

Tourmaline as a Petrologic Forensic Mineral: A Unique Recorder of Its Geologic Past

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Photomicrograph of an hourglass sector zoned tourmaline in a metapelite (blue +c sector, brown -c sector and yellow a sector)

Tourmaline is nature's perfect forensic mineral. From a single grain, the full geological past of its host rock can be reconstructed, including the pressure-temperature path it has taken through the Earth and the changing fluid compositions it has encountered. Tourmaline is able to provide this record owing to its compositional and textural sensitivity to the environment in which it grows, and is able to preserve this record because element diffusion in its structure is negligible. Furthermore, tourmaline has an exceptionally broad stability range, allowing it to record conditions in igneous, sedimentary, metamorphic, and hydrothermal settings. As our mineralogical and geochemical tools advance, we are able to interrogate tourmaline's memory with increasing precision, making tourmaline a truly powerful indicator of conditions in the Earth.

KEYWORDS: tourmaline, petrogenetic indicator, compositional zoning, growth history

INTRODUCTION

Tourmaline has precisely the characteristics of a forensic mineral: it is widespread, occurring in most rock types; it is stable over a significant portion of the pressure (P)-temperature (T)-composition (X) space of the crust (Dutrow and Henry 2011 this issue); its crystal structure accommodates an exceptional range of geochemically different elements (Hawthorne and Dirlam 2011 this issue); its (trace) element and isotopic compositions are responsive and reflective of physical and chemical conditions encountered and of element source-reservoirs (e.g. Marschall and Jiang 2011 this issue; Slack and Trumbull 2011 this issue); and it shows negligible intracrystalline element diffusion over geologic time, even at temperatures in excess of 600°C (van Hinsberg et al. 2011). Because of these characteristics, tourmaline records a signature of the conditions and chemistry of its environment, in an extraordinary range of settings within the Earth, and, most crucially, preserves this signature for later interrogation. Moreover, tourmaline grains are commonly growth-zoned, and this "memory" is recorded and stored for the full growth history of the grain, just as tree rings store information about the tree's environment during its growth. Unconformities can develop in this record, when growth stalls for lack of boron (B) or growth zones are eroded away, but these can be informative as well (e.g. van Hinsberg and Schumacher 2011).

The primary microstructures and compositions of tourmaline are commonly well preserved, even when grains are weathered from their parent rocks and transferred to sedi-

ment. When these are properly interpreted, they provide robust evidence that tracks the mineral's formation and modification by igneous, sedimentary, and metamorphic processes. In this article, we explore a hypothetical record of a single, multigenerational tourmaline grain and illustrate how tourmaline can record geologic information in igneous, sedimentary, and metamorphic settings (Figs. 1, 2). This "tourmaline construct" provides a framework for discussion of tourmaline formation and modification in these varied geologic settings.

TOURMALINE IN IGNEOUS ROCKS

Many tourmalines begin "life" in the geologic record as crystallization products of an igneous melt. The most common tourmaline-bearing igneous rocks are those that have undergone significant chemical fractionation, because boron, an essential constituent of tourmaline, behaves incompatibly in igneous systems and is therefore highly enriched in fractionated melts (e.g. London et al. 1996). Tourmaline is most important in silicic and peraluminous volcanic and plutonic rocks, such as rhyolites, granites, granitic pegmatites, and nodular granites. If these rocks are derived from the melting of metasedimentary material, which is commonly enriched in B compared to average crust, tourmaline may occur in substantial modal amounts.

Tourmaline displays a myriad of morphologies in igneous deposits, from beautiful faceted prisms (e.g. Pezzotta and Lours 2011 this issue), to skeletal grains, to interstitial masses, and to mineral fibers. These shapes reveal the timing and style of tourmaline growth in the melt. Commonly, tourmaline forms late in the crystallization history of the magma, and its growth may be rapid owing to the enhanced concentration of boron and water in the residual melt.

Chemically, igneous tourmaline tracks the composition and mineral assemblage of its host magma. Therefore, it provides a first-order approximation of the composition of the magma from which it nucleated, including changes in major components such as Fe, Mg, and Mn (e.g. Jolliff et al. 1986). Tourmaline in intermediate igneous rocks generally has compositions that are Na-rich and intermediate in Fe and Mg contents, e.g. schorl and dravite, whereas tourmaline crystallized in moderately fractionated granitic rocks tends to be Fe-rich (i.e. schorl and foitite; see nomenclature in Hawthorne and Dirlam 2011). With increased fractionation, tourmaline gets enriched in Li, so that in

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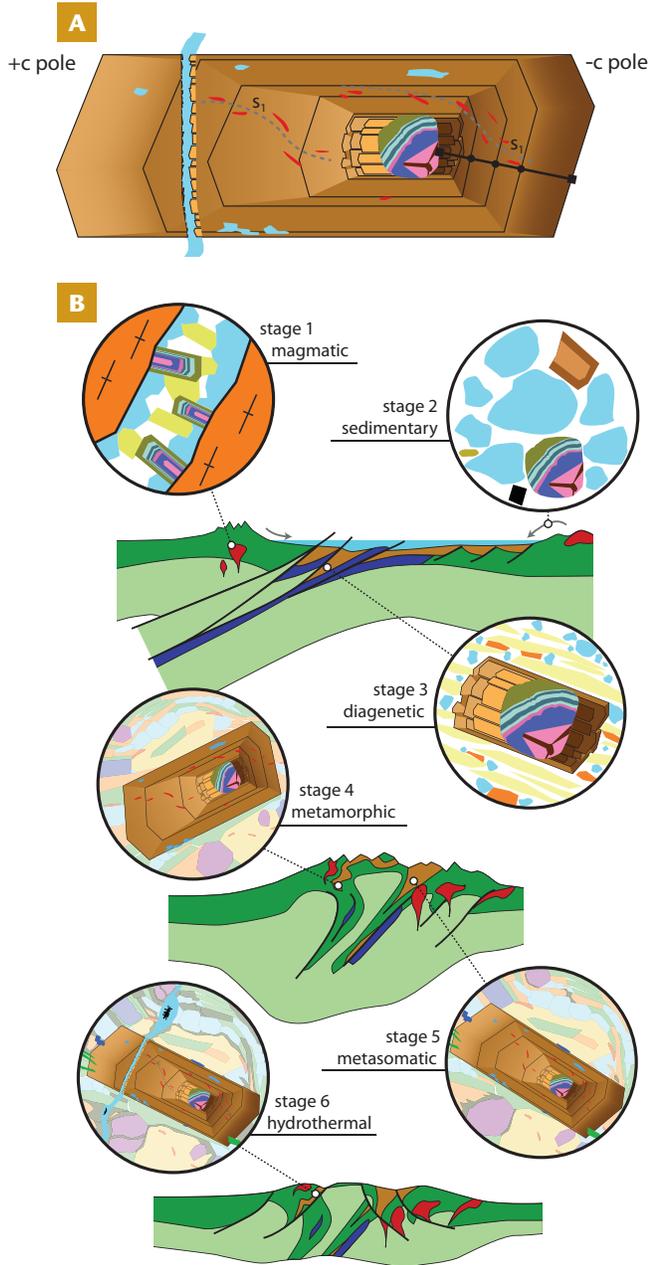


FIGURE 1 (A) Schematic drawing of an “idealized” multigenerational tourmaline that encountered various geologic processes and environments (SEE FIGURE 1B). From the inside outward, the grain contains: a rounded detrital core that formed by crystallization from a melt; asymmetric diagenetic overgrowths with preferred growth towards the +c pole; metamorphic and metasomatic zones overgrowing an internal foliation (s₁) marked by inclusions; and a fracture sealed by hydrothermal growth on the fracture surfaces. Polar growth and hourglass sector zoning are marked by color shading. The heavy black line marks the transect described in FIGURE 2. (B) Geologic settings for growth of the tourmaline grain shown in A. These are: magmatic setting (stage 1) with subsequent weathering (stage 2); diagenetic growth on relict grains in a sedimentary basin (stage 3); prograde metamorphic growth (stage 4); retrograde metasomatic growth owing to input of boron in fluids from a cooling pluton (stage 5); and growth in extensional brittle fractures associated with ore formation (stage 6).

highly differentiated pegmatites, the Li species elbaite, fluor-liddicoatite, and rossmanite are characteristic. Tourmaline is most common in the B-enriched Li–Cs–Ta family of pegmatites and occurs more rarely in Nb–Y–F pegmatites (e.g. London 2008). Volatile-rich, commonly

late-stage cavities in pegmatites can contain gem varieties (see Pezzotta and Laurs 2011).

Because the environment continuously changes in a differentiating magmatic system, tourmaline commonly exhibits well-developed color and compositional growth zoning, in addition to sector zoning (FIG. 1B STAGE 1; FIGS. 2, 3; Hawthorne and Dirlam 2011). Chemical transects across such zoned grains provide a record not only of the evolving melt composition but also of dissolution/precipitation events and changes in alkalinity, fluorine content, and redox state of the melt and associated fluid (e.g. Dutrow and Henry 2000; London 2008).

The late-stage hydrothermal fluids associated with many igneous plutonic rocks are enriched in B and can infiltrate the surrounding host rocks. This influx of boron may cause tourmaline to form, creating tourmaline-rich rocks at the margins of igneous bodies and in their country rocks. Such fluids proximal to igneous bodies can be highly oxidized, yielding tourmaline with a significant proportion of Fe³⁺ (e.g. povondraite), and they are associated with many types of ore deposits (Slack and Trumbull 2011). Metasomatic tourmaline generally exhibits fine-scaled oscillatory zoning and typically displays a hybrid composition that reflects reaction between the host rock and a B-bearing fluid phase. One can commonly determine the relative contributions of the host rock and fluid to these metasomatic tourmalines from their isotopic and trace element compositions, as well as reconstruct changes in these contributions over time. Tourmaline thus tracks the evolution of magmatic–hydrothermal systems, and it will retain this information despite separation from its site of crystallization by weathering.

TOURMALINE IN SEDIMENTS AND SEDIMENTARY ROCKS

Tourmaline as a Detrital Mineral and Provenance Indicator

The exceptional mechanical and chemical stability of tourmaline makes it highly resistant during weathering. Once exposed to surface conditions, tourmaline can be disaggregated from its igneous, metamorphic, or sedimentary parent rock to become a clastic component in sediment. Together with zircon and rutile, tourmaline is one of the most durable heavy minerals in sedimentary environments.

Tourmaline in sediment retains the signature of its original host rock (FIG. 1A, 1B STAGE 2) and has, therefore, long been a provenance indicator in clastic sedimentary rocks. Early attempts focused on features such as absorption color, grain size, and degree of roundness either to infer provenance or to correlate clastic sedimentary units (e.g. Krynine 1946). However, absorption colors can yield equivocal results in source-rock correlations. The compositions of detrital tourmaline grains are much better indicators of likely source rocks. “Environmental diagrams” that compare Al–Fe–Mg and Ca–Fe–Mg abundances show how detrital tourmaline compositions relate to probable source rock types (FIG. 4; Henry and Guidotti 1985). These diagrams, along with other compositional and textural variables, successfully yield provenance determinations in a number of different lithologic settings (e.g. Henry and Dutrow 1992; Morton et al. 2005). In addition, the relative degrees of rounding of tourmaline clasts provide general information on the energetics and potential cycles of sedimentation that each clast has undergone (Krynine 1946).

A challenge in using tourmaline composition to derive sediment provenance is that composition is not solely reflective of host rock. Variations in pressure, temperature, and oxygen fugacity, among others, can modify the parent-rock signature. The presence of compositional zoning in

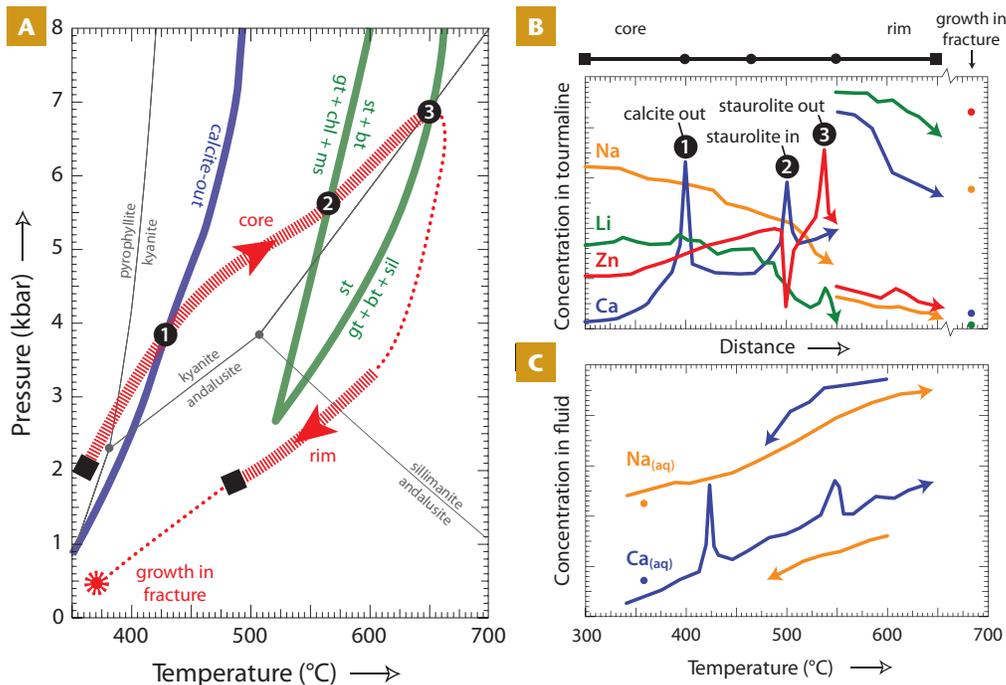


FIGURE 2 *P-T* conditions (A) and element contents (B, C) for selected major and trace elements along a core-rim transect of the tourmaline grain shown in FIGURE 1A, as well as the fracture growth (shown as a star in A). Arrows show the time direction. The spikes in composition (points 1–3, FIG. 2B) allow for mineral reactions to be recognized and for a temperature to be assigned to each reaction using inter-sector tourmaline thermometry. Combined with reaction positions from the literature (the green and blue lines in the *P-T* diagram), this allows the *P-T* path to be constrained (in red; stippled parts of the *P-T* path were not recorded for lack of tourmaline growth). Tourmaline compositions, combined with partition coefficients from the literature, allow Ca and Na contents in the fluid to be reconstructed, shown schematically against temperature along the *P-T* path in FIGURE 2C.

detrital grains provides a further challenge. However, such zoning also provides an opportunity, because it allows trends in composition to be matched to a source region. Trends are more distinctive than a single composition, thereby improving source identification, and may even be used to pinpoint a specific location within a source terrane. For example, if the model tourmaline in FIGURE 1 were to end up as a detrital grain, the *P-T* and compositional history retrieved from it would provide a highly characteristic signature for use in provenance studies.

Diagenetic Tourmaline

The burial and lithification of sedimentary detritus to form sedimentary rock commonly lead to new tourmaline growth on detrital grains or nucleation of a new tourmaline generation. A diagenetic origin is inferred for these occurrences because overgrowths typically develop as fragile, slender, syntactic needles (FIG. 5) that would not have survived transport in a clastic sedimentary environment (Krynine 1946). Most commonly, such tourmaline occurs as monopolar (restricted to one side of the grain) or highly asymmetric overgrowths on detrital tourmaline (e.g. Krynine 1946; Sperlich et al. 1996; Henry and Dutrow 1996), with distinctly different colors for overgrowths on either side of their detrital core (commonly blue and brown). A pale-hued overgrowth is found on the +*c* end of the detrital grain, whereas a darker-colored overgrowth develops on the –*c* end (see Hawthorne and Dirlam 2011). Growth also predominates on, and may even be restricted to, the +*c* side, which, together with color, provides a good marker of the crystallographic orientation of rounded detrital grains (FIGS. 1B STAGE 3; FIG. 5). The distinctive overgrowths on the two sides of a detrital grain testify to tourmaline’s polar nature (see Hawthorne and Dirlam 2011), which results in tourmaline growing in the +*c* direction taking up different elements than tourmaline growing in the –*c* direction. This feature is useful, because these polar differences are temperature dependent and can be used to constrain the temperature of diagenetic tourmaline formation (e.g. Henry and Dutrow 1996).

In contrast, diagenetic tourmaline with no evidence of a detrital tourmaline nucleus is common in carbonate rocks, stromatolites, and, rarely, in mudstones (Srivastava and Schnitzer 1976). Compositions of pale-colored, diagenetic

tourmaline are generally X-site-vacant foitite or magnesio-foitite species (e.g. Henry et al. 1994; Rosenberg and Foit 2006). These diagenetic tourmaline grains continue to grow as temperature and pressure increase and B is released from associated minerals.

TOURMALINE IN METAMORPHISM

Metamorphic rocks, especially those of metapelitic composition, are the second most important host of tourmaline. In contrast to their igneous counterparts, many metamorphic tourmaline grains develop on preexisting detrital grains or diagenetic cores, as is shown in the model tourmaline (FIG. 1A). Tourmaline textures and compositions reflect both local metamorphic reactions and changing *P-T-X* conditions, and this chemical and textural evidence of events can be preserved from the lowest to the highest grades of metamorphism (FIG. 1A, 1B STAGES 4 AND 5; FIG. 2).

During progressive metamorphism, tourmaline grows when B is available and the composition of the fluid is amenable to tourmaline formation (e.g. Dutrow et al. 1999). In sediments and metasedimentary rocks prior to the formation of tourmaline, B predominantly resides in layer silicates, with concentrations up to several hundred parts per million (Grew 1996; Steppan 2003). Even after tourmaline begins to grow, coexisting phases retain appreciable amounts of B. In a typical pelitic metasediment (Steppan 2003), the B distribution among coexisting phases is in the order tourmaline >> muscovite > andalusite > chlorite > biotite > plagioclase > garnet > kyanite > staurolite, although it varies as a function of metamorphic grade. In general, the sheet silicates contain more B than their breakdown products, leading to release of B during prograde metamorphism.

The release of B along a typical prograde metamorphic path (e.g. FIG. 2) can be predicted by combining thermodynamic calculations of changes in mineral proportions for a metapelitic bulk composition (using the PerpleX suite of programs; Connolly 2005) with typical B contents for metamorphic minerals (e.g. Steppan 2003). These calculations suggest a steady, but punctuated, supply of B on the prograde metamorphic path, with the largest B release at low grade by breakdown of muscovite and chlorite (FIG. 6). Consequently, tourmaline develops episodically as B is

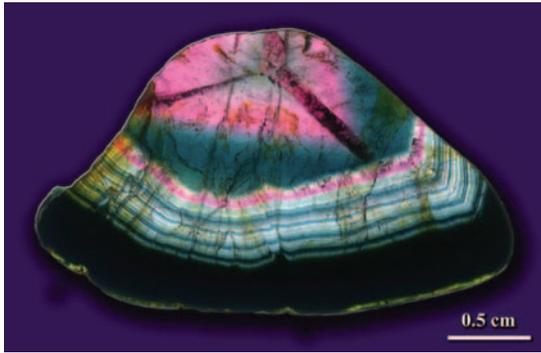


FIGURE 3 Polished slab of color-zoned tourmaline cut perpendicular to the *c* axis from a pegmatite in Madagascar. The tourmaline exhibits color zoning related to both sector zoning (cross in core) and oscillatory zoning (rim).

released in mineral reactions, and the timing and amount of tourmaline growth are linked to changes in the assemblage of associated minerals. A rock dominated by muscovite will release its B load at different times along the metamorphic path compared to one dominated by chlorite, because of differences in their respective stability. Boron released in a mica-rich unit, which releases aqueous fluid upon mica decomposition, is likely to infiltrate enclosing rocks, where it may form distinct tourmaline overgrowths or lead to mineral replacement and/or development of tourmaline-rich pseudomorphs (Dutrow et al. 1999). The liberation of B is nearly complete at peak metamorphic conditions such that, for a closed system, tourmaline is unlikely to grow on the retrograde path (Fig. 6). Comparison of the thermodynamically calculated B release with the timing of growth of tourmaline from three different metapelites from the Massif Central, France (colored lines in FIGURE 6) shows good overall agreement and matches the prediction that the most substantial growth takes place at lowest grade.

The composition of metamorphic tourmaline changes notably throughout its growth history as it directly reflects the changing environment (Fig. 2). Nonetheless, typical compositions are primarily schorl to dravite (i.e. the Fe²⁺ to Mg series), albeit with appreciable foitite, olenite, and uvite components, which introduce X-site vacancies, Al on the Y site and Ca on the X site, respectively. With increasing grade, the Mg/Fe²⁺ ratio and the content of Al on the Y site increase, along with vacancies and Ca content on the X site (van Hinsberg et al. 2011). However, these general trends are easily disturbed. For example, where sulfides sequester most of the Fe, anomalously Mg-rich tourmaline ensues (Henry and Dutrow 1992). Whereas the Mg/Fe²⁺ ratio of tourmaline commonly shows a smooth change from core to rim with changing conditions, other elements, including Ca, show spikes and troughs that reflect sudden changes in element abundance as the mineral assemblage or fluid composition changes (e.g. calcite breakdown; Fig. 2B, C).

Constraining Conditions of Tourmaline Formation

Recently, it has become possible to directly constrain the temperature of tourmaline formation on the metamorphic path by using tourmaline geothermometry. The most promising approach is the temperature-dependent partitioning of elements among sectors in a single tourmaline grain that displays hourglass-shaped sector zoning, i.e. different compositions in a single growth horizon for domains that originated on different growth surfaces (van Hinsberg and Schumacher 2007). This inter-sector thermometry can be applied to isolated grains, including detrital clasts and tourmaline inclusions, and to single

growth zones. Its greatest value lies in application to tourmaline grains that show both sector and growth zoning, because in these cases complete temperature histories can be extracted from single grains (e.g. van Hinsberg and Schumacher 2007, 2011). Moreover, tourmaline thermometry accesses the low-temperature prograde conditions of metamorphic growth, for which few other robust mineral thermometers are available.

In sections cut parallel to tourmaline's long axis, hourglass zoning occurs as a pale-colored, commonly blue sector in the +*c* direction, a dark-colored, typically dark brown sector in the -*c* direction, and an intermediate-colored sector on either side (Fig. 1A). In sections perpendicular to the long axis, tourmaline exhibits a homogeneous, light- or dark-colored core surrounded by a zoned rim. This core-rim color difference can be mistaken for two-stage growth. Sector zoning reflects tourmaline's polar nature and is a different manifestation of polar diagenetic growth. Although tourmaline sector zoning is commonly regarded as a disequilibrium feature, this is a misconception. The sector differences form as a result of different local equilibria between the various growth surfaces and their identical host environment (van Hinsberg and Schumacher 2007). There is no direct exchange of elements between the sectors; instead, they communicate through the fluid, an exchange that equals direct exchange in thermodynamic terms.

Sector zoning and polar growth are controlled by differences in the surface properties of the growth surfaces; differences in charge are of most importance in tourmaline. Because the Si-tetrahedra all point in the same direction along the *c* axis in the tourmaline structure (Hawthorne and Dirlam 2011), a partial positive charge develops on surfaces at high angles to *c*. A corresponding negative charge develops on the opposite side, leading to the preferential incorporation of higher-charged cations for growth in this direction, such as Ti⁴⁺ on the Y site and Ca²⁺ on the X site. With increasing temperature, the ability of time-equivalent, but crystallographically distinct, growth surfaces to segregate elements decreases because the increased vibration of the atoms diminishes the charge asymmetry along the *c* axis; the inter-sector partition coefficients converge to unity. This change in partition coefficients provides the basis for thermometry. Because the compositional contrasts are in equilibrium only at the growth surface, sector zoning should disappear by element

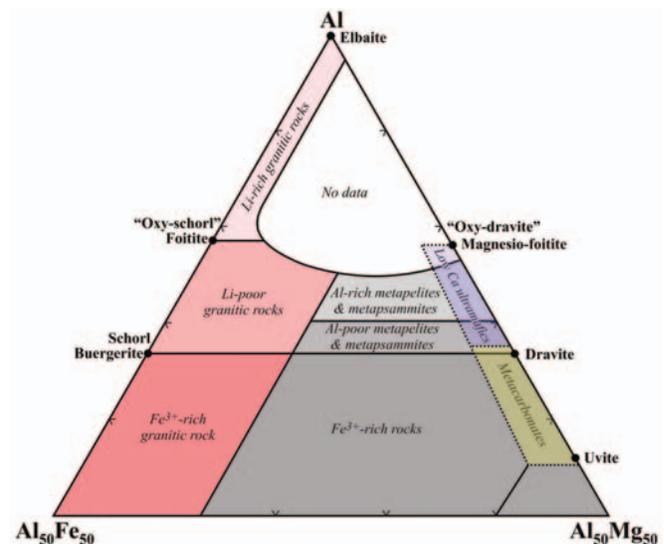


FIGURE 4 Environmental diagram correlating tourmaline composition to host-rock type. The locations of selected tourmaline species are indicated. The diagram is modified after Henry and Guidotti (1985).

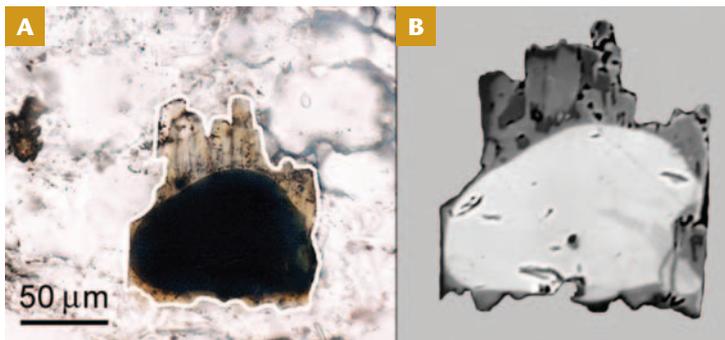


FIGURE 5 Detrital tourmaline grain with asymmetric diagenetic tourmaline overgrowth. (A) Optical photomicrograph highlighting the color distinction between the detrital core (blue) and overgrowth (yellow; top is +c). (B) Backscattered-electron image illustrating the textural and chemical complexity of the diagenetic overgrowth shown in A.

diffusion in the crystal bulk. The preservation of sector zoning is therefore not only evidence of slow diffusion in tourmaline, but also a confirmation that a grain has retained its chemical signature.

At present, other tourmaline thermometers only provide broad indications of conditions. The scatter observed in calibration attempts seems to reflect disorder of cations over the different tourmaline sites, in particular Fe, Mg, and Al over the *Y* and *Z* sites (Hawthorne and Dirlam 2011), and changes therein with changing conditions (van Hinsberg and Schumacher 2009). Element exchange and occupancy on the *X* site is more promising, especially Na–Ca exchange between tourmaline and plagioclase (van Hinsberg and Schumacher 2009) and *X*-site occupancy (Henry and Dutrow 1996; Ertl et al. 2010).

Constraining the pressure of formation is more difficult. Tourmaline barometers have not as yet been established, although tourmaline's *K/Na* ratio increases with pressure in exchange with biotite or phengite (van Hinsberg, unpublished data). Nonetheless, pressures can be constrained indirectly, for example, by barometry on mineral or fluid inclusions. In addition, specific mineral reactions are seen as sharp changes in tourmaline composition. If the position of such a reaction is known in *P–T* space and the temperature can be constrained from tourmaline thermometry, pressure can be established from the intersection of this reaction line in *P–T* space (e.g. van Hinsberg and Schumacher 2011). This approach is highlighted for our model tourmaline, in which the terminal breakdown of carbonate appears as a spike in Ca (FIG. 2B), whereas the reaction garnet + chlorite + muscovite to staurolite + biotite + quartz + fluid is seen by the combination of a trough in Zn + Li and a spike in Mn + Ca owing to the different element preferences of products and reactants. By combining this information, the *P–T* path of a tourmaline-bearing rock can be established (FIG. 2A).

Our model tourmaline shows both growth and sector zoning (FIG. 1A), allowing reconstruction of its thermal history. Compositions within the same growth zone, but on either side of the sector boundary, provide an intersector partition coefficient that constrains the formation temperature of this growth zone. These calculations can be performed along the entire length of the crystal. From core to rim, the compositional differences between the sectors decrease, which shows that this sequence corresponds to prograde growth (growth with increasing temperature). Qualitatively, this decrease in compositional contrasts among sectors is seen as a decrease in color contrast, and the peak growth zone is identical in color for all sectors. In natural metamorphic tourmalines, this convergence is observed for temperatures in excess of 650°C (van Hinsberg and Schumacher 2007).

Growth of tourmaline during cooling and exhumation (retrograde growth) is unlikely in a closed system, because B has already been sequestered in tourmaline or lost to the fluid upon reaching peak metamorphic conditions (FIG. 6).

Metasomatic introduction of B is the most common cause of tourmaline growth on the retrograde path, although such metasomatism can also take place during other stages of the rock's formation. The typical retrograde rehydration observed in metamorphic rocks and the high solubility of B in hydrothermal fluids suggest that this process is common. Intrusion of late “suturing” granites in orogenic belts and the likelihood of release of fluids from such plutons is a common source for retrograde boron addition, as is shown for our model tourmaline (FIG 1B STAGE 5). In many cases, this retrograde overprint takes place over a range of temperature, and tourmaline may record this history (van Hinsberg and Schumacher 2007). The growth of metamorphic tourmaline can thus span a remarkable range of conditions and provide a treasure trove of information on the *P–T* history of its host rock.

Tourmaline as an Indicator of Fluid Composition

Tourmaline not only preserves *P–T* information but also captures a fingerprint of the *composition* of its growth environment(s). This fingerprint allows changes in mineral paragenesis to be recognized, but its real power is the record provided on trace element mobility and the isotopic signature of the host environment. For example, in hydrothermal settings this fingerprint of element mobility has allowed tourmaline to be used as an exploration tool in the search for ore deposits (e.g. Slack and Trumbull 2011).

Recent experimental work on element partitioning between tourmaline and fluid permits a quantitative reconstruction of element contents in the coexisting aqueous fluid (von Goerne et al. 2011 and references therein). In a way that

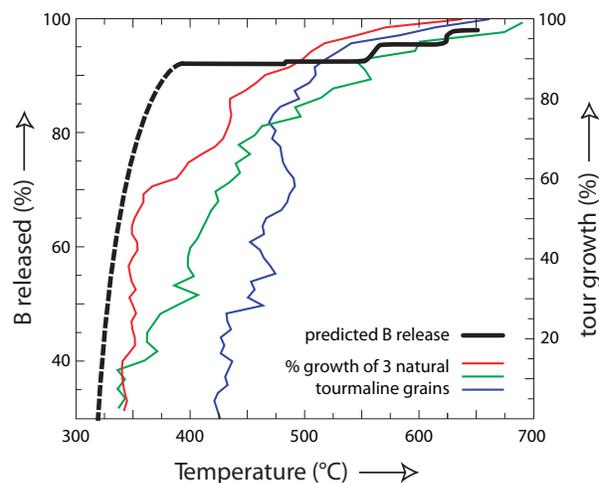


FIGURE 6 For a typical prograde path (FIG. 2A), B is liberated as grade increases (black line), as a result of decreasing modal abundance of the sheet silicates. This progressive, but episodic, B release agrees well with the growth history of three natural metamorphic tourmaline grains (colored lines; data from van Hinsberg and Schumacher 2011).

is analogous to reconstructing a thermal history using sequential growth zones, one can reconstruct the evolution of fluid composition. Because inter-sector partition coefficients for trace elements are poorly known, the **a** sector composition should be used in such reconstructions because its growth is perpendicular to the polar axis and therefore unaffected by polar element preferences. This technique used for our model tourmaline (Fig. 2c) highlights characteristic differences in composition between the metamorphic and metasomatic fluids. Partition coefficients are sensitive to *P-T* conditions, and this requires that coefficients be matched to those of tourmaline formation. For example, a static coefficient predicts a decrease in Na in the fluid with increasing grade, whereas the use of temperature-dependent partitioning produces an increase in predicted Na (Fig. 2c).

In the model tourmaline, final growth takes place on fracture surfaces, a feature commonly observed in nature (e.g. Henry et al. 2002). Typically, this growth reflects late-stage fluid infiltration in a brittle extensional regime (e.g. during orogenic collapse, Fig. 1B STAGE 6). New tourmaline growth is typically fibrous, with **+c** and **-c** polar differences, and compositionally distinct from its tourmaline substrate, marked here by elevated Zn and accompanied by a high Na/Ca ratio. This signature is suggestive of the infiltration of basinal-brine fluids, and such episodes have been linked to the formation of several types of ore deposits (Slack and

Trumbull 2011). A combination of polar tourmaline thermometry and fluid-inclusion barometry constrains the *P-T* conditions of this final stage of tourmaline growth.

CLOSING REMARKS

Tourmaline has the unique ability to record and retain chemical and textural information that testifies to the geologic evolution of the rocks in which it develops. It can survive through weathering, diagenesis, metamorphism, and exhumation to track a complete geologic “life-cycle.” With our current understanding of the crystallography and element partitioning of tourmaline, the results of recent tourmaline–fluid experiments, and the availability of a new generation of analytical equipment, tourmaline has the potential to become the prime forensic tool in the mineral sciences.

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