over from melt emplacement as a means for plate separation. The next slide will present the conceptual model proposed to account for such large changes in the thermal regime of the axis, over distances of 35 km or less.



Magma is the principal carrier of heat into the axial region and as such it may contribute to thin the axial lithosphere, hence diminishing the volume of new plate material formed at each increment of plate separation. Magma as a heat carrier may also, however, if emplaced in the more permeable upper lithosphere, attract and fuel vigorous hydrothermal circulation and contribute instead to overcooling the newly formed upper plate.

Magma is also a powerful agent for strain localization in the axial region: magma and melt-crystal mushes are weak; gabbros that crystallize from these melts are weaker than peridotites because they contain abundant plagioclase; and hydrothermally-altered gabbros, and gabbro-peridotite mixtures, are weaker than serpentinites because of minerals such as chlorite and talc.

comments for slide 8:

This sketch shows the proposed axial geotherms for the nearly amagmatic, and more volcanic spreading cases represented in the previous slide.

In the nearly amagmatic case, the proposed geotherm is close to a conductive one, with moderate impact from hydrothermal circulation in the upper lithosphere.

In the more magmatic case, magma injected in the upper lithosphere triggers efficient hydrothermal circulation, resulting in an overall overcooling with laterally variable geotherms (cooler in downflow regions, hotter in hydrothermal upflows). Magma also pools at the base of the lithosphere, and is intruded in the deep lithosphere, below the reach of hydrothermal circulation, providing heat that thins the plate. As a result, the geotherm in this more common magmatically active case departs clearly from a conductive one.

This contrast in the thermal regime results in significant differences in the mechanical properties of the axial lithosphere, which are enhanced by the strain softening effect of magma, and of hydrous alteration minerals that develop from magmatic rocks.