Crystallization sequence and tectonic significance of andalusite, kyanite, and sillimanite 'triple point' localities, including a new locality: Lesjaverk, Norway.

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Abstract

Rocks containing three Al_2SiO_5 polymorphs (andalusite, kyanite, sillimanite) are uncommon; only ten localities have previously been reported. By determining the crystallization sequence of the polymorphs, tectonic/metamorphic histories can be unlocked. Two crystallization sequences have been proposed: (1) kyanite -> sillimanite -> andalusite (Idaho, New Mexico, Spain, Italy), and (2) andalusite -> kyanite -> sillimanite (Colombia, Turkey, Iran, Russia, South Korea, and Japan). The newest locality is Lesjaverk, Norway. Sequence (1) suggests continental collision in which exhumation of moderate-P/T (Barrovian) rocks was followed by high-P / low-T conditions, whereas Sequence (2) suggests contact metamorphism preceded more typical Barrovian metamorphism.

In the Lesjaverk, Norway, rock that contains andalusite, kyanite, and sillimanite, observation of the Al_2SiO_5 polymorphs in thin section indicate crystallization Sequence (2). Temperatures were calculated using Zr-in-rutile thermometry; results of 580-650°C indicate that rutile likely equilibrated in the kyanite or sillimanite stability field. Analysis of trace elements in rutile further indicate that Zr, Nb, Cr, and Fe participate in elemental substitution in rutile.

Introduction

Kyanite, andalusite, and sillimanite bearing rocks are uncommon, as only ten localities have been previously reported. Two crystallization sequences have been proposed for the ten localities (Fig. 1) with South Korea, Japan, and Russia yet to be confirmed, as only two of three polymorphs have been found in a single sample. In order for a locality to be classified as a "triple point locality", all three polymorphs must be found in the same sample.

All three polymorphs occur in schists from Lesjaverk, Norway (Fig. 2). In this study, the crystallization sequence was determined, as this indicates the pressure and temperature path for the rock and therefore explains the possible tectonic environment, although such interpretations are uncertain without absolute age information for polymorph crystallization.

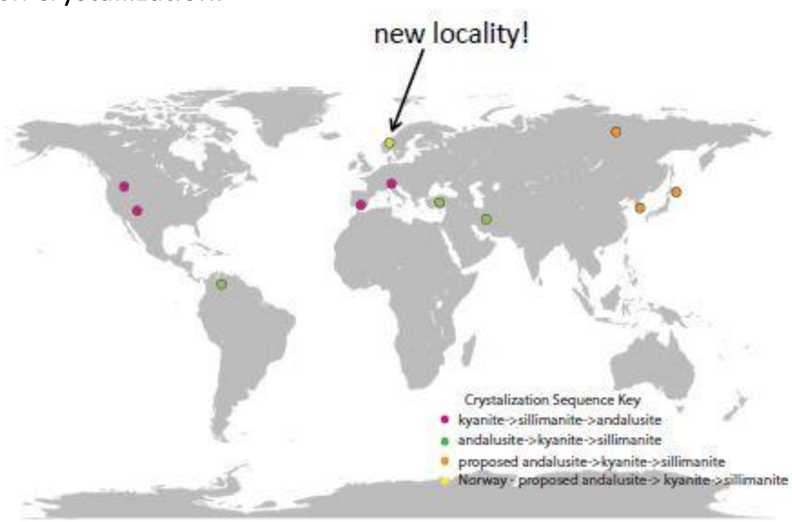


Fig. 1: World map of proposed triple point localities. The colors indicate crystallization sequence. Pink: Sequence (1) for Idaho, New Mexico, Spain, and Italy. Green: Sequence (2) for Colombia, Turkey, and Iran. Orange: proposed Sequence (2) for Russia, South Korea, and Japan. Yellow: proposed Sequence (2) for Norway. Map provided by *D.L. Whitney*, map key by *W.J. Samuelson*

(a)  (b) 

Fig. 2: Photographs of one sample from Lesjaverk, Norway with a ballpoint pen for scale. The dark blue crystal is kyanite, with visible red andalusite. *D.L. Whitney.*

World Localities

Table 1 is a compilation of the other world localities, excluding Norway. Each locality has been divided into location, crystallization sequence, host rock, accessory minerals, pressure and temperature path, and tectonic environment. (A = andalusite; K = kyanite; S = sillimanite; L = low; H = high; T = temperature; P = pressure). Table 1 has been made to more clearly organize each locality, crystallization sequence, and correlating reference and serve as a reference table.

Table 1

Sequence (1)

Boehls Butte Area, IDAHO	
Crystalization Order	KSA
rock	Ms, Bt, Qtz metapelic schist
P/T path	START: K=6.5kbar, 540C
	max S= 6.5kbar, 650C
	END: A=3kbar, 540C
Additional Info	KS regionally present, A much later
Reference	Pattison, 2001

Rio Mora, Picuris, Tusas, Truchas, NEW MEXICO	
Crystalization Order	KAS (Holdaway, 1978), KSA (Whitney, 2002)
rock	Ms, Bt, Qtz pelitic schist
Other minerals present	garnet, staurolite, cordierite, chlorite, graphite
P/T	just above triple point
Additional Info	manganiferous quartzites and schists containing KAS
Reference	Pattison, 2001

Betic Belt Southern SPAIN	
Crystalization Order	KSA
rock	metapelite
other minerals	staurolite, biotite, garnet, quartz, muscovite, ilmenite, rutile
P/T path	P=11kbar, T=625C [Fig. 14 & 17 (Garcia and Torres 1996)]
Additional Info	decompression
Tectonic Environment	extensional collapse of crustal region
Reference	Garcia-Casco & Torres-Roldan, 1996

Sequence (2)

Sivrihisar, TURKEY	
Crystalization Order	AKS
rock	Ms-quartzites; interlayered mica schists
	Qtzites: staurolite, garnet,
other minerals present	Schists: chloritoid, garnet, staurolite
P/T path	5.5kbar(max.), 540-560C
Additional info	not one event: burial= AK;
	collision/heating/decompression=KS
Reference	Whitney, 2002
	Whitney et. al, 2011

Hamadan, IRAN	
Crystalization order	AKS
rock	quartz rich veins in metapelic schists
other minerals present	staurolite, muscovite
P/T path	slightly above and or below triple point
Additional Info	AKS vein lies within a AS host rock;
	vein A enriched in Fe_2O_3
tectonic environment	terrane evolved from continental arc to collisional orogen
Reference	Sepahi et. al, 2004

Yinisei Ridge region, RUSSIA	
Crystalization Order	AKS
rock	metapelite
other minerals	staurolite, garnet, muscovite, biotite, chlorotoid, ilmenite, plagioclase
P/T path	just below triple point
Additional Info	kyanite bearing blastomylonites?
Tectonic Environment	overthrusting of continental blocks. collisional metamorphism
Reference	Likhanov et. al, 2009

JAPAN	
Crystalization Order	AKS
rock	pelitic gneisses
other minerals	garnet, rutile (in garnet), corundum, cordierite, biotite, muscovite, quartz
P/T path	P=6kbar, T=700C [Fig. 9 (Hiroi et. al, 1998)]
Additional Info	garnet with Ca-poor rims - lots of zoning, zircon age dating
	relic kyanite
Tectonic Environment	subduction of oceanic ridge
Reference	Hiroi et. al, 1998

SOUTH KOREA	
Crystallization sequence	AKS
Rock	low-grade: muscovite-chlorite phyllite
	high-grade: mica schist
other minerals	low grade: chloritoid, A, +/- K
	high-grade: AS +/- K, staurolite, garnet
P/T path	LT/MP: 550-580C, 5-6kbar
	HT/LP: 590-610C, 3.0-4.8kbar
Tectonic environment	contact metamorphism
Additional info	staurolite and garnet growth in the KS fields
Reference	Kim and Ree, 2010

Petrographic Analysis

In the a Lesjaverk rock, kyanite crystals are kinked, andalusite shows the most deformation, and sillimanite is texturally present as fibrolite. Other major minerals in the rock are quartz, plagioclase, and muscovite. Accessory minerals include staurolite, garnet, zircon, and rutile. Figure 3 shows scans of three thin sections in cross-polarized (XPL) and plain-polarized light (PPL) along with the rutile grains. The presence of zircon and quartz makes the Zr-in-rutile-thermometry possible. Plagioclase grains show euhedral zoning including some occurrences of oscillatory zoning. Muscovite commonly bends around the plagioclase grains and the quartz grains show recrystallization.

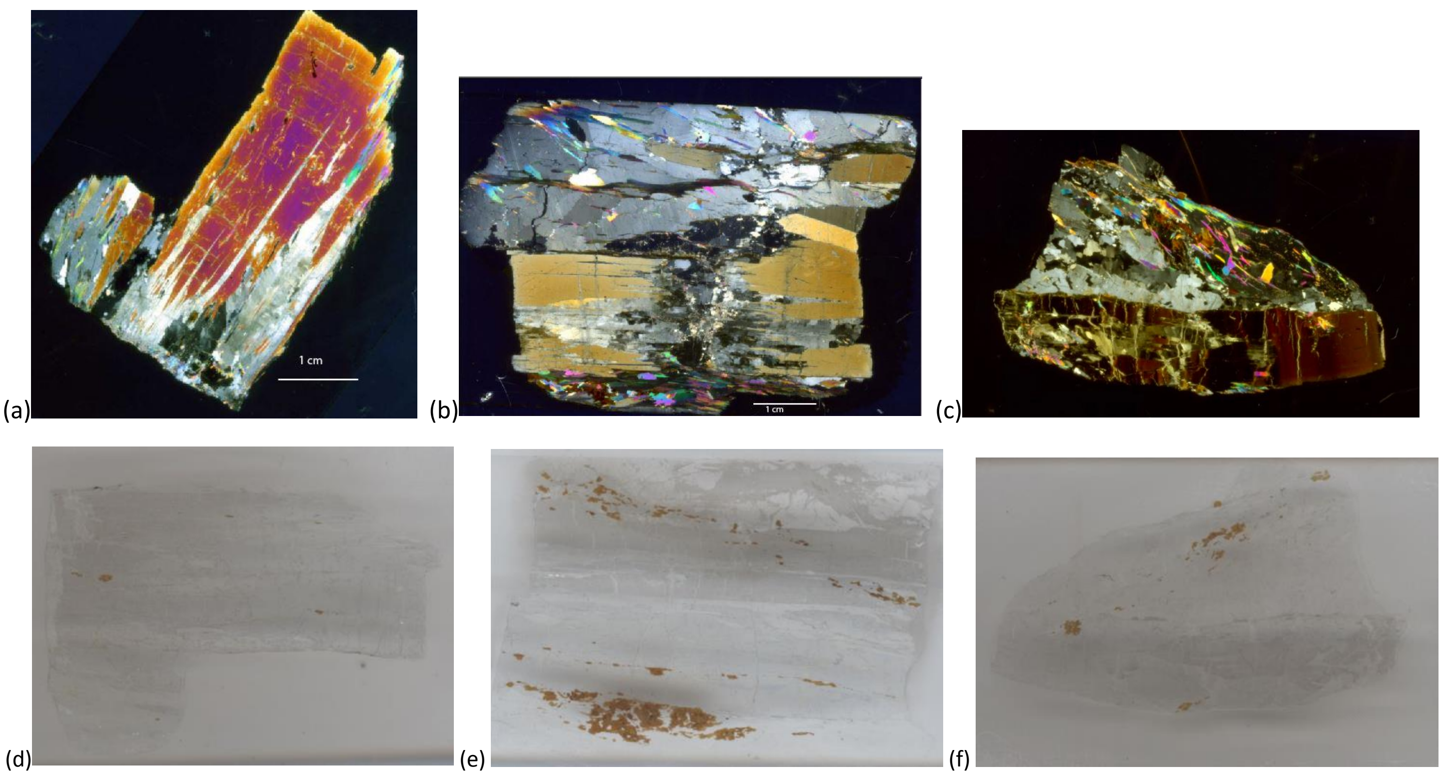


Figure 3: Scans of three thin sections, top and directly below correspond to the same thin section. (a), (b), and (c) are in XPL, and (d), (e), and (f) are in PPL. The dark brown grains are rutile, occurring in the matrix and in kyanite.

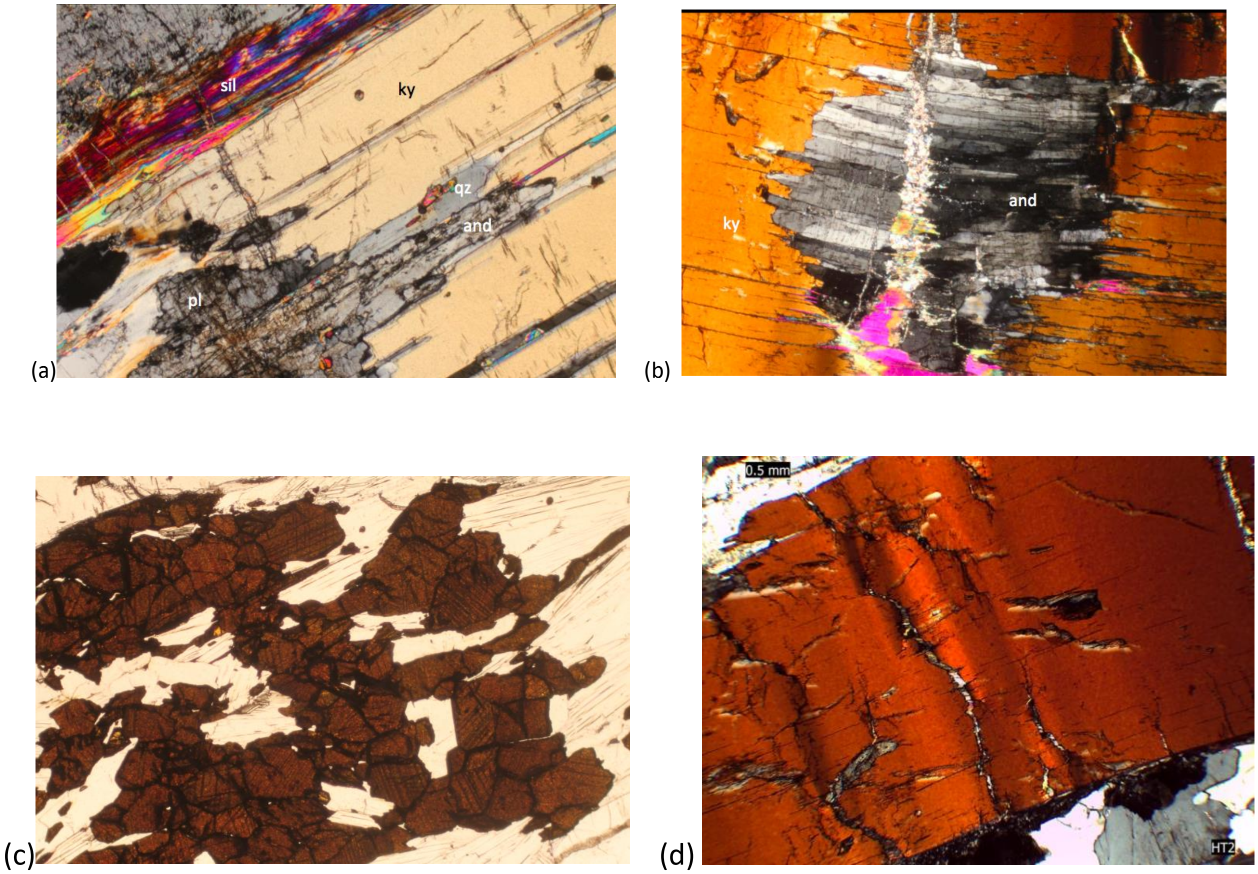


Fig. 4: Photomicrographs. (a) and (b) the growth of kyanite and the deformation of andalustie. (c) rutile. (d) kinked kyanite.

Zr-in-rutile thermometry

Rutile was found in the matrix and within inclusion in kyanite grains and composition was analyzed for application of the Zr-in-rutile thermometer. Using 16 sample points within 5 rutile grains from 2 samples, temperatures were calculated using equations from Tomkins et al. (2007) at 4-9 kbar for both the alpha and beta-quartz fields (Equations 1, 2).

Equation (1):

α-quartz field:

$$T(^{\circ}C) = \frac{83.9 + 0.410P}{0.1428 - Rln\Phi} - 273$$

Equation (2):

β-quartz field:

$$T(^{\circ}C) = \frac{85.7 + 0.473P}{0.1453 - Rln\Phi} - 273$$

Results indicate temperatures of 580 - 660°C. The calculated temperatures were then plotted against estimated pressures (Fig. 5). This temperature range suggests the rutile equilibrated within the kyanite and/or sillimanite P-T stability fields.

Analyses in 5 rutile grains were taken from grain rims and cores (Fig. 7). Of the 16 sample points, 4 were within a rutile inclusion in kyanite (Fig. 8b, 8c), the remaining 10 were in the matrix (Fig. 8a). In matrix rutile, Zr abundance is much greater in rutile rims (262 ppm) than the cores (218 ppm) (Fig. 8a), similar to one of the rutile inclusions in kyanite (rim: 261 ppm; core: 197 ppm) (Table 2). The other inclusion showed significant zoning with a darker core and a lighter colored rim visible in the BSE image (Fig. 8c). The lighter rim has higher Zr ppm than the darker core (rim: 305 ppm; core: 350 ppm) which is the opposite trend (Table 2).

Rutile trace-element composition

Abundances of different elements were plotted against each other to evaluate trends (Fig. 5). Some elements appear to be correlated with each other, and some are not. As Zr increases, Nb and Cr also increase; as Zr increases, Ti decreases and Fe very slightly decreases. Trends for Nb are very similar, as Nb increases, Cr increases, and Ti decreased with Fe showing the same slight decrease. Other element trends include: increased Ti with decreased Fe, increased Cr with decreased Fe, and a very slight decrease of Ti with Cr increase indicating a very slight relationship. The Zr and Nb appear to behave similarly, indicating elemental substitution.

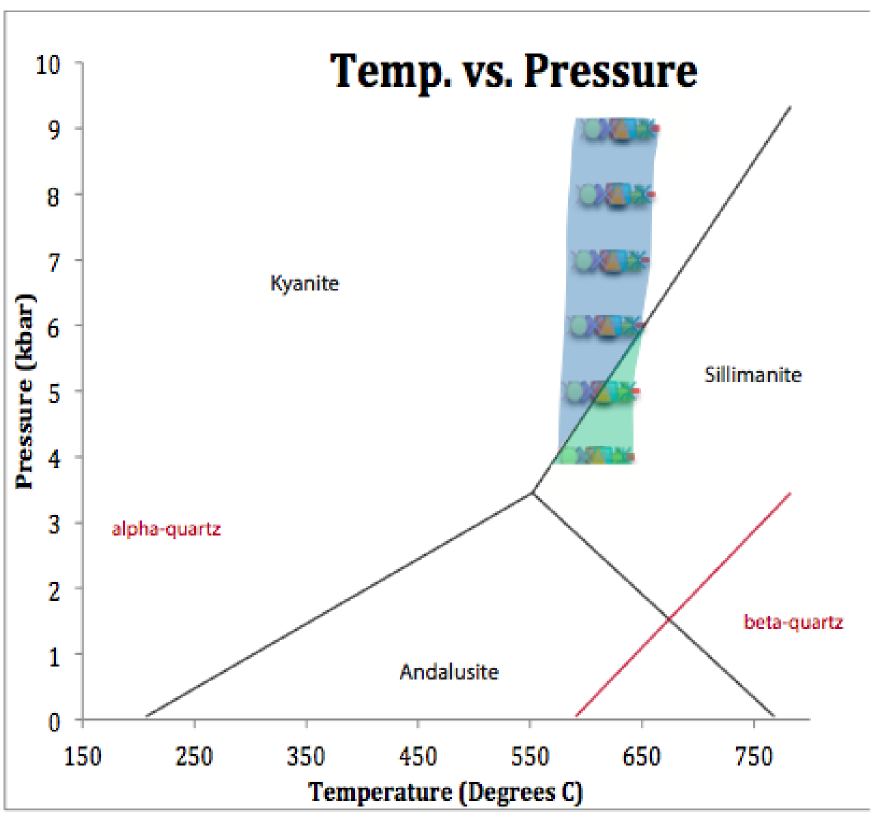


Fig. 5: Pressure-temperature graph for 16 rutile samples gathered from Microprobe data and calculated using Tomkins et al. (2007).

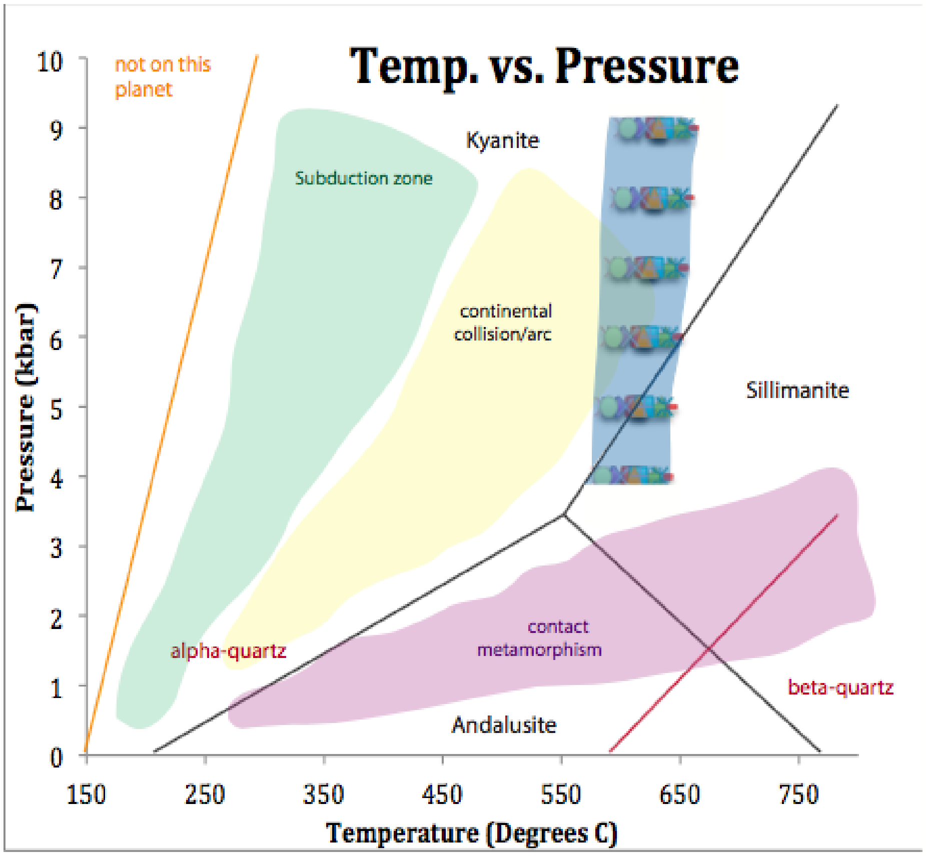


Fig. 6: Pressure-temperature graph with kyanite-andalusite-sillimanite triple-point boundary. In addition the alpha-beta quartz boundary is included in red. Tectonic environments corresponding to pressure-temperature regimes are overlaid.

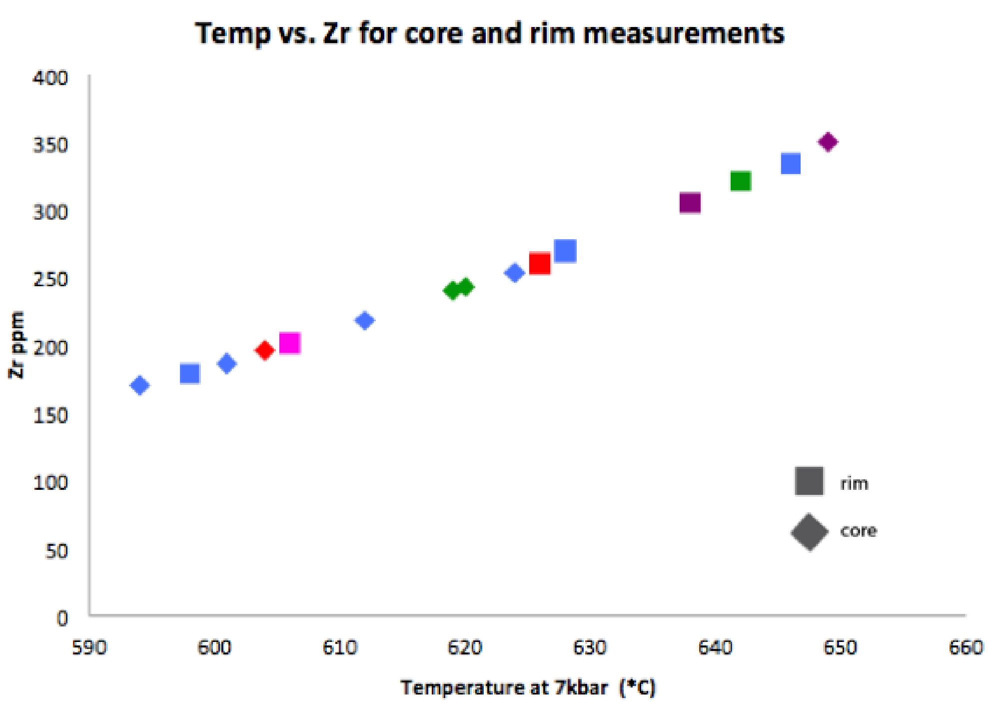


Fig. 7: Temperature plotted against Zr in ppm for rutile grain rim and core. Temperatures used at 7kbar in pressure.

Table 2:

(a)

Zr ppm CORE	Temp at 7kbar
240	619
243	620
186	601
196	604
350	649
253	624
218	612
170	594

(b)

Zr ppm RIM	Temp at 7kbar
321	642
334	646
260	626
305	638
201	606
269	628
179	598
269	628

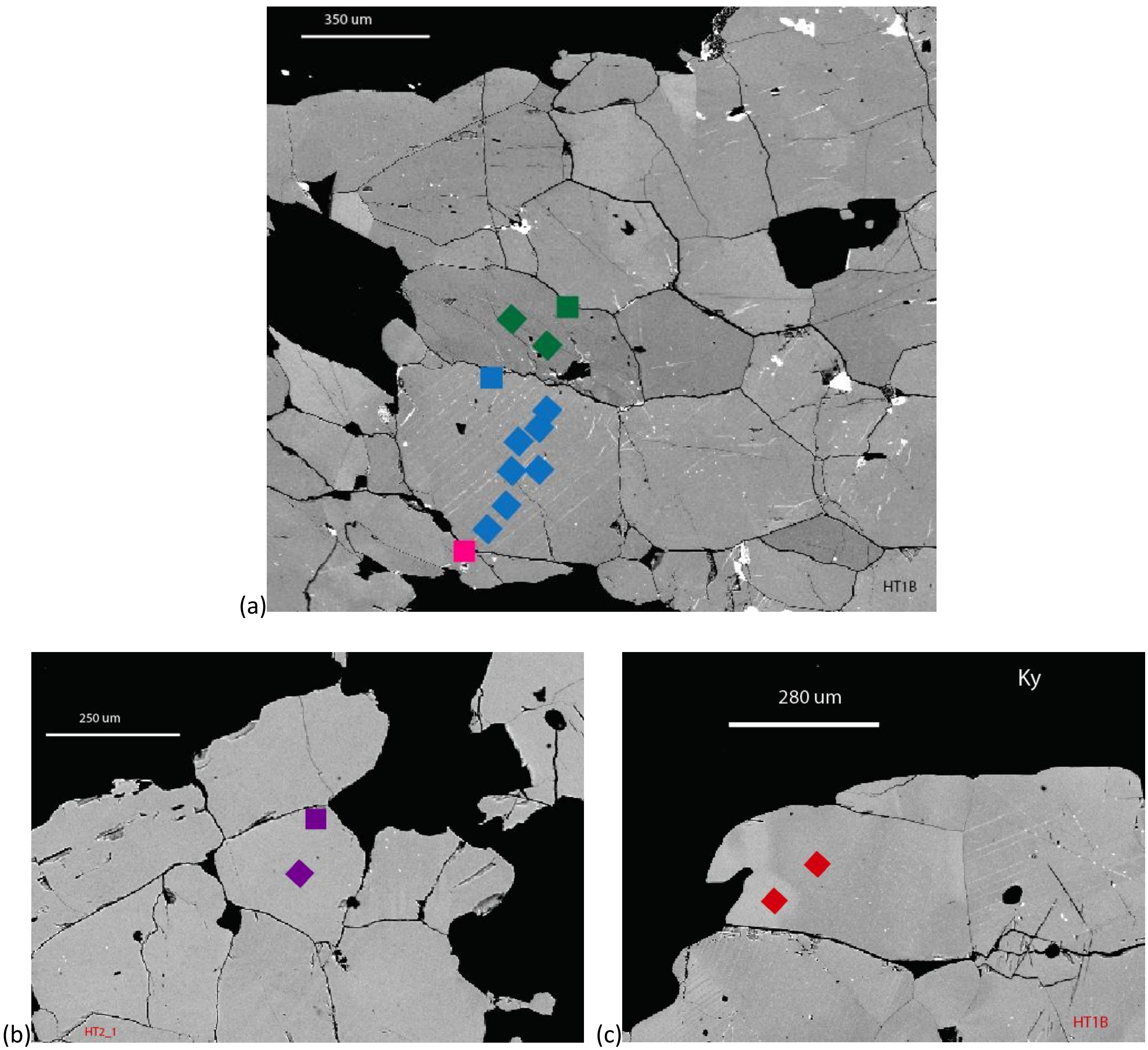
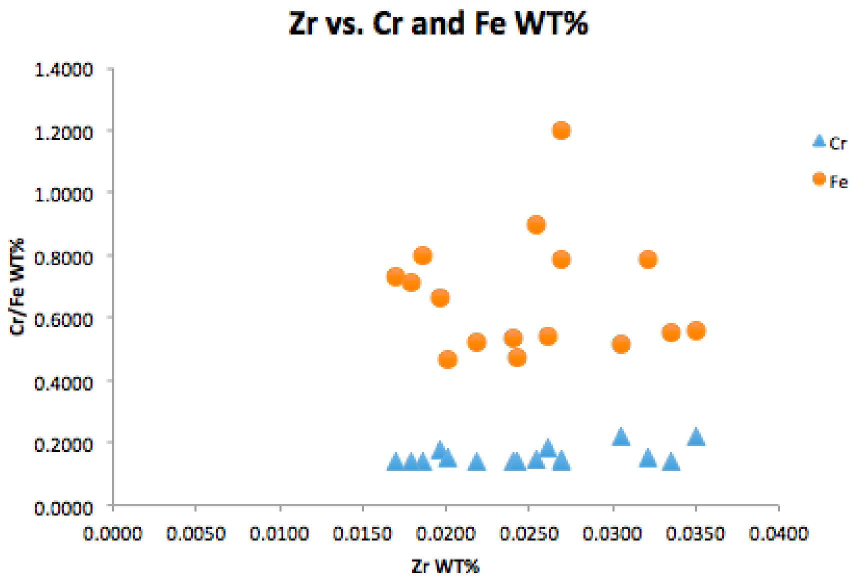
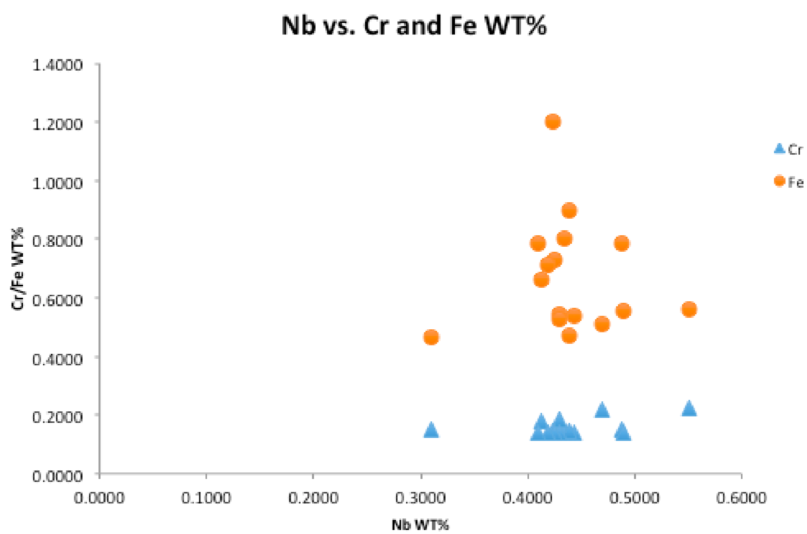


Fig 8: Sample points indicated by red dots. (a) Rutile grain in the matrix. (b) Rutile grain in kyanite. (c) Rutile grain in kyanite, shaded zoning.



(a)



(b)

Fig. 9: Nb and Zr elemental trend graphs, both plotted against Cr and Fe. Nb and Zr behave similarly indicating elemental substitution.

Interpretation

Contact metamorphism occurred early on, with andalusite forming first. A second or additional event of continental collision occurred later, although timing is unknown. A counter-clockwise crystallization path of andalusite->kyanite->sillimanite aligns with the tectonic regimes of contact metamorphism then continental collision (Fig. 6). In matrix rutile, Zr abundance is greater at the rim than in the cores, similar to one of the analyzed rutile inclusions in kyanite, indicating an increase in temperature during rutile growth. The other analyzed rutile inclusion in kyanite has higher Zr ppm in the core compared to the rim with zoning present. This indicates a decrease in temperature as rutile grew. Some elements appear to be related to others: as Zr increases, Nb and Cr increase and Fe very slightly decreases. Zr and Nb appear to behave similarly, indicating elemental substitution in rutile (Fig. 9, Appendix). Ti does not participate in elemental substitution as no relationship was indicated between Ti and Zr or Nb.

Lesjaverk, Norway has Sequence (2) crystallization order, which is the common sequence in 3-Al_2SiO_5 localities. Accessory minerals of staurolite and garnet are reported, though rutile has rarely been reported for triple point localities, making Lesjavery, Norway, unique. Pressure ranges of 4-9 kbar encompass all locality pressure measurements, and 580-660°C is on the higher end of reported temperatures, with the exception of Japan with 700°C.

Conclusion

In matrix rutile, Zr is lower in the core and higher at the rim, indicating an increase in temperature during rutile growth. Rutile primarily formed in the kyanite stability field, indicating moderately high temperatures and moderate pressures. Zr and Nb, Fe, and Cr participate in elemental substitution in rutile. Crystallization order was andalusite->kyanite->sillimanite. These P-T conditions are consistent with metamorphism during early contact/arc metamorphism followed by continental collision. Though timing of events are unknown, at least two tectonic events took place in Lesjaverk, Norway.

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Appendix

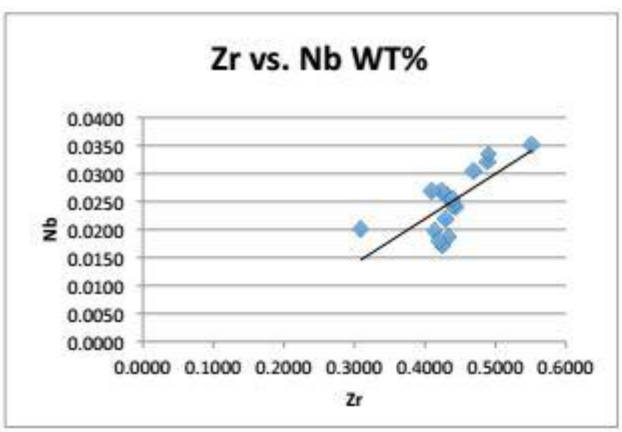

Fig. 10: Zr vs. Nb graph, As Zr wt % increases, the Nb wt % also increases.

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