Constraints on fluids in subduction zones from electromagnetic data

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ABSTRACT

Magnetotelluric data have been increasingly used to image subduction zones. Models of electrical resistivity commonly show features related to the release of fluids at several depths through the systems imaged, consistent with thermal and petrologic models of dehydration of the descending slab. Imaging the release of fluids from sediments and pore space in the crust requires controlled source electromagnetic techniques, which have to date only been used in one setting, offshore Nicaragua. The release of fluids related to the transition of basalt to eclogite is commonly imaged with magnetotelluric data. Deeper fluid release signals, from the breakdown of minerals like serpentine, are highly variable. We hypothesize that regions where very strong conductive anomalies are observed in the mantle wedge at depths of ~80–100 km are related to the subduction of anomalous seafloor, either related to excessive fracturing of the crust (e.g., fracture zones), subduction of seamounts, or other ridges and areas of high relief. These features deform the seafloor prior to entering the trench, permitting more widespread serpentinization of the mantle than would otherwise occur. An alternative explanation is that the large conductors represent melts with higher contents of crustal-derived volatiles (such as C and H), suggesting in particular locally higher fluxes of carbon into the mantle wedge, perhaps also associated with subduction of anomalous seafloor structures with greater degrees of hydrothermal alteration.

INTRODUCTION

The cycle of fluids in subduction zones, especially volatile-bearing melts, is a major component of slab recycling, arc volcanism, and continent-building processes. A better understanding of the role of melt and volatiles in subduction, combining field and laboratory-based electrical models, is key to improving our knowledge of the thermal and petrologic structure of subduction zones as well as the dynamic processes at work. It can also help us better assess tangible hazards in these contexts by examining, for example, links between fluid release and seismicity and properties of the megathrust that can rupture and generate tsunamis and volcanic eruptions (e.g., Polet and Kanamori, 2000; Walter and Amelung, 2007; Davey and Ristau, 2011).

Though fluids and volatiles efficiently subducted via pore fluids are largely expelled by compaction at shallow depth (Moore and Vrolijk, 1992; Solomon et al., 2009), some amount of volatiles persists to greater depth (>15 km), bound in the crystallographic structure of minerals (e.g., Iwamori, 1998). These volatiles are then released and transported through metamorphism and melting processes (e.g., Hermann et al., 2006; Iwamori et al., 2007). The hydrous fluid–melt cycle in subduction zones can be constrained through geophysical investigations that image fluid-bearing reservoirs and channels in present-day subduction zones, in particular by electromagnetic (EM) techniques (e.g., McGary et al., 2014; Pommier, 2014a). Because electrical conductivity is sensitive to thermal and compositional changes (e.g., Yoshino, 2010, and references therein; Pommier, 2014b, and references therein; Tyburczy and DuFrane, 2015), EM profiles across subduction zones can be used to constrain both time and space evolution of subduction, and in particular, locate the origin of primary arc magmas, constrain the extent of melting, and identify the main chemical fluxes from shallow slab dehydration to deeper partial melting, thus providing critical constraints for petrological and geodynamic modeling.

EM studies of subduction zones have increased significantly over the past decade, and numerous soundings have been completed. A compilation of global results suggested the widespread presence of a lower crustal–upper mantle (15–30 km depth) conductor situated on the trench side of the volcanic arc (Worzewski et al., 2010; Fig. 1) that is attributed to an accumulation of aqueous fluids. In some cases, this interpretation seems appropriate; however, there are also instances where such conductors are probably the signature of melt accumulation (e.g., McGary et al., 2014). Untangling these competing possibilities requires detailed EM transects. Ideal studies would be those that permit a view of an entire system from the undeformed incoming plate across the volcanic arc, as well as providing insights into along-strike variability in fluid release. There are almost no studies that meet those criteria, and so here we consider the best data sets available. Two EM approaches have been used in subduction settings. Controlled source electromagnetics (CSEM) is a tool used for crustal-scale studies. It has been used in one subduction zone setting, offshore Nicaragua, where it constrains the free fluid budget of the incoming crust (Key et al., 2012; Naif et al., 2015) and identifies processes of shallow fluid release and transport related to squeezing of pore fluids and the breakdown of clay minerals (Naif et al., 2016). EM methods are not sensitive to the hydrous alteration products of the oceanic crust, and so constraints on this component of the incoming fluid budget must come from seismic methods (e.g., Hornig et al., 2016). The magnetotelluric method (MT) is used for deeper imaging into the mantle where it is well suited for imaging the release of aqueous fluids from the slab and the generation and transport of melt to the volcanic arc. MT is not, however, well suited to mapping resistive...
features, and so frequently has limited ability to constrain the properties of the cool downgoing slab. In most cases it is desirable to include an a priori slab in MT inversion models to maximize the information returned from MT sounding data (e.g., Matsuno et al., 2010; McGary et al., 2014; Ichiki et al., 2015). Many models in the literature that do not impose a priori structure contain resistive features that bear little resemblance to a slab. This is more than a cosmetic issue: McGary et al. (2014) showed how imposing the slab improves the fit to the data at key sites, and, as the relaxation of regularization across the slab surface permits the inversion algorithm to fully explore model space, the relaxation permits conductive features associated with fluids and melts to be placed adjacent to the slab where they are generated. In discussing models herein, where possible, we try to use examples where slabs have been included in some manner in the inversion process. In all cases, there are limits on our ability to infer the spatial extent and size of conductivity anomalies arising from the slab, but these limits are greater where no slab has been imposed in the inversion.

Subduction zones can be characterized primarily by a few key parameters that may be related to each other; i.e., whether the system is ocean-ocean or ocean-continent, the age of the incoming plate, the speed of convergence, the obliquity of convergence, and the dip angle of the slab (e.g., Jarrard, 1988). Numerical models that quantify the effects of these parameters on subduction structure and dynamics are well documented (e.g., Syracuse et al., 2010; van Keken et al., 2008; Penniston-Dorland et al., 2015). Less well understood interactions include the role of flexure of the incoming plate and the angle of convergence creating on reactivating faults for fluid migration through the crust and into the mantle (e.g., Naliboff et al., 2013). The role of inherited fabric, formed at or close to the mid-ocean ridge, on the generation of faults at the trench is also not well known. These faults may act as sinks of fluids that are brought to depth, causing conductive anomalies at shallow depths. Crust formed at slow-spread ing ridges, where deep penetrating faults as well as low-angle detachment faults are thought to cause widespread mantle serpentinization (e.g., Tucholke et al., 1998; Blackman et al., 1998; de Martin et al., 2007; Canales et al., 2000), might result in much higher fluid inputs into a system than one where the serpentinization occurs at the trench; therefore, an understanding of the basin-wide system back to the ridge can be important, although this is not well quantified.

Even though a single subduction system such as Cascadia can be reasonably quantified by single values for the primary descriptors of a subduction system, as we carry out more detailed studies of entire systems we see substantial variability along strike, reminding us that these systems are always more complex than they appear at first glance. Recent MT studies in several settings have highlighted this variability; we give examples and try to shed light on what other important structural controls or processes can influence the release of fluids and the generation of melts in subduction settings. We also highlight the role of a high-relief seafloor (i.e., containing features such as fracture zones or seamounts) on the generation of highly conductive anomalies at depths of ~80–100 km.

### Conductivity as a Probe of the Hydrogen and Carbon Cycles

Many of the subduction setting parameters mentioned here work together to control the physical evolution of the downgoing slab and are tied to the volatiles cycle (in particular hydrogen and carbon). For example, a relatively young (and therefore hot) incoming plate that has a slow convergence will heat at shallow depths, releasing water more rapidly downdip (e.g., van Keken et al., 2011).

### Hydrogen Cycle and Electrical Anomalies

Water increases the electrical conductivity of the upper mantle through the diffusion of hydrogen, which enhances the mobility of charge carriers (e.g., Mg vacancies and polarons in olivine; e.g., Karato, 2013) and triggers partial melting by lowering the mantle solidus temperature (Hirschmann et al., 2009; Sarafian et al., 2017). Therefore, the interpretation of electrical conductivity models, accounting for phase transitions and dehydration reactions, should reflect the cycle of water, with conductive zones caused by hydrous phases (minerals and fluids) expected at mantle depths in water-rich subduction contexts. Furthermore, these hydrogen-related field electrical anomalies are expected to reflect the state of subduction zones, as thermal modeling suggests that water is brought efficiently to mantle depths in old and fast subduction zones (e.g., in the western Pacific), whereas in hot subduction zones (e.g., Cascadia) a nearly complete slab dehydration is...
predicted (e.g., van Keken et al., 2011). Estimates of potential fluid flux range from ~0.1 to 0.3 kg H$_2$O/m$^2$/yr, depending on the convergence rate (Peacock, 1987, 1990, 1993; Gerya et al., 2002; Penniston-Dorland et al., 2015). This fluid flow causes a thermal perturbation, but the resulting heat transfer is thought to be significant only at shallow to moderate depths (<40 km), where high shear stress and fluid fluxes enhance heat transport (e.g., Penniston-Dorland et al., 2015), whereas at higher depths the thermal structure is mainly governed by heat conduction and advection processes by subducting oceanic lithosphere (e.g., Peacock, 1990).

A suite of hydrous phases such as amphibole, brucite, serpentine, and chlorite is thermodynamically stable at specific depth and temperature ranges in the incoming hydrated oceanic crust and upper mantle (e.g., Poli and Schmidt, 1995; Hacker, 2008; Grove et al., 2012; Timm et al., 2014; Fig. 2). These phases contribute to the H$_2$O flux in subduction zones because they can accommodate significant amounts of water (as much as 12 wt% water) in their crystallographic structure as OH groups that are eventually released at higher depth as free fluid phases upon the breakdown reaction. In particular, the main flux of subducted water in the mantle may be controlled by the abundance of serpentine (Rüpké et al., 2004). A few laboratory studies have measured a high conductivity for hydrous minerals, especially once the breakdown reaction occurs, because the presence of a low-viscosity interconnected fluid phase enhances the bulk electrical conductivity. However, the difference in conductivity between these hydrous minerals is often too small to be discriminated using field electrical measurements alone. To illustrate this point, we consider the example of Cascadia, where a conductivity anomaly of ~0.1 S/m is observed next to the slab at 40 km depth (Fig. 2). The electrical conductivity of lawsonite is as high as 0.1 S/m before it dehydrates and can be as high as 10 S/m at temperatures where the fluid is released as a free fluid phase (Manthilake et al., 2015), and comparable conductivity values have been obtained for chlorite as it dehydrates and coexists with magnetite (Manthilake et al., 2016). A conductivity value as high as 0.1 S/m is also consistent with serpentine with as much as 20 vol% magnetite before dehydration (Kawano et al., 2012). Although we can rule out the presence of lawsonite at this depth because its stability field is expected to start at higher pressure (e.g., Poli and Schmidt, 2002), it is not possible to attribute the field anomaly in the Cascades to serpentine or chlorite without further petrological constraints. These observations point out the need for combining electrical observations with phase equilibria in order to interpret conductivity anomalies in terms of chemistry. Figure 3 shows the stability field of hydrous phases in the basalt + H$_2$O system. Comparison of these phase equilibria with the expected pressure-temperature ($P$-$T$) paths of slabs from different subduction zones allows the prediction of the depth of hydrous fluid release from breakdown reactions as well as the onset of melting. As illustrated in Figure 3, the high temperatures in Cascadia (and hot subduction zones in general) do not overlap with the stability field of lawsonite, and so it is the breakdown of other stable minerals (chlorite, amphibole) that will occur in these settings, whereas metamorphosed oceanic crust in cold subduction zones (e.g., northeastern Japan) is expected to be mainly composed of lawsonite blueschist.

![Figure 2. Detection of fluids using electromagnetic studies. Comparison between the petrological view of a subduction zone (left: after Schmidt and Poli, 1998; Grove et al., 2012; Timm et al., 2014) and an electromagnetic profile (right: Cascadia, McGary et al., 2014). Labels in the slab correspond to stable hydrous minerals: amph — amphibole; cld — chloritoid; law — lawsonite; serp — serpentine; chl — chlorite. The location of the model profile is shown on the inset map of Figure 6. Dashed lines correspond to isotherms and associated numbers refer to temperature in °C.](image-url)
Carbon Cycle and Electrical Anomalies

Carbon is another key volatile in subduction mechanisms, and estimates of the amount of C initially subducted (from sediments, crust and mantle) vary from 40 to 114 Mt/yr, whereas the amount of C transferred from the subducting plate to the convecting mantle ranges from 0.0001 to 52 Mt/yr (Dasgupta and Hirschmann, 2010; Kelemen and Manning, 2015). Very low estimates of carbon fluxes in the convecting mantle suggest that most of the carbon subducted through sediments (overall annual flux of ~0.9–1.8 t mol C/yr; Evans, 2012) and oceanic plate may be recycled in fluids (such as carbonate melts) or C-bearing solidus diapirs into the overlying plate (e.g., Kelemen and Manning, 2015). The few existing electrical laboratory studies of carbonate melts observed very high conductivities at atmospheric (Gaillard et al., 2008) and uppermost mantle conditions (e.g., Yoshino et al., 2012; Sifré et al., 2014), suggesting that some field electrical anomalies may be explained with a small fraction of carbonate melt. At temperatures relevant to subduction zones, the investigated carbonatic and extremely carbon-rich silicate melts present conductivities >10 S/m, suggesting that a small melt fraction could explain field anomalies of ~1 S/m or less in the mantle wedge (see Fig. 2). Carbon at depth may trigger incipient melting and produce high-conductivity and low-viscosity melts (Sifré et al., 2014) that should be detectable using MT surveys. The carbonatic liquids that can be formed from CO2 release are extremely mobile and provide a potential pathway for carbon recycling at shallow depths beneath arcs (especially in warm active margins) through percolation processes into the mantle wedge (<120 km depth; Poli, 2015). However, Mann and Schmidt (2015) estimated that near the solidus, a silicate melt may only transport 0.05–0.6 wt% bulk CO2, which should motivate electrical studies of melts containing small amounts of carbon.

Further electrical laboratory investigations of solid carbon phases and their dissolution are also needed to interpret field conductivity anomalies in terms of metamorphic processes. If the melting of sediments from the slab has been proposed to explain some geochemical signatures of arc magmas (e.g., Plank, 2005), geodynamic simulations suggest that sediment melting requires slab surface temperatures higher than the temperatures predicted by thermal models (Behn et al., 2011), even in warm subduction environments. Alternative mechanisms for the melting and transport of sediments in the mantle wedge involve (1) the incorporation of sediments into mélange diapirs, exposing sediments to temperatures higher than the slab temperature (>1000 °C; e.g., Marschall and Schumacher, 2012), and (2) flux melting, with fluid being added from metamorphic reactions (such as water release from serpentine breakdown) in underlying slab lithologies (Mann and Schmidt, 2015). However, as underlined by the experimental work of Mann and Schmidt (2015), sediment melting in a descending slab cannot be a general subduction process because it causes an almost complete dehydration of the slab that would lead the mantle to dry out on geological time scales. Phase equilibria suggest that the release of C-rich fluids from sediments may only occur in the warmest of subduction zones (e.g., Cascadia; Fig. 3), and even in this context fluids may be expelled before the crust intersects the solidus. Fluid release and
partial melting triggered by carbon does not lead to complete decarbonation of the slab, as calcite remains stable at temperatures above the fluid-saturated solidus (Mann and Schmidt, 2015; Fig. 3). Laboratory experiments also show that carbonate destabilization in subduction zones does not necessarily imply carbon loss from the slab in C-bearing fluid (essentially as CO₂) (Galvez et al., 2013). Galvez et al. (2013) suggested that, under reducing and low fluid flux conditions, carbon might be stored as graphite in the downgoing slab and may be injected into the mantle under a high-P phase such as diamond, although C in diamond form is not thought to represent a significant part of the global carbon inventory (Kelemen and Manning, 2015).

Competing Effects of Hydrogen and Carbon

Both hydrogen and carbon cycles affect subduction in different ways. It has been suggested that in present-day Earth, carbon subduction is more efficient than H₂O subduction because nearly complete dehydration of the crust is expected at shallow depth for all but the coldest subduction zones (e.g., Hacker, 2008), whereas a significant amount of C can be brought to the mantle (e.g., Dasgupta and Hirschmann, 2010). From a geodynamic viewpoint, H₂O may dominate deep subduction mechanisms because it significantly decreases the viscosity and density of mantle minerals (e.g., Mei and Kohlstedt, 2000; Nakao et al., 2016), whereas C is mostly hosted in accessory mantle minerals with a smaller effect than H₂O on physical properties. However, C influences the onset of partial melting (e.g., Dasgupta et al., 2007a, 2007b), and thus indirectly affects geophysical (electrical, seismic) measurements.

How hydrogen-bearing and carbon-bearing fluids hydrate the overlying mantle is not completely understood and their effects on an electromagnetic profile can be intertwined. In particular, bulk conductivity alone cannot easily constrain melt chemistry (carbon-rich versus hydrogen-rich melt) and requires input from petrology studies. For example, the deep conductor in Cascadia starts at ~60 km depth and has a conductivity ranging from ~0.1 to 1 S/m, and has been interpreted as partial melt (McGary et al., 2014) (Fig. 2). At 1200 °C, a conductivity value of 0.1 S/m is compatible with a dry or low water content basalt (extrapolating the data from Ni et al., 2011), an andesitic melt containing ~2 wt% H₂O (Laumonier et al., 2017), or a carbonate-bearing melt containing <10 wt% CO₂ (Yoshino et al., 2012). It might also be compatible with a melt containing both H₂O and CO₂ (Sifré et al., 2014). Because hydrous melting is expected in the mantle wedge and because the first melts formed are expected to be basaltic (e.g., Grove et al., 2012), an anhydrous basaltic melt and an andesitic melt are less likely to explain the field electrical anomaly than a basaltic melt containing both carbon and hydrogen, assuming complete miscibility of the system.

As detailed in the following, the location of electrically conductive anomalies at depths where the breakdown of volatile-bearing minerals is expected underlines the relevance of relationships between metamorphism and electrical conductivity, particularly through carbonation and hydration reactions and decarbonation and dehydration reactions of the downgoing slab.

INCOMING PLATE

Fluids are introduced into the subduction system through a variety of mechanisms. Fluids can be present as a free phase in pore space, either of sediments or oceanic crust, or they can be carried through hydrous alteration products. EM methods are highly sensitive to the presence of interconnected free fluid phases, but have almost no sensitivity to crustal alteration products. Water in the mantle is carried by the suite of hydrous phases discussed above. In this section we highlight the constraints that EM methods are able to place on fluid flux in the incoming plate, which will primarily be confined to free pore fluids, as well as the limitations on our current knowledge, primarily arising from the limited number of soundings completed.

Subduction zones are broadly categorized into either accretionary or non-accretionary systems describing how sediments accumulate into an accretionary prism (e.g., von Huene and Scholl, 1991) and are left behind as the slab descends, or how sediments are carried down into the mantle. The thickness of the sediment pile on the incoming plate can be mapped seismically and the bulk porosity quantified using CSEM methods. The oceanic crust has an intrinsic porosity that can be as high as ~20% near the seafloor in young seafloor and decreases with depth (Evans et al., 1991, 1994). Alteration and sedimentary infill with age act to reduce these values (e.g., Becker et al., 1982). There is only one data set of crustal conductivity structure around a trench, collected by the SERPENT (serpentinite, extension and regional porosity) experiment offshore Nicaragua, across the Nicaragua trench (Key et al., 2012; Naif et al., 2015) (Fig. 4). These data show the development of electrical anisotropy associated with the generation of bending faults and the increase in porosity as these faults open and allow seawater to enter through the crust and into the upper mantle. Porosity values throughout the crust essentially double due to the creation of plate-bending faults. These observations also suggest that, in the absence of other vehicles for fluid penetration, most serpentinization of the upper mantle, a key component of the water carried deeper into the subduction system, occurs at the trench. Nicaragua has been noted as an end-member system as arc-lava compositions suggest a high flux of water into the system (e.g., Patino et al., 2000), which has been related to the nearly parallel orientation of plate faults with the trench. We do not have complementary data from systems where the fault orientation is oblique to the trench to test the hypothesis that preexisting fault fabric influences the fault density and fluid content of the crust.

SHALLOW FLUID RELEASE (<15 km DEPTH)

In the shallow part of subduction (<15 km), there is rapid fluid loss from pore spaces in both the sedimentary layer and upper crust. This release results in aqueous fluid migration along channels atop the décollement and back toward the trench, and through interconnected cracks and faults in the overlying plate (Lauer and Saffer, 2015). These channels are prefered transport paths for...
Figure 4. Electrical structure of the incoming Cocos plate (Naif et al., 2015, 2016), highlighting the relationship between topography and conductive fluid-bearing faults. (A) The map shows the location of the profile (black line) that featured deployment of 54 seafloor instruments and transmission using a deep-towed controlled source electromagnetic (CSEM) transmitter. (B) The resistivity model derived from two-dimensional inversion of the CSEM data as discussed in the text (model from Naif et al., 2016).
We do not have a data set from an accretionary sedimentary forearc system. Assuming the hotter end-member model for the system, although other hypotheses for the conductor are observed at a depth broadly consistent with clay breakdown as well as seep activity above the slab (e.g., Worzewski et al., 2010). The data permit estimation of a total free water budget for the system. A large high-porosity décollement, and a reduction in porosity with depth broadly consistent with the role of fluids in weakening the plate interface can result in decoupling of the mantle wedge from the slab, allowing a stagnant corner to form that is conducive to serpentinization (Wada et al., 2008). There are also potential links between fluid release at these depths and seismicity (e.g., Peacock, 1993; Poli and Schmidt, 1995). This process is thought to be important for subduction initiation (e.g., Gurnis et al., 2004) as eclogite is significantly denser than basalt.

Shallow fluid release involves the breakdown of clay minerals in the downgoing sediments (if they are carried down with the plate and not accreted) (Spinelli et al., 2006; Lauer and Saffer, 2015). These fluids are typically fresh and released at temperatures of ~60–150 °C. They can either pool at the décollement where they might play a role in plate slip, or can find their way through faults to the seafloor where they exist through seeps.

We have a single image of the conductivity structure of a forearc (Nicaragua; Naif et al., 2016) through CSEM imaging. This setting is largely erosional, with sediments subducting beneath a forearc interpreted to largely consist of crystalline basement (e.g., von Huene et al., 2004). The CSEM data show the high-porosity décollement, and a reduction in porosity with depth broadly consistent with compaction models (Lauer and Saffer, 2015; Spinelli et al., 2006). The data permit estimation of a total free water budget for the system. A large conductor is observed at a depth broadly consistent with clay breakdown assuming the hotter end-member model for the system, although other hypotheses for this conductor include the accumulation of sediments (Naif et al., 2016). We do not have a data set from an accretionary sedimentary forearc system.

**INTERMEDIATE DEPTH FLUID RELEASE (15–50 km DEPTH IN WARM SUBDUCTION ZONES, ~100 km DEPTH IN COLD SUBDUCTION ZONES)**

As basaltic crust descends into a subduction zone, it undergoes a transition to eclogite with a resultant release of water (e.g., Peacock, 1993; Poli and Schmidt, 1995). This process is thought to be important for subduction initiation (e.g., Gurnis et al., 2004) as eclogite is significantly denser than basalt. The role of fluids in weakening the plate interface can result in decoupling of the mantle wedge from the slab, allowing a stagnant corner to form that is conducive to serpentinitization (Wada et al., 2008). There are also potential links between fluid release at these depth and seismicity (e.g., Hacker et al., 2003a) and aseismic transients (e.g., Liu and Rice, 2007).

Scattered teleseismic data have been used to image changes in shear velocity along downgoing slabs; the velocity increase is inferred to represent the basalt-eclogite transition (e.g., Bostock et al., 2002; Rondenay et al., 2008). Data sets from Cascadia show conductive anomalies leaving the slab at ~40 km depth and migrating toward the continental Moho (e.g., Evans et al., 2014; McGary et al., 2014; Wannamaker et al., 2014; Fig. 2). The depth of fluid release is consistent with thermodynamic models of basalt-eclogite transition for this hot, young end-member system (Hacker et al., 2003b; van Keken et al., 2002) and with seismically imaged increases in velocity (e.g., Bostock et al., 2002; Rondenay et al., 2008; Abers et al., 2009; McGary et al., 2014). Constraining the volume fraction of fluid is difficult without knowing the composition (primarily the salinity) of the fluid released from the slab as well as the thermal structure. Using numerical models of thermal structure, molecular dynamics calculations of fluid conductivity suggest that the Cascadia anomalies are consistent with a low-volume fraction of fluid with a modest salinity (about 0.5 wt% NaCl) (Sakuma and Ichiki, 2016).

Similar fluid release is seen in many other MT profiles spanning the forearc and into the arc; this led Worzewski et al. (2010) to identify a conductive feature present in all considered locations at 20–30 km depth, and situated between the arc and the trench, ~30 km from the arc (Fig. 1). In addition to the Costa Rica system imaged by Worzewski et al. (2010), another example of this feature includes that imaged across the Marlborough strike-slip system in New Zealand (Wannamaker et al., 2009), where the fluids released from the downgoing slab in the 40–60 km depth range rise through buoyancy and interact with a sequence of strike-slip faults, possibly lubricating the faults. However, while most features imaged at these depths are likely to be aqueous fluids released from the slab, there is the likelihood for some to be ponded melts. Distinguishing the two requires tracing the conductor back to the slab, and that requires good data density as well as imposition of the slab in the inversion model for reasons discussed herein.

Electromagnetic and seismic signals in the crust and mantle depend on temperature, fluid fraction and interconnection in differing degrees. In particular, links between fluid release and transport and seismicity are intriguing. Heise et al. (2012, 2013) showed how, on the North Island of New Zealand, the onset of seismicity above the slab corresponds with a transition from conductive sediments to a region of more resistive material at ~10 km depth (Fig. 5). This band of seismicity continues down the slab, where it overlaps with a conductor that can be interpreted as due to fluid release processes. The densest seismic activity appears closely related to the connection between the conductor and the slab. The depth of this conductor is shallower (~20 km) than expected for basalt eclogite, and Heise et al. (2012, 2013) suggested that instead this feature is related to underplated sediments. In Cascadia, seismicity extends along the slab through the region of fluid release, but there is a decrease in seismicity once the transition to eclogite is complete (McGary et al., 2014); in general, through the system, there is a reasonable correlation between areas of slow slip events and steady plate sliding and fluid release from eclogitization (Wannamaker et al., 2014).

The subduction of the incoming plate triggers high degree of deformation in the crust and the mantle, forming zones of high strain. Electrical experiments on sheared partially molten rocks showed that conductivity and electrical anisotropy are enhanced by shear (Caricchi et al., 11; Zhang et al., 2014;
In particular, experiments on deformed polycrystalline olivine showed that grain-boundary conduction can explain high conductivities (\(8 \times 10^{-2}\) S/m at 1300 °C for a shear strain of 7.3) and electrical anisotropy as high as 4.5 without the presence of volatiles or melt, due to a noticeable effect of grain boundary orientation distribution (Pommier et al., 2016). These experimental results suggest that the interpretation of EM data requires consideration of the effect of rock deformation on the bulk electrical response, instead of attributing high electrical conductivities solely to rock chemistry (presence of aqueous fluids and/or melt). Highly conductive anomalies where high strains are expected (such as the slab–mantle wedge interface) may be explained by smaller amounts of fluids than estimates made when considering an undeformed solid matrix. Constraining the amount of fluids from electrical conductivity requires an understanding of the degree of interconnectivity of the liquid phase, because its geometry affects bulk conductivity (e.g., ten Grotenhuis et al., 2005, and references therein; Miller et al., 2015). However, the current electrical database does not allow us to place tight constraints on melt or aqueous fluid fraction at conditions (P-T composition rheology) relevant to subduction zones.

Figure 5. (A) Magnetotelluric (MT) model from the North Island of New Zealand that shows how the onset of seismicity above the slab corresponds with a transition from conductive sediments to a region of more resistive material at ~10 km depth, as well as the start of a large conductor thought to represent sediments or perhaps the release of fluids. (B) Contours show coincident Vp seismic velocities. (C) Contours show Vp/Vs (P-wave to S-wave velocity ratios), which also show reductions in velocities with a greater drop in Vs, as expected for a fluid-rich region (from Heise et al., 2012). The location of the profile is shown by the line in A.
DEEP FLUID RELEASE AND MELT GENERATION
(>~50 km DEPTH)

The presence of significant quantities of aqueous fluids and partial melt can lower the viscosity of the upper mantle (e.g., Dixon et al., 2004). This lowered viscosity, along with fluid processes involved in plate-mantle coupling, results in convection in the mantle wedge above the subducting plate and elevated surface heat flow (e.g., Wada and Wang, 2009). Existing EM profiles across subduction zones reveal different electrical structures, highlighting the complexity of subduction mechanisms at work and the dependence on geological setting. Differences in electrical profiles between cold versus hot subduction zones can be explained by differences in the thermal evolution of the slab and surrounding mantle and the location of major metamorphic reactions, influencing the extent of partial melting in the mantle wedge. For example, the thermal structure in warm subduction zones will cause the top of the subducted oceanic crust to intersect several dehydration reactions of hydrous minerals at shallow depth as well as the possible partial melting of hydrous basalt, leading to the formation of high-conductivity fluid-bearing zones at the slab-mantle interface and in the mantle wedge. In colder subduction zones (e.g., northeastern Japan), the slab can transport surface water in the form of hydrous minerals (serpentinite) into the deep mantle, resulting in the release of fluids at greater depths than in warm subduction environments such as Cascadia (Toh et al., 2006; Iwamori and Zhao, 2000).

The onset and extent of partial melting are directly related to the abundance of volatiles and the thermal structure (the presence of water decreasing the solidus temperature). Very hydrous melts are expected in subduction zones and may coexist with free aqueous fluid phases. These partially molten zones are expected to be very conductive, in agreement with laboratory studies on hydrous melts containing several weight percent H2O and carbon-bearing silicate melts (Gaillard, 2004; Pommier et al., 2008; Ni et al., 2011; Yoshino et al., 2012; Sifré et al., 2014; Laumonier et al., 2014, 2017; Guo et al., 2016).

Variability in the Presence of a Deep Conductor

Considerable work has been conducted in Cascadia (Meqbel et al., 2014; Bedrosian and Feucht, 2014; McGary et al., 2014; Soyer and Unsworth, 2006; Wannamaker et al., 2014). Earthscope Transportable Array data (www.usarray.org), provide a good three-dimensional (3D) framework for Cascadia, and MT models derived from the ~70 km spaced transportable array (TA) coverage highlight the variability across the system, although with this station spacing, many details of the subduction system are not resolved. More densely spaced wide-band and long-period MT data were collected on the Café line through Washington State (McGary et al., 2014; Fig. 2), coincident with a large seismic deployment (Abers et al., 2008). This permitted use of the seismic imaging to guide the MT inversion. In this case, an a priori model containing a slab as well as relaxation of regularization across the slab interface was implemented in inverting the MT data. The resulting model shows two key features. The first feature is a conductor associated with the release of fluids from the transition of basalts to eclogite at ~40 km depth (as discussed herein). It is important to note that dehydration of chlorite could also contribute to electrical anomalies at ~40–50 km depth (Fig. 3) and lead to higher conductivities at the slab–mantle wedge interface. The second key feature of the model is a deeper conductor associated with serpentinite breakdown that releases fluids and triggers melting above the slab. This melt is imaged migrating upward toward the arc volcano (McGary et al., 2014; Fig. 2). Partial melting is expected to start at ~60 km depth, where the slab surface temperature intersects the solidus curve, and extends to higher depths (Fig. 3).

Other profiles across Cascadia and 3D inversions of Earthscope TA data show variability in the along-strike structure, particularly at depths associated with serpentinite breakdown (~80 km) and generation of melt (Fig. 6) (Wannamaker et al., 2014; Meqbel et al., 2014; Bedrosian and Feucht, 2014). In particular, the 3D model of Bedrosian and Feucht (2014) shows the largest conductive anomaly at 75 km roughly in the same region as the Café line, although in this inversion (with no slab imposed) the conductor is widespread and shifted to the west of the arc. There are other smaller conductors along strike at the same depth, but these are also all shifted westward of the arc. Putting aside the geometry of the conductors, the variability in conductivity at these depths suggests primary differences in the amounts of water released from the slab and in the generation of melts along strike.

Similarly, in the Kyushu subduction zone, which has featured 3D electromagnetic imaging using both network MT and geomagnetic transfer function approaches (Hata et al., 2015, 2017), there is significant variability in the mantle wedge conductivity, with only one region, beneath Kirishima volcano, associated with a significant melt-related conductor (Fig. 7). In this system the Philippine Sea plate subducts, carrying with it the relict Kyushu-Palau Ridge. The Kyushu-Palau Ridge was formed as part of the backarc system and features anomalously thick oceanic crust (Nishizawa et al., 2007). The projection of this ridge in the direction of plate convergence is roughly in the region of high mantle conductivity, as discussed in Hata et al. (2017).

The central Mariana trench is an ocean-ocean subduction system and is another example of where a strong conductor comes from the subducting plate at depths of 100 km and greater. The incoming Pacific plate in this section of the Mariana is very old (ca. 150–140 Ma), but also contains abundant seamounts. The central Mariana trench is host to a series of diapiric serpentinite seamounts (Maekawa et al., 2001), although the source of serpentinite is thought to come from the mantle wedge rather than the downgoing mantle, and is related to the impact of the subduction of seamounts on the incoming plate (Fryer et al., 1985). A seafloor MT profile across the system from incoming old Pacific plate through to the backarc was discussed in Matsuno et al. (2010). Final models of the measured data contain a highly conductive mantle above the slab over a wide range of depths, suggesting that a significant amount of volatiles is carried into the system with subsequent melt generation. However, there is no signal of conductive melt in the mantle associated with the backarc spreading system. Matsuno et al. (2012) examined the 3D geometries of melt features that could exist beneath the backarc and would be undetected by the data collected.
LINKAGES BETWEEN INCOMING PLATE PROPERTIES AND FLUID RELEASE SIGNALS

Large conductors, like that seen in the Café MT line (McGary et al., 2014), have been seen elsewhere (e.g., Hata et al., 2015, 2017), but they are not ubiquitous features of subduction zone conductivity models. Understanding why this is the case requires an understanding of the along-strike variability inherent in a system and relating this back to the controlling properties of the subduction process.

Interpretations of geochemical data have suggested that the subduction of fracture zones results in the passage of greater amounts of water into the subduction system through more extensive serpentinization of the incoming mantle (e.g., Singer et al., 2007). Supporting this model, it has been shown that the presence of faults and fractures in the oceanic crust and uppermost mantle contributes to expose peridotite to seawater hydrothermal alteration, leading to the formation of serpentine at or near the plate surface (Kerrick, 2002). Because serpentine is stable to depths of 120–200 km in subducted oceanic crust and upper mantle rocks (e.g., Ulmer and Trommsdorf, 1995; Poli and Schmidt, 2002; Rüpke et al., 2004), it may be an important vector of fluids that helps release large volumes of water deep into the mantle (e.g., Singer et al., 2007), thus enhancing mantle conductivity. However, the conductivity of serpentine is unlikely to explain high conductivity values (Reynard et al.,...
(2011), even if it contains magnetite (Kawano et al., 2012), unless the magnetite forms a well-connected network.

The presence of seamounts is another potential vector for high water flux into the deeper parts of the subduction system. Seamounts are known to cause flexure in the crust where sediments accumulate around the volcanic edifices (e.g., Bassett and Watts, 2015). This extra amount of sediments brought to depth (compared to an incoming plate that does not contain seamounts) may enhance dehydration processes at shallow depth. The influence of subducted seamounts on slab dehydration processes is supported by isotopic measurements on fluids from the Mariana arc (Ishikawa and Tera, 1999). In this study, local differences in isotopic composition of fluids along the arc are likely to be explained by variable amounts of subducted sediments and are attributed to the subduction of seamounts. We further suggest that the seamount loading of the plate creates additional pathways for fluids through the crust and into the upper mantle, resulting in more extensive serpentinization of the mantle than would otherwise be the case. This high degree of serpentinization could be responsible for the large fluid release and melting triggered above the downgoing slab.

If we accept that the fluids released to create these large conductors come from serpentinite, then we can conceive of two ways in which variability can be created along strike: (1) there is variability in the degree of mantle serpentinization beneath the incoming plate, before the creation of bending faults, or (2) the process of creating bending faults and the associated fluid penetration into the mantle create variability along strike. In this model, the large conductors seen would represent larger amounts of released fluids and, presumably, higher melt generation above the slab.

Figure 7. (A) Slices through a three-dimensional (3D) resistivity model derived from network magnetotelluric (MT) data collected on Kyushu, Japan. The model reveals significant variability in mantle wedge structure, with a large conductor seen only beneath Kirishima volcano (from Hata et al., 2017). (B) Plan view of the 3D model at a depth of 45–50 km. (C) Cross sections at locations as shown in A and on the model plan view in B.
Another possibility is that the regions where large conductors are present represent loci of larger carbon release from the slab, perhaps also related to the subduction of anomalous seafloor, although in this case the anomalous structure could be related to thicker crust where most of the carbon carried into the system is thought to reside through alteration products (Alt and Teagle, 1999). In this model, the strong conductors do not necessarily represent higher melt fractions, but rather CO₂-enriched melts that are more electrically conductive (Yoshino et al., 2012; Sifré et al., 2014). Melting processes involving carbon might be important in a hot system like Cascadia and thus may explain some of the electrically conductive anomalies, as the expected P-T conditions of the slab cross the solidus of fluid-saturated metabasalt and metasediments (Fig. 3).

In the following we discuss some of the evidence to support these models, but neither model can be conclusively proven at present. There are likely geochemical analyses of lavas, as well as geophysical surveys in ideally chosen locations that would help discriminate between the water and carbon models of melt generation.

Evidence for Faulting and Fracture Zones as Agents of Fluid Transport (Cascadia, Kyushu, and South America)

The topography and faulting of the incoming plate control the amount of fluid and sediment transported to depth, and thus may explain partly the differences in the conductivity profiles observed in several subduction zones. The crustal porosity and the density of conductive faults progressively increase with proximity to the trench and represent efficient fluids pathways to the shallow part of a subduction system (Fig. 4). If these faults extend sufficiently deep, through the crust and into the mantle, then serpentinization at the trench can occur. Nicaragua is cited as an end-member case for trench serpentinitization, where the formation of deep faults is permitted by the alignment of preexisting seafloor fabric and the trench. However, to date, there are limited land-based MT data that would identify the presence of a large conductor associated with the breakdown of this serpentinite. We do not have a good contrasting profile from a system where fault orientation is oblique to the trench, nor have we constrained the porosity structure of the incoming plate to see if this really makes a difference in the fluid content of the crust and serpentinization of the mantle. Numerical models suggest that plate bending is able to generate deep faults regardless of preexisting fabric (e.g., Naliboff et al., 2013); this in turn would suggest a degree of mantle serpentinitization at all subduction systems, as long as thermal conditions permit serpentine stability. An ideal place to test variability in serpentinitization associated with preexisting fabric is in the eastern Aleutians, where adjacent segments of seafloor subduct with very different fabric alignments.

Offshore Cascadia, detailed seismic imaging points out significant along-strike variability in the density of mantle penetrating faults, suggesting that there are likely to be variations in the degree of mantle serpentinitization (Han et al., 2016), although an analysis of seismic velocities also predicts a thermal regime that is too hot to permit serpentine stability in the upper mantle (Canales et al., 2014). Convergence of the Juan de Fuca and Gorda plates beneath Cascadia is highly oblique, so that examination of seafloor morphology offshore needs to be extrapolated back to a likely point of origin that is much further south than the profile. Examination of the seafloor geology of the subduction Juan de Fuca and Gorda plates shows evidence for a region of damage (Wilson, 1988), referred to as a propagator wake, that projects to the location of the large conductor beneath the Café line. We infer that this damage zone, when at the seafloor, would have allowed a greater addition of fluid into the mantle, cooling both the crust and mantle, and possibly a greater degree of serpentinitization.

Subduction into the western side of the South American continent features many transform faults and ridges. For example, a series of fracture zones and areas of anomalously high seafloor was observed in the Chile-Peru region of the South American subduction system by Contreras-Reyes and Carrizo (2011), who showed evidence linking the subduction of seafloor that has high topographic relief (e.g., Iquique Ridge) with areas where earthquake rupture has occurred along the Chile-Peru margin. Contreras-Reyes and Carrizo (2011) hypothesized that the excess topography is related to thicker crust, but also to higher degrees of mantle serpentinization related to faulting that permits more fluids to enter the mantle. It can be difficult to distinguish between thickened crust and serpentined peridotite on the basis of seismic velocity, because there is a similarity in physical properties of gabbro and peridotite at low degrees of serpentinitization (Carlson and Miller, 1997; Hyndman and Peacock, 2003). The number of seismic surveys around seamounts or ridges with the ability to constrain serpentinitization is limited. In the Kyushu subduction zone, the high conductivity zone in the mantle wedge, which is beneath Kirishima volcano, coincides with the projection of this Kyushu-Palau Ridge in the direction of plate convergence (Hata et al., 2015, 2017). A working hypothesis is that a large release of water and hence melting are related to the subduction of this anomalous seafloor. Seismic refraction data across the ridge show anomalously thick crust ranging from 8 to 20 km (Nishizawa et al., 2007). P-wave velocities <8 km/s are seen in the uppermost mantle, but this would only support modest serpentinitization (Hyndman and Peacock, 2003), unless some of the low velocities ascribed to the lower crust are due to serpentinite.

A number of MT surveys in South America have looked at subduction zone processes (e.g., Echtcnacht et al., 1997; Brasse and Soyer, 2001; Brasse et al., 2002, 2008; Brasse and Eydam, 2008; Kühn et al., 2014). Although some of these surveys see zones of high conductivity (e.g., Brasse et al., 2002; Brasse and Soyer, 2001), the thick continental crust contains high-conductivity anomalies that mask deeper anomalies and the models do not generally image the slab and conductors associated with fluid release and melting. One exception is the region around Pocho volcano shown by Booker et al. (2004); here the arc is much further inland than the rest of the system, as the slab geometry is flat for a long distance beneath the continent before finally descending. A conductive signal associated with melt release is present to depths of at least 250 km, although the association of the conductor with the slab is not well resolved and the strength of the conductor in the mantle wedge is not as strong as some of the other anomalies we have discussed. Although there is a line of seamounts
offshore that could potentially line up with the location of the arc, the age of the slab at the point where melt is being generated makes any inference of the effects of anomalous seafloor tenuous at best. Unfortunately, although there are potentially other locations along the South American system that could identify the impacts of subduction of transform faults or ridges on the generation of melts, there are currently no suitable MT profiles that can accomplish this.

CONCLUDING REMARKS

EM surveys have great potential to improve constraints on fluid fluxes at subduction zones, both in terms of inputs from the incoming plate and outputs related to volcanism. However, we have not, for example, attempted to place constraints on melt fractions in the mantle wedge based on conductivity models. Some of the publications reporting the original results attempt to do this at varying degrees of sophistication. Putting aside issues of model resolution, some of which are tied to the slab geometry as discussed herein, a significant challenge to estimating melt fractions is knowing the interactions between aqueous fluids and the melt. As fluid is released from the slab, it has a composition and temperature that control its conductivity. These compositions are not well known and there is also some uncertainty on the fluid conductivity as a function of temperature and salinity (e.g., Sakuma and Ichiki, 2016). The fluids trigger melting, and on melting, some of the water is partitioned into the melt (e.g., Gaetani and Grove, 1998). The initial and subsequent melt composition are a function of temperature and volatile (especially water and carbon dioxide) content (e.g., Dasgupta et al., 2013) and the bulk conductivity depends on the amounts of volatiles (e.g., Pommier et al., 2008; Ni et al., 2011; Laumonier et al., 2014; Sifré et al., 2014) and melt present as well as the melt network and the nature of the melt connectivity (e.g., Miller et al., 2015). This is a highly nonlinear and complex system; we do not have sufficient understanding to place tight constraints at present, but it offers a significant challenge for future research, including critical laboratory measurements and EM profiles in well-chosen settings.

There are clearly significant primary variations in electrical structure, even within a given subduction system, that point to variability in inputs and outputs. We have suggested two possibilities for this variability that can be tested by field observations, including petrology and geochemistry.

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