

Crystallization sequences of coexisting andalusite, kyanite, and sillimanite, and a report on a new locality: Lesjaverk, Norway

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Abstract: Rocks containing three Al_2SiO_5 polymorphs – andalusite (And), kyanite (Ky), and sillimanite (Sil) – represent disequilibrium resulting from polymorph instability driven by changing pressure–temperature (P – T) conditions during related or unrelated tectonometamorphic events. There are six possible crystallization sequences. The two most common sequences of seventeen localities surveyed are: (1) $\text{Ky} \rightarrow \text{Sil} \rightarrow \text{And}$ (six localities), and (2) $\text{And} \rightarrow \text{Ky} \rightarrow \text{Sil}$ (six localities), including one locality for which two different sequences have been proposed. The two most common crystallization sequences have very distinct P – T conditions and paths and differ in whether low- P /moderate- to high- T (And zone) metamorphism preceded or postdated Ky–Sil zone conditions. $\text{Ky} \rightarrow \text{Sil} \rightarrow \text{And}$ sequences may form by a continuum of tectonometamorphic events that drive isothermal decompression from Ky zone conditions through the Sil zone to shallow (And zone) crustal levels, such as during extension $\pm$ magmatism that ultimately results in thin, hot crust. In sequences with early andalusite ($\text{And} \rightarrow \text{Ky} \rightarrow \text{Sil}$), formation of andalusite is typically unrelated to the later Barrovian metamorphism that formed Ky–Sil at moderate P – T conditions. Two other sequences have been reported but are much rarer: (3) $\text{Ky} \rightarrow \text{And} \rightarrow \text{Sil}$ (three localities), and (4) $\text{And} \rightarrow \text{Sil} \rightarrow \text{Ky}$ (two, possibly three localities). In these, Ky-zone metamorphism occurred as a distinct tectonometamorphic episode before or after the one that formed And–Sil. In cases in which Al_2SiO_5 polymorphs occur in veins or shear zones, the effects of deformation and fluids, including the possibility of non-lithostatic pressure effects, must be considered. Three- Al_2SiO_5 polymorph-bearing rocks from Lesjaverk, Norway, have not previously been described in the literature, and are interpreted here as forming by the sequence $\text{And} \rightarrow \text{Ky} \rightarrow \text{Sil}$. Metamorphic conditions determined using Zr-in-rutile thermometry indicate peak $T = 600$ – 640 °C at moderate P near the Ky–Sil boundary, similar to the peak conditions reported for other localities with the same crystallization sequence. These results are consistent with the finding that $\text{And} \rightarrow \text{Ky} \rightarrow \text{Sil}$ rocks record lower P – T conditions than the other reported sequences.

Key-words: andalusite; kyanite; polymorphs; sillimanite; metamorphism.

1. Introduction

The coexistence of three Al_2SiO_5 polymorphs (andalusite, kyanite, sillimanite) in a rock occurs as a result of metastable persistence of the phases during one or more metamorphic episodes (e.g., Hietanen, 1956; Grambling, 1981; Grover *et al.*, 1992; Garcia-Casco & Torres-Roldan, 1996). The crystallization sequence provides information about the pressure–temperature (P – T) path and therefore the tectonic history of a region, in many cases over tens to hundreds of millions of years if one or more of the polymorphs formed in distinct tectonometamorphic episodes. In some cases, the presence of the first-formed polymorph may be the only remaining evidence for an earlier metamorphic event or pre-peak metamorphic conditions; e.g., relict andalusite in a rock with later kyanite and sillimanite may be the only indication of a preceding tectonic event involving low- P metamorphism (e.g., Whitney, 2002).

A new locality of coexisting andalusite, kyanite, and sillimanite has recently been discovered in mica schist near

Lesjaverk, Norway (H. Taagvold, pers. comm.) (Fig. 1). The opportunity provided by this locality is used to survey seventeen examples of three- Al_2SiO_5 -bearing rocks worldwide (Table 1) and to discuss their inferred crystallization sequences and implications for tectonometamorphic processes.

2. Petrology of the Lesjaverk, Norway, three- Al_2SiO_5 rock

Lesjaverk, Norway, is located in the eastern part of the Western Gneiss Region of Norway (Fig. 1a). The Al_2SiO_5 -bearing rock was collected on the north side of the Romsdalen glacial valley at latitude $62^\circ 12' 26.50''$ N; longitude $8^\circ 31' 43.37''$ E (Fig. 1b). The bedrock geology in this region involves complex folding of high-grade gneiss with allochthonous units of the Caledonian nappe complex (Fig. 1a), including metasedimentary rocks such as the Al_2SiO_5 -bearing mica schist (Fig. 1b). The age of

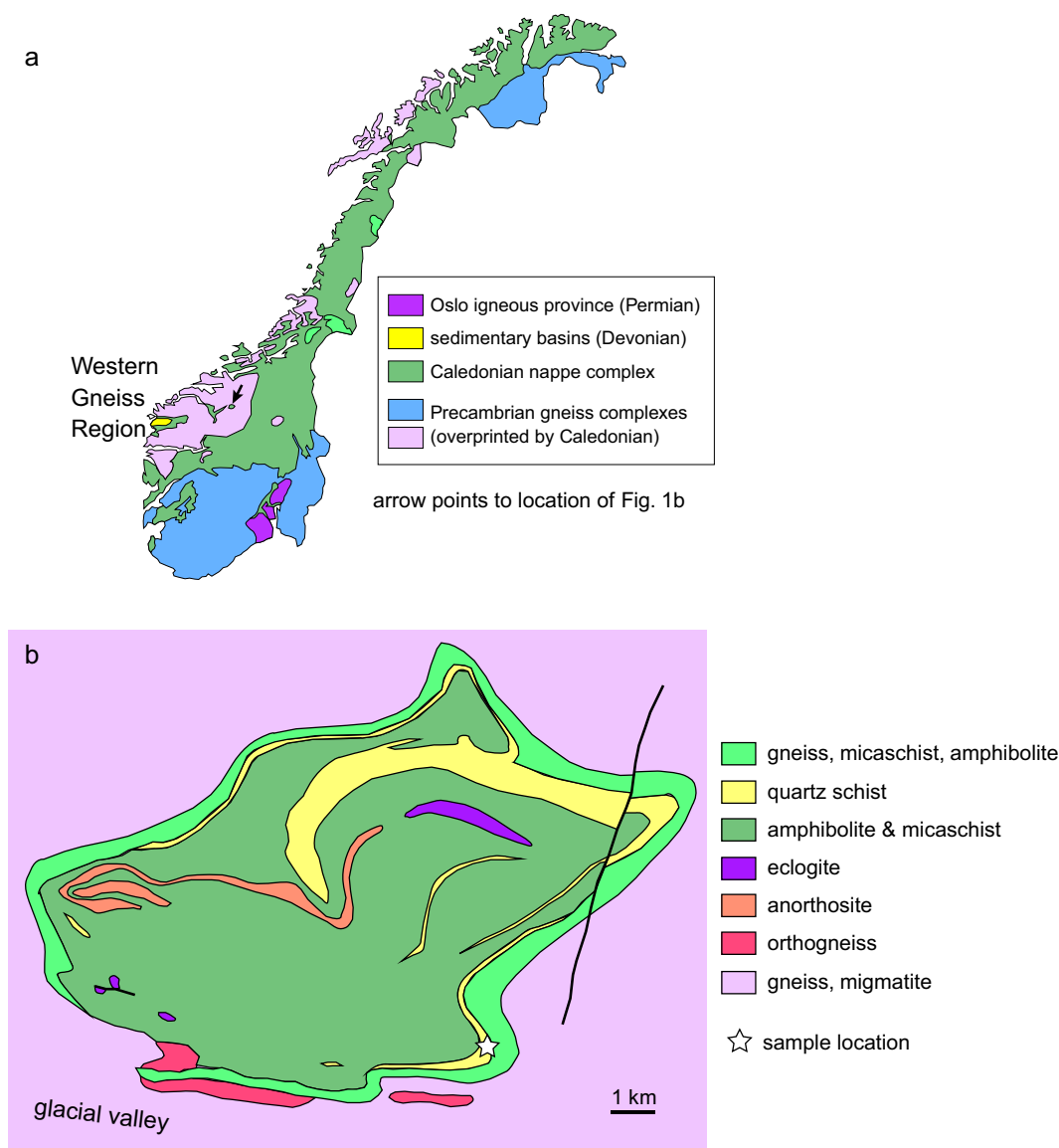


Fig. 1. (a) Simplified geologic map of Norway showing the location of Fig. 1b (arrow); (b) Geology of the Lesjaverk area, with the sample location indicated (star).

metamorphism is not known, but peak metamorphism in the kyanite and sillimanite zones was likely Caledonian.

The rock containing three Al_2SiO_5 polymorphs is a crenulated quartzofeldspathic mica schist (Fig. 2a) that contains coarse kyanite (up to 3 cm; Fig. 2b) intergrown with texturally-earlier andalusite (Fig. 3a and b); fibrous sillimanite is texturally late relative to andalusite and kyanite (Fig. 3a and b). Matrix phases are quartz, plagioclase, muscovite, rutile (locally abundant in aggregates, Fig. 4), and accessory zircon. Minor, texturally-late chlorite is intergrown with muscovite, and a thin rim of zoisite locally separates kyanite from matrix plagioclase.

Kyanite contains small amounts of Fe (0.6–1.4 wt% FeO^*) and Cr (0.1–0.4 wt% Cr_2O_3), as well as Ti, Mn, and Mg (Table 2). Relative to core regions, Fe is lower and Cr higher in a $\leq 400 \mu\text{m}$ wide zone at kyanite rims.

Andalusite has less Cr than kyanite but otherwise has a similar minor element composition. Sillimanite is fibrolitic so it was difficult to obtain a good analysis of composition with an electron microprobe. Kyanite and andalusite exhibit evidence for deformation: kyanite is kinked, and andalusite has locally developed subgrains.

Foliation is defined by muscovite ($\text{Si} \sim 2.9\text{--}3.0 \text{ apfu}$), and kyanite is aligned in this foliation. Muscovite has $\sim 20\%$ paragonite component and small amounts of Fe, Mg, Ti, and Cr (Table 2). Fine-grained muscovite is included in plagioclase and defines a fabric oblique to matrix foliation, but there is no difference in composition of inclusions vs. matrix muscovite. Plagioclase is zoned (Fig. 3b): rims are slightly less calcic ($X_{\text{an}} = 0.11\text{--}0.15$) than cores ($X_{\text{an}} = 0.16\text{--}0.18$) (Table 2), with a sharp, irregular boundary between core and rim.

Table 1. Localities with coexisting andalusite, kyanite, and sillimanite.

Locality	Rock type	Other minerals*	<i>P–T</i> ** GPa/°C	References***
Sequence: And-Ky-Sil (AKS)				
Sivrihisar, Turkey	Quartz-rich schist	Grt, St	0.6/550–600	Whitney (2002), Whitney <i>et al.</i> (2011)
Hamedan, Iran [see also ASK]	Quartz vein	St	0.4/600–740	Sepahi <i>et al.</i> (2004)
Yenisei Ridge, Russia	Metapelite	Grt, St, Cld, Bt	0.4–0.6/530–560	Likhanov <i>et al.</i> (2009)
Pyeongang, South Korea	Metapelite	Grt, St, Cld, Bt	0.4–0.5/520–620	Kim & Ree (2010)
Mt. Isa, Australia	Metapelite	Grt, St, Crd, Bt	Ky: 0.5–0.6/, 580; Sil: 0.5/580–670	Sayab (2006)
Lesjaverk, Norway	Metapelite	(No other Al-rich porphyroblasts)	Ky: med. P/600–640	This study
Ky-Sil-And (KSA)				
Boehls Butte, Idaho USA	Metapelite	Grt, Crd, Bt	Ky: 1.1/750; Sil: 0.5/650–700	Hietanen (1956), Carey <i>et al.</i> (1992), Grover <i>et al.</i> (1992)
New Mexico (Rio Mora, Picuris, Tusas, Truchas)	Metapelite	Grt, St, Cld, Crd, Bt	~0.4/510–600	Grambling (1981), Grambling & Williams (1985)
Betic Cordillera, Spain	Metapelite	Grt, St, Crd	1.0–0.20.3/600–650	Garcia-Casco & Torres-Roldan (1996)
Santander, Colombia	Metapelite	Grt, St, Bt	Ky: 0.8/700; Sil: 0.7/750; And: <0.3/600	Castellanos <i>et al.</i> (2008)
Monashee Mts, British Columbia, Canada	Leucosome	Grt, Bt	Ky: ~1/700–800; Sil: 0.75–1/800–850; And: <0.3/<650	Gervais (2018)
Abukuma terrane, Japan	Metapelite	Grt, Crd, Bt (St inclusions)	Ky: 1.2/700–750; Sil: 0.6/750–800; And: 0.3/500–600	Hiroi <i>et al.</i> (1998)
And-Sil-Ky (ASK)				
Karakoram Mts, Pakistan	Metapelite	Grt, St, Bt	0.7–0.8/650	Palin <i>et al.</i> (2012)
Broken Hill, Australia	Metapelite	Grt, Crd, Bt	0.6–0.9/>750 °C	Gibson <i>et al.</i> (2004)
Hamedan, Iran	Metapelite	Grt, St, Bt	0.4/600–740	Baharifar <i>et al.</i> (2019)
Ky-And-Sil (KAS)				
Balcooma Complex, Australia	Metapelite	Grt, St, Crd, Bt	Ky: 0.45/530; Sil: 0.6/630	Ali (2010)
Lepontine Alps, Switzerland	Quartz veins	Grt, St, Bt (host)	0.7–0.8/550–650	Klein (1976), Ferro (2003), Allaz <i>et al.</i> (2005)
Fiordland, NZ (possibly SKAS)	Mica schist	Grt, Bt	Ky: 0.85/720	Blatchford & Klepeis, pers. comm.

*Abbreviations after Whitney & Evans (2010). Listed minerals are primarily Al-rich porphyroblasts; the presence of biotite is also noted.

**In some cases only peak *P–T* conditions are reported, and in others, *P–T* path information is given for crystallization of one or more of the polymorphs.

***References in italics provided *P–T* conditions for locality but did not document Al₂SiO₅ textures.

Rutile occurs in the matrix and as inclusions in kyanite, and contains lamellae and patches of ilmenite (Fig. 4). Locally, polygonal rutile comprises clusters of tens of grains (Fig. 4). The composition of matrix rutile and inclusions in kyanite was determined by electron microprobe (Department of Earth Sciences, University of Minnesota) for application of the Zr-in-rutile thermometer (Table 3). Rutile varies in Zr content within and among grains. Most analyzed rutile (matrix and inclusions in Ky) exhibits an increase in Zr from core (~170–220 ppm) to rim (~270–335 ppm) (Fig. 4; Table 3). A rutile inclusion that has the highest Zr content analyzed exhibits a decrease in Zr from core (350 ppm) to rim (305 ppm).

Zr-in-rutile temperatures were calculated at 0.4–0.9 GPa (Tomkins *et al.*, 2007). Although pressure is not known,

the difference in calculated temperature for a variation of 0.2–0.4 GPa is <50 °C. Results are ~600 °C for rutile cores and ~640–660 °C for rims (Table 3), indicating that rutile likely grew in the kyanite stability field and equilibrated near the Ky-Sil boundary (Fig. 5).

3. Discussion

In most reported cases, kyanite and sillimanite formed sequentially during heating and/or decompression, before or after low-*P* metamorphism that formed andalusite (Table 1). In the common sequence And → Ky → Sil (AKS) (Sivrihisar, Turkey; Hamedan, Iran; Yenisei Ridge, Russia; Pyeongan, South Korea; Mt. Isa, Australia;

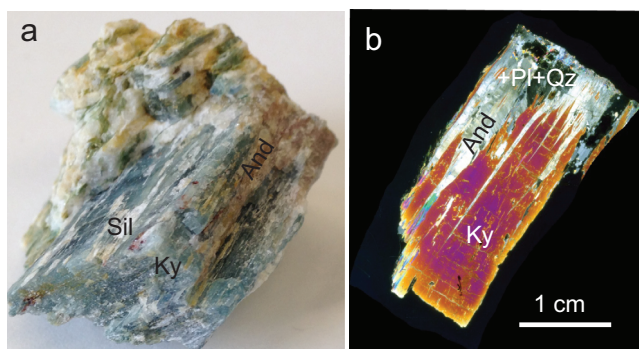


Fig. 2. (a) Photograph of three- Al_2SiO_5 mica schist, showing ~3 cm long coarse blue kyanite and intergrown red/pink andalusite. Fibrous white sillimanite is on the kyanite upper surface; (b) Digital scan of coarse ~3 cm-long crystal of kyanite with intergrown andalusite, plagioclase, and quartz under crossed polarized light. Differences in interference color of kyanite from core to rim correspond to zoning in transition metals.

Lesjaverk, Norway), metamorphism at shallow levels (andalusite zone) in an arc, continental rift, or other setting with a high geothermal gradient at shallow crustal levels is succeeded by higher- P (Ky zone), Barrovian metamorphism during collision, followed by further heating into the sillimanite zone (e.g., Whitney, 2002; Sepahi *et al.*, 2004; Likhanov *et al.*, 2009; Kim & Ree, 2010). Peak T typically does not exceed 600 °C and P is moderate (typically ~0.5 GPa), close to the Ky-Sil boundary (Fig. 5).

In another common sequence, Ky → Sil → And (KSA) (Boehs Butte, Idaho; New Mexico; Betic Cordillera, Spain; Santander, Colombia; Monashee Mts, Canada; Abukuma, Japan), the transition of kyanite to sillimanite typically occurs during decompression, with andalusite forming during late-orogenic intrusive activity at shallow levels of thinned crust (e.g., Hietanen, 1956; Grover *et al.*, 1992; Garcia-Casco & Torres-Roldan, 1996; Hiroi *et al.*, 1998). In all but one of these cases (New Mexico), P - T conditions are higher than those of the AKS sequence, with a significant component of decompression at high T (Fig. 5).

In two (possibly three) reported localities, early andalusite has been completely or partially pseudomorphed by Sil and then succeeded by (and, in some cases, partially replaced

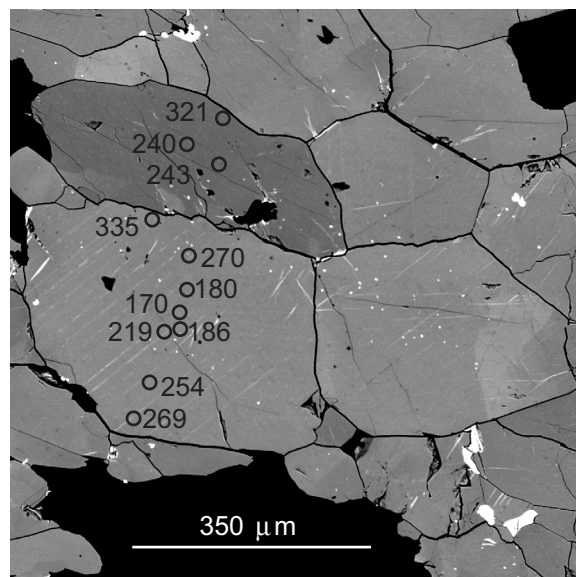


Fig. 4. Backscattered electron image of matrix rutile, with Zr content in ppm labeled. Lamellae and patchy replacement by ilmenite can be seen (white). Variation in gray scale of rutile is an effect of different crystallographic orientation of rutile.

by) kyanite in a later, unrelated event (ASK sequence; Karakoram, Pakistan; Broken Hill, Australia; Hamedan, Iran; Table 1). The distinctive shape and inclusion texture (chiastolite) of andalusite allows its former presence to be inferred with confidence even in cases in which the replacement process went to completion. In three other localities (Balcooma, Australia; Lepontine, Switzerland; and possibly Fiordland, New Zealand; Table 1), early kyanite has been overprinted by later andalusite, followed by sillimanite (KAS). All of these cases (AKS, KSA, ASK, KAS) are to some extent “polymetamorphic” in the sense of recording a change in tectonic regime and associated metamorphic conditions, but the rarer sequences are perhaps most likely to require metamorphism during distinct, unrelated orogenies.

Formation and preservation of three Al_2SiO_5 polymorphs may be influenced by rock type, as mineral assemblage affects whether an Al_2SiO_5 -consuming reaction operates or

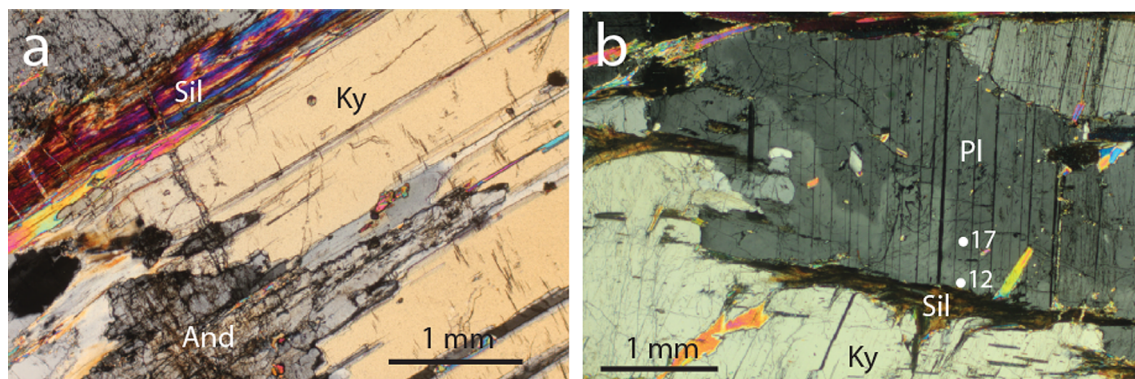


Fig. 3. Photomicrographs taken under crossed polarized light of (a) texturally-early andalusite overgrown by kyanite, which is rimmed by fibrous sillimanite; and (b) zoned plagioclase, with mol% anorthite contents labeled, adjacent to kyanite with fibrous sillimanite along the boundary.

Table 2. Representative compositions of major silicate minerals in the Lesjaverk three- Al_2SiO_5 rock.

Mineral	Pl	Pl	Ms	Ky	Ky	And
	Core	Rim		Core	Rim	
SiO_2	64.22	65.60	44.47	37.08	37.09	37.21
TiO_2	N.a.	N.a.	0.59	0.02	0.02	0.01
Al_2O_3	23.04	22.21	36.08	62.16	62.12	62.09
Cr_2O_3	N.a.	N.a.	0.25	0.11	0.44	0.06
FeO	0.00	0.06	2.77	1.04	0.78	0.78
MnO	N.a.	N.a.	<d.l.	<d.l.	0.01	<d.l.
MgO	N.a.	N.a.	0.81	<d.l.	<d.l.	<d.l.
CaO	3.50	2.58	<d.l.	<d.l.	<d.l.	<d.l.
Na_2O	9.35	9.62	1.66	<d.l.	<d.l.	<d.l.
K_2O	0.09	0.07	9.72	<d.l.	<d.l.	<d.l.
Total	100.21	100.15	96.36	100.41	100.46	100.13
Cations	8 ox.	8 ox.	11 ox.	5 ox.	5 ox.	5 ox.
Si	2.82	2.87	2.96	1.00	1.00	0.99
Ti	—	—	0.03	—	—	—
Al	1.19	1.15	2.83	1.98	1.98	1.98
Cr	—	—	0.01	—	0.01	0.01
Fe*	—	—	0.15	0.02	0.02	0.02
Mn	—	—	—	—	—	—
Mg	—	—	0.08	—	—	—
Ca	0.16	0.12	—	—	—	—
Na	0.80	0.82	0.21	—	—	—
K	—	0.01	0.83	—	—	—
an (mol%)	17	13				

*Calculated as Fe^{2+} in plagioclase, muscovite; Fe^{3+} in kyanite.

Table 3. Representative compositions of rutile and temperatures calculated with the Zr-in-rutile thermometer for the Lesjaverk three- Al_2SiO_5 rock.*

	Rim		Core	Core		Rim
ZrO_2	0.04	0.03	0.03	0.03	0.04	0.05
TiO_2	97.24	97.66	98.87	98.10	97.34	98.06
Nb_2O_5	0.61	0.63	0.62	0.61	0.59	0.70
FeO	1.55	1.16	1.03	0.67	1.01	0.71
Cr_2O_3	0.21	0.21	0.20	0.20	0.20	0.20
Total	99.65	99.69	100.75	99.61	99.18	99.72
Zr (ppm)	269	254	186	219	270	335
T °C**	624	619	596	608	624	641

*All analyses are from a single matrix grain (Fig. 1f) and were obtained with a JEOL 8900 electron microprobe following the analytical protocols described in Whitney *et al.* (2015).

**Tomkins *et al.* (2007) calibration, estimated $P = 0.6$ GPa.

not (Pattison, 2001). However, rocks containing three Al_2SiO_5 polymorphs in a reaction sequence occur in both mica-rich (metapelitic) schist and quartz-rich rocks (quartzite, quartz-rich schist, quartzofeldspathic rock/leucosome, quartz vein), and there is no apparent relationship between reaction sequence and rock type for those sites in which three polymorphs have been preserved (Table 1).

Polymorphs in many localities, representing the range of reported crystallization sequences, exhibit deformation features (*e.g.*, Sivrihisar, Turkey; Lesjaverk, Norway). Deformation may influence polymorphic transformation (Goergen *et al.*, 2008) and is therefore a possible factor in whether the polymorphs crystallize along a P – T path and

whether they are preserved. In the Idaho KSA locality, strained kyanite has partially transformed to andalusite (Grover *et al.*, 1992), and in the Hamedan, Iran, locality, andalusite in meter-scale shear zones has been partially replaced by kyanite, whereas andalusite outside the shear zone has not (A. Sepahi, pers. comm.). The latter observation may indicate that non-transformed andalusite was metastable under kyanite zone conditions and only transformed where kinetically favorable, or that differential pressure in the shear zone was sufficient to stabilize kyanite only there. Note that this history is distinct from that observed in quartz veins in the region (Sepahi *et al.*, 2004; Table 1).

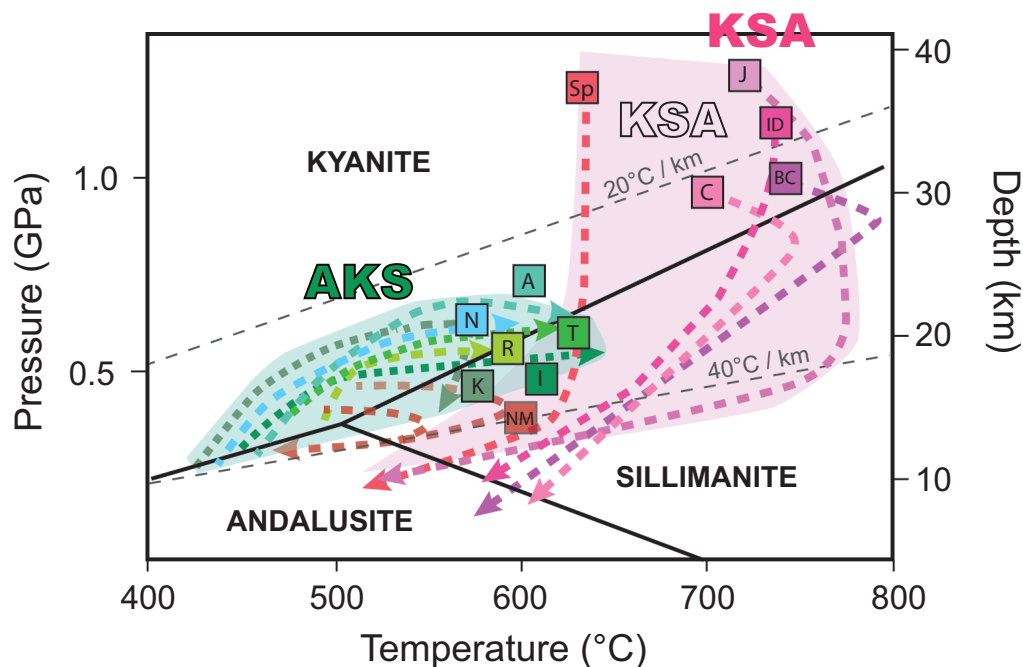


Fig. 5. P - T diagram showing conditions and *inferred* paths for rocks with coexisting andalusite, kyanite, and sillimanite and exhibiting the two most common crystallization sequences. P - T paths are schematic and intended to highlight trends in crystallization sequences; in some cases the paths, as drawn, connect conditions that occurred in distinct tectonometamorphic events. Localities reported with the And $\rightarrow$ Ky $\rightarrow$ Sil (AKS) sequence all have similar peak conditions near the Ky-Sil boundary. Most of the Ky $\rightarrow$ Sil $\rightarrow$ And (KSA) localities experienced higher P - T metamorphism and significant decompression compared to AKS rocks. Key to locality abbreviations (see Table 1 for references): A, Australia (Mt. Isa); BC, British Columbia, Canada (Monashee Mts); C, Colombia (Santander Massif); I, Iran (Hamedan AKS); ID, Idaho, USA (Boehls Butte); K, Korea (Pyeongang); J, Japan (Abukuma); N, Norway (Lesjaverk); NM, New Mexico, USA; R, Russia (Yenisei); Sp, Spain (Betic Cordillera); T, Turkey (Sivrihisar).

4. Summary and implications

Three coexisting Al_2SiO_5 polymorphs occur in metapelitic schist and a range of quartz-rich rock types, including veins and leucosomes. This survey of seventeen localities with coexisting andalusite, kyanite, and sillimanite reveals that two crystallization sequences (AKS, KSA) are most common and are distinct from each other in P - T conditions and paths (Fig. 5). Other crystallization sequences (ASK, KAS) occur, but are rarer.

The common AKS sequence involves prograde kyanite $\rightarrow$ sillimanite reaction at moderate PT conditions (~ 0.4 – 0.6 GPa, 500 – 625 $^{\circ}\text{C}$), and peak P - T is near the Ky-Sil boundary (Fig. 5). The early formation of andalusite was likely in a tectonometamorphic event unrelated to the later formation of kyanite and sillimanite. In some cases, the presence of relict andalusite is the only evidence for early low- P metamorphism in a region; *e.g.*, the Lesjaverk, Norway, locality described for the first time here. In contrast, KSA involves higher P (in many cases > 1 GPa), isothermal decompression through the sillimanite zone at high T (typically > 700 $^{\circ}\text{C}$), and possible formation of andalusite as a result of the extension ($\pm$ magmatism) that drove decompression. For most reported localities, there is no overlap in P - T conditions for the two most common sequences, indicating the importance of careful inference of the order of crystallization and determination of P - T conditions and paths.

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