Thanks to its unique chemical and mechanical properties, garnet records evidence of rocks’ paths through the crust at tectonic plate boundaries. The compositions of garnet and coexisting mineral phases permit metamorphic pressure and temperature to be determined, while garnet’s compositional zoning allows the evolution of these parameters to be constrained. But careful study of garnet reveals far more, including the dehydration history of subducted oceanic crust, the depths reached during the earliest stages of continental collision, and the mechanisms driving heat and mass flow as orogens develop. Overall, chemical and textural characterization of garnet can be coupled with thermodynamic, thermoelastic, geochronologic, diffusion, and geodynamic models to constrain the evolution of rocks in a wide variety of settings.

**INTRODUCTION**

Garnet plays a special role in revealing the thermal and mechanical processes controlling the evolution of Earth’s crust at plate boundaries. In particular, after geologists recognized that specific indicator minerals and preserved garnet compositions can be used as reliable proxies for metamorphic grade, garnet gradually assumed a central position for inferring depths, temperatures, and durations of metamorphism, metasomatism, deformation, and melting. Its unique compositional and mechanical characteristics provide sensitive records of metamorphic conditions, and these records are commonly far better preserved and easier to interpret than in other minerals. Furthermore, its stability over a wide range of temperatures and crustal depths (Fig. 1) permits its use in remarkably diverse tectonic settings. Here, we illustrate garnet’s power by concentrating on three evolutionary stages of destructive tectonic plate boundaries: subduction of oceanic crust, subduction of continental crust as an early phase of collision, and crustal thickening during continent–continent collision. Metamorphic garnet growth occurs at key stages in the evolution of each of these systems and has proven invaluable for understanding each process. In the absence of garnet (or any understanding of its properties), our knowledge of the processes and rates of evolution of plate boundaries would be far poorer, particularly as garnet growth can often be placed within the context of other events in the evolving rock package (e.g. rapid burial or heating, growth or decay of other metamorphic phases, and dehydration).

**DETERMINING METAMORPHIC PRESSURE AND TEMPERATURE**

Conditions of thermodynamic equilibrium and mass balance interrelate mineral compositions, mineral abundances, pressure (P), and temperature (T) (e.g. Spear 1988), and garnet compositions in equilibrium with other minerals are commonly employed for quantitative calculation of metamorphic conditions. Garnet’s prominent role arises crystallographically because its large cubic site favors Fe rather than Mg and can accept Ca and Mn (Fig. 1). A high Fe/Mg ratio imparts temperature sensitivity to numerous Fe–Mg-exchange thermometers involving minerals such as chlorite, biotite, hornblende, and pyroxene, whose octahedral sites prefer Mg. Garnet’s high density means that reactions involving low-density plagioclase are highly sensitive to pressure. The analysis of appropriate coexisting mineral compositions has thus been the basis of metamorphic P–T determination for more than 30 years. Many calibrations of compositional relationships between garnet and coexisting phases as functions of P and T have been proposed and refined as new natural and experimental constraints have emerged. It is beyond the scope of this article to list these, but the reader is directed to Spear (1993) for more information.

Consider the implications of such mineral equilibria. If garnet’s abundance and chemistry in a rock reflect a particular P and T, then changes in P and T should drive changes in garnet’s modal abundance and composition. Reactions cannot proceed at true thermodynamic equilibrium, so in nature, oversteps in P and T (and thus time, t) are required to approach equilibrium at the thin section scale (for more information on kinetic controls on metamorphic equilibration, see Ague and Carlson 2013 this issue). If changing P and T cause garnet to grow, intracrystalline diffusion is not too fast, then garnet crystals may encode a series of near-equilibrium compositions from their core to their rim (which can be visualized by assuming equilibrium crystal growth along an arbitrary P–T vector in Figure 1). Such simple growth zoning is extremely common at intermediate metamorphic grades in a variety of tectonic settings, where garnet crystals generally grow upon heating and/or loading, and it usually manifests itself as decreasing Mn and increasing Mg from core to rim (Fig. 2). Ca and
Fe may increase or decrease, depending on the exact P–T path, the reactivity of other minerals such as plagioclase, and changes in the mineral assemblage. Decreasing core-to-rim Mn and heavy rare earth elements (HREEs) also reflect these elements’ typically low bulk-rock abundances and strong preferential incorporation into garnet over many other major phases, resulting in progressive fractionation from the reactive matrix during garnet growth (e.g. Hollister 1966).

If rocks continue to heat up, intracrystalline diffusion eventually flattens and destroys prograde zoning, usually at upper amphibolite to granulite facies conditions (Yardley 1977). Even at lower temperatures and during rapid metamorphism, compositions associated with specific P–T conditions of growth can be lost through diffusion long before peak metamorphic conditions are reached, while still retaining broadly “prograde” zoning patterns (e.g. Florence and Spear 1991; Caddick et al. 2010). During cooling, reverse profiles can develop (i.e. increasing Mn and decreasing Mg towards the rim; Tracy et al. 1976; Fig. 2c, d), especially if garnet partially dissolves and previously sequestered components are liberated. The repercussions of such changes for thermobarometry are clear: erroneous peak-metamorphic P–T conditions will be inferred if original equilibrium compositions are assumed to be preserved yet have actually been modified. However, numerous strategies have been devised in attempts to counter this modification (e.g. Pattison et al. 2003) or to use it as a way of constraining rates of metamorphic processes (e.g. Spear and Parrish 1996).

If chemical zoning in garnet progressively records its passage through P–T space, surely we must be able to retrieve information about this journey from the zoning. Indeed, thermodynamic inversion of preserved growth zoning in garnet is a powerful method for inferring a rock’s P–T history, which in turn provides insight into tectonic processes (e.g. Spear et al. 1984). That is, if changes in P and T (ΔP and ΔT) cause compositional changes in a zoned garnet, one can invert these changes to infer ΔP and ΔT. Different practitioners apply somewhat different methods for this inversion, specifically either employing thermodynamic interrelationships alone (which requires more composition measurements but fewer assumptions) or including rock-specific mass balance constraints (which requires fewer composition measurements but more assumptions). Spear (1993) details these different methods, which are further illustrated below.

Forward modeling of garnet composition by calculating equilibria for a specific rock composition (e.g. Fig. 1) has become an increasingly important way of deciphering metamorphic histories due to the acquisition of thermodynamic data and the development of models for an ever-expanding range of minerals, fluids, and melts (see, for example, reviews in volume 6, issue 5 of Elements). The sequestration of garnet-forming elements into the cores of growing crystals, however, will progressively deplete the “residual” rock, effectively requiring stepwise recalculating of the phase equilibria in many cases. Increasingly sophisticated methodology now records fractionation of both porphyroblast-forming phases and evolved fluids, and it can predict the suite of mineral phases that might be trapped as inclusions along specific P–T paths and the composition of those phases (e.g. Konrad-Schmolke et al. 2005). Prediction of changing garnet composition through P–T evolution has revealed the metamorphic histories of rocks from a variety of tectonic settings, which we summarize here with respect to three stages in the evolution of a destructive plate boundary.

**SUBDUCTION OF OCEANIC CRUST**

Garnet plays a signature role in unraveling subduction geodynamics and elucidating fluid-mediated mass transfer processes across the slab–mantle interface, with implications for arc magmatism and mantle geochemistry (e.g. Bebout 2007). Deciphering P–T evolution in subduction zones is required to estimate paleosubduction rates and exhumation processes, and currently, there is particular interest in understanding the maximum depths that rocks...
However, such interpretation (and a broader discussion of the development of extensional shear zones) requires very accurate constraint of the evolving metamorphic conditions of individual metamorphic rocks. Fortunately, garnet is abundant in subducted oceanic crust, and its sedimentary cover (e.g., Fig. 3a). High $P$ in subduction zone settings initiates growth at temperatures as low as 300°C, and low peak $T$ prevents substantial diffusive modification of its chemical record of subduction processes. In contrast to other mineral equilibria, which may reflect resetting during exhumation, garnet-based equilibria for Sifnos consistently indicate maximum $P$ values of $\leq 1.7$ GPa, and textural evidence suggests that this reflects overgrowth following an earlier lawsonite-blueschist metamorphic stage (Forster and Lister 2005). Although exhumation-related breakdown of garnet did occur in some Sifnos lithologies, many samples preserve strong evidence for near-peak conditions in which garnet composition has not been strongly modified after apparent equilibration. Indeed, recent studies (g to h in Fig. 3c) that combined garnet and coexisting mineral compositions with phase equilibria and microtextural constraints (e.g., the presence of reaction products from lawsonite breakdown) suggest that some of Sifnos’s blueschists reached $\sim 2.2$ GPa, some 50 km deeper than paths based primarily on pyroxene and phengite compositions (e.g., a to c in Fig. 3c).

In addition to garnet’s chemical advantages, novel application of Raman spectroscopy to quartz inclusions in garnet from Sifnos’s blueschist–eclogite unit confirms maximum pressure of approximately 2.0 GPa (Ashley et al. 2012). In the latter case, the physical properties of garnet, especially its high bulk modulus, protect inclusions from post-entrapment pressure variation. In particular, core-to-rim inclusion suites suggest minimal compression during garnet growth over a temperature interval of approximately 100°C. Available evidence based on multizone Sm–Nd analyses of garnet further implies that this heating required $< 1$ My (Dragovic et al. 2012). The tectonic configuration that produces this phase of heating and then exhumation can reach while still retaining the possibility of exhumation. Whereas estimating temperature has proven relatively straightforward from phase equilibria, trace element thermometers, and major element exchange thermometers, estimating pressures accurately has proven elusive. For example, estimates of maximum pressure for blueschist–eclogite rocks of Sifnos island, Greece, range from 1.4 to 2.4 GPa (55–85 km depth; Fig. 3a, c), but maximum temperature is relatively well constrained at $\sim 500$ to $550$ °C. It is possible that this wide $P$ range partly reflects tectonic juxtaposition of rocks with diverse subduction histories; multiple high-$P$ deformation and metamorphism stages have been interpreted in these rocks from microstructurally distinct mineral-growth episodes (Forster and Lister 2005), and pervasive overprinting of much of the island is associated with the development of extensional shear zones. However, such interpretation (and a broader discussion of the importance of mélangé zones in facilitating exhumation) requires very accurate constraint of the evolving metamorphic conditions of individual metamorphic rocks.

**FIGURE 2** (A–F) X-ray maps of Himalayan garnet crystals. Concentric decreases in Mn and increases in Mg from core to rim in LHS and THS garnet grains reflect simple growth zoning. Reverse zoning in GHS garnet reflects resorption and diffusional reequilibration. The numbers are percent spessartine (Mn) and pyrope (Mg) components in core and rim. Scale bars are 500 µm. LHS = Lesser Himalayan Sequence; THS = Tethyan Himalayan Sequence; GHS = Greater Himalayan Sequence.

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**FIGURE 3** (A) Geological sketch map of the island of Sifnos, Greece, after Matthews and Schliestedt (1984). (B) Large garnet porphyroblasts in an amphibole-rich matrix at Paros, Greece. (C) Summarized $P$–$T$ constraints from Sifnos, Greece, modified after Ashley et al. (2012); see Dragovic et al. (2012) for the cited literature.
requires further investigation, but both the chemical and physical properties of garnet play an important role in establishing important constraints on subduction pressures and temperatures, and on the duration of their evolution.

Subduction zone metamorphic fluids may influence or control volatile flux into the mantle, arc-magma genesis, physical properties including seismicity, and the global circulation of H\textsubscript{2}O (e.g. Kerrick and Connolly 2001; Hacker 2008). Although the production of fluid is typically difficult to detect, most dehydration reactions produce both H\textsubscript{2}O and garnet. Thus, the P–T–t history of garnet growth directly records part of the history of fluid generation (e.g. Baxter and Caddick 2013), with the breakdown of specific hydrous parent phases (e.g. lawsonite) representing particularly important volatile sources. Models for subduction zone metamorphism of both hydrated basalts and pelitic rocks suggest that extensive garnet growth between 1.4 and 3.0 GPa is coupled with significant fluid production. As such, the ~100 °C of heating at ~65 km depth inferred above for Sifnos probably generated a distinct pulse of hydrous fluid (Dragovic et al. 2012), consistent with the short-lived channelized fluid pulses interpreted for other subduction zones based on geochemical and isotopic traces (John et al. 2012), predicted from phase equilibria (Schmidt 2008). Although the production of fluid is typically diff-}

**SUBDUCTION OF CONTINENTAL MATERIAL**

The early stages of orogenesis can involve subduction of continental material to ≥100 km depth, but the scarce rocks exhumed from these conditions invariably contain an enigmatic metamorphic record of their journey. Indeed, these rocks often contain no strong evidence for ultrahigh-pressure (UHP) conditions, because key indicator minerals either never transformed to high-pressure polymorphs (e.g. diamond or coesite) or experienced almost complete inversion to low-pressure forms (graphite and quartz). However, as in the case of oceanic subduction, garnet plays a key role in evaluating geodynamic scenarios that permit deep subduction and subsequent exhumation, primarily by elucidating depths, temperatures, and burial/exhumation rates.

The preservation of coesite as inclusions in garnet led to the first unambiguous evidence of UHP conditions in rocks from the Dora-Maira massif, Italy (Chopin 1984; reviewed in Elements volume 9, number 4). These samples, which contain abundant matrix quartz, characteristically exhibit coesite inclusions surrounded by polygonal quartz haloes and cracks radiating into the Mg-rich host garnet (Fig. 4). Clearly, these rocks equilibrated at coesite-stable pressures but failed to preserve such evidence except where the inclusions were shielded by garnet. As in the Sifnos example, the physical properties of garnet allow large pressure gradients to be preserved, although it is clearer here that these supported gradients must be of the order of several gigapascals over millimeter length scales. P–T histories for these southern Dora-Maira rocks now indicate that maximum pressures reached or exceeded 3.5 GPa (ca 120 km depth), at temperatures in the range of 700–800°C (Fig. 5n). Perhaps surprisingly, given the high temperature from which they cooled and depth from which they exhumed, southern Dora-Maira garnet crystals still preserve some evidence of zoning that is interpreted to be due to growth during burial. This interpretation concurs with other evidence implying rapid exhumation at rates of >3 cm y\textsuperscript{-1} (e.g. Rubatto and Hermann 2001).

Garnet from northern Dora-Maira tells a different story through its preserved compositional zoning (Fig. 5a, b). Forward modeling of mineral abundance and composition for an appropriate rock composition suggests that the outer-

**FIGURE 4** Garnet from a southern Dora-Maira (Case Ramello) whiteschist in plane-polarized light (A) and under crossed polarizers (B). Highlighted inclusions of coesite are rimmed by a thin, polycrystalline quartz halo (palisade texture). In the rock matrix (upper left of each image), quartz is the only SiO\textsubscript{2} polymorph present. COURTESY OF R. TRACY

**FIGURE 5** (A, B) Strongly zoned garnet from a chloritoid–garnet schist (northern Dora-Maira massif), from Gasco et al. (2011). (C) Modeled garnet compositions for this sample (from Gasco et al. 2011). Blue lines = X\textsubscript{Alps}; red lines = mol% grossular; yellow fields represent the compositions of the inner and outer garnet “mantle” labeled in panel A; underlying gray shading denotes thermodynamic variance (darker = higher variance). (D) Resultant P–T path for this sample (blue line) compared to the paths for coesite-bearing southern Dora-Maira samples like that in Figure 4. The green and red paths are from Castelli et al. (2007) and Rubatto and Hermann (2001), respectively.

most parts of these crystals record growth during both decompression and heating (Gasco et al. 2011; Fig. 5c, d). There is little evidence that these samples reached the high P and T seen by the coesite-bearing samples from farther south, confirming earlier suggestions that the Dora-Maira massif represents at least three tectonic slices, each of which experienced different early-Alpine conditions before later juxtaposition.
**Continent–Continental Collision**

Garnet-based *P–T* paths are particularly useful because the shape of the path distinguishes tectonic processes (Spear et al. 1984; Thompson and England 1984). For example, recent debate about Himalayan geodynamics centers on the magnitude of lower-crustal flow. Large-scale flow, or “channel flow,” transports heat and mass laterally in response to focused erosion at the orogenic front (Fig. 6A). In contrast, classic models of orogenic (critical) wedges commonly infer progressive in-sequence thrusting, potentially interspersed with extensional events, generally in response to distributed erosion; this maintains a regular, material-specific geometry without requiring lower-crustal flow (Fig. 6B). These two end-members predict distinctly different metamorphic *P–T* paths (Kohn 2008). Channel flow’s profound lateral heat transport virtually contact metamorphoses over- and underlying rocks at nearly constant pressure. In contrast, thrust duplexing rapidly loads rocks as a higher thrust is emplaced, then soon after exhumes them as the next lower thrust activates. Thus garnet above and below a flowing channel should record isobaric heating over many tens of degrees Celsius, whereas, depending on thrusting and erosion rates, thrust-duplex garnet should record either loading or possibly exhumation with slight heating (Fig. 6).

This geodynamics debate has focused on the metamorphic core of the Himalaya, specifically migmatitic rocks of the Greater Himalayan Sequence (GHS), which are sandwiched between mid-amphibolite facies rocks of the Lesser Himalayan Sequence (LHS), below, and the Tethyan Himalayan Sequence (THS), above (Fig. 6). Thus, the GHS represents the weak high-*T* channel, whereas the THS and LHS represent the stiff over- and underlying sheets, respectively. *P–T* paths from the central and eastern Himalaya have now been calculated from zoned LHS and THS garnet crystals (Kohn 2008), and these consistently show minimal heating during substantial loading (Fig. 6D). While some lateral heat transport is permissible, these paths imply that channel flow must have been far less effective than implied by present models, at least at these localities. Approximately equivalent LHS and THS rocks from a section in the western Himalaya preserve greater evidence of synburial heating (Chambers et al. 2009), with interpreted *P–T* paths being more consistent with channel flow predictions and implying along-strike variability in the orogen. The degree to which one model or another is preferred requires acquisition and integration of numerous other data sets that can be compared to predictions of geodynamic models. Of these, temperature–time histories are particularly distinctive and informative, but are beyond the scope of this review (see Kohn 2008).

The dating of garnet growth is discussed elsewhere in this issue, but trace element compositions and zoning within garnet porphyroblasts can also be used to link the systematics of garnet growth and dissolution with that of accessory phases, such as monazite (e.g. Pyle and Spear 1999), amenable to (U–Th)–Pb dating. Thus, the growth of accessory phases can be directly linked to stages of a *P–T* history, constraining rates of metamorphic evolution (e.g. Foster et al. 2004). In the absence of such information, garnet found in orogenic belts is typically considered to preserve the story of continental collision, subject to the potential loss of compositional information through diffusive modification, described above. However, mounting geochronological evidence from both garnet and its included phases suggests that garnet is readily inherited from earlier metamorphic events and may not “reset” its composition during later heating (e.g. Argles et al. 1999). This inheritance may arise through direct polymetamorphism of the rocks of interest or the presence of detrital garnet in sediments that themselves experience a relatively simple metamorphic history. Either case demands particular caution when using garnet for thermobarometry as its composition may preserve a record of its growth rather than that of equilibrium with minerals in the last metamorphic episode. However, with careful teasing out of appropriate crystals and compositions, metamorphic *P–T* paths based on garnet zoning will continue to provide important insights and constraints into geodynamic processes.

**CONCLUDING REMARKS**

Garnets preserve diverse records of orogenic processes in their chemical zoning. Petrologists commonly employ thermodynamic modeling and interpretation of major and minor element zoning in garnet as their first line of geochemical inquiry in tectonic studies. Such a scientifically mature approach elucidates many aspects of orogenesis, from oceanic subduction through all stages of
continental collision. Recent work on major and minor element geochemistry now emphasizes length scales and mineralogical controls on thermodynamic and chemical equilibrium, with implications for biases to P–T path calculations. Other important aspects of garnets, including their elastic properties and trace element and isotopic zoning, remain less well studied and are promising areas for future investigations into orogenic processes.

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