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Ophiolites as compressive strain-recording media: an example drawn from the Mesohellenic ophiolitic slab, Greece

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Ophiolites as analogues of ocean crust are studied extensively to decipher extensional processes at oceanic spreading centers, and their distribution and geochemical signatures are essential in modeling of the tectonic evolution of ancient ocean basins. However, less well studied is the deformation encountered during a relatively rare event among earth processes – ophiolite emplacement itself. Emplacement processes span the period during which an ophiolitic slab is transposed from its extensional setting of igneous origin to its final position in a continental margin within a convergent plate boundary. This lithospheric-scale process entails extensive lateral and at least fifteen kilometres of vertical offset. Ophiolitic subunits are expected to record the structural, textural, and mineralogical evidence for the essential mechanisms of these displacements, allowing us to constrain the kinematics within an oceanic slab in tectonic transport. .

Here, we examine an extensive database of detailed structural analyses within the Mesohellenic ophiolite belt to characterize contractional deformation structures associated with this emplacement tectonics. This ophiolite slab, largely buried by Cenozoic sedimentary rocks, includes the Vourinos, Pindos, Koziakas, and Othris ophiolites as well as other ophiolitic fragments. It is continuous in the subsurface of the Mesohellenic trough, and extends northward into Albania as far as the Mirdita Complex.

The period of ophiolite emplacement is framed by the crystallization age of the ophiolite as the older limit, and includes contractional structures up to the time when the ophiolite deforms as part of the continental margin series, including both older and younger strata, rather than as an “independent” entity. In the case of the Mesohel-

lenic slab, crystallization ages and the age of radiolarian cherts considered part of the ophiolitic assemblage overlap with amphibolite sole ages: the “average” age for crystallization dates is ∼170Ma, while that of the sole is ∼168 Ma , each with accuracy envelopes of ∼1 m.y.. While more dating is needed, we can estimate the emplacement “window” of the Mesohellenic ophiolite as a period of only three to four million years. Furthermore, for crust and mantle slabs of similar thickness to Vourinos, a reasonable period for parts of the slab to remain in ductile field conditions is about four million years following their crystallization age (reference here). This overlap implies that emplacement structures in the Mesohellenic ophiolite ought to have initiated in ductile conditions.

Extensional (S_0), structures within ophiolites are used to determine “way up” within the emplaced slab and the orientation of the original spreading axis. These include pillow lava stratigraphy, igneous layering, sheeted dike geometries and chilling directions, as well as mantle structures such as layering and high-temperature mineral fabrics. Some contractional structures penetrate the entire ophiolite slab, whereas others are limited to specific zones. In areas of rapid displacement across the ductile-brittle boundary, high temperature structures are “frozen in” and lack significant intermediate deformation. Emplacement, however, is a mono-directional process: whether ductile or brittle field, whether *via* folding or faulting or granular flow, all emplacement structures verge to the same direction.

From “high” to lower temperature conditions, crossing ductile into brittle conditions, compressive structures that deform S_0spreading-related features include the following:

- High temperature mineral foliation and mantle layers in the vicinity of the Xerolivado Chrome Ore district of Vourinos describe folds on the scale of ten to thirty meters in wavelength, that extend thirty to 200 meters along ∼arcuate, NE-trending fold axes plunging to the SE. Their morphology is similar to that of sheath folds with a dextral shear sense.

- The Konivos Ore District, ∼five kilometres north of Xerolivado, includes tighter, deeper folding on similar scale, with the initiation of a strong spinel lineation. Highly attenuated fold limbs grade to mylonitic zones, which facilitated differential forward motion in the slab, with ductile shears and ductile-brittle shears developing between the mylonitic zones.

- In the Pindos, Koziakas and Othris ophiolites, the extent of mylonitic-cataclastic deformation is widespread and intensive; kilometre-scale NE trending zones of pervasive mylonitic fabric cross the southern part of the Pindos nappe, with inclusions of less mylonitic mantle peridotite rotating between these zones. A continuation of this ductile zone across the Mesohellenic trough appears to connect it to the southern boundary of the Vourinos emplacement sole.

- Both Koziakas and Othris peridotites show mylonitic-cataclastic folding on mesoscopic scale that includes formation of “new” mineral fabrics and lineations which are in turn folded. The lowest temperature flow fabric consists of a mylonitic breccia at the base of the Mesovouni block and located within the Koziakas thrust series.
- Ramp structures are pervasive throughout the ophiolitic slab including ductile, ductile-brittle, and brittle structures of imbricate thrust geometry.

On the scale of the entire complex, tectonic thinning, and rotation (horizontal and vertical) are relatively dated to the emplacement window. Thinning has been observed on scales down to centimetre scale via pervasive “microthrusts” and as large as intra-slab ramping and nappe formation. “Hot” ramps and thrusts have sole zones above other ophiolitic units that include mylonitic deformation, shearing of less competent lithologies, entrapment of competent lithologies such as massive chromitites, and even gabbroic intrusions. Vertical rotations that must affect the entire ophiolitic section are best discerned by changes in form lines of mantle and cumulate rocks within contiguous ophiolitic exposures. Horizontal rotations, with the most extreme case being that of Vourinos itself, can be dated to within the oceanic period (between late Jurassic to mid Cretaceous). All these types of contractional deformation features within the Mesohellenic ophiolite verge to the NE.

Sheath folds undoubtably show transport on the scale of tens of kilometres; mineral deformation in the broad ductile shear zones crossing the belt imply a transport of at least an additional ten kilometres; tectonic thinning as pervasive shear zones or imbricate and nappe formation cumulatively transport the slab further, though these distances cannot be easily estimated. Concurrent to this motion, vertical rotations of the upper crust is inescapable when the lower crustal and mantle parts of the slab deform along the flank of the emplacing slab. In light of this complex history of deformation, the original geographic orientation of the spreading center, that is, “S_0” geometry, probably cannot be reconstructed. However, these structures collectively suggest that the Mesohellenic ophiolite slab was displaced from its original tectonic setting of igneous formation above a west-dipping (in present coordinate system) subduction zone and that it was tectonically transported eastwards above this rapidly retreating subducting slab while undergoing upper-plate extension.