Unraveling subduction zone processes: Evidence from exhumed rocks

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Introduction

Subduction zones are a major source of seismic and volcanic hazard, the site of recycling of crustal material and volatiles, and the creation of new crust that ultimately forms continents. Exhumed rocks, returned to the surface of the earth by uplift and erosion, offer the only opportunity for direct observations of the architecture, deformation mechanisms, mineralogy, and chemistry of the subduction plate interface at depths greater than drilling can reach (Moore et al., 2007). To date, ocean drilling has sampled shallow décollements and splay faults in both creeping margins (Saffer et al., 2018) and the rupture zones of great earthquakes about 1-3 km below the ocean floor (Chester et al., 2013; Tobin et al., 2019). The constraints of sample size and lack of local structural context in drill cores can be restricting, and the technological limits of drilling make it impossible to sample the depths where locking, healing and creeping behaviors are controlled or where metamorphic reactions and fluid-mineral elemental exchanges start to significantly modify the composition and structure of rocks. These rocks display the incredible complexity, diversity and richness of mechanical and chemical processes at work in subduction thrust systems and represent the key resource for understanding locking and earthquake cycles, fluid cycling, episodic tremor and slip, flux of elements from slabs to forearcs and to arc magma systems, and other processes of interest at depths greater than the limits of drilling.

From 2000-2012, MARGINS supported several field-based studies of exhumed subduction rocks. More recently (2010-present), GeoPRISMS has been supportive of the community of scientists studying exhumed rocks through research grants, support of workshops focused on exhumed rocks, and web support for initiatives like the ExTerra Field Institute and Research Endeavor project (E-FIRE). E-FIRE has involved a group of students, post-docs and faculty from nine different U.S. institutions investigating exhumed rocks through Field Institutes in the Western Alps in active collaboration with European scientists. The samples collected through E-FIRE are integrated into a shared collection that will also be made available to the public upon request. Since only a few of these types of studies have been explicitly funded by MARGINS/ GeoPRISMS grants, this contribution covers a broader range of studies and describes recent insights from research investigating subduction-related rocks.

A common goal in studies of exhumed subduction-related rocks is connecting the record of processes in the rocks to the record of processes occurring in active subduction zones. Sibson (1989) and Moore et al. (2007) laid out the argument for comparing studying exhumed rocks to geophysical observations of active margins to understand controls on locking and rupture within the seismogenic zone (approx. 150-350°C: Hyndman et al., 1997). Connections between geologic observations and active systems can be made, for example, through seismology and geophysical surveys (Abers, 2005; Moore et al., 2007), magnetotelluric and geodetic observations, and the chemistry of arc volcanic rocks (Bebout, 2007; Marschall and Schumacher, 2012). Interpreting the metamorphic mineral assemblages, deformation fabrics, and structural and chemical tracers of fluids in exhumed rocks therefore requires a broad understanding of how and why these features form under high-pressure/low-temperature and variable stress states in active subduction zones.

Contextualizing field exposures, particularly those for deeper rocks, in terms of modern plate boundaries can present a significant challenge. One important caveat is that only a fraction of subducted rocks is returned to the surface with the record of subduction-related structures and metamorphism intact and this sampling may be non-random, creating a biased sample (van Keken et al., 2018). Geophysical observations of active subduction zones typically reveal variations on the km-scale or greater while observations of exhumed rocks can be made at much smaller scales, down to the submicron-scale. Observations of processes at active subduction margins are limited to the temporal scale of human observations (hundreds of years) while geochronological methods permit accessing timescales on the order of millions of years of subduction history. Understanding sample context and being able to properly correlate processes observed in the rock record with processes in active subduction systems is especially important.

In this contribution, we describe recent themes of research on exhumed subduction-related rocks that relate to the goals of GeoPRISMS and MARGINS, highlighting studies that make connections to our observations from active subduction zones (e.g. seismic, geodetic, and geochemical studies of sediments, rocks and fluids from trenches, forearcs and arc volcanoes). Looking ahead, we also identify some areas of opportunity for future research. It will be important to determine how we can better integrate data from rocks exhumed from fossil subduction systems with observations of modern subduction zones to better understand the processes that generate dangerous volcanic eruptions and megathrust earthquakes.

Metamorphic conditions and timing of processes at the plate interface

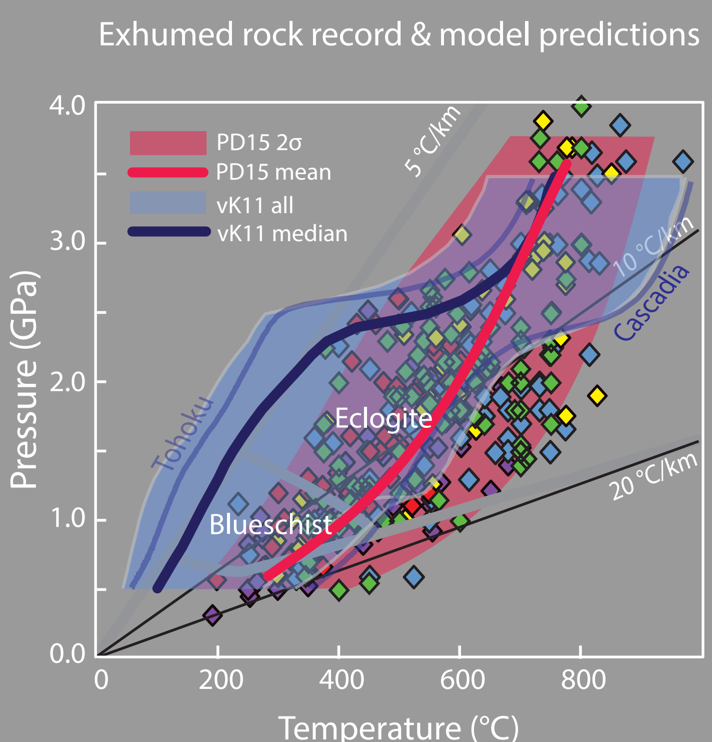
Linking exhumed rocks to particular depths, temperature conditions, or slip behaviors in active subduction zones forms the basis for applying insights from studies of exhumed rocks back to modern settings. Exhumed rocks were a key component in the understanding of subduction zones and the new paradigm of plate tectonics in the late 1960s-early 1970s. The mineral assemblages of blueschist and eclogite were found to be consistent with relatively cold temperatures for a given pressure (high pressure/temperature, written as high P/T) and this fact, along with their field relationships, led to the recognition that these were rocks exhumed from fossil subduction zones (Ernst 1970, 1971).The identification of paired metamorphic belts in which exhumed rocks containing these high P/T assemblages were found in regional-scale belts parallel to rocks containing low P/T assemblages led to the understanding of a relatively cold plate subducting underneath a relatively hot volcanic arc (Miyashiro, 1973). These studies and many others confirmed that the conditions within a subduction zone were relatively cold, but just how cold is still an outstanding question. This issue is critical as it is central to understanding the thermal structure of the plate interface, which controls the rheological behavior of materials, release of volatiles, and the cycling of elements during subduction metamorphism. Estimates of the thermal structure of the plate interface comes from prograde paths and peak P-T conditions of exhumed metamorphic rocks record temperatures that are on average 200-300°C hotter than geodynamic models of the thermal structure of modern subduction zones (see Fig. 1 for comparison, Penniston-Dorland et al., 2015; van Keken et al., 2011, 2018). This discrepancy is an active area of debate and ongoing research.

Classically, evaluation of P-T conditions has relied on equilibrium thermodynamics.This methodology relies on the underlying assumption of equilibrium among minerals in rocks, which can be problematic due to reaction kinetics. Care must also be taken in this type of analysis to avoid overprints acquired on the exhumation path. Recent advances in methods have allowed researchers to overcome some of these barriers. Advances in bulk-rock thermodynamic modeling include using thin section scale X-ray maps to properly determine the effective bulk composition of a rock (Lanari et al., 2014; Lanari and Engi, 2017). Methods for fractionating garnet from the bulk rock chemistry (Dragovic et al., 2012) allow for greater accuracy in modeling. Recent developments in trace-element thermometry (such as that based on Zr-in-rutile,Tomkins et al., 2007) require analysis of only a single phase, removing some of the concerns about equilibrium among multiple phases. Elastic thermobarometry using Raman spectroscopy (e.g., quartz in garnet;

Angel et al., 2017a, b), relying on the elastic properties of minerals, allow petrologists to explore P-T conditions recorded by rocks unhindered by assumptions of equilibrium.

At shallow depths within subduction systems where temperatures are lower than ~300-350°C, mineral growth is sluggish and not at equilibrium. Subduction-related metamorphism can be difficult to distinguish from seafloor metasomatism and/or ridge-crest metamorphism of oceanic crust. Peak temperatures can be estimated using fluid inclusion thermometry (Vrolijk et al., 1988, Hashimoto et al. 2014), clay maturity (Kawamura et al., 2011; Fukuchi et al., 2014), thermal maturity of organic molecules (Savage et al., 2014), opal diagenesis (Spinelli et al., 2006), and vitrinite reflectance (Underwood, 1989, Sakaguchi et al., 2011). Pressure, often used as a proxy for depth, is more difficult than temperature to precisely estimate. Past workers have used compaction-depth curves derived from oil industry empirical data (Moore and Allwardt, 1980) and fluid inclusion barometry, although this records fluid pressure rather than lithostatic stress (Vrolijk, 1987). Pressure and/or temperature estimates can be gained from the appearance of indicator minerals (e.g., lawsonite or jadeite in greywackes of the Franciscan Complex; Maruyama et al., 1985).

Figure 1. Comparison of P-T estimates from exhumed rocks and P-T estimates from geodynamic models. Geothermal gradients of 5° C to 20° C/km are indicated with thin black lines. Thick light gray lines show boundaries for blueschist (lower) and eclogite (upper) facies metamorphism. Colored diamonds are peak P-T estimates from exhumed rocks, different colors correspond to geographic location of data and red line and shaded red field represent the average and 2 standard deviation spread of those estimates (see Penniston-Dorland et al., 2015). Thick blue line and shaded blue field are median and spread of P-T paths from geodynamic models and P-T paths for Tohoku and Cascadia are shown as thin blue lines (van Keken et al., 2011).



Fluids and geochemical cycling

Subduction zones are sites of extensive chemical and physical exchange between Earth's surface and the mantle. Fluid release from subducting slabs may influence seismicity and is associated with the generation of the magmas that feed arc volcanic eruptions. Mass transfer associated with subduction includes cycling of volatiles such as H_2O and CO_2 between Earth's surface and deep mantle (see this issue Fischer et al. p. 40). This cycling affects the CO_2 content of Earth's atmosphere and directly impacts Earth's climate and affects Earth's habitability (Stewart et al., 2019). These volatile elements also affect the rheological behavior of deep materials both within the subduction system and deeper in the mantle. Studies of exhumed rocks contribute to our understanding of both geochemical cycling (what is returned to the surface and what continues into the mantle) and chemistry of subduction-related fluids and the nature of fluid flow. Fluid release by prograde mineral reactions has also been invoked to explain many plate boundary-scale phenomena, including the existence of double Wadati-Benioff zones (Iyer et al., 2012), and the strengthening of the slab pull force due to density increase with eclogitization (e.g. Spence, 1987).

Fluid release during subduction occurs first at shallow depths due to compaction and mechanical expulsion of fluids in the first ~3-7 km of burial (Jarrard, 2003, Saffer and Tobin, 2011). Pore fluid release by compaction may be channelized with deeper-sourced fluids along the plate boundary fault and forearc structures, modulating pore pressure conditions in those faults which affect seismic activity and forearc temperature structure (Kastner et al. 2014). Breakdown of clays and biogenic opal, along with hydrocarbon maturation, liberate significant volumes of fluid and dissolved minerals (Saffer and Tobin, 2011). Sheeted vein sets of zeolites and calcite at temperatures ~60-100° C, transitioning to calcite-quartz above 125-150° C, have been interpreted to record advection of connate and metamorphic fluids from deeper in the subducting plate (Fig 2a; Meneghini and Moore, 2007; Yamaguchi et al., 2012). Advecting fluids contribute to solution creep which forms anisotropic foliations and contributes to fault healing through cementation and veining (Rowe et al., 2011; Fagereng and den Hartog, 2017).

Further release at greater depths occurs due to prograde dehydration and decarbonation reactions (Hacker 2008). Some elements which are mobile at P-T conditions of subduction metamorphism have been defined as tracers of contributions from subducting slabs in lavas erupting from modern volcanic arcs (Elliott, 2003) (see summaries in Bebout, 2007; 2014; Bebout and Penniston-Dorland, 2016).

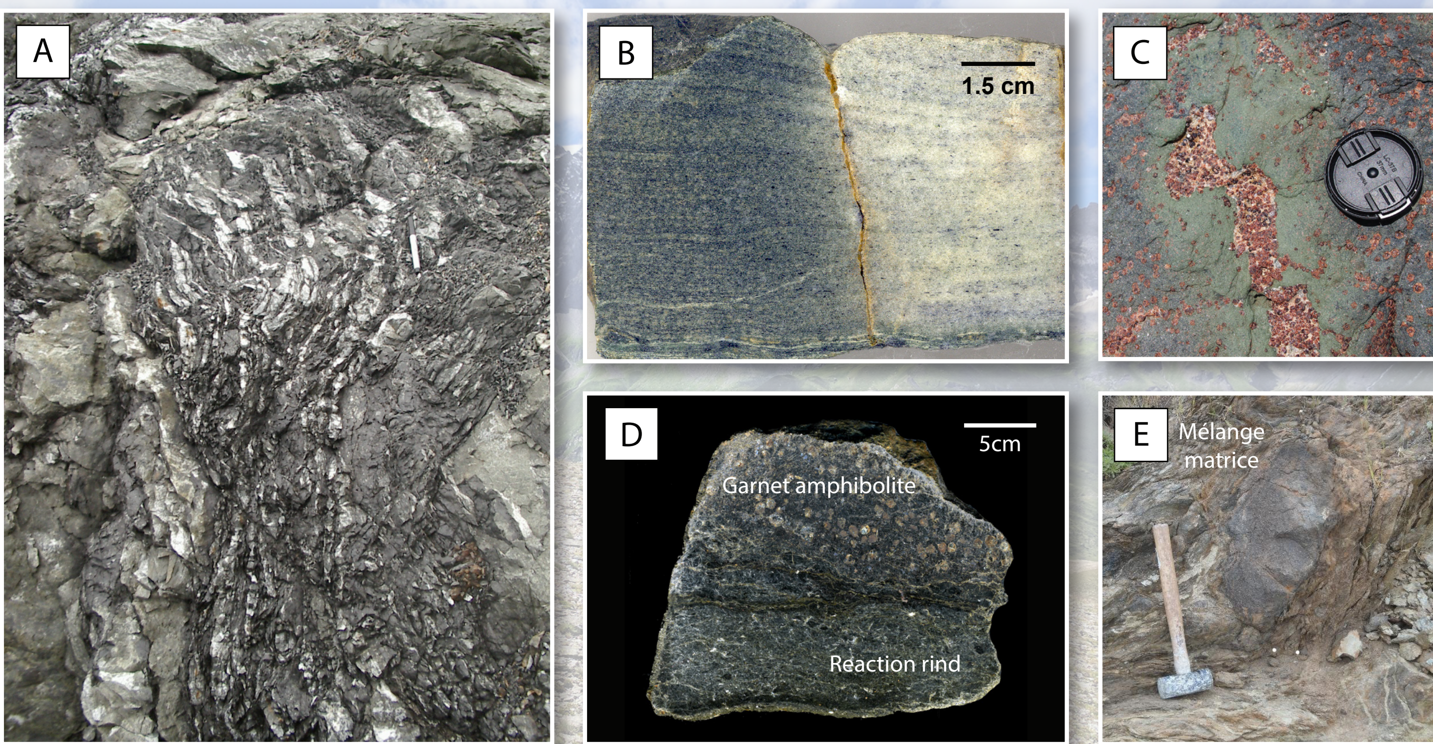


Figure 2. Images of subduction-related exhumed rocks illustrating features of fluid-rock interaction. A) Tensile veins formed by diagenetic fluid release and fracture of deforming sediments, Sitkinak Formation, AK (Moore and Allwardt, 1980). B) Layered schist with unaltered rock on the left and rock altered by infiltrating fluid which dissolved calcite on the right, Syros, Greece (Ague and Nicolescu, 2014). C) Vein in blueschist rock with eclogite reaction selvage formed due to interaction with externally-derived fluid over timescales of months, Pouébo eclogite mélange, New Caledonia (Taetz et al., 2018). D) Reaction rind surrounding garnet amphibolite block formed in part due to reaction with fluid infiltrating through mélange matrix, Catalina Schist, CA (Penniston-Dorland et al., 2014); e) Mafic block surrounded by finer-grained mélange matrix metasomatized by infiltrating fluids, Catalina Schist, CA (Bebout and Barton, 2002). Photo credit: A) C. Rowe, B) J.J. Ague, C) T. John, D) A.J. Kaufman, E) S. Penniston-Dorland.

Enrichments in these slab tracers, including large ion lithophile elements such as Ba, Rb, Cs and K in addition to U, Th and Pb found in arc volcanic rocks are reflected in enrichments of these same elements observed in exhumed metamorphic rocks (e.g., Bebout, 2007; 2014) in features such as veins, reaction rinds (Figs. 2C, 2D) and mélange zones (Fig. 2E) that are associated with fluid-rock interaction. These features are a record of channelized fluid flow released during prograde devolatilization reactions. The geochemistry of mélange zones reflects mass transport by fluids but also chemical changes due to mechanical mixing processes that lead to an unusual hybridized rock chemistry that is in many ways similar to that of arc volcanic rocks (Marschall and Schumacher, 2012; Nielsen and Marschall, 2017). The relative role of devolatilization reactions, partial melting at depth, or diapiric rise of hybridized rocks followed by shallower partial melting in driving the transfer of the slab 'signature' to arc magmas is an area of ongoing research.

While the cycling of H_2O in subduction zones has received considerable attention, recent efforts have turned towards constraining the cycling of other volatile elements, including carbon (see this issue Fischer et al. p. 40 for further discussion). Carbon is transported into the mantle during subduction bound in oceanic sediments, in altered basaltic ocean crust and possibly also as a constituent of oceanic mantle altered by serpentinization along faults in the outer rise of subduction trenches (Dasgupta and Hirschmann, 2010; Kelemen and Manning, 2015). There is considerable debate about the amount of subducted carbon that is released due to metamorphic degassing and returned to Earth's surface and the amount stored in the mantle (Piccoli et al. 2016; Scambelluri et al., 2016; Stewart et al., 2019; Menzel et al., 2020). Recent work has shed light on two major mechanisms of carbon release during subduction: decarbonation reactions involving silicates, and congruent carbonate dissolution (Fig. 2B; Frezzotti et al., 2011; Ague and Nicolescu, 2014). The latter mechanism may be more efficient at releasing a greater proportion of subducted carbonate compared to the former - a clearer picture of the fluxes of carbon produced by these two mechanisms in subduction systems is needed in order to constrain the amount of carbon returned to Earth's surface.

Arc volcano magmas are oxidized relative to other mantle-derived magmas (Kelley and Cottrell, 2009). This oxidation has been postulated to be produced due to the release of oxidized fluids from the subducting slab. Release of oxidized fluids during prograde metamorphism would result in a decrease in fO_2 of the subducting slab over time. There is evidence for such a decrease in fO_2 in metamorphic rocks during prograde subduction (e.g., Gerrits et al., 2019), consistent with such fluids contributing to the elevated oxidation state of the subarc mantle and ultimately to the oxidation of subduction zone magmas. Some candidates for these oxidizing species include sulfate and carbonate. Components such as sulfur are likely to be lost during prograde subduction (Evans et al., 2014; Walters et al., 2020), and fluids containing sulfate and other oxidized species (e.g., carbonate) have the potential to affect geochemical cycling of other chemical constituents as well. Evidence from metamorphosed serpentinites of the Western Alps suggests that the release of sulfate- or chlorine-rich fluids contributed to the loss of Fe and Zn from the rocks during prograde metamorphism (Debret et al., 2014; 2016; Pons et al., 2016). Other possibilities for oxidation of the subarc mantle wedge include reactions involving H^+ dissolved in the aqueous fluid (Iacovino et al., 2020) or oxidation of the mantle wedge due to interaction with ascending melt that is progressively oxidized due to H_2 loss to orthopyroxene during melt ascent (Tollan and Hermann, 2019).

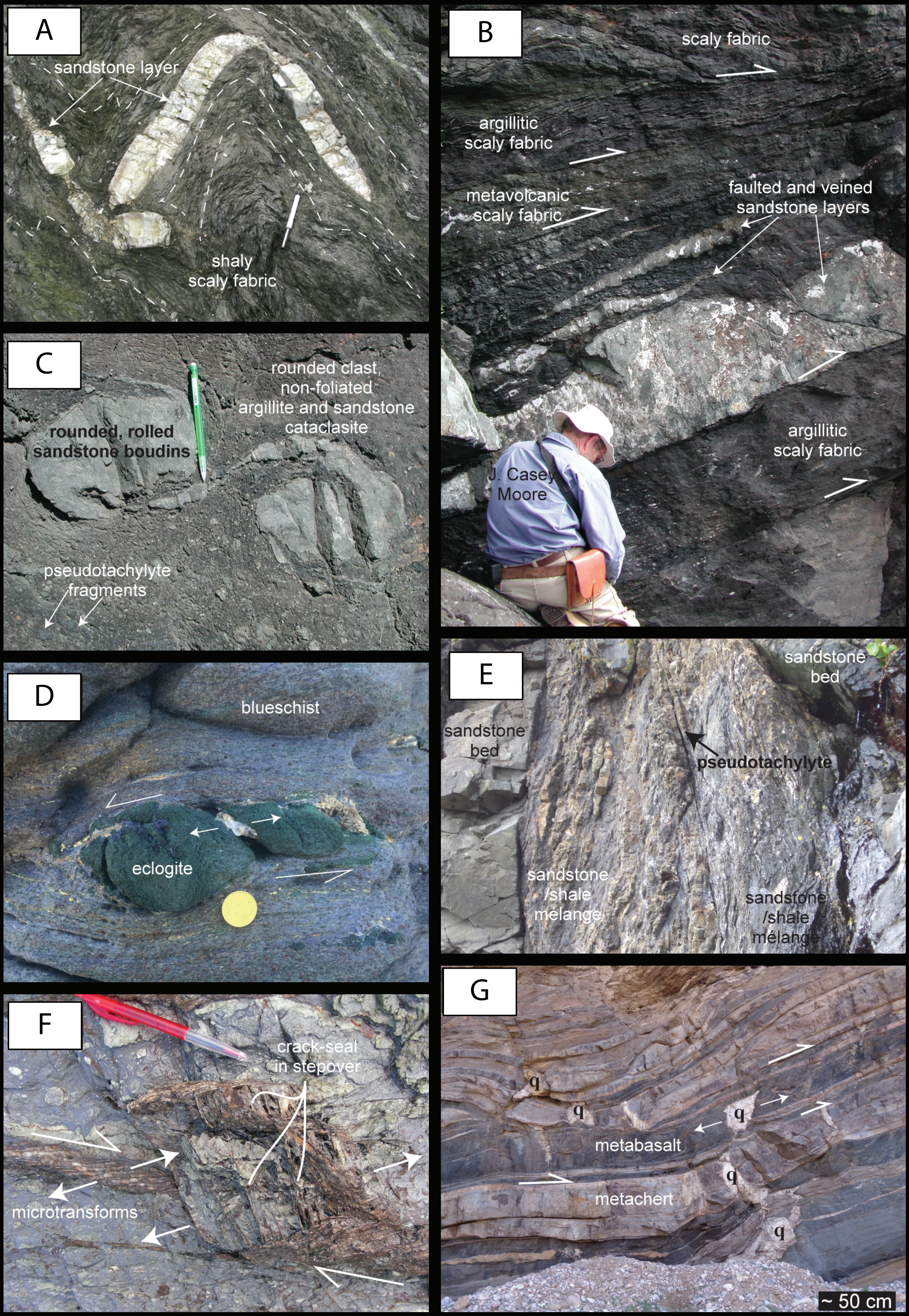
The mechanisms by which the fluids escape from the relatively low-permeability high-pressure rocks in which they are generated are not well understood (Ague, 2007; Zack and John, 2007). Seismic velocity models of subduction zones are sensitive to fluid content in the subducting slab (Bloch et al., 2018) and along the plate boundary (Audet and Schaeffer, 2018). The locations of episodic tremor and slip are correlated with low P-wave velocity zones interpreted to indicate high fluid content (Shiina et al., 2013; Audet and Schaeffer, 2018), which correspond with model predictions of the loci of metamorphic dehydration (Rondenay et al., 2008; van Keken et al., 2012). Fluid production has been associated with tremor and slip observed in active subduction zones at depths up to ~50 km, including slow slip events and non-volcanic tremor (Fagereng and Diener, 2011; Cruz-Atienza et al., 2018). Exhumed rocks provide clues related to fluid production, including the nature of the release of metamorphic fluids, the paths that fluids take once released, and the duration of fluid flow. Many studies focus on the role of fluid overpressure in brittle fracturing of rocks resulting in fluid flow through these fractures, producing veins (Fig 2a; Compton et al., 2017; Tarling et al., 2019; Nishiyama et al., 2020).

In addition, recent work (Plümper et al., 2017) provides evidence that small, micron-scale channelization of fluid produced by dehydration reactions developed in metamorphosed serpentinites because of chemical heterogeneities in the rocks. These heterogeneities resulted in differential development of reaction porosity, which acts to focus fluids as they are released. This small-scale process is thought to lead to larger-scale channelization of fluid escape through veins that are observed in many subduction-related terranes without requiring fluid overpressure. Advances in geochronology have allowed geologists to be able to determine timescales of processes that are longer than those observed in active subduction systems. Dating of different growth zones in garnets show that prograde fluid release that formed garnets occurred in short pulses associated with heating in events that lasted less than 1 Myr (Dragovic et al., 2012; 2015). Other studies focused on fluid flow pathways have used diffusion speedometry to infer the duration of fluid-rock interactions. These studies have revealed even shorter timescales representing the duration of fluid flow on the order of days to thousands of years (Fig. 2C; Penniston-Dorland et al., 2010; John et al., 2012; Taetz et al., 2018). These short-duration fluid release events have been linked to seismic and non-seismic slip phenomena at the plate interface (Taetz et al., 2018).

Deformation and rheology

Field studies of exhumed faults allow direct observation at the scales which control plate boundary strength. Deformation is mainly studied at the crystal lattice or grain scale, far below the scale of resolution for observing processes at active tectonic plate boundaries such as interface coupling, earthquake mechanics, transient slip/creep, fluid flow events, and steady-state creep. Numerical and geodetic models yield surface displacement fields associated with plate boundary deformation, most commonly using rate-and-state friction with elastic plates, and viscoelastic and/or viscous plates and upper asthenosphere (Gerya, 2011, Gao and Wang, 2017). In most cases, these models prescribe simplified rheological properties to a geometrically abstracted plate boundary architecture. Exhumed rock studies can bridge the gap by identifying the scales of importance, the minerals and the structures responsible for regional deformation and enabling selection of the most appropriate rheologic models (Moore et al., 2007; Wang et al. 2012, Agard et al., 2018, Bilek and Lay, 2018).

Figure 3. Evidence of mixed-mode deformation in exhumed subduction faults. a) Flattening boudinage of sand layer and scaly shale, fabric folded (~125°C, 2-4 km depth, Sitkalidak Island, AK); b) Boudinage of thin sand layers, sharp faults cutting along lower edge of thick sand layer in scaly black shale matrix (~250°C, 12-14 km depth, Pasagshak Point, AK); c) "Snowball" sandstone boudins reveal granular flow as disturbance of bedding-scale sedimentary structures with rounding of rock fragments, Pasagshak Point (Rowe et al., 2011); d) Eclogite with extensional veins boudinaged in garnet blueschist matrix, illustrating competency contrast, Kini Beach, Syros, Greece (Kotowski and Behr 2019); e) Pseudotachylyte cross cuts fragmented sandstone boudins in argillite matrix (Ujiie et al., 2007); f) Crack-seal veins in a record 10s micron-scale increments of slip and opening consistent with low frequency earthquake scaling (~300°C, Crystalls Beach mélange, Fagereng et al. 2010); g) Boudinaged metabasalt and meta chert in metapelite matrix, boudin-normal quartz veins, (~600°C, Damara Belt, Fagereng et al. 2014). Photos a-c) C. Rowe, d) A. Kotowski, e) K. Ujiie, f-g) Å. Fagereng.


A
sandstone layer
shaly
scaly fabric
B
scaly fabric
argillitic
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metavolcanic
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C
rounded clast,
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argillite and sandstone
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Tectonic underplating may preserve subduction plate boundary fault surfaces, enabling observation of local structural architecture in field studies of faults from 15 km depth (Kato et al., 2004, Kimura et al., 2012, Rowe et al., 2013, Agard et al., 2016; Regalla et al., 2018), but often, especially for deeper examples, reactivation and retrogression during exhumation and the development of exhumation-related structures overprint original geometries and kinematic indicators (Ring and Brandon, 1994, Tembayashi et al., 1996, Mihalynuk et al., 2004). Field and microstructural studies of exhumed plate boundary faults reveal the action of multiple deformation mechanisms in complex geometric arrangements, most of which are poorly understood in terms of their rheology, and both mechanisms and rheology change dramatically with depth in the subduction zone. Snapshots of structural complexities in exhumed faults show that changes in material properties during deformation affect strain localization, fluid pressure and fluid distribution, and trade-offs between deformation mechanisms, which all impact strength and rheology of the plate boundary. Observations of deformation mechanisms, scale and geometry of deforming zones, and changes in localization with time can directly contribute to models of subduction plate boundary processes which more closely approximate the relevant characteristics of the natural system.

Studies of drill core from accretionary wedges (for the shallowest examples) and exhumed rocks and faults from subduction zones provide insight into the mechanisms and architecture of the plate boundary zone, and their evolution with depth. Discrete faults accommodating localized slip develop very shallowly (Rowe et al., 2013), synchronous with distributed granular flow in subducting sediments which is prevalent in the uppermost few kilometers (Figs. 3A, C; Fagereng et al., 2019), and may take up a significant component of shear strain while facilitating consolidation, contributing to the formation of scaly fabrics in clay-rich sediments (Figs. 3A, B; Karig, 1990, Vannucchi et al., 2003, Vannucchi, 2019). The rheology of granular deformation is difficult to describe (Chaudhuri et al. 2012), but strong feedbacks between shear strength and pore fluid pressure (Xing et al., 2019) are reflected in correlations between deformation events and pressure transients measured in borehole observatories (Davis et al. 2011; 2013, Araki et al., 2017). Dissolution-precipitation begins to modify the mineralogy and fabrics in subducting sediments very soon after burial (Moore et al., 1986; Vannucchi, 2019).

At depths of ~5-10 km, subducting sediments begin to lithify and subduction thrusts begin to lock and generate earthquakes (Fagereng, 2011, Almeida et al., 2018). In the plate boundary, mixed-mode deformation becomes prevalent and tectonic mélanges form, with stiffer lithologies forming blocks within a finer grained, phyllosilicate-rich matrix (Fisher and Byrne, 1987; Byrne 1982, Kimura et al., 2012). At temperatures below ~350°C, most structural fabrics are attributable to the action of more than one deformation mechanism acting in concert (Figs. 3A-C; e.g., dissolution-precipitation and both localized and distributed frictional sliding, granular flow, and tensile fracturing; Rowe et al. 2011; Wassmann and Stöckhert, 2013; Ujiie and Kimura, 2014; Fagereng and den Hartog, 2017).

At higher temperatures (≥300°C), dissolution-precipitation creep is more efficient (Gratier et al., 1999; Stöckhert et al., 1999) and crystal plastic deformation becomes prevalent in some minerals, leading to more crystalline textures with interlocking grain boundaries, lower permeability rock with deformation fabrics which are more consistently aligned with shear and flattening plane orientations (Figs. 3D-G). The deformation behavior of most minerals in greenschist-blueschist-eclogite metabasites is not well known from experiments, but the appearance of crystallographic preferred orientations demonstrates the prevalence of dislocation creep, sometimes in addition to solution creep, predicting bulk viscous (as opposed to frictional) behavior (Fig. 3; Kim et al., 2012; Kotowski and Behr, 2019, also see Wheeler, 1992). The combined action of multiple grain-scale deformation mechanisms contributes to more distributed strain, forming increasingly penetrative foliations (Behr and Platt, 2013; Angiboust et al., 2015; Kotowski and Behr, 2019).

The introduction of serpentinite from the subducting plate through faulting of the oceanic crust (Polonia et al., 2017) or from mantle hydration of the upper plate, can have dramatic effect on the plate boundary strength. Serpentinites are frictionally very weak and deform viscously at low shear stresses compared to other rock types at the same conditions (Hirth and Guillot, 2013). The near disappearance of earthquake hypocenters in the plate boundary at depths below the upper plate Moho has been attributed to the probable low shear stress and tendency to creep in serpentinite (Hyndman et al., 1997, Peacock and Hyndman, 1999).

The spectrum of slip rates in subduction zones has been the focus of considerable research during the GeoPRISMS decade (Peng and Gomberg, 2010, Araki et al., 2017). Field observations of exhumed faults have contributed phenomenological models of how deformation at different slip speeds is accommodated, whether on discrete faults or through volumetric strain, and over what scales.

Sharp through-going faults experience transient temperature spikes during earthquakes which are preserved in many forms. One spectacular example is pseudotachylytes (Fig. 3E, Ikesawa et al. 2003, Austrheim and Andersen, 2004; Kitamura et al., 2005, Rowe et al., 2005, Andersen and Austrheim, 2006, Ujiie et al., 2007). Pseudotachylytes are rarely identified due to post-seismic alteration and deformation (Kirkpatrick and Rowe, 2013; Phillips et al., 2019), but new methods for are expanding the possibilities of detecting heat spikes caused by past seismic slip, including organic molecule thermal maturity (Savage et al., 2014, Rabinowitz et al., 2020), fluid inclusion stretching (Ujiie et al. 2008), and clay metamorphism (Kameda et al., 2011). Brittle deformation is also evident in rocks exhumed from deeper within the subduction system. For example, eclogite facies breccias have been linked to transient, periodic intermediate-depth (80 km) rupture and associated fluid flow (Angiboust et al., 2012; Hertgen et al., 2017; Locatelli et al., 2018; Broadwell et al., 2019).

In addition to evidence for past earthquakes, exhumed plate boundary faults and shear zones record evidence for mixed brittle-ductile behavior that may correspond to geophysical observations of creep or slip transients such as episodic tremor and slip, across a variety of depth and temperature conditions. The ubiquity of these patterns suggests that diverse micromechanical processes may result in similar plate boundary behavior (Kirkpatrick et al., submitted). The mixed brittle-ductile behavior is recorded by block-in-matrix fabrics with anastomosing fault systems. These geometries originate in shallowly subducted sediments when disruption of stratigraphic layers is driven by contrasts in strength and permeability: coarser grained sandstones and volcanic rock experience consolidation, cementation, fracturing and draining, while phyllosilicate-rich layers of shale and altered basalt develop strong foliations which accommodate viscous creep (Fig. 3; Moore and Saffer, 2001, Phillips et al., 2020). Block-in-matrix fabrics may also arise through progressive, structurally controlled dehydration of blueschist to eclogite, or metamorphism of mixed lithologies which produce a dramatic strength contrast (Hayman and Lavier, 2014, Behr et al., 2018, Kotowski and Behr, 2019). Vein patterns may record high and fluctuating pore pressure (Ujiie et al. 2018, Fagereng et al., 2018, Tarling et al., 2019) on short timescales (Fisher and Brantley, 1992; 2014), which has been linked to tremor and slip in modern subduction zones (Audet and Schaffer 2018). Studies of exhumed faults have revealed the details of many processes, but outstanding questions remain, such as how strain and stress are transferred from deeper creeping zones to the seismogenic zone, how structures control fluid flow and pore pressure, and how to characterize plate boundary rheology and on what scales.

Exhumation

In most subduction complexes, the mechanisms and pathways of exhumation of subducted oceanic crust are poorly known and this represents a growth opportunity for future studies. Models for exhumation include 1) underplating and exhumation due to extensional uplift and erosion (Platt, 1975; 1986), 2) return flow of material along the plate boundary interface returning fragments of metamorphosed oceanic slab to the trench (Cloos, 1982), and 3) buoyancy-driven diapiric rise of high pressure blocks entrained in serpentinite or mélange matrix (Takasu, 1989; Platt, 1993; Marschall and Schumacher, 2012). Evaluation of the exhumed rock record suggests that exhumation occurs in short-lived episodes at varying times during the life of a subduction zone (Agard et al., 2009, Guillot et al., 2009, Husson et al., 2009). Estimates for rates of exhumation vary but are typically less than plate velocities (Agard et al., 2009; 2018) and few oceanic crustal rocks are recovered from depths >80 km (Plunder et al., 2015). Recent advances in geochronology such as (U-Th)/He dating of magnetite (Cooperdock and Stockli, 2016), Lu-Hf dating of lawsonite (Mulcahy et al., 2009), and Ar/Ar dating on various minerals (Rutte et al., 2020) allow geologists to determine the timing of exhumation-related processes such as serpentinization and retrograde metamorphism.

Understanding the effects of fluid-rock interaction (e.g. Miller et al., 2002) and structural modification during exhumation will elucidate the mechanisms of exhumation of subducted rocks which are critical to connecting them to the records of active subduction.

Heading into the future

The many outstanding questions described above can be addressed through future studies of exhumed rocks. Information about important earth processes can also be gained by exploring differences between observations and modeling of active subduction zones and observations and modeling based on outcrop data. Areas of active debate include questions of how the thermal structure of subduction zones has changed over time (van Hunen and Moyen, 2012; Brown and Johnson, 2019; Palin et al., 2020) and how this change might affect the comparison between exhumed rocks and observations of active subduction. Another actively investigated question is whether the process of exhumation itself impacts the rock record of subduction - through preferential return of samples or through exhumation-related modification of subduction conditions (Penniston-Dorland et al., 2015; van Keken et al., 2018; Agard et al., 2018). Advances in geochronology are revealing processes and timing of subduction initiation (Mulcahy et al., 2018) and retrogression/exhumation (Mulcahy et al. 2009; Bröcker et al., 2013). Shear stress on the plate interface at depth influences slip and creep, but we have few tools for interrogating shear or differential stress. It has been suggested that mineral equilibria may be affected by differential stress, which is not presently accounted for in pseudosection modeling but could potentially be leveraged as a paleopiezometer (Wheeler, 2018). Integrated structural and petrologic studies extend our capacity for unraveling the deformational and metamorphic history (Pollok et al., 2008).

Many subduction complexes are well-known in the literature (e.g., the Franciscan Complex in California, and Shimanto Belt in Japan) but others have barely been explored (e.g., the Damara Southern Zone in Namibia; Meneghini et al., 2014, and Gariep Belt in South Africa; Frimmel et al., 1996) and represent the possibility of using analog fossil subduction zones to understand individual modern plate boundaries. Future research should strive to better integrate data from rocks exhumed from fossil subduction systems with observations of active subduction, as these rocks provide the perspective of longer timescales and shorter lengthscales inaccessible to methods of observing modern subduction systems. Collaborative training initiatives such as the E-FIRE project are a great way to prepare future generations to work together to achieve these goals under the umbrella of interdisciplinary communities such as GeoPRISMS.

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