ex solo ad solem, वसुधैव कुटुम्बकम्
ex solo ad solem, Vasudhaiva Kutumbakam
from the earth to the sun, the world is one family

2nd Conference of the International Association for Structural Geology and Tectonics (IASGT)
(22-24 July, Accra, Ghana)

Multiscale Fabric Data from Deformed Rocks

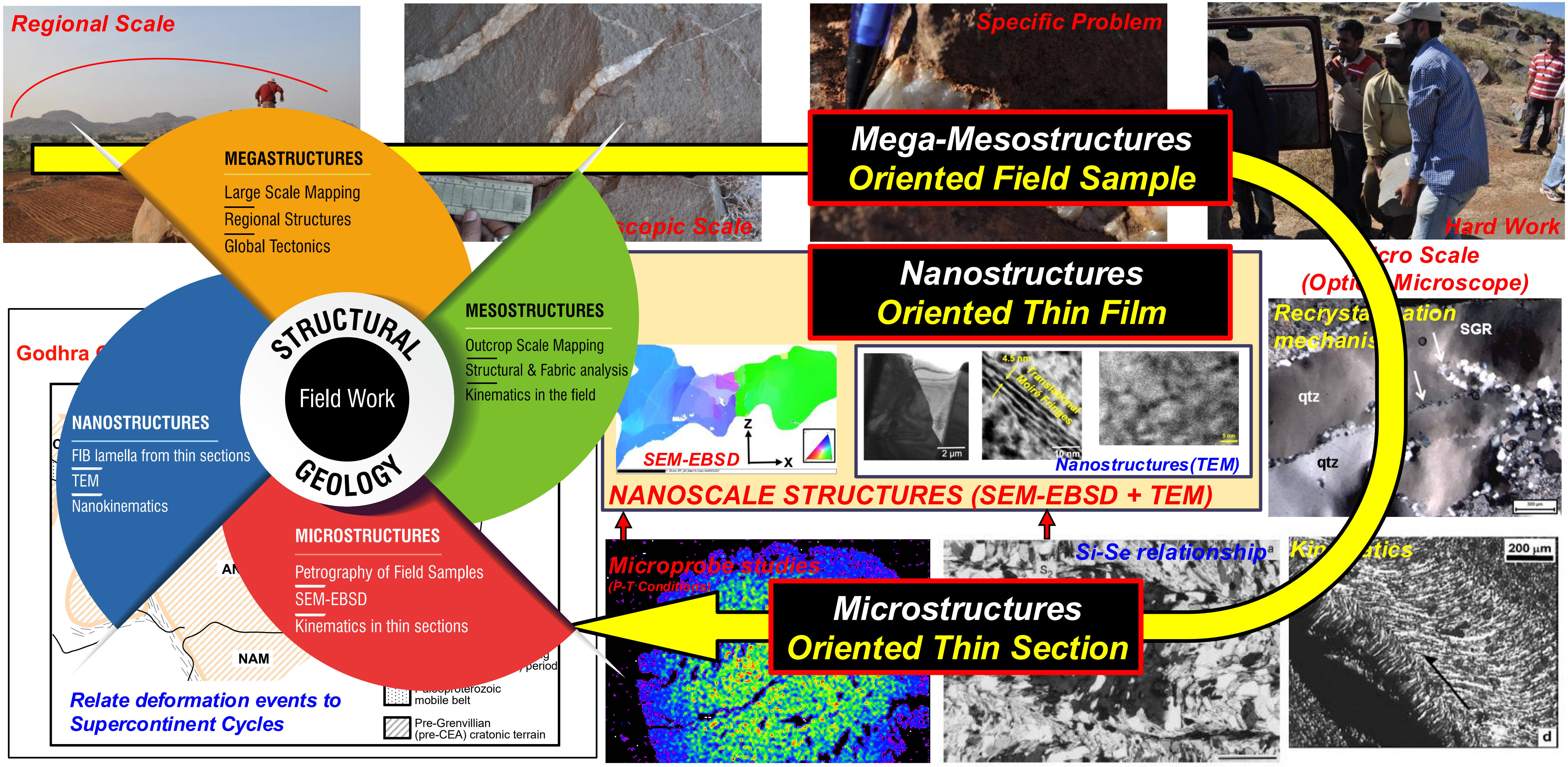
Meso to Nano Scale Analysis

Presentation By

Manish A. Mamtani

Department of Geology & Geophysics
Indian Institute of Technology, Kharagpur, India

Structural Geology Is A Game of Scales



Structural Geology from the Mesoscopic to the Nanoscale

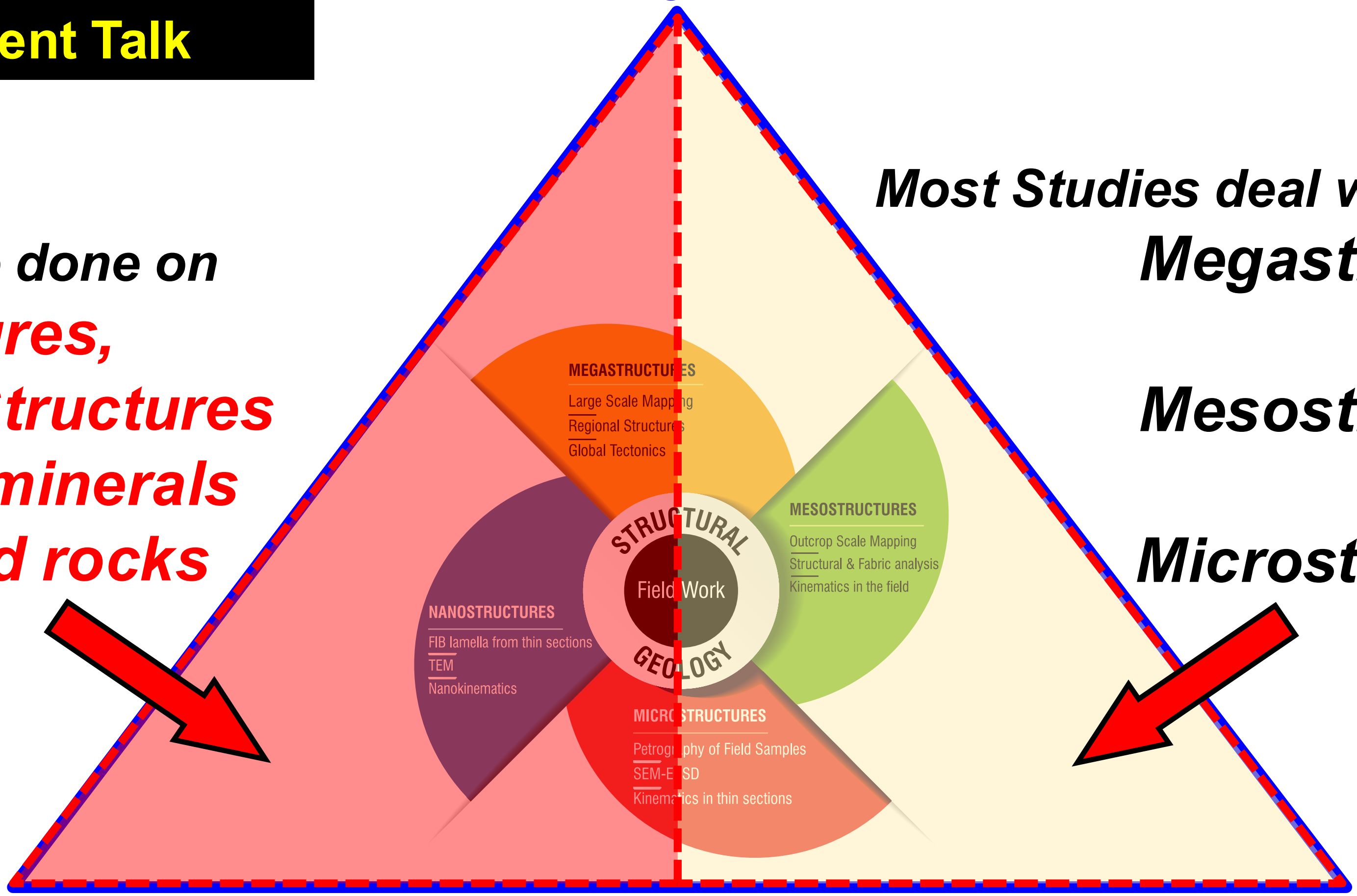
Integrating Field, AMS, SEM-EBSD and TEM Studies

Focus of the Present Talk

A lot remains to be done on
Nanostructures,
Atomistic Scale Structures
& Processes in minerals
within deformed rocks

Mega-Mesostructures

Remote Sensing/Drones/Fieldwork/Kinematics in the Field/AMS/Regional Structures etc.



Most Studies deal with a combination of
Megastructures
±
Mesostructures
±
Microstructures

Nanostructures

Deformation Mechanisms/TEM/dislocation studies/nanokinematics in oriented thin films etc.

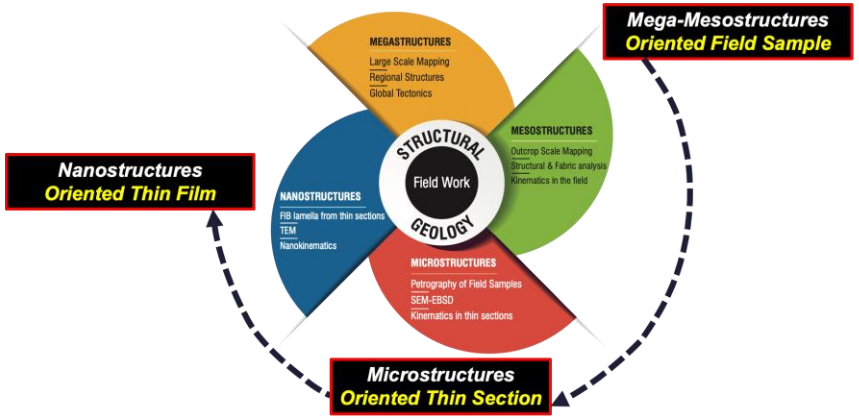
Microstructures

Kinematics in oriented thin sections/deformation textures/recrystallization processes/SEM-EBSD etc.

Multiscale Analysis of Deformation Structures

Integrating Field, AMS, SEM-EBSD and TEM Studies

- Many structural geological investigations require kinematic analysis.
- Kinematic analysis/determining sense of shear has implications for understanding strain localization, mineralization and large scale tectonics.
- Quantification of vorticity is an important aspect of kinematics that helps evaluate the type of flow responsible for deformation (pure vs. simple shear). This improves understanding of deformation and structural evolution at various scales.



- *Fieldwork provides the Oriented Sample.*
- *AMS of Oriented Field Sample helps identify the XZ section (Kinematic Reference Frame).*
- *CPO analysis from SEM-EBSD studies in XZ (thin section) section gives kinematic information.*
- *TEM studies from thin films extracted from XZ sections gives nanokinematic data.*

Kinematic Analysis At Any Scale Requires a Reference Frame

The Kinematic Reference Frame = XZ Section of the Strain Ellipsoid

© 1930

Gefügekunde der Gesteine

Mit Besonderer Berücksichtigung der Tektonite

Autoren: **Sander**, Bruno, **Sander**, Bruno

Bruno Sander

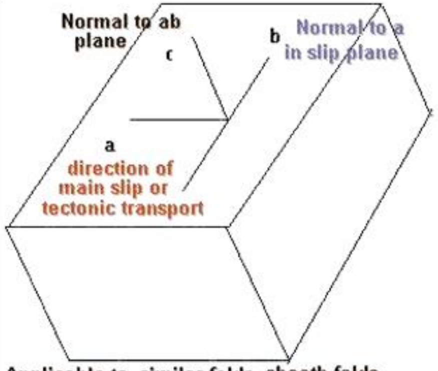
Portrait, Naturhistorisches Museum Wien, Mineralogisch-Petrographische Abteilung

An Introduction to the Study of Fabrics of Geological Bodies

Book • 1970

Authors:

BRUNO SANDER



Applicable to, similar folds, sheath folds, petrofabrics of Sander

Journal of Geological Education, 1986, v. 34, p. 246

Determination of Movement Sense in Mylonites

Carol Simpson

Department of Geological Sciences
Virginia Polytechnic Institute and State University
4044 Derring Hall
Blacksburg, Virginia 24061-0796

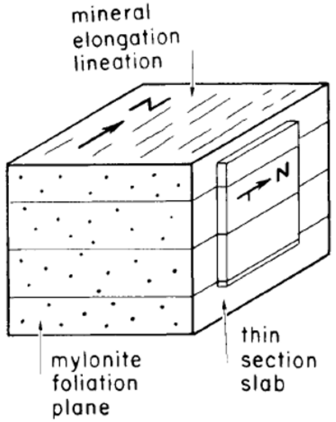


Figure 4. Recommended orientation symbol for hand specimen and thin section. The section is cut perpendicular to foliation and parallel to mineral elongation lineation in the mylonite.

Crystallographic fabrics: a selective review of their applications to research in structural geology

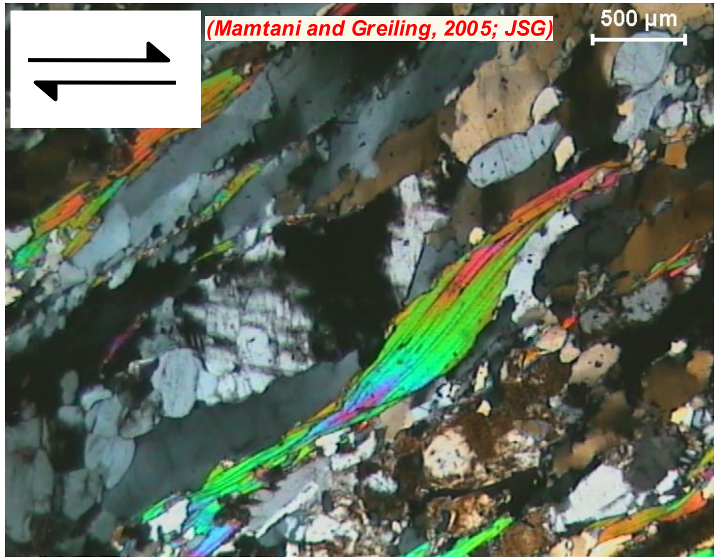
R.D. LAW

Department of Geological Sciences Virginia Polytechnic Institute & State University, Blacksburg, Virginia 24061, USA

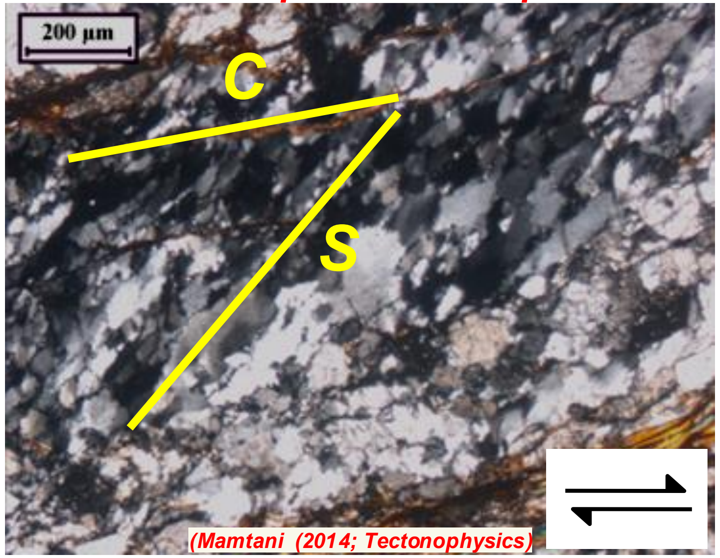
In the older (pre-mid-1970s) geological literature, fabric data were frequently presented on projection planes orientated perpendicular to both foliation and lineation (e.g. Sylvester & Christie 1968). In such projections, however, the fabric data (at least for quartz and calcite) is generally concentrated near the projection periphery and may easily be misinterpreted. It is therefore recommended that sections for fabric analysis should be cut perpendicular to foliation and parallel to lineation. This approach has the additional advantage that results of most fabric simulations are also presented in a projection plane containing the XZ finite strain axes.

From Knipe, R. J. & Rutter, E. H. (eds) 1990, *Deformation Mechanisms, Rheology and Tectonics*, Geological Society Special Publication No. 54, pp. 335–352.

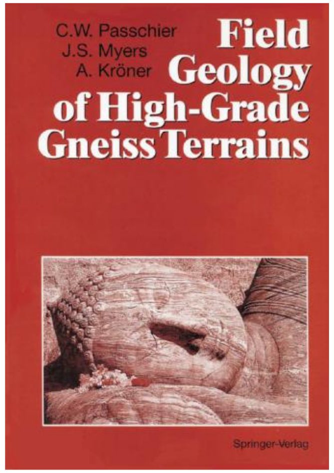
Mica Fish

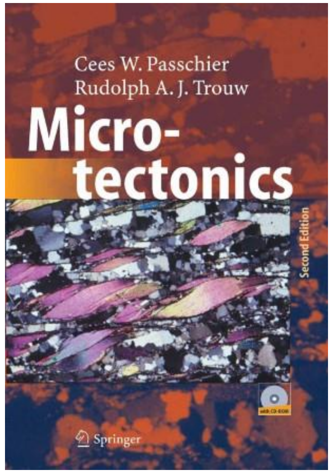


Quartz Oblique Grain Shape Fabric



Kinematic Studies in rock thin sections are done in *XZ reference frame*





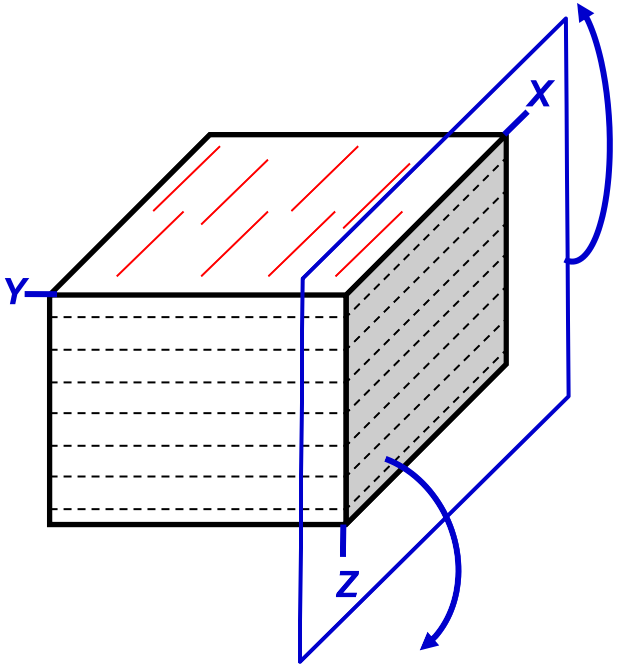
Section 4.4.2 (Passchier, et al., 1990, p. 59)
Stretching and mineral lineations are commonly parallel to the X-axis of the finite strain ellipsoid.

Section 4.4.4 (Passchier et al., 1990, p.61)
In the absence of lineations it can be very difficult or even impossible to determine the movement direction in shear zones.

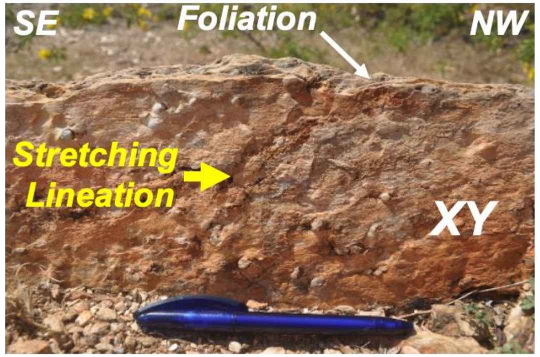
Hunting for "Stretching Lineation" !!!

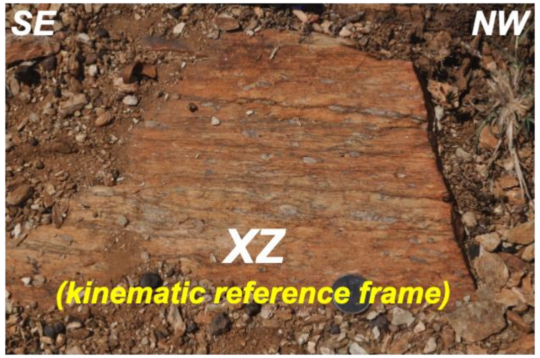
Kinematic Reference Frame in Structural Geology

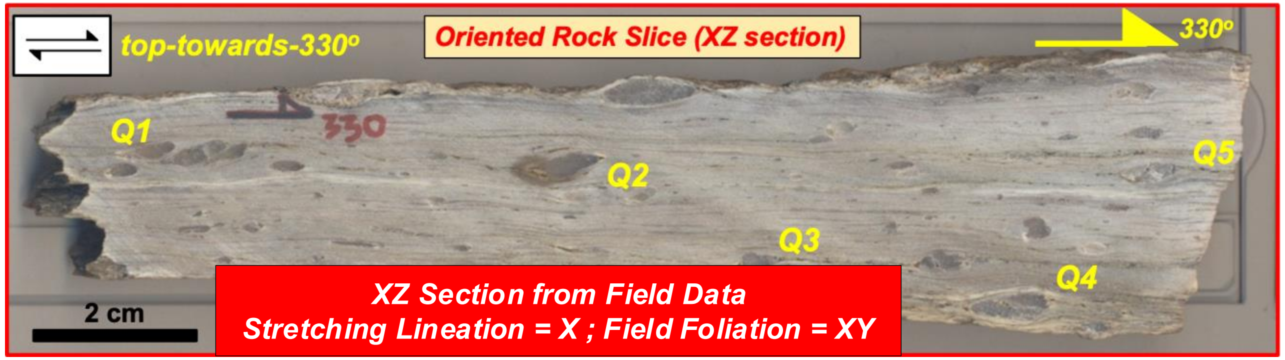
REFERENCE FRAME
FOR KINEMATIC STUDIES
is the
XZ section (Strain Ellipsoid)

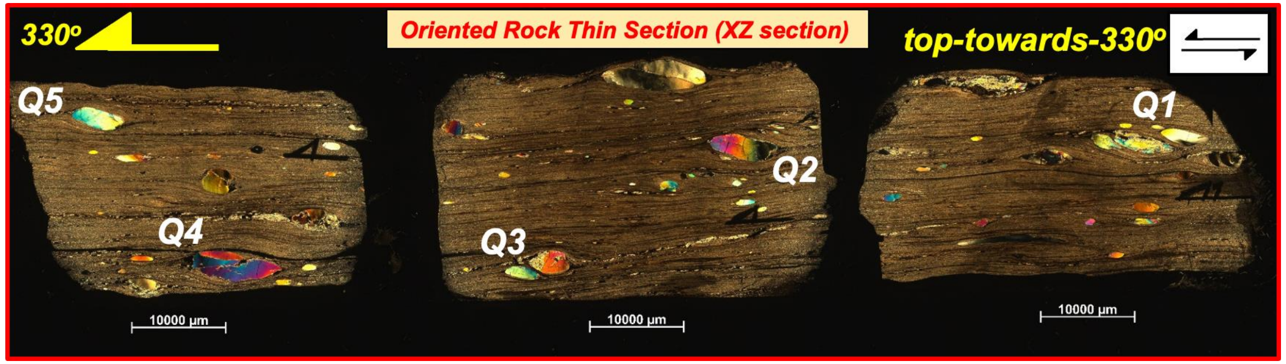


Parallel to Stretching Lineation
&
Perpendicular to Foliation
(= XZ section of the Strain Ellipsoid)



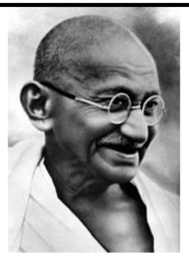






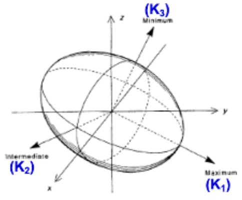
No
Stretching
Lineation !

Where is the
Kinematic
Reference
Frame
(XZ section) ?

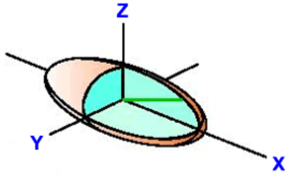


Forces of nature act in a mysterious manner. We can but solve the mystery by deducing the unknown result from the known results of similar events.

Identifying the kinematic reference frame in the absence of a visible stretching lineation using an alternative technique e.g., Anisotropy of Magnetic Susceptibility (AMS)



AMS Ellipsoid = Strain Ellipsoid
$K_1 \longleftrightarrow X$
$K_2 \longleftrightarrow Y$
$K_3 \longleftrightarrow Z$



Known
Orientation of AMS Ellipsoid (K_1, K_2, K_3)

Unknown
Orientation of Strain Ellipsoid (X, Y, Z)

AMS Ellipsoid vs. Strain Ellipsoid in LS-Tectonites (Quartzite from Naxos, Greece)

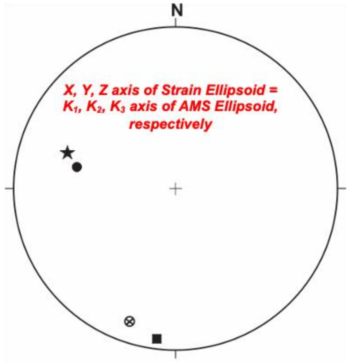
(Renjith, Mamtani & Urai, 2016; Journal of Structural Geology)

Graphite-bearing Quartzite (Naxos, Greece)

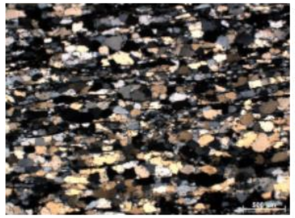
XZ section

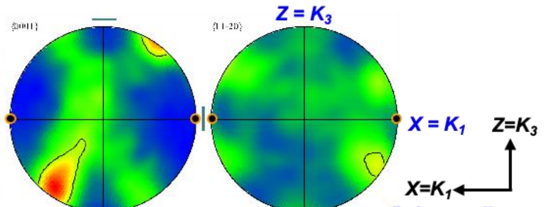
Stretching Lineation (on foliation plane)

Similar Orientation of Field and Magnetic Fabric



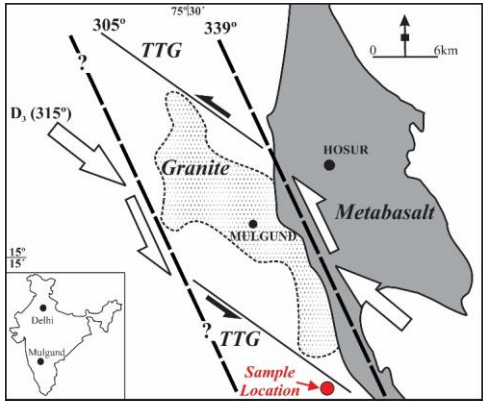
★ Pole to field foliation
● Pole to magnetic foliation
⊗ Stretching lineation
■ Magnetic lineation





Reference Frame

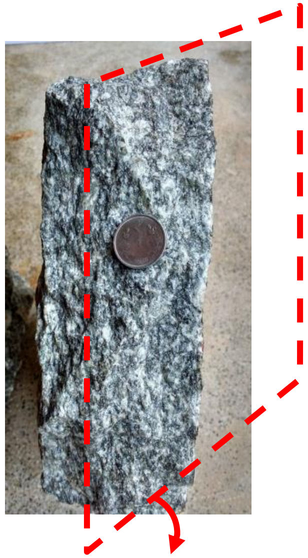
Sense of Shear fits with Regional Kinematics



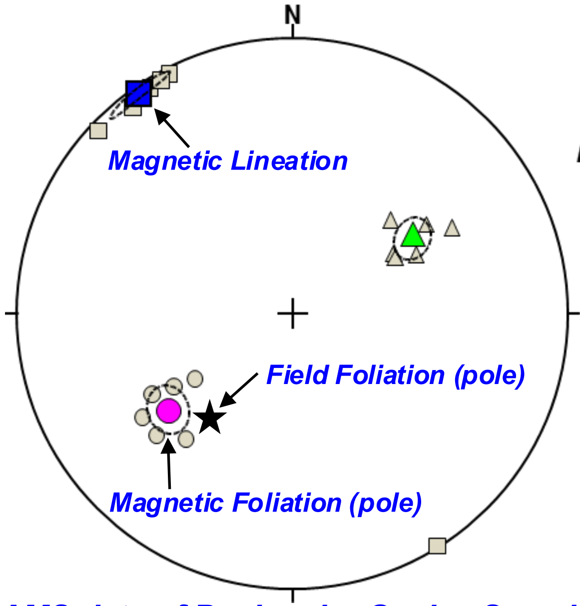
Mondal and Mamtani (2015; Jr. Geol. Soc. London)

AMS Ellipsoid vs. Strain Ellipsoid in S-Tectonites Peninsular Gneiss, Dharwar Craton (India)

(Mamtani et al., 2017; Journal of the Geological Society of India)

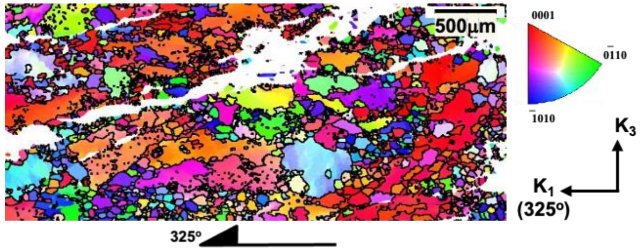


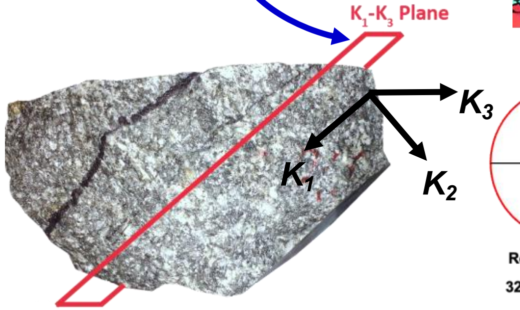
Foliation (XY plane)
But no stretching lineation

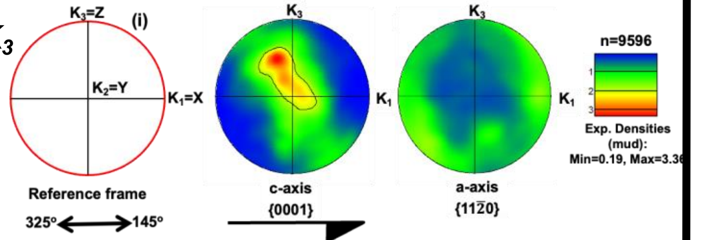


AMS data of Peninsular Gneiss Sample

K_1K_3 plane of AMS ellipsoid = XZ section of Strain Ellipsoid







$K_1K_3 = XZ =$ Kinematic Reference Frame

Nanostructures in minerals in the kinematic reference frame of deformed rocks

Modus Operandi for an integrated SEM-TEM study


Journal of Structural Geology 135 (2020) 104045

Contents lists available at ScienceDirect

Journal of Structural Geology

journal homepage: http://www.elsevier.com/locate/jsg

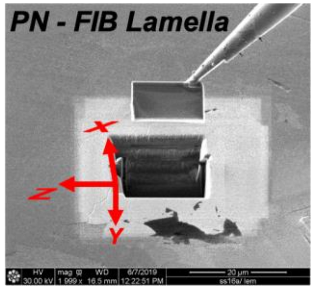
Intracrystalline deformation and nanotectonic processes in magnetite from a naturally deformed rock

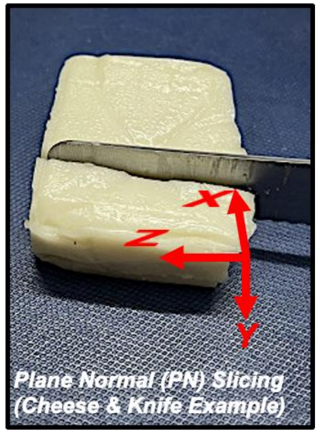
Manish A. Mamtani[a,*], Boris Reznik[b], Agnes Kontny[b]

[a] *Department of Geology and Geophysics, Indian Institute of Technology (IIT), Kharagpur, 721302, India*
[b] *Institute of Applied Geosciences, Karlsruhe Institute of Technology (KIT), D-76131, Karlsruhe, Germany*

Mamtani et al. (2020)
Journal of Structural Geology

Plane Normal (PN) Thin Film Excavation





Rock Thin Section Parallel to the Kinematic Reference Frame (=XZ/K_1K_3)

⇓

SEM-EBSD of the mineral of interest in the Kinematic Reference Frame

⇓

Identification of Region of Interest (ROI) for TEM studies from SEM-EBSD data

⇓

Thin Film Excavation from ROI
Perpendicular / Parallel to the Kinematic Reference Frame

⇓

TEM investigation in thin film

Sharing My Experience with TEM studies of Magnetite in thin films Excavated using Focused Ion Beam (FIB)

DAAD
Deutscher Akademischer Austauschdienst
German Academic Exchange Service

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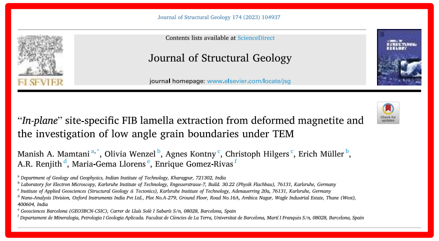
Alexander von HUMBOLDT STIFTUNG


Journal of Structural Geology 174 (2023) 104937

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journal homepage: www.elsevier.com/locate/jsg

"*In-plane*" site-specific FIB lamella extraction from deformed magnetite and the investigation of low angle grain boundaries under TEM

Manish A. Mamtani[a,*], Olivia Wenzel[b], Agnes Kontny[c], Christoph Hilgers[c], Erich Müller[b], A.R. Renjith[d], Maria-Gema Llorens[e], Enrique Gomez-Rivas[f]

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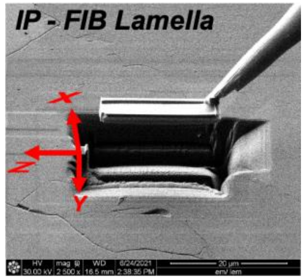
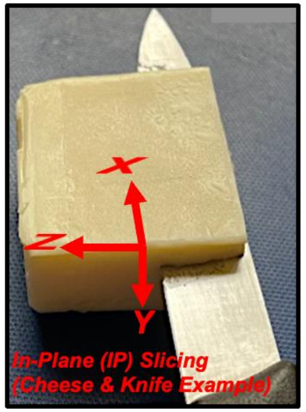
[b] *Laboratory for Electron Microscopy, Karlsruhe Institute of Technology, Engesserstrasse-7, Build. 30.22 (Physik Flachbau), 76131, Karlsruhe, Germany*
[c] *Institute of Applied Geosciences (Structural Geology & Tectonics), Karlsruhe Institute of Technology, Adenauerring 20a, 76131, Karlsruhe, Germany*
[d] *Nano-Analysis Division, Oxford Instruments India Pvt Ltd., Plot No.A-279, Ground Floor, Road No.16A, Ambica Nagar, Wagle Industrial Estate, Thane (West), 400604, India*
[e] *Geosciences Barcelona (GEO3BCN-CSIC), Carrer de Lluís Solé I Sabarís S/n, 08028, Barcelona, Spain*
[f] *Departament de Mineralogia, Petrologia I Geologia Aplicada. Facultat de Ciències de La Terra, Universitat de Barcelona, Martí I Franquès S/n, 08028, Barcelona, Spain*

Mamtani et al. (2023)
Journal of Structural Geology

In-Plane (IP) Thin Film Excavation





Modus Operandi for TEM Studies
(My Experience with Magnetite)

Karlsruher Institut für Technologie

SEM-EBSD done at IIT Kharagpur (India)
(Identification of Region of Interest, ROI)

+

FIB+TEM done at KIT Karlsruhe (Germany)
(Thin Film Excavation and TEM imaging)

SEM-EBSD Study of Magnetite

Super polishing thin section with colloidal silica solution and Leica EM-TIC 3X triple Broad Ion Beam Milling System (MFAL Protocol)
Department of Geology & Geophysics, IIT Kharagpur (INDIA)

⇩

Coating with 5 nm carbon layer(Leica EM ACE200 Sputter Coater)
Department of Geology & Geophysics, IIT Kharagpur (INDIA)

⇩

SEM-EBSD Analysis using Carl Zeiss Auriga Compact FEG-SEM fitted with Oxford Instruments NordlysMax2 EBSD detector
Central Research Facility, IIT Kharagpur (INDIA)

⇩

SEM-EBSD Data Acquisition with AZtec Software
Central Research Facility, IIT Kharagpur (INDIA)

⇩

Post Acquisition EBSD Data Processing using HKL Channel 5
Department of Geology & Geophysics, IIT Kharagpur (INDIA)
Identify Low and High Angle Grain Boundaries (Region of Interest)

TEM Study of Magnetite

FOCUSED ION BEAM (FIB) Lamella Extraction
FEI Dual Beam Strata 400S with a Gallium Ga+ source
Laboratory for Electron Microscopy (KIT Karlsruhe, GERMANY)

- Coating the thin section with platinum
- Depositing platinum strap at identified Region of Interest (ROI)
- FIB Lamella preparation (30 kV/6.5 nA Gallium ion beam)
- Mounting FIB Lamella on FIB Lift-Out TEM Grid (Copper/2 posts)
- Further thinning of mounted FIB Lamella to 50 nm (30 kV/26 pA Gallium ion beam)
- Final polishing and cleaning of thin film (5 kV/71 pA ion current)

⇩

TEM and HRTEM Investigations
Philips CM 200 FEG/ST TEM
Laboratory for Electron Microscopy (KIT Karlsruhe, GERMANY)

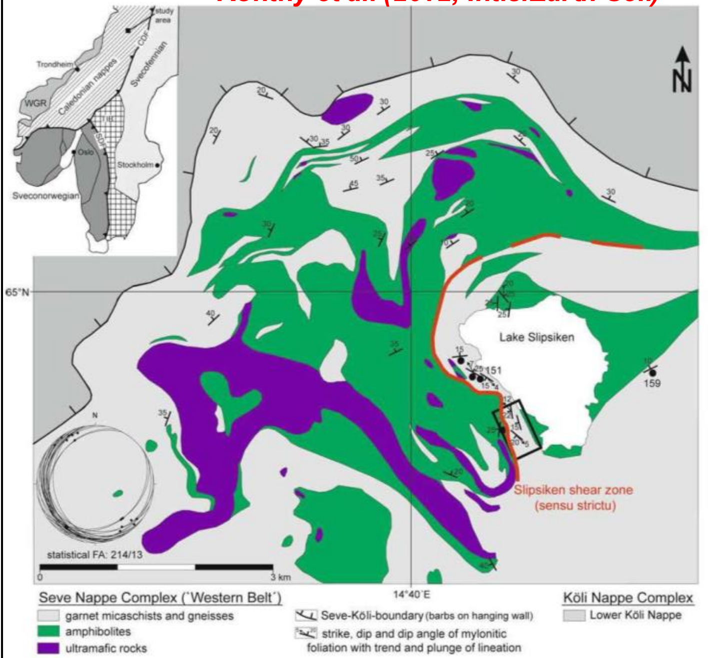
- Operated at 200 kV
- Selected Area Electron Diffraction (SAED) using 100 μm condenser aperture at 300 nm spot size.
- Bright Field/Dark Field/Weak Beam Dark Field Conditions

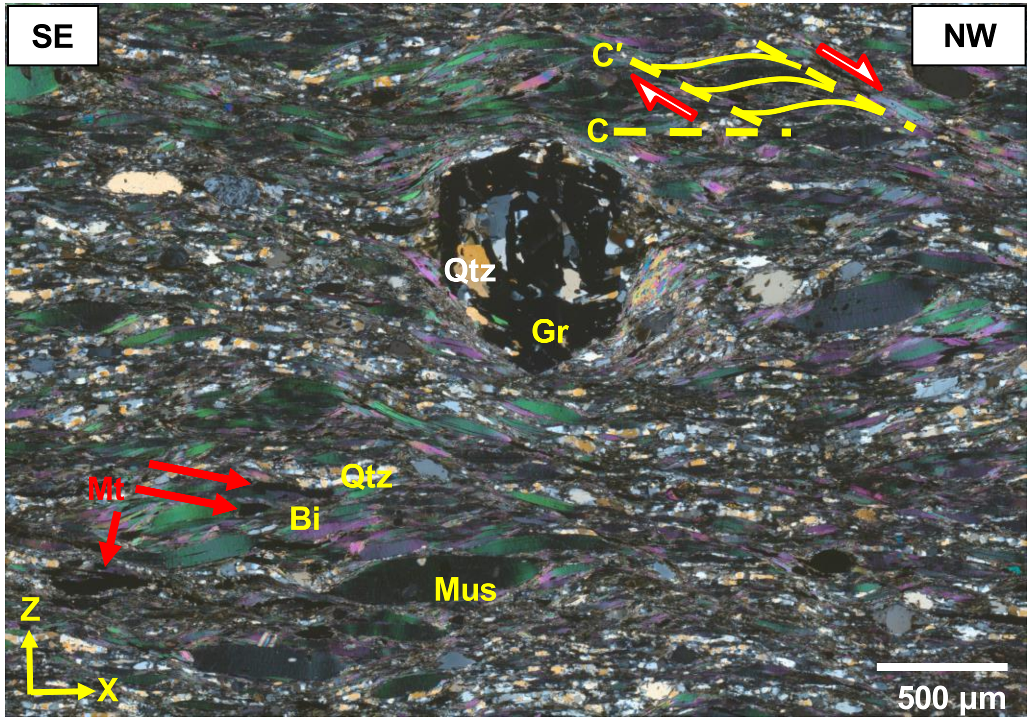
Williams & Carter (2009)

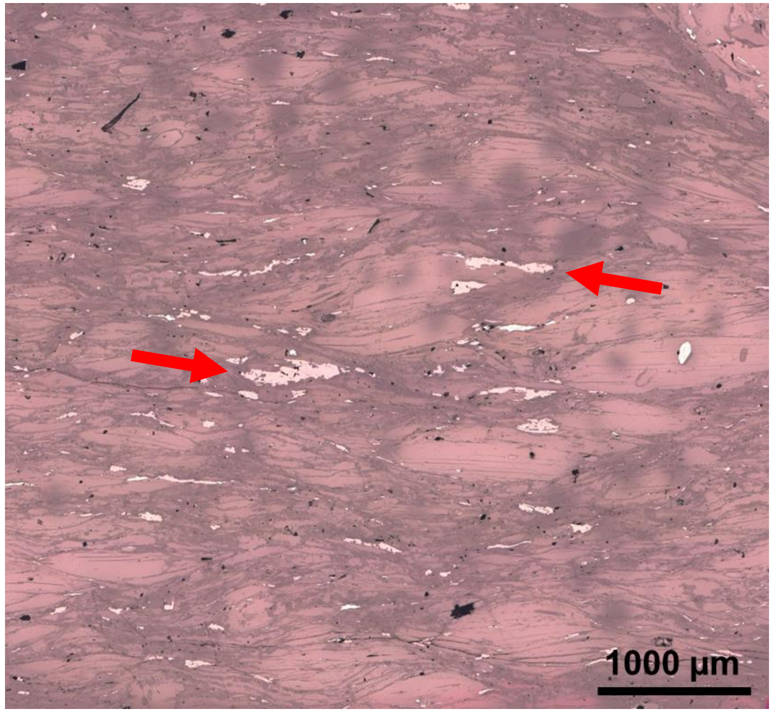
Oriented Thin Film excavation and TEM investigation of Magnetite from Mylonitic Schist (Slipsiken Shear Zone, Swedish Caledonides)

top-to-NW sense of shear

Kontny et al. (2012; Int.J.Earth Sci.)







- The Slipsiken Shear Zone (SSZ) is located close to the hanging wall of the Seve Nappe Complex (SNC, Sweden).
- SNC is composed of three major belts with contrasting metamorphic grades of eclogite, granulite, and amphibolite.
- Deformation of the SNC is dominated by simple shear.
- SSZ developed in garnet–micaschists intercalated with amphibolites and tectonic lenses of ultramafic rocks near Lake Slipsiken (Sweden).

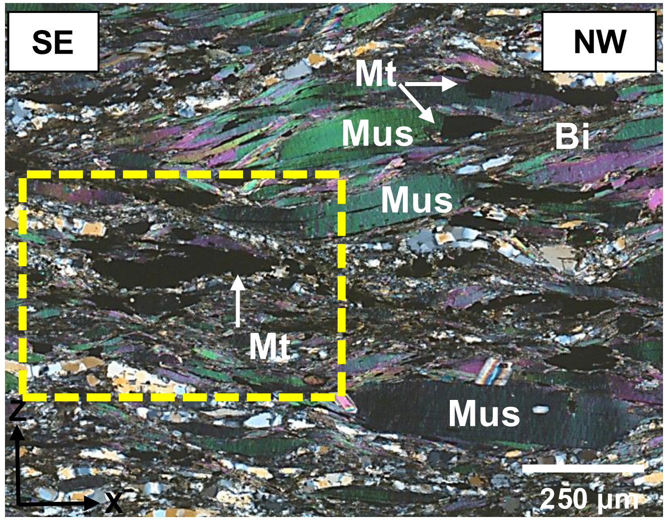
Kontny et al. (2012; Int.J.Earth Sci.)
Grimmer et al. (2015; Geology)

- **Sense of shear is top-to-NW.**
- **Mylonitization of schists occurred at ≥550°C.**
- **Mica schists contain pure magnetite**
- **Mean Magnetic susceptibility is 97×10^{-3} SI units.**
- **Extremely high degree of magnetic anisotropy (P>3.9)**

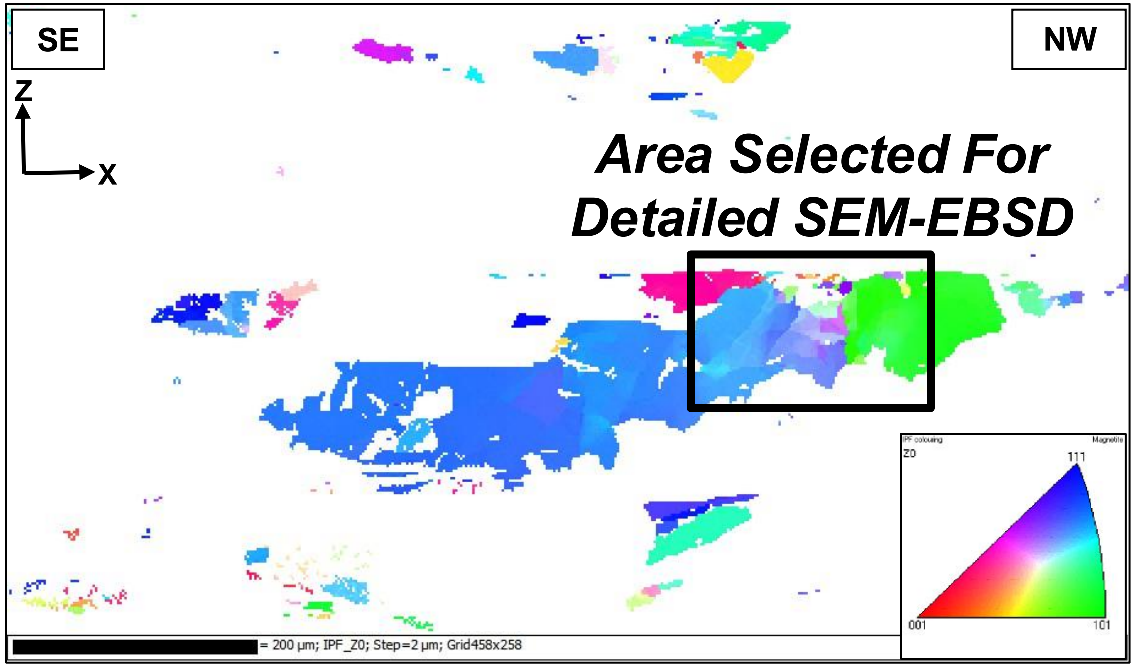
SEM-EBSD Analysis of Magnetite in Schist

(Slipsiken Shear Zone, Swedish Caledonides)

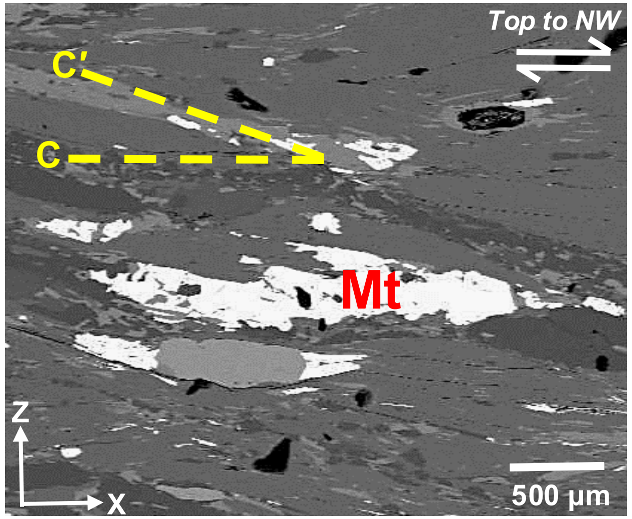
(after Mamtani et al., Journal of Structural Geology, 2020)



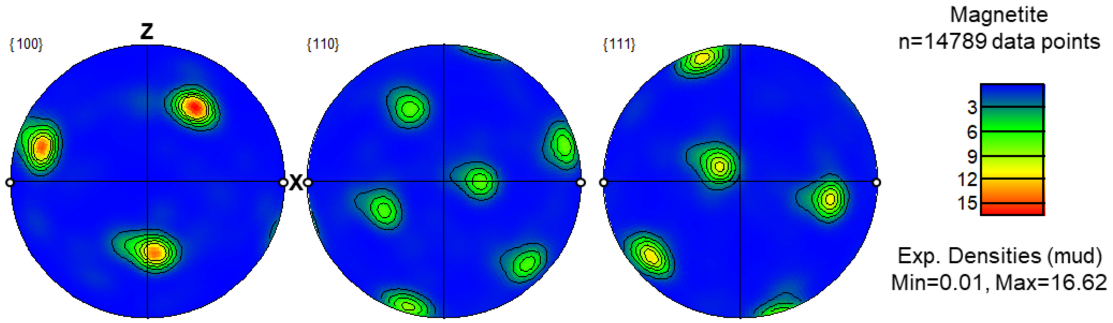
Light Microscopy



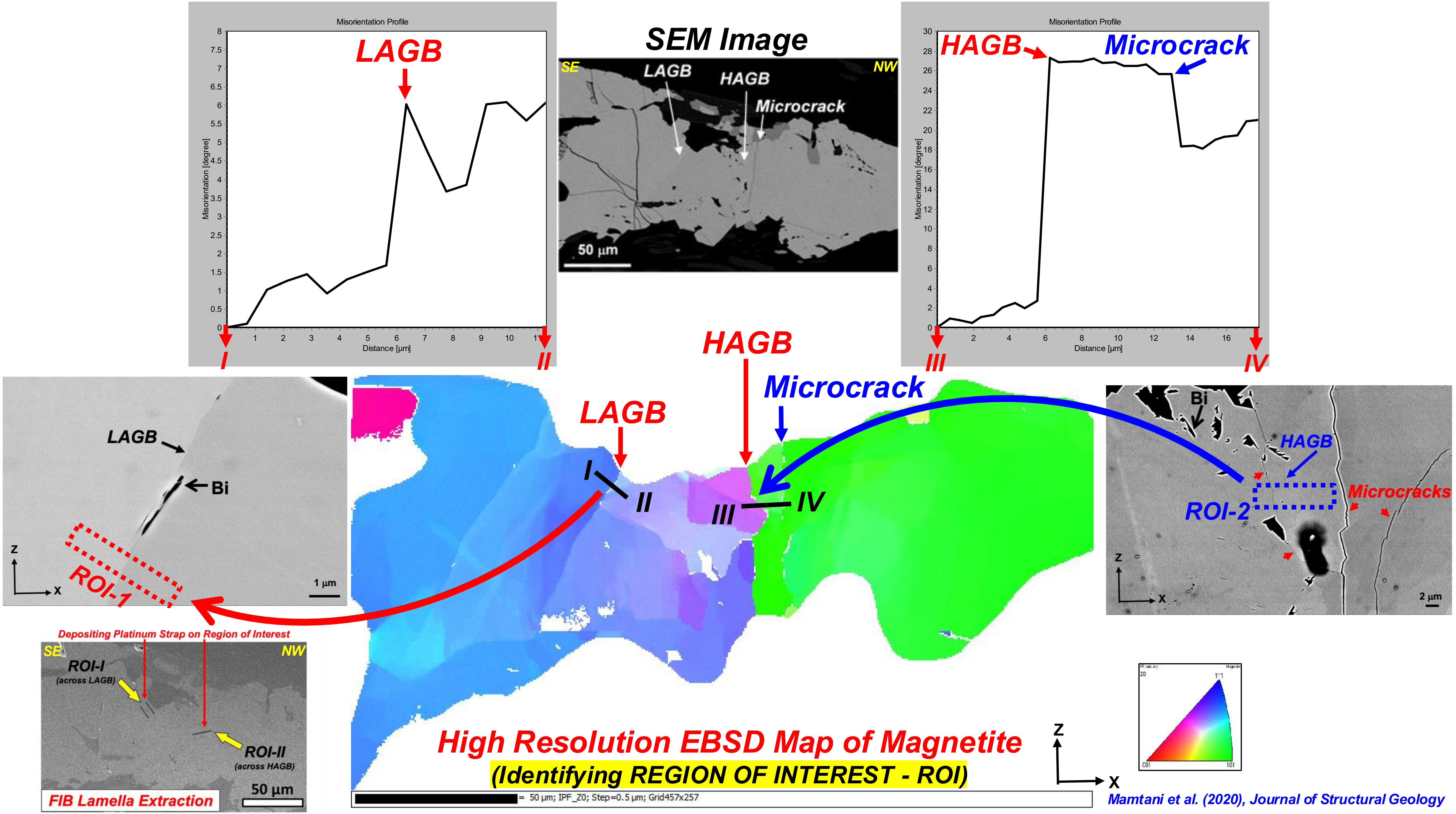
EBSD Map of Magnetite



SEM Image



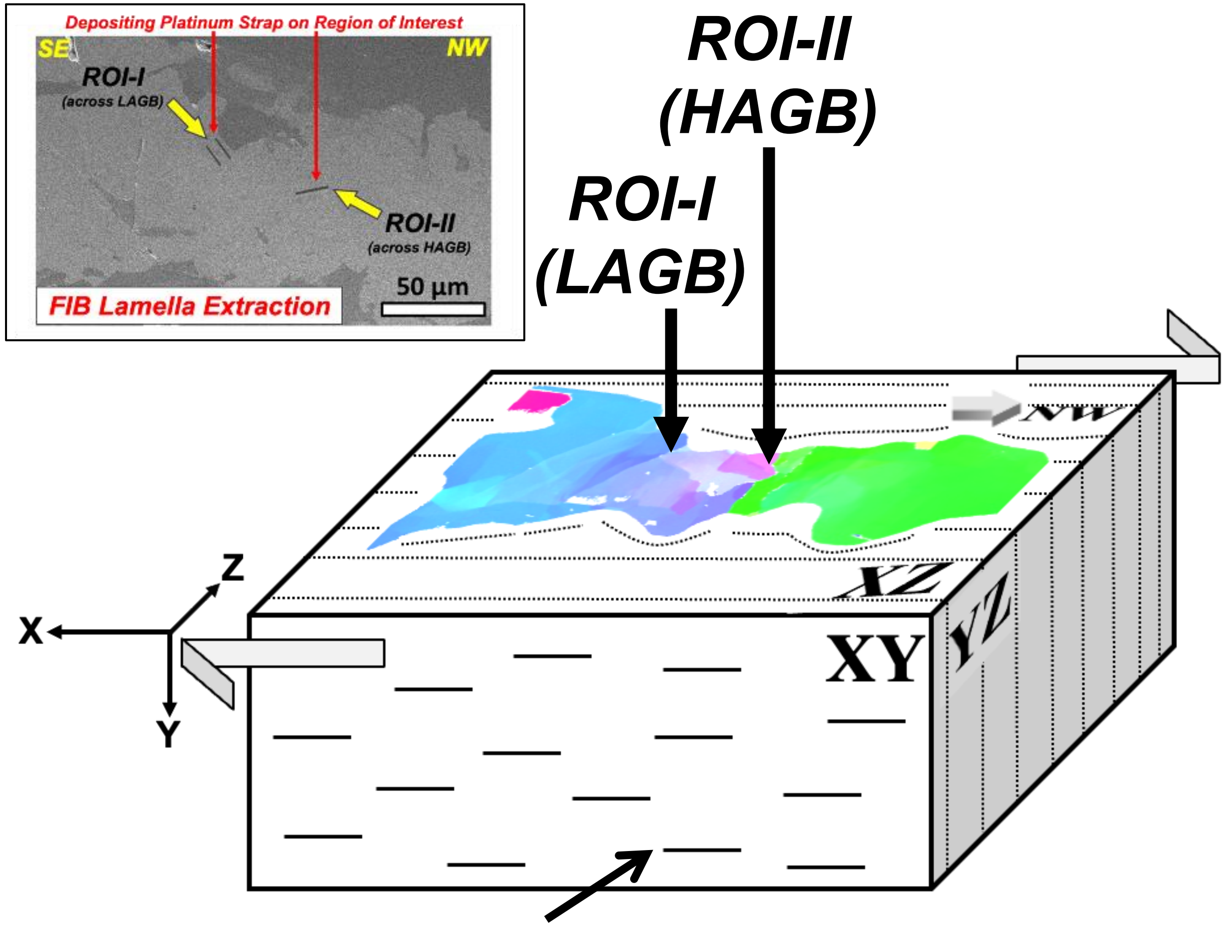
Pole Figures - Magnetite



Misorientation Profile
LAGB
Misorientation [degree]
Distance [µm]
I
II
SEM Image
SE
NW
LAGB
HAGB
Microcrack
50 µm
Misorientation Profile
HAGB
Microcrack
III
IV
HAGB
Microcrack
LAGB
LAGB
Bi
ROI-1
1 µm
Z
X
Bi
HAGB
Microcracks
ROI-2
2 µm
Depositing Platinum Strap on Region of Interest
ROI-I
(across LAGB)
ROI-II
(across HAGB)
50 µm
FIB Lamella Extraction
High Resolution EBSD Map of Magnetite
(Identifying REGION OF INTEREST - ROI)
= 50 µm; IPF_Z0; Step=0.5 µm; Grid457x257
Mamtani et al. (2020), Journal of Structural Geology

Question-1

- How To Excavate FIB Lamella from XZ section?
- Plane Normal (PN) or In-Plane (IP)?



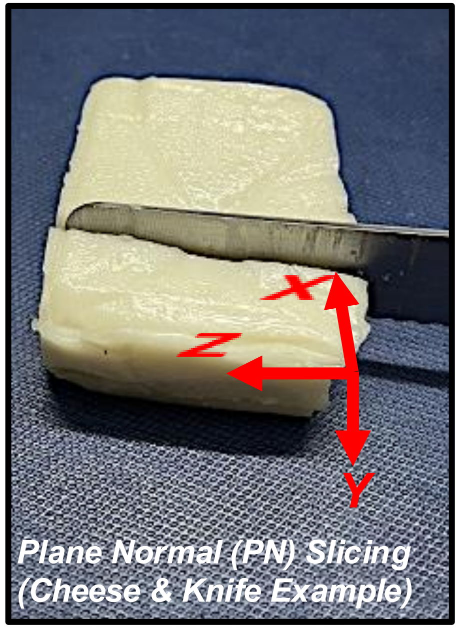
Stretching lineation (X direction)
on foliation (XY) plane

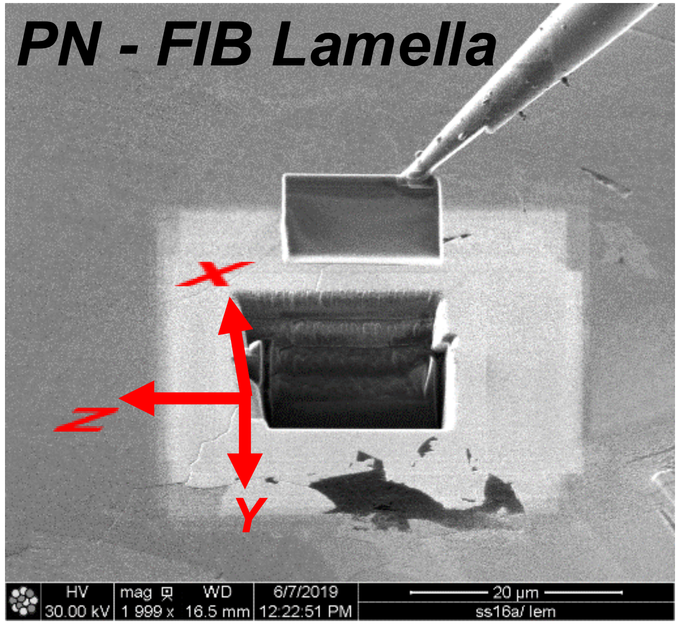
Question-2

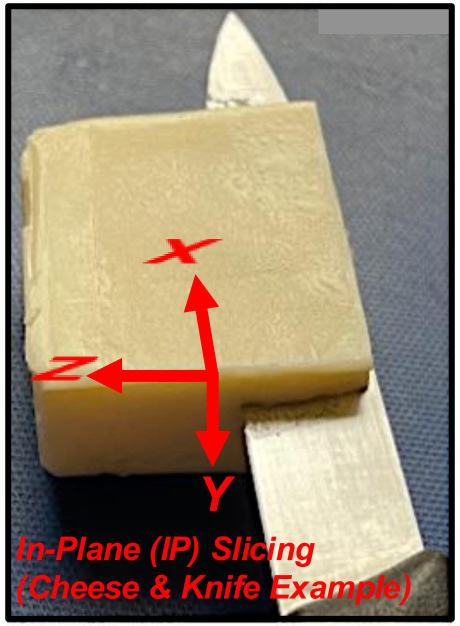
- How To Keep Track of Kinematic Reference frame and Geographic Orientation for the FIB Lamella?

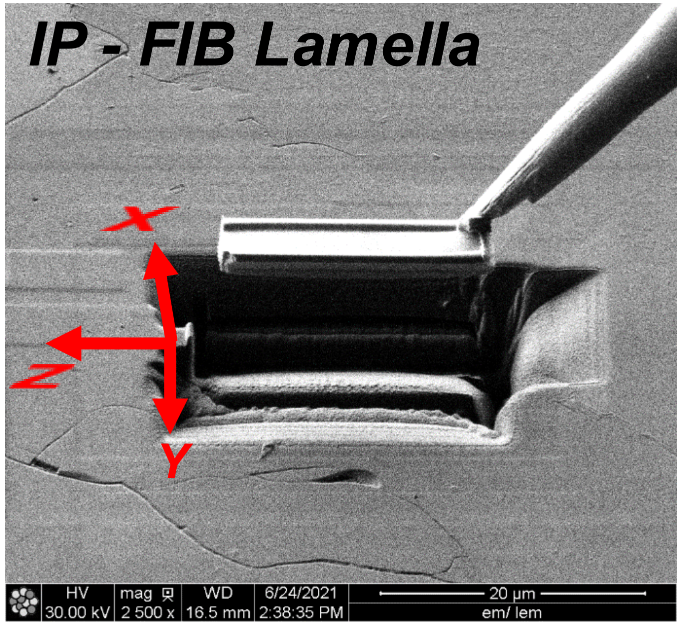
Cheese & Knife Example

(Mamtani, 2025; Springer Book Chapter)

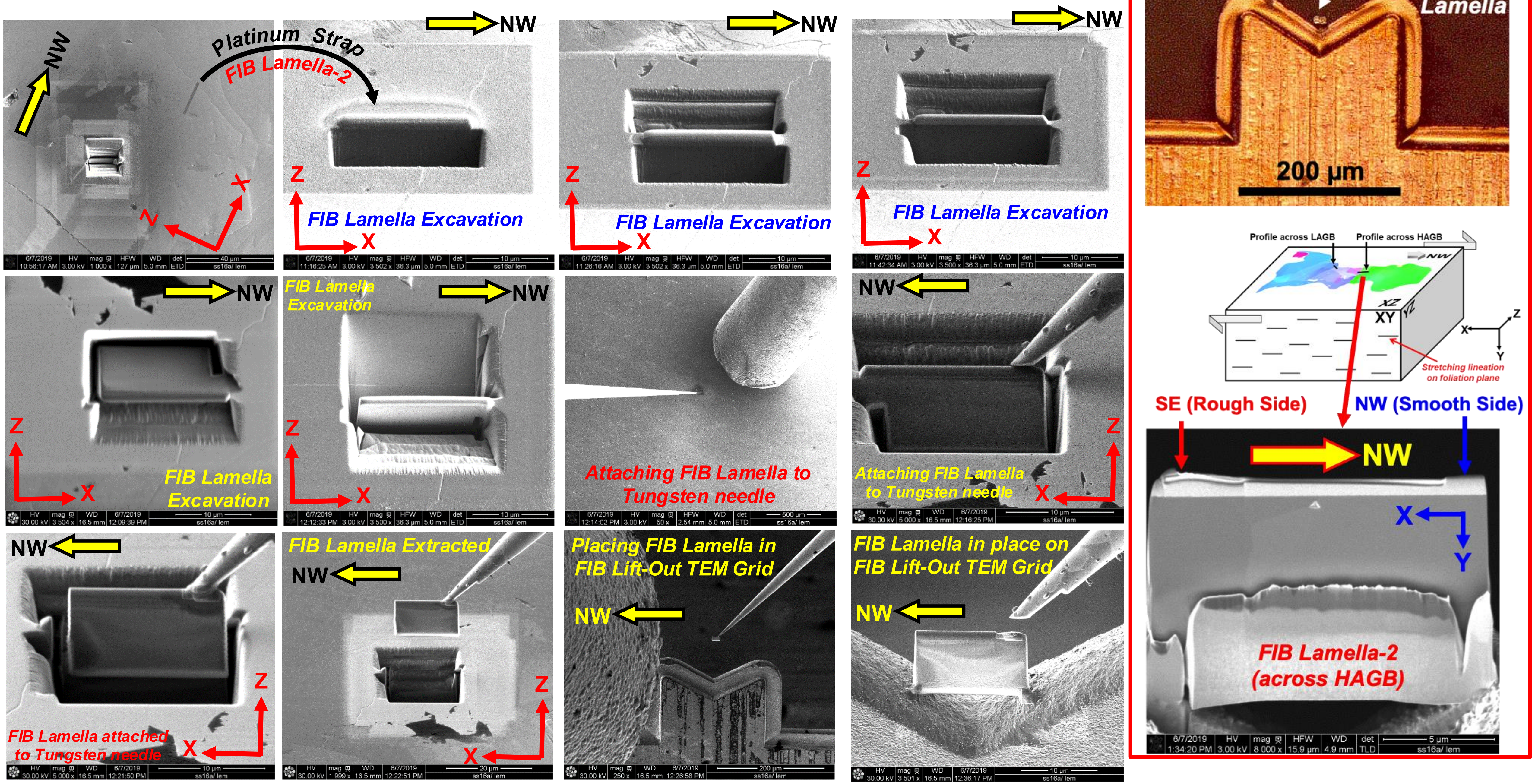




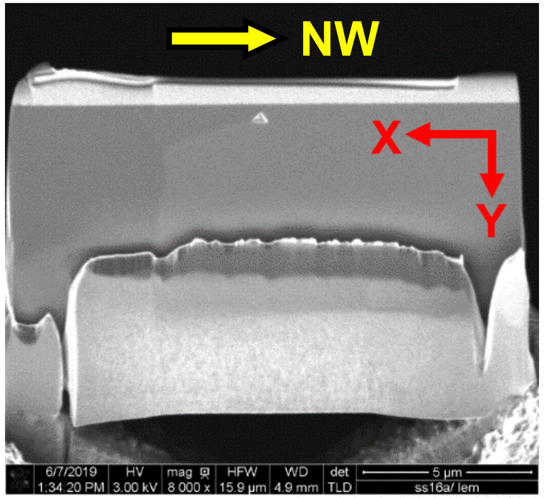


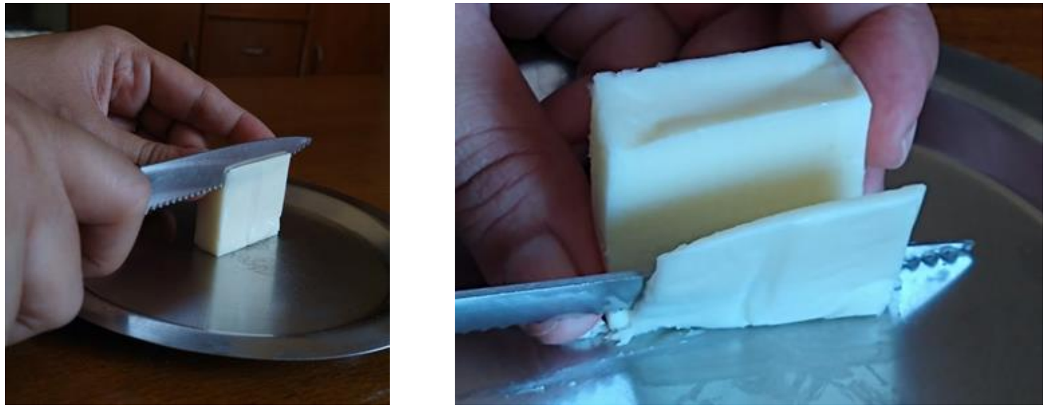


Orientation of FIB Lamella in Tectonic & Geographic Reference Frame



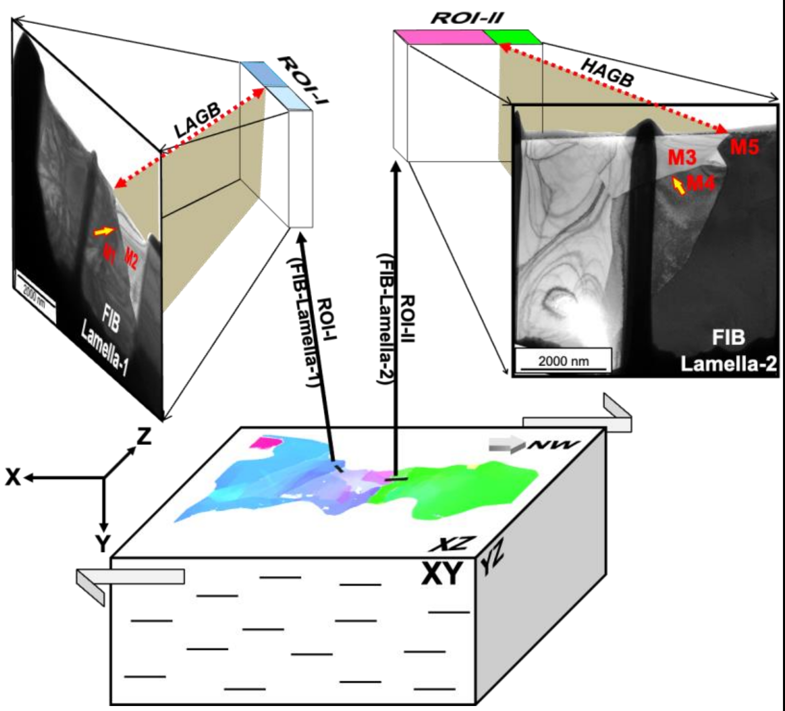
Thinning of FIB Lamella (50 nm) to achieve Electron Transmission

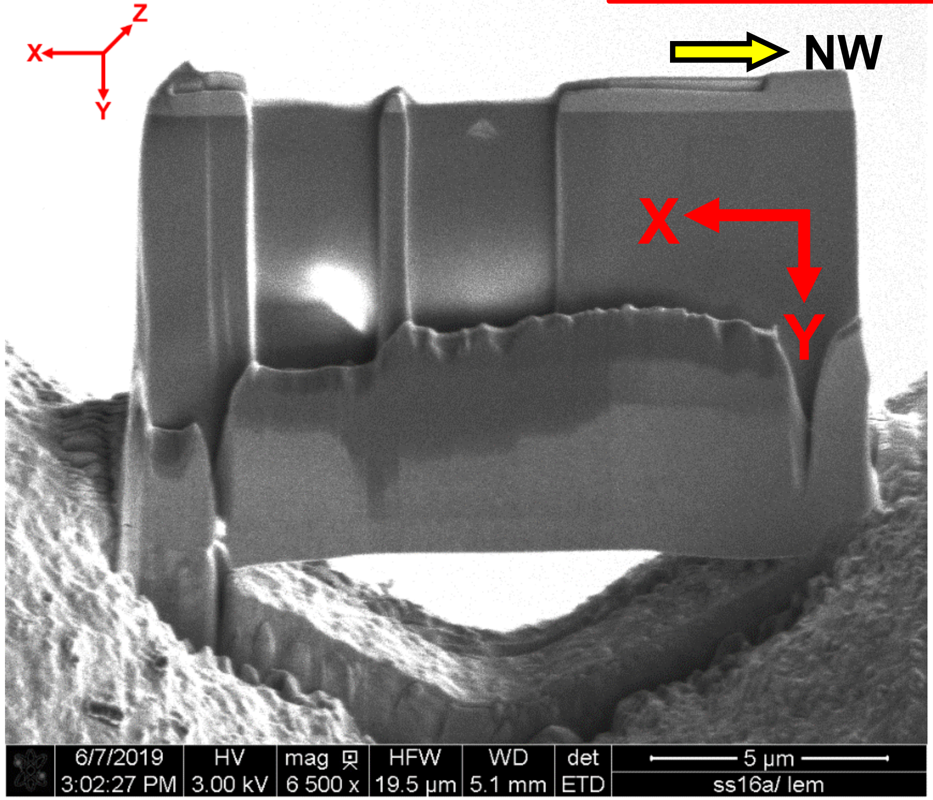


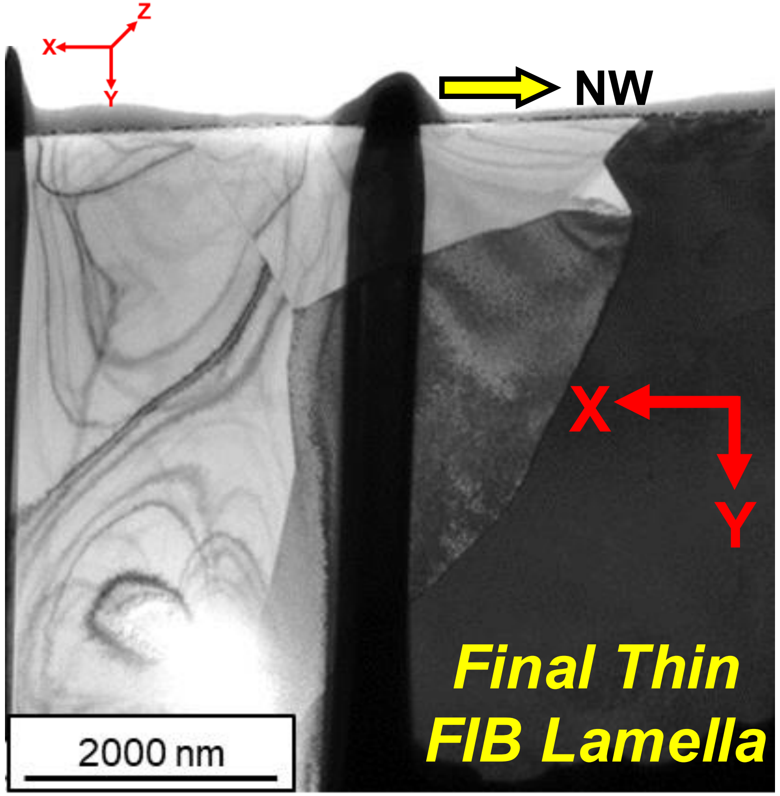


Slicing of Cheese with a Knife

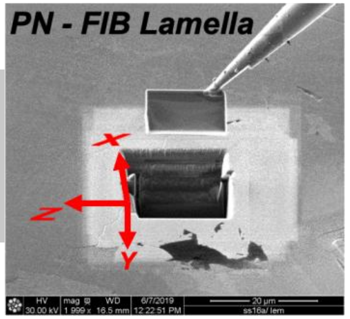
FIB Lamella (Thin Film) in Geographical Reference Frame





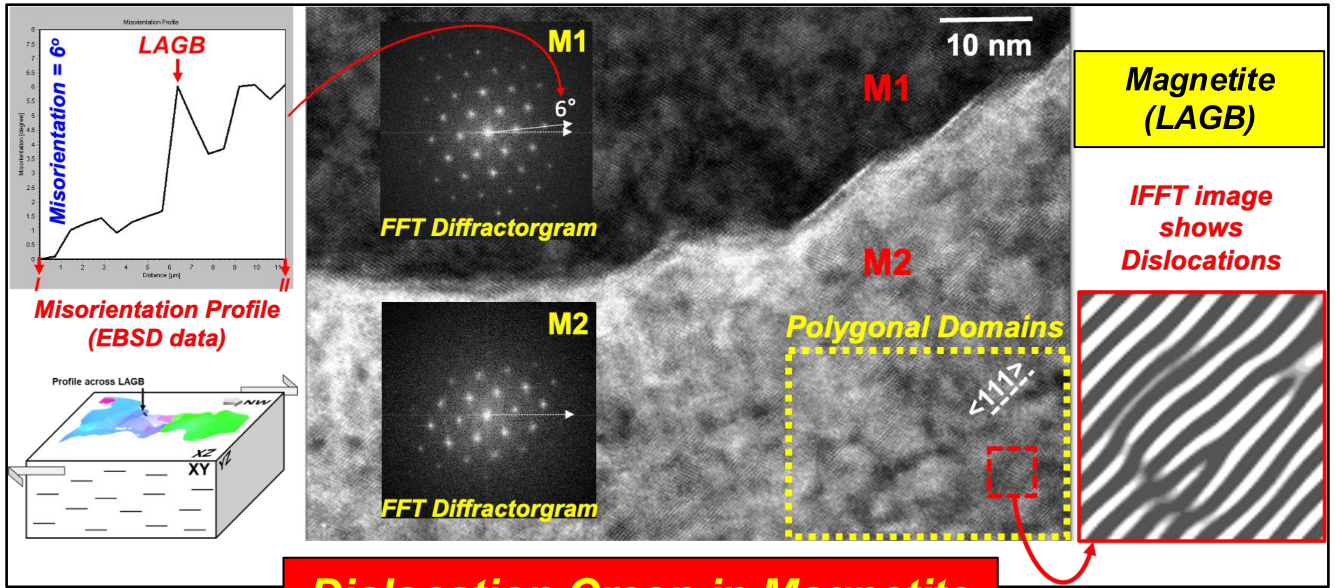


FIB Lamella Excavation is PLANE NORMAL (PN), i.e., Perpendicular to the Kinematic Reference Frame

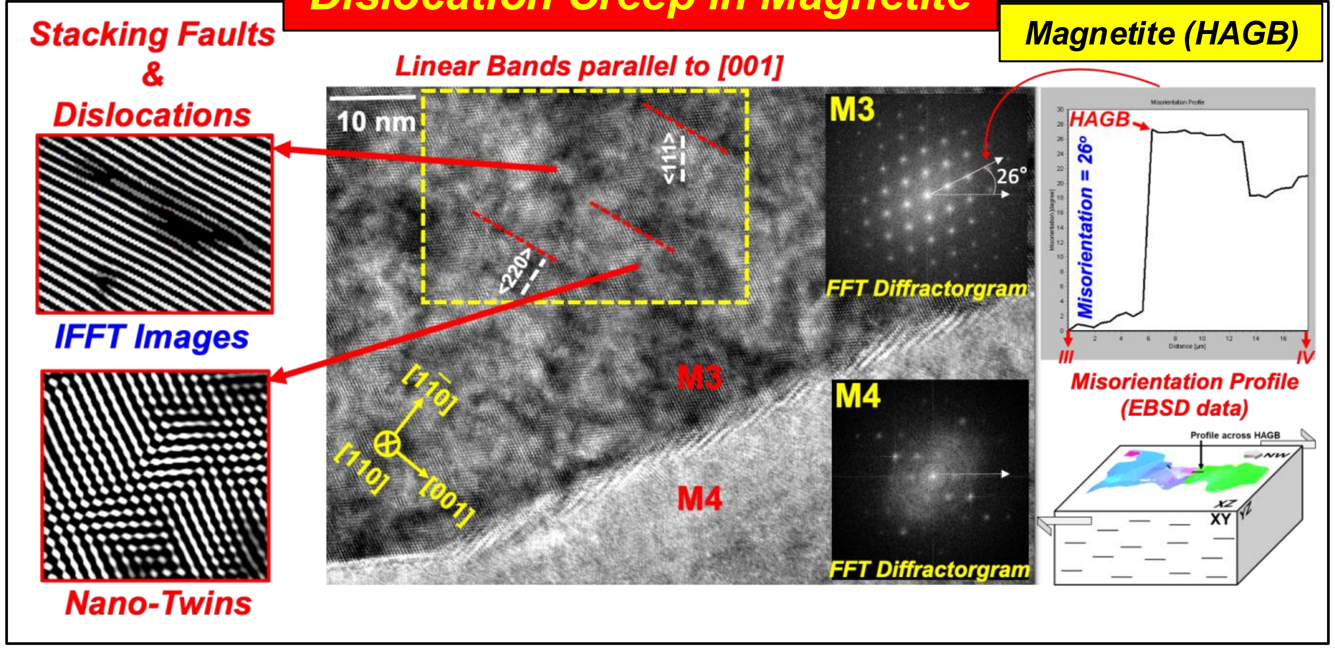


Nanostructures in Magnetite – Deformation Mechanisms and Nanotectonics

(after Mamtani et al., 2020, Journal of Structural Geology)

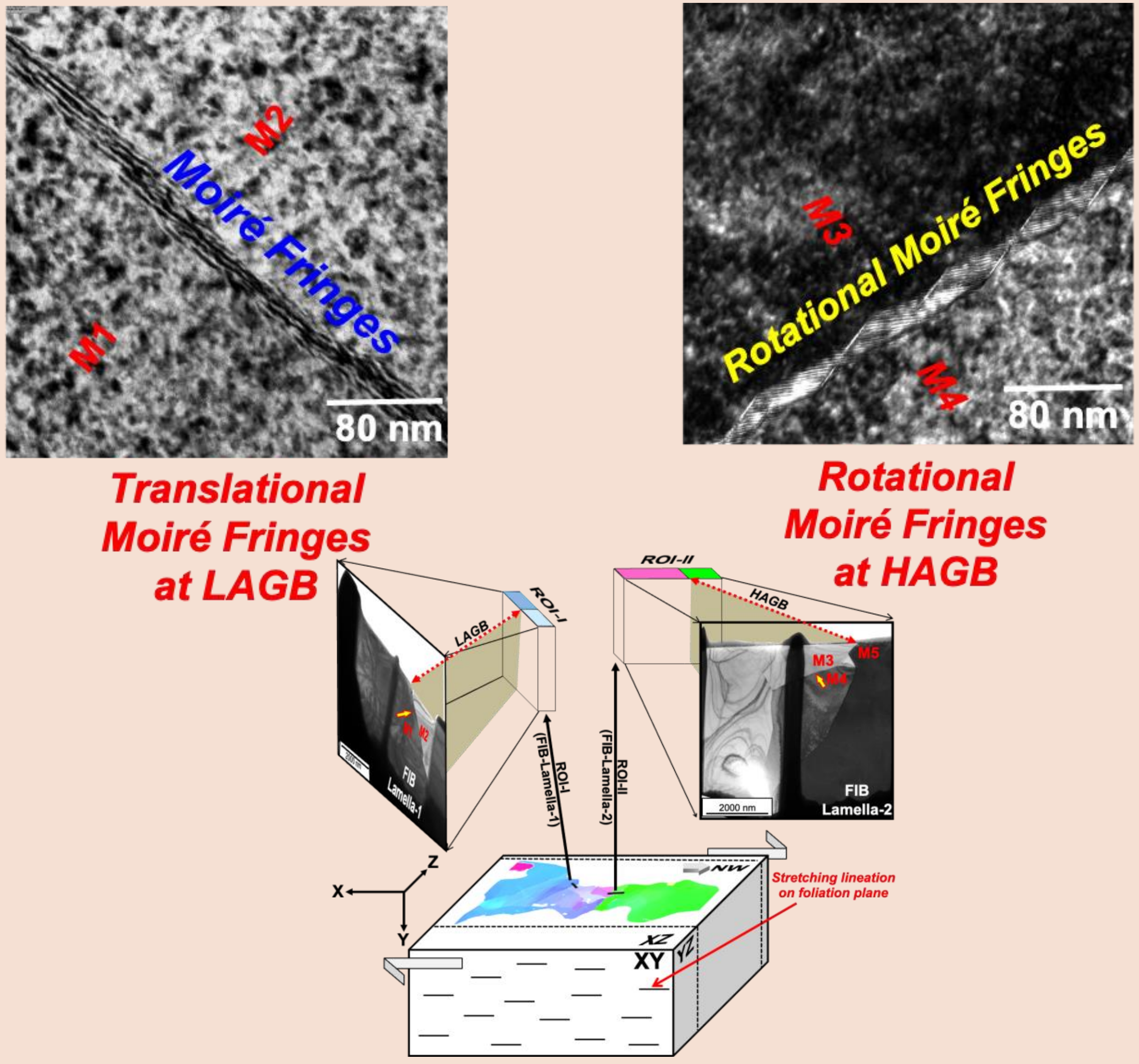


Dislocation Creep in Magnetite

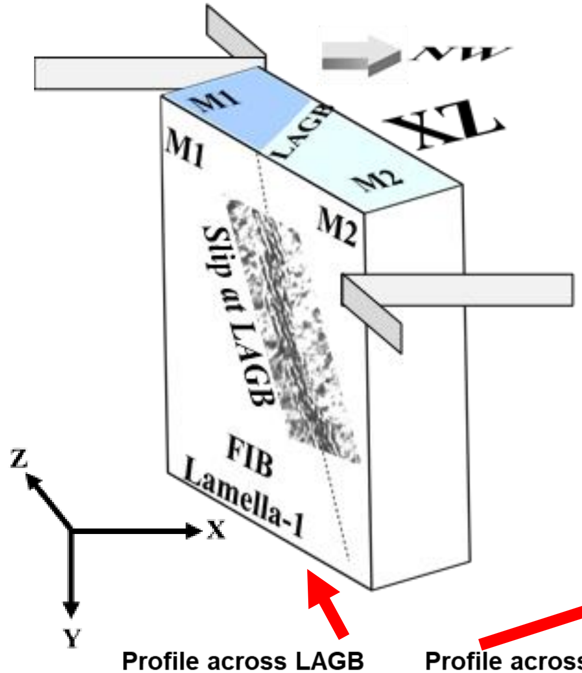


FIB Lamellae In Tectonic Reference Frame

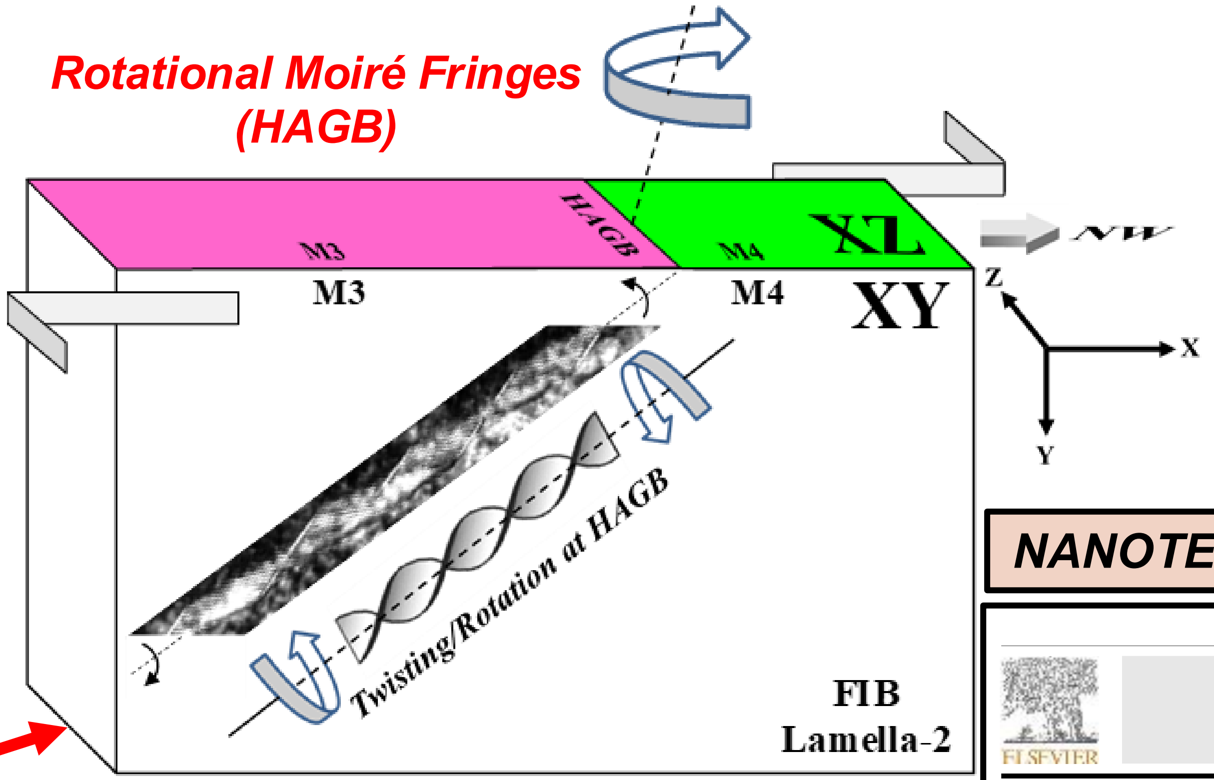
(after Mamtani et al., 2020, Journal of Structural Geology)

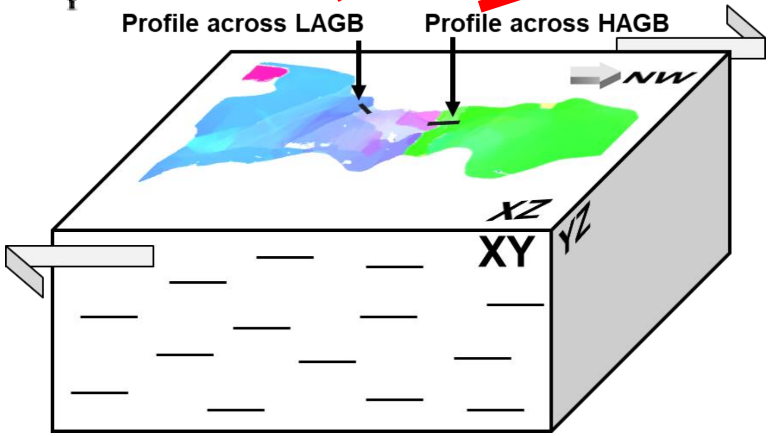


Translational Moiré Fringes (LAGB)



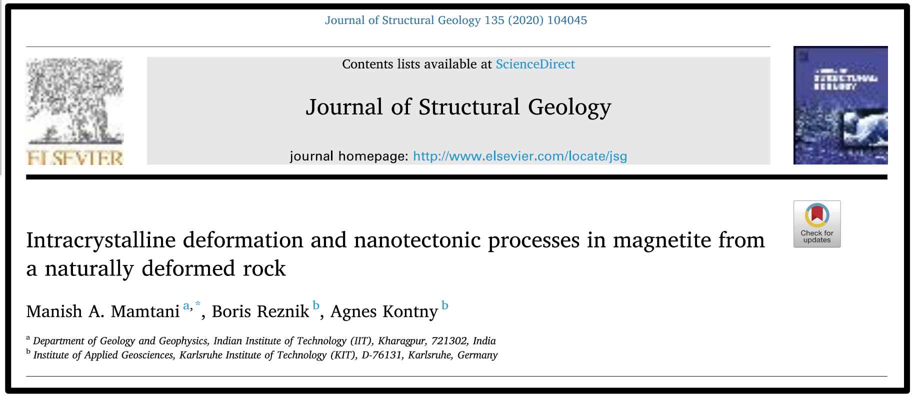
Rotational Moiré Fringes (HAGB)





Sense of rotation inferred from nanostructures is in-sync with regional kinematics (top-to-NW shear sense)

NANOTECTONICS IN GEOSCIENCES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Intracrystalline deformation and nanotectonic processes in magnetite from a naturally deformed rock

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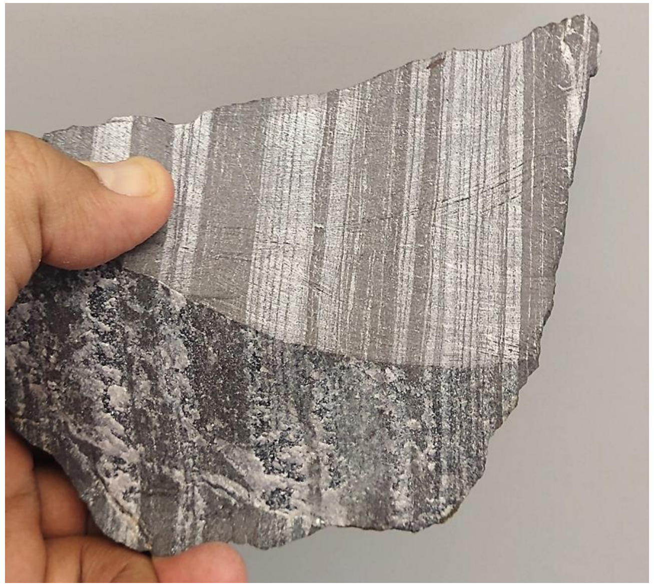
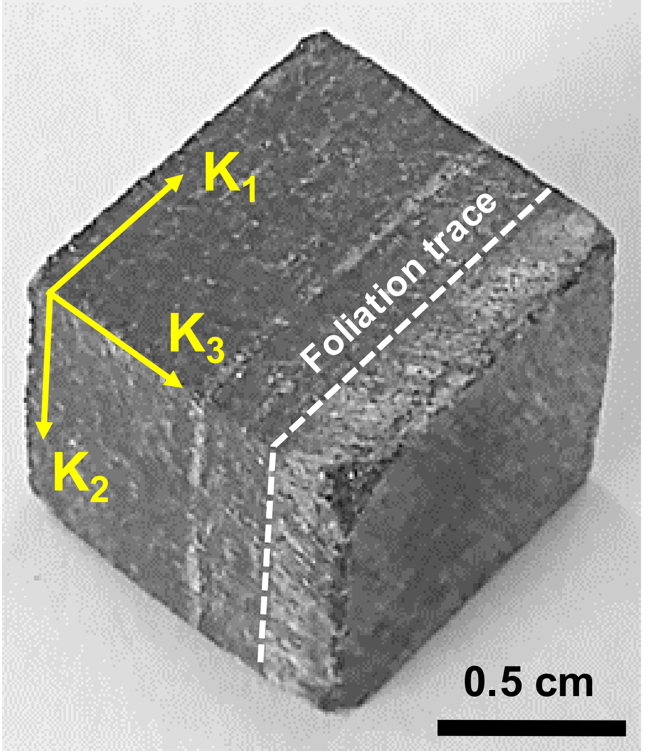
Study of nanostructures under TEM in oriented FIB-lamella of minerals in rocks that can be related to regional tectonics and kinematics is NANOTECTONICS IN GEOSCIENCES

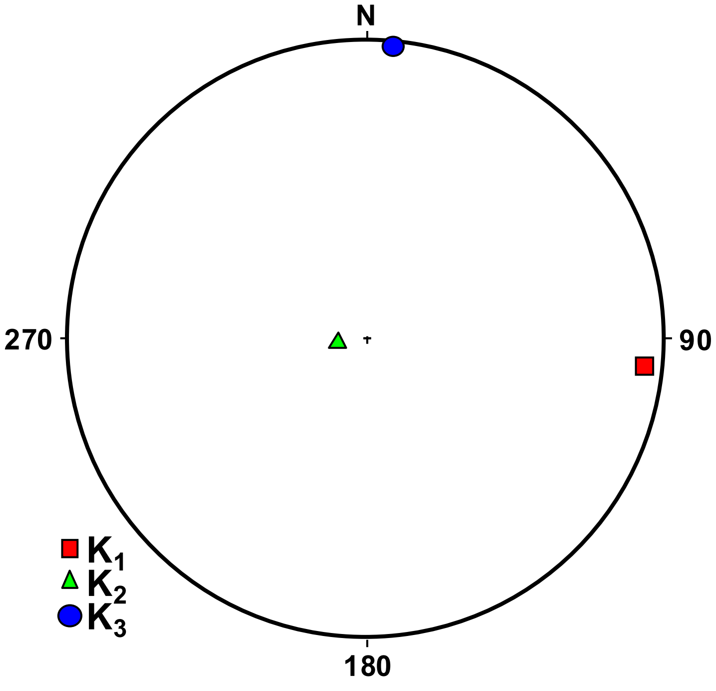
(Mamtani et al., 2020; Journal of Structural Geology)



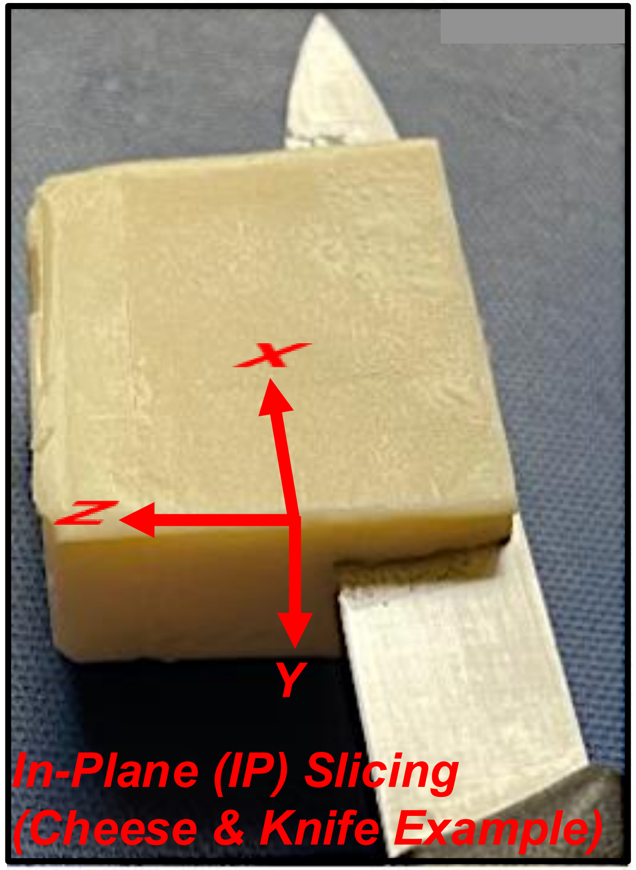
In-Plane FIB Lamella Excavation

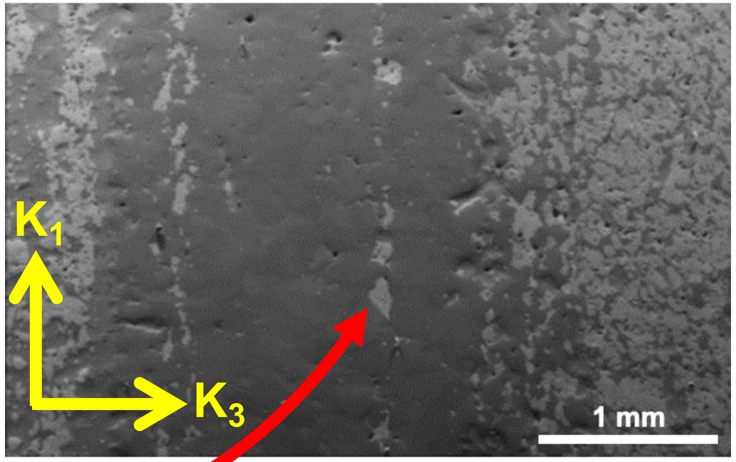
(BIF from Norway)

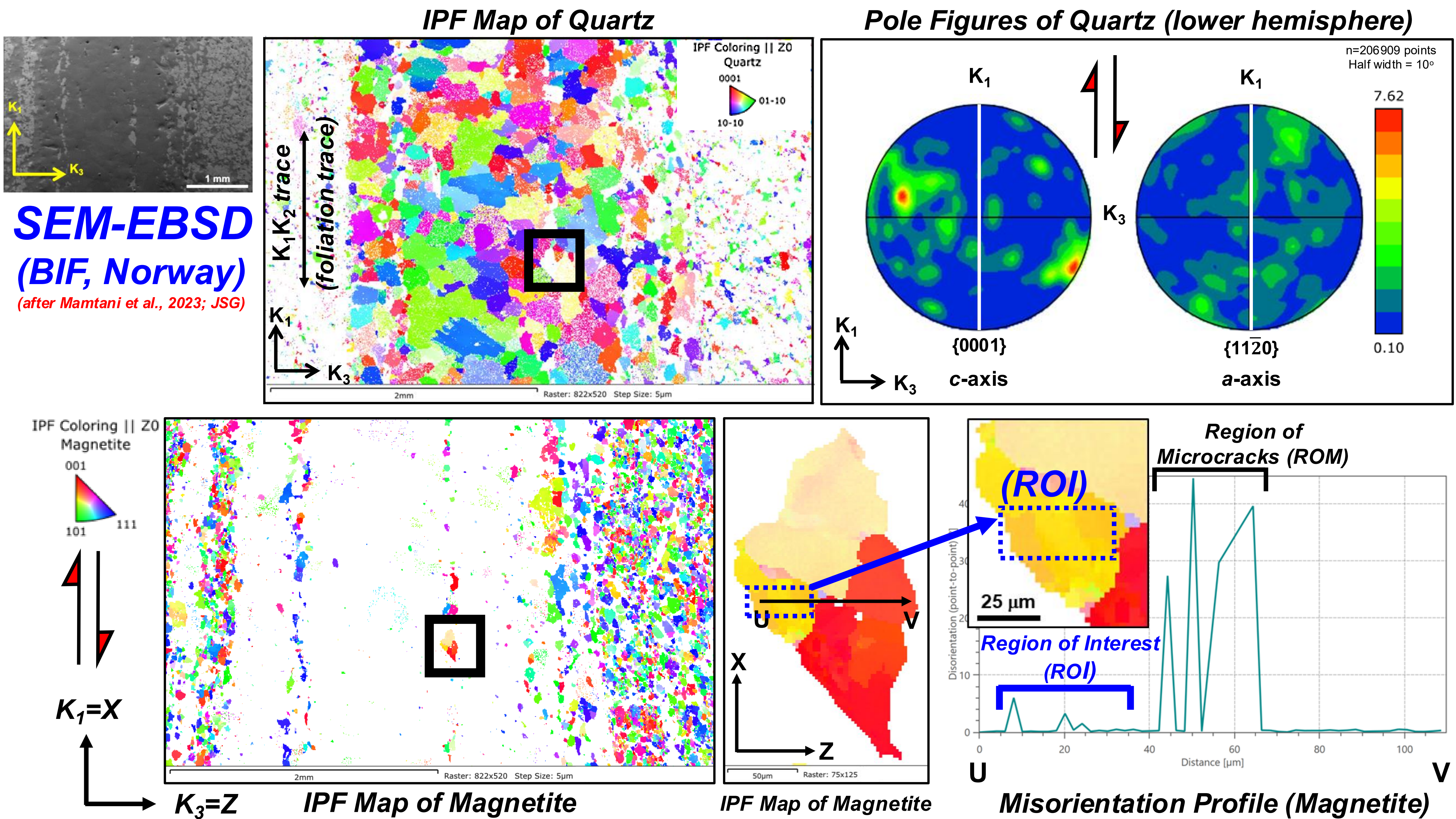




AMS Data
(Norway BIF sample)

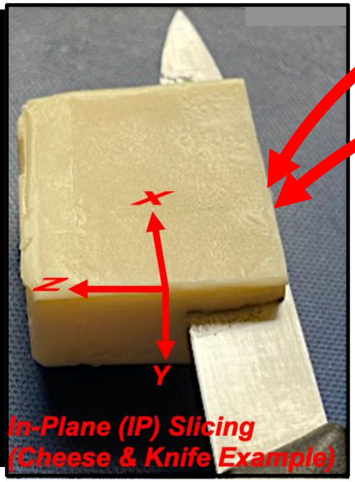


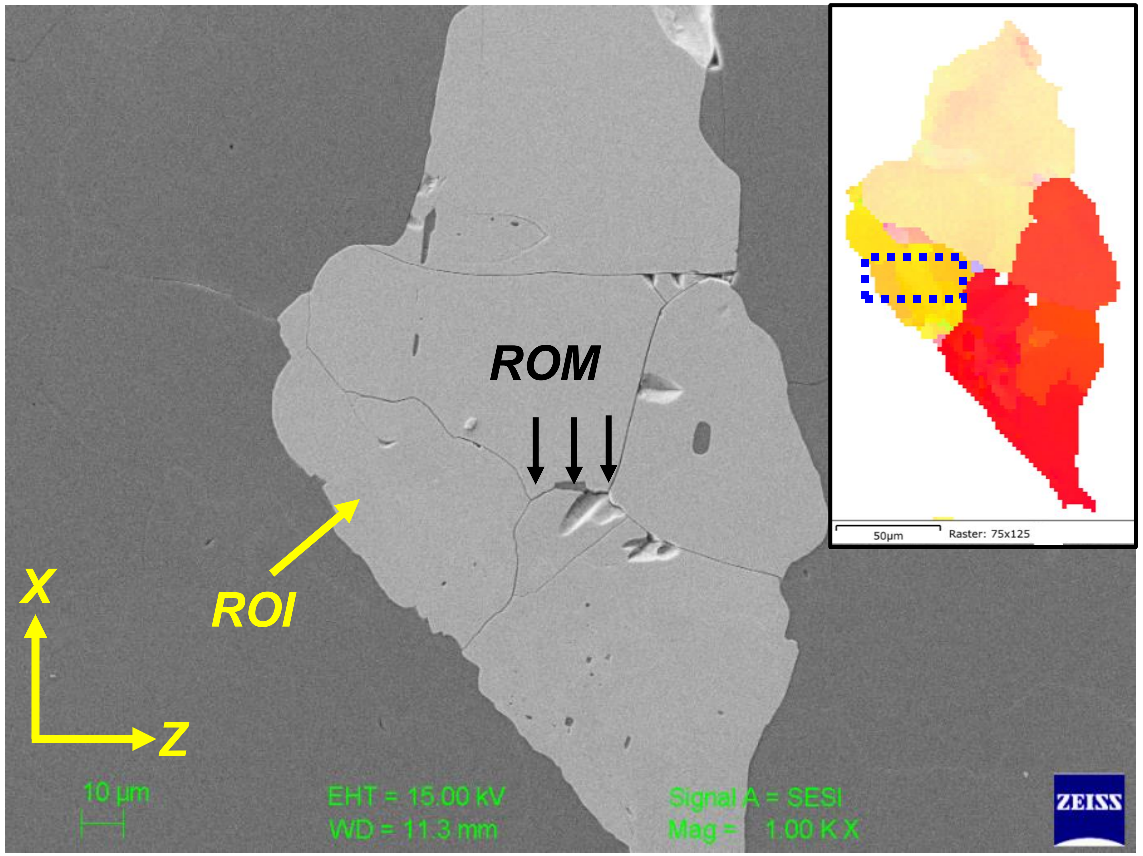


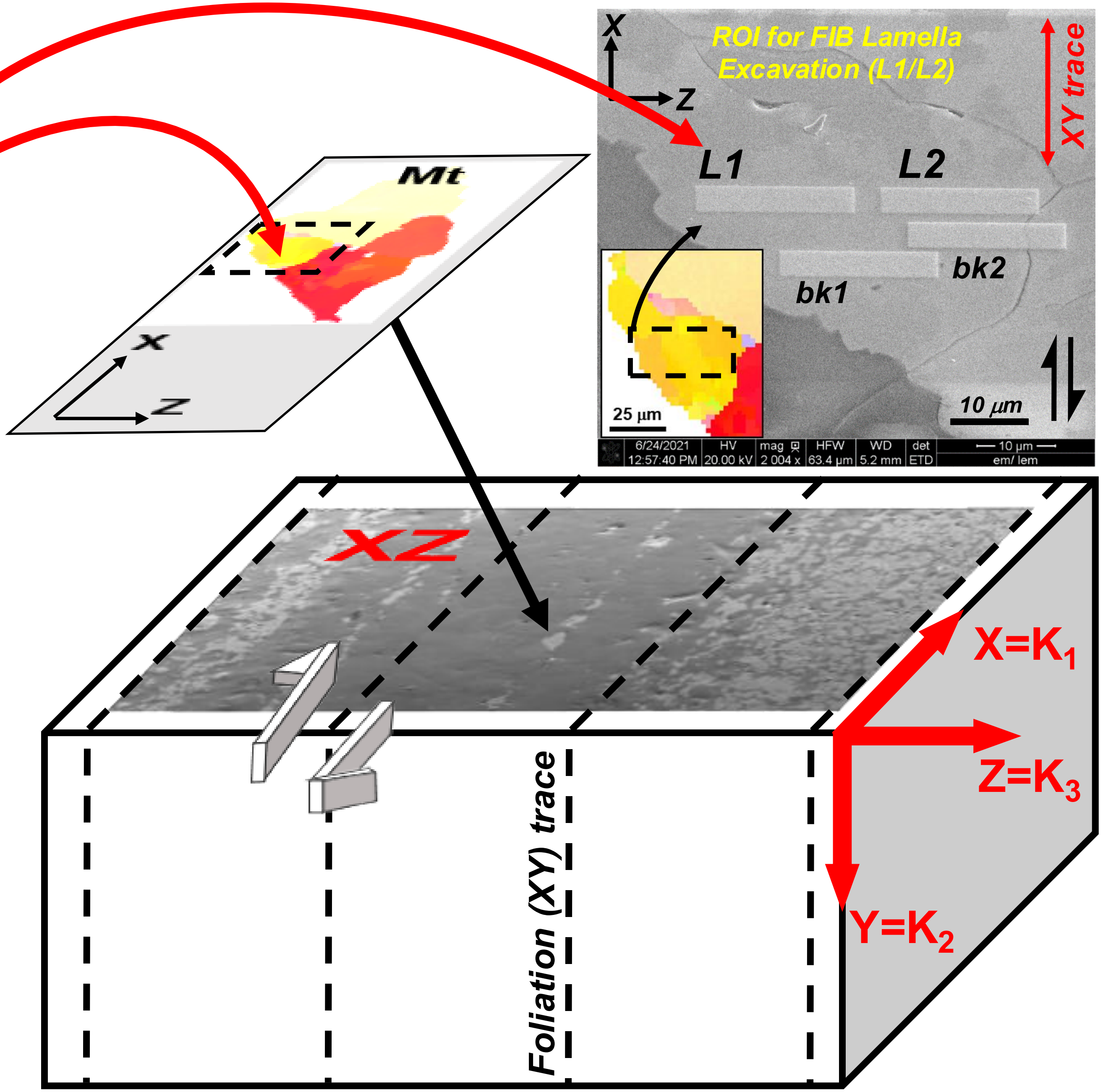


IPF Map of Quartz
Pole Figures of Quartz (lower hemisphere)
1 mm
SEM-EBSD
(BIF, Norway)
(after Mamtani et al., 2023; JSG)
K1K2 trace
(foliation trace)
IPF Coloring || Z0
Quartz
0001
01-10
10-10
2mm
Raster: 822x520 Step Size: 5μm
n=206909 points
Half width = 10°
7.62
0.10
{0001}
c-axis
{11$\bar{2}$0}
a-axis
IPF Coloring || Z0
Magnetite
001
101
111
K1=X
K3=Z
IPF Map of Magnetite
2mm
Raster: 822x520 Step Size: 5μm
50μm
Raster: 75x125
IPF Map of Magnetite
(ROI)
25 μm
Region of Microcracks (ROM)
Region of Interest (ROI)
Disorientation (point-to-point)
Distance [μm]
Misorientation Profile (Magnetite)

Our Objective!
Excavate
In-Plane FIB-Lamella



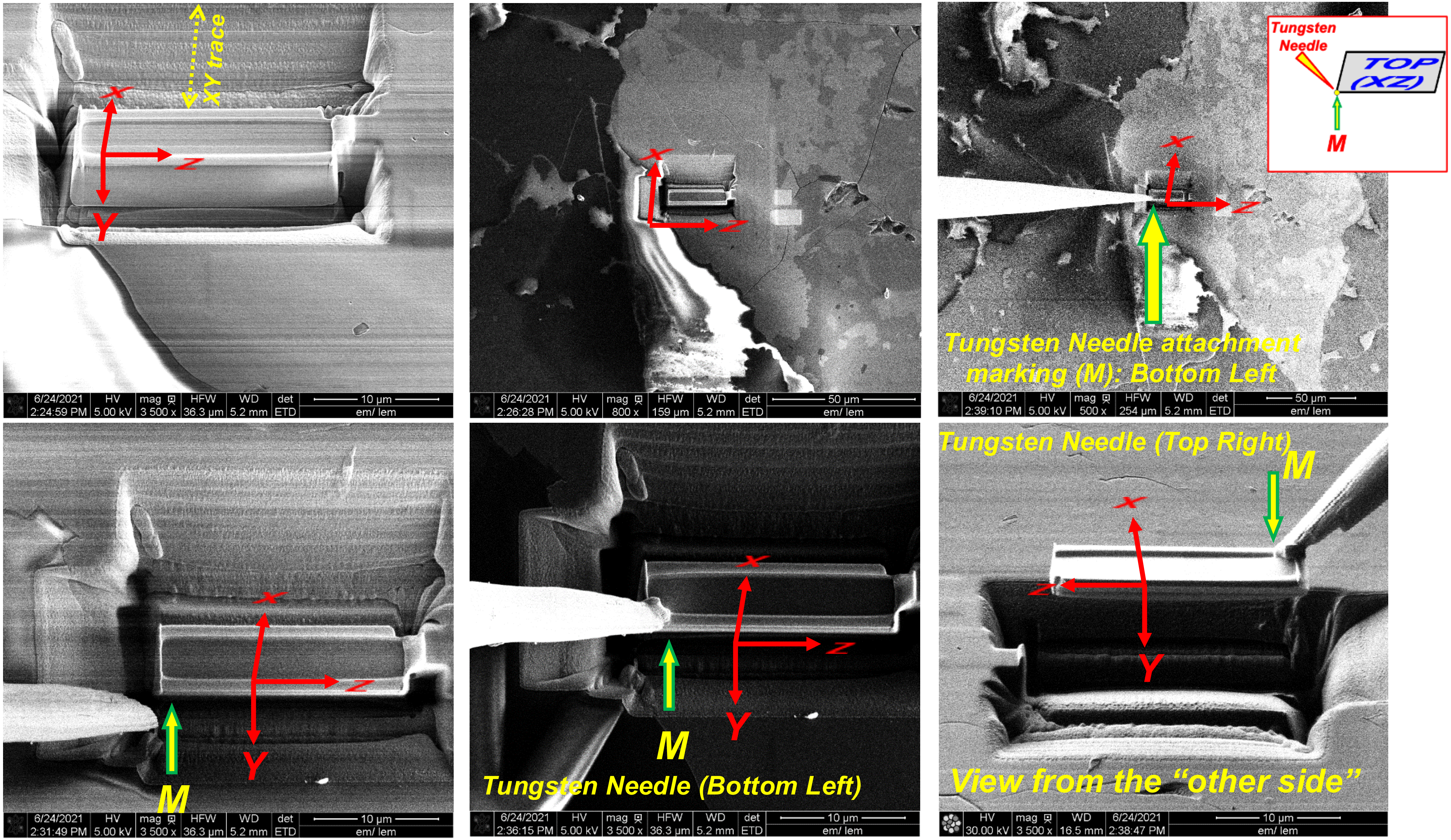




Kinematic Reference Frame Visualization in 3D

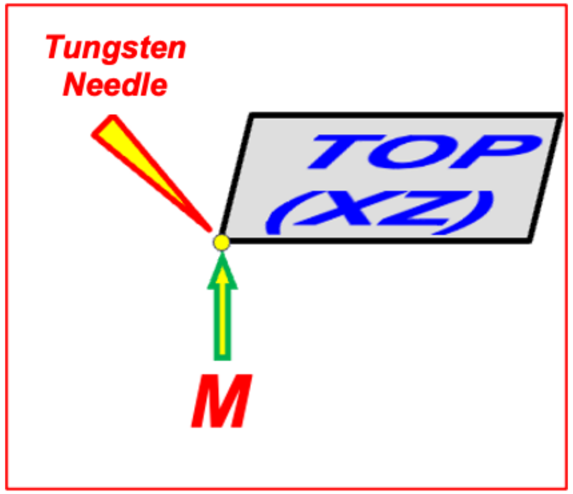
(after Mamtani et al., 2023; Journal of Structural Geology)

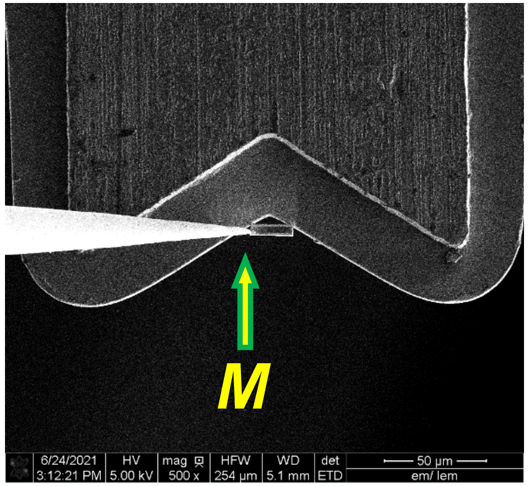
In-Plane FIB-Lamella Excavation from Magnetite (modus operandi in Liu et al., 2018, Ultramicroscopy)

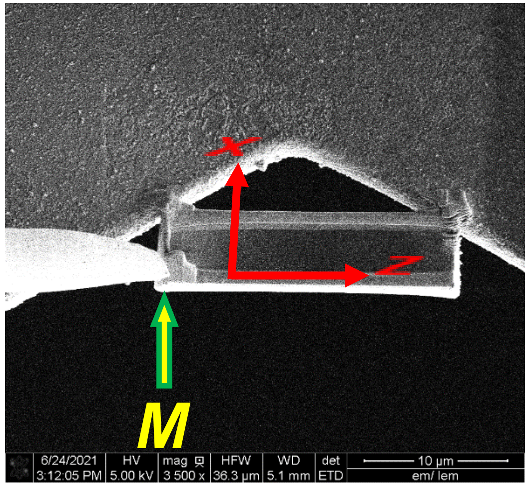


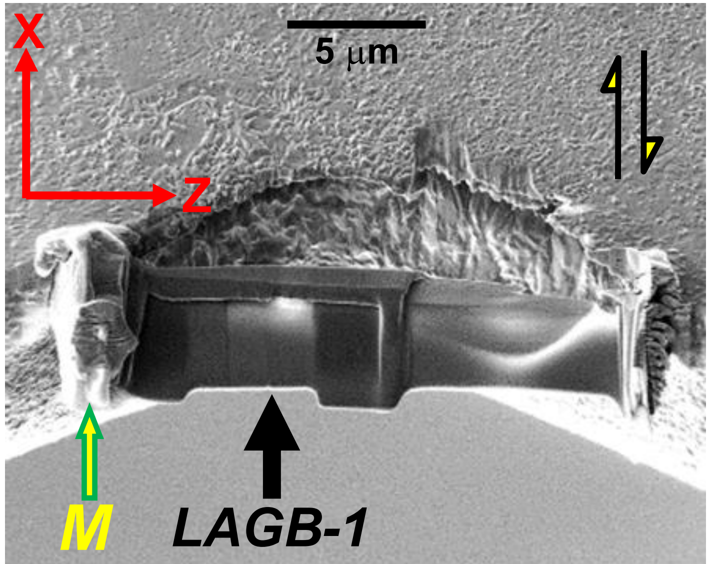
In-Plane FIB-Lamella - Attaching on TEM-Grid and Thinning

➢ *Arrow “M” = Marker Position (where Tungsten needle was attached).*

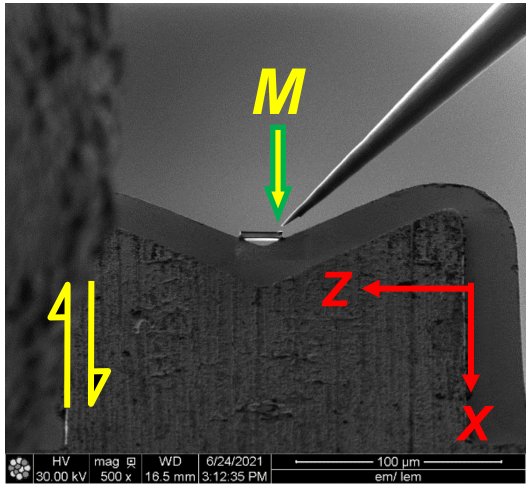




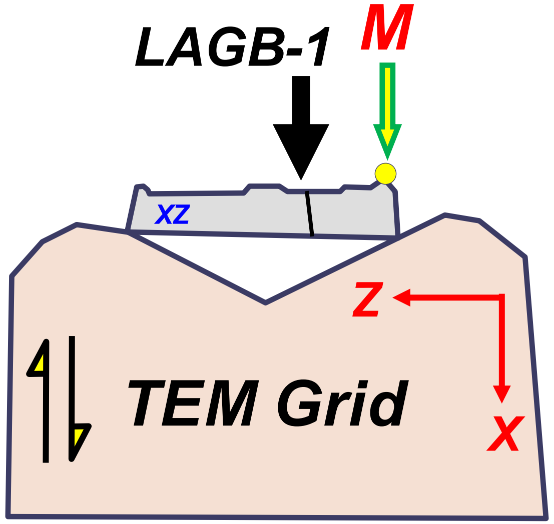




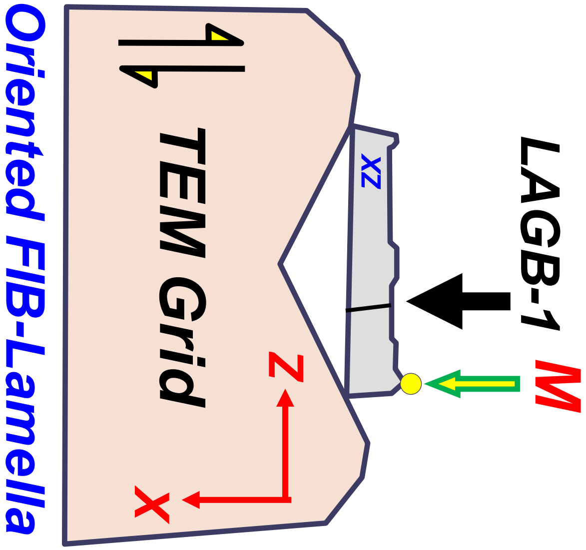
Thinned FIB Lamella on TEM Grid



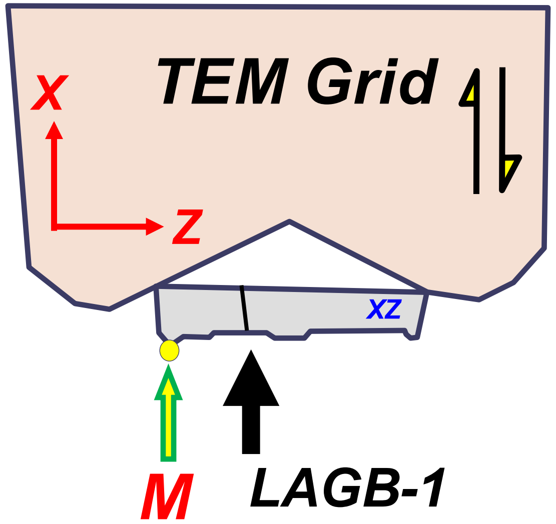
Right Side Up (On TEM Grid)

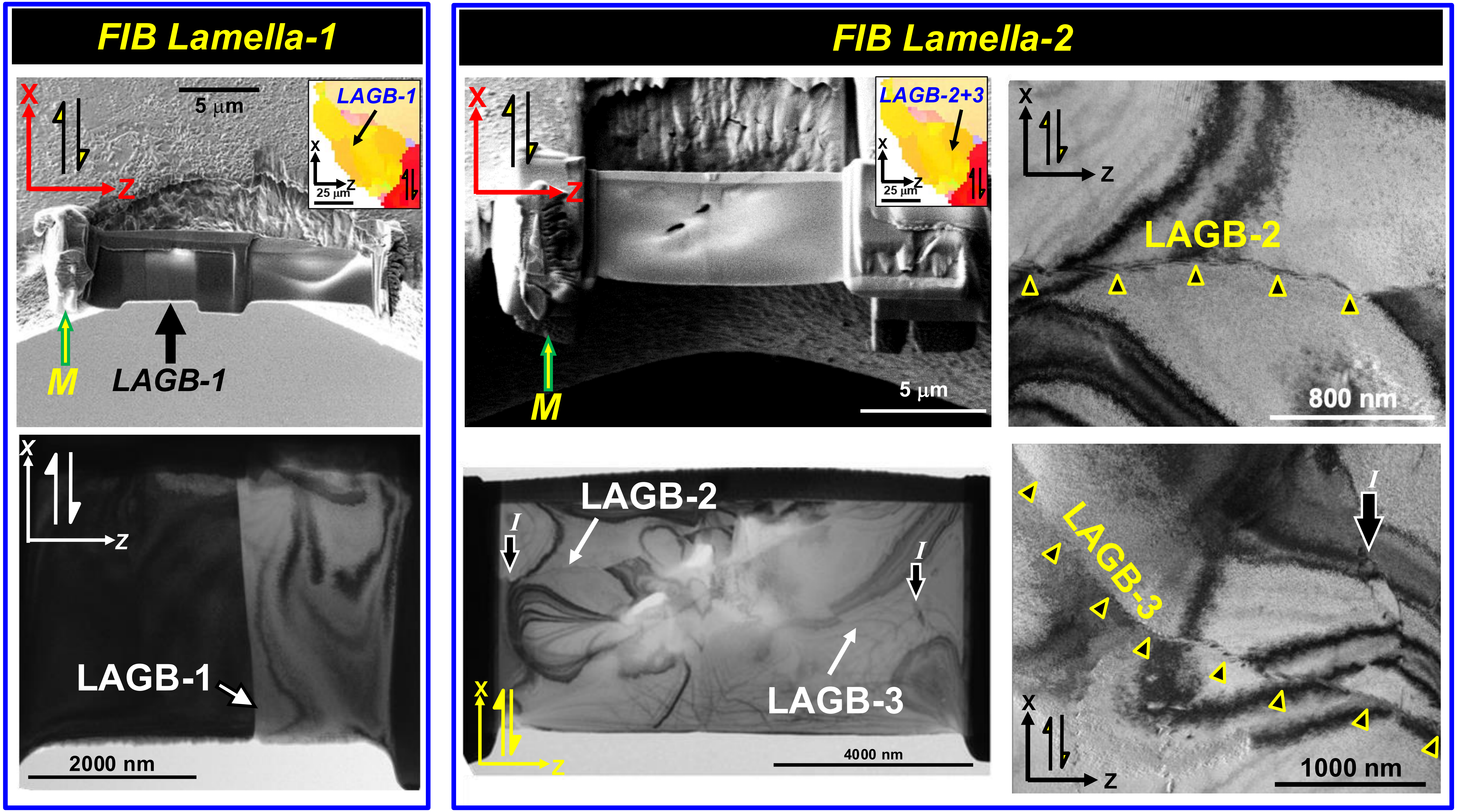


Oriented FIB-Lamella



Oriented FIB-Lamella

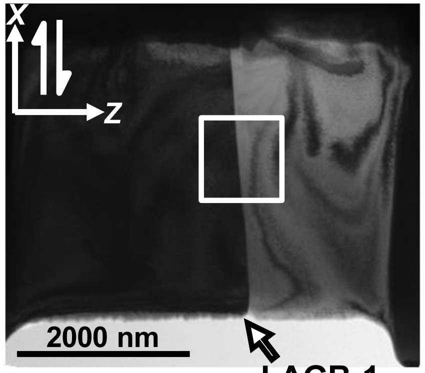


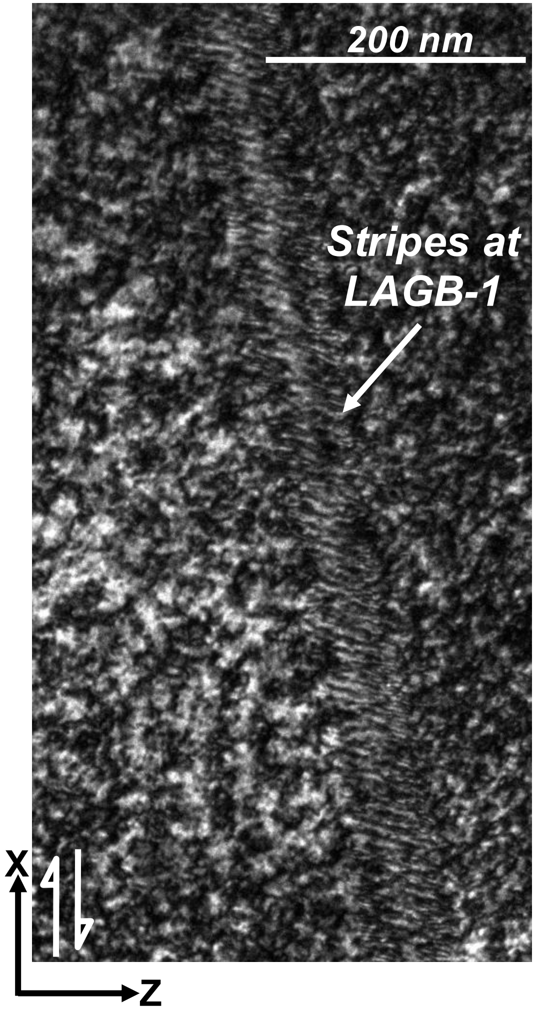


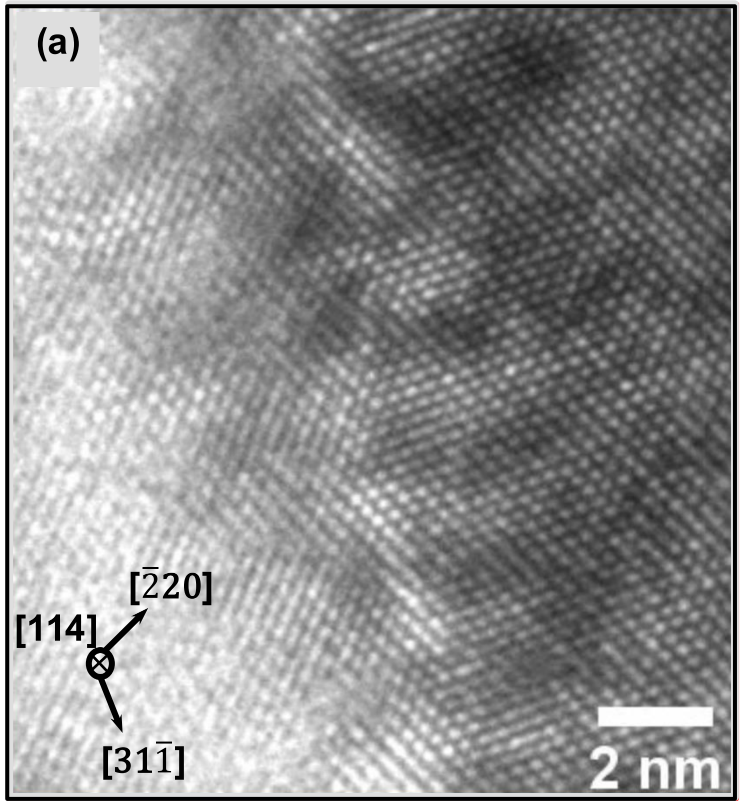
FIB Lamella-1
5 μm
LAGB-1
25 μm
M
LAGB-1
2000 nm
LAGB-1
FIB Lamella-2
LAGB-2+3
25 μm
M
5 μm
LAGB-2
800 nm
LAGB-2
LAGB-3
I
I
4000 nm
LAGB-3
I
1000 nm

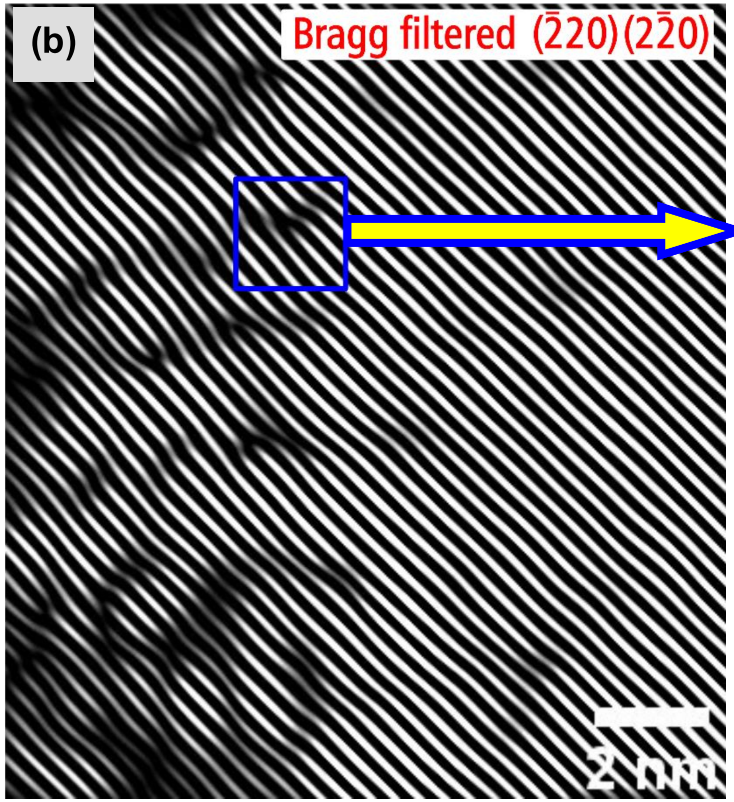
NANOSTRUCTURES IN MAGNETITE UNDER TEM IN FIB LAMELLA-1

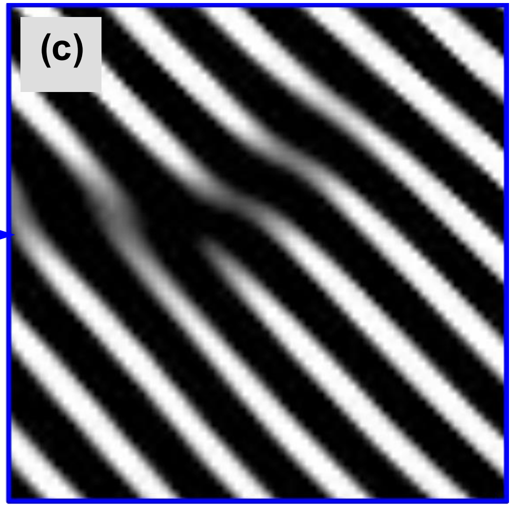
Low Angle Grain Boundary-1 (LAGB-1)









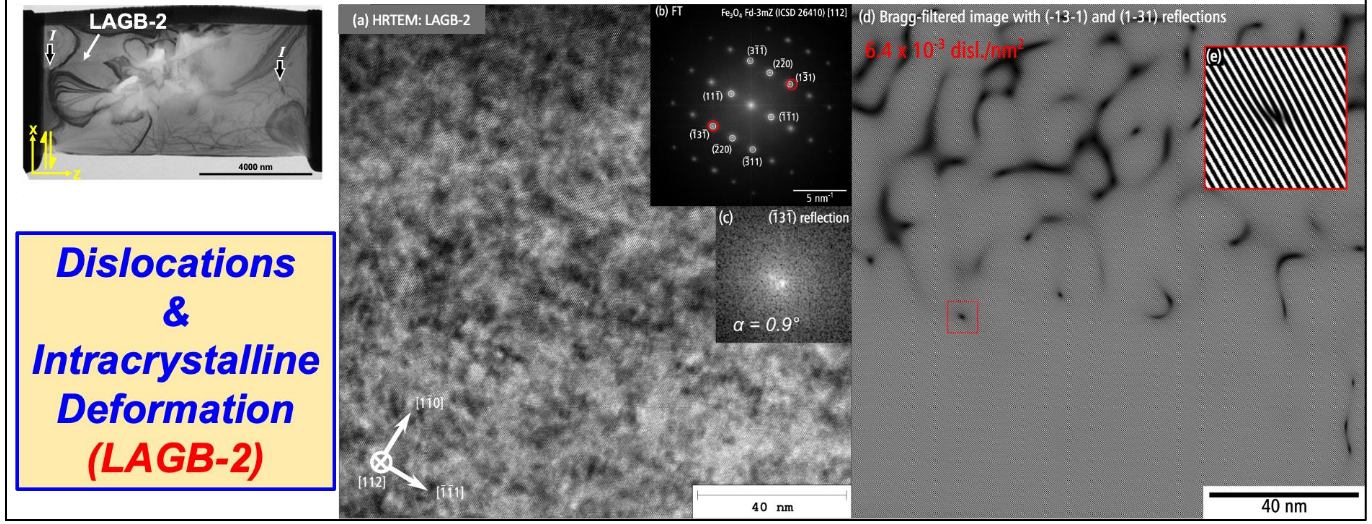


dislocation density
ρ=4.4-1.2*10^{-1} disl. /nm^2

Dislocations: Evidence of Intracrystalline Deformation of Magnetite

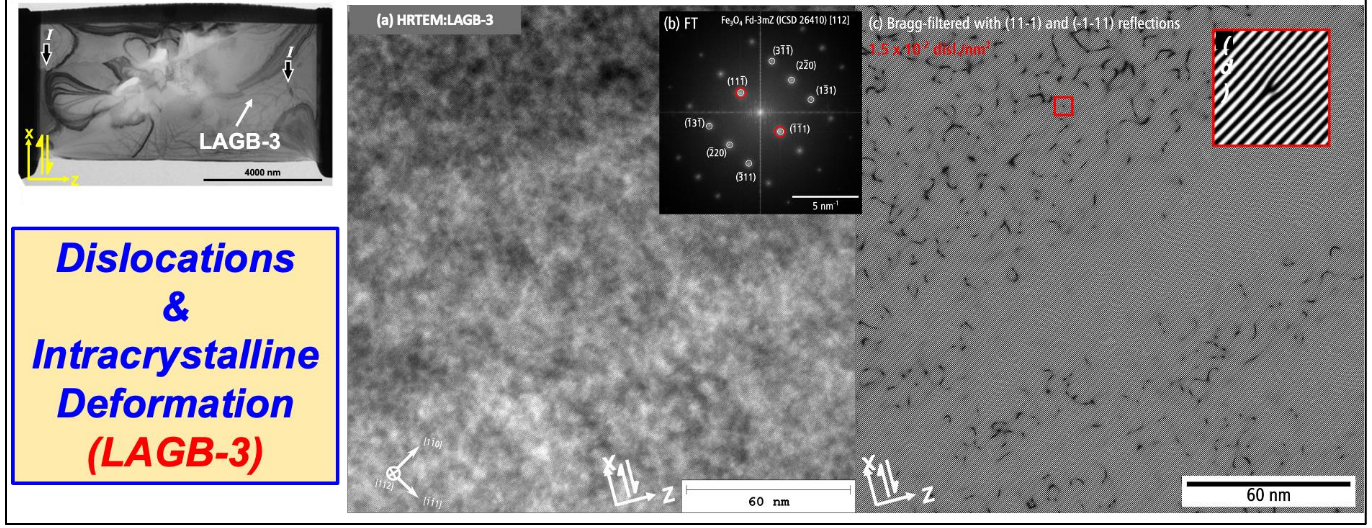
NANOSTRUCTURES IN MAGNETITE UNDER TEM IN FIB LAMELLA-2

Low Angle Grain Boundaries-2 & 3 (LAGB-2 and LAGB-3)



Dislocations & Intracrystalline Deformation (LAGB-2)

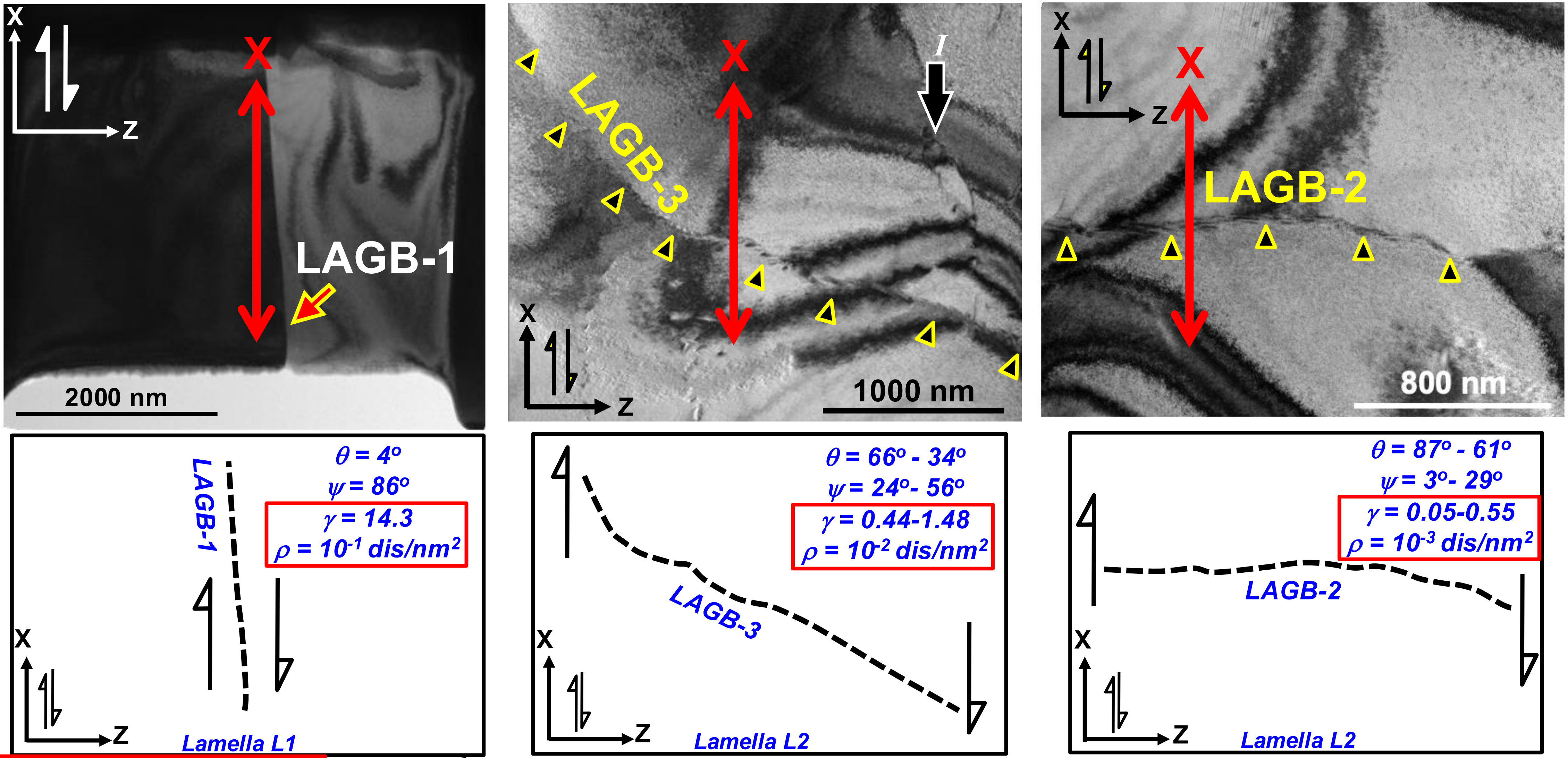
Dislocation Density
6.4 x 10^{-3} dislocations/nm^2



Dislocations & Intracrystalline Deformation (LAGB-3)

Dislocation Density
1.5 x 10^{-2} dislocations/nm^2

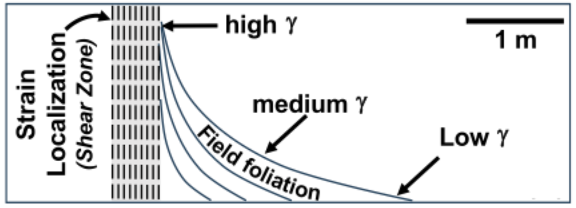
NANOKINEMATICS – 2D EMPIRICAL EVIDENCE



θ = Angle between LAGB and X direction
ψ = Angular Shear
γ = Shear Strain
ρ = Dislocation Density

Dislocation Density (ρ) increases with increasing Shear Strain (γ)

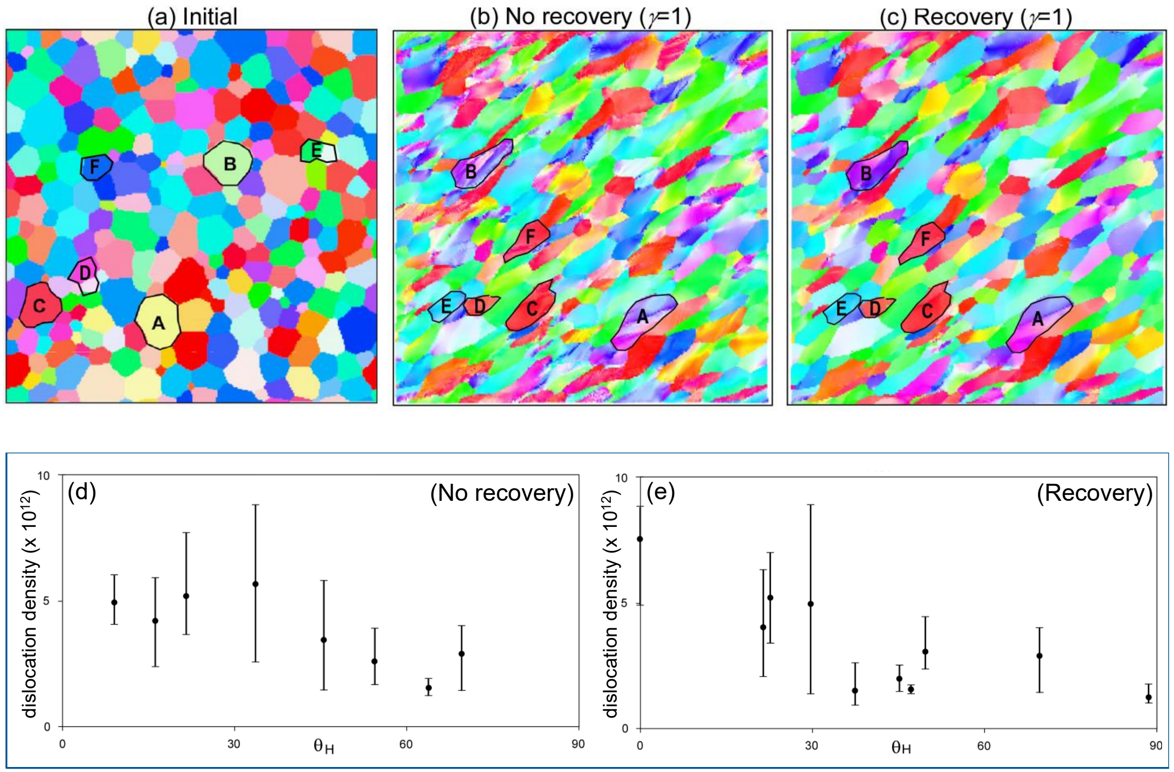
Mamtani et al. (2023; Journal of Structural Geology)



This is analogous to strain localization towards a shear zone in the field!

Numerical Simulations Of Deformation Of Halite Polycrystalline Aggregates

(Mamtani et al. 2023; Journal of Structural Geology)



θ_H vs. ρ plot

(ρ increases with the decrease in θ_H)

- ELLE-VPFFT software is used.
- Initial Microstructure.
- Random distribution of CPO.
- 6 grains (A-F) are selected.
- Dextral simple shear strain (γ = 1) is applied.
- ρ (dislocation density) is calculated across LAGB's in the 6 grains.
- θ_H [angle between LAGB and X (horizontal direction)] is measured.

Real Data & Empirical Relations

θ = Angle between LAGB and X direction
ψ = Angular Shear
γ = Shear Strain
ρ = Dislocation Density

- $\theta_{LAGB-1} < \theta_{LAGB-3} < \theta_{LAGB-3}$
- $\psi_{LAGB-1} > \psi_{LAGB-3} > \psi_{LAGB-3}$
- $\gamma_{LAGB-1} > \gamma_{LAGB-3} > \gamma_{LAGB-3}$
- $\rho_{LAGB-1} > \rho_{LAGB-3} > \rho_{LAGB3}$

Interpretation

- *LAGB's can be visualized as nanoscale shear zones*
- *LAGB's in the present example are similar to zones of strain localization*
- *Therefore dislocation density increases with increasing strain*

Magnetite Real Data

This example highlights the usefulness of integrating SEM-EBSD with TEM data for Nanokinematic Analysis

Lots of Fundamental Research and Papers integrating field, microstructural, SEM-EBSD and TEM

….A Lot of Multiscale Data…..BUT SO WHAT ???

(Mamtani, 2025; J. Geol. Soc. India)

Oriented Field Sample

⇓

Petrophysical Property Analysis
Porosity/permeability studies in oriented core
P-wave velocity and other (non-destructive) measurements

⇓

3D-Fabric Analysis
AMS, X-ray micro-CT of oriented core

⇓

2D-Microstructural Analysis
Petrography of oriented thin section
Digital imaging of complete thin section
Large area mapping under SEM (including *In-Lens)*
Microstructure quantification
SEM-EBSD

⇓

Nanoscale Analysis
TEM studies of oriented thin films

Fig. 11. Flow chart documenting the studies that can be undertaken in the 21st century to investigate rock structures from the field scale to the nanoscale. It is envisaged that the schematically represented work-flow involving petrophysical studies in sample cores, 3D fabric analysis in cores, 2D microstructural analysis in rock thin sections and nanoscale studies in thin films can help in a comprehensive analysis of structures from the meso- to nano- scale. See text for discussion.

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https://doi.org/10.17491/jgsi/2025/174056

(Mamtani, 2025; J. Geol. Soc. India)

REVIEW ARTICLE

The Future of Structural Geology in the 21st Century – Moving from Mesoscale to Nanoscale Observations in Tectonically Deformed Rocks

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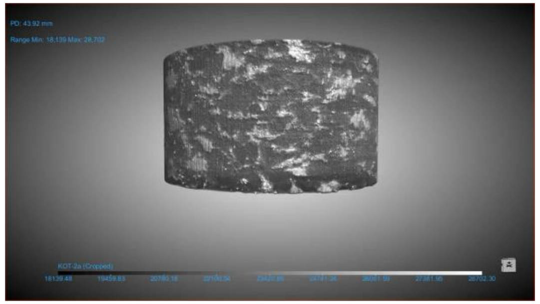
E-mail: mamtani@gg.iitkgp.ac.in

ABSTRACT

The importance of integrating field studies with various micro- and nano-scale structural geological investigations using petrographic microscope, scanning electron microscope (SEM), electron backscatter diffraction (EBSD) and transmission electron microscope (TEM) is highlighted in this paper. The author's past studies dealing with SEM-EBSD and TEM investigations to decipher deformation mechanism of magnetite are taken as examples to support the robustness of investigating nanostructures in thin films excavated parallel to the kinematic reference frame. In addition, the author also shares a work flow involving collection of oriented field samples, followed by petrophysical investigations (e.g., porosity, permeability, P-wave velocity of oriented samples, etc.), 3D fabric analysis (e.g., AMS, X-ray micro-CT of oriented samples), 2D-microstructural analysis in oriented thin sections (petrography, SEM imaging including in-lens, EBSD, etc.) and finally nanostructural studies in oriented thin films using TEM (in that order). The importance of this integrated approach to evaluate structures at different scales and utilize the results for fundamental research as well as applications such as in the field of understanding fluid flow, mineralization, geothermal systems and radioactive waste management is discussed. Hence the paper provides an overview to the reader about some of the possibilities that exist today (21st century) in the field of structural geology.

MULTISCALE DATA
Applied Structural Geology

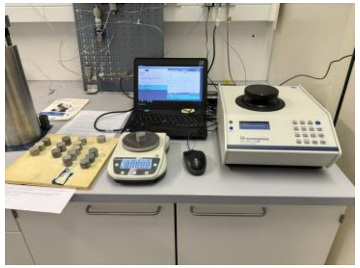
- ➢ ***Fluid Flow & Mineralization***
- ➢ ***Geothermal Systems***
- ➢ ***Deep Seated Nuclear Waste Disposal***
- ➢ ***CO_2 Storage***



Oriented Field Sample

P-wave velocity measurement

Permeability measurement



Porosity measurement

Petrophysical Property Analysis

Porosity/permeability studies in oriented core

P-wave velocity and other (non-destructive) measurements

3D-Fabric Analysis

AMS, X-ray micro-CT of oriented core

2D-Microstructural Analysis

Petrography of oriented thin section

Digital imaging of complete thin section

Large area mapping under SEM (including In-Lens)

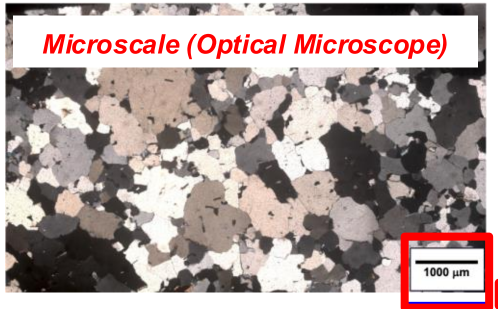
Microstructure quantification

SEM-EBSD

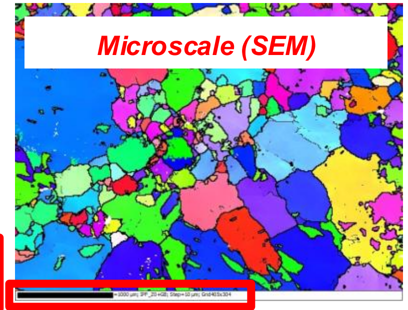
Nanoscale Analysis

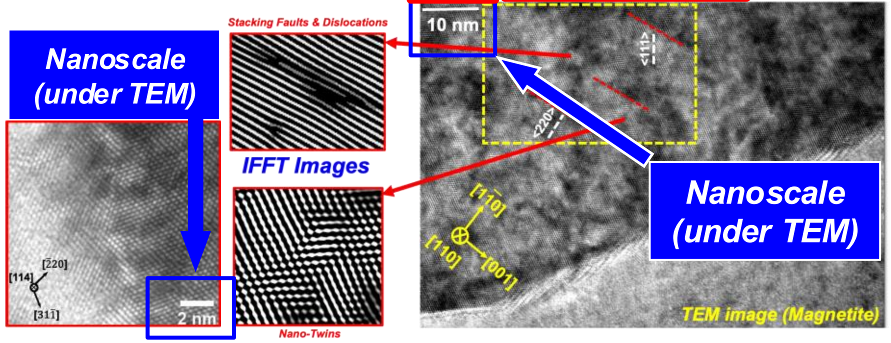
TEM studies of oriented thin films

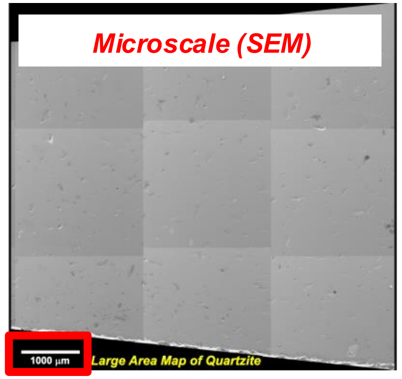
Petrography

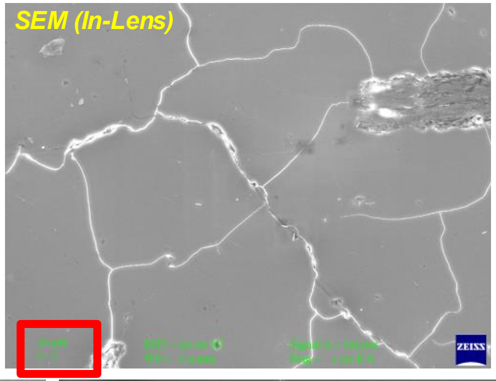


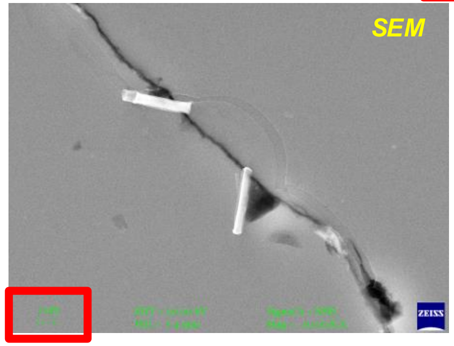
SEM-EBSD

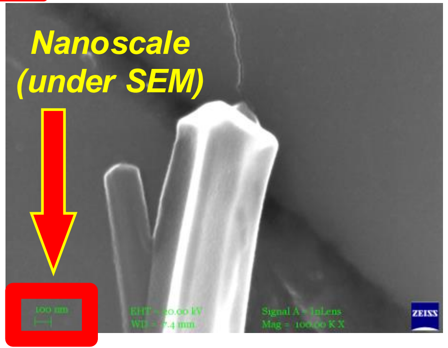




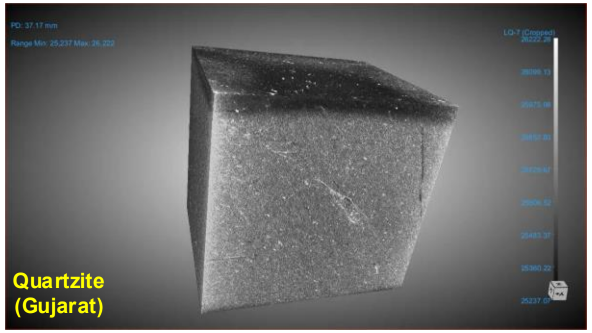


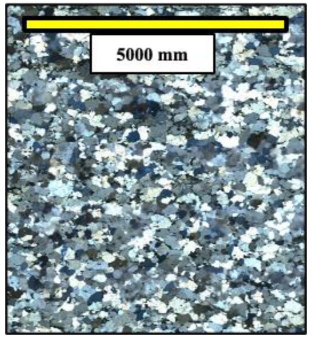


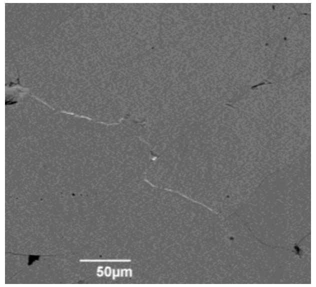




Multiscale Studies of Rock Structures & Application to Society Is the Future

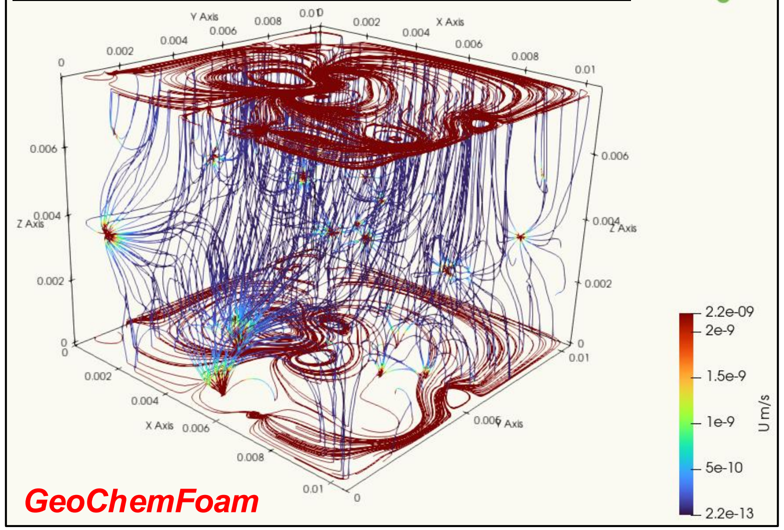


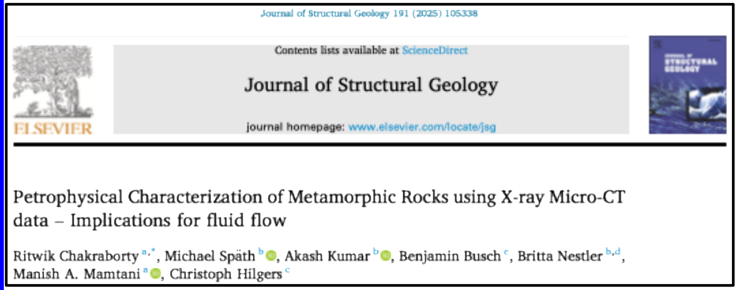




Fracture Topology

Fluid Flow Modelling

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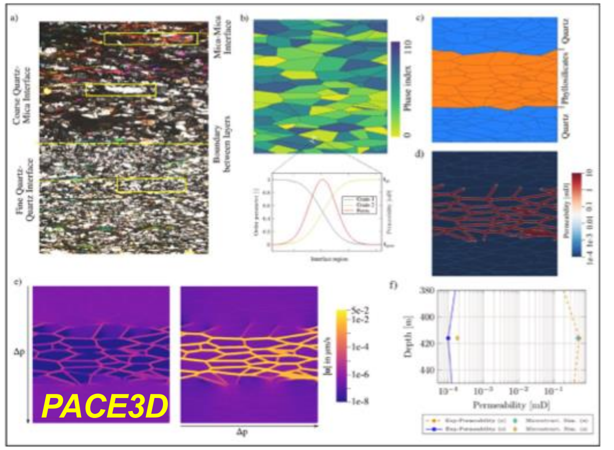
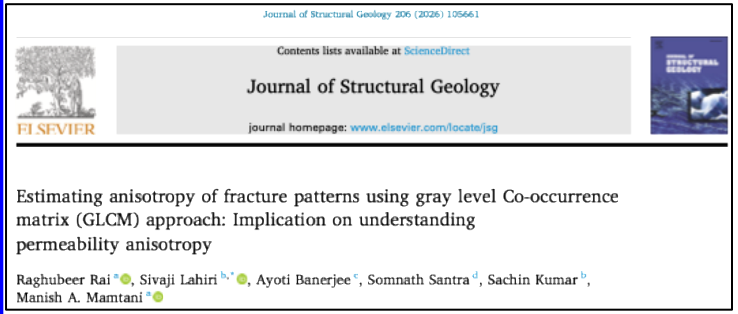
Petrophysical Characterization of Metamorphic Rocks using X-ray Micro-CT data – Implications for fluid flow

Ritwik Chakraborty [a,*], Michael Späth [b], Akash Kumar [b], Benjamin Busch [c], Britta Nestler [b,d], Manish A. Mamtani [a], Christoph Hilgers [c]

Fluid Flow Modelling using PACE3D

(Chakraborty et al., 2025; Journal of Structural Geology)

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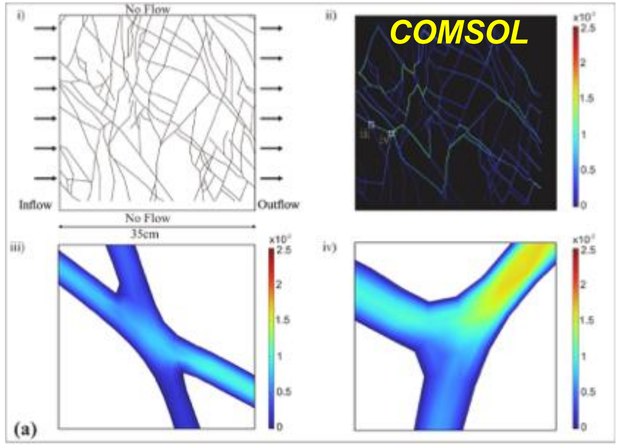
Estimating anisotropy of fracture patterns using gray level Co-occurrence matrix (GLCM) approach: Implication on understanding permeability anisotropy

Raghubeer Rai [a], Sivaji Lahiri [b,*], Ayoti Banerjee [c], Somnath Santra [d], Sachin Kumar [b], Manish A. Mamtani [a]

Permeability Anisotropy using COMSOL

(Rai et al., 2026; Journal of Structural Geology)



- ➢ How does alteration affect porosity/permeability and fluid flow?
- ➢ How does vesicle-distribution affect porosity/permeability and fluid flow?
- ➢ How does foliation affect porosity/permeability and fluid flow?
- ➢ How do petrophysical properties change with depth?
- ➢ How do these changes affect fluid flow and mineralization?
- ➢ How are petrophysical properties of granitoids related to fabric?

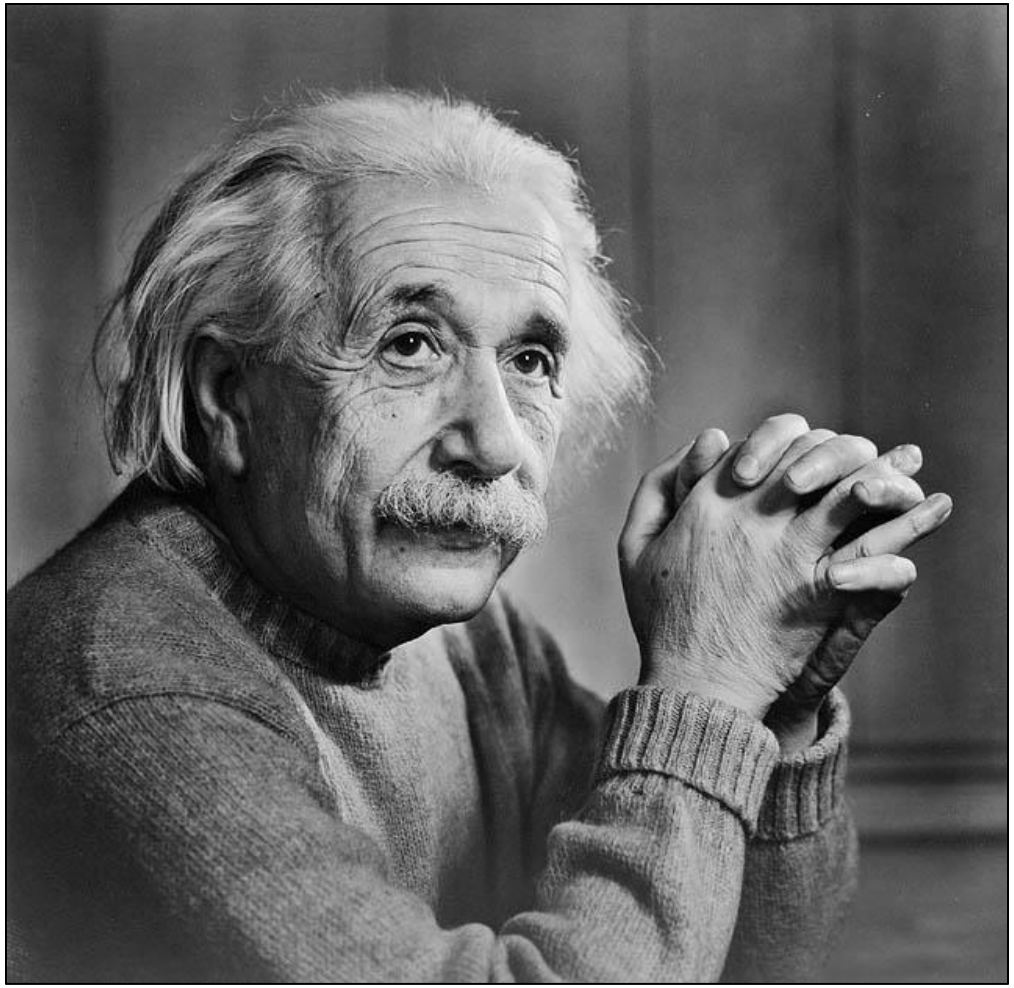
Future Scope is Immense

Fluid Flow & Mineralization

Geothermal Systems

Deep Seated Nuclear Waste Disposal

CO_2 Storage



Intellectual growth should commence at birth and cease only at death

Thank You For Your Attention!