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Rapid fore-arc extension and detachment-mode spreading following subduction initiation

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ABSTRACT

Most ophiolites have geochemical signatures that indicate formation by suprasubduction seafloor spreading above newly initiated subduction zones, and hence they record fore-arc processes operating following subduction initiation. They are frequently underlain by a metamorphic sole formed at the top of the downgoing plate and accreted below the overlying suprasubduction zone lithosphere immediately following ophiolite formation. Paleomagnetic analyses of ophiolites can provide important insights into the enigmatic geodynamic processes operating in this setting via identification of tectonic rotations related to upper plate extension. Here we present net tectonic rotation results from the Late Cretaceous Mersin ophiolite of southern Turkey that document rapid and progressive rotation of ophiolitic rocks and their associated metamorphic sole. Specifically, we demonstrate that lower crustal cumulate rocks and early dykes intruded into the underlying mantle section have undergone extreme rotation around ridge-parallel, shallowly-plunging axes, consistent with oceanic detachment faulting during spreading. Importantly, later dykes cutting the metamorphic sole experienced rotation around the same axis but with a lower magnitude. We show that these rotations occurred via a common mechanism in a pre-obduction, fore-arc setting, and are best explained by combining (hyper)extension resulting from detachment-mode, amagmatic suprasubduction zone spreading in a fore-arc environment with a recently proposed mechanism for exhumation of metamorphic soles driven by upper plate extension. Available age constraints demonstrate that extreme rotation of these units was accommodated rapidly by these processes over a time period of $<\sim 3$ Myr, comparable with rates of rotation seen in oceanic core complexes in the modern oceans.

1. Introduction

Ophiolites provide insights into fundamental oceanic tectonic processes associated with their formation at spreading axes and subsequent intraoceanic- and emplacement-related deformation. The majority of the world's ophiolites have a geochemical signature interpreted as indicating formation above newly initiated intraoceanic subduction zones, in so-called suprasubduction zone environments (e.g. Pearce and Robinson, 2010). This setting can also account for the observation that ophiolite accretion is often closely followed by subduction-related emplacement onto continental margins (Robertson, 2002). In contrast to true mid-ocean ridge systems, suprasubduction zone ophiolite formation and subsequent evolution is the result of a complex process controlled by both the subducting plate and tectonic processes in the fore-arc region. This is clearly demonstrated by the occurrence of so-called metamorphic soles below many suprasubduction zone ophiolites. Metamorphic soles are thin (<500 m) layers of granulite to greenschist facies rocks, which experienced high temperature and pressure metamorphism (850–900 °C, 10–15 kbar) above a subducting lithosphere, prior to their accretion to the overriding plate (for a review see van Hinsbergen et al., 2015). In several well-preserved ophiolites like that of Oman, the metamorphic sole is spread over a broad area below the ophiolite, up to c. 100 km away from the paleo-trench, suggesting original accretion as a large semi-continuous metamorphic layer. The accretion of metamorphic soles below ophiolites necessarily requires some sort of fore-arc thinning to exhume the sole from peak metamorphic depths, either tectonically via extension of the overriding plate (e.g.

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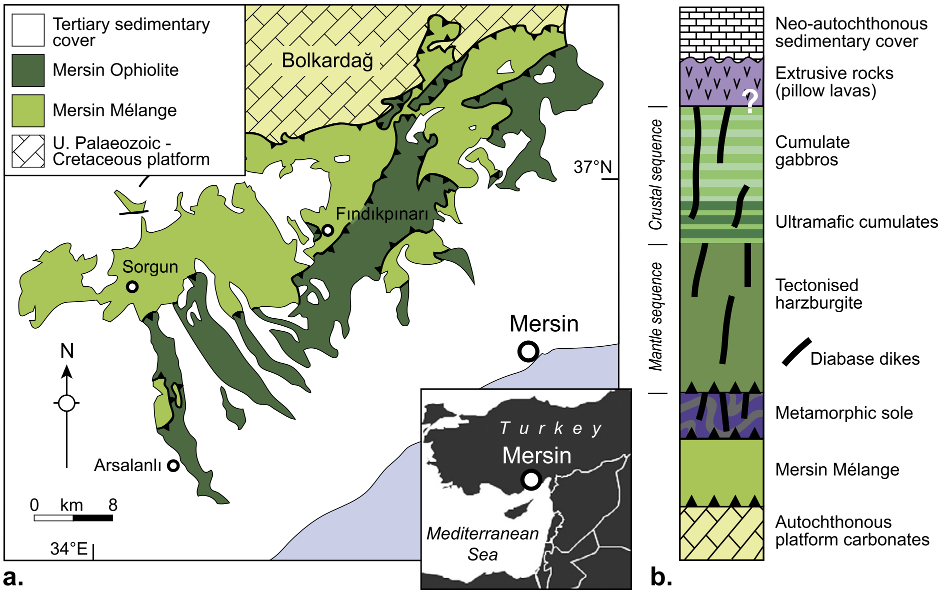

Fig. 1. Summary of the geology of the Mersin ophiolite of southern Turkey. (a) Simplified geological map (after Tekin et al., 2016); (b) tectonostratigraphic column (after Parlak et al., 1996b). In this study we have sampled dykes cutting the metamorphic sole of the ophiolite, dykes cutting the mantle sequence, and ultramafic and gabbroic cumulates of the lower crust for paleomagnetic analysis. (A color version of this figure is available with the web version of the article.)

Hacker and Gnos, 1997), or magmatically via partial melting and resulting volume decrease of the forearc mantle wedge below the newly formed suprasubduction zone crust (van Hinsbergen et al., 2015). The similarity of ages of ophiolitic crust and peak metamorphism of associated metamorphic soles observed in nearly all ophiolites indicates that spreading and metamorphic sole exhumation are almost simultaneous processes, and both occur during or shortly after subduction initiation.

Obtaining geological evidence that constrains the kinematics and timing of tectonic processes affecting fore-arc systems during subduction initiation in the modern oceans is difficult as incipient subduction zones are rare (Gurnis et al., 2004). Hence, well-exposed ophiolites provide important records of fore-arc processes operating during and following subduction initiation that are otherwise difficult to investigate (Stern and Bloomer, 1992; Robertson, 2002). Numerous studies have highlighted how paleomagnetic analyses of ophiolites can help to unravel the tectonic evolution of these systems. A focus has been the Tethyan ophiolites of the eastern Mediterranean/Middle East region, where magnetic techniques have been used to constrain the structure and orientation of suprasubduction spreading axes (e.g. Allerton and Vine, 1987; Hurst et al., 1992; Morris and Maffione, 2016; Maffione et al., 2017), patterns of magmatic flow during crustal accretion (e.g. Staudigel et al., 1992; Granot et al., 2011), the kinematics of transform fault systems (e.g. Morris et al., 1990; MacLeod et al., 1990; Morris and Maffione, 2016), and the response of the upper plate to impingement of continental margins with subduction zones (Clube et al., 1985; Inwood et al., 2009; Morris et al., 2002).

Renewed interest in ophiolites has followed the discovery of the importance of oceanic detachment faulting and the formation of oceanic core complexes (OCCs) in slow-ultraslow spreading lithosphere in the Atlantic and Indian Oceans (e.g. Smith et al., 2008; MacLeod et al., 2017) and the definition of a new amagmatic "detachment-mode" of seafloor spreading (Escartín and Canales, 2011). This is fundamentally different from classic magmatic spreading and involves plate divergence being taken up by slip on lithospheric-scale faults that rotate during displacement, resulting in exhumation of their footwall sections and exposure of lower crustal and mantle rocks on the seafloor. Studies of samples recovered by scientific ocean drilling have shown 45–65° rolling-hinge rotations of OCC footwalls in the Atlantic Ocean around ridge-parallel, sub-horizontal axes (Garcés and Gee, 2007; Morris et al., 2009; MacLeod et al., 2011). This characteristic has allowed Maffione et al. (2013) to extend the record of detachment-mode spreading back to the Jurassic by demonstrating the existence of a fossil OCC preserved within the Mirdita ophiolite of Albania. More recently, Maffione et al. (2015) showed that oceanic detachment faulting was responsible for large tectonic rotations and extensional thinning of fore-arc lithosphere preserved in the Cretaceous ophiolites of southern Tibet. This led them to propose a new concept of "fore-arc hyperextension", demonstrating how the exchange of ideas between studies in the modern oceans and in ophiolites can lead to advances in our understanding of lithospheric processes.

Here we present the first paleomagnetic data from the Late Cretaceous Mersin ophiolite of southern Turkey. Like many Tauride ophiolites (Dilek et al., 1999), Mersin consists predominantly of tectonized mantle rocks and ultramafic/mafic cumulates, with no sheeted dyke complex and only limited exposures of extrusive rocks, and is underlain by a metamorphic sole that has ^{40}Ar–^{39}Ar cooling ages that are similar to the age of the ophiolitic magmatic rocks (Parlak et al., 2013; van Hinsbergen et al., 2016). Our data constrain the axes, magnitudes and timing of tectonic rotations in these units, and provide evidence for rapid fore-arc (hyper)extension via detachment-mode seafloor spreading (Escartín and Canales, 2011). We show that this style of Neotethyan suprasubduction zone spreading provides a viable mechanism to explain the exhumation of metamorphic soles, their structural disruption following welding to the base of the lithosphere, and the lack of upper crustal sequences in many Tauride ophiolites.

2. The Mersin ophiolite

The Mersin ophiolite complex outcrops over a 60 km long, 25 km wide area in southern Turkey (Fig. 1a). It consists of an Upper Cretaceous ophiolite sequence, underlain by metamorphic sole rocks and then by the Mersin Mélange (Fig. 1b; Parlak and Delaloye, 1996, 1999; Parlak et al., 2013). These units form the highest structural unit of the uppermost Cretaceous–Eocene Tau-