Magnetic properties of variably serpentinized peridotites and their implication for remanence acquisition during the evolution of oceanic core complexes

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MARIE CURIE ACTIONS

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EARTH SCIENCES WITH PLYMOUTH UNIVERSITY

Abstract

Serpentinization of mafic and ultramafic rocks during hydrothermal alteration at mid-ocean ridges is a process that profoundly changes the physical, chemical, rheological and magnetic properties of the oceanic lithosphere. There has recently been renewed interest in this process following the discovery of widespread exposures of serpentinized mantle at modern slow-spreading seafloors. Unroofing of mantle rocks in these settings is achieved by displacement along oceanic detachment faults, which eventually results in uplifted and rotated footwall sections known as oceanic core complexes (OCCs). Complexities inherent in direct sampling and observation of abyssal peridotites exposed at OCCs have, however, limited our knowledge of the mechanisms of serpentinization at the seafloors and in particular its relationship with the evolution at OCCs.

Here we present the results of an integrated, rock magnetic, paleomagnetic and petrological study of variably serpentinized peridotites from the first fossil OCC recognized in an ophiolite[1]. Being magnetite a direct product of serpentinizatiton, the variation of magnetic properties in variably serpentinized peridotites can provide unique insights into the intrinsic mechanisms of this process and its evolution in the oceanic lithosphere. Furthermore, integration with existing data from abyssal peridotites recovered from several deep sea drilling (ODP and DSDP) sites (called "MAP")[2,3] provides the first complete magnetic database for variably (0-100%) serpentinized peridotites.

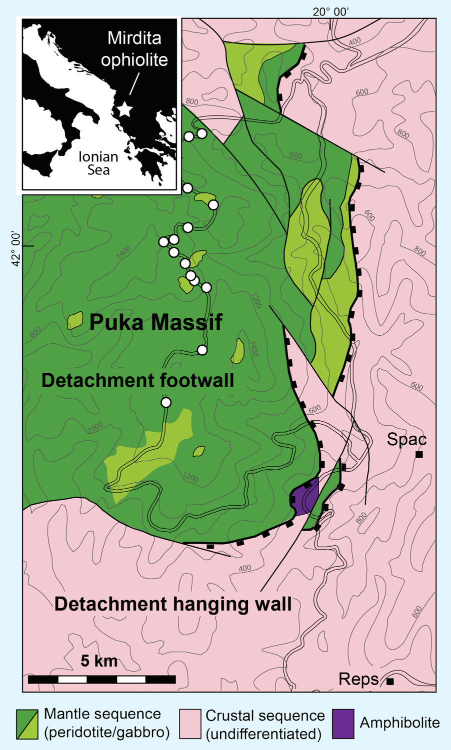


Figure 1. Geological map of the sampling area in the Mirdita ophiolite, northern Albania. The Puka massif is an ultramafic mantle body representing a fossil (Jurassic) oceanic core complex.

1. Serpentinization degree computation

Serpentinization is a low-temperature hydrothermal alteration of mainly Olivine minerals:

Olivine ± Pyroxene + H_2O *= serpentine + brucite ± magnetite ± talc ± tremolite +* H_2

Serpentinization degree (*Sc*) can be calculated from density measurements, according to the empirical formula[2,4]:

$$Sc = \{3.3 - [(d - 5.2 \times m)/(1 - m)]\} / 0.785$$

where:
d = density (g/cm^3)
3.3 = density of fresh peridotite (g/cm^3)
m = magnetite volume fraction (%)

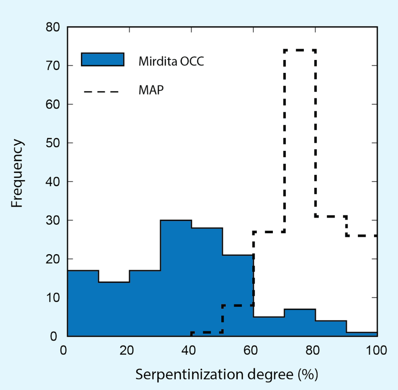


Figure 2. Frequency distribution of the degree of serpentinization of 144 peridotite samples from the Mirdita OCC, and 210 samples from the MAP database.

2. Nature and distribution of the magnetic carriers

Both back-scattered electron (BSE) images (Figure 3) and the thermal variation of the low-field magnetic susceptibility (Figure 4) indicate that magnetite is the main magnetic carrier in the Mirdita OCC peridotites. Magnetite always occurs within serpentine veins, as dispersed (sub)micron-sized particles (Figure 3a, 3b) in weakly serpentinized samples. At higher serpentinization degrees (>40%, Figure 3c-h) magnetite occurs along thicker veins as major grain aggregates (>50 μm).

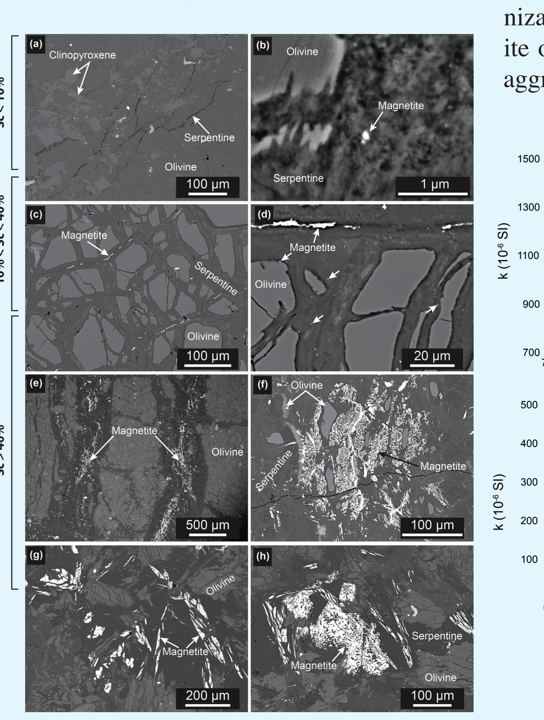


Figure 3. BSE images of serpentinized peridotites from the Mirdita OCC.

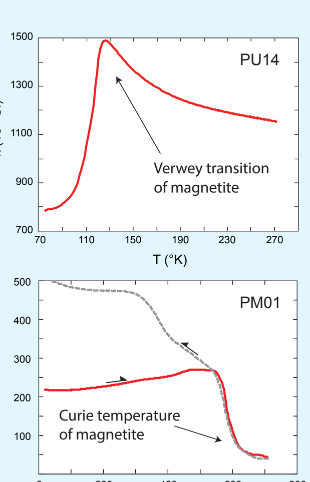


Figure 4. Low- (above) and high- (below) temperature variation of the low-field magnetic susceptibility during heating-cooling paths (red and gray lines, respectively).

3. Variation of NRM, magnetic susceptibility, and magnetite content during serpentinization

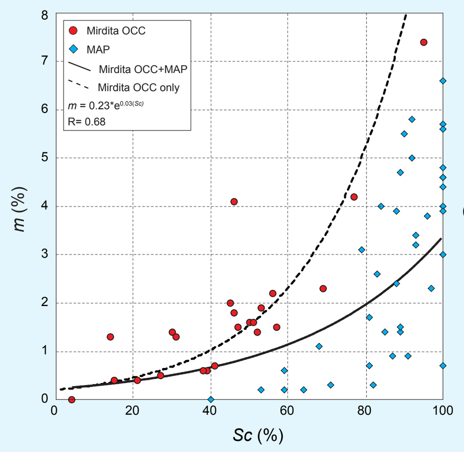


Figure 5. Magnetite volume content (m) calculated vs. serpentinization degree (Sc). Best-fit curves are calculated separately for the Mirdita OCC and a combined dataset.

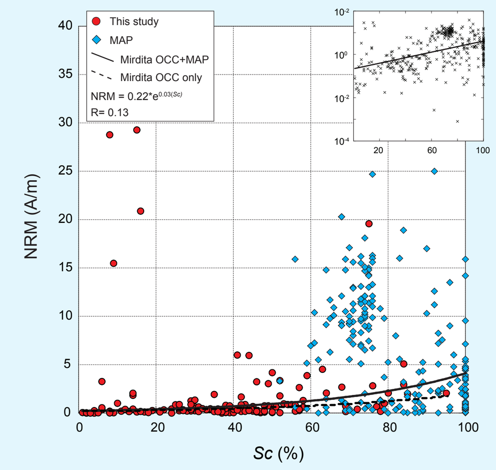


Figure 6. Natural remanent magnetization (NRM) vs. serpentinization degree (Sc). Best-fit curves are computed as in Figure 5.

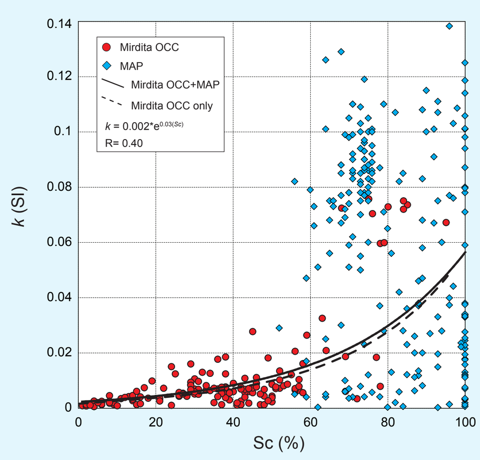
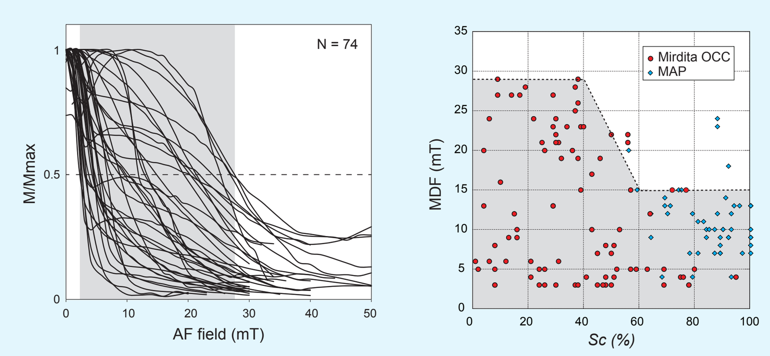


Figure 7. Magnetic susceptibility (k) vs. serpentinization degree (Sc). Best-fit curves are computed as in Figure 5.

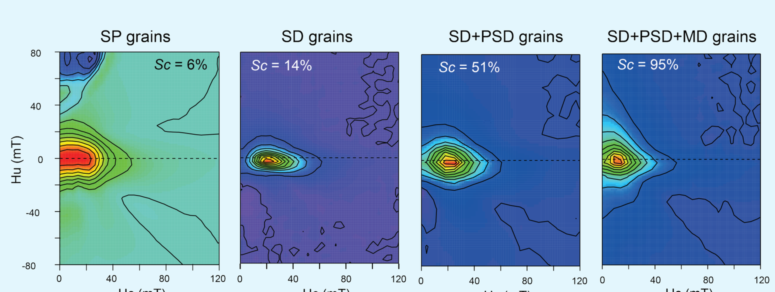
Magnetite volume content appears to be a direct function of the serpentinization degree in variably serpentinized peridotites. Such relationship indicates that magnetite production during serpentinization increase exponentially, with a rapid acceleration after 60% serpentinization. The scatter of magnetite content at a specific degree of serpentinization may be related to the variable feature of the interacting fluids (i.e., silica activity and oxigen fugacity. This effect is significant (±5% variation) in the MAP database, and moderate (±1% variation) in the Mirdita OCC dataset. Such variable amount of newly formed magnetite is reflected in the scattering of NRM (Figure 6) and k (Figure 7) values along the y-axis. Both the NRM and k, however, appear to increase exponentially with serpentinization progression.

4. Magnetite grain size variation during serpentinization



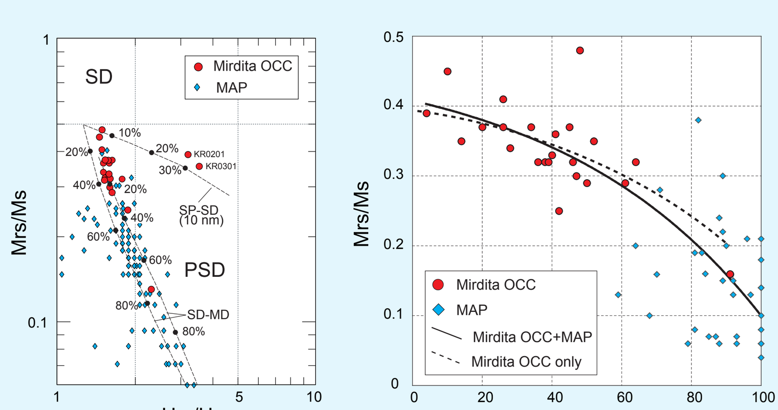
MDF values indicate that weakly serpentinized peridotites (Sc<40%) are dominated by high-coercivity, fine-grained (single domain - SD) magnetite, while rocks with Sc>60% have a larger low-coercivity, coarse-grained (multidomain - MD) magnetite fraction.

Figure 8 and 9. (Left) Alternating field (AF) demagnetization curves showing the decay of magnetization (M) during increasing AF steps. Gray area is the range of median distructive fields (MDF) given by the intersection between the decay curve and the 0.5 M/Mmax line. (Right) MDF values vs. serpentinization degree (Sc). Gray area is the envelope of the MDF distribution.



Grain size of magnetite increases progressively with the serpentinization degree: superparamagnetic (SP) grains form at Sc<10%. Then, single domain (SD), pseudo-single domain (PSD), and multidomain (MD) magnetite grains are produced at Sc of 10%, 40%, and 60%, respectively.

Figure 10. First order reversal curves (FORC) diagrams of four samples characterized by a variable degree of serpentinization (Sc).



Data from the Mirdita OCC and MAP are characterized by a mixture of SD and MD magnetite. The proportion of MD grains varies between <10% and ~80% (Figure 11, left). The abundance of MD fraction (inversely proportional to the remanence ratio - Mrs/Ms) increases progressively with the serpentinization degree (Sc) (Figure 11, right).

Figure 11. (Left) Day plot with the teoretical SD-MD mixing curves for magnetite. (Right) Remanence ratio (Mrs/Ms) vs. serpentinization degree (Sc) diagram. Best-fit curves have been computed for the Mirdita OCC and MAP datasets.

5. Role of serpentinized peridotites in the origin of the marine magnetic anomalies

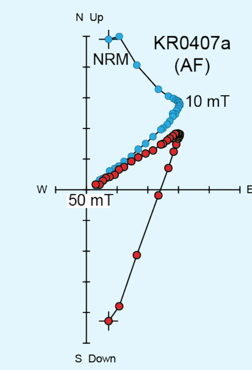


Figure 12. Zijderveld diagram of a representative sample showing two well-defined components of magnetization.

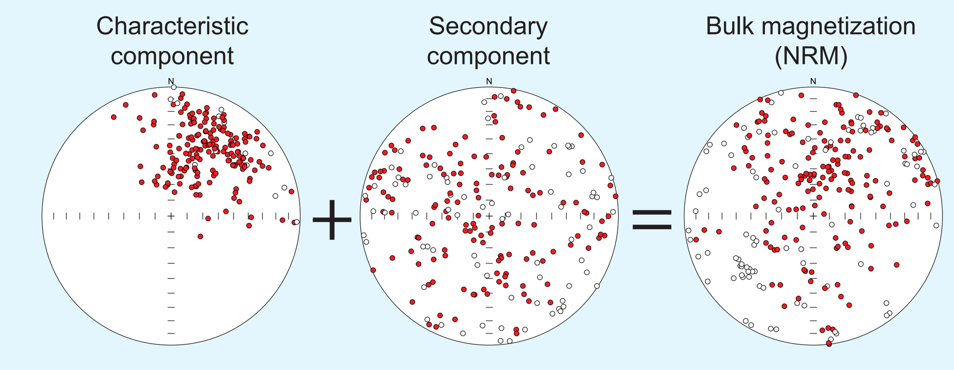


Figure 13. The bulk magnetization of a rock sample, also called natural remanent magnetization (NRM), is here the resultant of two components of magnetization: a characteristic and a secondary component. Scattered secondary components, coupled with well-custered characteristic components, result in scattered NRM directions.

The scattered nature of the secondary components of magnetization, carried by large MD magnetite grains, significantly affect the final bulk magnetization (NRM). The resulting scatter of NRMs (Figure 13) makes those rocks unlikely to contribute to regionally-coherent patterns of marine magnetic anomalies. This is also supported by the Q ratios (Figure 14), that indicate a variable potential for those rocks to contribute to the marine magnetic anomalies.

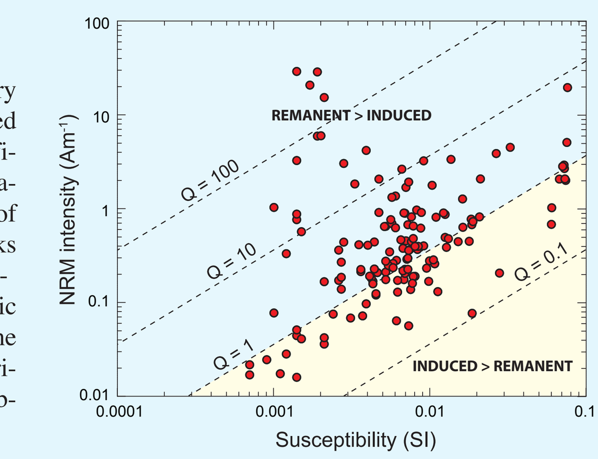


Figure 14. The Konigsberger or Q ratio (NRM/H*k) is the remanent vs. induced magnetization. Q>1 (gray shaded area) indicates stable remanence, while Q < 1 (yellow area) are relative to less stabe remanences, more susceptible to the influence of the external geomagnetic field.

6. Composite effect of serpentinization on the magnetic properties of peridotites

Magnetite is produced during serpentinization at an exponential rate, with significant increases after ~60% serpentinization. In the early stages (Sc<60%) smaller grains (SD and PSD) of magnetite are produced that are responsible for a stable, regionally-coherent magnetization. After ~60% serpentinization, the growth of larger (MD) magnetite grains produce an unstable, randomly oriented remanence (secondary component). The change of the magnetite production rate at Sc=60% is likely related to a dramatic increase of permeability due to pervasive cracking (i.e., rock- to fluid-dominated transition). The production of magnetite at specific stages of serpentinization is variable and depends on the local composition of the reacting fluids (i.e., silica activity and oxigen fugacity).

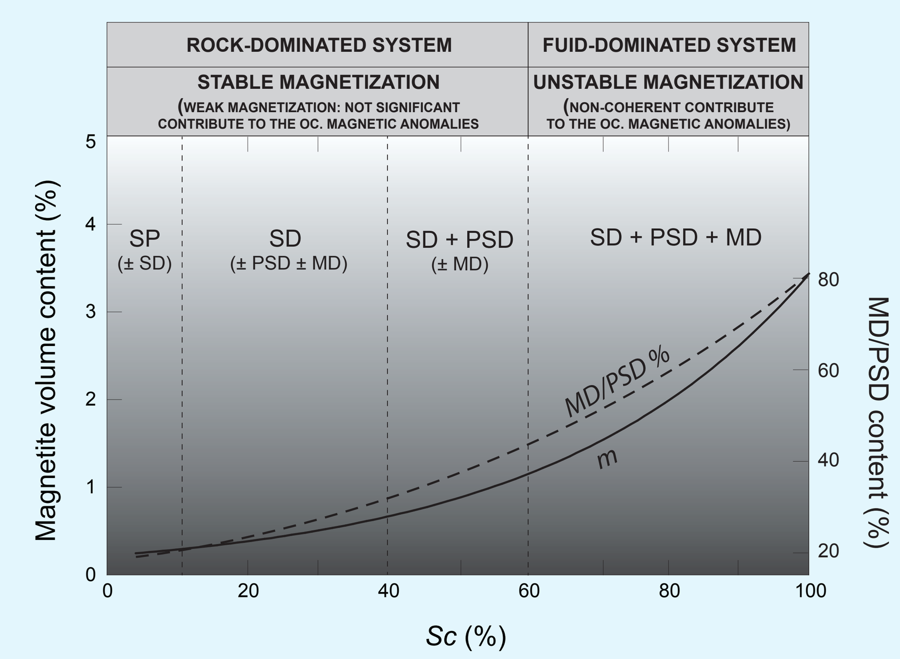


Figure 15. Summary graphyc showing the effect of serpentinization on the production of magnetite (m), its grain-size, and the resulting magnetic remanence.

7. Serpentinization of oceanic core complexes

Serpentinization of oceanic upper mantle peridotites can be triggered by the activity of oceanic detachment faults operating during amagmatic periods of seafloor spreading. Water influx at depth (up to 8 km) starts the reaction within the olivine-bearing mantle peridotites, leding to serpentinization and magnetization (blue layer). This layer will record the maximum amount of rotation if the oceanic core complex is associated to footwall rotation (as for the 15°45'N OCC[5]). From the fault surface, the serpentinization front migrates into the footwall, producing progressively deeper serpentinized and magnetized layers. Deeper portion of the footwall (orange layer) will dysplay defferent amounts of rotation. Serpentinizazion and remanence acquisition in the deepest portions of the footwall (red layer) may continue after the end of tectonic activity at the fault. The remanence of these deeep portions will display no rotation (i.e., Mirdtia OCC and Fifteen-Twenty Fracture Zone[6]).

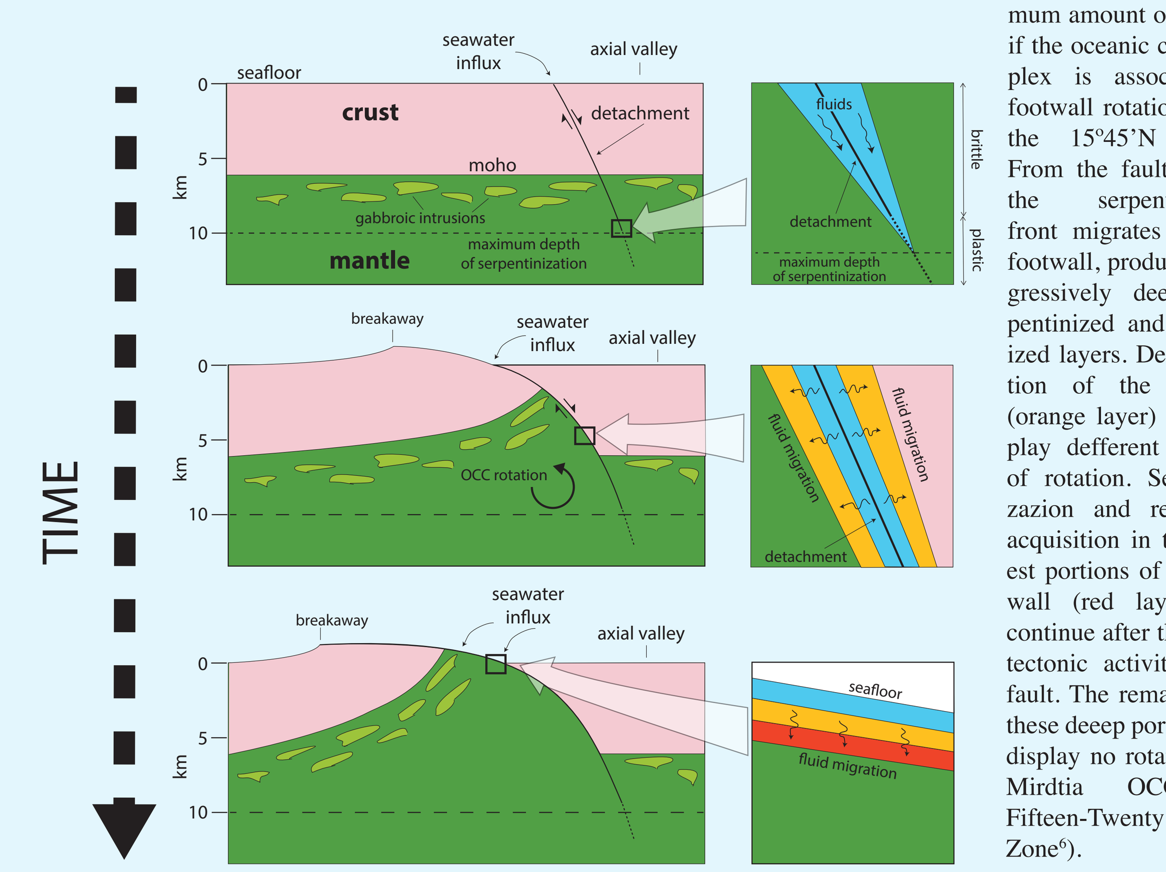


Figure 16. Evolutionary model for serpentinization at oceanic core complexes.

8. Conclusions

1. We documented for the first time the variation of magnetic properties across the complete range of serpentinization degrees (0-100%).
2. The exponential increase of NRM, magnetic susceptibility, and magnetite content during serpentinization implies a major change in alteration conditions from rock-dominated to fluid-dominated systems at a critical serpentinization threshold of 60%. We suggest that this transition is caused by a dramatic increase in transient permeability due to a pervasive mechanical weakening of the reacting rock during serpentinization.
3. The grain size of newly formed magnetite is directly correlated with the serpentinization degree. Very fine, super-paramagnetic (SP) particles are formed during the initial stages of serpentinization (<10%), single-domain (SD) magnetite is produced up to 40% reaction progression, while pseudo-single-domain (PSD), and multidomain (MD) grains are formed at 40% and 60% reaction progress onwards, respectively.
4. SD and PSD magnetite grains, mostly produced during the initial stages of serpentinization (Sc<60%), can carry stable magnetizations. The MD fraction formed within sparse, larger veins at later serpentinization stages (Sc>60%), carries only scattered low stability components. This evidence, together with variable Königsberger ratios, suggests that variably serpentinized peridotites are likely not able to contribute to a regionally-coherent pattern of oceanic magnetic anomalies.
5. Serpentinization at oceanic core complexes migrates from the fault surface into the footwall. Magnetization acquisition starts at the fault surface and may continue until complete footwall uplift and rotation. Serpentinized peridotites close to the detachment surface acquire their remanence early in the evolution of the OCC and may record substantial footwall rotation[5], whereas rocks deeper in the footwall may undergo serpentinization after (near) complete unroofing and rotation[1,6].

References

1. Maffione, M., A. Morris, and M. W. Anderson (2013), Recognizing detachment-mode seafloor spreading in the deep geological past, Scientific Reports, 3, 2336, doi:10.1038/srep02336
2. Oufi, O., M. Cannat, and H. Horen (2002), Magnetic properties of variably serpentinized abyssal peridotites, J. Geophys. Res., 107(5), EPM 3-1 - EPM 3-20
3. Kelemen, P.B., Kikawa, E., Miller, D.J., et al. (2004). Proc. ODP, Init. Repts., 209: College Station, TX (Ocean Drilling Program), doi:10.2973/odp.proc.ir.209.101.2004
4. Miller, D. J., and N. I. Christensen (1997), Seismic velocities of lower crustal and upper mantle rocks from the slow-spreading Mid-Atlantic Ridge, south of the Kane transform zone (MARK), Proc. Ocean Drill. Program Sci. Results, 153, 437–454.
5. MacLeod, C. J., J. Carlut, J. Escartín, H. Horen, and A. Morris (2011), Quantitative constraint on footwall rotations at the 15°45 N oceanic core complex, Mid-Atlantic Ridge: Implications for oceanic detachment fault processes, Geochem. Geophys. Geosyst., 12(5), Q0AG03, doi: 10.1029/2011GC003503.
6. Garcés, M., and J. S. Gee (2007), Paleomagnetic evidence of large footwall rotations associated with low-angle faults at the Mid-Atlantic Ridge, Geology, 35(3), 279, doi: 10.1130/G23165A.1.