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Research Article

Serpentinite Diapirs and the Evolution of Oceanic Core Complexes

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Abstract

Serpentinites and peridotites are the predominant lithological components of Oceanic Core Complexes (OCCs), located commonly at triple junctions of slow-spreading oceanic accreting ridges, fracture zones and transform faults. These lithologies differ from the surrounding oceanic brittle lithosphere, built of basalt and gabbro, and the structural evolution of these OCCs is enigmatic. The present investigation suggests that the tectonics of OCCs is derived from the ascent of serpentinic diapirs generated by the unique proximity of shallow asthenosphere, faulted lithosphere and the juxtaposition of oceanic crusts of contrasting densities. Such setting initiated two structural stages in the evolution of the OCC, the first is spontaneous subduction of old and dense oceanic crust under the fresh and lighter basalt at the edge of the MOR across its intersection with transform fault - fracture zone. The sub ducted slab would be affected by the combined effect of the steep thermal gradient and the availability of volatiles there to enhance the alteration of pyroxene into serpentine. Analog and numeric experiments show that spontaneous subduction can initiate spontaneously if the density contrast between the juxtaposed slabs is significant, as is the case between fresh basalt ($\rho \sim 2.7$ g/cm^3) and older basalt ($\rho \sim 2.9$ g/cm^3). Since the average thermal gradient under the MOR is ca. 130°/km, then at depth of 4-5 km the pyroxene and plagioclase would start their alteration, mostly to serpentine. The abundant faults of MOR normal rifting and strike-slip transform faulting could enable the light and malleable serpentinite to form diapirs, which would ascent to the seafloor at the rift-fracture zone intersections. The friction at the top of the diapirs during their ascent would probably generate breccia at their tops.

Highlights

a) OCCs are built mostly of serpentinite diapirs that carry peridotite inclusions.
b) Serpentinization occurs under low pressure-high temperature conditions.
c) OCC source rock is slab of cold oceanic crust sub ducted under fresh crust.
d) Such subduction occurs mostly where large density contrast between slabs exists.
e) The link between OCCs and detachment normal faults requires support.

Introduction

Already the early explorers of marine geology found out that the ocean floor at the mid-ocean ridges and the marine basins is built predominantly of basalt that is characterized by its normal and reverse magnetization. The pioneering scientific exploration cruises encountered in some select locations also rock samples of peridotites and serpentinites, where the peridotites were attributed to partial melting of xenoliths from the upper mantle, exhumed by the upward flow of the basaltic lavas of the MidOcean Ridge (MOR), while the serpentinite was considered a seafloor alteration product [1]. The abundance of serpentinites was also discerned by [2], who remarked that serpentinite is highly mobile due to its low density and low cohesive strength, therefore it would tend to flow up diapirically along fault planes, and outcrop at the seafloor. Dredging rubble of peridotites and serpentinites from the marine valleys of several fracture zones and transform faults in the Atlantic Ocean, led [3] to suggest that these valleys offer windows into the deeper layers of the oceanic crust through extensive faulting. Contrariwise, [4] presumed that the transform faults form weakness domains in the oceanic crust that enable the diapiric ascent of serpentinites, with inclusions of peridotites from the upper mantle, to outcrop at the seafloor. These unique occurrences of peridotites and serpentinites were encountered mostly along slow and ultra-slow oceanic accreting rifts and they were termed “Oceanic Core Complexes” (OCCs). They were observed, sampled, drilled and analyzed, and commonly the origin of the peridotites was presumed to derive from the upper mantle, while the serpentinites were considered as seafloor alteration of the original ultrabasic mineralogy [5,6]. The abundance and variability of the peridotites in the OCC’s led many researchers to the interpretation that ascent and exposure of these rock suites is attributed to offsets caused by large scale, low angle normal detachment faults (Figure 1).

These faults presumably transect the oceanic lithosphere, and their footwalls expose the upper mantle at the OCCs [7,8]. However, the structural validity of that model is somewhat doubted [9,10] and the rareness of high-pressure rocks, such as eclogites, casts doubt on the upper mantle origin of the OCCs as well. The marine geological and geophysical research of OCCs found out that although many such features were encountered in the Equatorial Atlantic Ocean, such core complex lithologies were explored also in the SW Indian Ocean [11,12], and in Parece Vela back-arc basin in the western Pacific [13]. Surprisingly OCC was also discerned in the very fastspreading East Pacific Rise at its intersection with Garrett Transform Fault at 13°28’S [14-16].

The present investigation explored a novel concept, suggesting that OCCs were generated in two stages. The first is that lithological origin of the OCC is cold oceanic lithosphere that is subducted under the fresh and light lithosphere of the accreting oceanic rift. The second stage starts where the subducted slab undergoes serpentinization at temperature of circa 450°C, which, at the ridge-transform intersection, is located at depths of about 5 km. The serpentinites form diapirs that ascend from shallow depths into the external flank of the rift due to the extreme thermal gradient at the accreting rift -fracture zone junction. Although apparently unlikely, analytical investigations, as well as analog and numeric models showed that subduction initiate along fracture zones. The juxtaposition of two crustal slabs of contrasting densities, such as those of the fresh rift basalt and old oceanic crust across a fracture zone, would initiate spontaneous subduction, which would underthrust the denser slab

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[18,19,20]. The extreme thermal gradient under the accreting rift and the availability of volatiles would cause the alteration of the basalts into serpentinites at the shallow depth of ca. 5 km. Subsequently diapiric ascent of these serpentinites, carrying along blocks of peridotites, into the rift flank, would form the OCC.

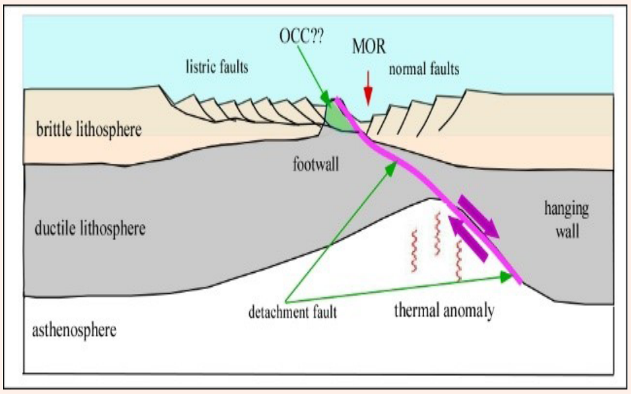

Figure 1: A schematic cartoon showing the OCC as a part of the footwall of a low angle normal detachment fault that transects the lithosphere and exposes the upper mantle on the external flank of the accreting Mid-Ocean rift. In-situ alteration of the peridotite into serpentinite leads to the observed lithology of the OCCs. Partly after [17,8].

Results

The mid-ocean rift-transform fault-fracture zone composite intersection

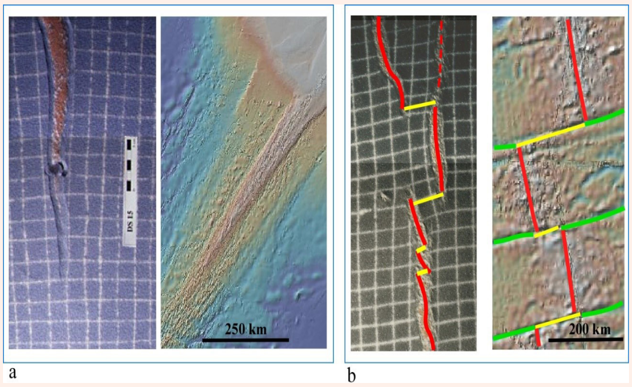

Figure 2: Rifting - model and prototype. a. Sand-box model of normal extension with 4o obliquity led to the development of a continuous wedge-shaped rift of crustal accretion (left), seems similar to Reykjanes Ridge off Iceland in its wedge-shape continuity and absence of transform faults (right). b. Sandbox model of oblique extension with 15^0 obliquity led to the simultaneous development of basins located right and left of the central line of the box (left). When the edges of proximal such basins overlapped, a trace of a transform fault (yellow lines) started to appear in the sand, offsetting the accretion rift (red) and turning into stable fracture zones (green). Inactive segment of the rift marke by a dashed red line. Note the similarity of the model with the Mid-Atlantic Ridge, its transform faults (yellow lines) and its fracture zones at ca. lat. 30^0N (right). For technical details of the displayed experiments, see [23].

The controls of the geographic distribution of OCCs are enigmatic. Most OCCs are located at the external side of the intersections of accreting oceanic rifts and the edge of the translation domains, where tectonically active oceanic transform faults are converted into tectonically passive fracture zones. Since the rifts at the crests of the MOR are known to accrete basalts and gabbro, the possibility that they would also produce peridotite and serpentinite is unlikely; therefore the occurrence of OCCs is probably constrained by the transform faults-fracture zones systems. The present investigation suggests that some oceanic crust is also subducted near the transform-fracture transition. Oceanic transform faults are commonly defined as tectonic plate boundaries where the displacement along them is horizontal and they are conservative, meaning that no basaltic crust is formed or lost along these faults [21]. However, recent research showed that crustal accretion does take place along these faults, and that the tectonic displacement along them is oblique [22]. This oblique extension led to crustal accretion, which formed the rugged bathymetric relief (Figure 2). The tectonic crustal deformation of the active transform faults generated the very rough bathymetry of the oceanic crust, which leaves behind long and seismically inactive bathymetric scars in the seafloor, the fracture zones, which transect the ocean basins.

Numerical modeling of transform faulting commonly wavered between attributing the origin of these faults either to inherited pre-rifting fault patterns, or to fault nucleation after the initiation of the oceanic rifting [24]. Alternately, analog models indicated that oblique tectonic extension produces a simultaneous linear series of structural basins that are offset laterally and that transform faults tend to connect their edges [23,25-28] in agreement with the sea-going findings of [22]. It is of interest to note that under experimental tectonic extension, where the extension is normal to the rift axial plane, a single large and continuous ridge would develop without transform faults (Figure 2). Such structure seems similar to Reykjanes Ridge that extends from Iceland southwards for nearly 1000 km without being offset by transform faults, and probably reflect on their extensional tectonic regime without obliquity [23,1]. The junction of the accreting oceanic rift with the fracture zone juxtaposes fresh and hot basalt, of average density of 2.7 g/cm^3, with older and cooler basalt, having density of at least 2.9 g/cm^3 [29]. Analog experiments suggested that such density differences between the slabs is sufficient to generate spontaneous thrusting of the denser slab under the lighter one without external lateral compression [19,30]. It seems plausible that the occurrence of OCCs off slow spreading centers is linked to horizontal offset of about 100 km between two segments of accreting rifts, with crustal accretion rate of 3 cm/year. Under such setting fresh basalts would juxtaposed against basalts of age gap of some 3 Ma with the plausible significant density difference. The density difference of the juxtaposed slabs at faster spreading rates would probably be insufficient to trigger the spontaneous under thrusting of the denser slab.

Subduction at the MOR? Spontaneous subduction due to density contrasts

Subduction is defined as thrust faulting where one tectonic plate is thrust under another and sinks into the mantle [31]. It is commonly conceived that subduction would take place between denser oceanic and lighter continental brittle lithospheres. However, the juxtaposition of two slabs of oceanic crust of contrasting densities across a fracture zone, with no lateral thrust, was suggested to be the cause for the initiation of ocean-ocean subduction, [18,32-34] That concept was supported by analog experiments [19,30] and numeric computation [35]. The effect of ocean – ocean subduction is significant, and [36] estimated that such subduction fronts comprise some 40% of the length of all subduction zones on earth.

Figure 3: Garnet crystals embedded in schist indicate the co-occurrence of low-density hydrosilicates and high-density garnets. The diameter of the coin is 2.5 cm. (Sample from the Zucker Mineralogical Collection of the University of Haifa).

The subducted oceanic tectonic plates are affected by constraints of increasing pressure and temperature as they penetrate into the ductile lithosphere. Presuming pressure increase by approximately one Kbar (100 MPa) per 3 km of depth and temperature rise by less than 10^{0}C per km [37], then under such constraints the subducted slab would be under pressure of 15 Kbar and temperature of 450^{0}C at 45 km depth. The alteration of its mineralogy under these constraints of high pressure and low-medium geological temperature could change the density of the lithology of the slab considerably, depending on the availability of water and volatiles. Drier constraints would enhance alteration of augite and olivine into denser minerals, such as garnet, to produce eclogite, while wetter environments would enhance the alteration of the pyroxenes into lighter hydrosilicate minerals such as serpentines or chlorite [38]. Sampling shows that hydrosilicates and garnets could occur simultaneously in nature (Figure 3). While increasing quantities of the lighter constituents could ascend diapirically back to the surface as metamorphic core complexes [39], the eclogitization of the basaltic crust would increase its density beyond that of the upper mantle, and facilitate the sub ducted slab to sink into the asthenosphere.

The initiation of subduction anywhere on earth at present is very rare [40-42] but analytical, analog and numeric modelers simulated subduction-like features. These models commonly suggested that the structural processes acting at converging tectonic boundaries between continent and ocean are constrained mainly by two major parameters, lateral pressure and negative buoyancy. The tectonic lateral pressure drives the oceanic plate landwards, due to the remote crustal accretion at the divergent plate boundary. The inverse buoyancy of the edge of the oceanic lithosphere enables its under thrusting and sub ducting into the asthenosphere [43-45,31]. However, the lateral push required for the ocean-continent initiation of subduction is difficult to envision at ocean-ocean subduction sites, which probably occurred along fracture zones or transform faults, which trend parallel to the direction of the motion of the accreting oceanic crust [34]. Unlike the conventional ocean-continent depiction, some analytical and analog models suggested the likelihood that the underthrusting of older and denser oceanic lithosphere would take place due to contrasting densities of adjacent lithospheres, even without the lateral push or the negative buoyancy [30],. As the underthrust slab was affected by the rising temperature at about 10^{0}C/km, reaching 450^{o}C at approximate depth of 40-50 km, its pyroxenes would remineralize into garnets and its lithological density would increase (Figure 3).

High-speed centrifuge could deform miniaturized experimental models by increasing its gravity acceleration due to very fast rotation and without lateral push [46]. The centrifuge experiments showed that the juxtaposition of two lithospheric plates of contrasting densities would initiate under thrusting, provided that the density contrast between two juxtaposed lithospheric slabs were considerable and the friction between them were low [19,30]. Numeric models support these findings [47]. The centrifuge experiments showed further that considerable stretching was discerned at the frontal edge of the overthrust slab, which would eventually break apart to form a back-arc basin, and would lead to the rollback of the subduction front. The possibility that subduction-like structural processes would occur also at the domain of the midocean rift seems, prima facie, impossible. However, the occurrence of OCCs at numerous flanks of slow-spreading accreting rifts suggests that as the fresh and hot basalts of the rift, with density of ca, 2.7 g/cm^3, would be juxtaposed against colder basalts with density of ca, 2.9 g/cm^3, across the weakness zone of the fracture zone, spontaneous initiation of subduction seems plausible. Indeed, the observation of experimental subduction due to density contrast between juxtaposed crustal slabs suggested that such a process is not impossible and numeric experiments encountered similar results [47]. Unlike the ocean-continent subduction, where the thermal gradient is subdued [37] the ocean-rift subduction would reach alteration temperatures of ca. 450^{0}C at the low-pressure zone at depth of some 5 km. Intensive serpentinization would raise the temperature and expedite the alteration further because the serpentinization is exothermic. It is of interest to note that the short range subduction of the older oceanic crust under the fresh oceanic basalt along the weakness plane of the fracture zone of the OCC would not produce noticeable seismic activity unlike ocean – continent subduction because the serpentinite is pliable.

Diapirism and the geodynamic emplacement of Oceanic Core Complexes

Vendeville et al. (2000) [48] suggested that earth materials that are lighter and weaker than their surrounding lithology tend to forms diapiric structures, and even though ascending igneous intrusions are described in different terminology, the emplacement of salt, shale, granite, ophiolite or OCC has many characteristics in common. Where overpressured and possibly overheated, such lithologies tend to become highly mobile, they ascend and form diapiric features that pierce through their surrounding country rocks [49]. While subduction accounts for the transfer of lithological masses from the surface down into the earth mantle, volcanoes, ophiolites, OCCs and other diapirs transfer of buried lithologies upwards to the surface. Commonly, the process that emplaces the OCCs upwards into the junctions of slow-spreading ridges and fracture zones is associated with large-scale normal detachment faulting. However, the comprehension that some ophiolites (which obtained their name due to their abundant serpentine), such as the well-explored Troodos ophiolites, are considered to have ascended diapirically to form a supra-subduction zone domain [50]. The upwards emplacement of metamorphic core complexes led to the association of OCC with subduction followed by diapirism.

The experimental observation that spontaneous subduction would initiate by the juxtaposition of modeled slabs of different density across fracture zones in the centrifuge, raised the plausibility that subduction could also take place at ridge-fracture zone intersection, where the density contrast between fresh and old basalts exceeds 0.2 g/cm^3. Such subduction in nature, which would take place in the anomalously hot domain of the accretion ridge, could account for the unique petrology of OCCs. The presumed thermal gradient near the mid-ocean rift is 130^{0}C/km because the top of the asthenosphere reaches depth of circa 10 km. Such thermal gradient and the availability of water would enhance the development of series of petrologic remineralization reactions of high temperature and low pressure [51] (Figure 4). The presumed mineralogical alterations of the basaltic pyroxene and plagioclase to hydrous silicates like serpentine under such constraints would occur at depth of ca. 5 km. Critical accumulations of this altered light and pliable lithology would plausibly enhance diapiric ascent to take place along the numerous faults at Mid-Ocean rift – fracture zone intersections. Concurrently, in places where volatiles content were low, the sub ducting slab would undergo ultramafic remineralization and generation of peridotites would take place. The presumption of the shallow roots of the peridotite-serpentinite petrology of the OCCs is compatible with the observed rareness of garnets and other high-pressure minerals there [52].

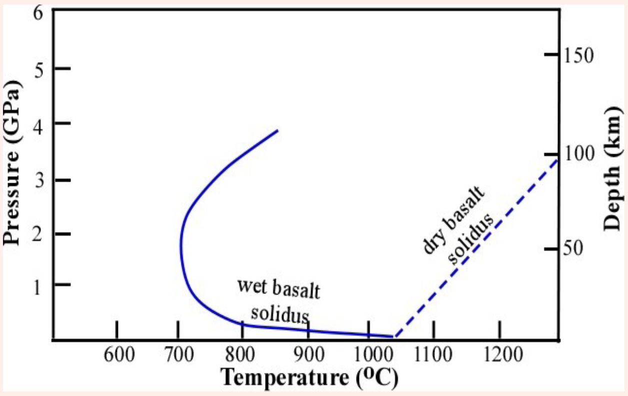

Figure 4: Solidus curves of dry and wet basalt under variable domains of pressure and temperature show the effect of hydration on the partial melting of basalts. After Kessel et al. (2005).

The conventional explanation to the emplacement of OCCs is that the lower parts of the oceanic lithosphere is exhumed at the intersection of slow-spreading ridges and transform faults due to very large offset along a low angle normal detachment fault, where the footwall is exposed at the flank of the accreting rift (Figure 1). According to that concept, the mantle peridotites were serpentinized during their long journey from the mantle to the seafloor. Friction during that journey would also produce a thick series of rubble and breccia, encountered at the top of many OCCs, which served as evidence to that type of detachment faulting [8]. However, such a long journey from the upper mantle should have led also to the occurrence of high-pressure minerals in the lithology of the OCCs, but eclogites are conspicuously absent there. Accretion rifts are underlain by elongated domes of upper asthenosphere matter that feed magma chambers under the MOR, which, in turn, supply the volcanic eruptions along the central rift. The build-up of the OCC is not a part of the evolution of these Ridges, but an appendix, added mostly where the spreading rate is slow. Therefore, where two crustal slabs were juxtaposed across a fracture zone and the older slab was dense enough to be under thrust at the edge of the accreting rift, then that under thrust slab would be affected by the steep subsurface temperature gradient. The prevailing high temperature due to the proximity to the magma chambers and the top of the asthenosphere, and the variations in the availability of seawater, would enhance the alteration of the pyroxenes and the plagioclases in the sub ducting slab. In sites where the density contrast between the adjacent slabs would be insufficient to initiates the under thrusting, the OCC would not develop. The subduction of the basaltic crust would alter its pyroxenes and plagioclases, either into ultramafic mineral assemblages or concurrently, into serpentine other hydrosilicates, depending on the rising temperatures and the availability of volatiles. The expected temperature in which such alteration takes place is ca. 500^{0}C, and it seems plausible that once formed, the light

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serpentine (ca. 2.5 g/cm^3) would generate diapirs that will ascend to the seafloor, carrying along occasional blocks of peridotites. Such features of serpentinite and peridotite were commonly discernible in the drilled cores obtained by several scientific ocean drilling campaigns at OCCs. However, if the density contrasts between the juxtaposed slabs would be too small or the friction between the slabs too high, then the evolution of the OCC would not take place. Once thrusting starts at the rift-fracture zone junction, the alteration of the mafic rocks into either ultramafics or hydrosilicates would start at the shallow depth of 4-5 km. However, as the overriding segment of the young lithosphere would be driven away laterally from the ridge-fracture zone intersection due to continued crustal accretion at the ridge, the densities contrasts between the older and the younger lithospheric slabs across the fracture zone would probably diminish, and the subduction processes would terminate. The OCCs are short-lived and their sites are well constrained. Considering the possible high content of volatiles in the shallow depth of the underthrust denser slab, the alteration of basalt and gabbro into large quantities of serpentinite seems plausible, as indeed the drilled cores of repeated deep sea drilling campaigns in various OCC show. Therefore, the occurrence of light serpentinites under the denser basalts and gabbros of the oceanic brittle lithosphere is likely to produce metastabilities, which would generate serpentinite diapirism. Such diapirs could ascend to the seafloor along pre-existing faults, carrying along blocks of ultra-mafic rocks. As the serpentinite diapirs force their way upwards, rubble and breccia are likely to accumulate at their crests due to friction associated with their emplacement.

Correlation with salt diapirs would suggest that the serpentinite diapirs would also have a relatively flat top and steep walls [53,54]. Observations of such features in the OCCs were linked to fault surfaces [55]. Therefore, the breccia discerned repeatedly at the crests of numerous OCCs, which was attributed to friction products generated during the long journey of these rock-suites from the upper mantle along those low-angle normal detachment faults [8], could alternately be linked to the short-range serpentinite diapirs. The presented concept of the evolution of OCCs presumes two stages for the evolution of these features. The first is the under thrusting of relatively dense slab of oceanic lithosphere from across the fracture zone under the fresh basalt at the flank of a slow-spreading Mid-Ocean Ridge, where sufficient density contrast between the two slabs, and low friction along the steeply plunging plane, occur. Considering the exceptional thermal gradient under the Mid-Ocean Ridge province, the high temperature and the shallow depth of the asthenosphere, the under thrust slab would undergo high temperature and low-pressure alteration and remineralization at depth of ca 5 km in two probable paths. The water-rich parts of the down-going slab would undergo serpentinization, and the remineralization of the drier parts would become peridotitic. The second stage in the core complex development is its diapiric ascent of the serpentinite, bearing peridotite suites upwards into the ridge flank (Figure 5). There is ground to presume that predominantly peridotite lithospheric slabs would plunge into the mantle and recirculate.

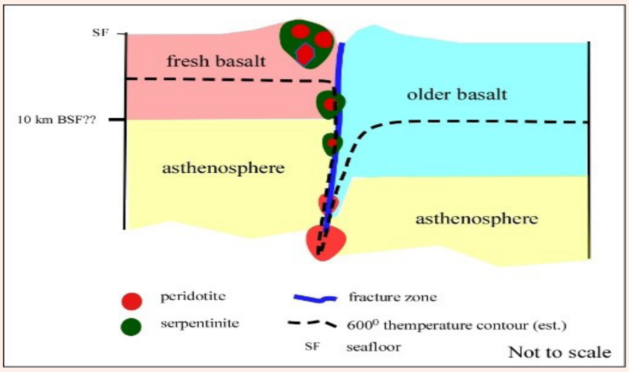

Figure 5: Conceptual schematic cartoon of the structural setting of OCC's, where relatively older lithospheric slab of basalt and gabbro is being thrust under the lighter fresh basalts of the MOR along a fracture zone. Metamorphic alteration of the subducted slab would generate serpentinites and peridotites, and diapirs of serpentinites would ascend to the seafloor, carrying along blocks of ultramafic rocks. Dashed black line marks to possible 600^{0}C isotherm, BSF-below sea floor. Dimensions not to scale.

Discussion

As mentioned before, the origin of oceanic core complexes is commonly attributed to peridotite lithologies from the deep crust-upper mantle domain, which were carried into several slowspreading ridge-fracture zone intersections as the footwall of low-angle normal detachment faults of very large throw (e.g. Parnell-Turner et al., 2017 and references therein). These low-angle faults supposedly uplifted the peridotite of their footwall from the distal upper mantle and embed it in the seafloor on one flank of the median rift, (Figure 1) while the conjugate hanging wall flank remained built of regular oceanic crust of basalt and gabbro [56]. However, computation of the structural restoration of the offsets of these detachment faults is difficult, because the presumed offsets substantially exceeds the thickness of the oceanic crust, therefore the validity of the detachment fault model is equivocal [57]. Investigations of the OCCs included several series of scientific boreholes [58] of IODP leg 304-305 that drilled Atlantis OCC, presented a concept that the occurrence of the OCCs at the intersections of slow divergent tectonic rifts and transform faults was derived from very large offset caused by detachment faults [58] ruled out the possibility that the proximity of the upper mantle under the accreting ridge could be the source of the serpentines of the OCC. Indeed, evidence for intensely shattered series of rocks at the top of many OCCs was explained as the product of intensive frictional erosion at the crests of the footwall blocks during their emplacement. Numerous researchers [59,60] used these observations, as well as analog experiments and numeric models, to develop explanations regarding the activity of the oceanic detachment faults. They founded their arguments on the presumption of low magma supply at the edges of segments of the accretion rift, a shortage that generated large and unique listric faults that were generated by upwards magma injection from the upper mantle. The exploration of another OCC was carried out near the intersection of the Mid-Atlantic Ridge (MAR) and Kane fracture zone, which extends from the Kane transform fault. The transform fault is associated with 160 km offset of the Ridge, but the western branch of the fracture zone extends for some 3000 km farther westwards, and its edge was dated to 80 Ma [61]. Studies of the Kane Megamullion (OCC) on the MAR and lat. 24^{0}N show that the OCC forms an elevated terrain on one flank of the rift, which faces the basalt-gabbro oceanic crust on the other flank to the east [62]. In that site of slow spreading accreting ridge, the explorers of ODP legs 158 and 209 argued for large detachment fault that was active from 3.3 to 2.1 Ma. That suggested detachment fault exhumed variable deep crustal and upper mantle lithologies that include peridotite, basalt, and gabbro, as well as diabase, greenschist and serpentinite [52,62,63] interpreted the ultramafic exhumation of that OCC as the product of local instability in the mantle, feeding into the accretion ridge where a fixed weakness zone focused episodes of repeated melt intrusions. Comparative multidisciplinary studies of the Atlantis Massif (OCC) at the MAR at 30^{o}N and the Fifteen Twenty Massif (OCC), located at that latitude, emphasized the occurrence of thick series breccia that were altered hydrothermally into talc-tremolite-chlorite schist on top of both OCCs. The evidence of temperatures of 600^{o}C, which prevailed during the hydrothermal alteration, was clear in these two massifs.

It was suggested that that temperature was probably caused by hydrothermal circulation along the permeable detachment fault plane [8]. Alternately, these somewhat high temperatures could be associated with heating due to the exothermic effect of serpentinization, added on top of the steep regional thermal gradient. The findings that the cooccurrence of peridotite, the representative lithology of the upper mantle, and serpentinite, its hydrated derivative were not discussed by [8]. There is ground to evaluate the probability that the peridotite-serpentinite co-occurrence could probably be the result of the presence of water at depths along the weakness plane of the fracture zone, where the prevailing temperature is circa 500o. The hot hydrothermal water would lower the solidus of both basalt and peridotite and enabled the serpentinization [51]. Consequently differences in the interpretations of the lithological observations and their tectonic significance regarding the various OCCs and other cooccurrences of peridotites and serpentinites [56,64] to suggest that the size, the structural style, and the lithology of the OCCs were determined by their rheological constraints. They suggested that distinct OCCs would develop from variations in the composite system of pressure, temperature, fluid content and time of mantle exhumation under the junctions of slow-spreading rifts and fracture zones [22], carried out multidisciplinary investigations of the OCC at the intersection of the Mid-Atlantic Rift and the fracture zone at 22o19'N, applying oblique seismic reflection and seismic refraction surveys, as well as gravity measurements and seafloor sampling. They confirmed previous observations that the mid-ocean ridge is not symmetric in sites where the OCC outcrops. They noticed further that while the flank built of normal oceanic crust merges gradually with the adjacent lithology, the transition of the core complex into the adjacent lithology is abrupt remarked that the depth to the Moho under the core complex is some 40% shallower than its depth under the adjacent normal oceanic crust on the conjugate margin of that mid-ocean rift. They too attributed the contrast in Moho depth across the MAR under the core complex province to the displacement of tens of kilometers along that large, but presumed, detachment fault and its massive supply of upper mantle material (Figure 1). They noticed temporal changes in lithospheric thicknesses and focused mantle upwelling, and suggested the development oflarge magmatic segments in the OCC's. the suggest further that the migration of of melt supply could stop the OCC formation. Evidence for structural intrusion of peridotite and serpentinite from the asthenosphere through the lithosphere into the intersection of the MAR and the fracture zone at 16°N, and the subsequent tectonic uplift of that site, was reported by [65]. They suggested that the extensional tectonic regime along the axial zone of the Ridge led to the emplacement of the peridotite-serpentinite body and its exhumation at the seafloor. Subsequent investigation [66] of the OCCs at latitudes 22° - 24°N of the MAR, showed correlation between positive free-air gravity anomalies and the occurrence of ultramafic lithologies, which led the investigators to presume that tectonic uplift introduced the ultramafic rocks into the junction of the Ridge with the transform valley [67] remarked that such uplift was not uniform along the transform valleys, because evidence for partial melting was less pronounced along the Kane transform fault than along transform faults of lesser offset in that domain of the slow-spreading Mid-Atlantic Ridge. The presumption is based on [9] observation that records of large earthquakes of low-angle normal faults are extremely rare. The asymmetric lithology of the MAR in sites where OCCs were encountered was estimated to encompass very large tracts in the central Ridge, where the abundant basaltic-gabbroidic brittle lithosphere on one flank would face a wall of serpentinite and other metamorphic lithologies at the conjugate flank [68,7] who described that distribution, attributed it to the tectonic contribution of active and extinct low-angle normal detachment faults to the evolution of OCCs. The hydrous geochemistry of mafic and ultramafic lithologies seems to play a critical role in the petrological evolution of OCCs [51] showed that presence of H_2O would lead to a significant drop in liquidus temperature of basalt and peridotite (Figure 4) [69] indicated further that hydrous peridotites in central Japan lithified at 650-750°C under pressure of circa 1.5 GPa (depth of ~45 km), together with serpentine, antigorite, and other hydrous silicate sampled serpentinized peridotites in the northern edge of a segment of the SW Indian Ridge, and they commented that the serpentinization there seemed amagmatic [70-72].

They concluded that the serpentinization there occurred due to seawater lithologic content of >10% [70], who reported on the significant buoyancy of serpentinites, presumed that the serpentinites could contribute to peridotite exhumation at the seafloor, and thus supported [4] concept of diapiric geodynamics of these hydrous silicates. A significant weakness of the interpretations of the generation of the OCCs due to detachment faulting is the absence of high-pressure lithologies, such as eclogites, in the lithological suites of OCCs. This absence casts doubt on the presumption that the origin of the ultramafic lithologies in OCCs is from the top of the mantle. Indeed doubts that low-angle normal faults really exist, because the seismic evidence for low-angle normal offsets is extremely rare cast a critical doubt on the occurrence of such large faults and therefore on their possible tectonic contribution. Consequently, it is suggested that the emplacement of the unique peridotite-serpentinite lithology of many OCCs was caused by serpentinite diapirs. Such diapirs were initiated due to spontaneous subduction of denser oceanic crust under fresh and lighter crust across the transform fault-fracture zone transition. Serpentinites and other hydrosilicates would be generated at the low pressure-high temperature domains of the intersections between the fracture zones and the accretion rifts at estimated depth of 4-5 km. Weakness zones in the overriding slab, due to the transform faulting would enhance the ascent of the serpentinite diapirs into the overlying oceanic basalts at the flank of the rift [73-76].

Conclusions

The geographic distribution of many OCCs at the intersection of slow Mid-Ocean Ridges and fracture zones suggests that these junctions carry critical structural parameters that enhance the intrusions of peridotite-serpentinite lithology into a flank of the accreting rift. It seems that the OCCs started due to the juxtaposition of the hot and light basalt of the accretion ridge against older and denser oceanic crust across the fracture zone, depending of sufficient density contrast between the slabs. Anomalously steep heat gradient at the edge of the active spreading rift and their volatiles content could have caused the underthrust slab to reach temperatures of remineralization at depth of 4-5 km. The exothermic serpentinization is likely to raise the temperature of the environment of the subducting slab further to approach the solidus of wet gabbro, which would relithify as peridotite, which, accounts for the co-occurrence of the serpentinites and the peridotites. The low density of the serpentinite could ascend back to the rift flank diapirically, while the abundant shattered rock at the top of many OCCs could serve as evidence for a diapiric ascent into the ridge-fracture zone external intersection.

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References

1. Ewing J, Ewing M (1959) Seismic refraction measurements in the Atlantic Ocean basins, in the Mediterranean Sea, on the Mid-Atlantic Ridge, and in the Norwegian Sea. Geological Society of America Bulletin 70(3): 291-318.
2. Hess HH (1955) Serpentinites, orogeny and epeirogeny. Geological Society of America Special Paper 62: 391-408.
3. Bonatti E (1968) Ultramafic rocks from the Mid-Atlantic Ridge. Nature 219: 363-364.
4. Francheteau J, Choukroune P, Hekinian R, Le Pichon X, Needham HD (1976) Oceanic fracture zones do not provide deep sections in the crust. Canadian Journal of Earth Sciences 13(9): 1223-1235.
5. Cann JR, Blackman DK, Smith DK, McAllister E, Janssen B, et al. (1997) Corrugated slip surfaces formed at ridge-transform intersections on the Mid-Atlantic Ridge. Nature 385(6614): 329-332.
6. Tucholke BE, Jian L, Kleinrock MC (1998) Megamullions and mullion structure defining oceanic metamorphic core complexes on the Mid-Atlantic Ridge. Journal of Geophysical Research Solid Earth 103(B5): 9857-9866.
7. Smith DK, Escartin J, Schouten H, Cann JR (2008) Fault rotation and core complex formation: Significant processes in seafloor formation at slow-spreading mid-ocean ridges (Mid-Atlantic Ridge, 13-15°N). Geochemistry Geophysics Geosystems 9(3): Q03003.
8. McCaig AM, Delacour A, Fallick AE, Castelain T, Frueh Green G (2010) Detachment fault control on hydrothermal circulation systems: Interpreting the subsurface beneath the TAT hydrothermal field using the Isotopic and geological evolution of oceanic core complexes in the Atlantic. (In:) Rona PA, Devey, CW, Dyment J, Murton BJ (Eds.), Diversity of Hydrothermal Systems on Slow Spreading Ocean Ridges. American Geophysical Union, Geophysical Monograph 188: 207-239.
9. Scholz CH (2002) The Mechanics of Earthquakes and Faulting. Cambridge University Press, Cambridge, (2nd Edn.), Ppp. 485.
10. Blackman DK, Canales P, Harding A (2009) Geophysical signatures of oceanic core complexes. Geophysical Journal International 178(2): 593-613.
11. Dick HJB, Bullen T (1984) Chromian spinel as a petrogenetic indicator in abyssal and alpine-type peridotites and spatially associated lavas. Contributions to Mineralogy and Petrology 86: 54-76.
12. Dick HJB (1989) Abyssal peridotites, very slow spreading ridges and ocean ridge magmatism. Geological Society of London, Special Publications 42: 71-105.
13. Ohara Y, Yoshida T, Kato Y, Kasuga S (2001) Giant Megamullion in the Parece Vela Backarc Basin. Marine Geophysical Researches 22: 47-61.
14. Cannat M, Bideau D, Hebert, R (1990) Plastic deformation and magmatic impregnation in serpentinized ultramafic rocks from the Garrett transform fault (East Pacific Rise). Earth and Planetary Science Letters 101: 216-232.
15. Constantin M, Hekinian R, Ackermand D, Stoffers P (1995) Mafic and Ultramafic Intrusions into Upper Mantle Peridotites from Fast Spreading Centers of the Easter Microplate (South East Pacific. (In:) Vissers, RLM, Nicolas A (Edt.), Mantle and Lower Crust Exposed in Oceanic Ridges and in Ophiolites, Springer, Netherlands, Pp. 71-120.
16. Hekinian R, Bideau D, Hebert R, Niu Y (1995) Magmatism in the Garrett transform fault (East Pacific Rise near 13°27'S. Journal of Geophysical Research 100(B7): 163-185.
17. Wernicke B (1985) Uniform-sense normal simple shear of the continental lithosphere. Canadian Journal of Earth Sciences 22(1): 108-125.
18. Casey JF, Dewey JF (1984) Initiation of subduction zones along transform and accreting plate boundaries, triple-junction evolution, and forearc spreading centres-implications for ophiolitic geology and obduction. Geological Society of London, Special Publications 13: 269-290.
19. Mart Y, Aharonov E, Mulugeta G, Ryan W, Tentler T, et al. (2005) Analogue modelling of the initiation of subduction. Geophyscal Journal International 160(3): 1081-1091.

20. Nikolaeva K, Gerya TV, Marques FO (2010) Subduction initiation at passive margins: Numerical modeling. Journal of Geophysical Research 115: B03406.
21. Wilson JT (1965) A new class of faults and their bearing on continental drift. Nature 207: 343-347.
22. Dannowski A, Grevenmeyer I, Ranero CR, Ceuleneer G, Maia M, et al. (2010) Seismic structure of an OCC at the Mid-Atlantic Ridge, 22°19’N. Journal of Geophysical Research 115(B7): B07106.
23. Mart Y, Dauteuil O (2000) Analogue experiments of propagation of oblique rifts. Tectonophysics 316(1-2): 121-132.
24. Gerya TV (2016) Origin, evolution, seismicity, and models of oceanic and continental transform boundaries, in Duarte JC, Schellart, WP. (Eds.), Plate Boundaries and Natural Hazards, Hoboken, N.J., AGU Geophysical Monographs Series 219: 39-76.
25. Mortimer E, Paton DA, Scholz CA, Strecker MR, Blisniuk P (2007) Orthogonal to oblique rifting, effect of rift basin orientation in the evolution of the North basin, Malawi Rift. East Africa, Basin Research 19(3): 393-407.
26. Agostini A, Corti G, Zeoli A, Mulugeta G (2009) Evolution, pattern, and partitioning of deformation during oblique continental rifting: Inferences from lithospheric-scale centrifuge models. Geochemistry Geophysics, Geosystems 10(11): Q11015.
27. Taylor B, Goodliffe A, Martinez F (2009) Initiation of transform faults at rifted continental margins. Comptes Rendus Geoscience 341: 428-438.
28. Brune S, Williams S, Mueller D (2018) Oblique rifting: the rule, not the exception. Solid Earth 9: 1187-1206.
29. Turcotte DL, Schubert G (2002) Geodynamics. (2nd Edn.), Cambridge University Press, USA Ppp. 456.
30. Goren L, Aharonov E, Mulugeta G, Koyi HA, Mart Y (2008) Ductile deformation of passive margins: A new mechanism for subduction initiation. Journal of Geophysical Research Solid Earth 11(B8): B08411.
31. Stern RJ, Gerya T (2018) Subduction initiation in nature and models: A review Tectonophysics 746: 173-198.
32. Dewey JF, Casey JF (2011) The origin of obducted large-slab ophiolite complexes. In: Brown, D., Ryan, P.D. (Editors), Arc-Continent Collision. Springer, Berlin, Ppp. 434-444.
33. Maffione M, Thieulot C, Van Hinsbergen DJJ, Morris A, Pluemper O, et al. (2015) Dynamics of intra-oceanic subduction initiation, part 1: Oceanic detachment fault inversion and the formation of forearc ophiolites. Geochemistry, Geophysics, Geosystems 16(6): 1753-1770.
34. Boutelier D, Beckett D (2018) Initiation of subduction along oceanic transform faults: insights from three-dimensional analog modeling experiments. Frontiers in Earth Science
35. Gerya TV (2011) Intra-oceanic subduction zones, in Brown D., Ryan, P.D. (editors). Arc-Continent Collision, Springer-Verlag, Berlin P. 23-53.
36. Stern RJ (2002) Subduction zones. Reviews of Geophysics 40(4): 3-338.
37. Wilson M (1989) Igneous Petrology. Unwin Hyman, London, Ppp. 466.
38. Hawkins JW (2003) Geology of supra-subduction zones - implications for the origin of ophiolites. (In:) Dilek Y, Newcomb S, (Eds.), Ophiolite Concept and the Evolution of Geological Thought. Geological Society of America, Special Paper 373: 227-268.
39. Tamaki K, Honza E (1985) Incipient subduction and deduction along the eastern margin 606 of the Japan Sea. Tectonophysics 119(1-4): 381-406.
40. Taira A (2001) Tectonic evolution of the Japanese island arc system. Annual Review of Earth and Planetary Sciences 29(1): 109-34.
41. Stern RJ (2004) Subduction initiation: spontaneous and induced. Earth and Planetary Science Letters 226(-4): 275-292.
42. Shemenda AI (1993) Subduction of the lithosphere and back arc dynamics: Insights from physical modeling. Journal of Geophysical Research, Solid Earth 98: 16167-16185.
43. Mulugeta G (1988) Squeeze box in a centrifuge. Tectonophysics 148: 323-335.
44. Chemenda AI, Mattauer M, Malavieille J, Bokun AN (1995) A mechanism for syn-collisional rock exhumation and associated normal faulting: Results from physical modelling. Earth and Planetary Science Letters 132: 225-232.
45. Ramberg H (1981) Gravity, Deformation and the Earth’s Crust, 2nd ed, Academic Press, London Ppp. 274.
46. Vendeville BC, Mart Y, Vigneresse JL (2000) Preface. (In:) Vendeville BC, Mart Y, Vigneresse JL Salt, Shale and Igneous Diapirs in and Around Europe. Geological Society Special Publication 174, London.
47. Kopf A, Behrmann JH (2000) Extrusion dynamics of mud volcanoes on the Mediterranean Ridge accretionary complex. (In:) Vendeville BC, Mart Y, Vigneresse JL: Salt, Shale and Igneous Diapirs in and Around Europe. Geological Society Special Publication 174, London: 169-204
48. Robertson AHF (1998) Tectonic significance of the Eratosthenes Seamount: a continental fragment in the process of collision with a subduction zone in the eastern Mediterranean (Ocean Drilling Program Leg 160). Tectonophysics 298(1-3): 63-82.
49. Kessel R, Ulmer O, Pettke T, Schmidt MW, Thompson AB (2005) The water–basalt system at 4 to 6 GPa: Phase relations and second critical endpoint in a K-free eclogite at 700 to 1400°C. Earth Planetary Science Letters 237: 837-892.
50. Kelemen PB, Kikawa E, Miller DJ (2007) 1. Leg 209 Summary: Processes in a 20-km-Thick Conductive Boundary Layer beneath the Mid-Atlantic Ridge, 140-160N. Scientific Results, Ocean Drilling Program, College Station, TX, 209, 133p.
51. Koyi H (1998) The shaping of salt diapirs. Journal of Structural Geology 20(4): 321-338.
52. Vendeville BC (2002) A new interpretation of Trusheim’s classic model of salt-diapir growth: Gulf Coast Association of Geological Societies Transactions 52: 943-952.
53. Blackman DK, Cann JR, Janssen B, Smith DK (1998) Origin of extensional core complexes: Evidence from the Mid-Atlantic Ridge at Atlantis Fracture Zone. Journal of Geophysical Research: Solid Earth 103(B9): 21315-21333.
54. Whitney DL, Teyssier C, Rey P, Buck WR (2013) Continental and oceanic core complexes. Geological Society of America Bulletin 125(3-4): 273-298.
55. John BE, Cheadle MJ (2013) Deformation and Alteration Associated With Oceanic And Continental Detachment Fault Systems: Are They Similar?, (In:) Rona PA, Devey CW, Dyment J, Murton BJ, (Eds.), Diversity Of Hydrothermal Systems On Slow Spreading Ocean Ridges, Volume 188, American Geophysical Union, Pp. 175-205.
56. Andreani M, Mevel C, Boullier AM, Escartin J (2007) Dynamic control on serpentine crystallization in veins: Constraints on hydration processes in oceanic peridotites. Geochemistry Geophysics Geosystems 8(2): Q02012.
57. Escartin J, Smith DK, Cann J, Schouten H, Langmuir CH, et al. (2008) Central role of detachment faults in accretion of slow-spreading oceanic lithosphere. Nature 455(7214): 790794.
58. MacLeod CJ, Searle RC, Murton BJ, Casey JF, Mallows C, et al. (2009) Life cycle of oceanic core complexes. Earth and Planetary Science Letters 287(3-4): 333-344.
59. Purdy GM, Rabinowitz PD, Velterop JJA (1979) The Kane fracture zone in the Central Atlantic Ocean. Earth and Planetary Science Letters 45 (2): 429-434.
60. Dick HJB, Tivey MA, Tucholke BE, (2008) Plutonic foundation of a slow-spreading ridge segment: OCC at Kane Megamullion, 23°30’N, 45°40’W. Geochemistry, Geophysics, Geosystems 9(5): Q05014.
61. Knott R, Fouquet Y, Honorez J, Peterson S, Bohn M (1998) 1. Petrology of hydrothermal mineralization: a vertical section through the TAG mound, (In:) Herzig PM, Humphris SE, Miller DJ, Zierenberg RA, (Eds.), Proceedings of the Ocean Drilling Program, Scientific Results, vol. 158. Texas A&M University, College Station, TX, Pp. 5-26.
62. Sibuet JC, Tucholke BE (2013) The geodynamic province of transitional lithosphere adjacent to magma-poor continental margins. Geological Society of London, Special Publications 369(1), 429-452.
63. Cannat M, Bideau D, Bougault H (1992) Serpentinized peridotites and gabbros in the Mid-Atlantic Ridge axial valley at 15°37”N and 16°52”N. Earth and Planetary Letters 109: 87-106.
64. Cannat M, Mevel C, Maia M, Deplus C, Durand C, et al. (1995) Thin crust, ultramafic exposures, and rugged faulting patterns at the Mid-Atlantic Ridge (22°-24°N). Geology 23: 49-52.
65. Ghose I, Cannat M, Seyler M (1996) Transform fault effect on mantle melting in the MARK area (Mid-Atlantic Ridge south of the Kane transform). Geology 24(12): 1139-1142.

66. Smith DK, Cann JR, Escartin J (2006) Widespread active detachment faulting and core complex formation near 13oN on the Mid-Atlantic Ridge. Nature 442(7101): 440-443.
67. Khedr MZ, Arai S, Python M, Tamura A (2014) Chemical variations of abyssal peridotites in the central Oman ophiolite: Evidence of oceanic mantle heterogeneity. Gondwana Research 25(3): 1242-1262.
68. Guillot SP, Schwartz SP, Reynard B, Agard P, Prigent Cc (2015) Tectonic significance of serpentinites. Tectonophysics 646: 1-19.
69. Gerya TV, Stern RJ, Baes M, Sobolev S, V Whattam SA (2015) Plate tectonics on the Earth triggered by plume-induced subduction initiation. Nature 527(7577): 221-225.
70. Grevemeyer I, Rüpke LH, Morgan JP, Iyer K, Devey CW (2021) Extensional tectonics and two-stage crustal accretion at oceanic transform faults. Nature 591(7850): 402-407.
71. Humphris SE, Miller DJ, Zierenberg RA (Edt.), Proceedings of the Ocean Drilling Program, Scientific Results leg 158, Ocean Drilling Program, Texas A & M University, College Station, TX 158: 5-26.
72. Mart Y (2020) The structural evolution of oceanic core complexes: A concept based on analog modeling. Geodynamics and Tectonophysics 11(1): 1-15.
73. Moll M, Paulick H, Suhr G, Bach W (2007) Data report: microprobe analyses of primary phases (olivine, pyroxene, and spinel) and alteration products (serpentine, iowaite, talc, magnetite, and sulfides) in Holes 1268A, 1272A, and 1274A. (In:) Kelemen PB, Kikawa E, Miller DJ (Eds.), Proc ODP, Sci. Results, 209: College Station, TX (Ocean Drilling Program) 1-13.
74. Parnell Turner R, Sohn RA, Peirce C, Reston TJ, MacLeod CJ, et al. (2017) Oceanic detachment faults generate compression in extension. Geology 45(10): 923-926.
75. Roumèjon S, Cannat M, Agrinier P, Godard M, Andreani M (2015) Serpentinization and Fluid Pathways in Tectonically Exhumed Peridotites from the Southwest Indian Ridge (6265°E). Journal of Petrology 56: 703-734.
76. Vigneresse JL, Clemens JD (2000) Granite magna ascent and emplacement: neither diapirism not neutral buoyancy. (In:) Vendeville BC, Mart Y, Vigneresse JL Salt, Shale and Igneous Diapirs in and Around Europe. Geological Society Special Publication 174, London: 1-20.