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Deformation fabrics of phyllite in Gunsan, South Korea and Implications for seismic anisotropy in continental crust

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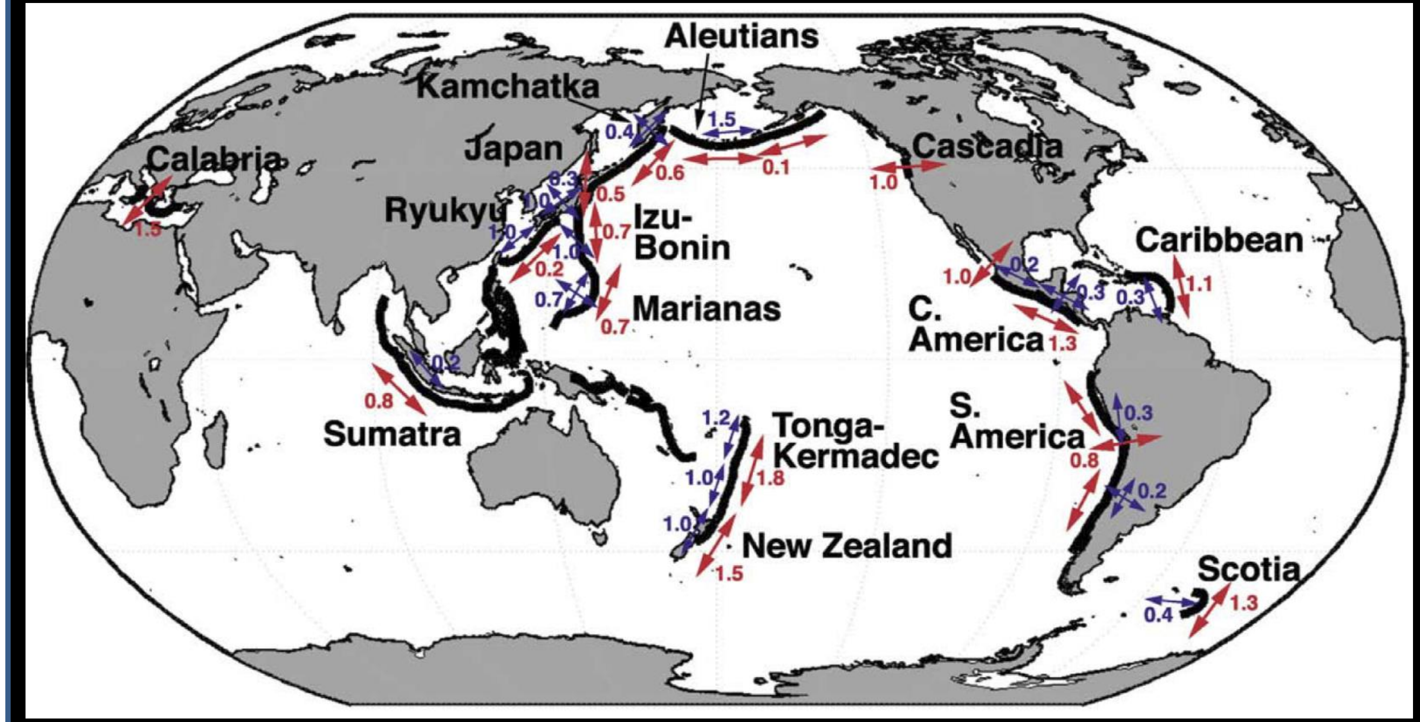
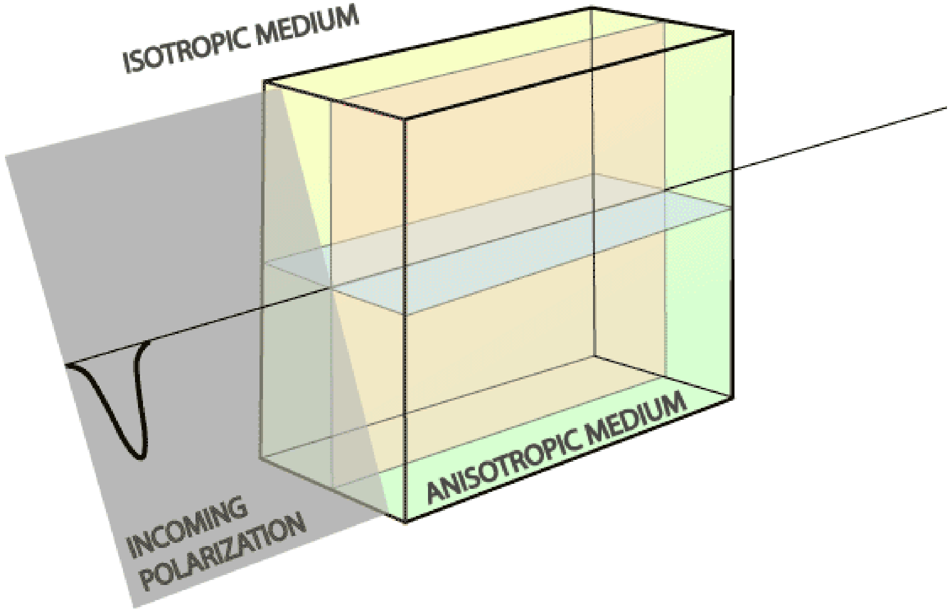
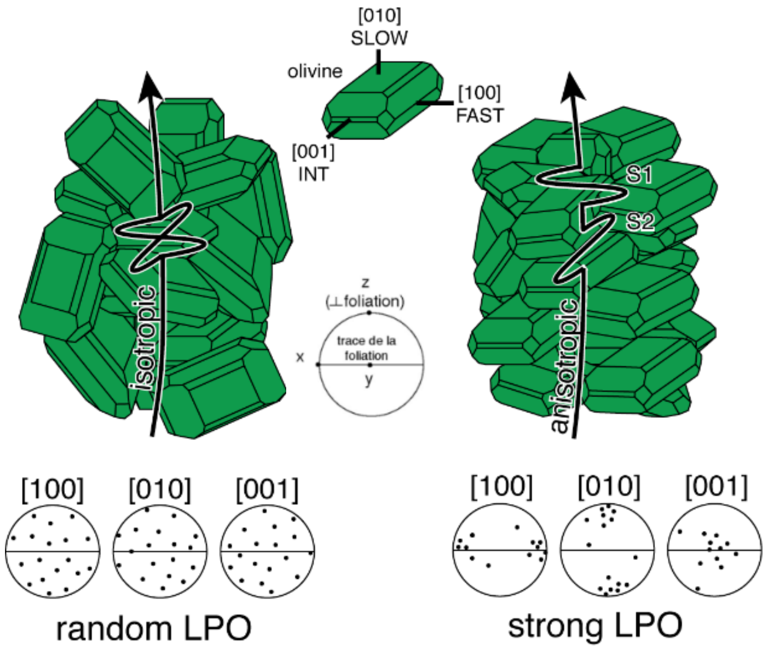
Seismic anisotropy observed in the Earth



Long and Silver, 2008; Long and Becker, 2010

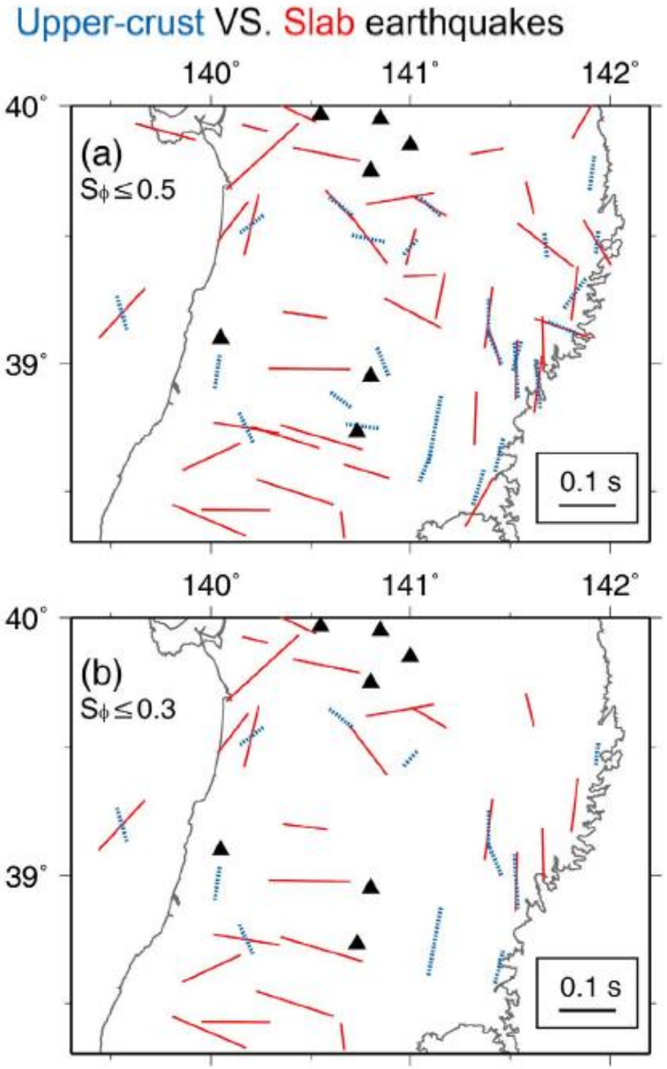




Seismic anisotropy originated in the interior of the Earth provides important information to understand tectonic processes, deep Earth structures and dynamics.

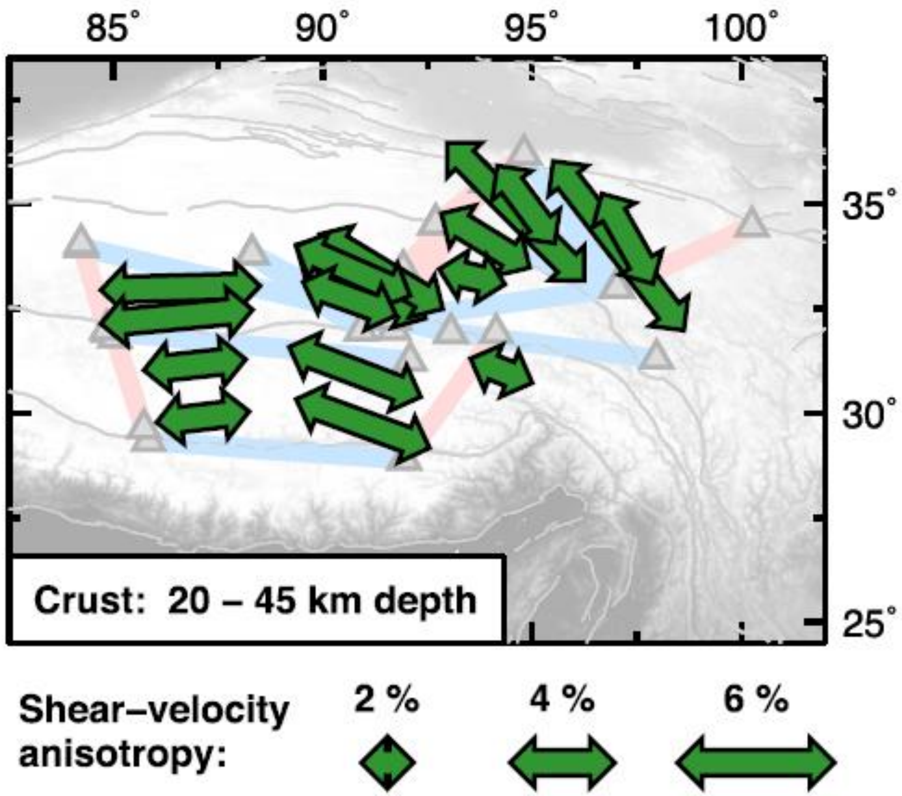
Seismic anisotropy observed in the continental crust

NE Japan



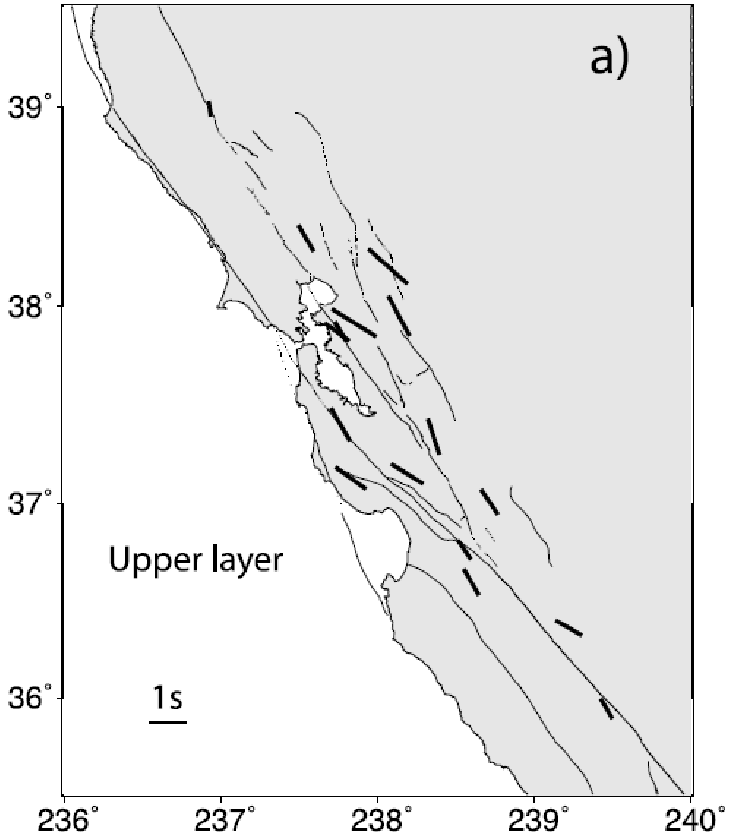
Huang et al., 2011

Tibet



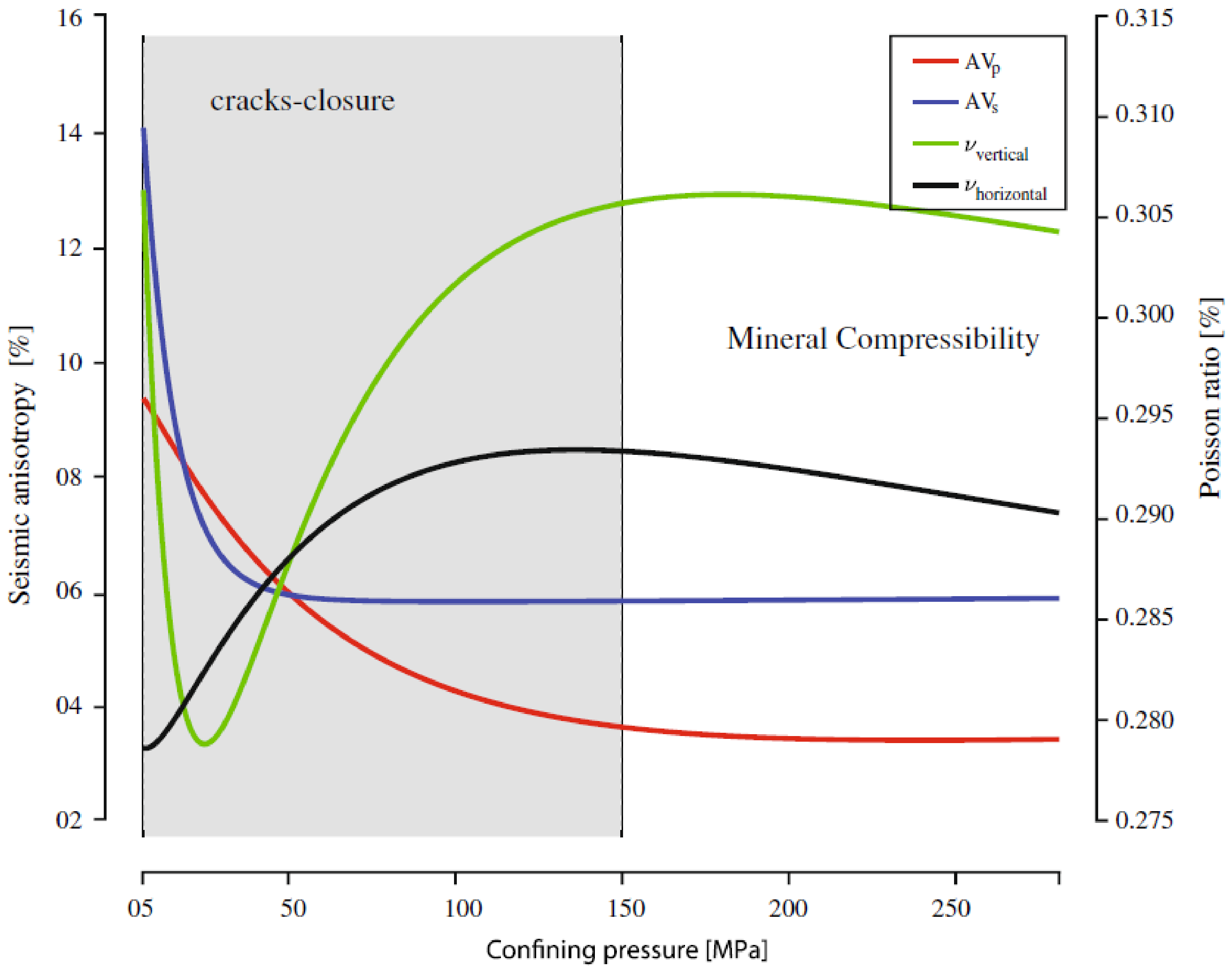
Agius and Lebedev, 2017

San Andreas Fault



Bonin et al., 2010

Importance of mineral fabrics on seismic anisotropy



Ultrasound waves propagation experiments

(Hefny et al., 2020)

Microcrack closure

- **Pressure = 200 ~ 250 MPa**

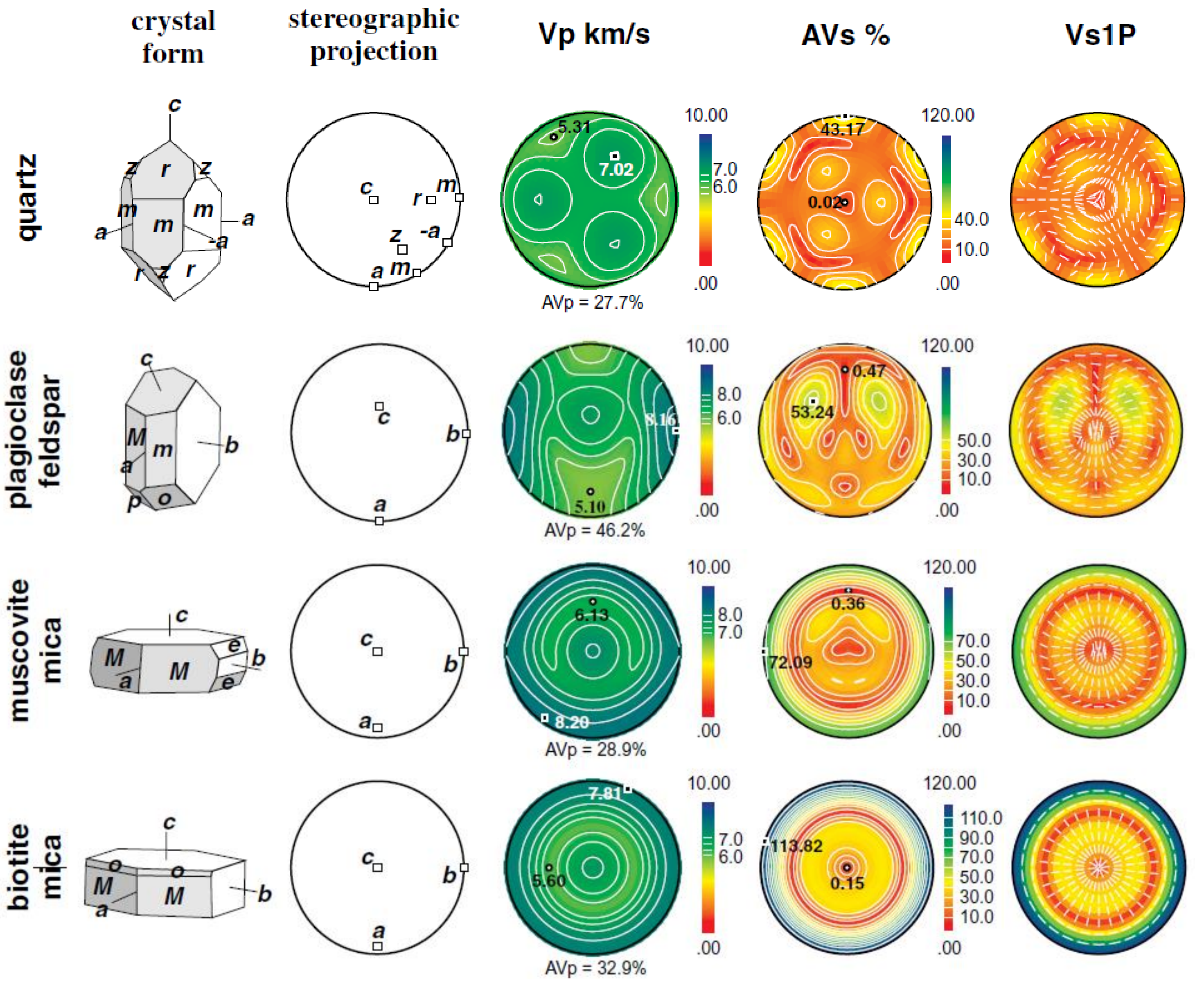
(Ji et al., 2013; Bianchi & Bokelmann, 2019)

- Even **P = 150 MPa**

(Hefny et al., 2020)

Lattice preferred orientation (LPO) of minerals is important in the middle crust.

Importance of mica group on seismic anisotropy



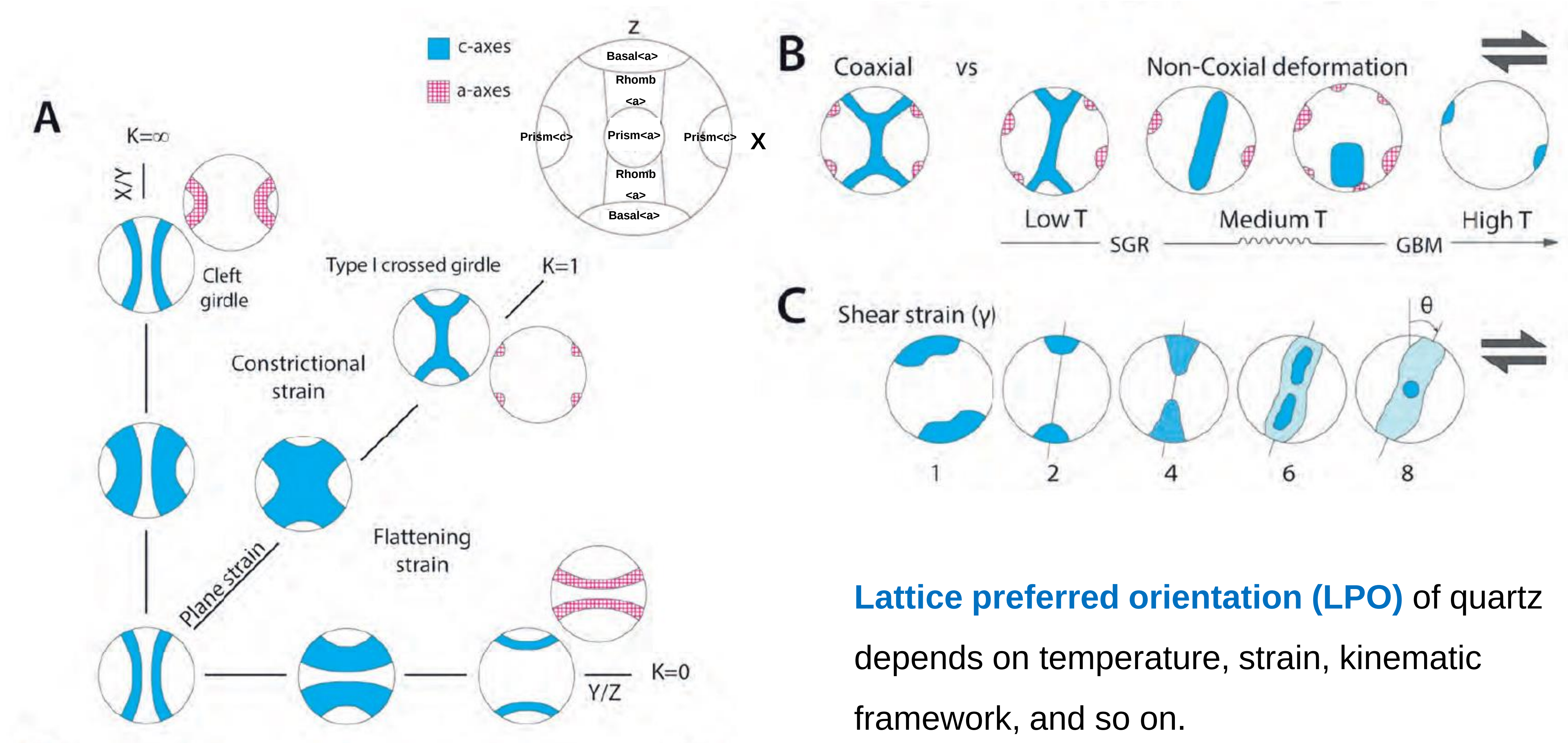
Modified from Lloyd et al., 2011

Phyllosilicates are one of major constituent mineral groups in the continental crust, showing the strongest elastic anisotropy.

Minerals of **mica group** in the continental crust have been suggested to play an important role in affecting seismic anisotropies observed in various tectonic settings.

LPO & fabric strength of mica need to be examined to understand its effect on seismic anisotropy.

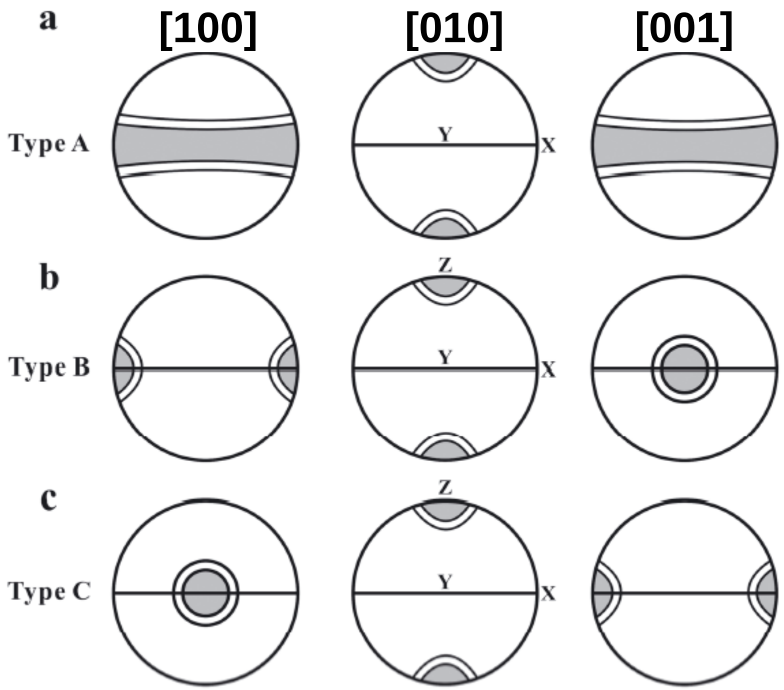
Lattice preferred orientation of quartz



Savignano et al., 2016

Lattice preferred orientation (LPO) of quartz depends on temperature, strain, kinematic framework, and so on.

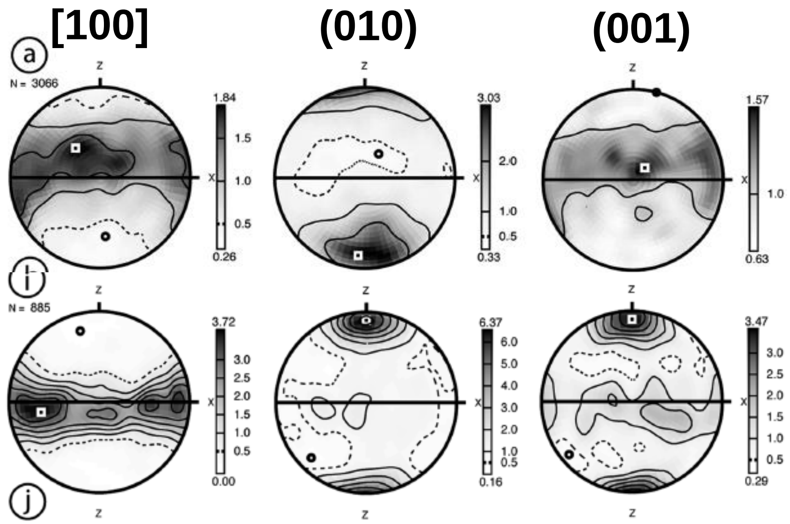
Lattice preferred orientation of plagioclase



Non-deformed

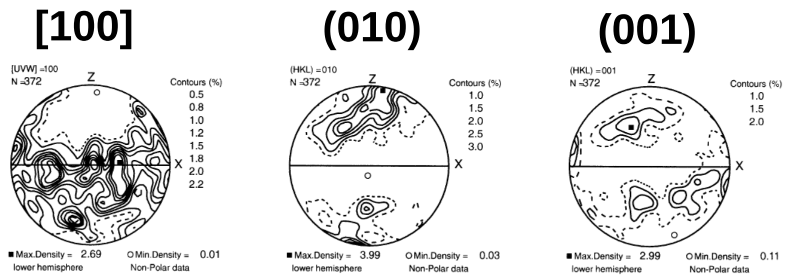
Ji et al. (2014)

Anorthosite & gabbro



Morales et al. (2011)

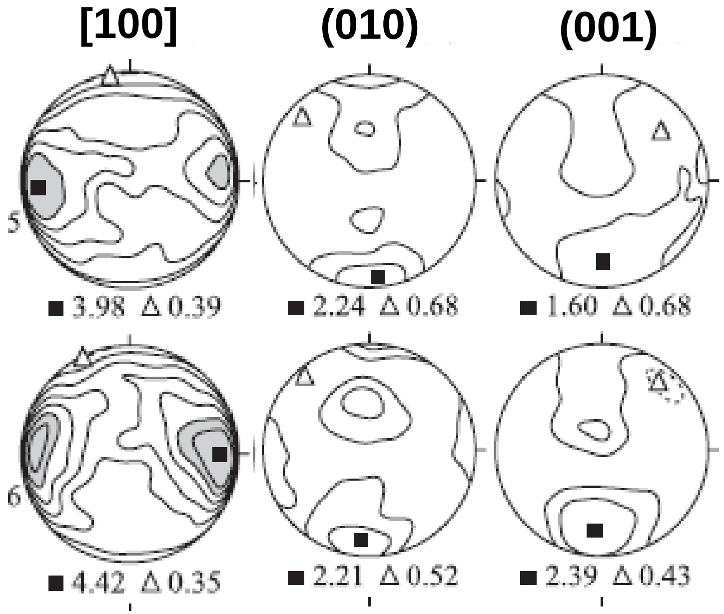
Anorthosite



Deformed

Egydio-Silva et al. (2011)

Granulite-facies mylonite



Díaz-azpiroz et al. (2011)

Amphibolite & mafic schist

Dominant slip systems of plagioclase have been reported:

(010)[001] (Olsen & Kohlstedt, 1984; Stünitz et al., 2003)

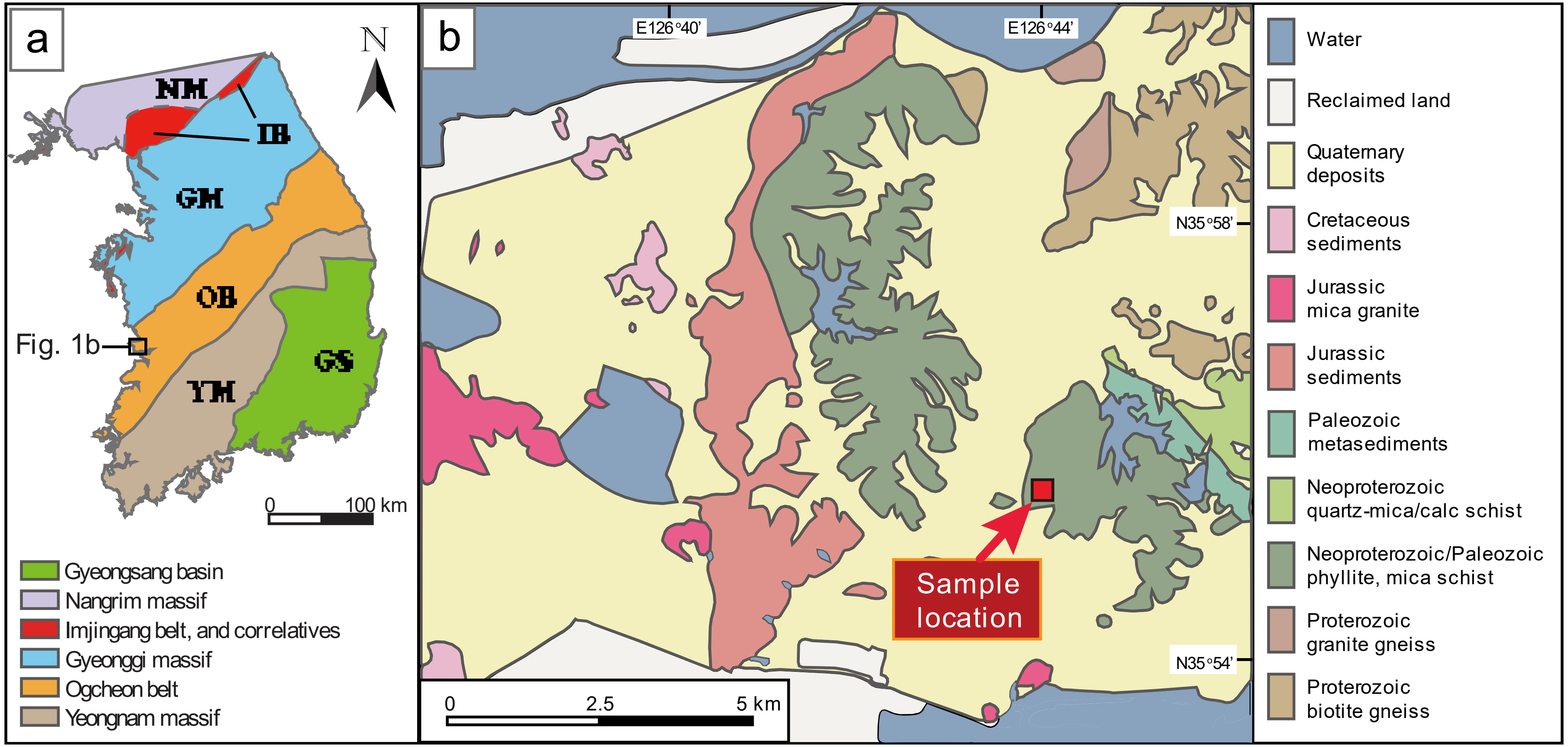
(010)[100] (Marshall & McLaren, 1977; Egydio-Silva et al., 2002)

Purpose of this study

In this study, we present data on **deformation microstructures** revealed by EBSD technique and **seismic properties of strongly deformed phyllites** which were collected from the Geumseongri Formation in Gunsan, South Korea in order to understand deformation mechanism and causes of seismic anisotropy in middle crustal level of highly deformed tectonic boundaries.

Sample description & method

Geological setting



Modified from Kim et al. (2012); Choi & Hwang (2013); de Jong et al. (2015)

Ogcheon Metamorphic Belt (OMB), South Korea

Study area: Geumseongri Fm. in SW OMB

Depositional age of protolith is controversial
(the youngest detrital zircon age is 806±19 Ma).

Metamorphic condition

Poen unit in NE OMB: 4.2-8.2 kbar and 490 - 540℃ (Jeungpyeong-Deokpyeong area; Kim et al., 1995; Cho and Kim, 2005)

Decrease in metamorphic grade towards the **SW OMB** (Miwon area; Kim and Cho, 1999)

Poen unit in SW OMB: 3.6-4.4 kbar and 350 - 450℃ (Hwasan area; Kim et al., 2002)

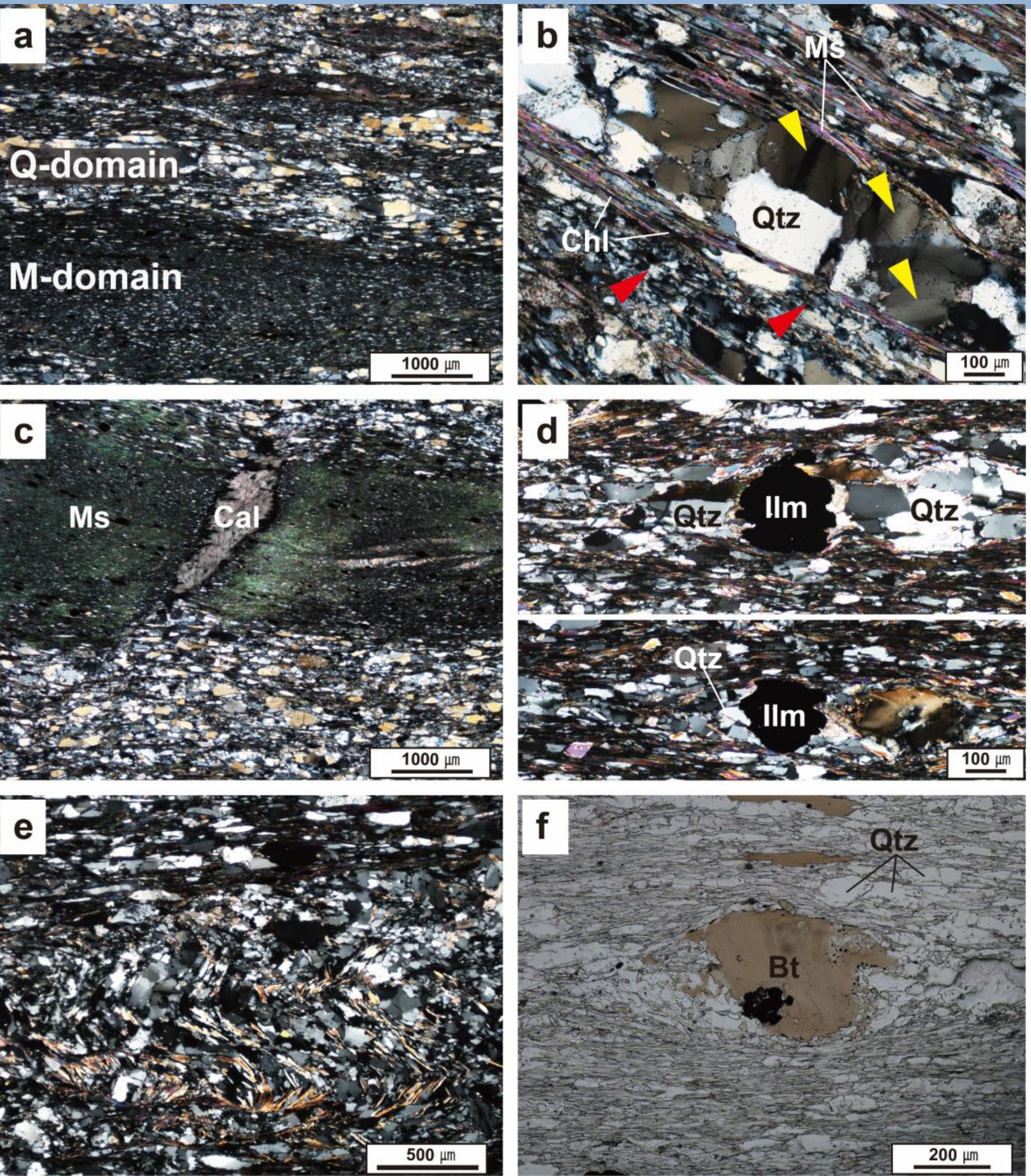
Outcrop of phyllite in Geumseongri Formation

Dark-grey phyllite with shiny mica-rich foliation

Folded and boudinaged quartz veins discordant with phyllite foliation

Axial planes and fold limbs of quartz veins are usually subparallel to the main foliation.

Optical micrograph of phyllite



Quartz + Albite + Muscovite + Chlorite + Calcite + Ilmenite + Biotite

Alternating Q-domain (quartz & albite) and M-domain (muscovite and chlorite)

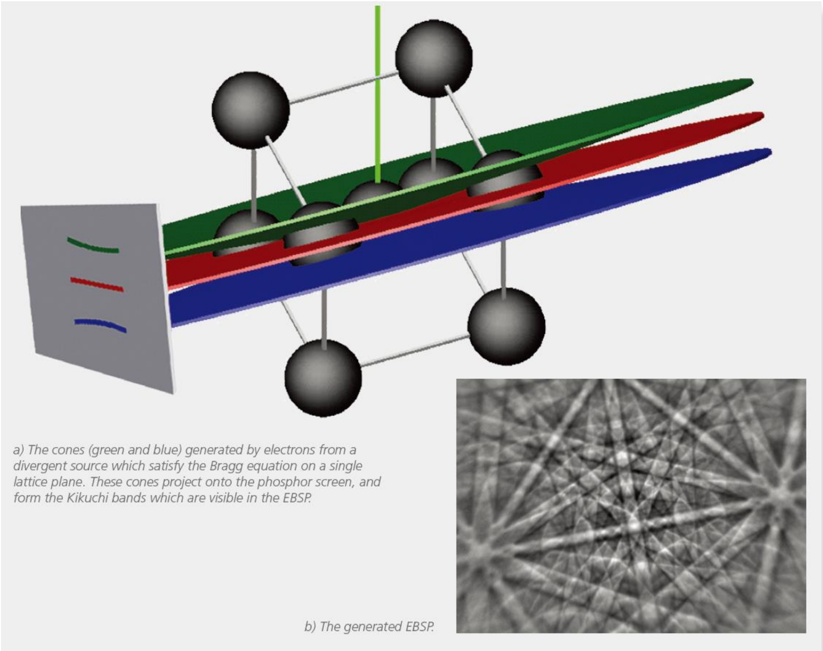
Quartz grains usually show subgrain boundaries and undulose extinction.

⇒ Intracrystalline deformation

Difficult to distinguish albite grain in microscope (rare twin)

Small-scale microfolds

EBSD mapping analysis & calculation of seismic anisotropy



JEOL JSM-7100F FE-SEM

Symmetry detector (EBSD)

EBSD analysis

Accelerating voltage: 20 kV, working distance: 25.0 mm, 70º tilted stage

Step size: 5 μm (4 samples) & 0.31 μm (1 sample)

zero solution correction based on 6 consistent pixels

Fabric strength: M-index (Skemer et al., 2005)

Seismic anisotropy

Single-crystal elastic stiffness tensors, LPOs & volume proportions of constituent minerals were used.

Voigt-Reuss-Hill averaging scheme

Software program (Mainprice, 1990)

Results & discussion

Modal compositions & seismic anisotropy

Sample No.	Modal Composition (%)[1]						Mean Aspect Ratio		Step Size (μm)
	Ms	Chl	Qtz	Ab	Cal	Accessory	Qtz	Ab	
G101	34.7	7.6	38.6	13.4	0.9	4.8	1.91	2.44	5
G102	31.1	11.3	33.0	15.0	0.9	8.7	1.93	2.11	5
G103	23.4	8.8	35.7	22.8	4.6	4.7	1.87	2.25	5
G104	22.1	13.8	47.6	14.0	0.8	1.7	2.12	3.39	5
G105	4.6	5.7	67.6	12.1	2.3	7.7	2.04	1.87	0.31

[1] Modal composition was estimated based on the EBSD map data. Ms: muscovite, Qtz: quartz, Chl: chlorite, Ab: albite, Cal: calcite

Sample No.	Muscovite		Quartz		Albite		Chlorite		Whole rock	
	AVp (%)	Max. AVs (%)	AVp (%)	Max. AVs (%)	AVp (%)	Max. AVs (%)	AVp (%)	Max. AVs (%)	AVp (%)	Max. AVs (%)
G101	51.1	58.1	4.5	5.7	1.2	1.5	26.7	51.1	21.7	24.2
G102	43.4	41.9	2.8	3.5	2.1	1.3	25.3	40.2	18.9	19.7
G103	44.4	47.7	3.9	4.7	1.3	1.7	21.4	34.9	14.3	15.4
G104	51.1	59.1	4.3	5.7	1.3	1.6	29.4	56.8	17.2	20.3
G105	43.9	42.8	7.1	9.8	15.6	24.8	26.5	47.4	9	9.6

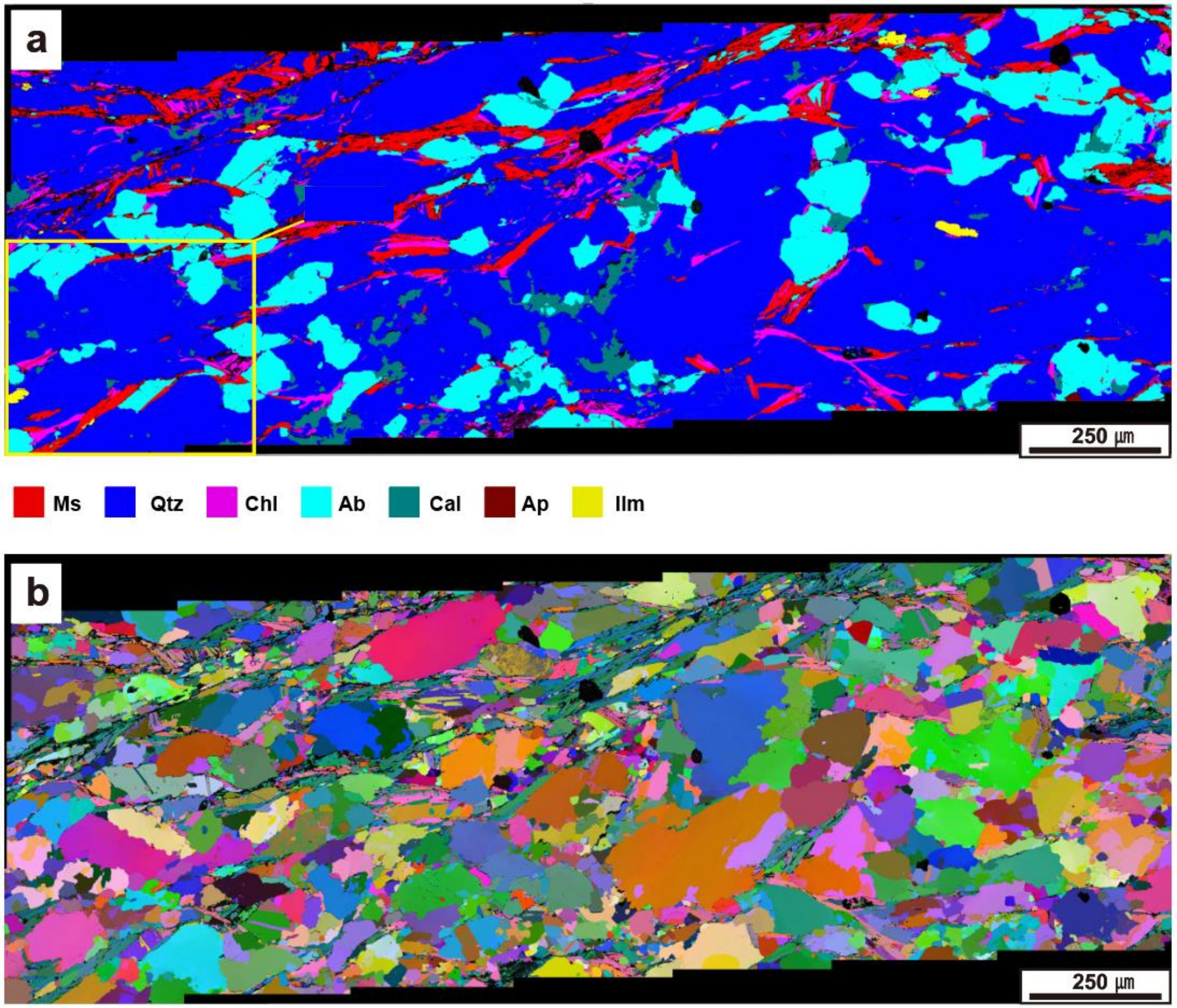
M-index & seismic anisotropy

Sample No.	M-Index							
	Ms		Chl		Qtz		Ab	
	Mean	CI [1]	Mean	CI	Mean	CI	Mean	CI
G101	0.3172	±0.01170	0.2510	±0.04770	0.0387	±0.00890	0.0627	±0.01395
G102	0.1693	±0.02335	0.1711	±0.04980	0.0326	±0.00670	0.0632	±0.01460
G103	0.2194	±0.02090	0.1578	±0.04575	0.0537	±0.01055	0.0639	±0.01295
G104	0.3175	±0.02775	0.2928	±0.06080	0.0555	±0.00570	0.0821	±0.01860
G105	0.21	-	0.293	-	0.09	-	0.379	-

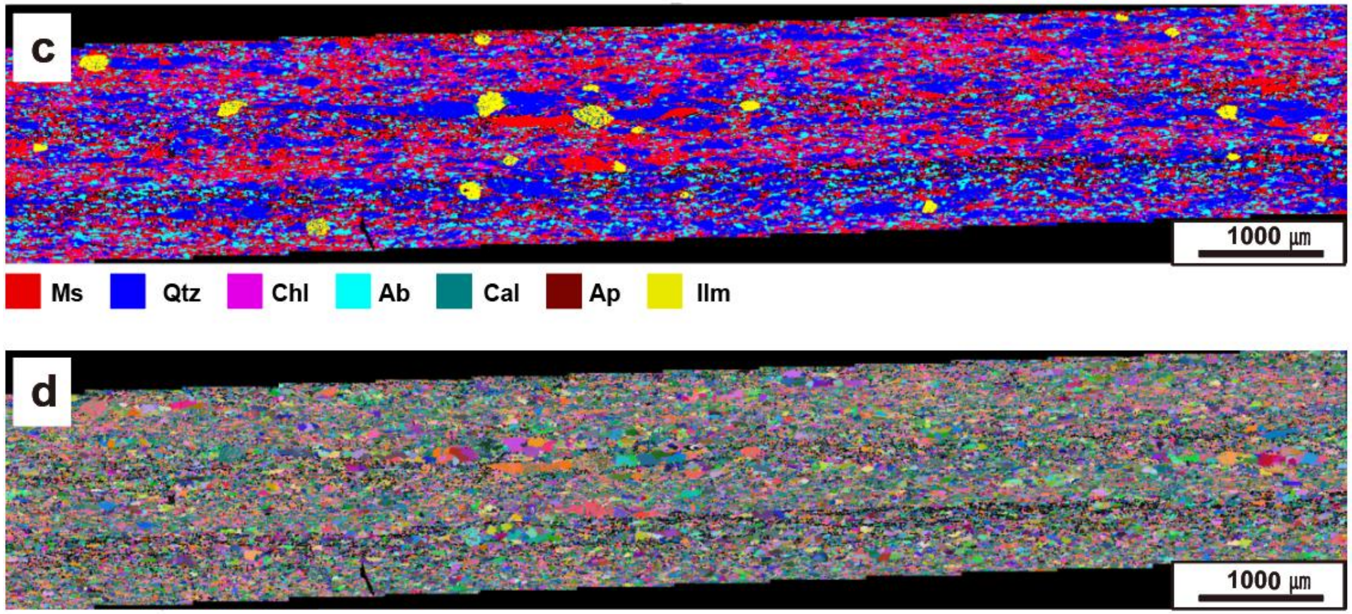
[1] CI: ± 95% confidence interval. Ms: muscovite, Qtz: quartz, Chl: chlorite, Ab: albite.

Sample No.	Muscovite		Quartz		Albite		Chlorite		Whole rock	
	AVp (%)	Max. AVs (%)	AVp (%)	Max. AVs (%)	AVp (%)	Max. AVs (%)	AVp (%)	Max. AVs (%)	AVp (%)	Max. AVs (%)
G101	51.1	58.1	4.5	5.7	1.2	1.5	26.7	51.1	21.7	24.2
G102	43.4	41.9	2.8	3.5	2.1	1.3	25.3	40.2	18.9	19.7
G103	44.4	47.7	3.9	4.7	1.3	1.7	21.4	34.9	14.3	15.4
G104	51.1	59.1	4.3	5.7	1.3	1.6	29.4	56.8	17.2	20.3
G105	43.9	42.8	7.1	9.8	15.6	24.8	26.5	47.4	9	9.6

EBSD Phase map and Euler map



G105 (step size: 0.31 µm)



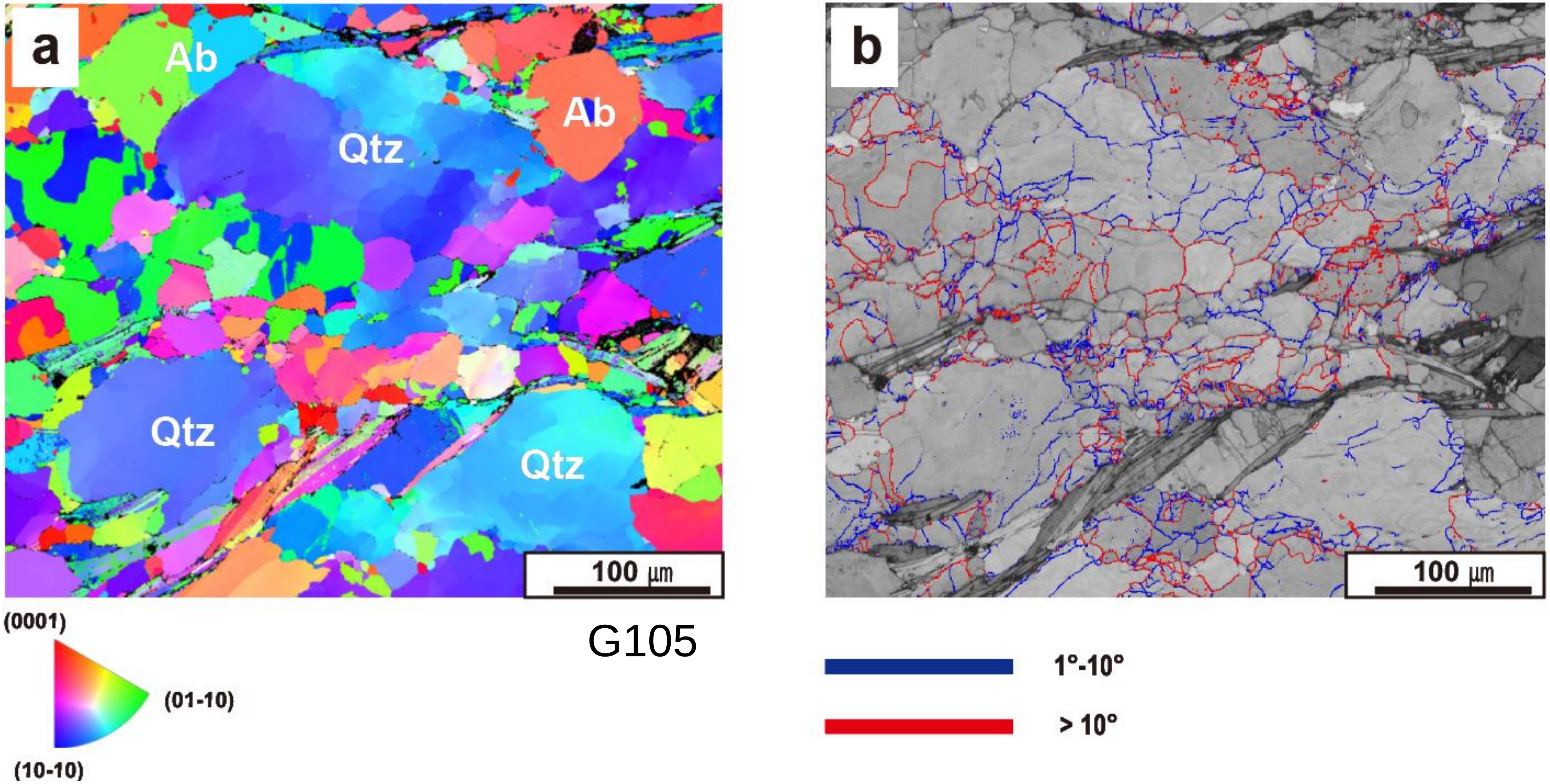
G102 (step size: 5 µm)

Step size of EBSD analysis

G101~G104: **5 µm**

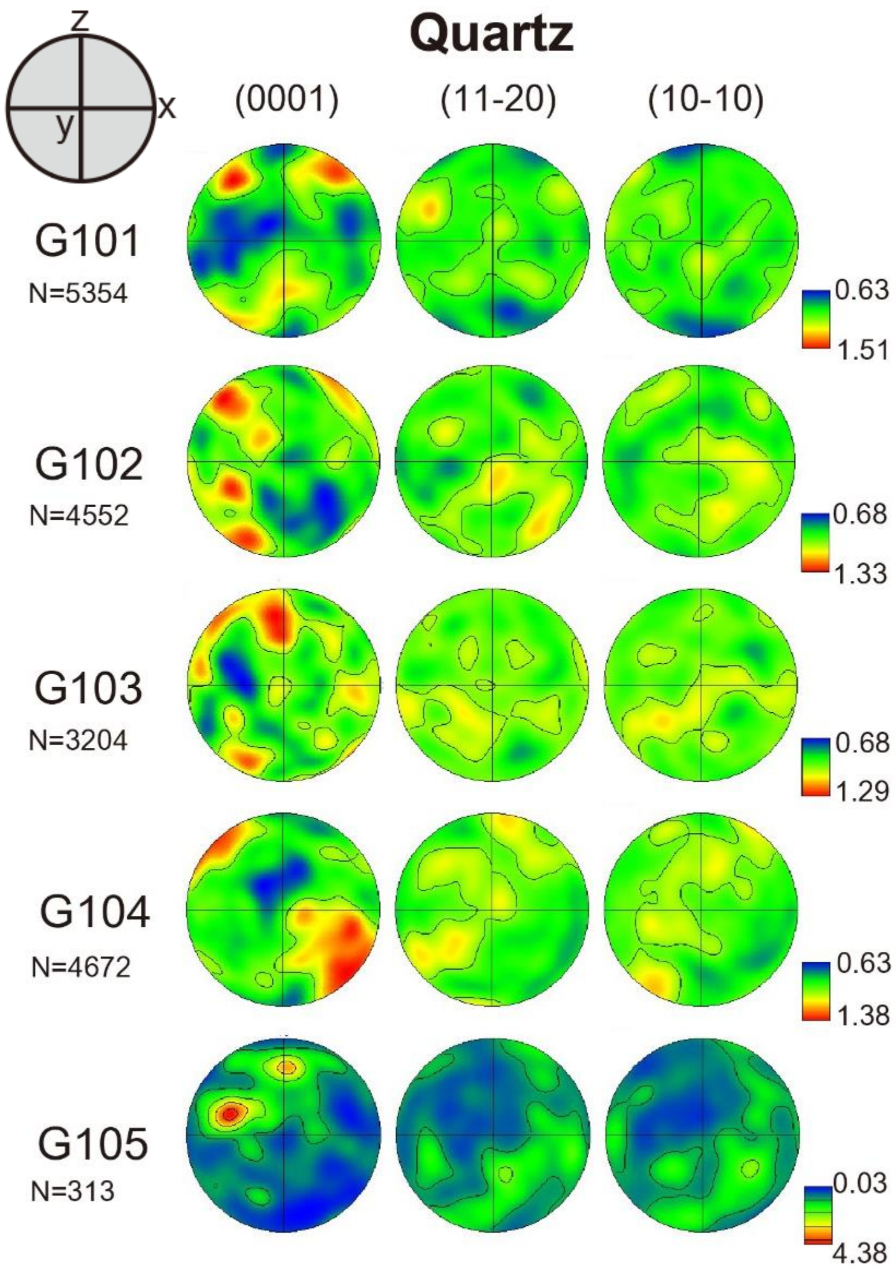
G105: **0.31 µm**

Inverse pole figure & grain boundary map from EBSD analysis



Different microstructure of quartz & albite

LPO of quartz



c-axes aligned at small angle to Z direction

G102 & G104: part of c-axes aligned subparallel to Y direction

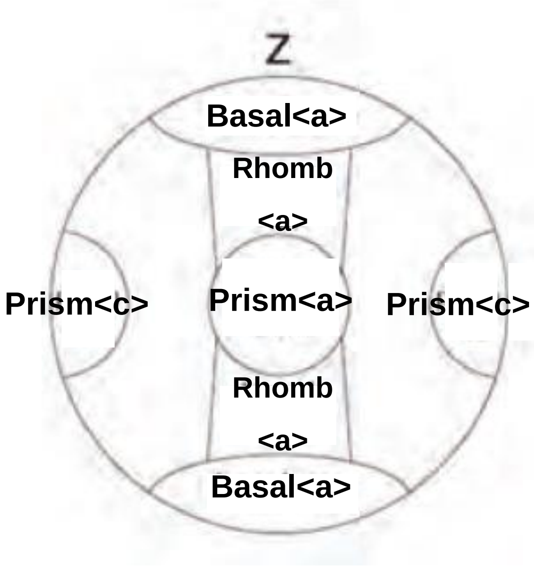
G102: crossed girdle

=> dislocation creep on basal<a>, prism<a>, and rhomb<a> slip systems

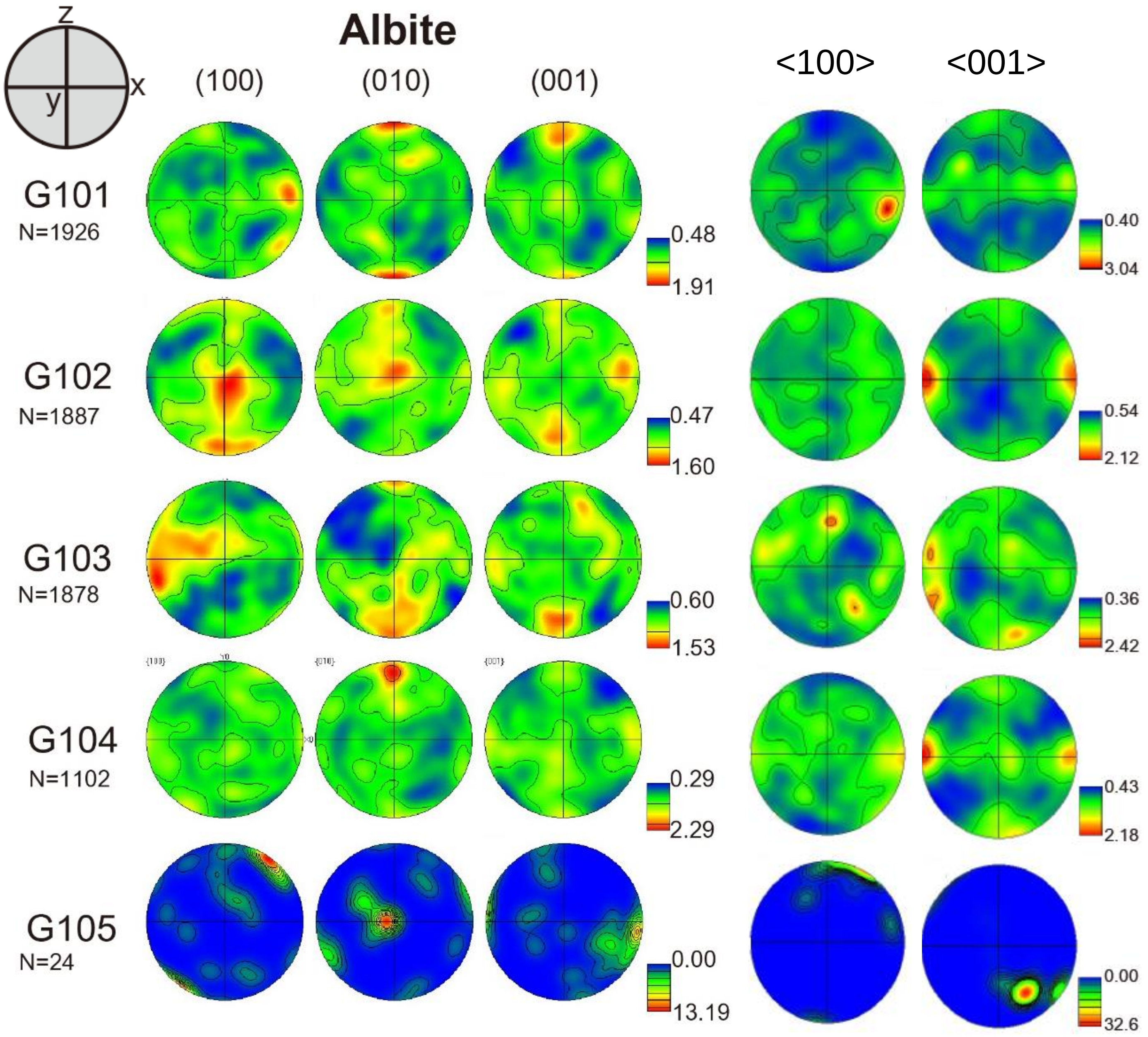
Plastic deformation **below 500 ℃**

(Stipp et al., 2002)

⇒ Consistent with metamorphic temperature estimated from **Poen Unit in OMB** (Kim et al., 1995; Kim & Cho, 1999; Kim et al., 2002)



LPO of albite



(010) & (001) poles aligned subparallel to Z direction

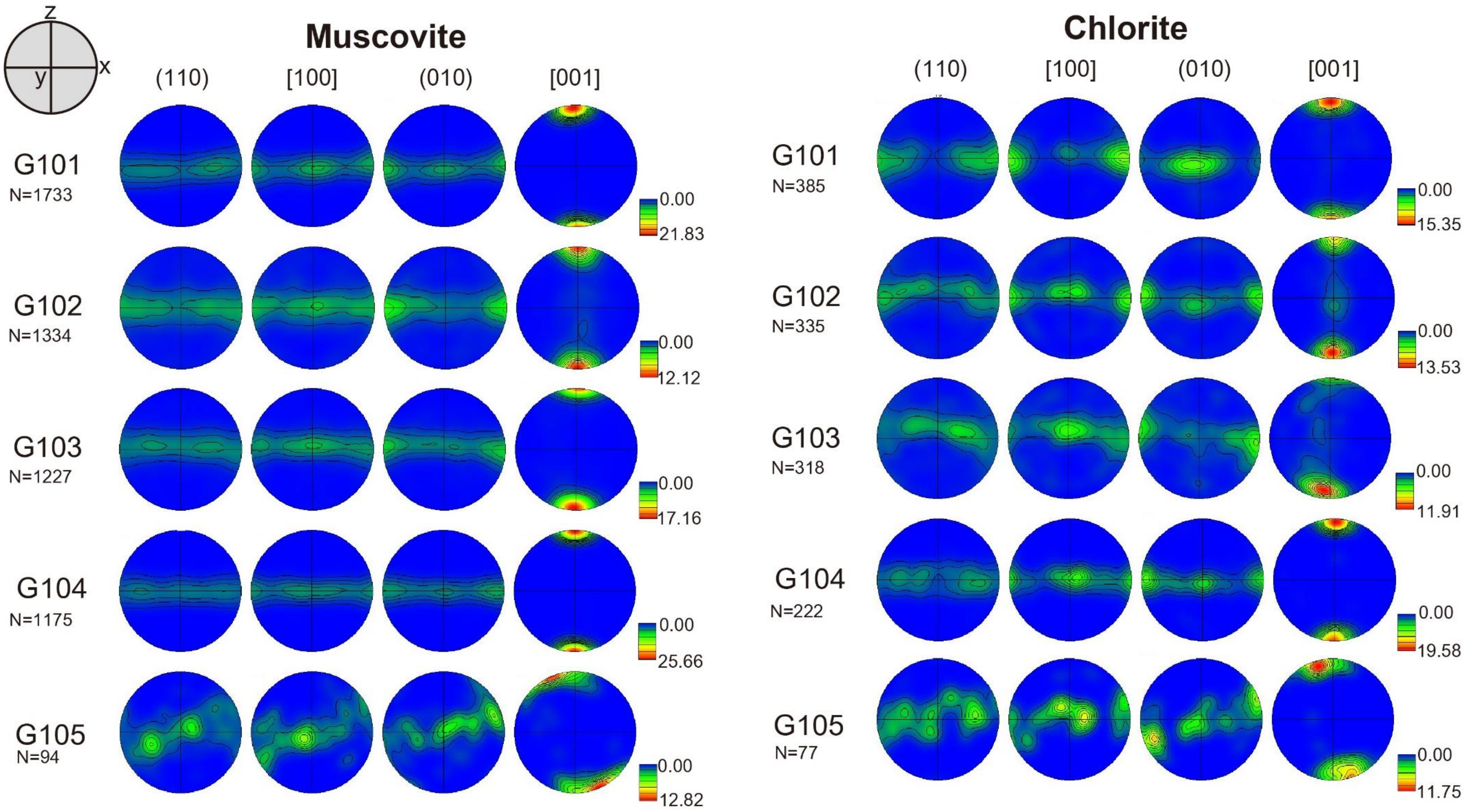
G102, G104:

- part of (001) poles aligned subparallel to X direction
- <001> axes form maxima parallel to X direction

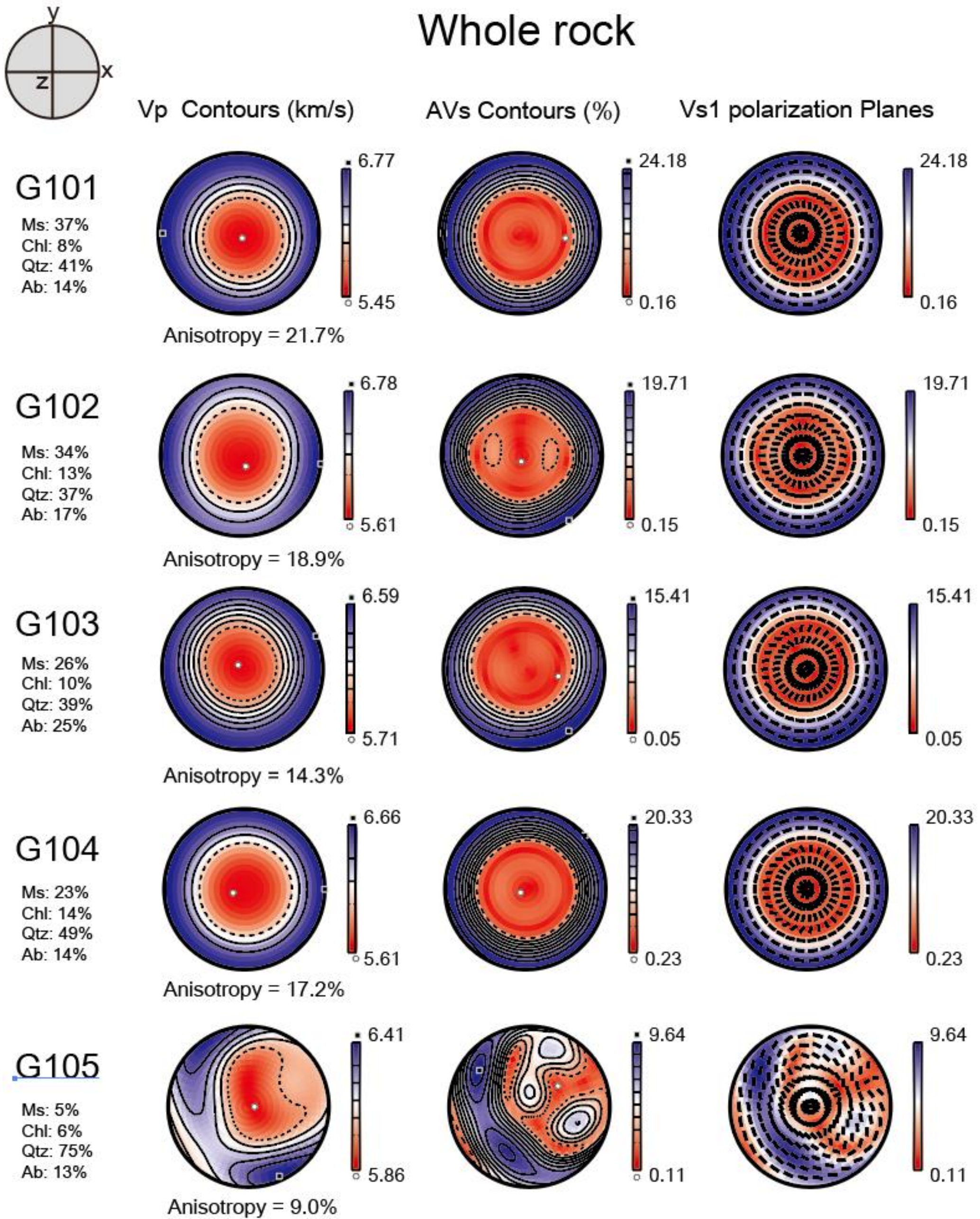
- Interchange in melt flow (Morales et al., 2011)
- Changes of dislocation systems (Díaz-azpiroz et al., 2011)

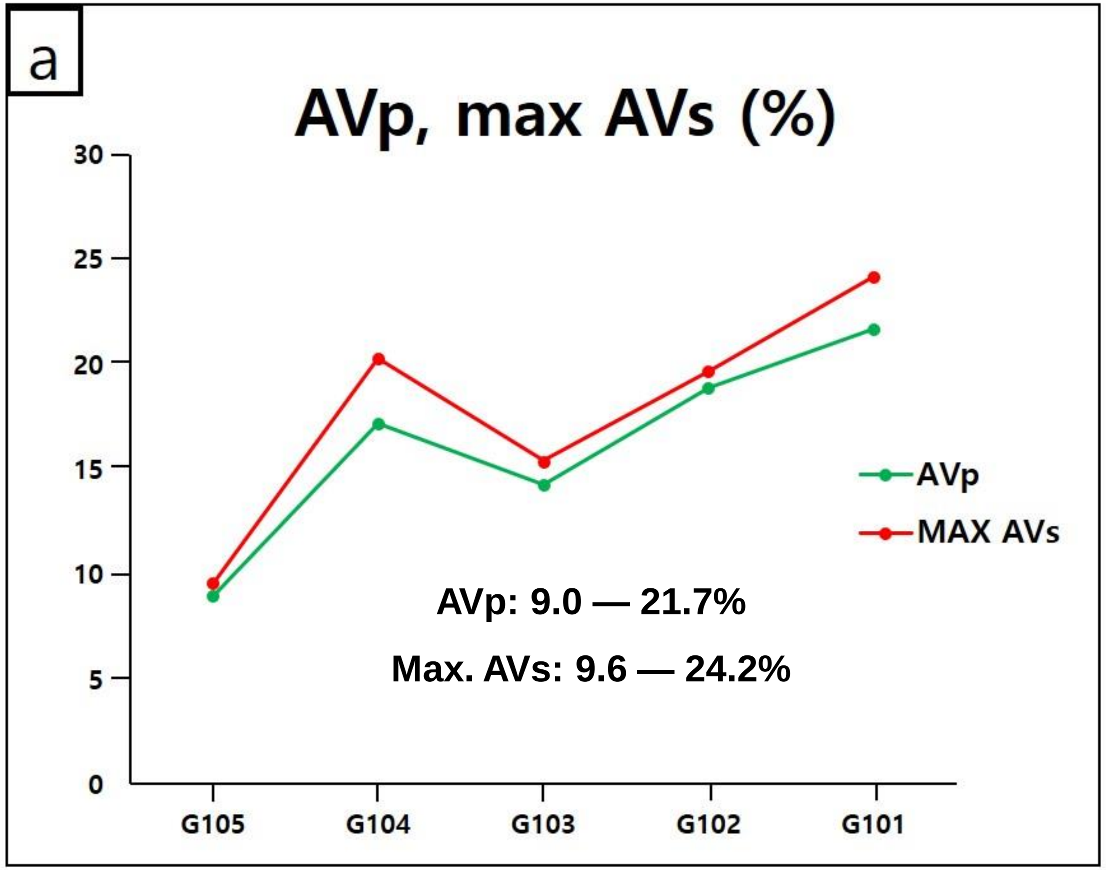
=> **rigid body rotation** with alignment of {010} and {001} cleavage planes parallel to the foliation, with minor dislocation creep with (010)[001] slip system

LPO of muscovite & chlorite



Seismic anisotropy of phyllite

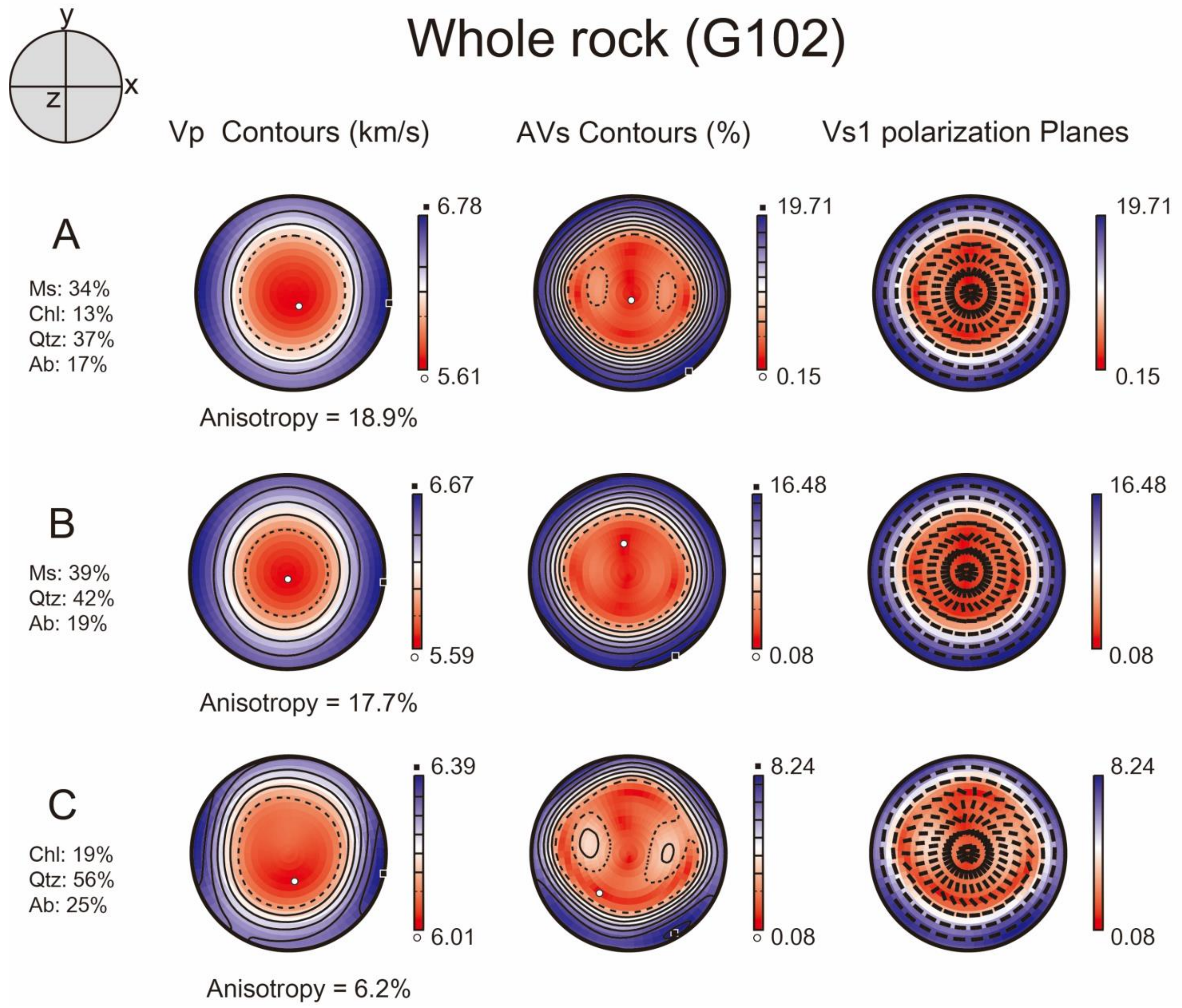




AVp: P-wave anisotropy, **max AVs**: maximum S-wave anisotropy

Patterns of contours were quite similar with those of **muscovite and chlorite** (except for G105; ~80% of quartz & albite).

Seismic anisotropy of phyllite

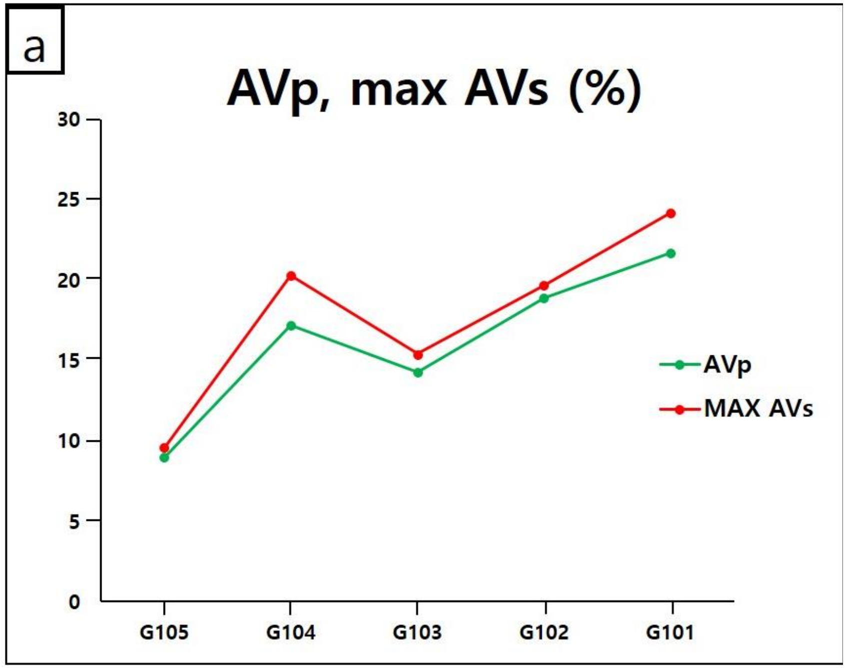


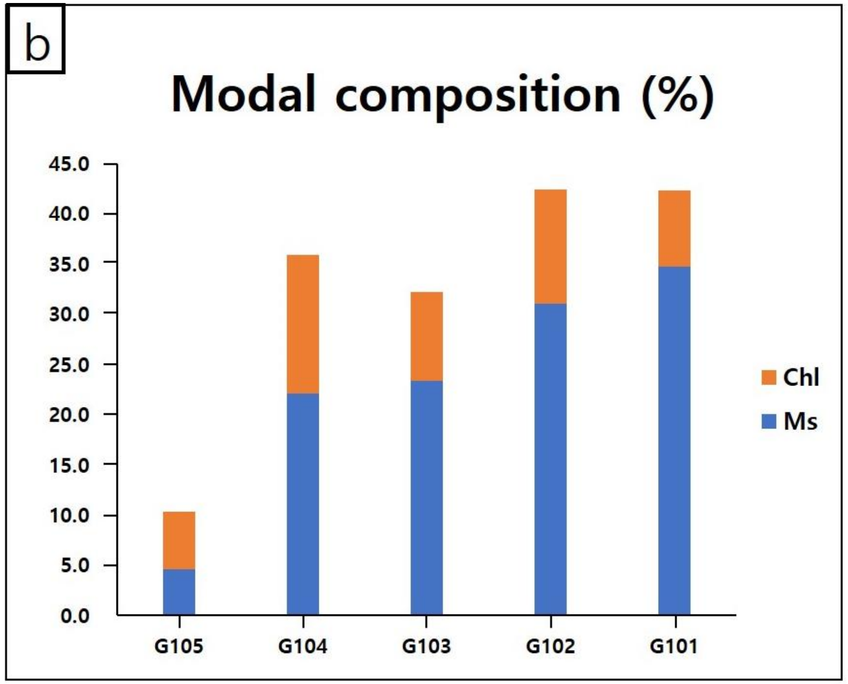
Additional seismic properties were calculated to understand the role of the coexistence of muscovite and chlorite.

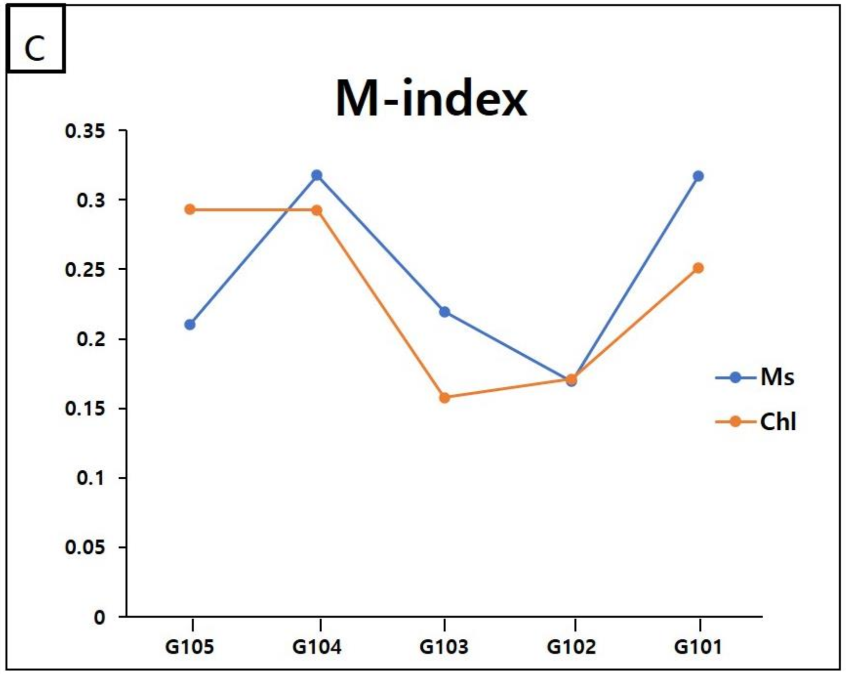
The strongest anisotropy was calculated in the assemblage of Qtz+Ab+Ms+Chl, indicating the constructive role of muscovite and chlorite.

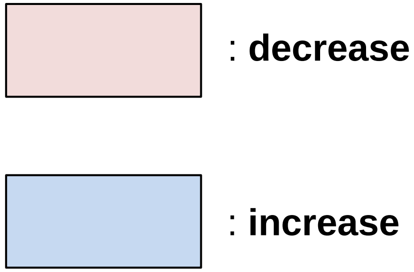
This contribution to the whole rock seismic anisotropies is due to their similar seismic patterns.

Role of fabric strength









	G104	G103
Modal composition (%) (Ms, Chl)	35.9	32.2
M-index (Ms, Chl)	0.318, 0.293	0.219, 0.158
AVp (%)	17.2	14.3
Max. AVs (%)	20.3	15.4

	G102	G101
Modal composition (%) (Ms, Chl)	42.4	42.3
M-index (Ms, Chl)	0.169, 0.171	0.317, 0.251
AVp (%)	18.9	21.7
Max. AVs (%)	19.7	24.2

Conclusion

- In this study, deformation microstructures of muscovite-quartz phyllites from the Geumseongri Formation in Gunsan, South Korea were studied using the electron backscattered diffraction technique.

- Our results showed that the [001] axes of muscovite and chlorite were strongly aligned subnormal to the foliation. The distribution of quartz c-axes indicates activation of the basal<a>, rhomb<a> and prism<a> slip systems, indicating deformation in the typical greenschist-facies condition in the middle crust.

- The calculated seismic anisotropies based on the lattice preferred orientation and modal compositions of minerals were in the range of 9.0–21.7% for the P-wave anisotropy and 9.6–24.2% for the maximum S-wave anisotropy.

- The modal composition and fabric strength of muscovite and chlorite significantly affect the magnitude and symmetry of seismic anisotropy.

minerals

MDPI

Article

Deformation Microstructures of Phyllite in Gunsan, Korea, and Implications for Seismic Anisotropy in Continental Crust

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Abstract: Muscovite is a major constituent mineral in the continental crust that exhibits very strong seismic anisotropy. Muscovite alignment in rocks can significantly affect the magnitude and symmetry of seismic anisotropy. In this study, deformation microstructures of muscovite-quartz phyllites from the Geumseongri Formation in Gunsan, Korea, were studied to investigate the relationship between muscovite and chlorite fabrics in strongly deformed rocks and the seismic anisotropy observed in the continental crust. The [001] axes of muscovite and chlorite were strongly aligned subnormal to the foliation, while the [100] and [010] axes were aligned subparallel to the foliation. The distribution of quartz c-axes indicates activation of the basal<a>, rhomb<a> and prism<a> slip systems. For albite, most samples showed (001) or (010) poles aligned subnormal to the foliation. The calculated seismic anisotropies based on the lattice preferred orientation and modal compositions were in the range of 9.0–21.7% for the P-wave anisotropy and 9.6–24.2% for the maximum S-wave anisotropy. Our results indicate that the modal composition and alignment of muscovite and chlorite significantly affect the magnitude and symmetry of seismic anisotropy. It was found that the coexistence of muscovite and chlorite contributes to seismic anisotropy constructively when their [001] axes are aligned in the same direction.

Keywords: phyllite; lattice preferred orientation; seismic anisotropy; deformation microstructures; muscovite; chlorite

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If you are interested in this study, see the recent paper published in *Minerals*.

Link:

https://www.mdpi.com/2075-163X/11/3/294

Citation:

Han S, Jung H. Deformation Microstructures of Phyllite in Gunsan, Korea, and Implications for Seismic Anisotropy in Continental Crust. *Minerals*. 2021; 11(3):294. https://doi.org/10.3390/min11030294