Paleomagnetism and Rock Magnetism of the 1999 Chi-Chi Earthquake Slip Zone and their Implications

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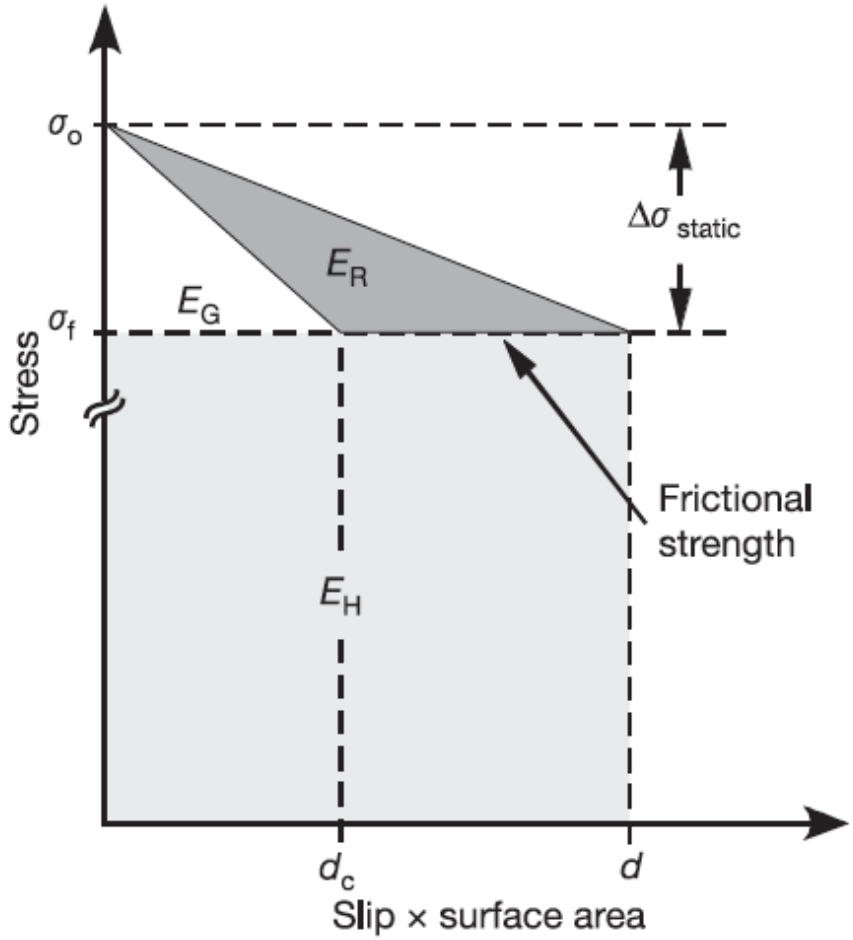
NCU, 2014/10/31

Energy Budget of Earthquake



(Chester et al., 2005)

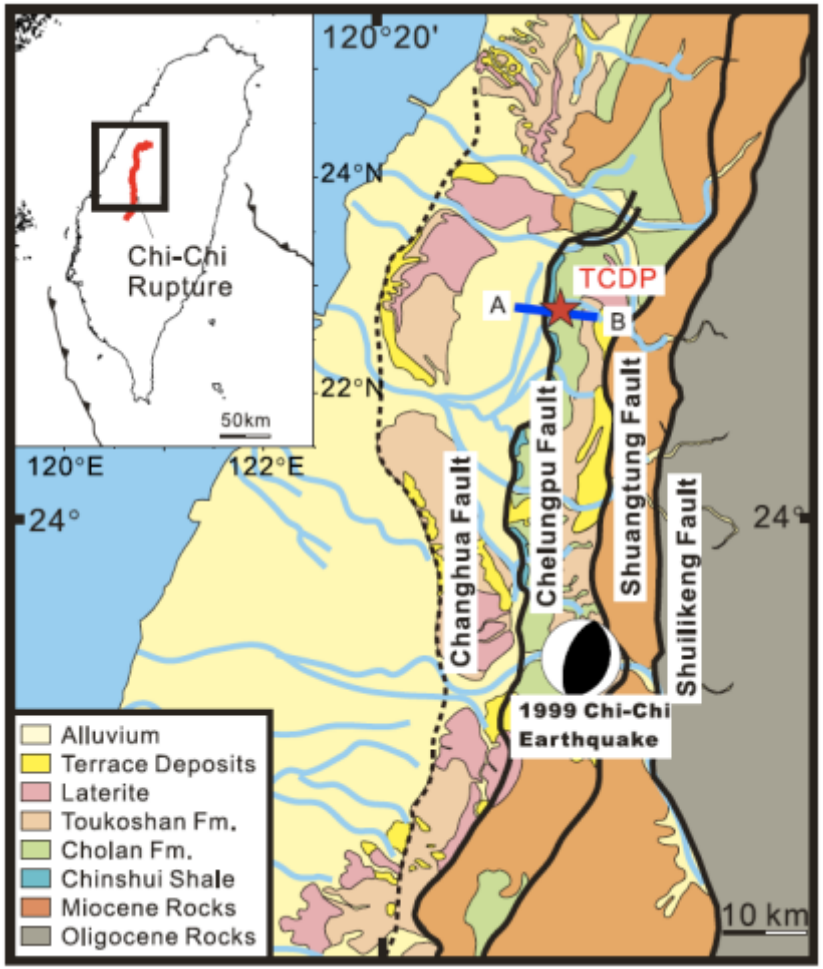
E_R = Radiated Energy

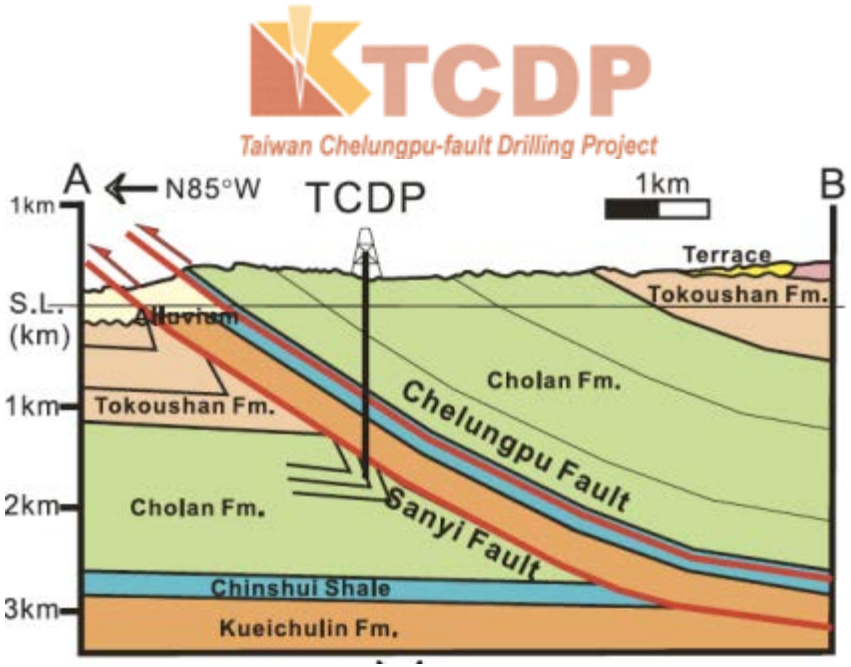
E_G = Fracture Energy

E_H = Frictional Heat

not easy observed

1999 Chi-Chi Earthquake & Taiwan Chenlungpu-fault Drilling Project (TCDP)





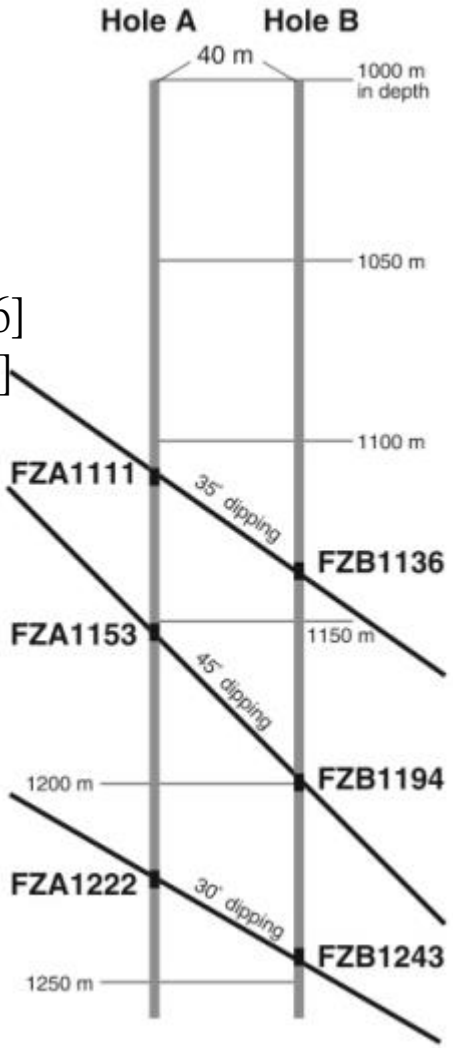
Hole A - 2,003 m

Hole B - 1,350 m

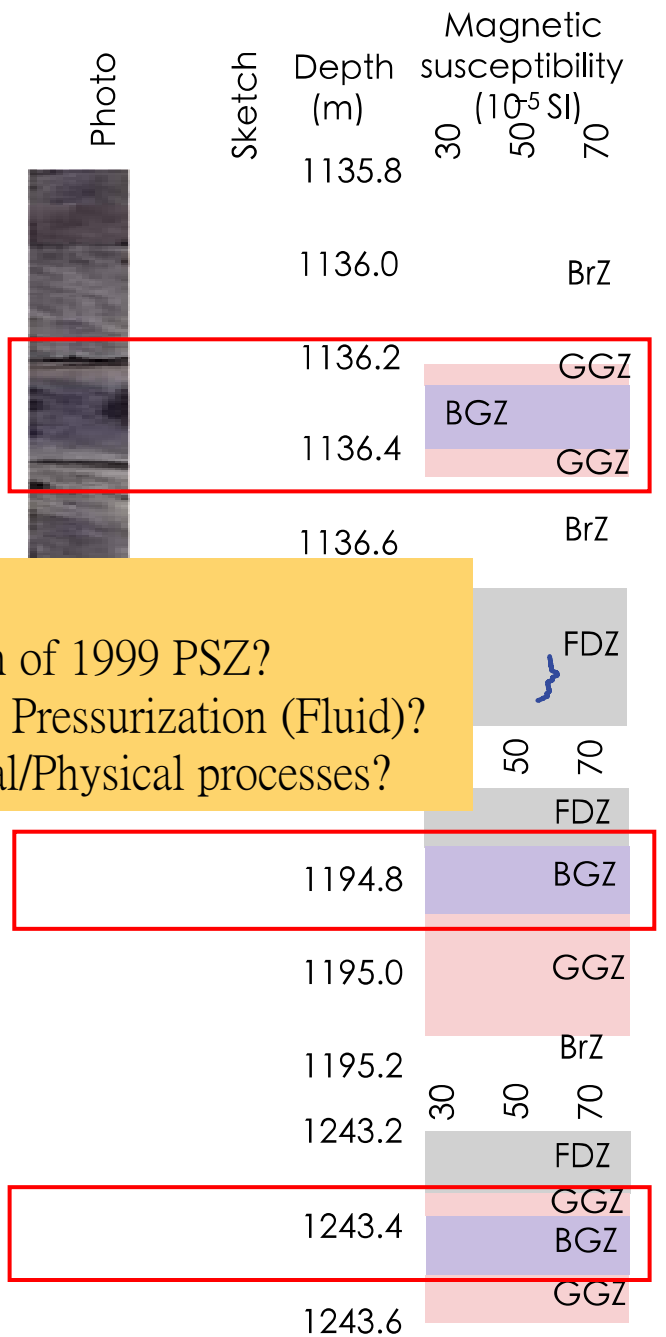
[Yeh et al., 2007]

Major Fault Zones

Most likely
Chi-Chi MSZ
[Kano et al.,2006]
[Ma et al., 2006]



[Hirono et al., 2006, 2007]



Questions:
1. Location of 1999 PSZ?
2. Thermal Pressurization (Fluid)?
3. Chemical/Physical processes?

Modified From [Ishikawa et al., 2008]

During an Earthquake….

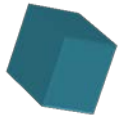
Frictional Heating
(Kano et a., 2007; Kuo et al., 2009)

Co-seismic Hot Fluid
(Ishikawa et al., 2008)

Grain Size Reducing
(Ma et al., 2006)

Thermal Pressurization
(Boullier et al., 2009; Lockner et al., 2009)

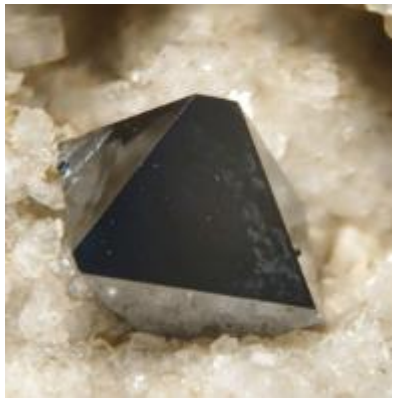
How magnetic minerals can help ?



It records the Earth magnetic field
Paleomagnetism

It has a preferred orientation.
Few cc provides the preferred orientation of billions grains
(not in this study)

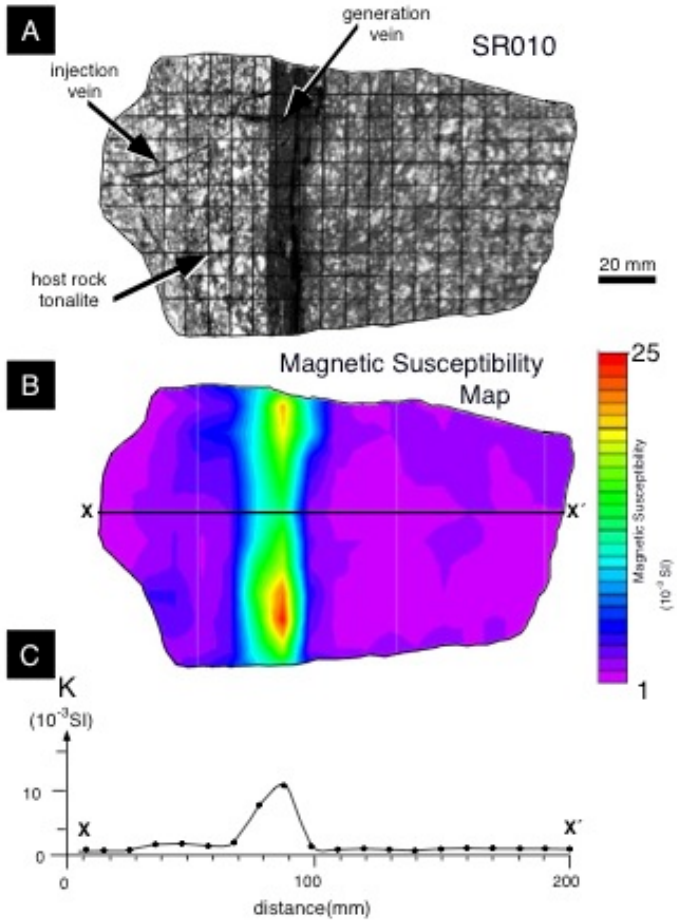
Its formation or alteration depends on physical / chemical constraints.



Magnetite

Motivation

- Modern fault gouges usually display a peak of magnetic susceptibility.
- This increase of magnetic susceptibility testifies for chemical and/or physical alterations.
- We aim to better understand the alteration process in the gouge.

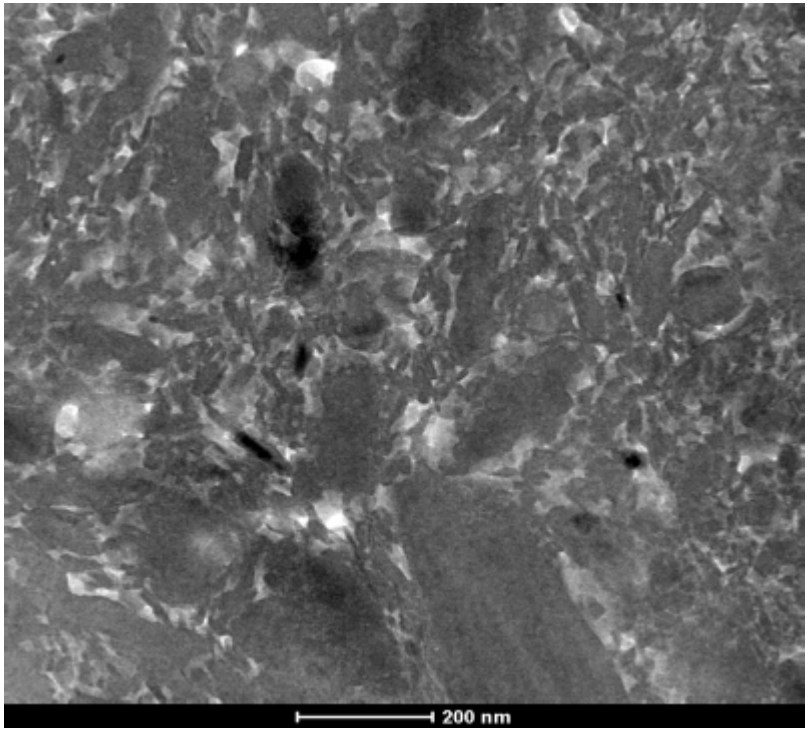


[Ferre et al., 2005]

Motivations

- Do we have magnetic record within gouge?
- To understand the mechanisms which are responsible of the magnetic overprint.

TEM



Motivations

1. To identify **1999 Chi-Chi slip zone**

2. To understand the **physical/chemical altered properties** of magnetic minerals in gouge zone during earthquake

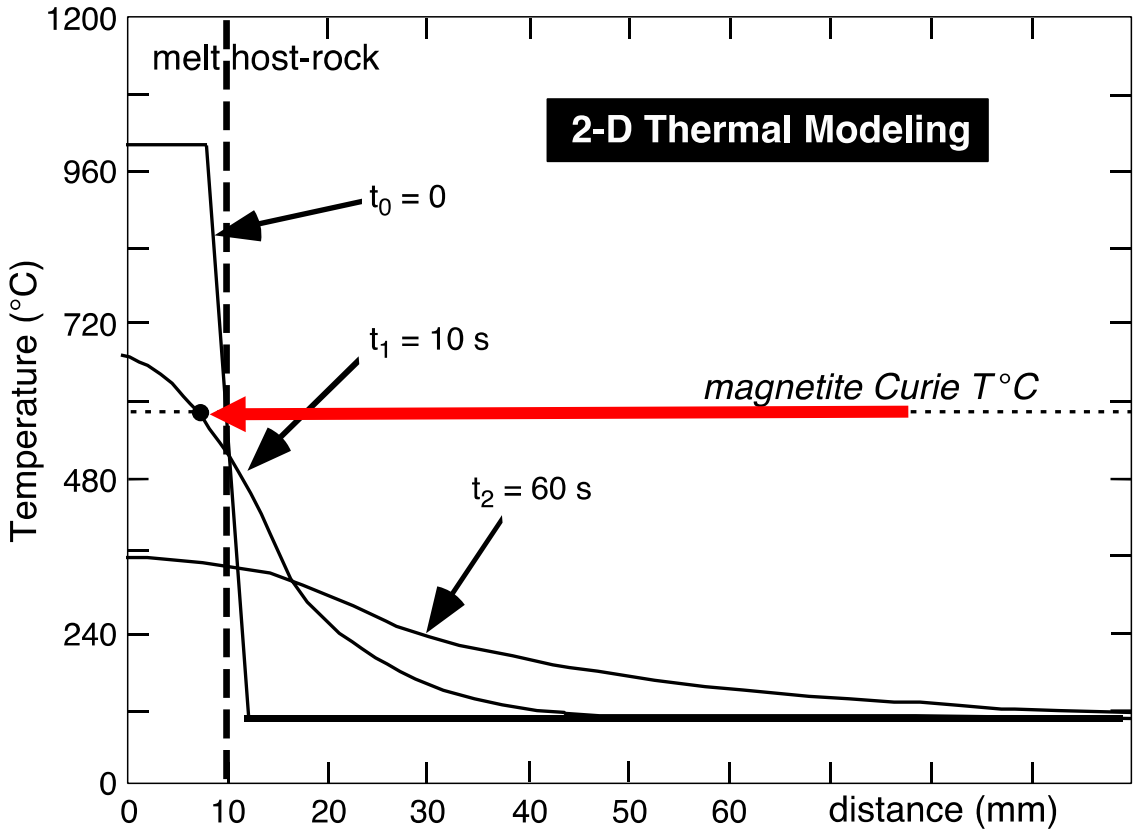
3. To **quantify concentration of magnetic minerals** within fault gouge

Part I

Which fault zone is Chi-Chi Slip Zone?

Possible Magnetization of Gouge

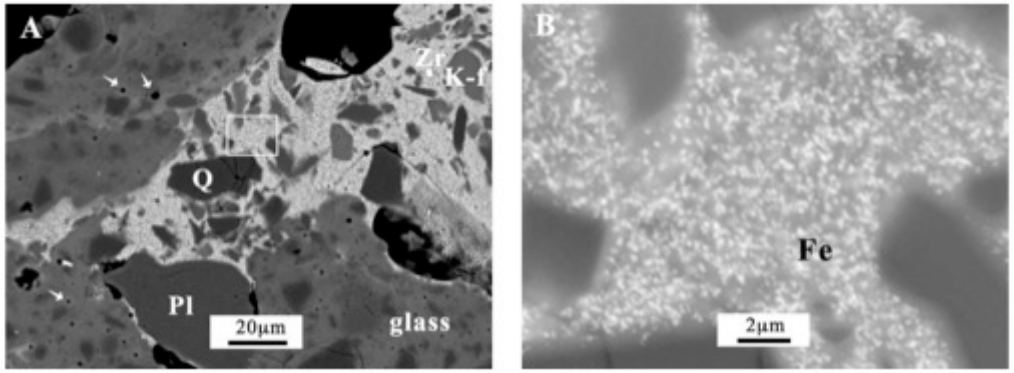
Thermo-Remanent Magnetization (TRM)



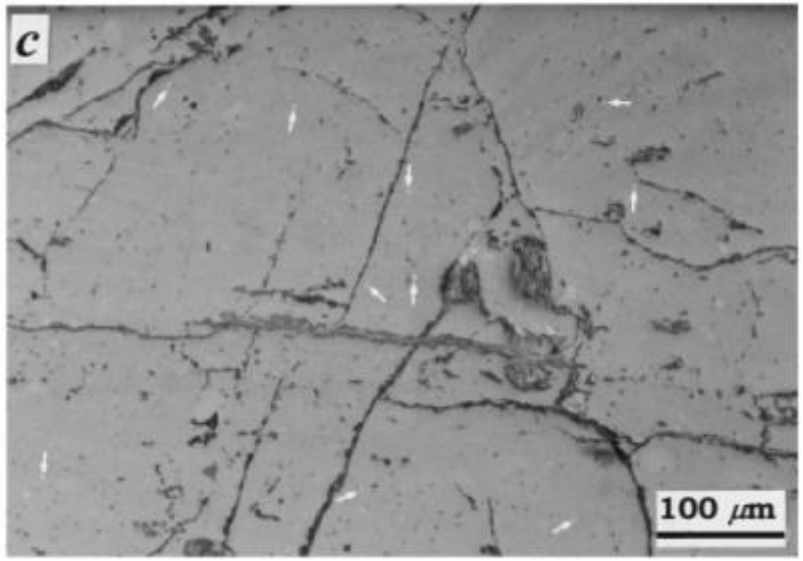
[Figure from Ferré et al., 2005]

Possible Magnetization of Gouge

Chemical Remanent Magnetization (CRM)



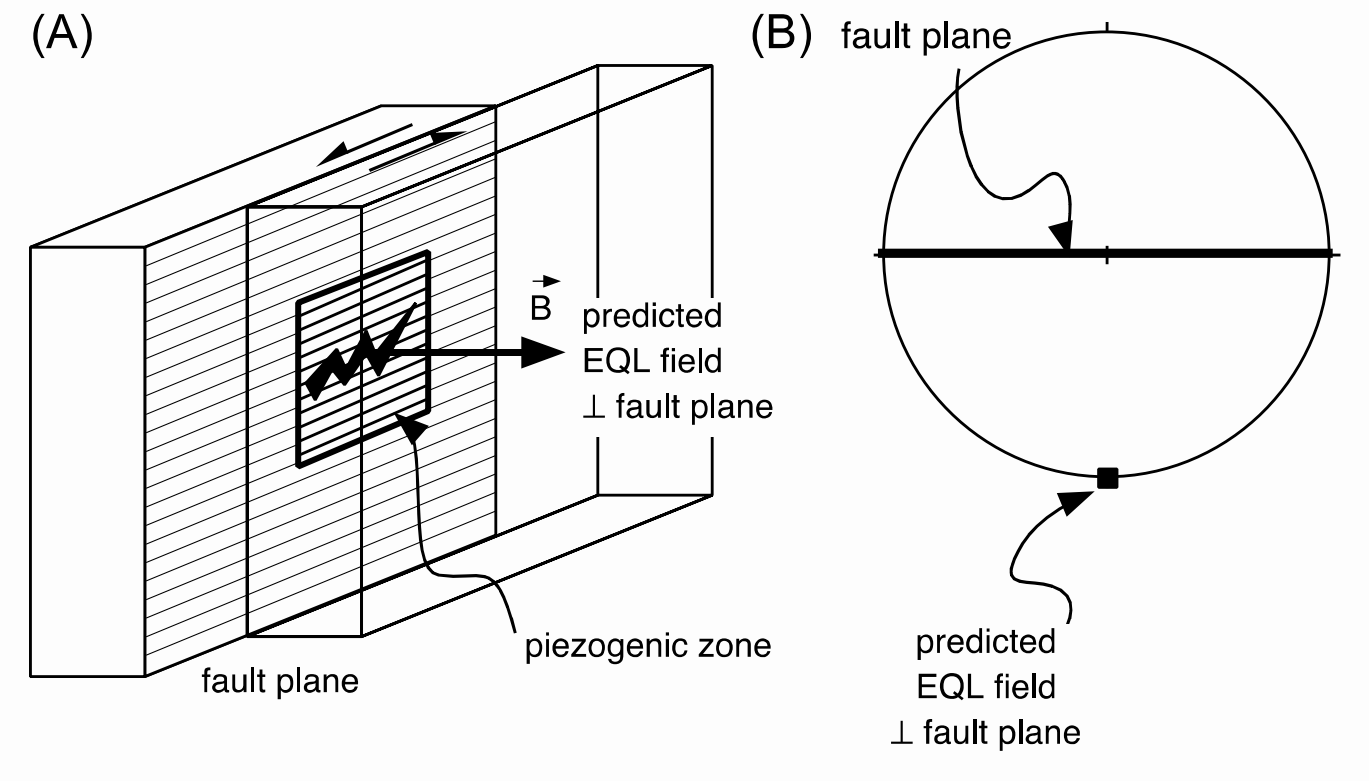
New magnetic minerals [Figure from Nakamura et al., 2002]



Goethite [Figure from Nakamura & Nagahama, 2001]

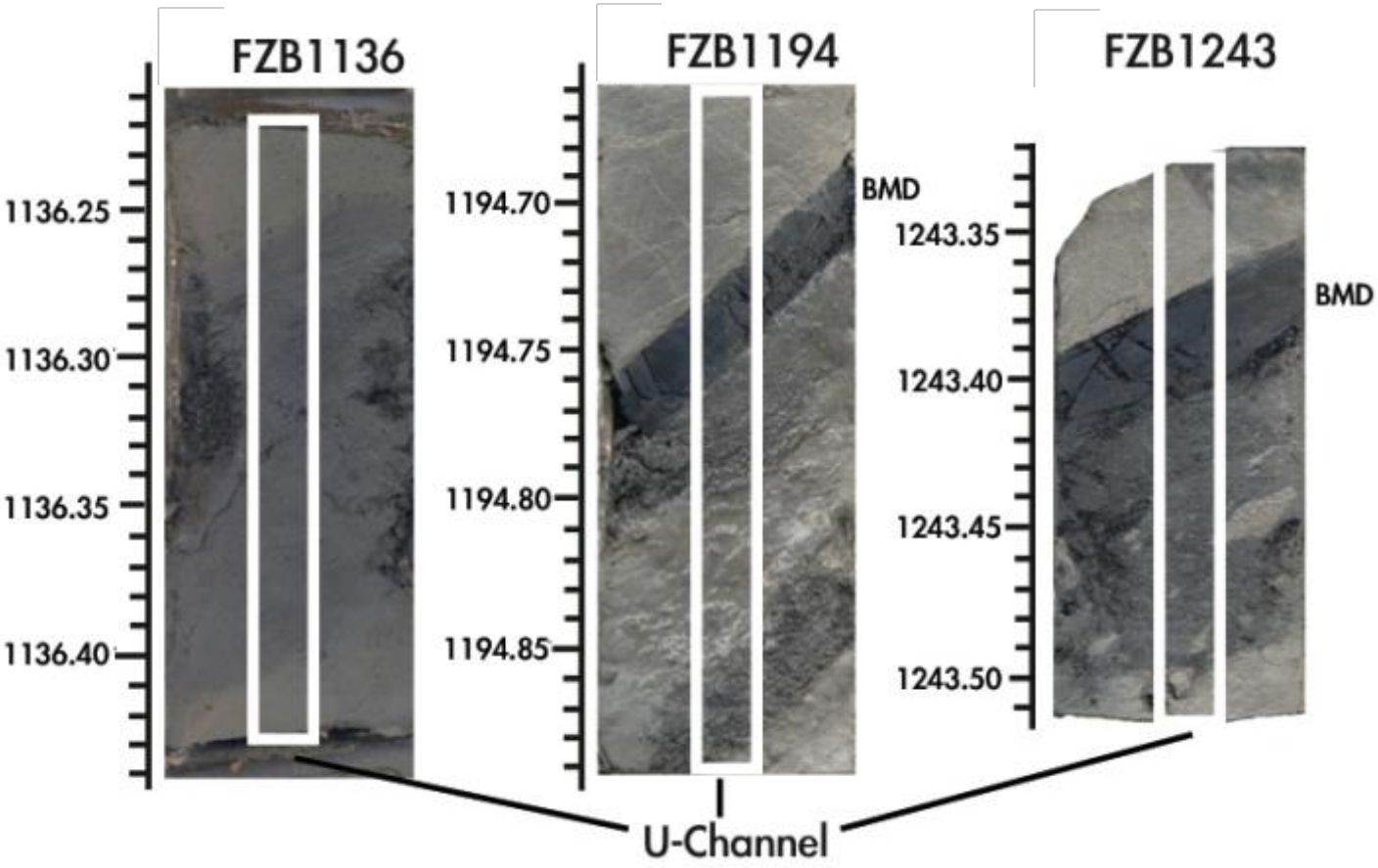
Possible Magnetization of Gouge

Earthquake Lightning (EQL)

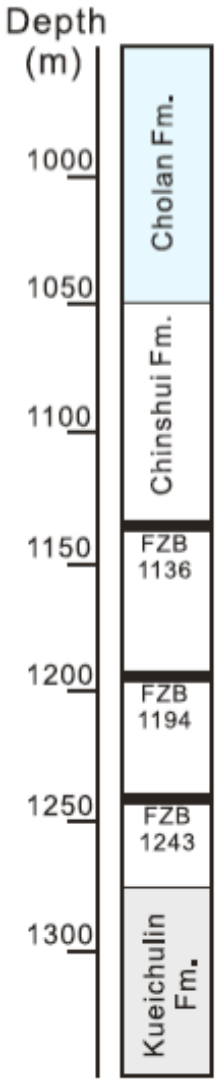


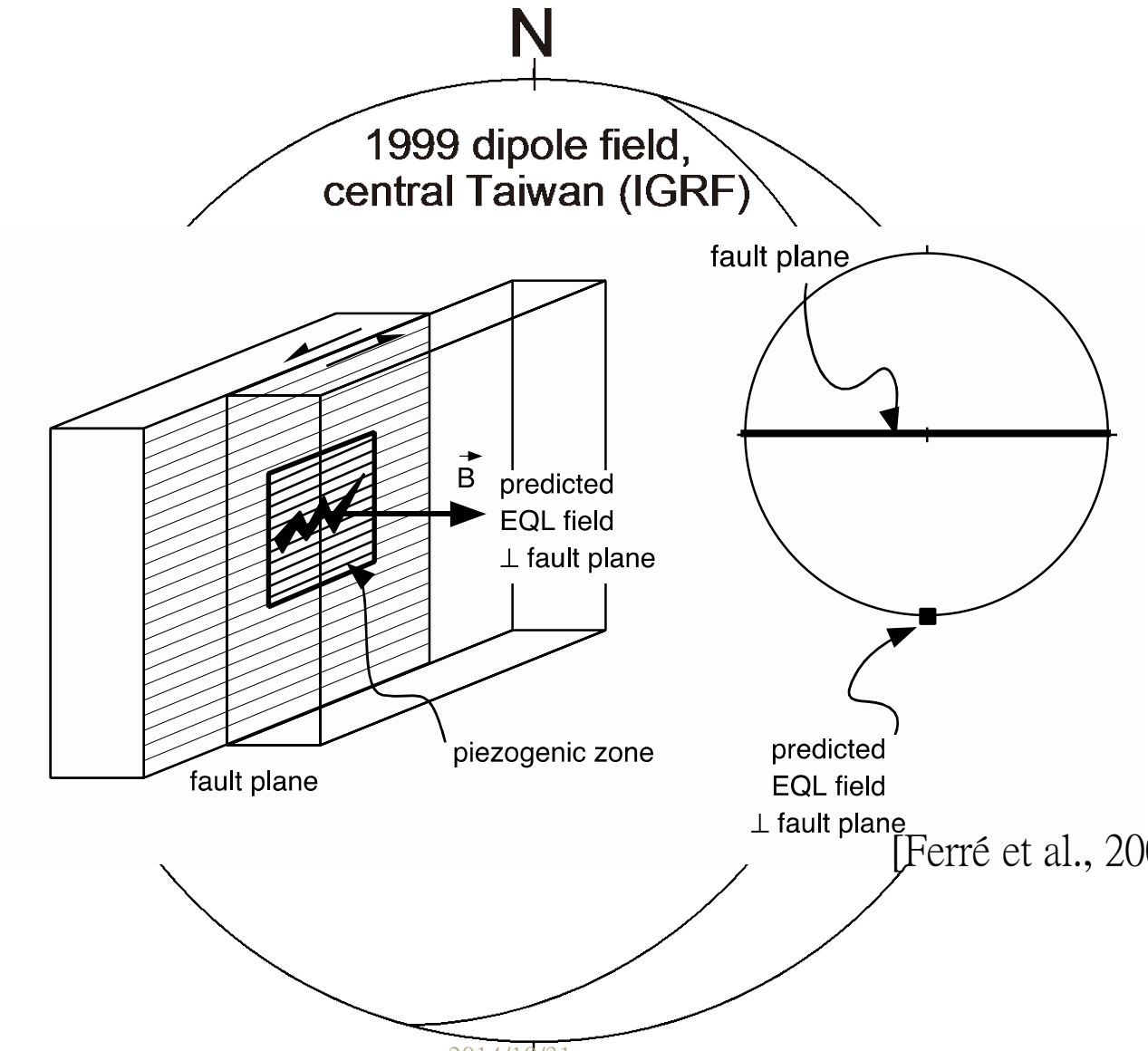
[Figure from Ferré et al., 2005]

U-Channel


FZB1136
1136.25
1136.30
1136.35
1136.40
FZB1194
1194.70
1194.75
1194.80
1194.85
BMD
FZB1243
1243.35
1243.40
1243.45
1243.50
BMD
U-Channel

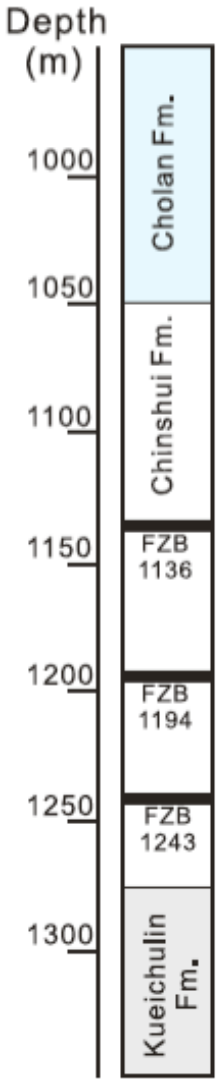
Paleomagnetic Field Direction

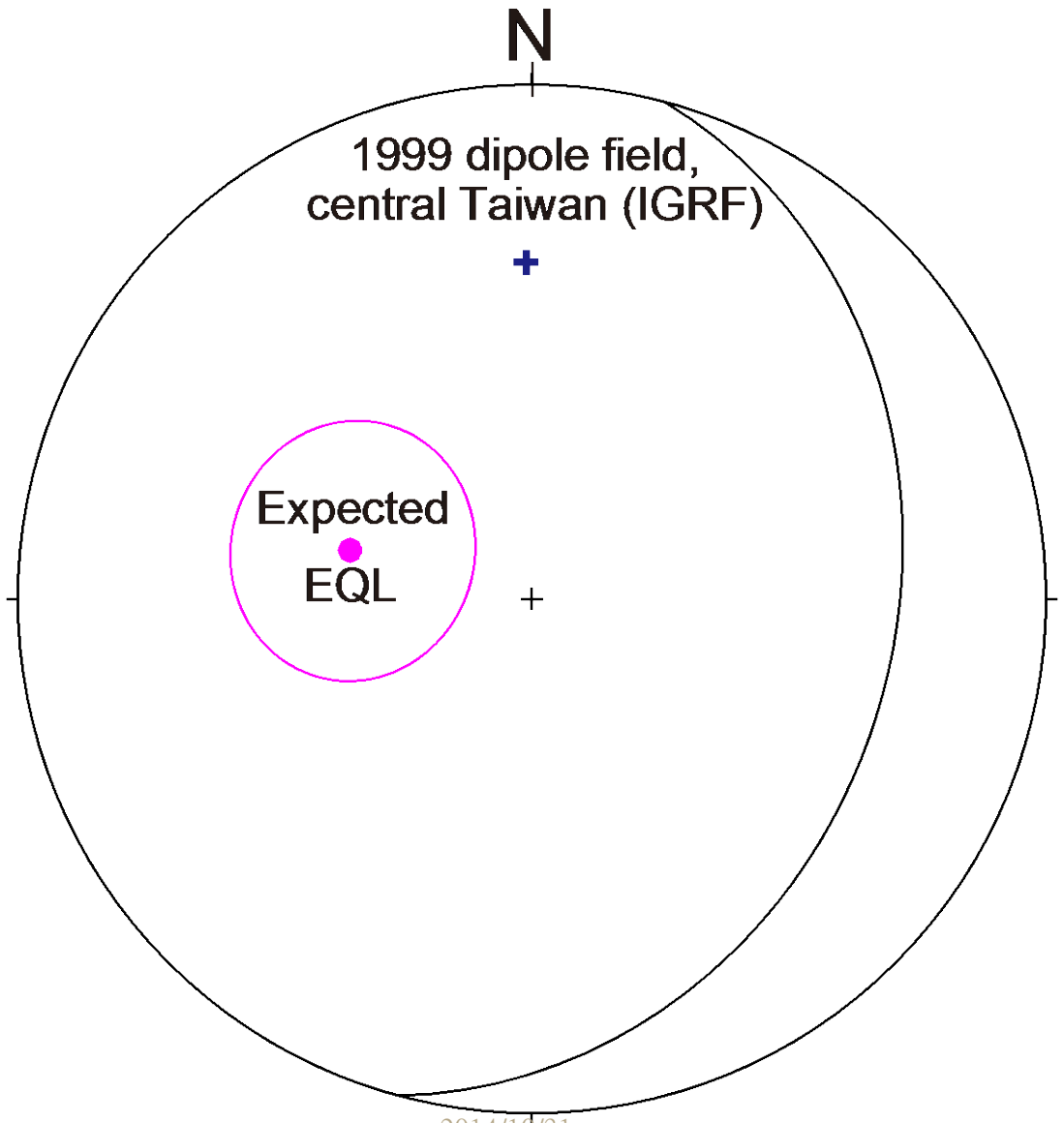




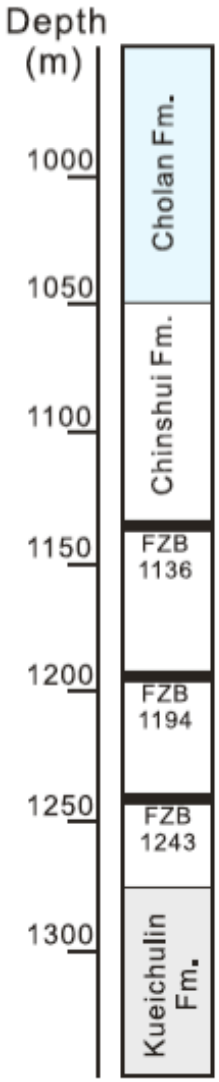
[Ferré et al., 2005]

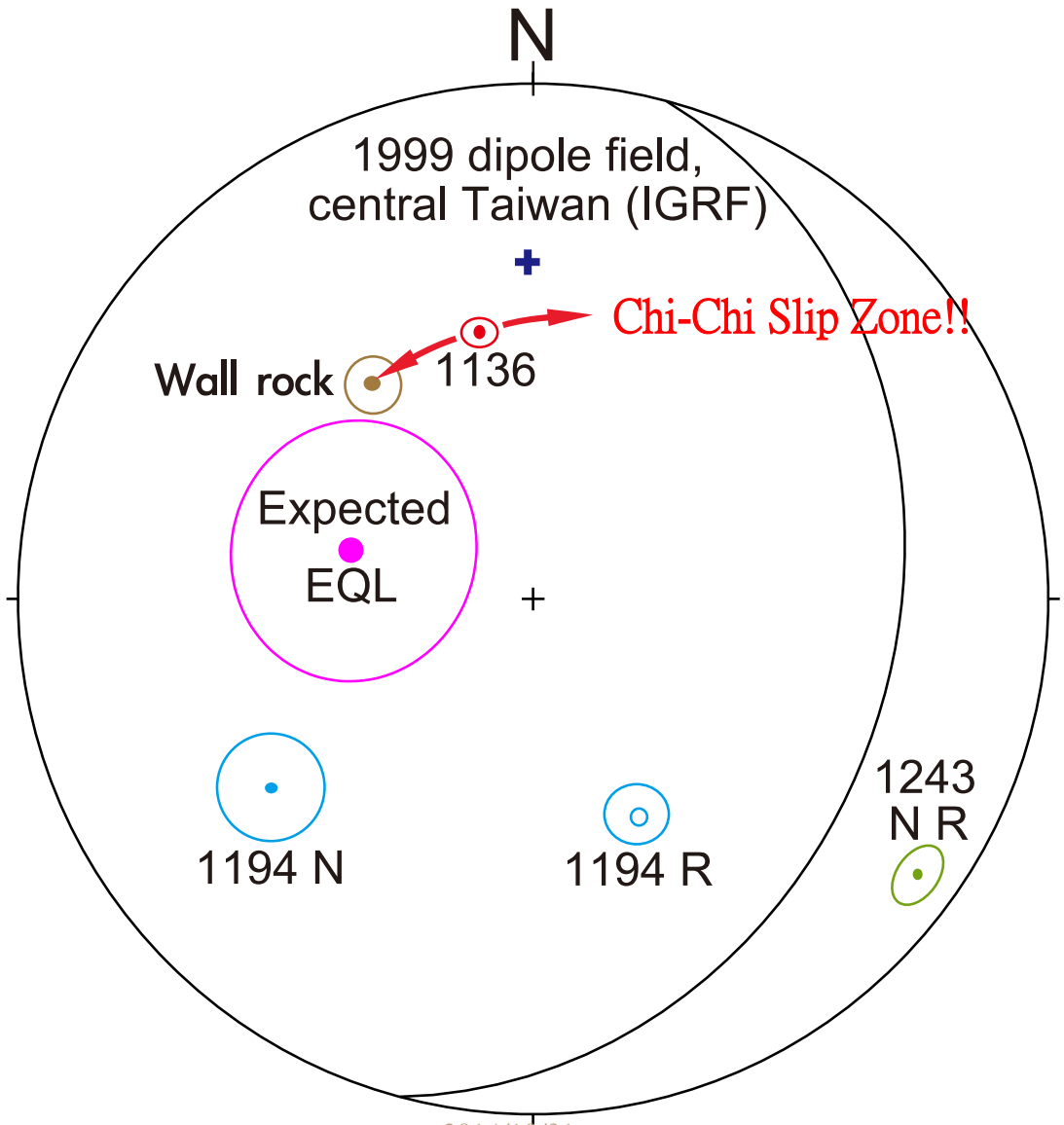
Paleomagnetic Field Direction



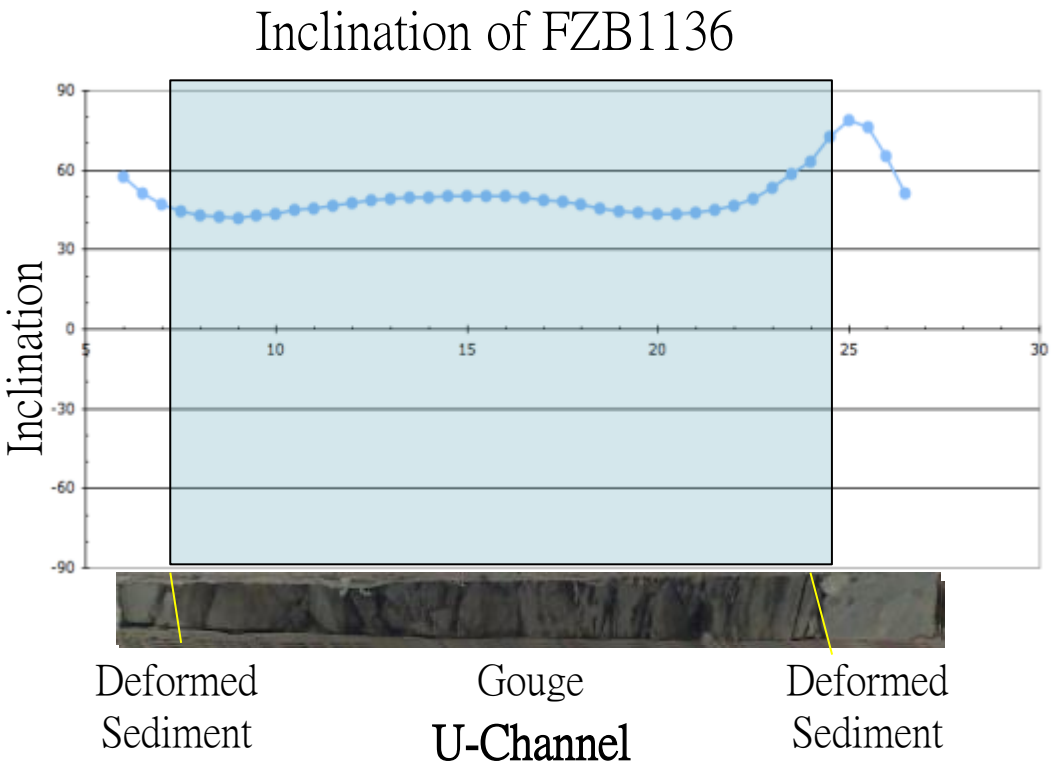


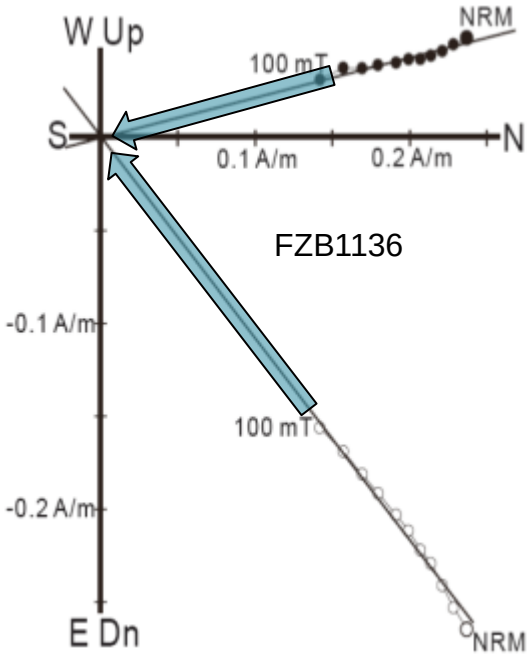
Paleomagnetic Field Direction





Paleomagnetic Result of FZB1136

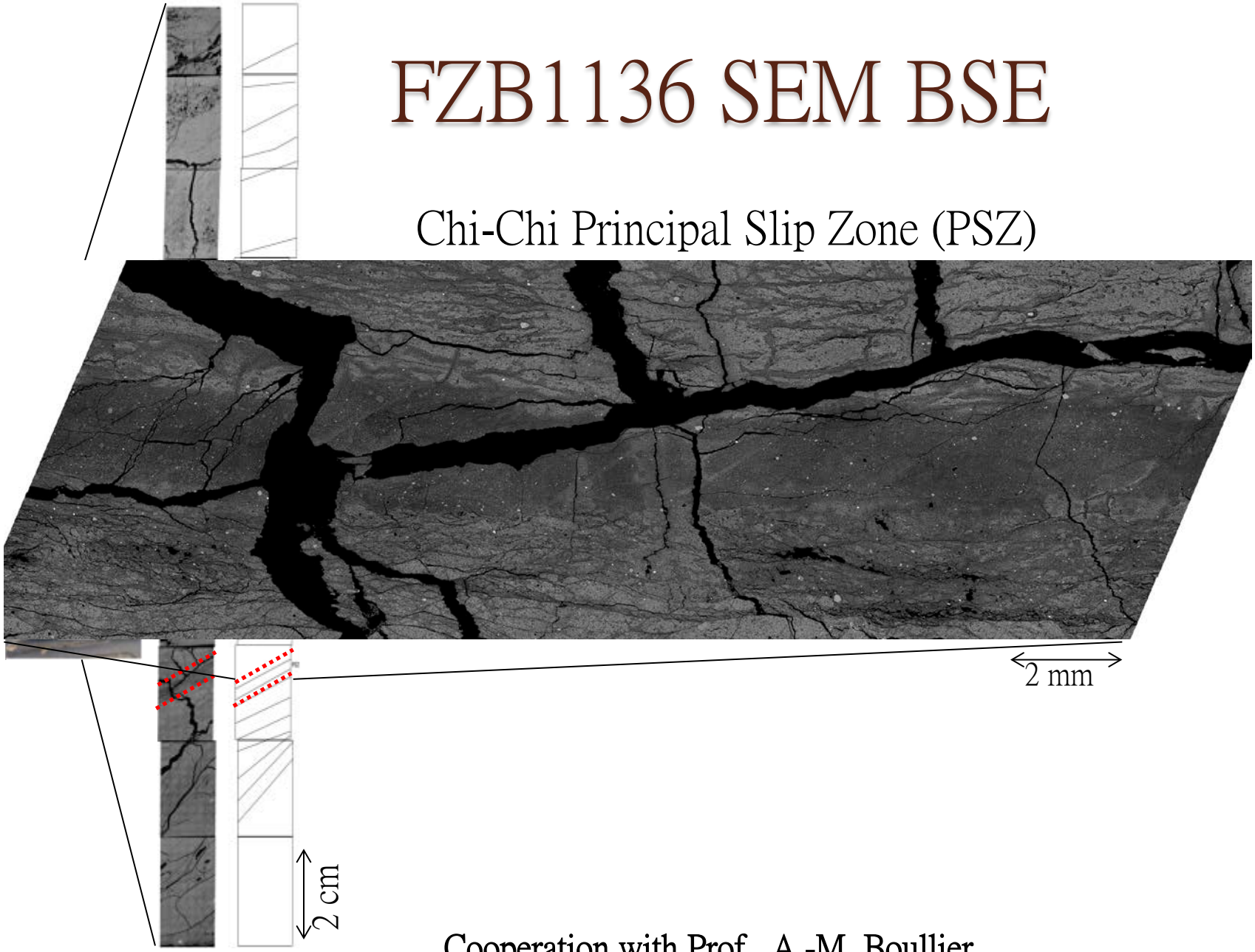




One stable magnetic record.

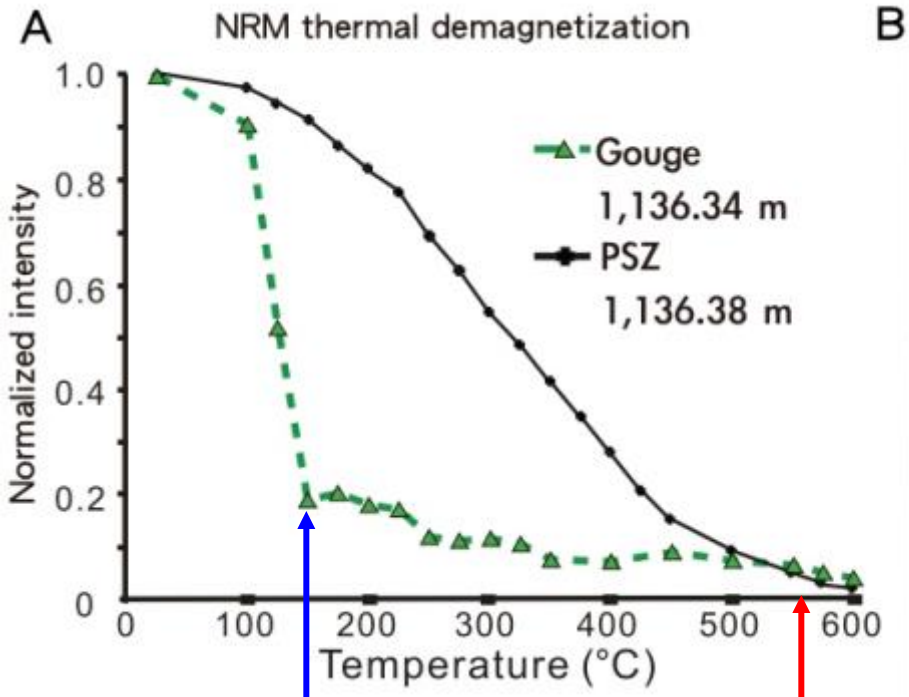
FZB1136 SEM BSE

Chi-Chi Principal Slip Zone (PSZ)



Cooperation with Prof. A.-M. Boullier

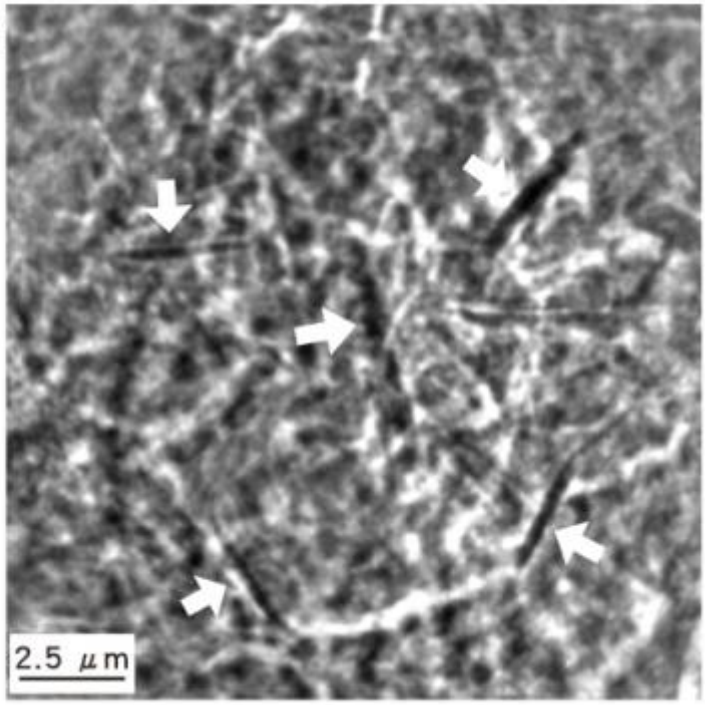
Neoformed minerals Acquire New Magnetization



T_N of Goethite 125ºC
α-FeOOH

T_C of Magnetite 575ºC
Fe_3O_4

TXM image within gouge



Goethite

Possible Magnetization of Gouge

1) a thermo-remanent magnetization (**TRM**) acquired post-seismically during cooling

O [**T>400° C**, Boullier et al., 2009]

2) a chemical remanent magnetization (**CRM**) acquired post-seismically and carried by neoformed magnetic minerals

O [**Hot fluid T>350° C**, Ishikawa et al., 2008; **Goethite**]

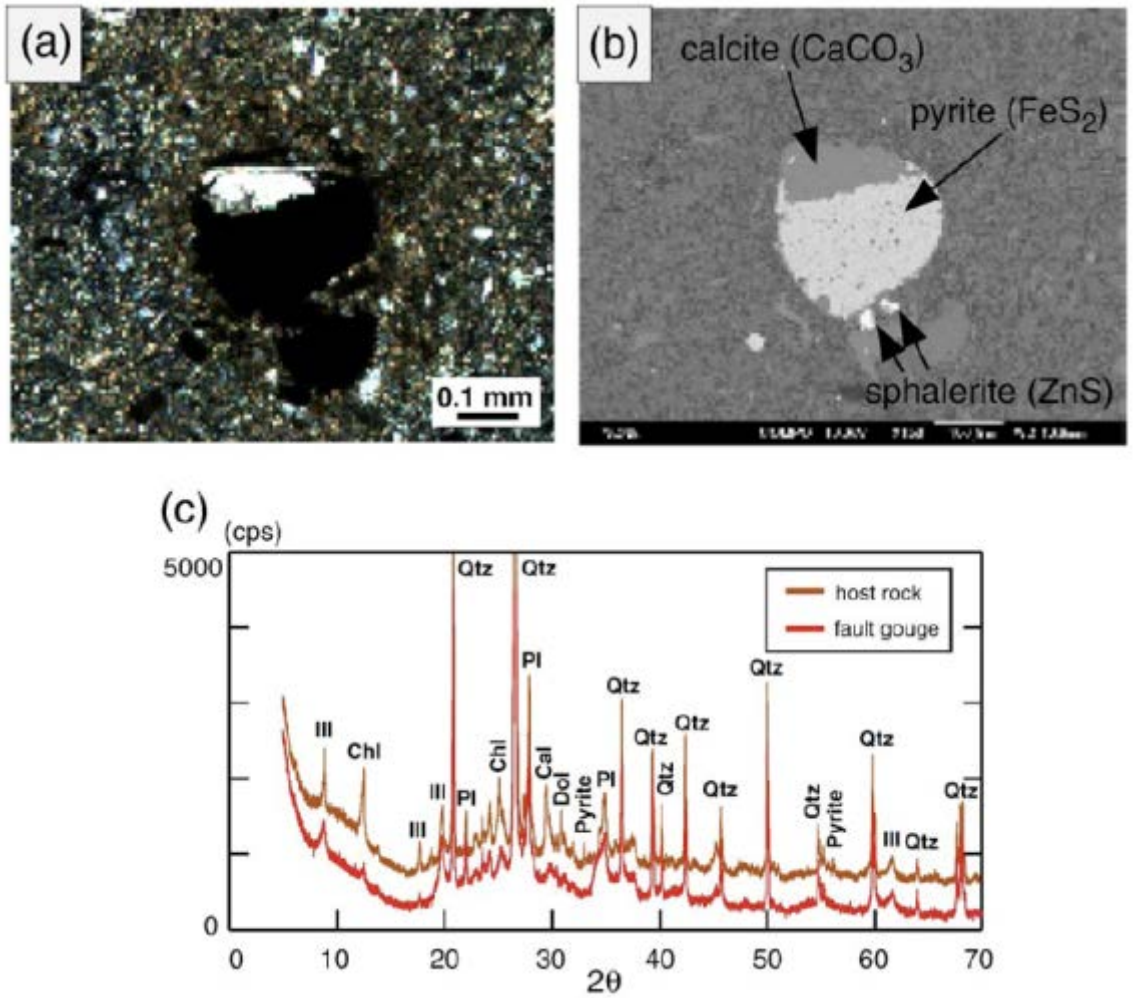
3) an isothermal remanent magnetization(IRM) acquired co-seismically during earthquake lightning (**EQL**)

X [Evidence of paelomagnetic record direction]

Part 1I

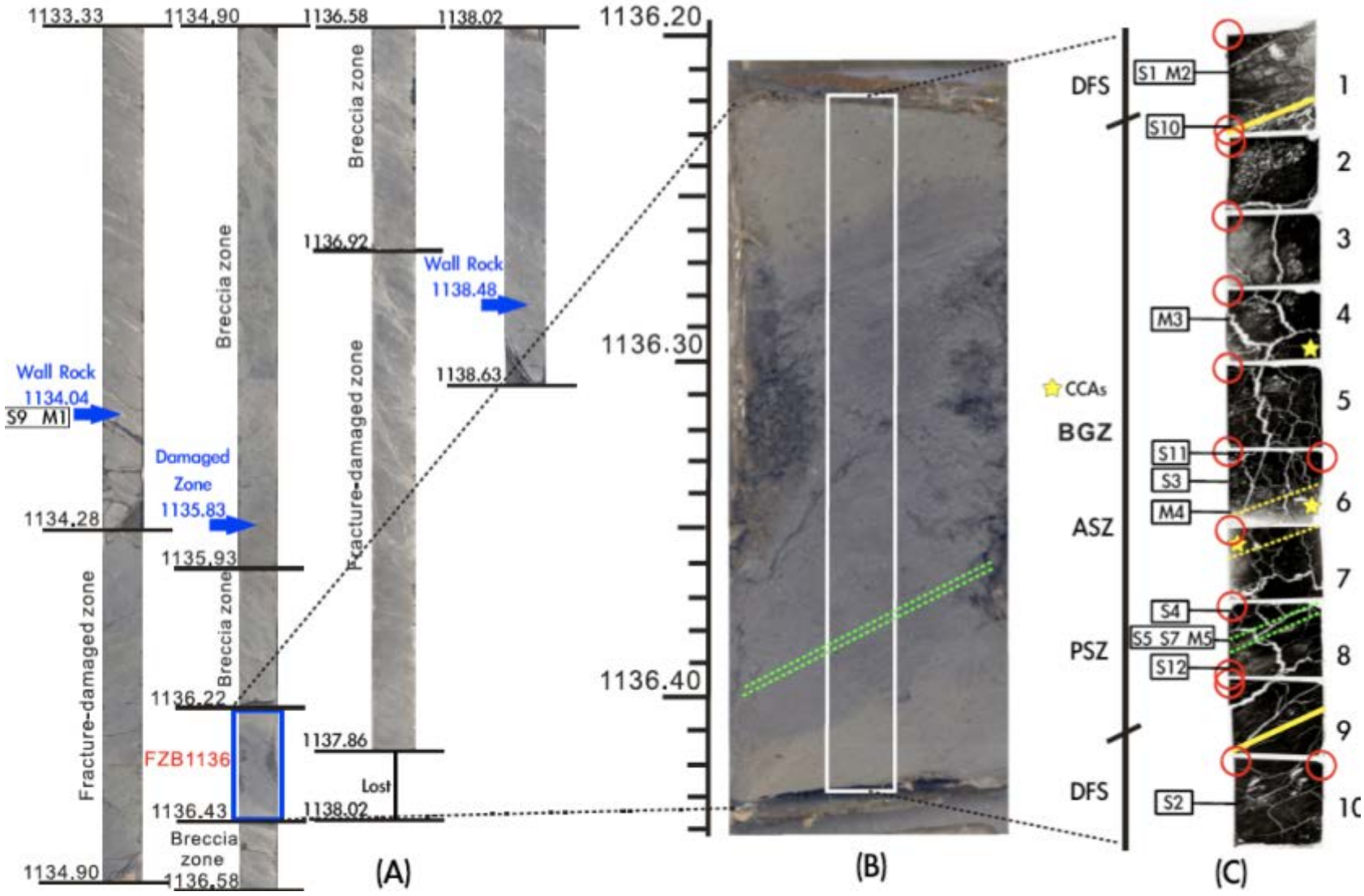
What are the magnetic carriers? Neoformed processes?

Pyrite (FeS_2) Dissolution in Gouge

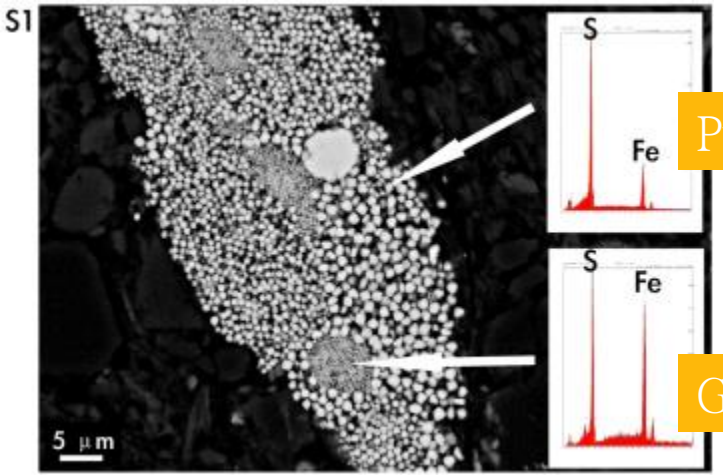


[Hirono et al., 2008]

Comprehensive Magnetic Investigation



SEM Observation

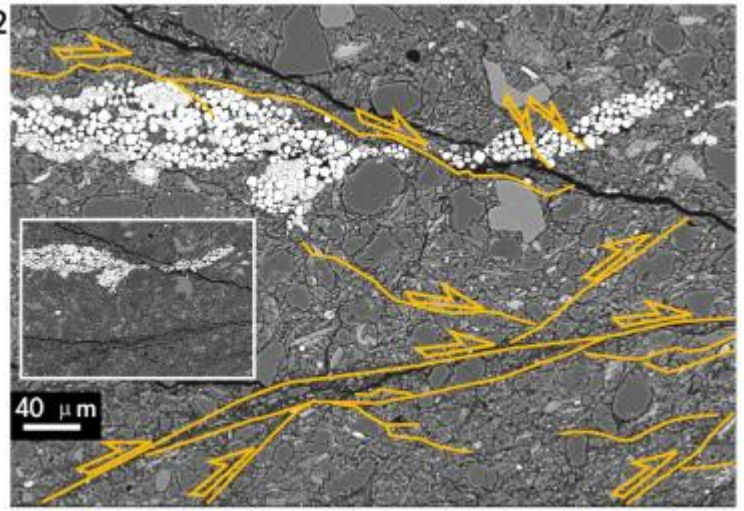


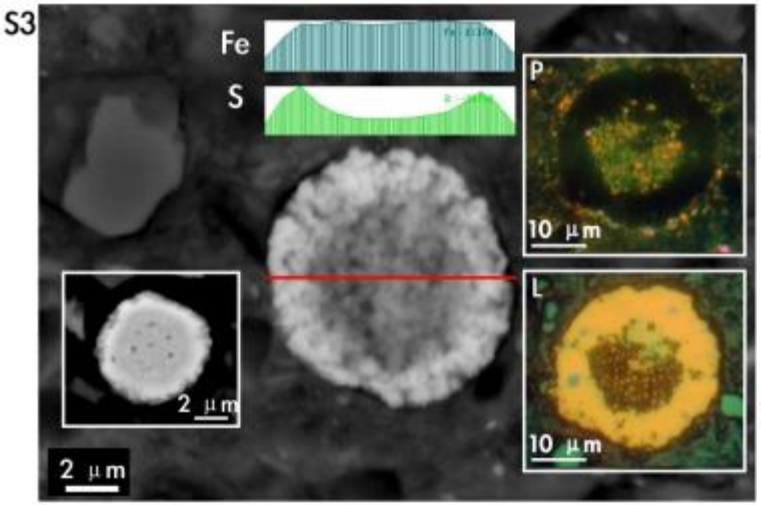
Pyrite

Greigite

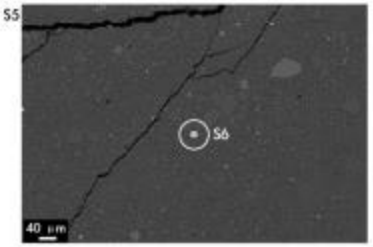
Wall Rock

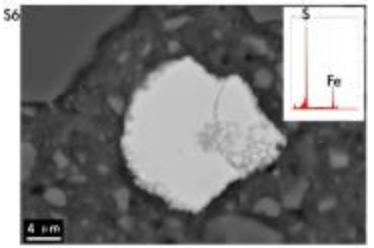
Deformed Sediment (DFS)

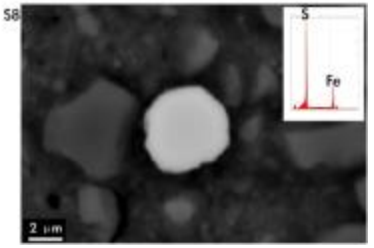


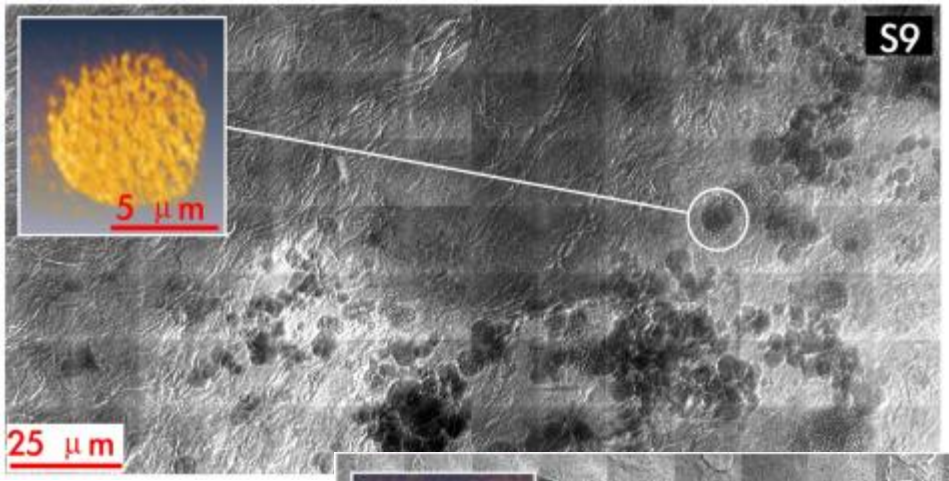


Gouge



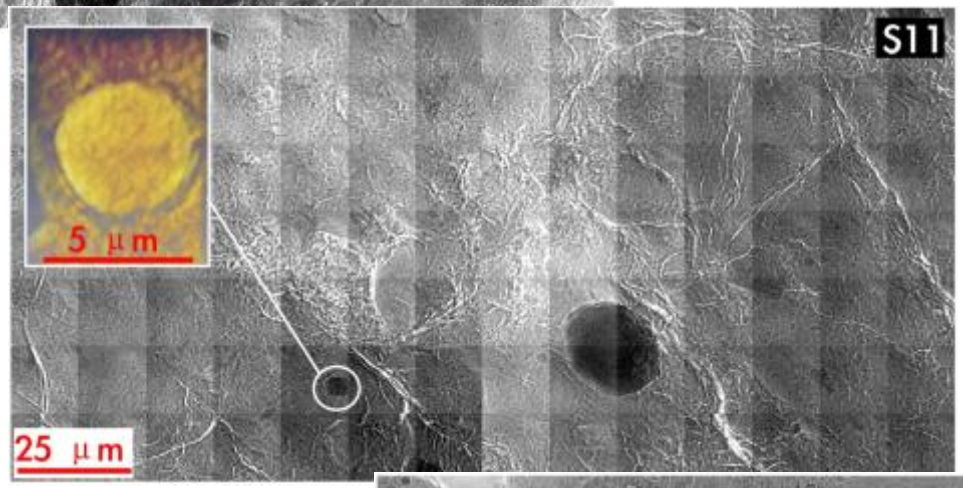




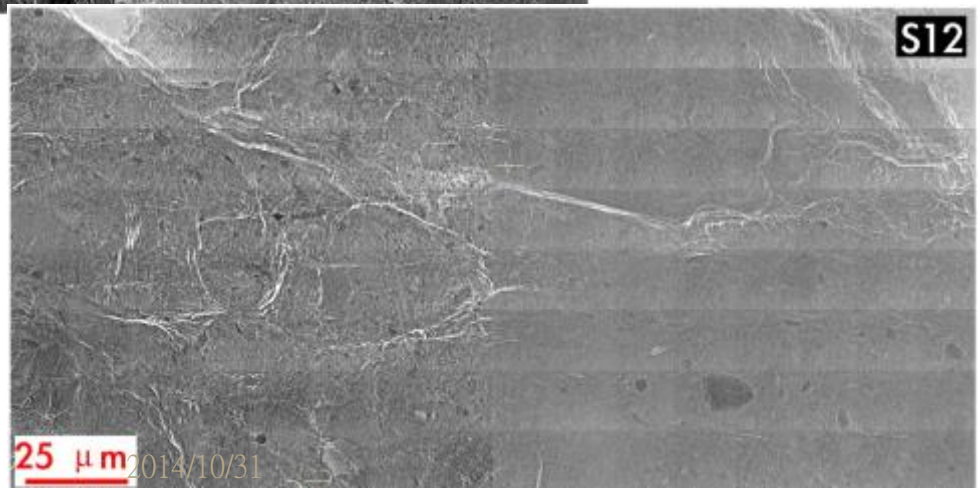


Wall Rock

Deformed Sediment (DFS)



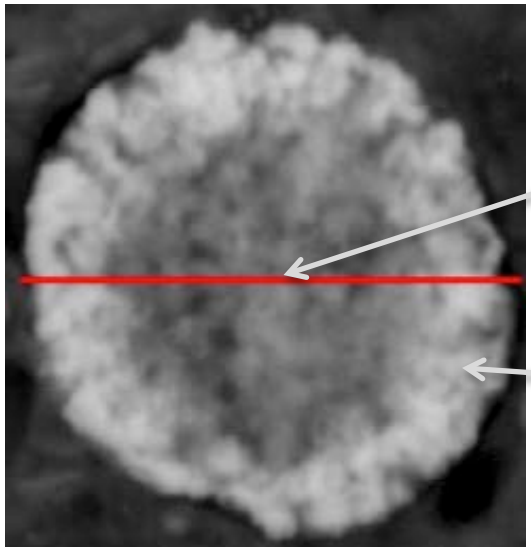
Gouge



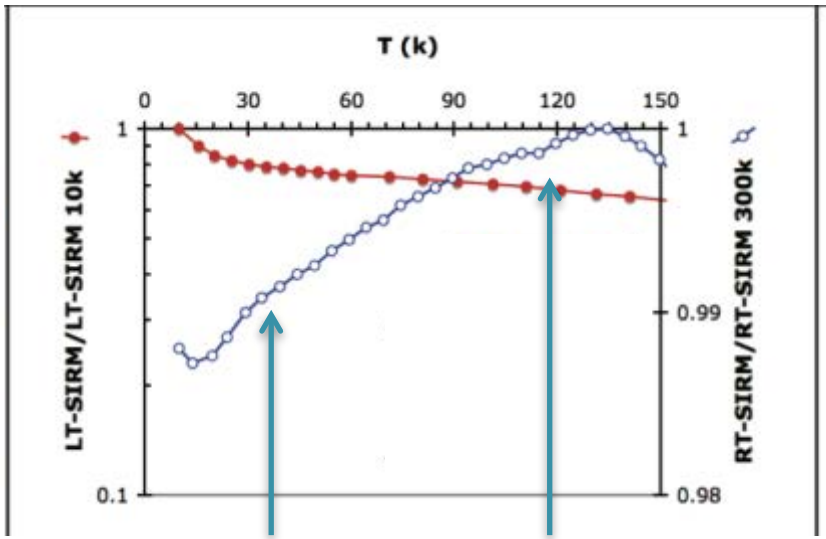
PSZ

TXM Observation

Identification of Pyrrhotite

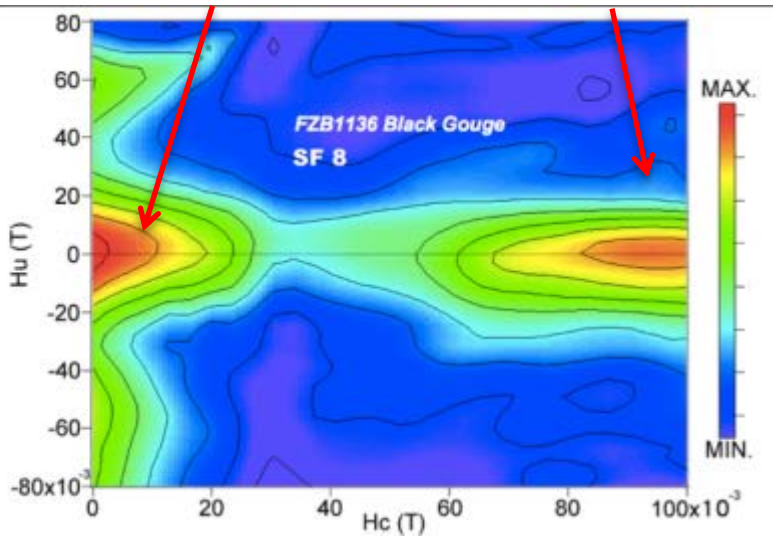


Black Gouge (M3)



Magnetite

Pyrrhotite



Pyrrhotite

Magnetite

Iron Sulphides Evolution

	Mineral
Wall Rock & DFS	Pyrite (framboids) Gregite Magnetite
Gouge & PSZ	Pyrite Pyrrhotite Partially Oxidized Magnetite Goethite

Pyrite Thermal Decomposition

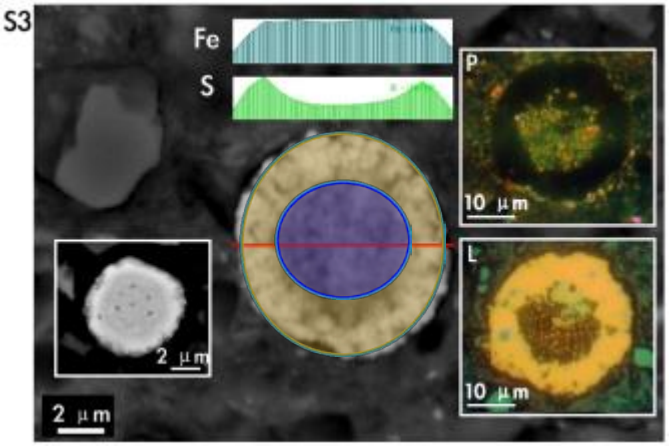
Heating

Pyrite → Pyrrhotite

>500°C

$$FeS_2 \rightarrow Fe_{1-x}S + \frac{1}{2}S_2$$

[Mayoral et al., 2002]



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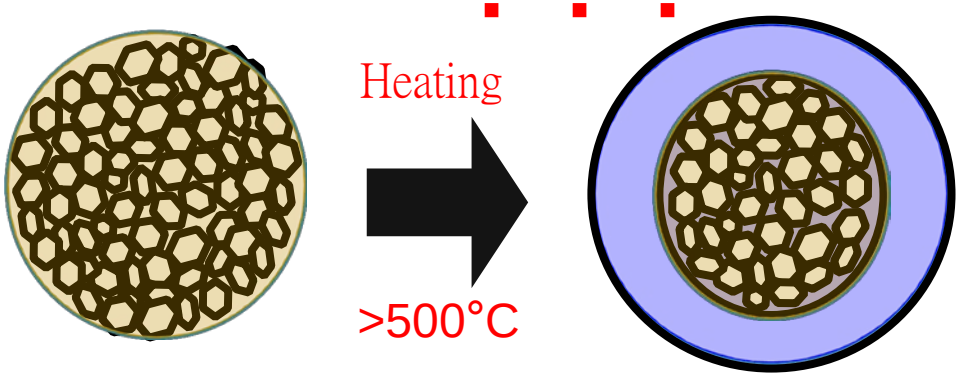
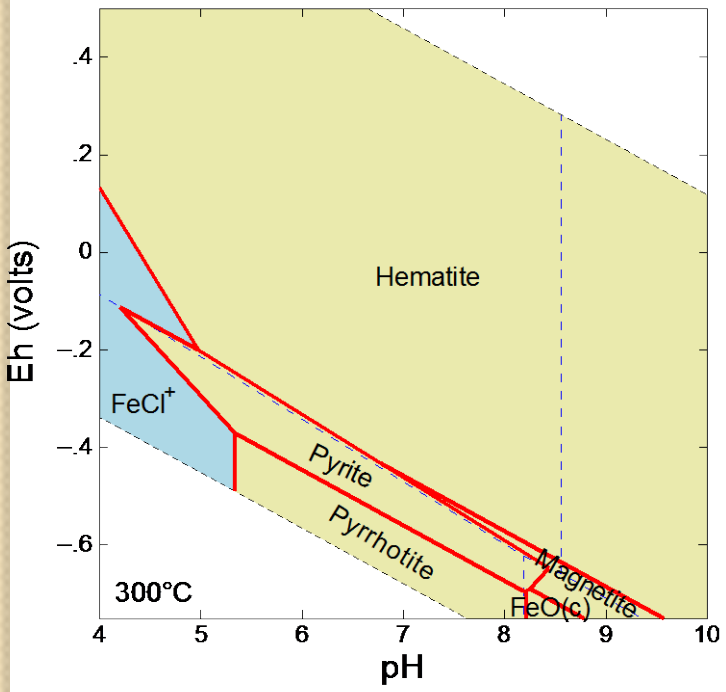
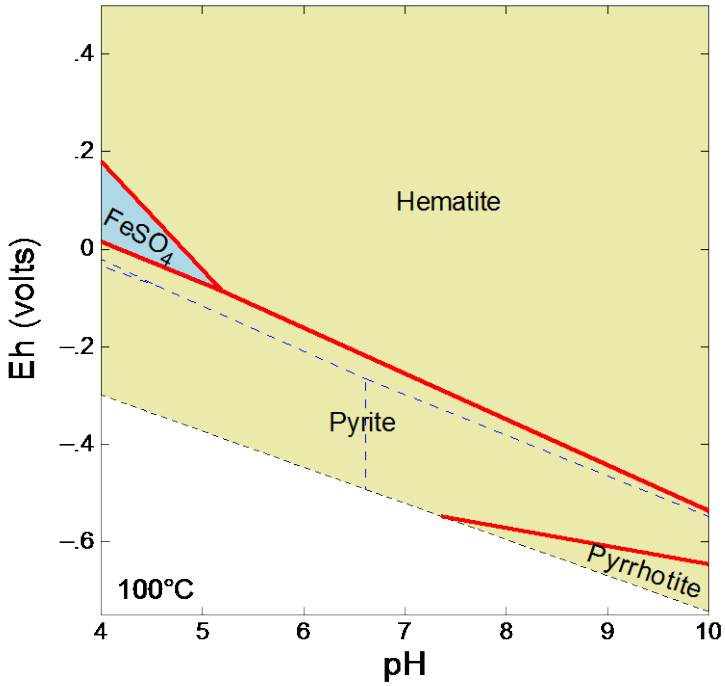


Eh-pH diagram Model 33MPa High Fe^{2+}

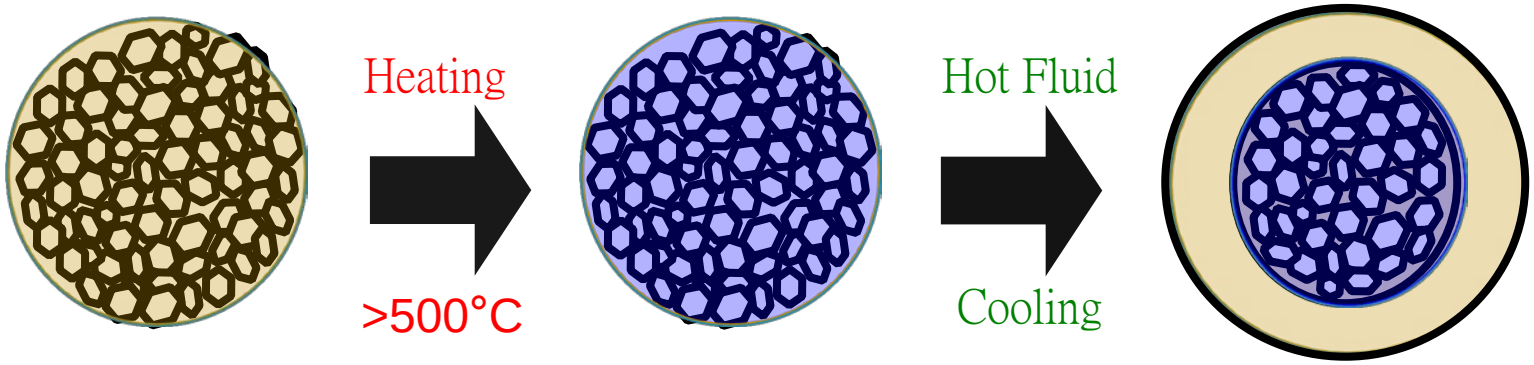


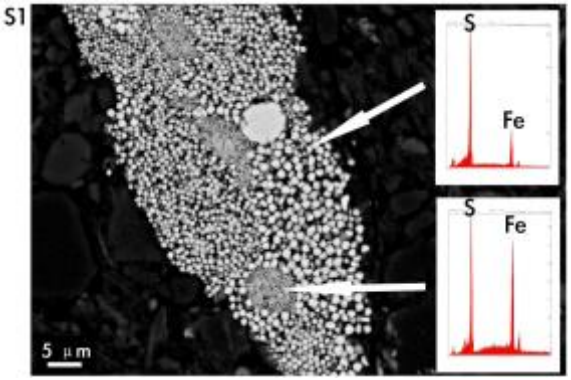


Pyrrhotite

Hot Fluid Cooling

Pyrite



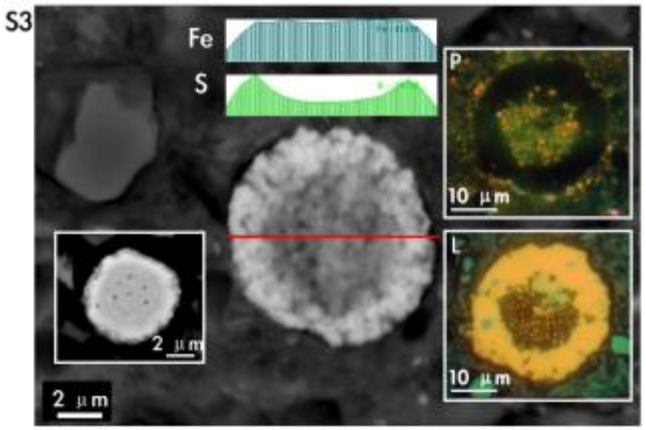


Pyrite

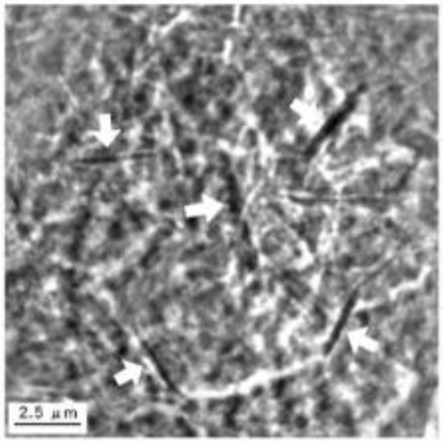
>500ºC frictional heating

Pyrrhotite

>350ºC Hot fluid cooling



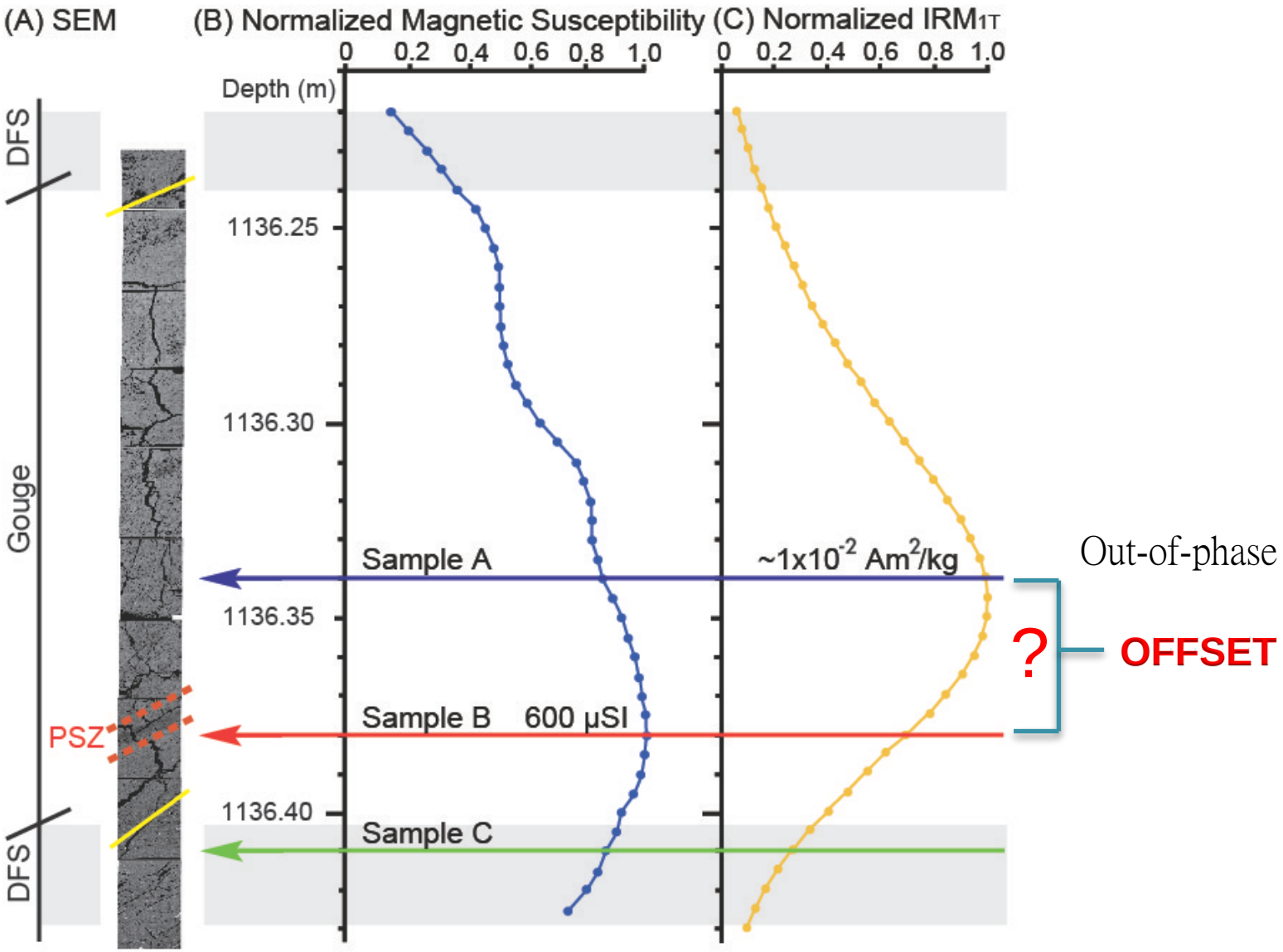
Pyrite/Pyrrhotite
+
Goethite



Part III

Quantify concentration of magnetic minerals within fault gouge

Magnetic Parameters



Offset: Two Hypothesis

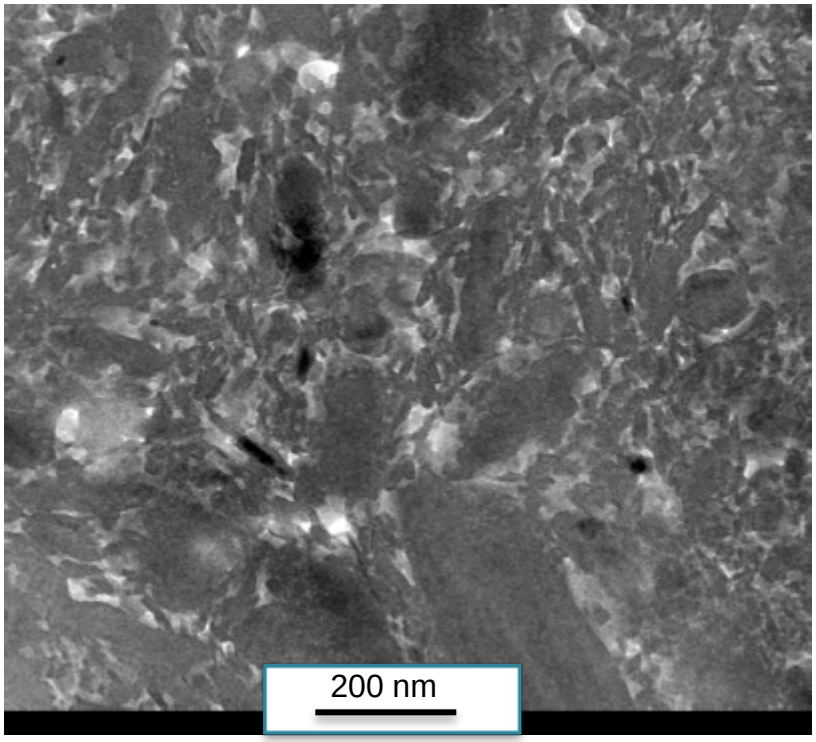
1) Due to Grain Size of Magnetic Mineral?

Grain size reduction

2)Due to different Magnetic Mineral Assemblages?

Neoformed magnetic minerals

1) Due to Grain Size of Magnetic Mineral?



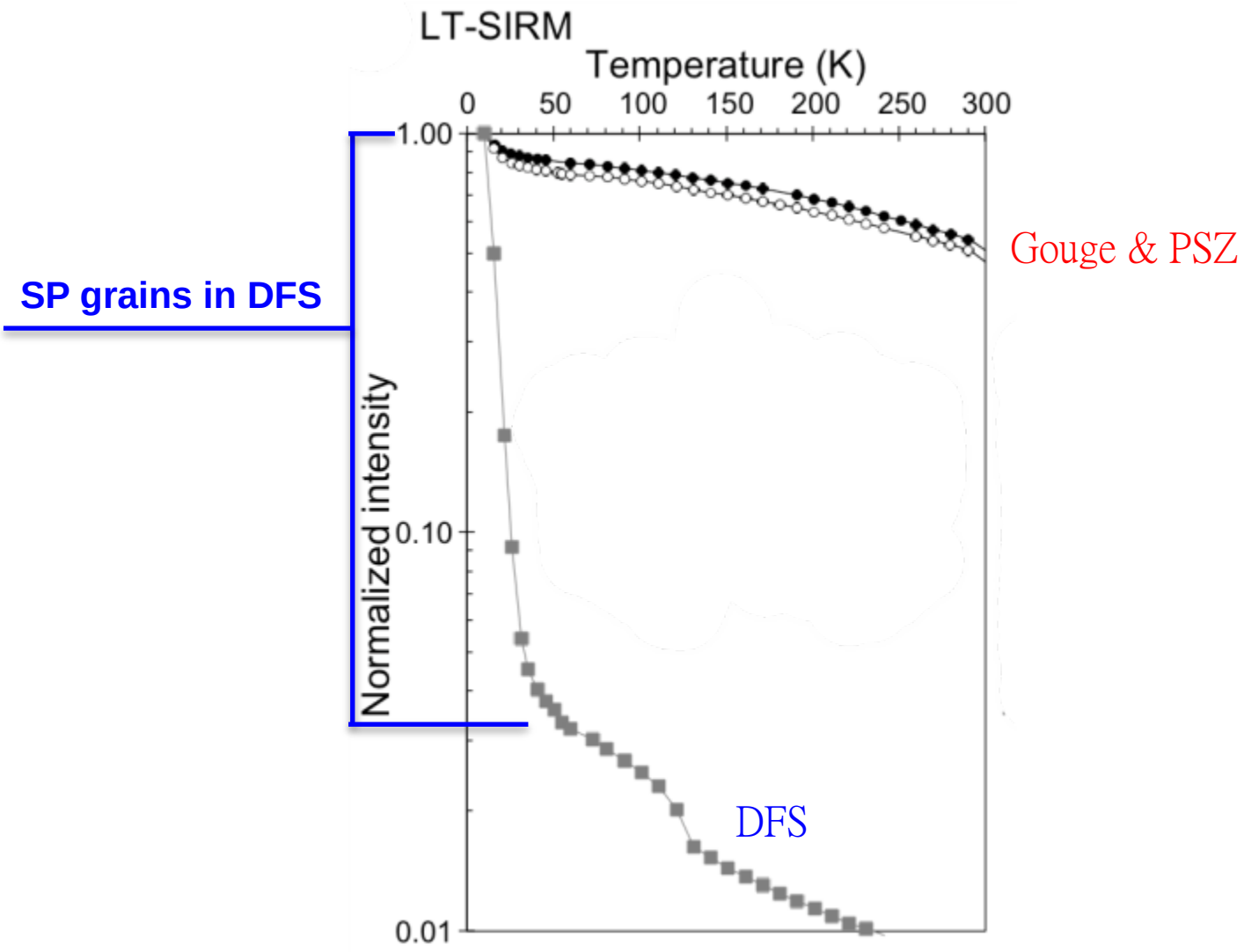
TEM Image of PSZ

Superparamagnetic Grain (SP)

(e.g. Magnetite <30 nm)

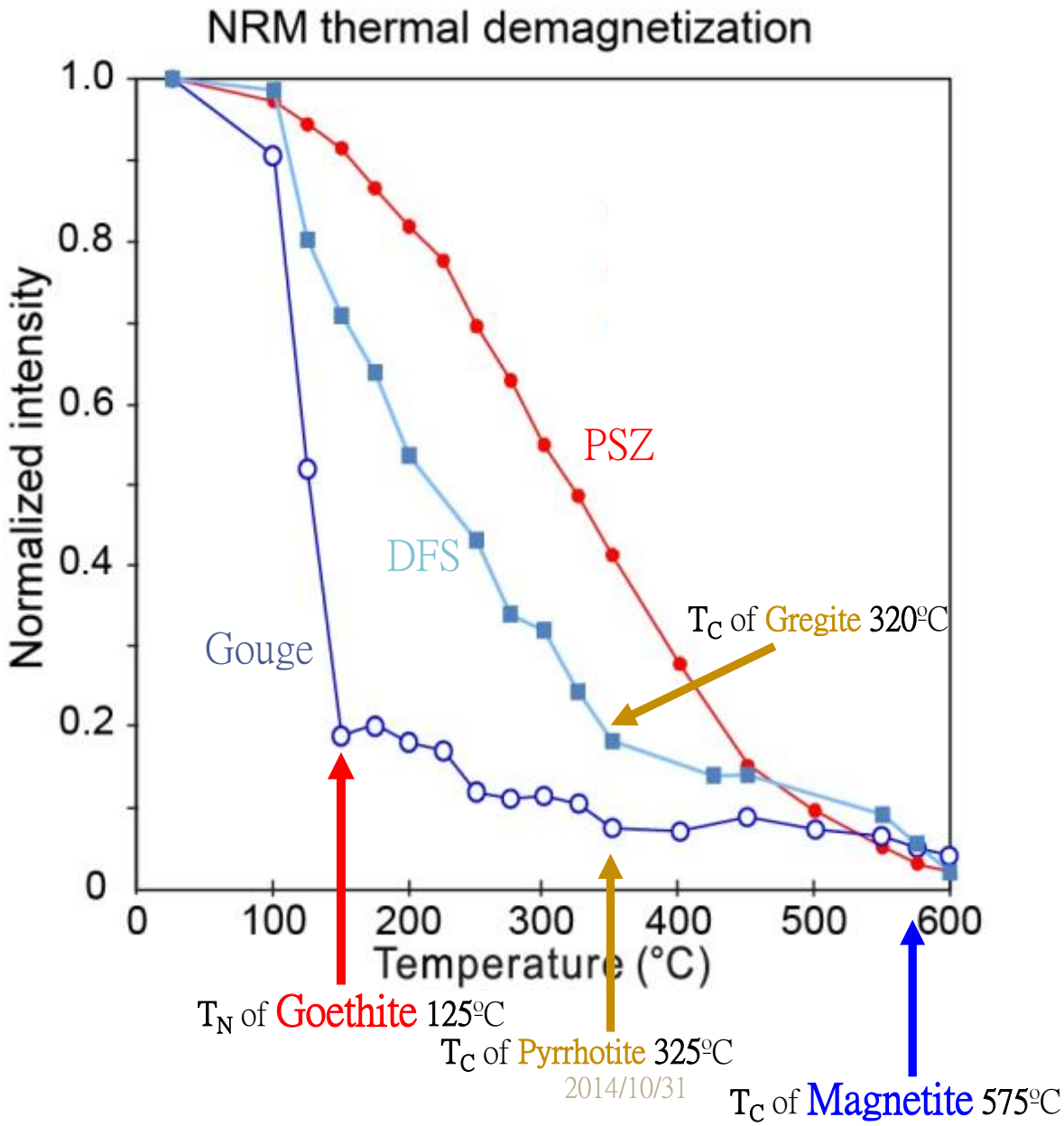
Magnetic Susceptibility – **YES**
Remanent Magnetization – **NO**

1) Due to Grain Size of Magnetic Mineral?



There is no nano-sized magnetite in gouge

2) Due to different Magnetic Mineral Assemblages?



2) Due to different Magnetic Mineral Assemblages?

	Magnetic Minerals
Wall Rock & DFS	Paramagnetic clays (Greigite) Nano-sized Magnetite
Gouge & PSZ	Paramagnetic clays Pyrrhotite Partially Oxidized Magnetite Goethite

Greigite & Pyrrhotite contribute <10% of remanent magnetization

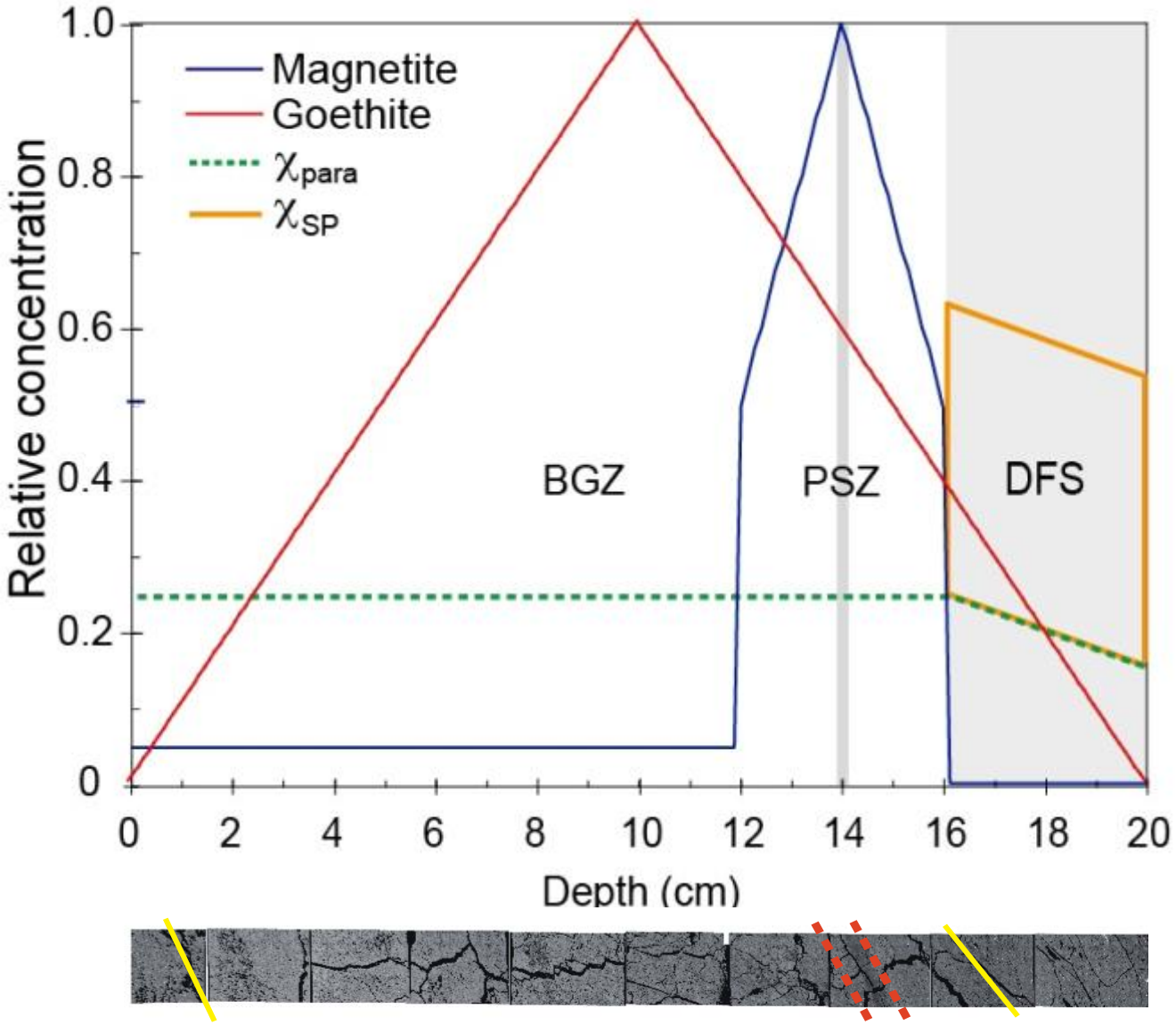
Magnetite v.s Goethite

Two magnetic minerals of contrasted properties

	Ferrimagnetic	Anti-Ferromagnetic
	Magnetite	Goethite
Saturated Remanence (SIRM, Am^2/kg)	9	0.05
Specific Susceptibility (χ, $10^{-6}m^3/kg$)	560	0.7
χ /SIRM	~62	~14

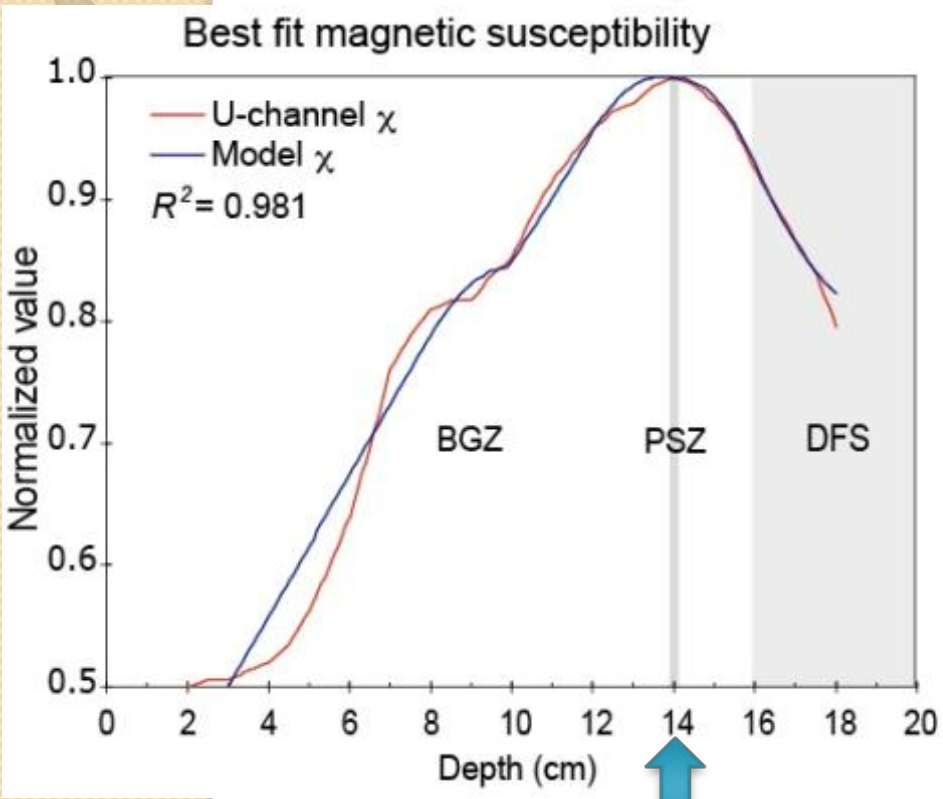
[Maher et al., 1999]

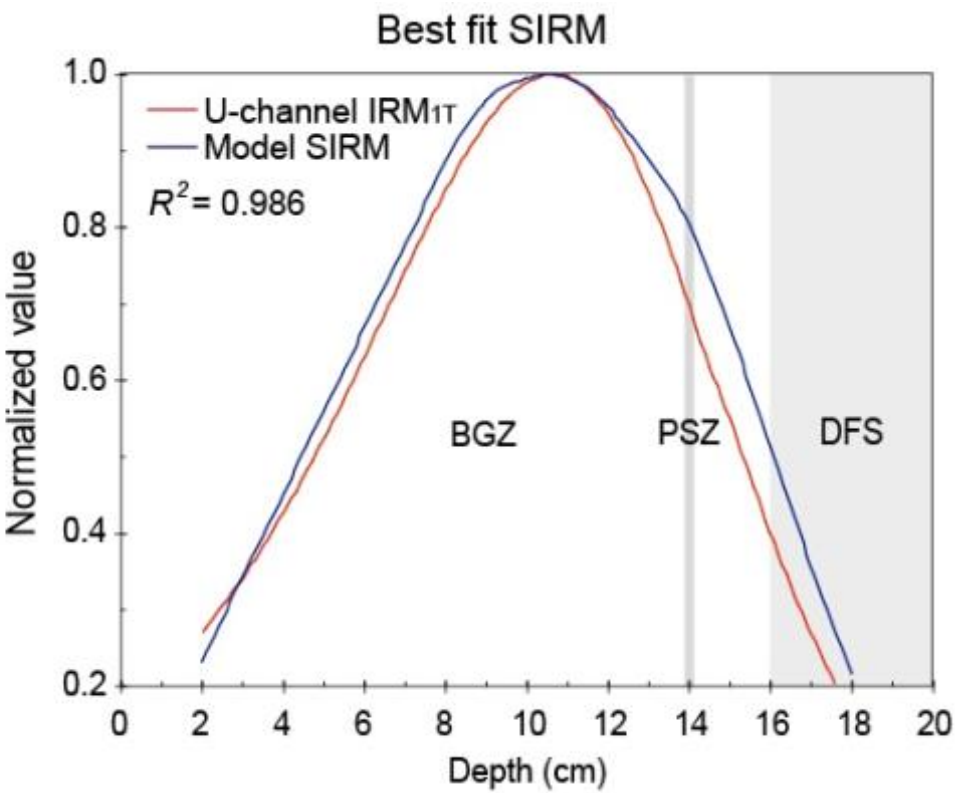
Magnetic Mineral Assemblage Model



Magnetic Mineral Assemblage Model

Why do we only see the Chi-Chi event?





High magnetic susceptibility An index of last PSZ within gouge

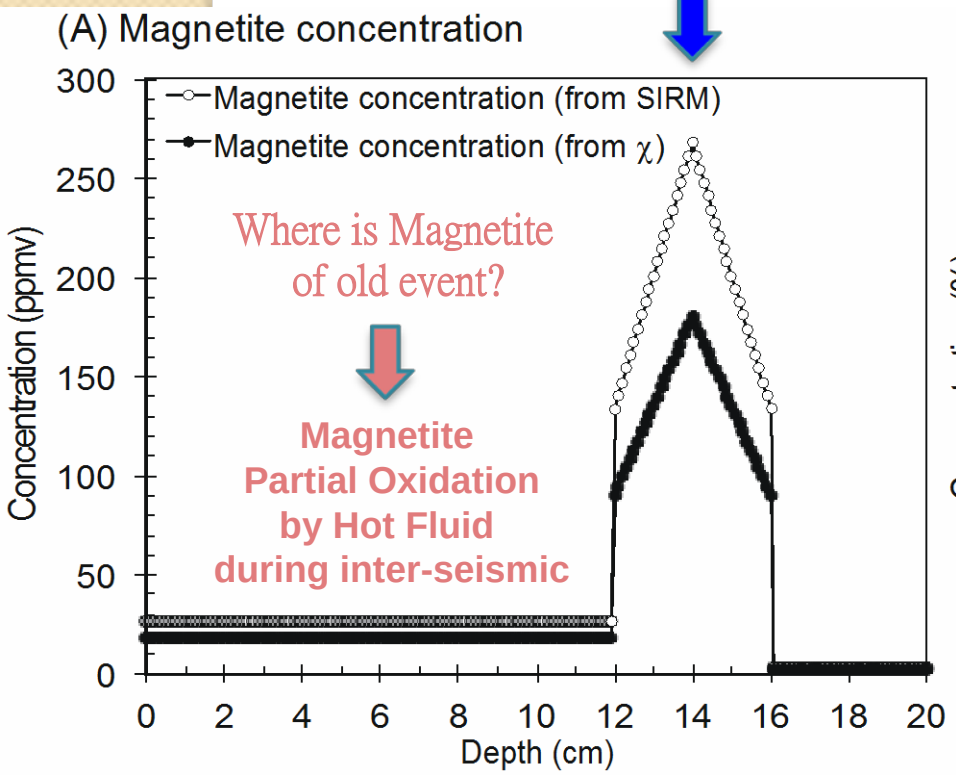
The peak **Magnetite** concentration is **150~300 ppmv**
The peak **Goethite** concentration is **1.5~2.5%**

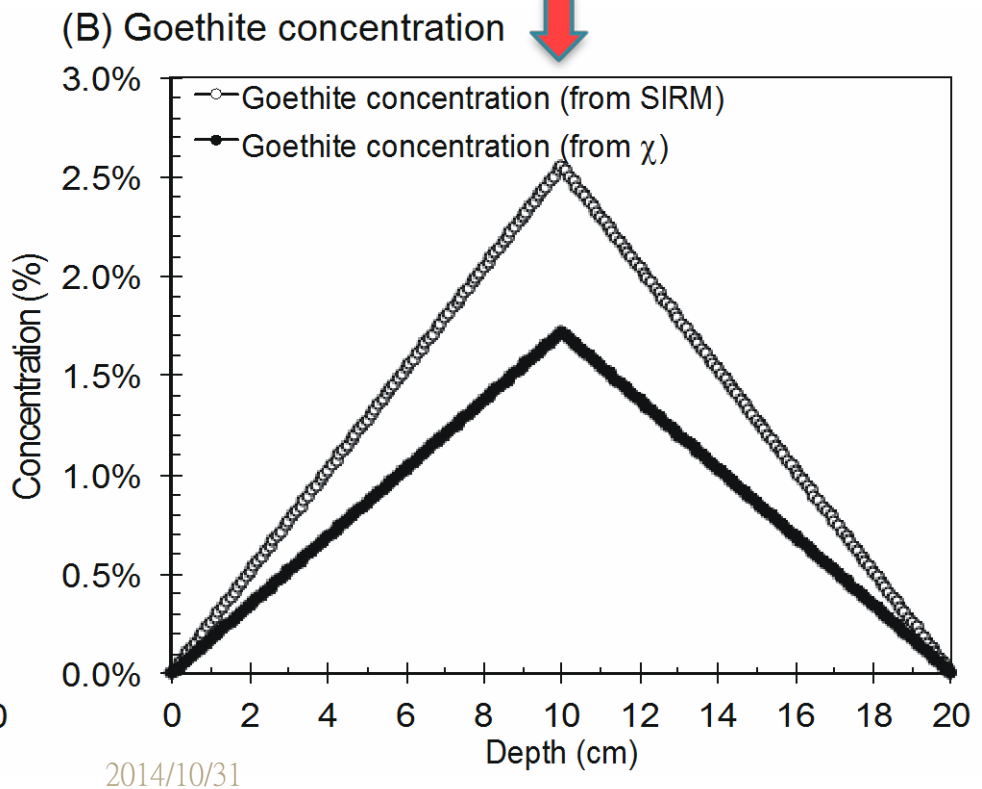
Oxidized during earthquake

There is **no SP grains** within gouge. **Magnetite** & **Goethite** **are neoformed**.

Neoformed by Chi-Chi around PSZ

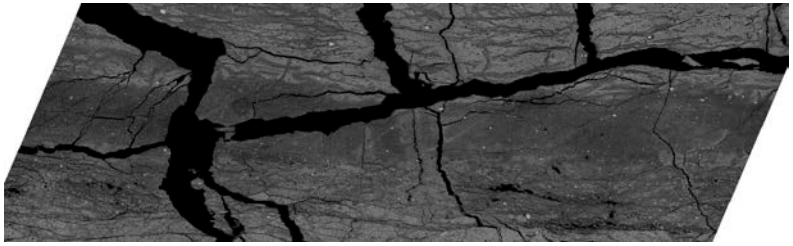
Hot fluid in gouge center





Part IV

An Earthquake Slip Zone is a Magnetic Recorder



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Process within PSZ and baked contact

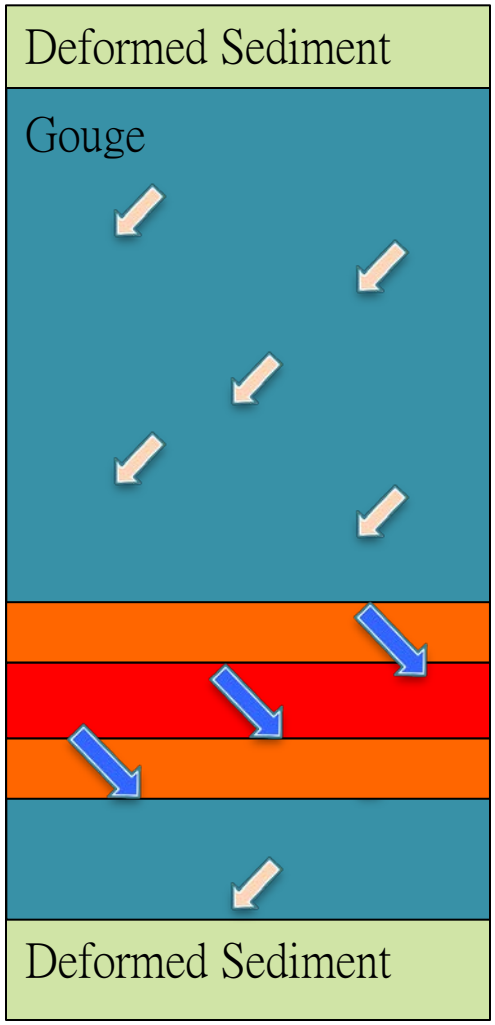
Post-seismic

T>400° C
[Boullier et al., 2009]

Baked contact

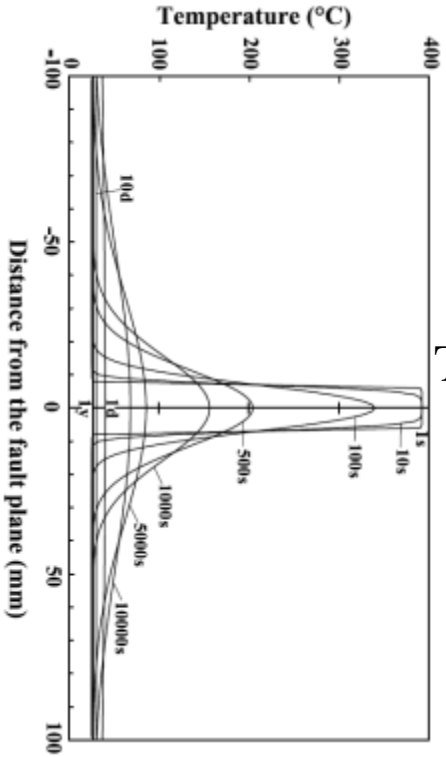
Slip zone

Baked contact



Earth magnetic field

Old Record

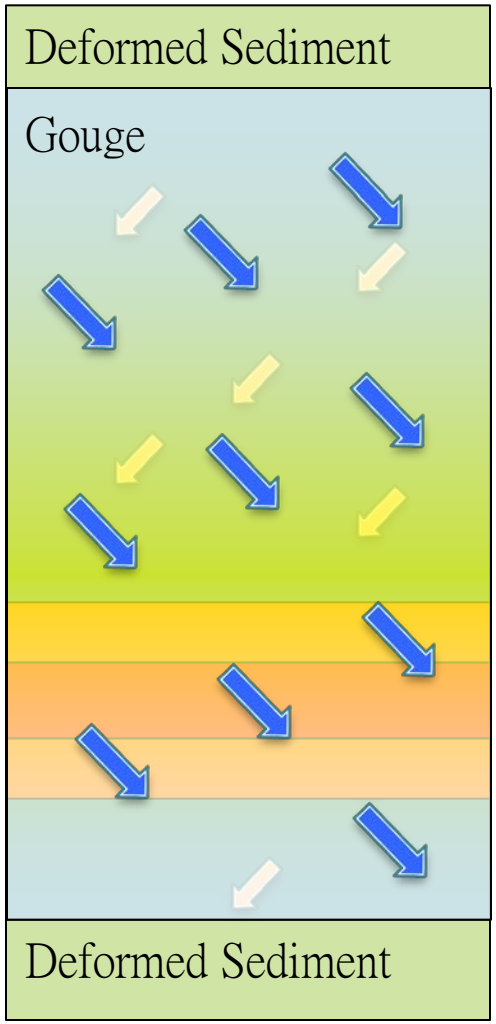


TRM + CRM
Neoformed
Magnetite

[Figure from Fukuchi et al., 2005]

Process within the whole gouge

Post-seismic



Earth magnetic field

Old Record

Hot fluid T>350° C
[Ishikawa et al., 2008]

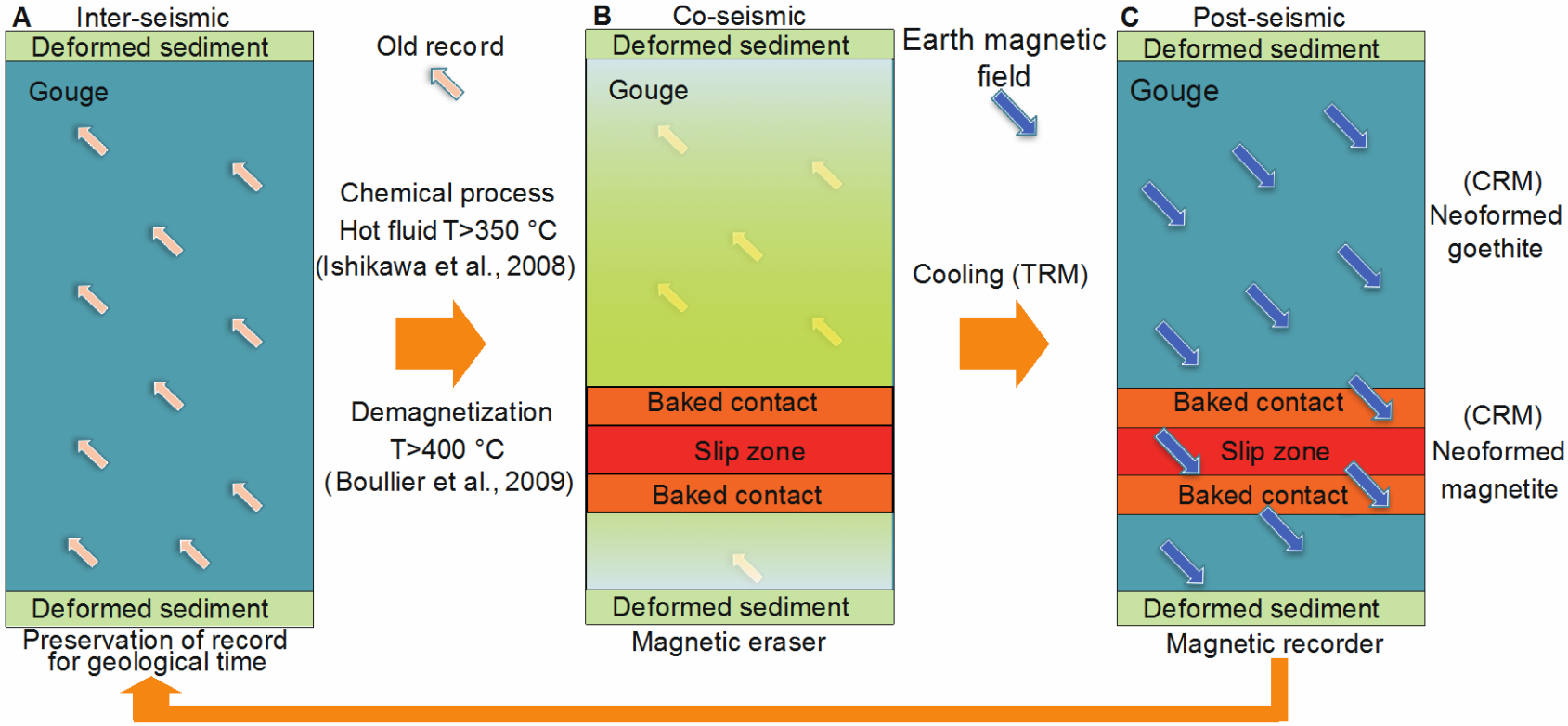
Baked contact

Slip zone

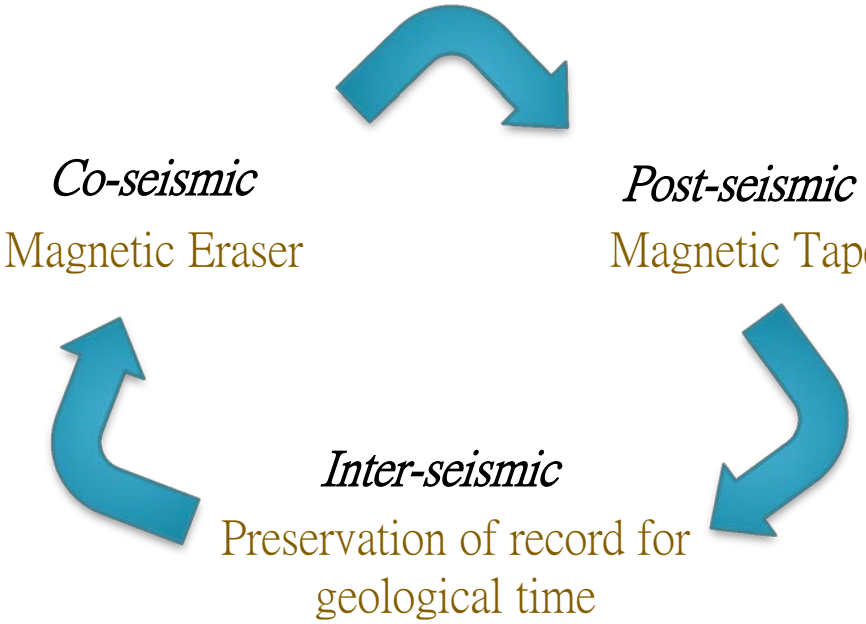
Baked contact

CRM
Neoformed
Goethite

Process within the whole gouge



Paleomagnetic record during large earthquake event



Identification of the last quake event

Potential to date earthquake event

謝謝!!

Merci!!

Thanks!!

Summaries

1. Making U-channel within fault gouge is of great values because nondestructive magnetic measurement can help to focus on specific horizons, and to estimate broadly the concentration of neoformed sediments.

2. For the first time, we identified a magnetic record of the Chi-Chi gouge. This is due to the combination of fluid circulation and temperature elevation.

3. The magnetic record in the gouge is carried by magnetite within the principal slip zone and goethite in the rest of the gouge. We propose a model where magnetic record: 1) is preserved during inter-seismic time, 2) is erased during co-seismic time and 3) is imprinted during post-seismic time when fluids cooled down.

4. In addition, we have identified pyrrhotite, which is an iron sulfide and forms at the expense of pyrite during high temperature (>500°C). The micron-size goethite forms on cooling of fluids that percolated within the gouge. The magnetite is oxidized in the gouge, and probably neoformed along the principal slip zone.

Summaries

5. We correlate the maximum magnetic susceptibility to the mm-thick Chi-Chi principal slip zone within the 16 cm-thick gouge. This constitutes a potential, fast, and nondestructive way to find the most recent principal slip zone in thick gouge.

6. The model of the magnetic mineral concentrations indicates that ~300 ppmv of magnetite formed in the PSZ and its main contact area. Similarly, ~1% of goethite is formed in the center of the gouge. This model provides us a new way to quantify magnetic mineral concentration.

[**Chou, Y.-M.,** S.-R. Song, C. Aubourg, T.-Q. Lee, A.-M. Boullier, Y.-F. Song, E.-C. Yeh, L.-W. Kuo, and C.-Y. Wang,
An Earthquake Slip Zone is a Magnetic Recorder, ***2012, Geology***]

[**Chou, Y.-M.,** S.-R. Song, C. Aubourg, Y.-F. Song, A.-M. Boullier, T.-Q. Lee, M. Evans, E.-C. Yeh, and Y.-M. Chen ,
Pyrite Alteration and Neoformed Magnetic Minerals in the Fault Zone of Chi-Chi Earthquake (M_w 7.6, 1999), Taiwan, ***2012, G-cubed***]

[Chou, Y.-M., S.-R. Song, C. Aubourg, T.-Q. Lee, Y.-. Song, and E,-C, Yeh,
Quantitative Modeling of the Newly Formed Magnetic Minerals in the Fault Gouge of 1999 Chi-Chi Earthquake (M_w 7.6), Taiwan, ***2014, JGR***]