Working group proposal on Oceanic Transform Faults

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Scientific objectives

Transform faults, especially large-offset ones, have been thoroughly investigated by different teams around the world (e.g., Bonatti et al., 1979; Bonatti, 1978; Karson and Dick, 1983; Sinha and Louden, 1983; Detrick et al., 1982; Cormier et al., 1984; ten Brink and Brocher, 1988; Tucholke and Schouten, 1988; Detrick et al., 1993; Wolfe et al., 1993; Bonatti et al., 1994; Mueller et al., 2000; Bonatti et al., 2005). From their work, we derived the vision of transform faults as complex plate boundaries that could deform under the influence of far field stresses, especially changes in plate motion (e.g. Bonatti et al., 1994; Gasperini et al., 2001). However, not all transforms react equally to equivalent stress changes, suggesting the influence of parameters such as offset length, spreading rates and mantle temperature and heterogeneities (e.g. Fornari et al., 1989; Michael et al., 1994; Pockalny et al., 1997; Bonatti et al., 2003; Maia et al., 2016). Furthermore, together with numerical models, observational studies also reveal the role of transform faults in shaping the geometry of mantle flow and active processes at mid-oceanic ridge axes (e.g. Bonatti et al., 2001 & 2003; Ligi et al, 2008; Cipriani et al., 2009; Gregg et al., 2009). Many of the above processes are most evident at the extreme limits of spreading rate and transform offset size. For example, at slow and ultra-slow spreading ridges, the notion of mega transforms was applied to the large-offset Romanche and Andrew Bain transforms to explain their particularly complex morphologies, which reflect complex evolution of the transform domain through time. In contrast to most oceanic transform boundaries that consist of a single narrow strike-slip zone offsetting two mid-ocean ridge segments, the slowly slipping Romanche and Andrew Bain transforms are characterized by a broad and complex multifault zone of deformation similar to some continental strike-slip systems (Ligi et al., 2002; Sclater et al., 2005). Such faulting system may act as pathways for seawater and allow for extensive fluid-rock interactions. Oceanic transform faults and fracture zones have long been hypothesized to be sites of enhanced fluid flow and biogeochemical exchange (Boschi et al., 2013; Detrick et al., 1993; Francis, 1981; Gregg et al., 2007; Roland et al., 2010). In this context, the serpentine forming interaction between seawater and cold lithospheric mantle rocks is particularly interesting. The transformation of peridotite to serpentinite not only leads to hydration of oceanic plates and is thereby an important agent of the geological water cycle (Rupke et al., 2004), it is also a mechanism of abiotic hydrogen and methane formation (McCollom and Bach, 2009; Seyfried Jr et al., 2007), which in the present seafloor support archeal and bacterial communities (Kelley et al., 2005; Perner et al., 2007; Shock and Holland, 2004). Inferring the likely amount of mantle undergoing serpentinization reactions therefore allows estimating the amount of biomass that may be autotrophically produced at and around oceanic transform faults and mid-ocean ridges (Cannat et al., 2010). Although the above studies have advanced our understanding of the enormous complexity of these major plate boundaries and their role on fundamental processes building the oceanic lithosphere, such as fluid circulation, mantle exhumation and mantle flow, several questions remain to be addressed because they require a joint effort of different communities such as geochemists, petrologists, geophysicists, microbiologists, fluid and numerical modeling specialists. This working group, would like to focus on five questions that are likely of large interest to the Earth sciences community:

- How do large and mega- transform domains react to both far- and near-field stress changes?
- How do transforms interact with the underlying mantle. What are the effects of temperature, rheology and composition?
- What is the interplay between transform dynamics and magmatism?
- Which relationship exist between oceanic transform faults and their counterparts on continental margins?
- Are oceanic transform faults sites of intense fluid-rock interaction and biogeochemical exchange?

The first question concerns the way large transforms and mega-transform domains react to both far- and near-field stress changes. It has been acknowledged that changes in plate motions, even minor, can induce stress changes at transforms yielding either extension or compression inside the transform domain. Yet, the questions of how the length of the offset and the amplitude of the stress changes control the transform response are still poorly understood. Along mega-transforms, relative motion involves the deformation of extraordinarily thick and cold lithosphere. Ligi et al. (2002) propose that the extreme thickness of the lithosphere, hence its rheology, must be a factor in determining the unusual width and complex geometry of mega-transforms. They find that long-offset (> 30 Ma) faults produce two major symmetrical faults joining the two ridge segments, with a lens-shaped area between, as observed around the Romanche and Andrew Bain transforms. Sclater et al. (2005) also supported the basic concept that the yield stresses associated with varying plate thicknesses around mega-transform faults control the type of deformation. However, they suggest that it is not just the vertical stresses that are important. They argue that whether or not the transform is in "transtension" or "transpression" has bearing on the stress field and that horizontal, as well as vertical stresses, need to be considered in the yield stress calculations. Moreover, changes to transform fault evolution due to the contribution of perturbations to the local stress field, such as by ridge propagation, is a point that is still poorly understood. An additional, but related question is that of fluid circulation in the transforms and fracture zones (e.g., Kolandaivelu et al., 2017), as even the "inactive" portions of these faults represent pathways for fluid penetration into the mantle. This raises the question of the depth of serpentinization at transforms and its relation to active processes at work there (e.g., Morrow et al., 2016). Today, we still lack data revealing the deep structure and physical properties of transform faults and fracture zones. For example, how deep, wide, heterogeneous and weak is the area affected by the transform/fracture zone? The response of these features when submitted to tectonic stresses provides crucial insights into their physical architecture. Such response can be found either on accessible oceanic plates by examining deformation characteristics under given stresses (transpressive ridges, aborted or incipient subduction), or on subducting oceanic plates (behavior and fate of subducting transforms and fracture zones). Typically, numerical modeling can test various scenarii and confront them to field observations (e.g., Gurnis et al., 2004; Gerya et al., 2008; Abecassis et al., 2016). There is a vigorous debate regarding the role of transform faults and fracture zones in the seismogenic behavior along subduction zones. Some authors (e.g., Müller and Landgrebe, 2012) argue that these features favor large earthquakes, whereas others (e.g., Schlaphorst et al., 2016) consider that oceanic fracture zones lubricate the seismogenic interface and thus reduce seismicity or arrest large ruptures.

The second question is how transforms interact with the underlying mantle. How do mantle temperature, rheology and composition, influence the transform fault? The thermal structure of a transform fault is likely to be a strong function of mantle rheology, which may in turn be influenced by composition, retained melt, and the age offset across a transform (e.g., Behn et al., 2007; Roland et al., 2010). Additionally, there is evidence of "disappearing" transforms near hot spot influenced ridges (for example, the Pico transform at the Azores plateau or the St Paul transform at Amsterdam-St Paul plateau in the Indian Ocean, Maia et al., 2011), suggesting a dependence upon lithosphere structure on sustainability of transform offsets. Thus, a key question is which kind of lithosphere (or which rheological conditions) can "sustain" an active transform fault, and how lithosphere rheology will govern the deformation at transforms faults. In addition, if their offset length is significant, transform faults might drastically reduce shallow asthenospheric along-axis flow. In turn, in some areas, transitional to abrupt isotopic boundaries between mantle domains occur near or at transform faults (e.g. 126°E TF, Hayes FZ, Kane FZ, Andrew Bain FZ, Menard FZ and Guamblin FZ (Klein et al., 1988; Machado et al., 1982; Mahoney et al., 1992; Smith et al., 1998; Sturm et al., 1999; Hanan et al., 2004; Hamelin et al., 2010) suggesting that they act as barriers to subaxial pipe flow beneath ridge axes away from hot spots, forming boundaries between mantle source regions. However, in other areas, such as the St. Paul transform, in the Equatorial Atlantic, the transition between two different mantle domains does not seem to be influenced by the transforms (Maia et al., 2016). Therefore, the interplay between transform faults and mantle domains, and hence mantle convection remains poorly understood.

The third question concerns the interplay between transform dynamics and magmatism. Due to the strong thermal gradient at Ridge-Transform Intersections (RTI), these areas constitute an ideal laboratory to constrain melting models and the nature of mantle heterogeneities. Greater conductive cooling to the surface, due to the juxtaposition of thin, young, hot lithosphere against thicker, older and colder lithosphere, might lead to a termination of melting at significantly deeper levels approaching the fracture zones, reducing the mean melting extent. This effect is already evident at ridge offsets of 150 km as reported for the Kane FZ (Ghose et al., 1996) reaching its maximum expression at the Romanche mega-transforms where the enhanced edge cooling generates a 50 km large steady state amagmatic spreading region at the RTI (Bonatti et al., 2001). Low magma supply, rapid transport, less cooling and fractionation due to the absence of large steady-state magma chambers are thus expected (Cannat, 1996) along with less efficient magma mixing that may enhance the diversity of magmas extracted from the melting column. This offers a greater opportunity to define mantle source lithologies (peridotite vs. pyroxenite) and the shape of the melting regime. Less efficient melt extraction might also favor mantle–melt interaction and high-pressure melt fractionation. These latter processes might account for the frequent eruption of high Al-Mg, low Si-Ti lavas close to fracture zones (e.g. Eason & Sinton, 2006). In addition to these unusual compositions, a wide range of magma compositions ranging from Depleted-MORB (D-MORB) to Enriched MORB (E-MORB), picritic to highly–fractionated magmas (e.g. ferrobasalt), has been found proximal to fracture zones (e.g. Perfit and Fornari, 1983; Elthon, 1988; Mahoney et al., 1994; Perfit et al., 1996; Wendt et al., 1999; Hays et al., 2004). At large offset transforms located in discordance regions (Australian-Antarctic Discordance and Atlantic Equatorial Discordance), alkali and water rich basalts have been recovered (Ligi et al., 2002, Schilling 1994, 1995; Klein et al., 1991). In these transform-dominated regions, weak magma supply and high peridotite to basalt ratio are observed (e.g. Schilling et al., 1995; Hékinian et al., 2000; Ligi et al., 2002; Christie et al., 1998), reflecting the presence of unusually cold underlying mantle (Bonatti et al 2001., Gurnis and Muller, 2003). A critical issue to address is thus how much does the transform fault cooling effect contribute to the local lowering of the mantle temperature? In addition, when the offset is moderate (50 km), the mantle flow might be deflected in the direction of the next ridge segment. (Georgen and Lin, 2003), suggesting the development of a potential asymmetry in the melting regime. Conversely, magmatism may affect the evolution of a transform offset. Magmatism within the transform domain may alter the thermal structure (rheology) of a transform, modifying the plate boundary's response to changes in the tectonic stress field. Indeed, magmatism may partially govern the locations of plate boundaries through time (e.g., Mittelstaedt 2008; 2011; 2012).

Magmatism constitutes a key tool to investigate the temporal, spatial and thermal evolution of the melting regime and plumbing system as it responds to variations of the spreading rates, potential temperature, mantle source heterogeneity and hence readjustment of the fracture zones to far field stress variations. The crustal exposures along the fracture zones are perfect loci to track temporal and thermal variations in the magmatic activity. Only a few detailed studies have been conducted on this issue demonstrating the absence of clear systematic relationships between the submantle thermal setting and dynamic and the magmatic cycling at the ridge axis (Bonatti et al., 2003; Brunelli et al., 2006; Cipriani et al., 2009a,b). Within this framework, some critical outstanding geophysical, petrological and geochemical questions are: What role does intra-transform magmatism (or lack thereof) play in the development of mega-transform zones? What are the proportions of melting of residual mantle relative to fertile heterogeneities? Are they dependent on the size of the heterogeneities? How do variations in mantle temperature and volatile contents influence these proportions? Alternatively, is the petrogenesis of the lavas mainly controlled by the distribution, size, and depth of melt lenses located within the transform? Do they result from the complex pattern of melt migration into the transform fault? Why are melts both efficiently and inefficiently pooled at transform faults? What is the shape of the melting region at transform faults?

A fourth question concerns the relationship between oceanic transform faults and their counterparts on continental margins. The birth of transform faults in a continental setting remains an open and fundamental question. This point is especially important when considering the origin of « transform passive margins » and their connection to nearby purely extensive or/and oblique passive margins (Sage et al., 2000). Early transforms appear to be highly dynamic systems, whose segmentation define the future architecture of the ocean-continent transition. The role of transforms in defining the Ocean-Continent Transition geometry seems to be dependent upon the degree of obliquity of the plate kinematics regarding the trend of early rifts. In highly oblique systems such as in the Gulf of California, early transforms appear to exert a mechanical control on continental break-up through pull-apart processes. We need to understand, through mixed continental/oceanic geodesy and seismology surveys, the strain and stress partitioning in the young oceanic transform systems, such as the Canal de Ballenas in the Gulf of California. In turn, some major oceanic transform faults might represent old pre-existing weakness lithospheric zones inherited from earlier continental rifting episodes in mobile belts. The Andrew Bain FZ along the SWIR might mark the western boundary of the Lwandle microplate (DeMets et al., 2017), representing the southern extension of the boundary between the Somalian and Nubian plates on the African continent. The fracture zone extensions of the main Australian-Antarctic Discordance transform faults stretch from the Australian to the Antarctic continental margins (Christie et al., 1998). Some megatransforms hence correspond to the extensions of continental shear zones (Reeves and De Witt, 2003). They may thus remain active and deform significantly during margin evolution. As an example, the Cote d'Ivoire-Ghana Transform continental margin results from still active motion along the Romanche Fracture Zone. Their study is thus relevant of our understanding of continental margin evolution.

The final question concerns the role that fluid-interactions around oceanic transform faults may play in global biogeochemical cycles. Oceanic transform faults and fracture zones are potential sites of substantial biogeochemical exchange between the solid Earth and the global ocean. This is particularly interesting with regard to the ocean biome. Deep-sea regions (>2000 m) make up 60% of the Earth's surface yet the role that deep-sea ecosystems play in global marine biogeochemical cycles is poorly known (Smith et al., 2009). Recent observations show that deep marine ecosystems are affected by variations in upper ocean conditions and climate (Smith et al., 2009), which points to a connectedness between deep and upper ocean biogeochemical fluxes. In the light of growing evidence that life is supported by chemosynthesis at hydrothermal vents and within the seafloor below (Amend et al., 2011; Boetius, 2005; Lever et al., 2013; Santelli et al., 2008), this opens up the possibility that ocean floor processes may have a notable impact on global marine biogeochemical cycles. Serpentinization reactions can release free hydrogen and methane, which can sustain chemosynthetic life at the seafloor (Kelley et al., 2005; Perner et al., 2007; Shock and Holland, 2004). Previous estimates of oceanic H_2 production by mantle serpentinization reactions have focused on mid-ocean ridges and are in the range of 10^{10}-10^{12} mol H_2 per year (Cannat et al., 2010; Emmanuel and Ague, 2007; Sleep and Bird, 2007; Worman et al., 2016). Interestingly, a complementary quantitative global assessment of mantle serpentinization and H_2 production at oceanic transform faults is still largely missing. Such an analysis requires assessing how the volume of mantle undergoing serpentinization reactions may change towards MOR segment ends and along transform faults. A recent 3-D numerical modeling study supports the concept of oceanic transform faults being sites of intense fluid-rock interaction and suggests that oceanic transform faults produce similar amounts of serpentinization-related H_2 as the entire global mid-ocean ridge system (Rüpke and Hasenclever, 2017). Constraining the hydrological regime of oceanic transform faults is not only relevant to biogeochemical processes, fluids are also likely to affect rheology, the stress state, and thereby seismicity (Gerya, 2012). For example, Geli et al. (2014) showed that oceanic transform faults can switch from dilatant and progressive deformation to rupture in response to fluid-related processes. This working group will promote future joint modeling and data studies to help constraining the extent of fluid cycling around oceanic transform faults, the way that fluids affect the stress state and seismogenic behavior, and the role that fluid-rock interactions may play in global biogeochemical cycles.

Working Group Proponents and Organization

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WG invited researchers
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The working group is composed of researchers with different specialties, spanning from structural geology to geochemistry and modeling. Specialists on subduction processes and on continental margins enlarge the scope of the group beyond the ridge community. The aim of this working group is to create a collaborative dynamic among different specialties and different communities in order to develop innovative and ambitious research projects on transform faults and fracture zones. Broadly, in the frame of this working group we intend:

- to exploit the large amount of available data on transform faults and fracture zones through collaborative research projects and the writing of synthesis papers;
- to improve the modeling approach through exchanges between different research groups as well as the joint work between model specialists and other specialties, such as tectonics, geochemistry and petrology;
- to target areas that would be "example systems", where new data should be acquired in order to answer the above questions and proceed to develop multi-cruise large international operations.

We intend to organize a first meeting at the AGU Fall session this year with the colleagues that will attend in order to start the group work and organize the first group workshop, to be held in 2018. As a first goal, this workshop will aim on making a synthesis of knowledge about transforms and fracture zones, including comparative views of the main studied systems. One of the first outcomes will be synthesis papers to be submitted to journals such as Earth Science Reviews. This is an important goal as these review papers are widely used by researchers and students. This work will also allow clarifying and establishing priorities for future research targets. The first workshop will also build the basis upon which international cruise proposals can be developed. We plan a second workshop in 2021 where we will discuss the on-going new projects (new model approaches, new cruises and inter-disciplinary projects) and evaluate the advances the working group dynamics was able to trigger. This workshop will be the final one. Between the first and the second workshops, we plan to hold regular meetings at the main international meetings (EGU, AGU) to insure a follow-up of the working group actions.

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