take home messages

UNDER PRESSURE:

HOW PRESSURE AFFECTS MAGNETIC REMANENCE

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We have added a few interactive links to the slides in the hope of making them more accessible. You can find links marked with *link*. The links might take you to a webpage with more information or the cited reference.

Rocks Under Pressure

All rocks are subjected to pressure (P) and temperature (T) during diagenesis. Especially with increasing burial, both P and T increase rapidly. Other sources of pressure include:

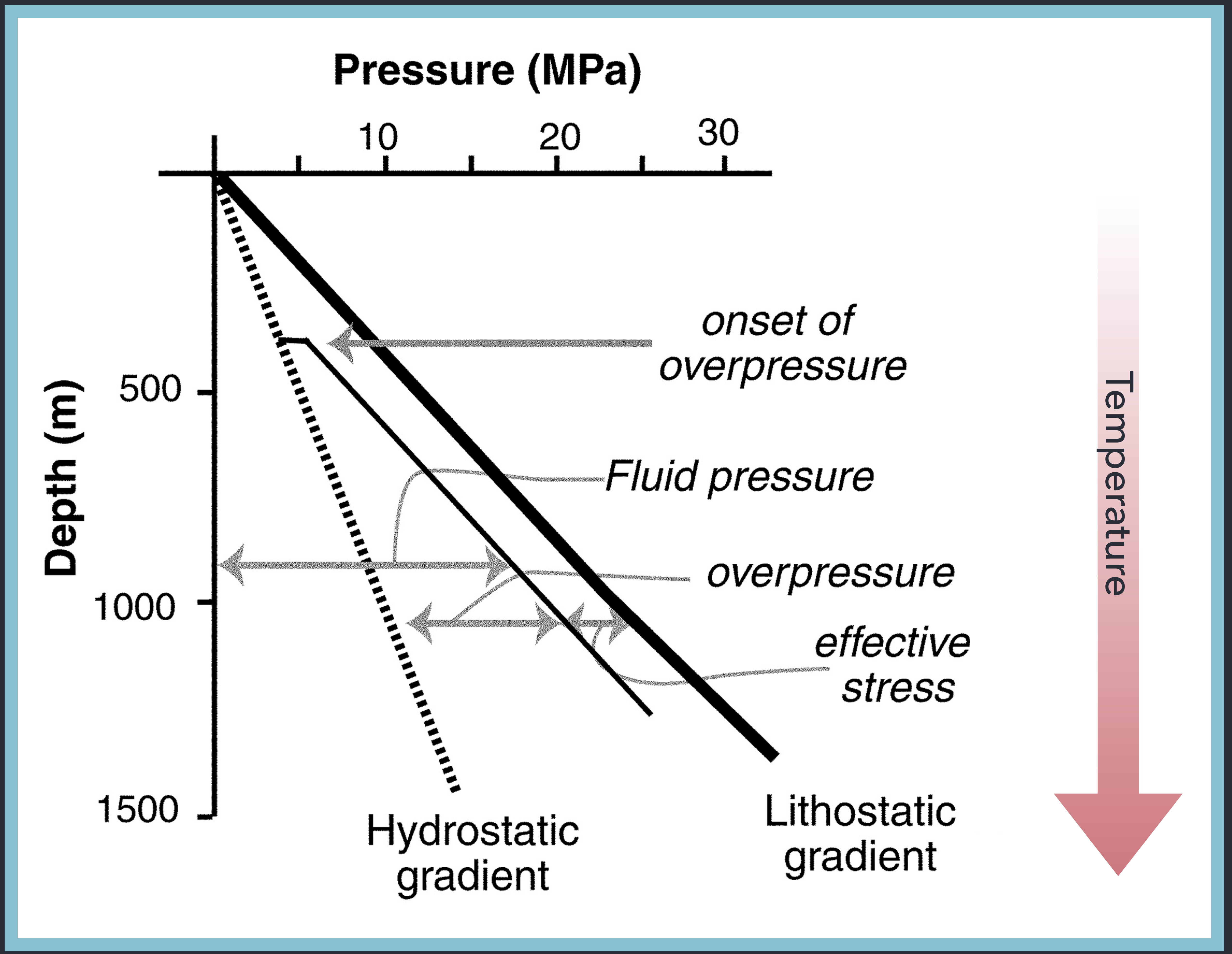
- Fluid and pore pressure
- Stress at tectonic faults

In the case of asteroid impacts

- Impact generated pressure

As paleo and rock- magnetists it is important to understand

WHAT HAPPENS TO THE MAGNETIC REMANENCE?



To get an idea of "*typical*" pressure, here are some examples:

≈1 MPa - Pressure of an average human bite
≈10 MPa - Stiletto-heels on floor
≈100 MPa - Pressure at bottom of Mariana Trench
< 5 GPa - Lowest shock stage for meteorites

Richard J. H. Jolly and Lidia Lonergan Journal of the Geological Society, 159, 605-617, 1 September 2002

1. Applying Pressure When No Magnetic Field Present

Reference: Louzada, et al. (2011)

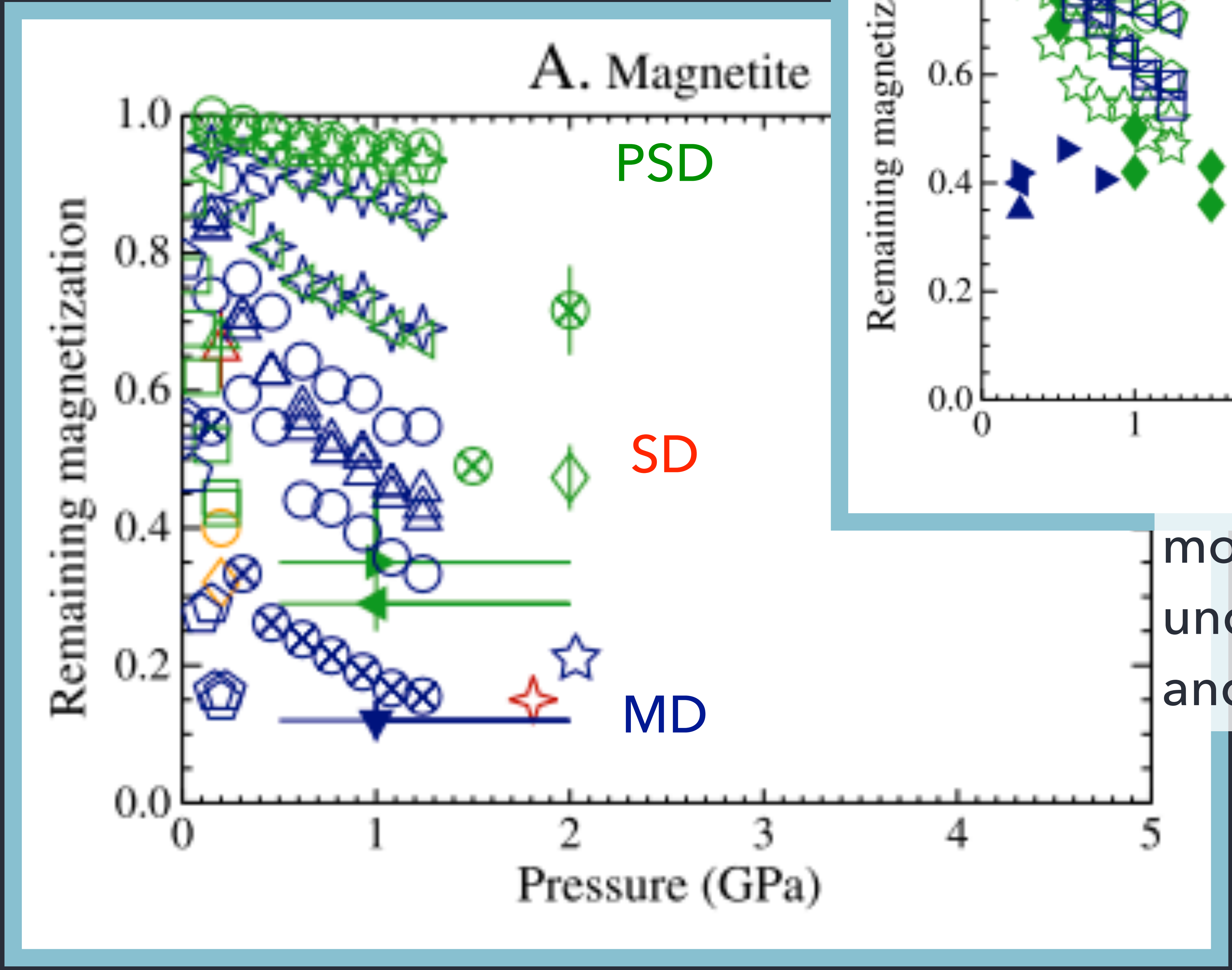
The easiest case is, if there is no magnetic field present when the rock is subjected to pressure[1].

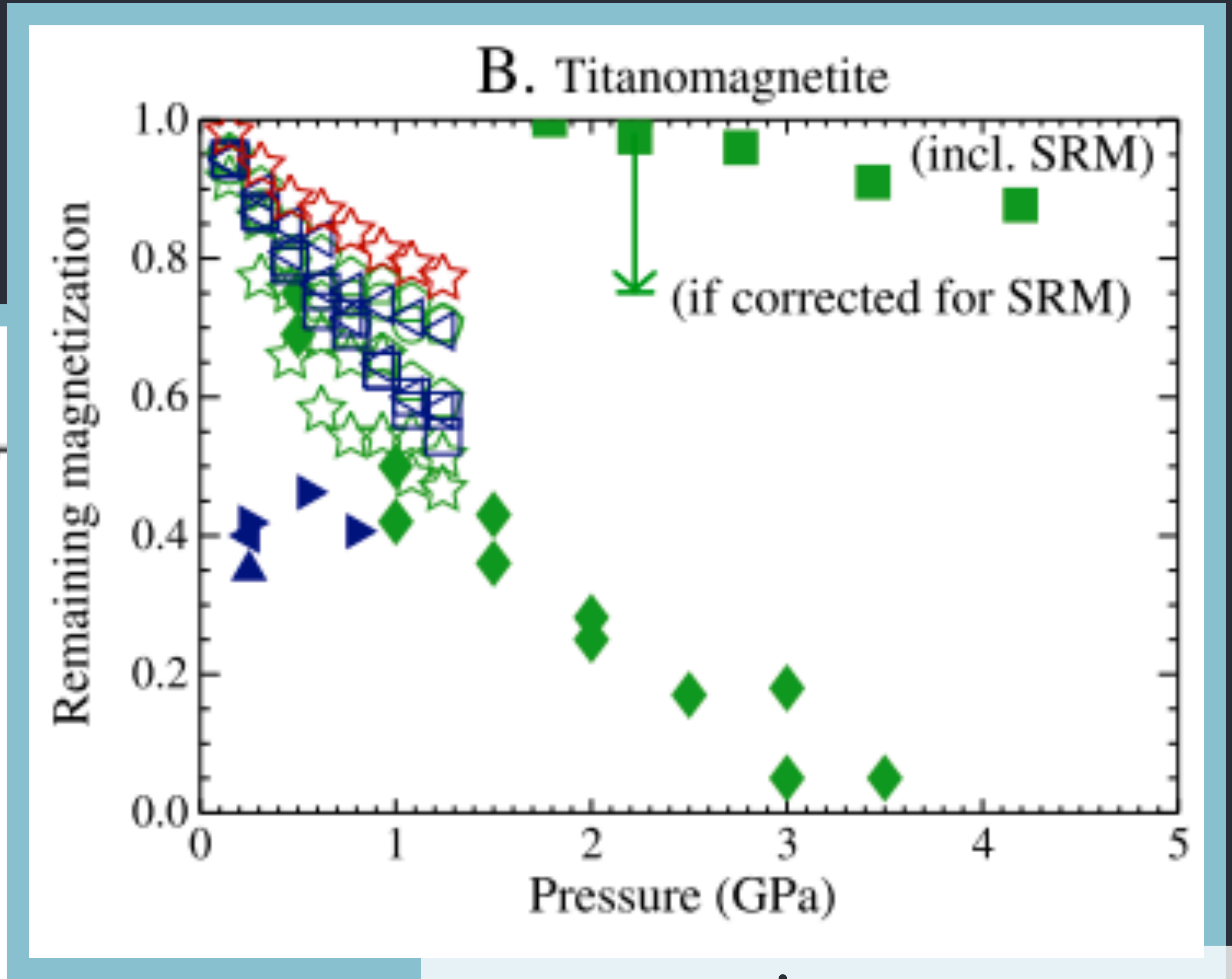
- Remanence is demagnetized under pressure

While there has been a number of great experiments, there is:

- No clear domain state trend
- Widely varying results

PRESSURE DEMAGNETIZATION CAN LEAD TO UNDERESTIMATED PALEOINTENSITIES



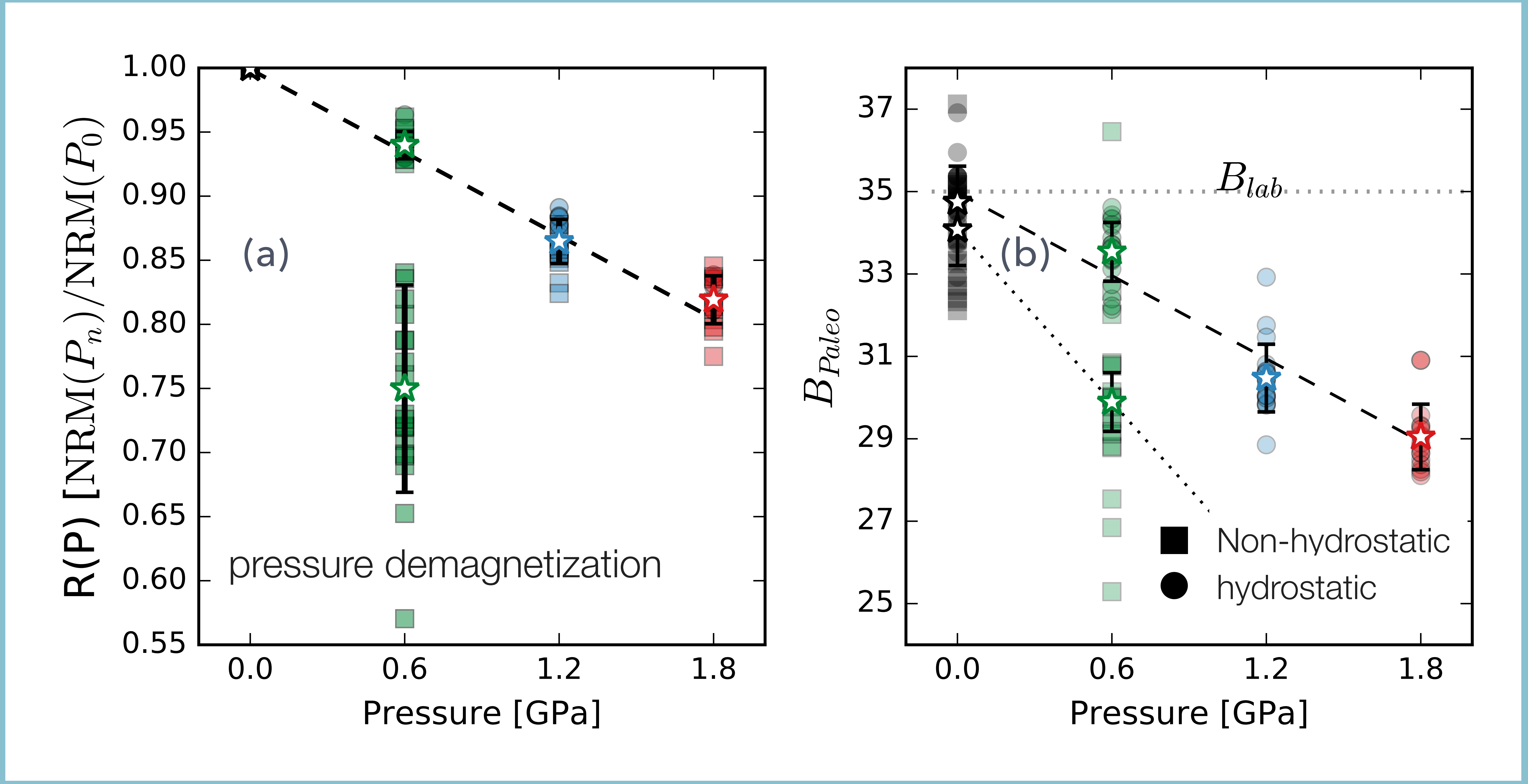


most experiments are under hydrostatic conditions and at room temperature

[1] This is important for the study of meteorites and for asteroid impacts on Moon and Mars for example.

Effect of pressure on paleointensities

The figures shows how hydrostatic (circle) and non-hydrostatic (square) pressure affect paleointensities. In both cases a Ti-magnetite (PSD) bearing obsidian from Lipari was given a thermal remanence (TRM) of 35 µT. After subjecting the sample to pressures up to 1.8 Gpa inside of a non-magnetic hydronic press, the initial TRM decreased (a) by 10 %/GPa. This pressure demagnetization (see *slide*) causes a similar underestimation of the paleointensity (b).



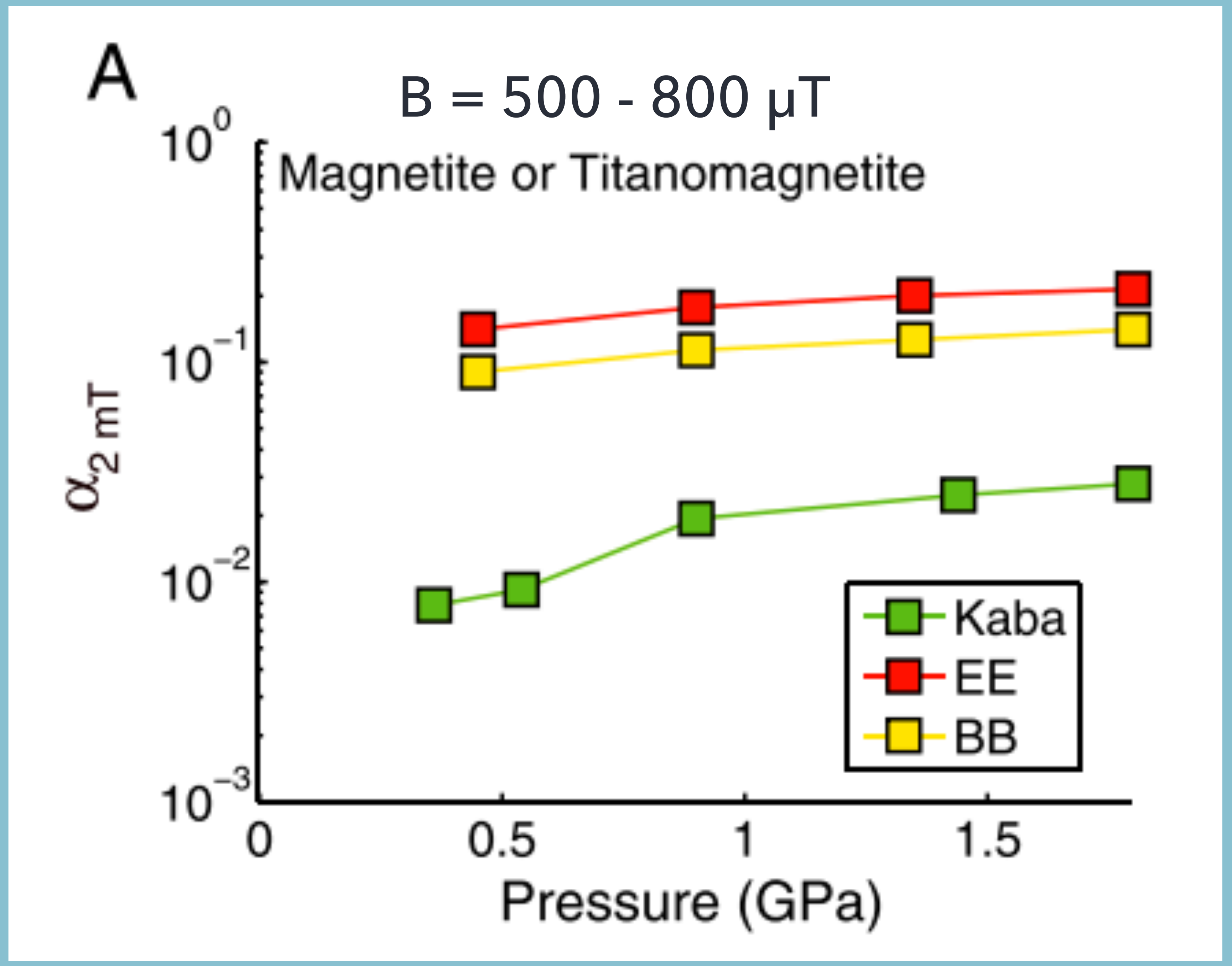
Pressure demagnetization can lead to underestimated paleointensities

Reference: Volk and Gilder (2016)

2. APPLYING PRESSURE WHEN A MAGNETIC FIELD IS PRESENT

In the presence of a magnetic field, the rock may acquire a pressure (or shock) remanent magnetization (PRM). Little data is available for the acquisition of pressure induced remanences, even less at elevated temperatures.

PRM - efficiency: $\alpha = \frac{\text{PRM (B,P)}}{\text{TRM(B)}}$

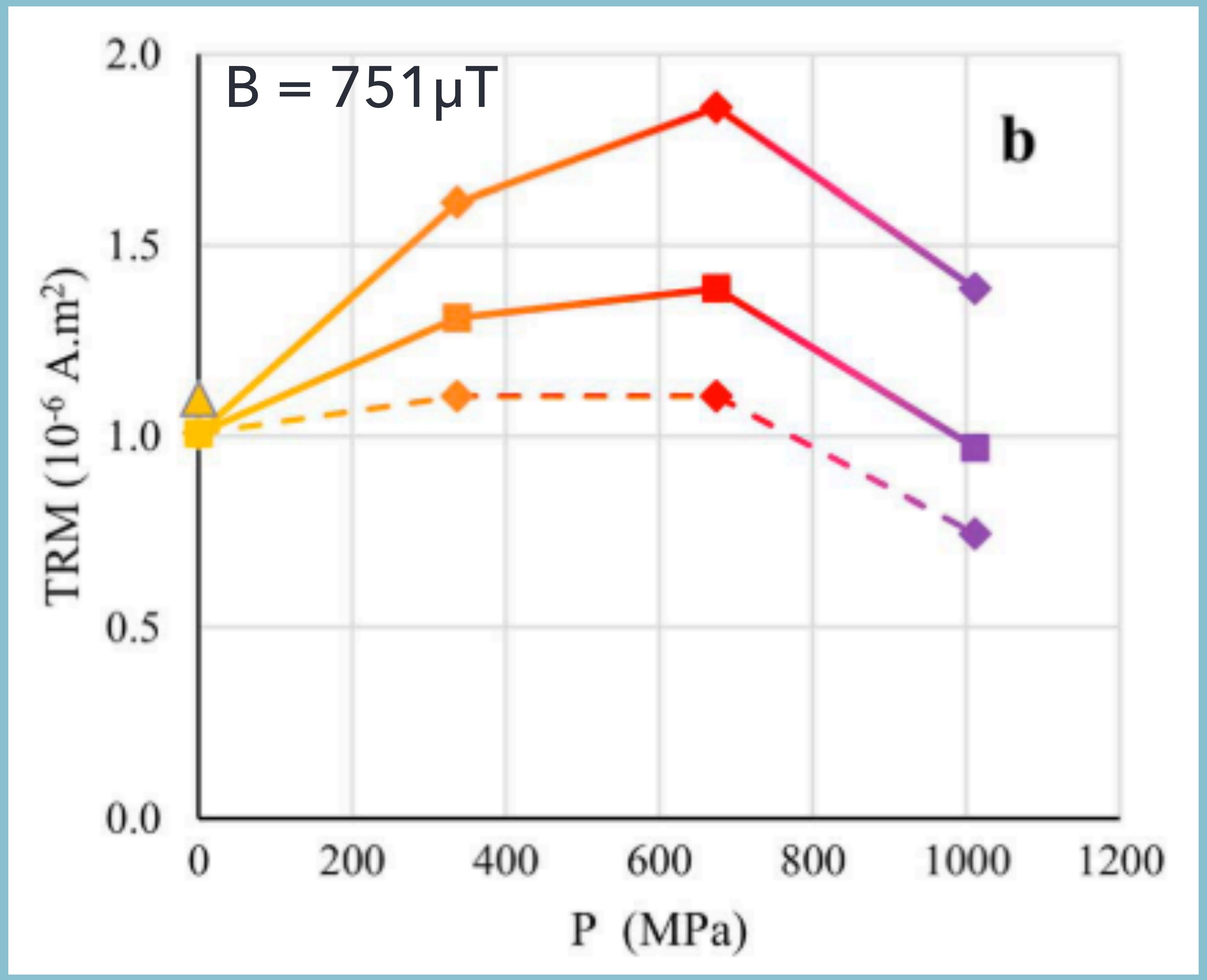


Reference: Tikoo, et al. (2015)

Existing data for PRM acquisition was:

- acquired in strong magnetic fields > 500 μT
  - Is this still in the linear regime of acquisition?
- at pressures > 0.5 GPa (equivalent to a depth of ≈ 20 km depth)
  - Great for meteorites
  - How relatable are these results for the Earths' crust?
- No information about domain state dependence

PRM acquired by cooling through the Curie temperature under pressure



Reference: Launay, et al. (2017)

As discussed *earlier*, both temperature and pressure increase with depth, thus they should be explored together.

The open questions remain:

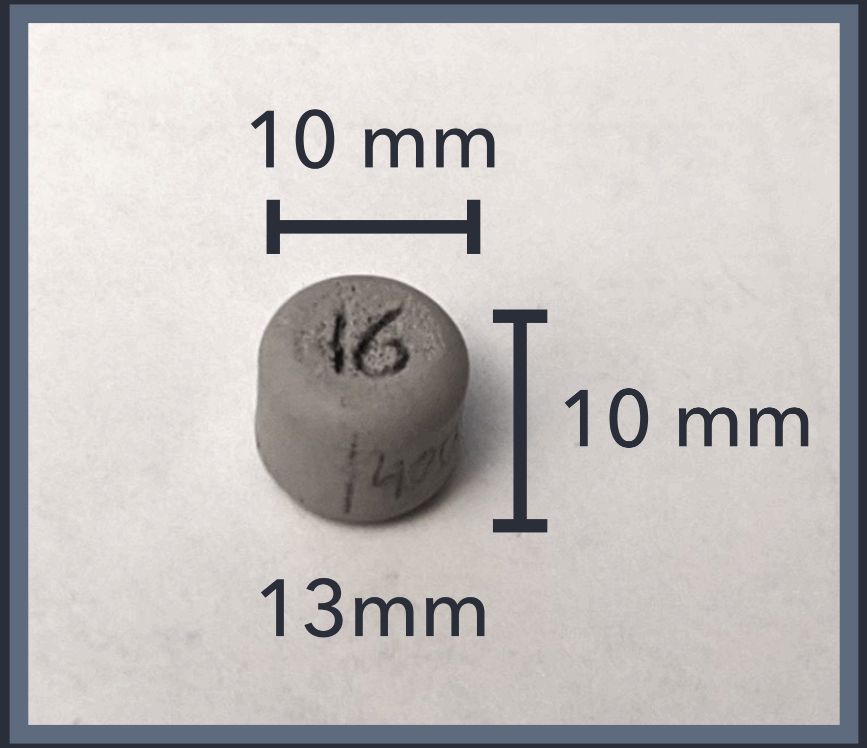
- How strong is a PRM "overprint"?
- Does the PRM acquisition change with increasing temperature?
- Is there a grain size (SD/MD) dependence in the acquisition?
- how can we detect a PRM?

Experiments And Samples

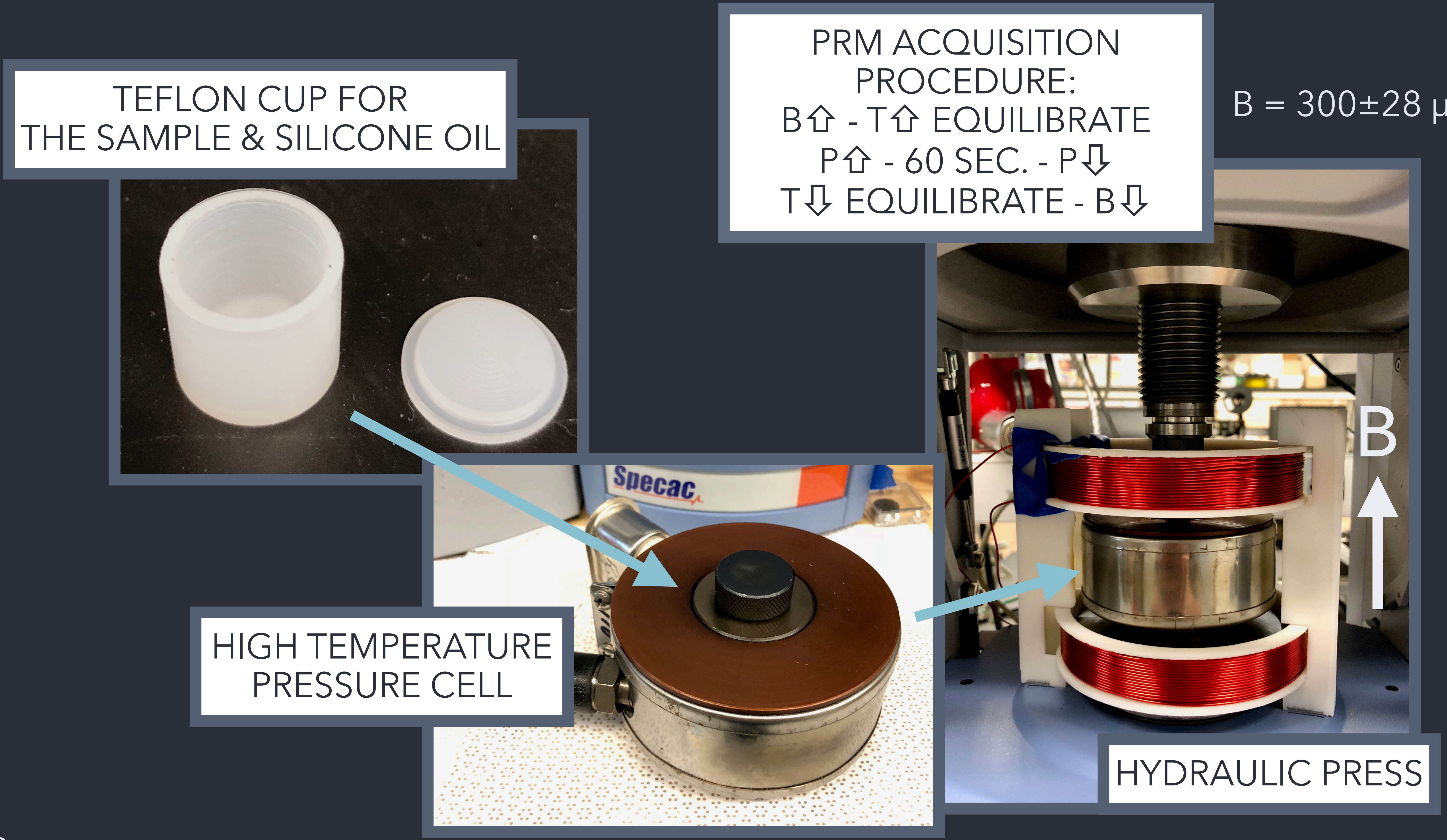
We used synthetic magnetite (Wright) in 4 grain-sizes. The Wright magnetites are well studied and have been used to explore everything from the additivity and reciprocity of ARM to Low-temperature magnetization and AC susceptibility.

First, the powders were annealed at 500˚C in CO/CO_2 atmosphere for 24 hours.

Then to create solid samples we mixed the powders with a high temperature cement and cast them into solid samples.



- Wright magnetites
- Annealed in CO/CO_2 at 500˚C for 24 hrs
- Cast in high temperature cement



B = 300±28 μT

4 Pressure Steps:
0, 3, 4, 5 T ⇆ 0, 226, 301, 376 MPa

3 Temperatures:
30˚C, 80˚C,150˚C

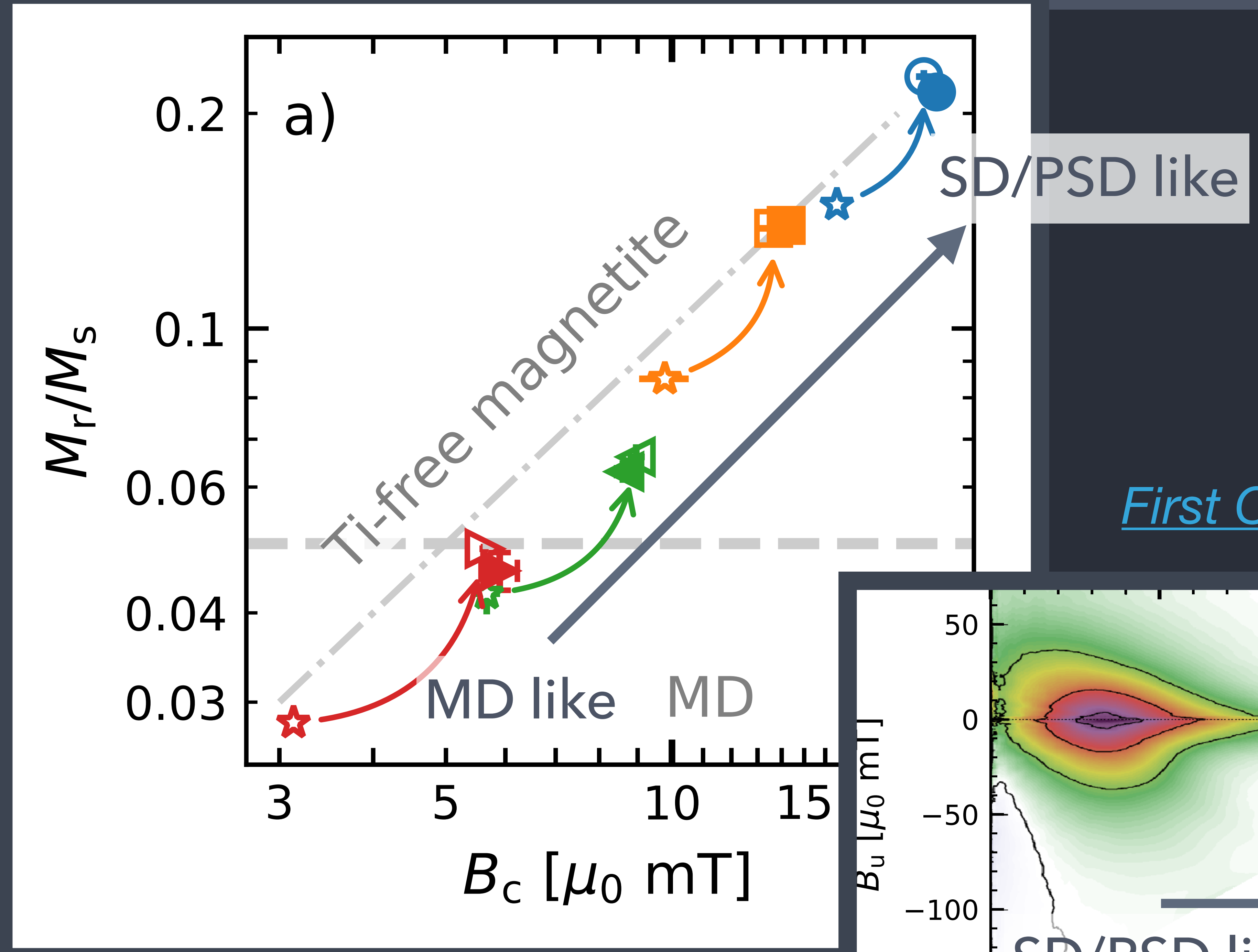
Rock Magnetism

● 4000 0.065 µm	■ 112978 0.44 µm	◀ 041183 16.9 µm	▶ 112882 18.3 µm

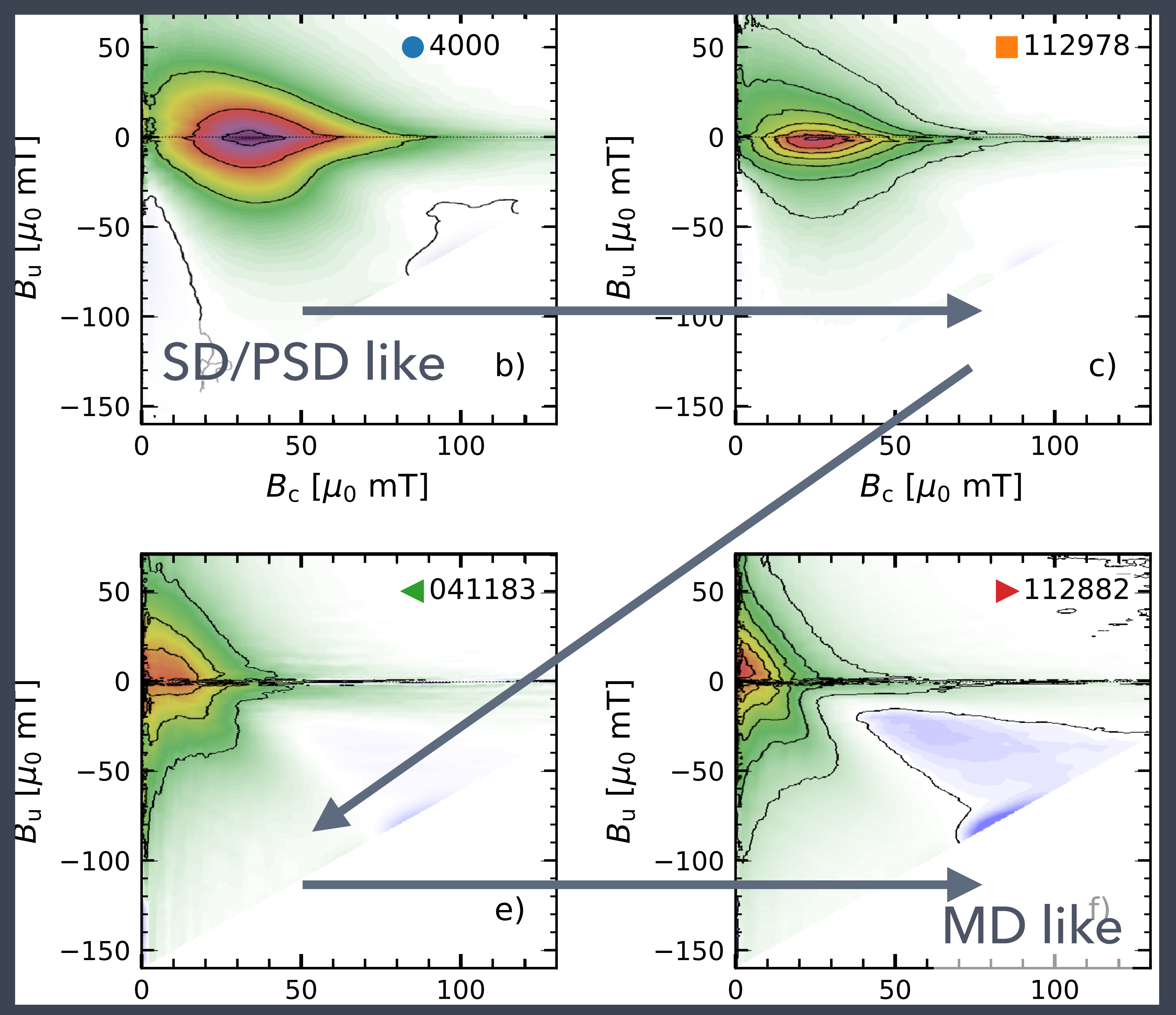
The wright magnetites are well suited for a study like this because they show a nice progression from almost single ➟ multi domain.
The stars in a) are the powders after annealing. Initial testing showed that the samples change volume when they are pressurized so we pre compressed them to 15 T (≈1.1 GPa) to exclude compaction during the experiment.

The pre compression showed a change towards a more SD like behavior.

After the actual P/T experiments no additional changes were visible.

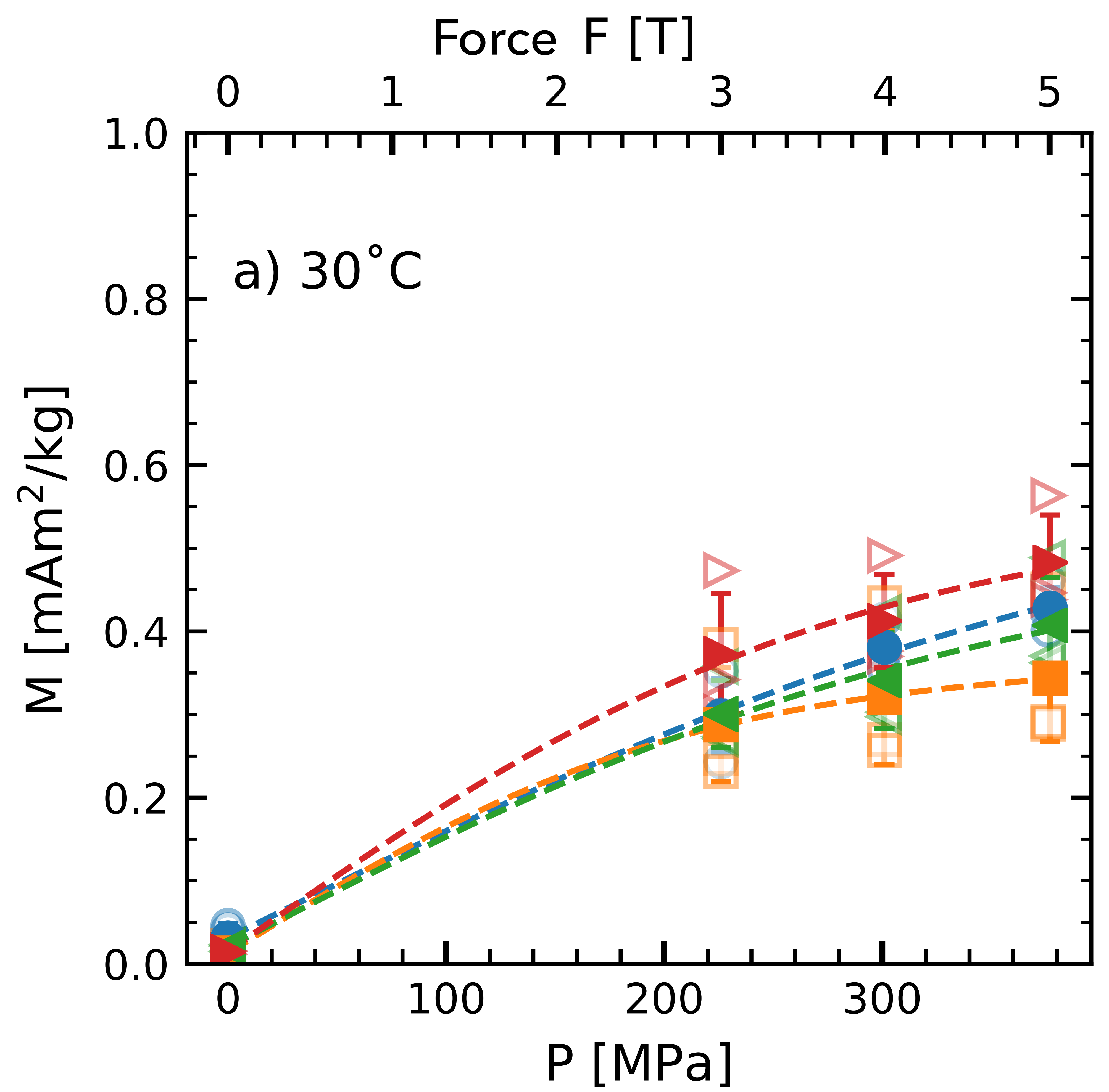


First Order Reversal Diagrams



PRM AT ROOM TEMPERATURE

4000	112978	041183	112882
0.065 µm	0.44 µm	16.9 µm	18.3 µm



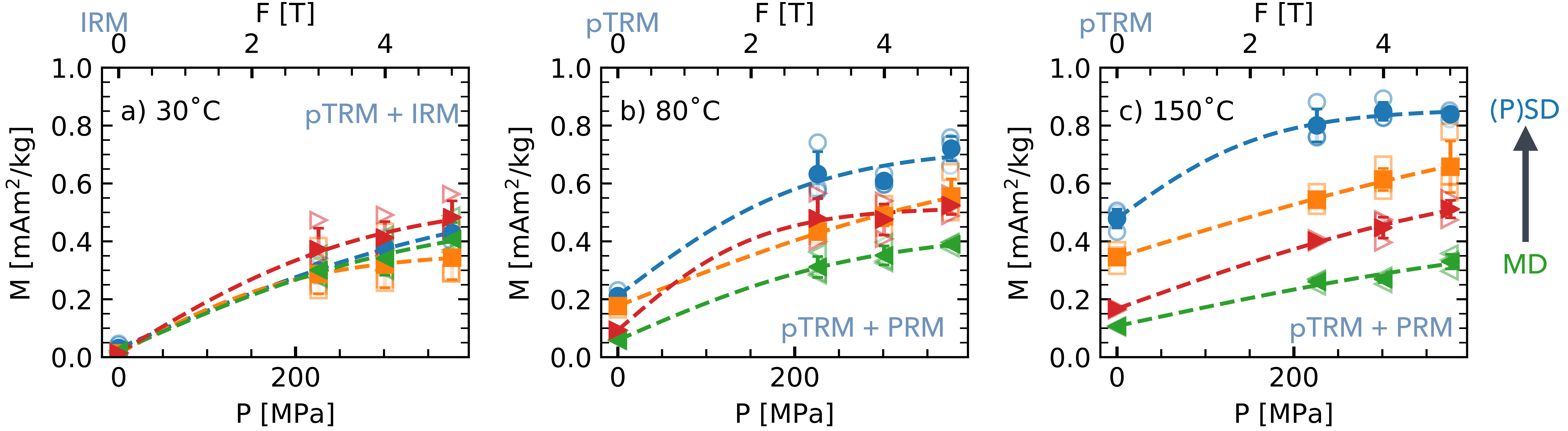
At ambient pressure and temperature, the remanence is equivalent to a weak (300µT) field isothermal remanent magnetization (IRM). With increasing pressure a stronger moment (i.e. PRM) is acquired.

The intensity of the PRM is about an order of magnitude stronger than the IRM (P=0). Within error there is no grain size dependence. This is surprising since other remanence acquisition processes are strongly dependent on grain size.

All experiments were repeated 3 times for each sample and each pressure

- At P = 0 ➟ weak field IRM remanence (300µT)
- increasing pressure ➟ PRM
- PRM one order of magnitude stronger than IRM
- no grain-size dependence

PRM AT ELEVATED TEMPERATURES



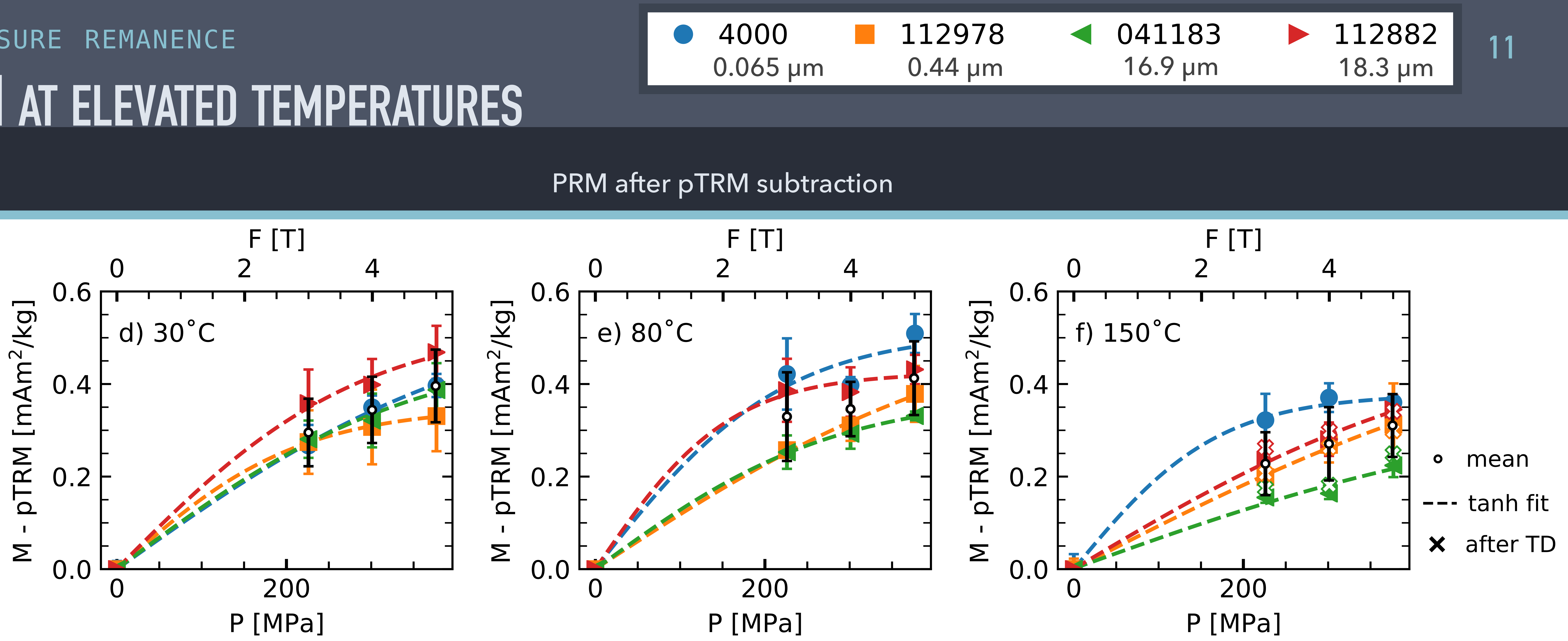
At elevated temperature (80˚C and 150˚C), the PRM shows a clear grain-size dependence. The smallest grains (PSD) acquire the most remanence.

However, the remanence at P=0 is technically a pTRM. Therefore all high pressure remanence should be the superposition of this pTRM and the true PRM.

$$M(T,P) = \text{pTRM} + \text{PRM}$$

To get the true PRM the pTRM $M(T,P_0)$ needs to be subtracted from the $M(T,P)$

PRM AT ELEVATED TEMPERATURES



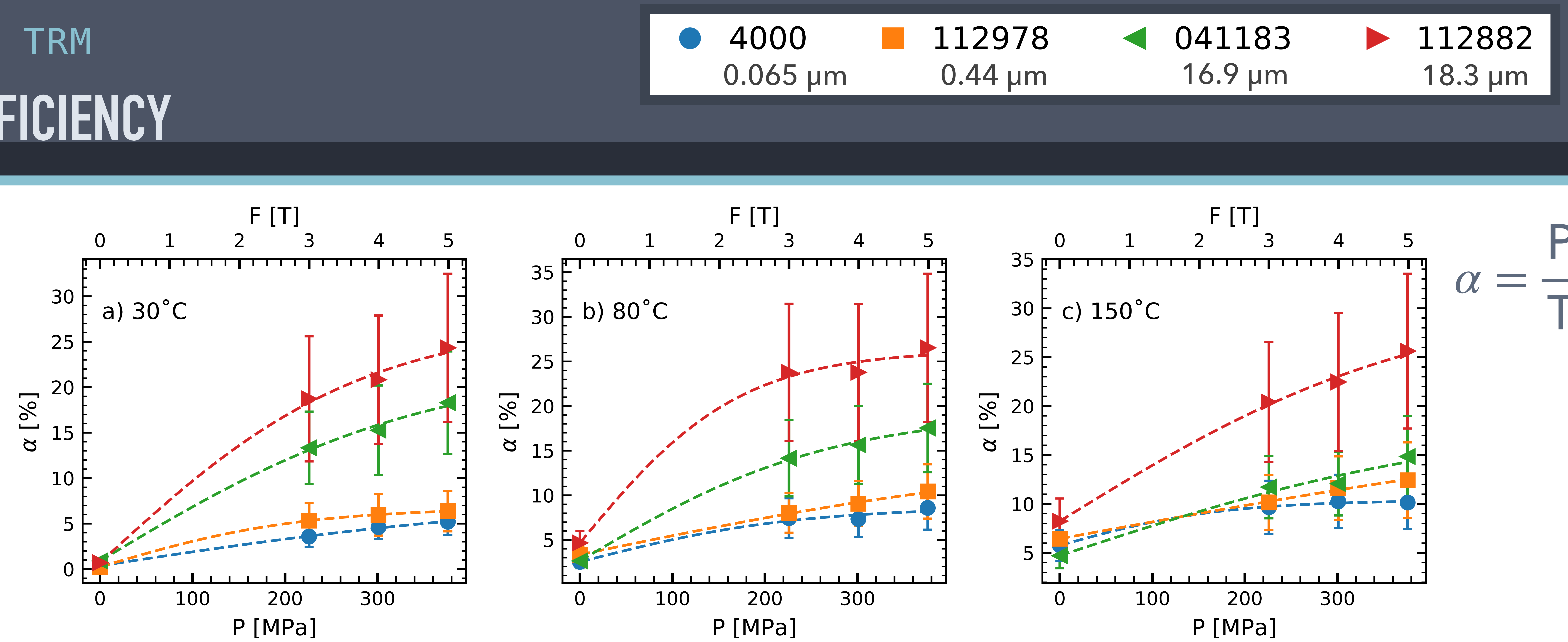
To test if a simply subtracting the pTRM from the PRM is valid, we gave a few of the samples a PRM at 150˚C and then thermally demagnetized (TD) it.

The crosses in f) show that the simple subtraction and demagnetization result in the same overall PRM.

This shows two things:

1. The pTRM and PRM seem to affect different grain populations and therefore are independent
2. After subtracting the pTRM to isolate the PRM there is no grain size dependence

PRM EFFICIENCY



$$\alpha = \frac{\text{PRM}}{\text{TRM}}$$

Ultimately the goal is to understand how strong a PRM overprint could be in a natural rock. Due to oxidation our magnetite samples couldn't be heated. We estimated the strength of the TRM using the REM method *(Keletschka et al. 2004)*.

$$\text{TRM} \approx \frac{M_{\text{rs}} \times B}{3000\mu T}$$

Similar to *Tikoo, et al. (2015)* we define the PRM efficiency α as the ratio of PRM and TRM.

Here, the strong grain size dependence of the TRM is the cause for the dependence in α. While SD like grains do not acquire a strong PRM compared to a full TRM, Multidomain particles are more susceptible and the PRM can be 20 - 30 % of a TRM.

Temperature only plays a minor role in PRM acquisition efficiency.

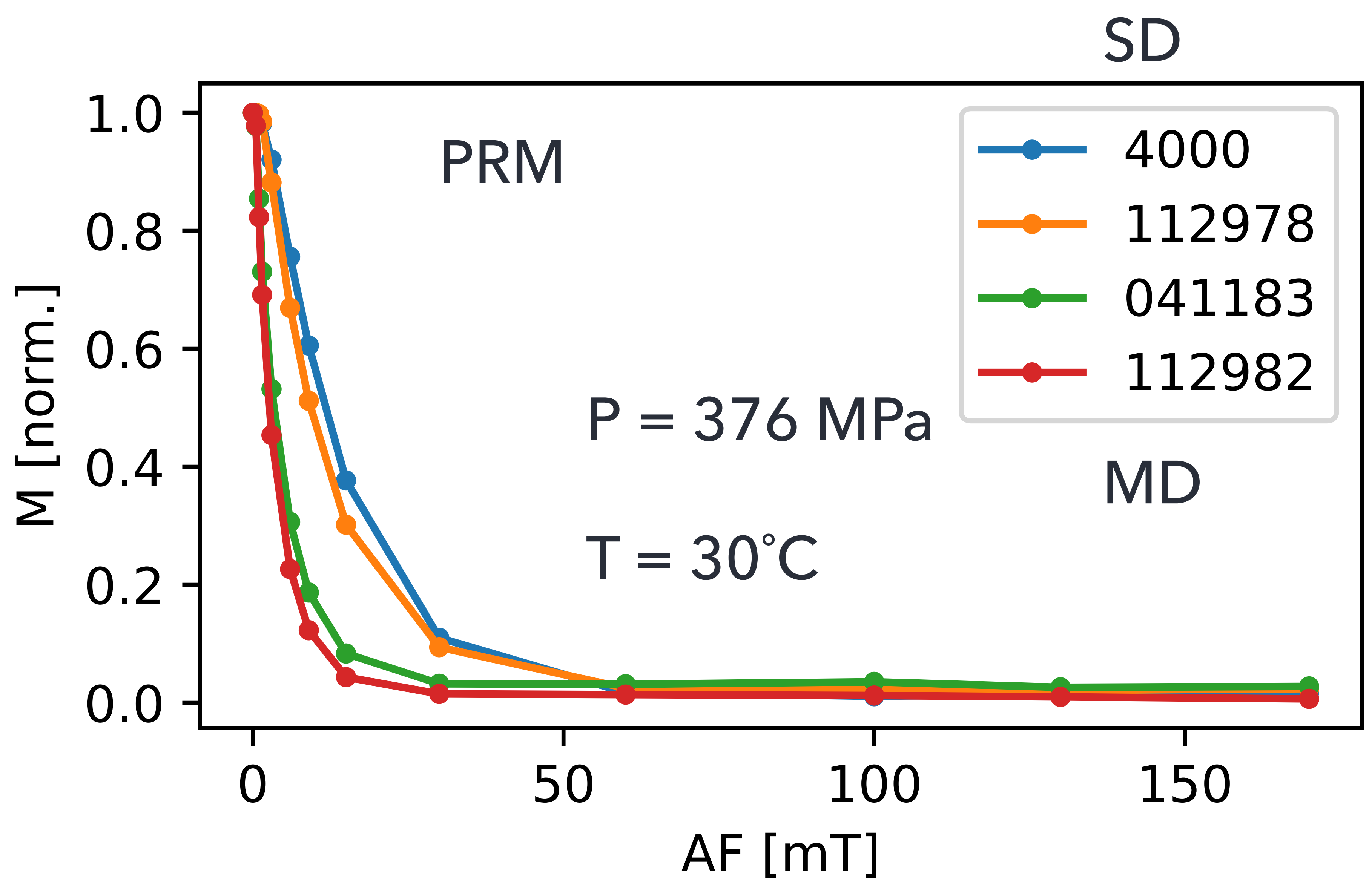
How to Detect a PRM

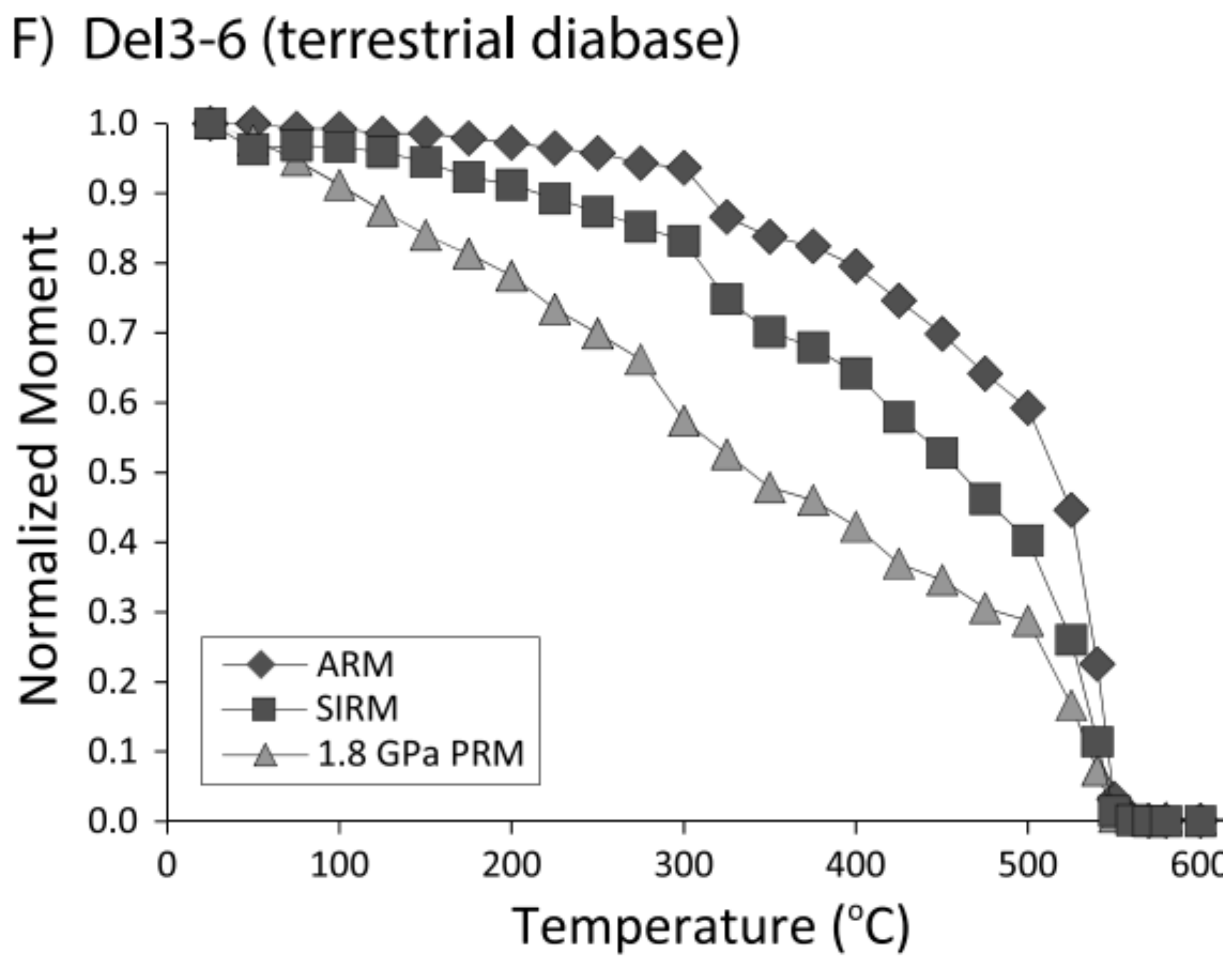
A PRM is demagnetized by relatively small alternating fields and the median destructive field is also low at 20 mT (SD) and 4 mT (MD) for PRM.

On the other hand, thermally demagnetizing a PRM overprint thermally can be more challenging. The overprint can be stable up to the Curie temperature of the mineral *(Tikoo, et al. , 2015)*.

This means:

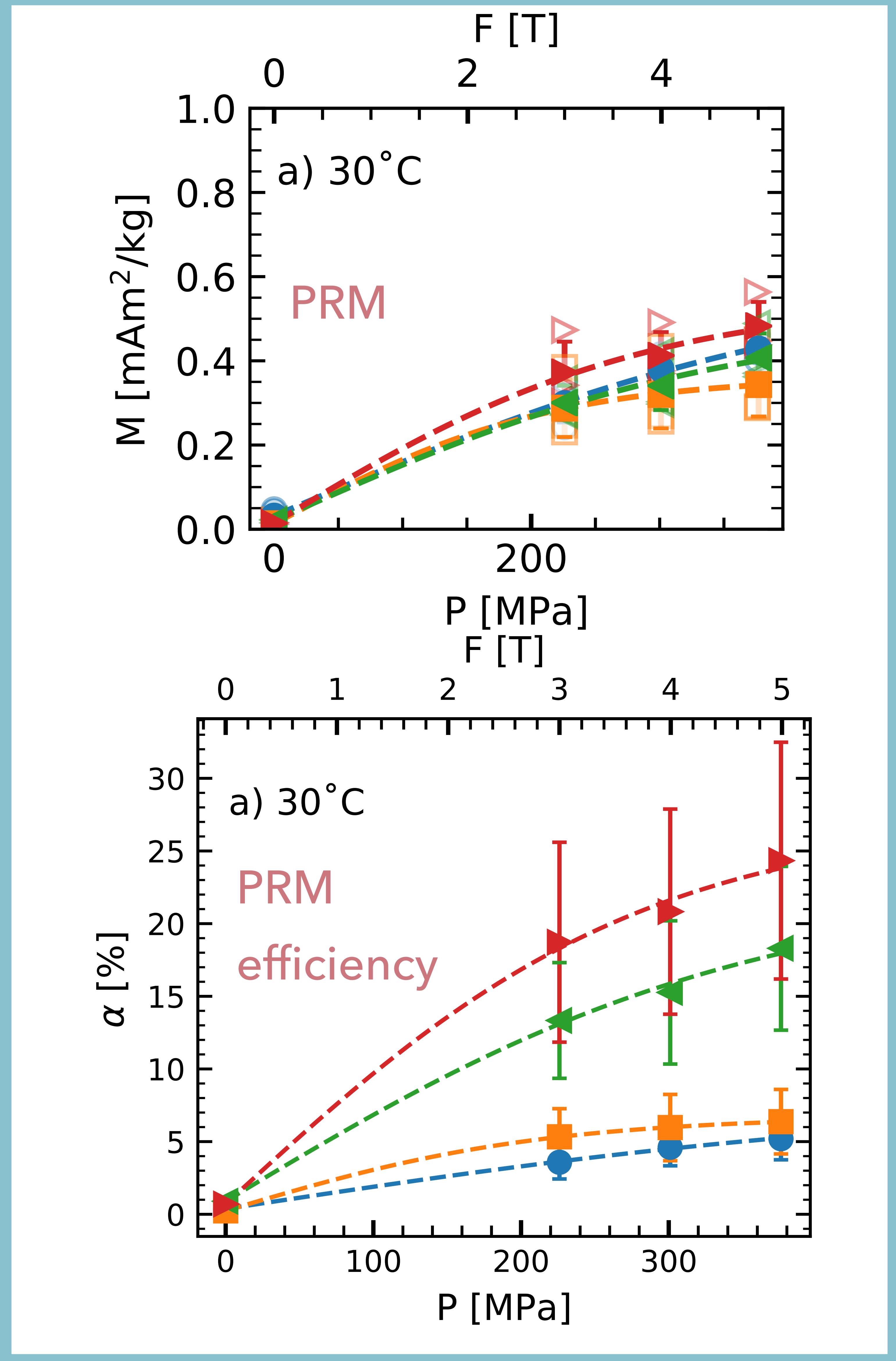
1. AF "cleaning" of the NRM can remove any possible overprints.
2. Due to a higher PRM/TRM ratio MD particles may be more prone to be overprinted
3. Thermal demagnetization alone may not pick up on a possible overprint





TAKE HOME MESSAGES

1. Pressure *demagnetizes* the NRM of a rock if no magnetic field is present.
    1. Can cause an underestimation of *paleointensities*
2. In the presence of a magnetic field, a rock will record a pressure remanent magnetization (PRM)
    1. PRM seems *independent* of domain state
    2. PRM and pTRM are independent
        ➡ They affect different grain populations
    3. PRM *efficiency* of MD grains can be ≈ 30 %



PRM CAN CAUSE A SIGNIFICANT OVERPRINT IN LOW T / HIGH P ENVIRONMENTS FOR MD CARRIER

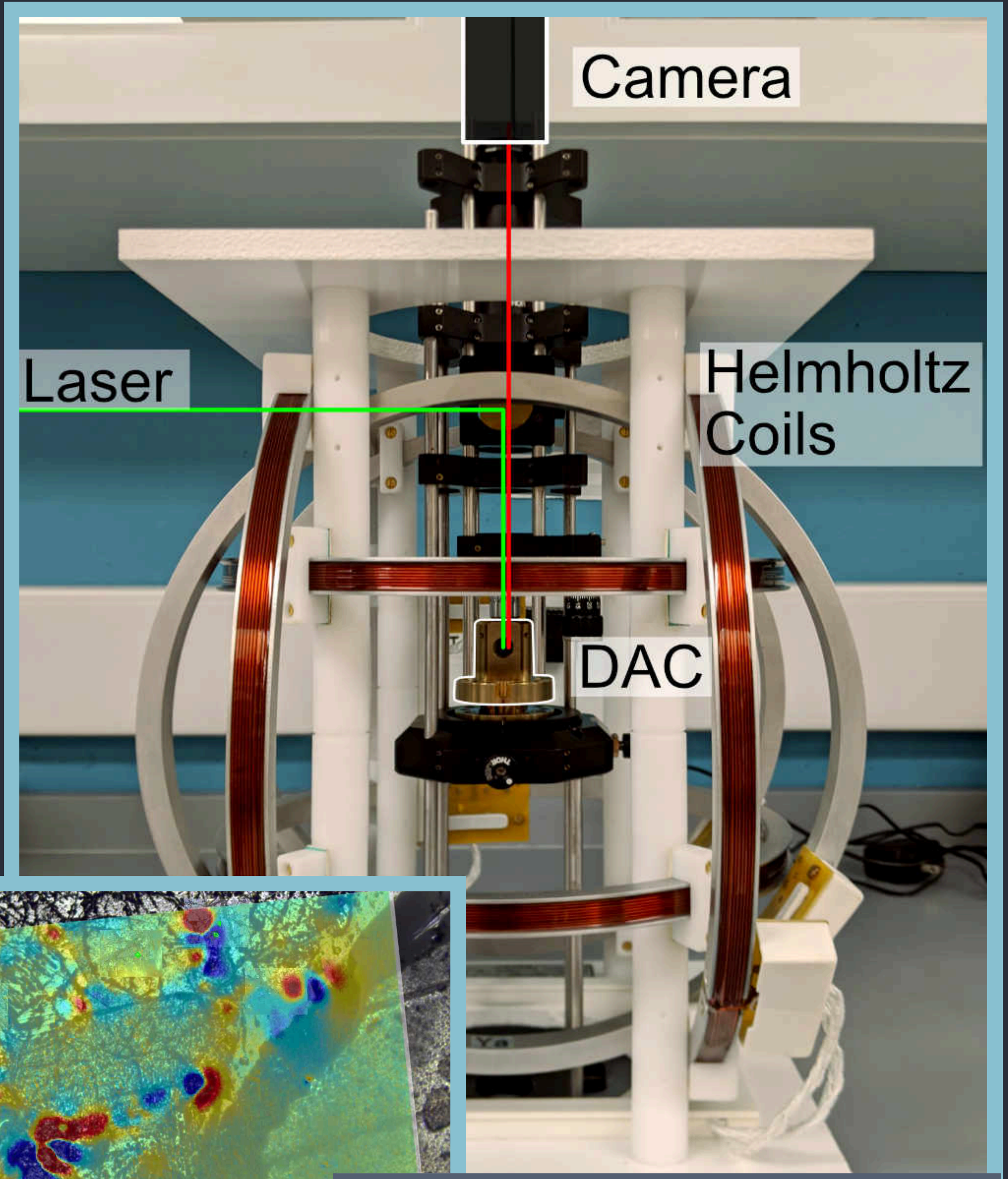
P.S. there is one more slide!

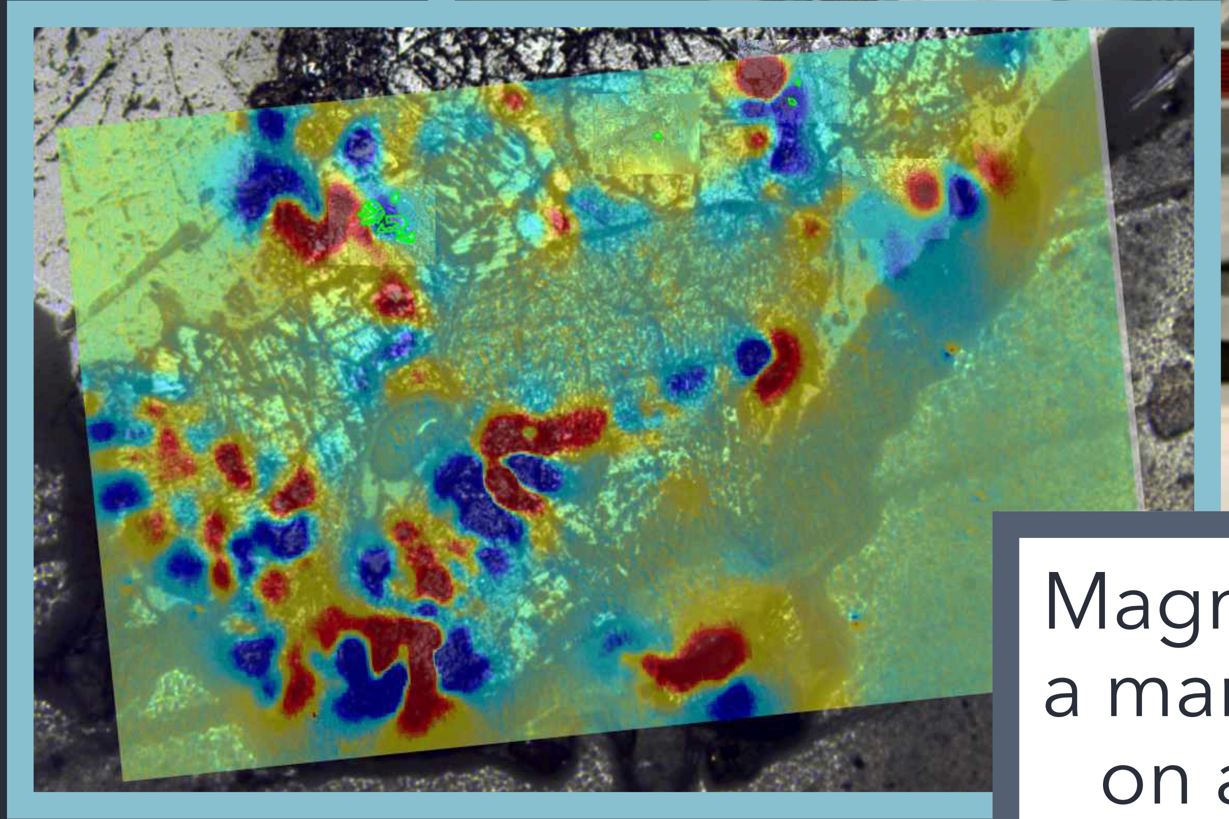
THE FUTURE OF ROCK MAGNETISM UNDER PRESSURE

In order to better understand what happens to the magnetic remanence at higher pressures (> 1GPa), we need a different approach since the usual materials can not with stand the immense forces.

Enter the *Quantum Diamond Microscope* (QDM). The QDM uses a diamond with Nitrogen-Vacancy (NV) centers to measure the magnetic field of a sample.

We will combine this new instrument with a specially built nonmagnetic diamond anvil cell. This allows us to detect small magnetic remanences with a μm fine resolution **under pressure (- 30 GPa)**, opening a host of new and exciting measurement possibilities.





Magnetic fields produced by a martian meteorite, overlaid on a reflected light image

Disclaimer: I was hoping to show some data from this, but for some unknown reason, I am not allowed to go to the lab and need to prepare this presentation in the confines of my apartment. Please feel free to ask questions about this.

start over

THANK YOU FOR READING THIS FAR. I HOPE YOU ENJOYED THIS. I AM HAPPY TO ANSWER ANY QUESTIONS YOU MAY HAVE AT THE Q&A SESSION ON MONDAY, MAY 4, 8:30-12:30 CET

CHAT SOON