Toward classifying magnetic properties of impact melts — An example from the Boltysh astrobleme

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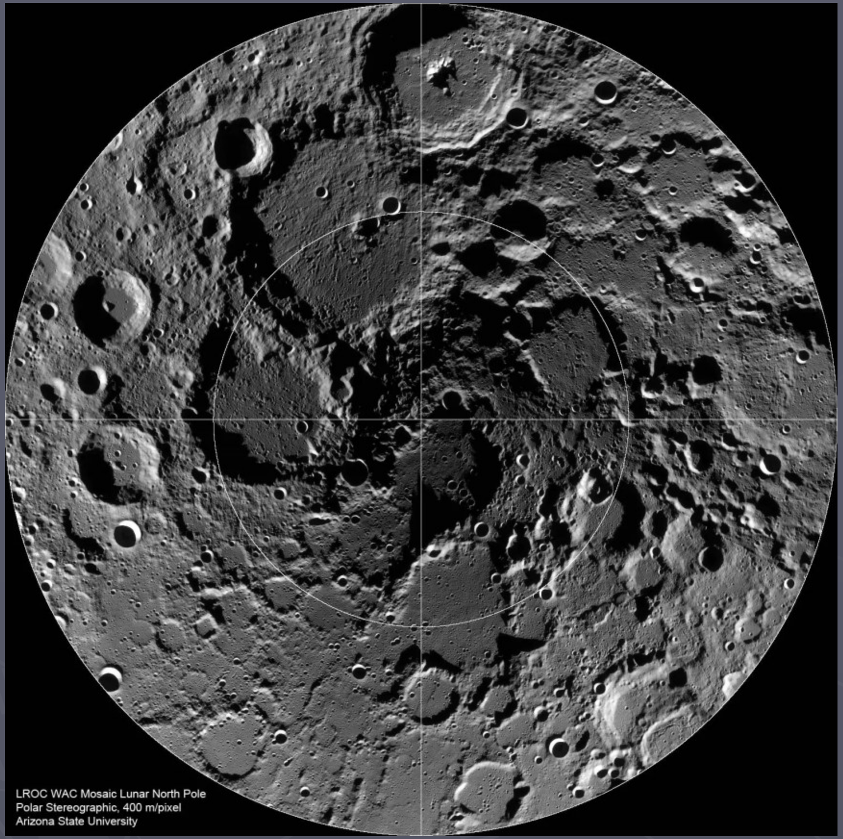
Cratering and impact (shock) metamorphism



The lunar north pole, captured by the Lunar Reconnaissance Orbiter Camera, is dappled with craters highlighted in a stark display of sunlight and shadow.

NASA/GSFC/Arizona State University

Moon hosts ~ 2 million craters
T. Kenkmann, Meteorit. Planet. Sci. 56, 1024-1070 (2021).

Map of all the confirmed (~ 200) impact craters on Earth.

Earth Impact Database, Planetary and Space Science Centre, University of New Brunswick, Canada

Impacts produce shock waves resulting in instantaneous heating, deformation, rock destruction, and crater excavation.

On the Earth, impact craters are constantly reworked by geological activity. To discover them and confirm their origin, field surveying, laboratory studies of impact-related rocks, and modelling need to be intimately interwoven.

P-T conditions of shock metamorphism

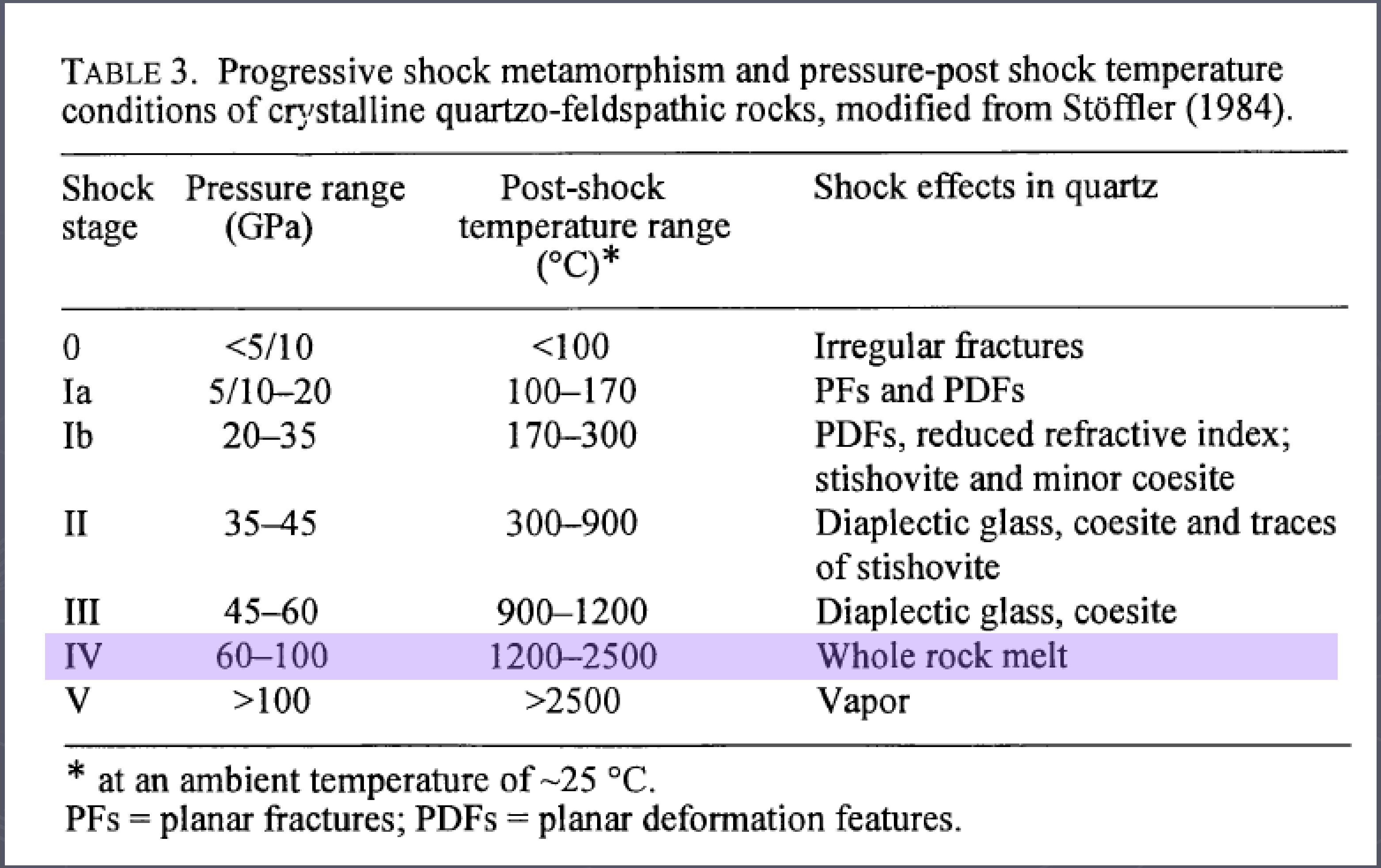


TABLE 3. Progressive shock metamorphism and pressure-post shock temperature conditions of crystalline quartzo-feldspathic rocks, modified from Stöffler (1984).

Shock stage	Pressure range (GPa)	Post-shock temperature range (°C)*	Shock effects in quartz
0	<5/10	<100	Irregular fractures
Ia	5/10–20	100–170	PFs and PDFs
Ib	20–35	170–300	PDFs, reduced refractive index; stishovite and minor coesite
II	35–45	300–900	Diaplectic glass, coesite and traces of stishovite
III	45–60	900–1200	Diaplectic glass, coesite
IV	60–100	1200–2500	Whole rock melt
V	>100	>2500	Vapor

* at an ambient temperature of ~25 °C.
PFs = planar fractures; PDFs = planar deformation features.

After Grieve, R. A. F., F. Langenhorst, and D. Stöffler (1996), Shock metamorphism of quartz in nature and experiment: II. Significance in geoscience, Meteorit. Planet. Sci., 31, 6-35.

Impactites – tagamites vs. impact glasses

Form at stage IV: peak pressures 60–100 GPa, T = 1200 – >2500 °C

Tagamites are produced by cooling of large melt masses; contain polymineral glass or crystallized melt, and also shocked rock fragments

Impact glasses form by cooling of individual melt splashes in air

Key challenge:

Impossible to experimentally simulate natural melt fractionation and cooling regimes

The Onorato-Simonds model (1978)

Onorato, P. I. K., D. R. Uhlmann, and C. H. Simonds (1978), The thermal history of the Manicouagan Impact Melt Sheet, Quebec, J. Geophys. Res., 83(B6), 2789-2798.

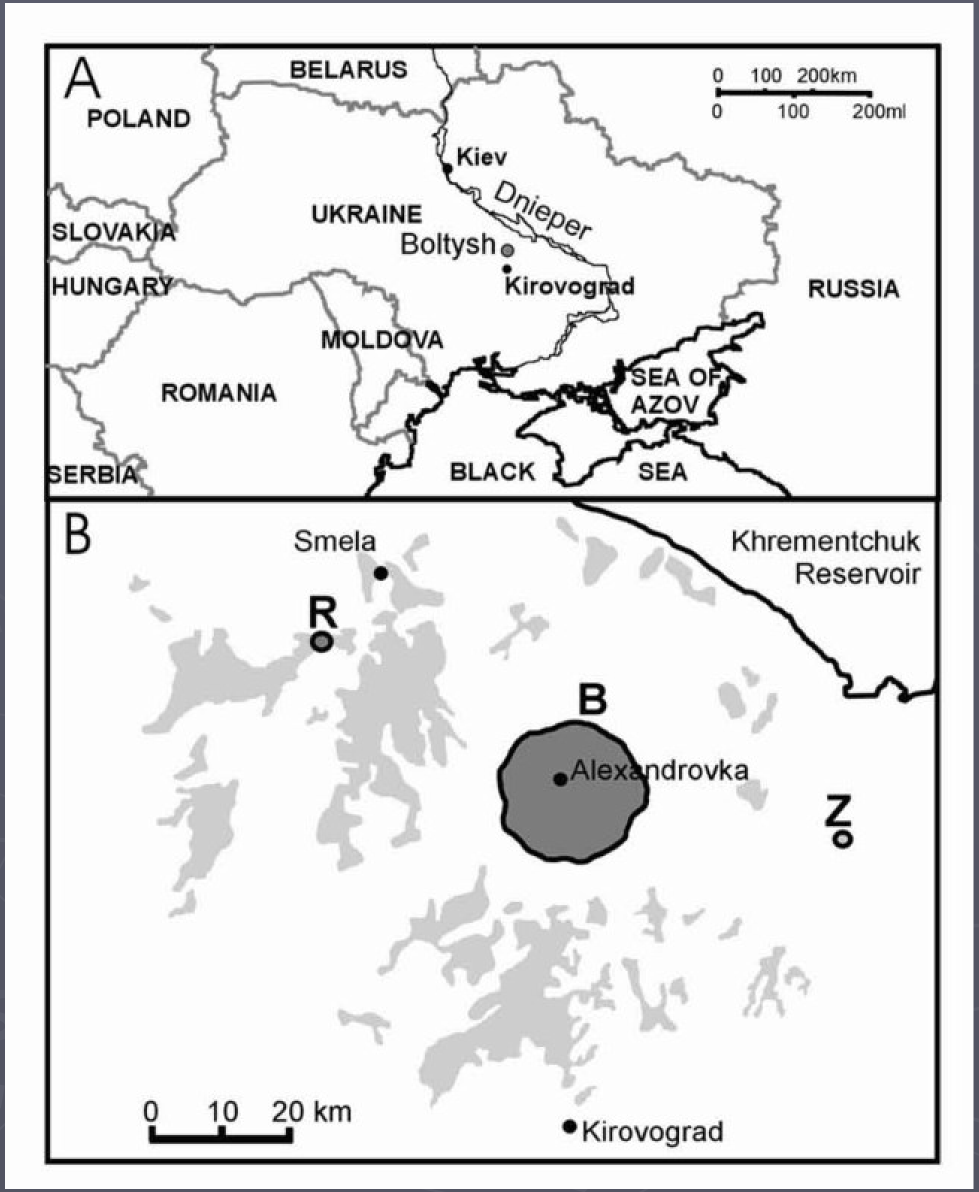
- Based on ~400 m thick tagamite body at **Manicouagan crater** (Canada, d~80 km)
- **Assumptions**:
  - Initial T of rock fragments = from shock effects in feldspar/quartz
  - Initial T of melt = from melting of sharp fragment edges
- **Two-stage cooling**:
  1. Thermal equilibrium between melt + fragments: **100–1000 sec**
  2. Cooling of central melt layer: up to **1600 years**

Limitations of the Onorato-Simonds model

1. Thicker melt bodies → slower cooling
2. Slow cooling → high-P minerals dissolve in melt → thermal transformations dominate
3. Model based **only on petrographic data** → needs independent validation

→ Magnetic methods may provide that independent test

Boltysh — an exemplary impact structure of medium size



Boltysh impact structure, Ukraine (48°45′N; 32°10′E)
Newly determined Ar-Ar age **65.39 ± 0.14 Ma**
A. E. Pickersgill et al., Science Advances 7, eabe6530 (2021)
~ 650 ky younger than Chicxulub crater

Approximately **24 km** in diameter with a **6-km**-diameter central uplift
Target rocks are Precambrian granites and granitic gneisses (1550 to 2220 Ma)
The structure is now buried beneath >500 m of post-impact sediments
R. A. F. Grieve et al., Contrib. Mineral. Petrol. 96, 56-62 (1987)

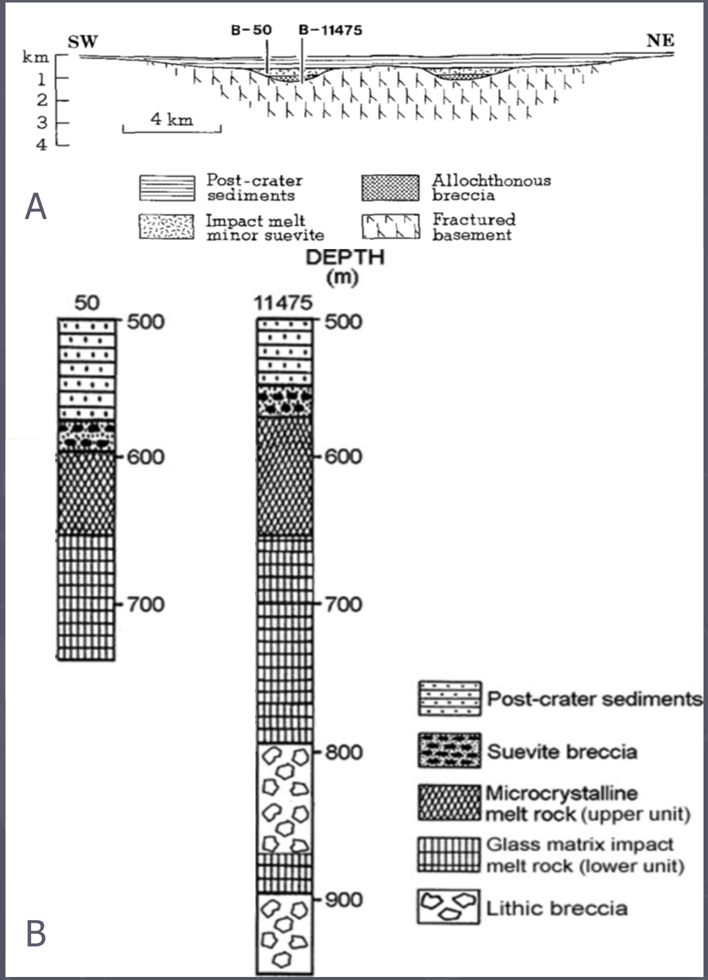
Tagamite body: total thickness ~240 m, melt volume ~10 km^3

(a) The Boltysh impact crater lies in central Ukraine, north of Kirovograd.
(b) The ejecta (pale shade) are distributed around the buried Boltysh impact crater (dark shade, marked "B"). Two other craters lie within this area, the Rotmistrovka (marked "R") and Zeleny Gay (marked "Z") craters.

After S. P. Kelley and E. Gurov, Meteorit. Planet. Sci. 37, 1031-1043 (2002)

Boltysh — an exemplary impact structure of medium size

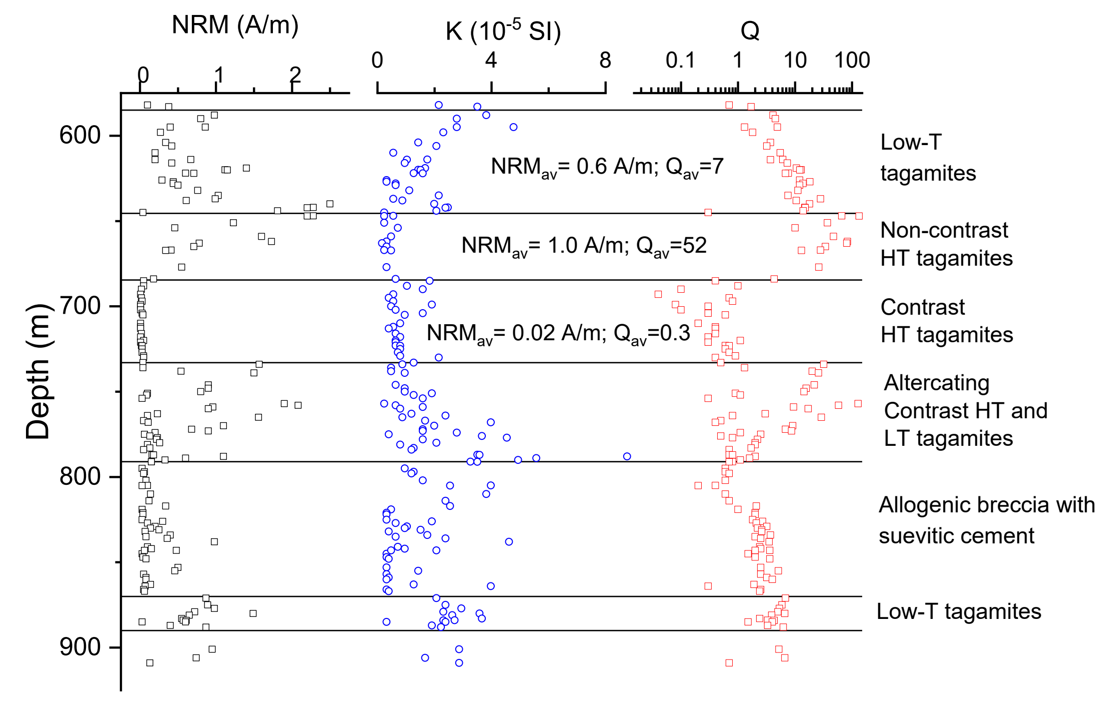
(A) Schematic section of the Boltysh impact structure showing the location of the drill holes 50 and 11475, and (B) stratigraphic columns of the impact melt rocks, suevites and overlying postimpact sediments



After R. A. F. Grieve et al., Contrib. Mineral. Petrol. 96, 56-62 (1987) and E. P. Gurov et al. Meteorit. Planet. Sci., 50, 1139-1155 (2015).

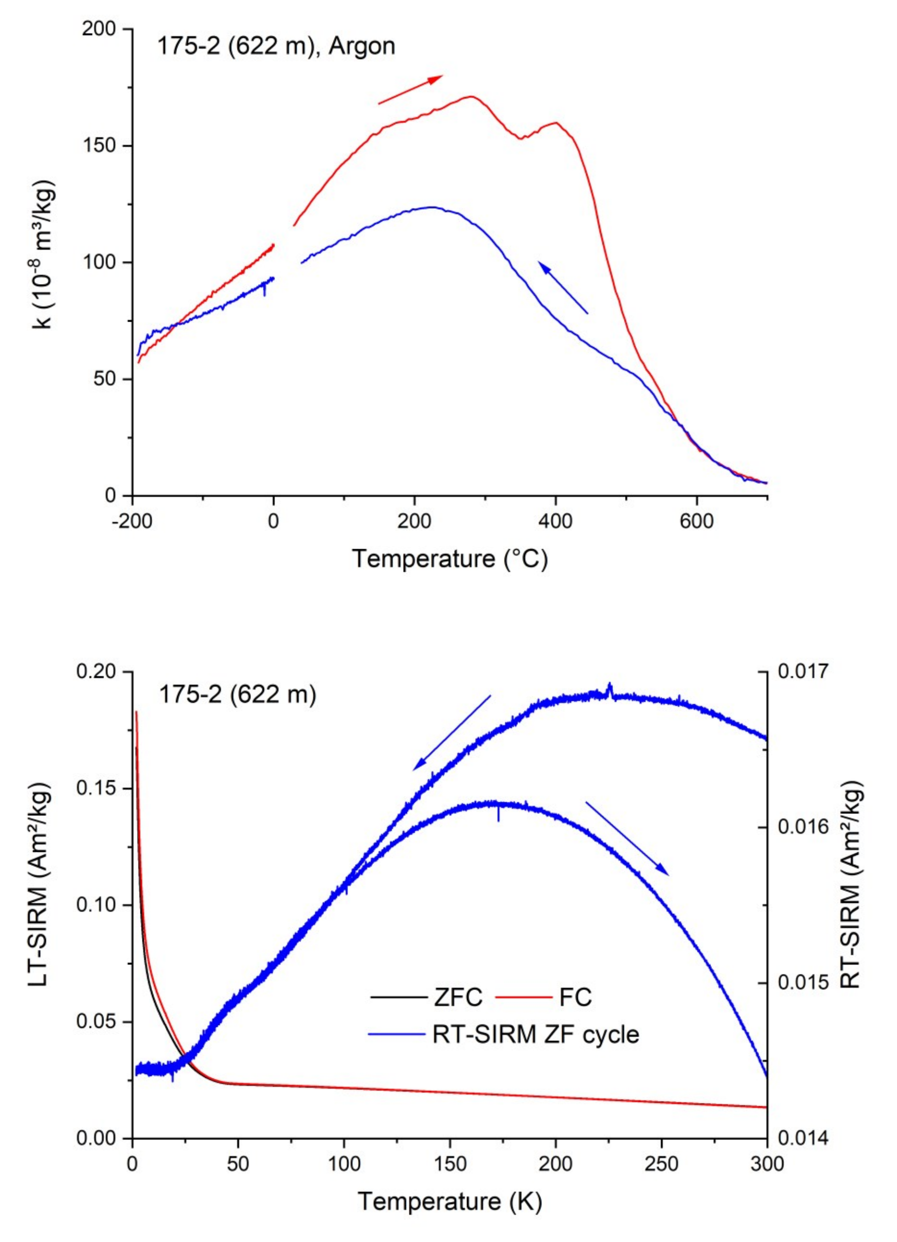
Kern material from drill hole 11475, described petrographically by V. L. Masaitis et al., Geology of astroblemes, Nedra, Leningrad (1980) and A. N. Danilin, Crystallization of impact melts (Using the example of some astroblemes of the USSR), Cand. Sci. thesis, Leningrad (1982).

Classification of impactites follows the scheme developed by Masaitis using impact melts from Popigai impact structure as an example. The crucial factor is the initial temperature of the impact melt gradually decreasing from ~2500 °C for contrast HT to about 1200 °C for LT varieties.



Changes of NRM, initial magnetic susceptibility and Koenigsberger factor with depth (V. A. Starunov, Magnetic properties of impactites, Cand. Sci. thesis, Leningrad, 1985).

622 m, low-T tagamites, upper layer



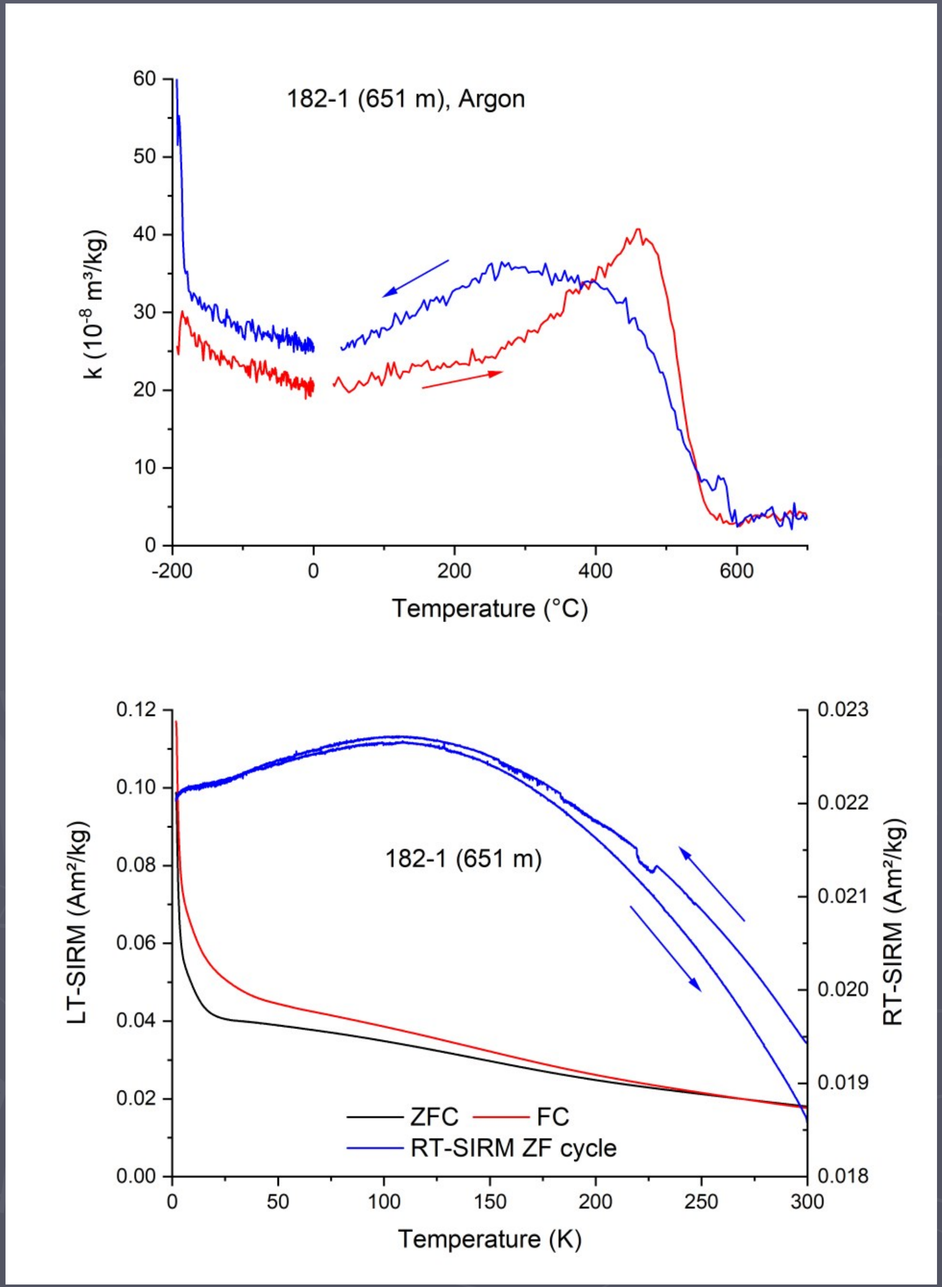
Curie temperatures on warming 310 °C and 460 °C

No Verwey transition

ZFC remanence loss between 1.8 and 10 K: 64 % of initial value

Irreversible zero-field cycle of SIRM acquired at 300 K

651 m, non-contrast high-T tagamites



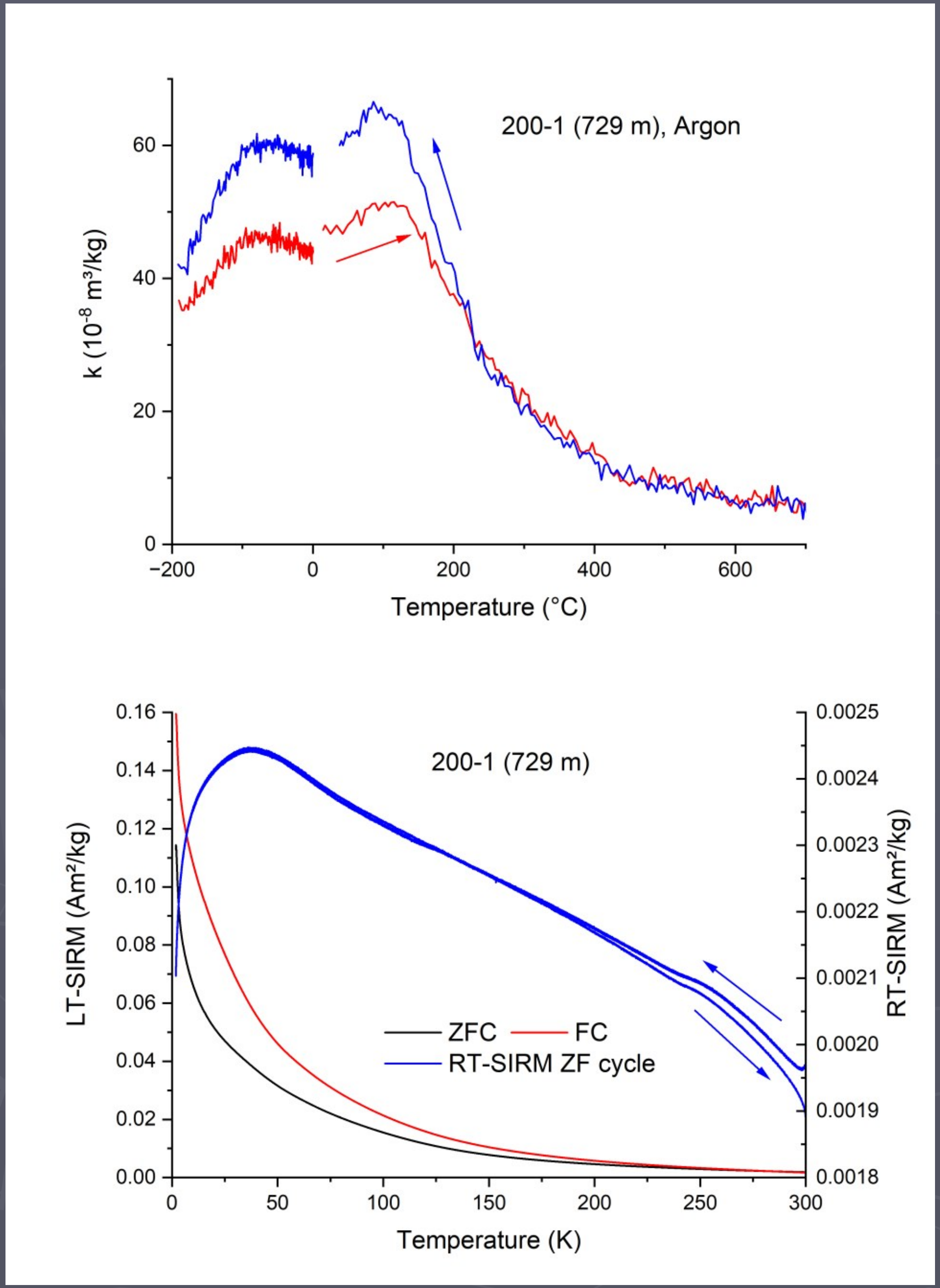
Curie temperature on warming 505 °C

No Verwey transition

ZFC remanence loss between 1.8 and 10 K: 51 % of initial value

Nearly reversible zero-field cycle of SIRM acquired at 300 K

729 m, contrast high-T tagamites



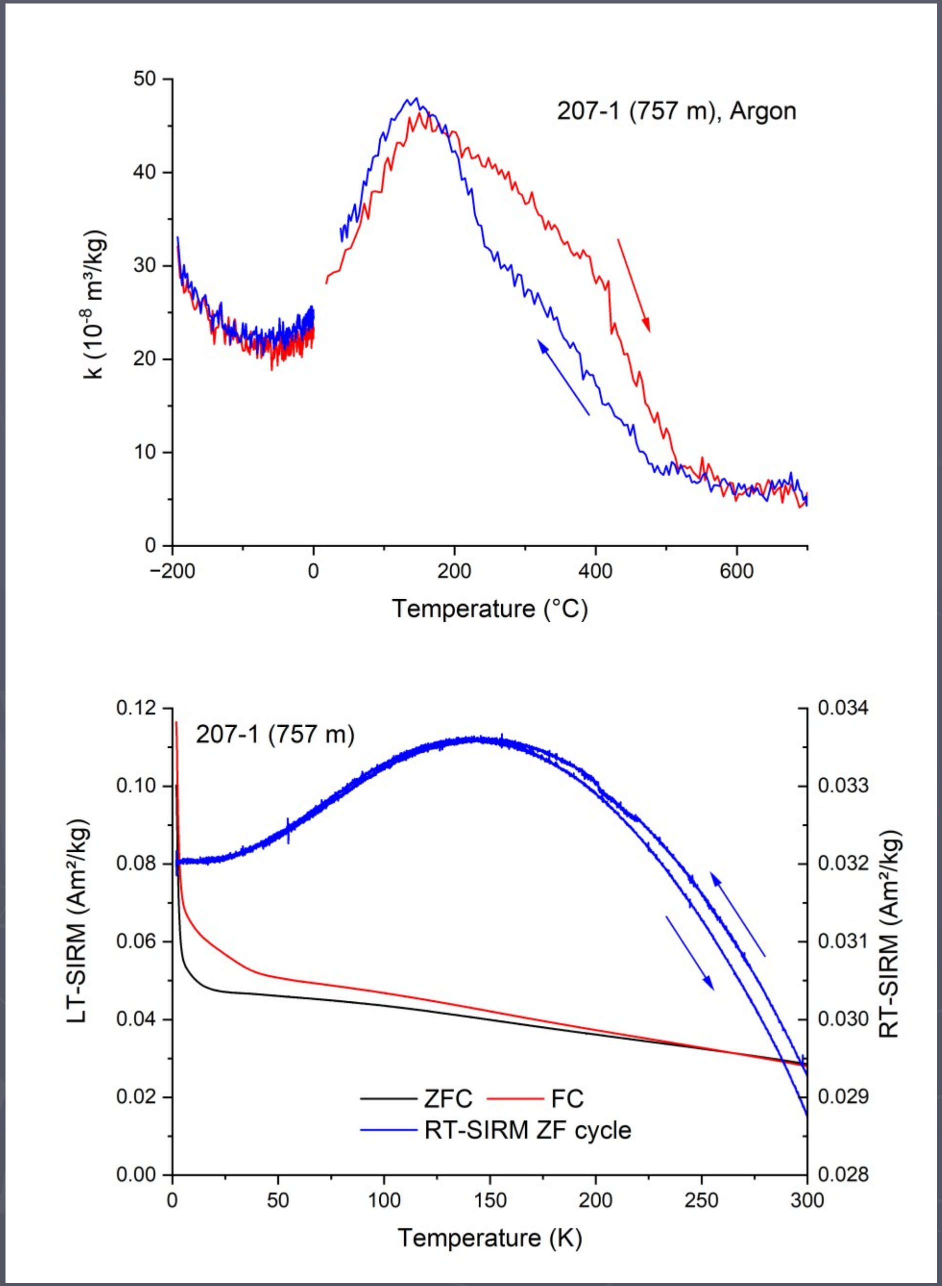
Curie temperature on warming ~150 °C

No Verwey transition

ZFC remanence loss between 1.8 and 10 K: 43 % of initial value

Nearly reversible zero-field cycle of SIRM acquired at 300 K

757 m, altercating low-T and high-T tagamites



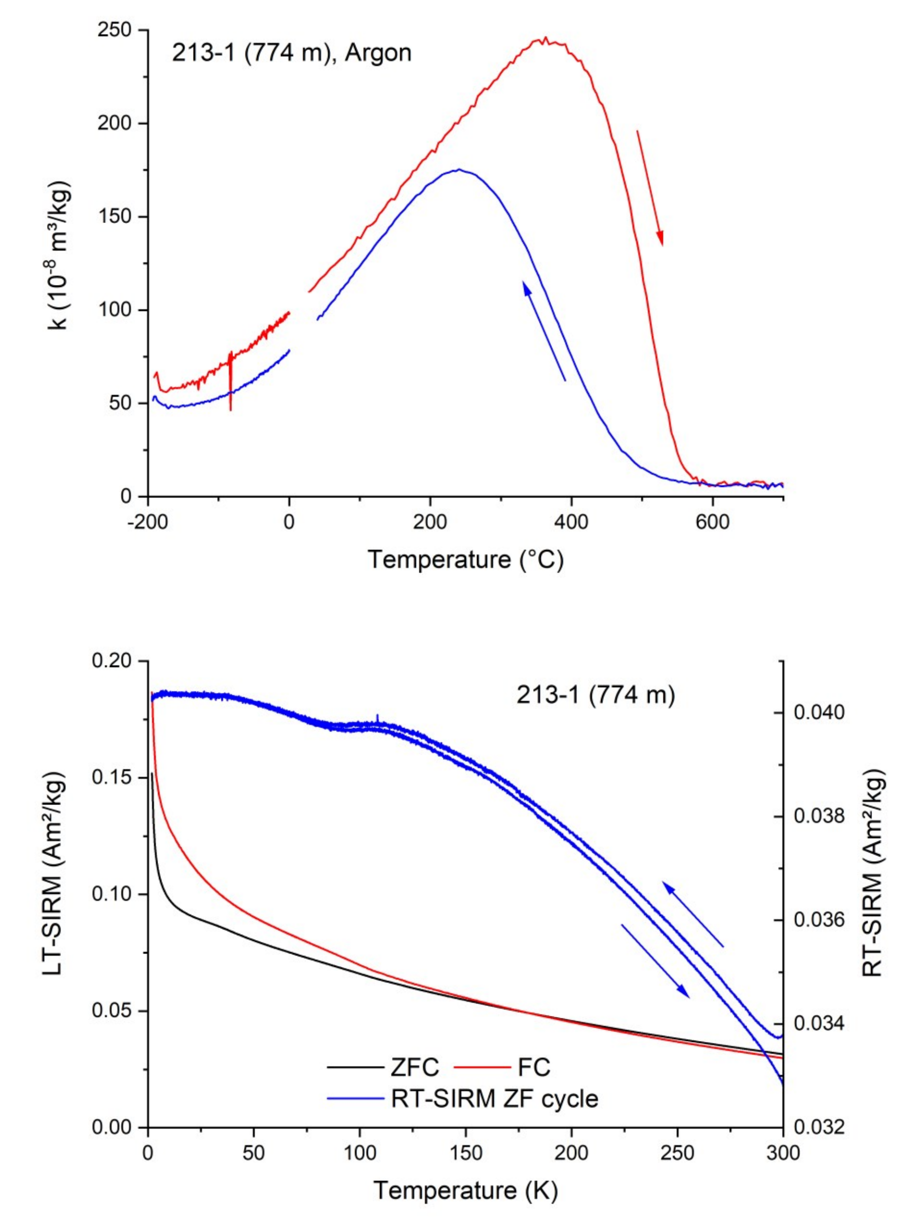
Curie temperature on warming ~440 °C

No Verwey transition

ZFC remanence loss between 1.8 and 10 K: 49 % of initial value

Nearly reversible zero-field cycle of SIRM acquired at 300 K

774 m, altercating low-T and high-T tagamites



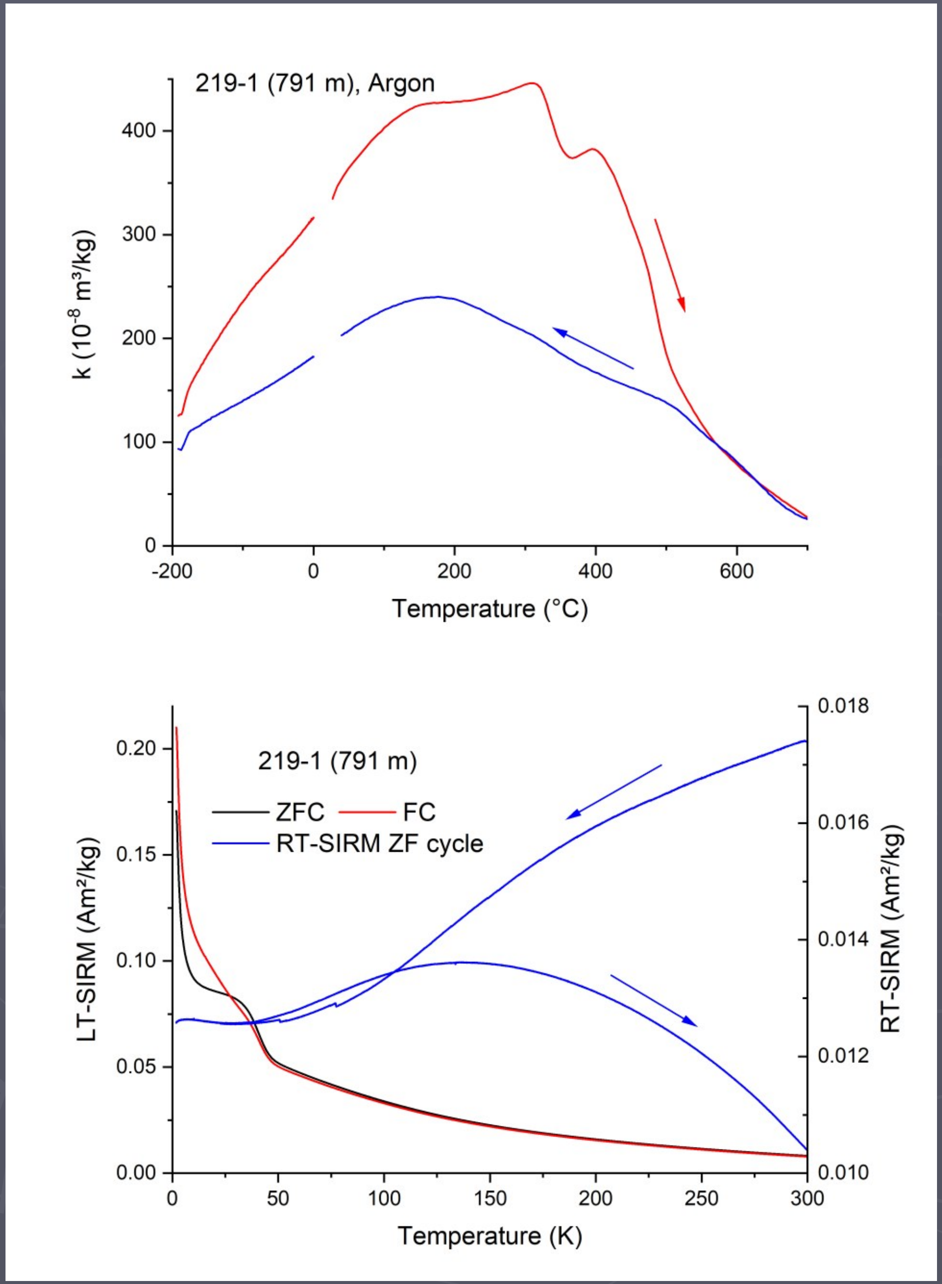
Curie temperature on warming 510 °C

No Verwey transition

ZFC remanence loss between 1.8 and 10 K: 36 % of initial value

Nearly reversible zero-field cycle of SIRM acquired at 300 K

791 m, altercating low-T and high-T tagamites



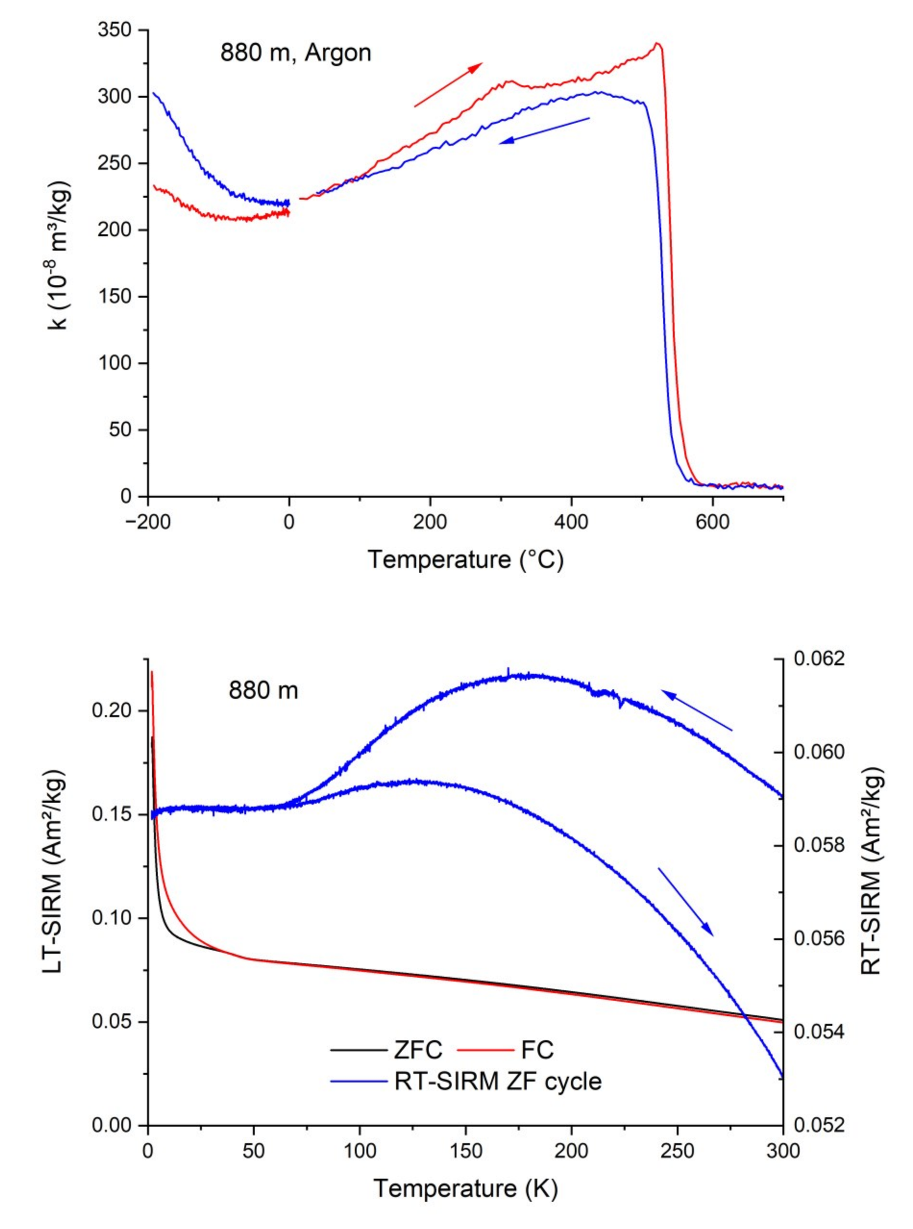
Curie temperatures on warming 335 °C and 485 °C

No Verwey transition

ZFC remanence loss between 1.8 and 10 K: 46 % of initial value

Strongly irreversible zero-field cycle of SIRM acquired at 300 K

880 m, low-T tagamites, lower layer



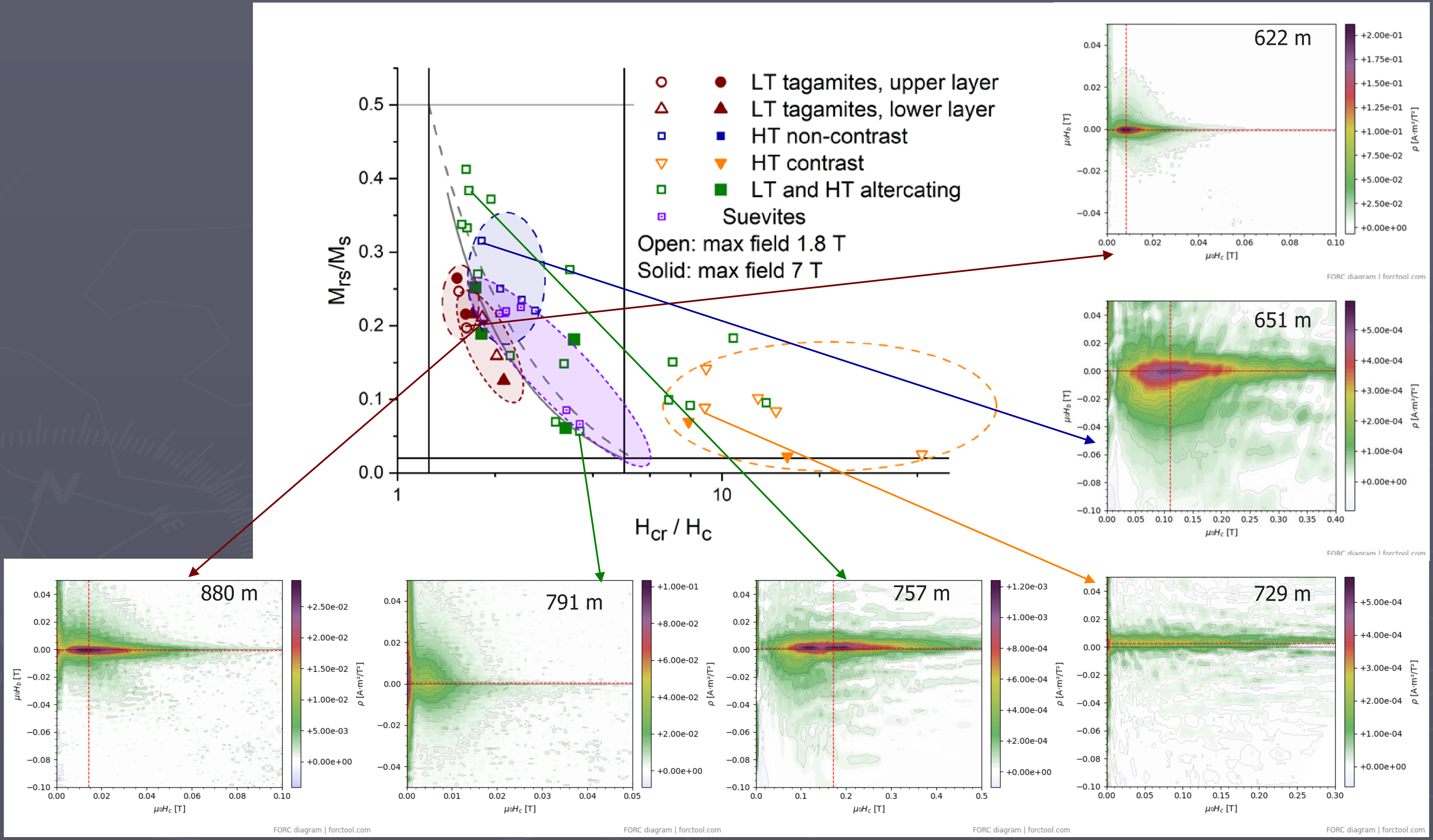
Curie temperature on warming 530 °C

No Verwey transition

ZFC remanence loss between 1.8 and 10 K: 51 % of initial value

Strongly irreversible zero-field cycle of SIRM acquired at 300 K

Boltysh Hole 11475, summary of room T hysteresis



Hole 11475, interpretation of magnetic properties

- ✓ No Verwey transition = no stochiometric magnetite
- ✓ Curie temperature gradually increases from HT- to LT-varieties of tagamites, implying the decrease of foreign cations in substituted magnetite lattice
- ✓ Magnetic coercivity reaches its extreme in non-contrast HT tagamites; contrast HT tagamites have very high B_{cr} but very low B_c due to an increased content of superparamagnetic material and thereby show up in a separate region of the Day plot; LT tagamites show moderate coercivities and lie squarely within the PSD range in the Day plot
- ✓ Measurements at cryogenic temperatures reveal a significant fraction of very fine superparamagnetic grains unblocking below 10 K. Remanence loss in this temperature range is noticeably higher in LT tagamites indicating higher content of SP material

New progressive metamorphism scale for tagamites

Stage	**Post-shock T (°C)**	**Magnetic effects**
I (LT 1 type)	1200 – 1500	PSD to MD > SD, SP; T_C ~ 500-600 °C
II (LT 2 type)	1500 – 1700	PSD to MD > SD, SP; T_C ~ 400–500, 350, and also (rarely) 770 °C
III (Non-contrast HT)	1700 – 2000	SD > SP; T_C ~400–500 °C
IV (Contrast HT)	2000 – 2500	SP >> SD; T_C ≤ 300 °C

First classification of impactites based solely on rock magnetism

Some takeaways

✓ Magnetic properties reveal **anomalously fast cooling** of impact melt (10^2–10^3 s) for thick (~240 m) tagamite bodies

✓ Fast cooling may enable **preservation of high-P minerals** and their decomposition products (e.g., wüstite → native Fe + magnetite)

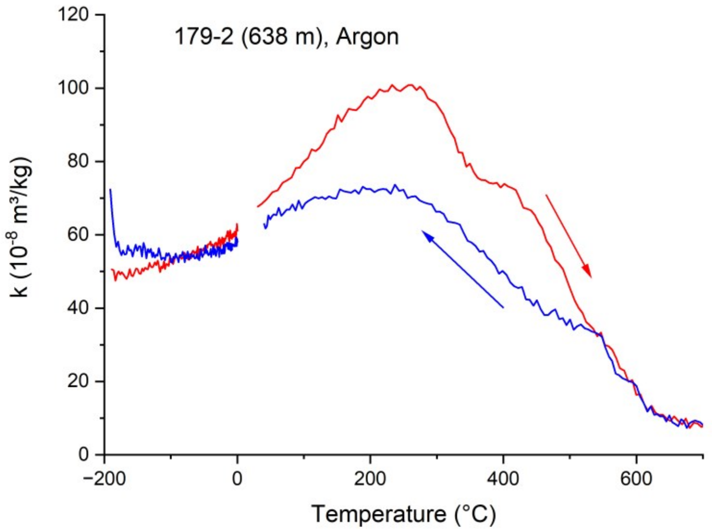
✓ Ultrafine-grained ferrimagnetic particles are **diagnostic of extreme formation conditions**

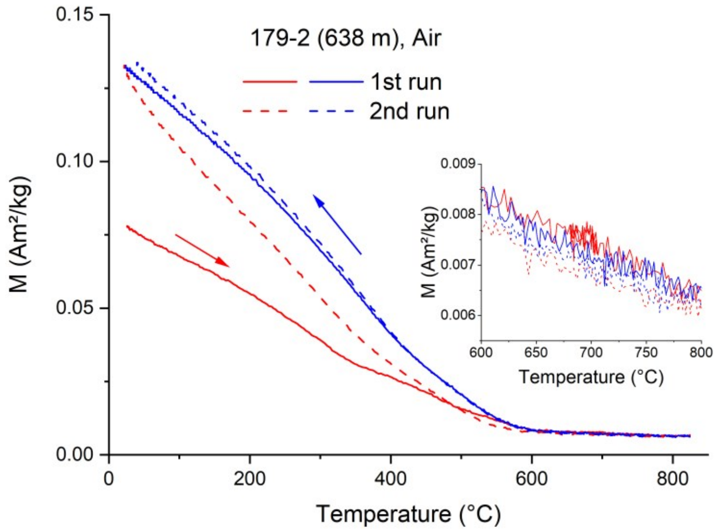
✓ The proposed magnetic-based scale **contradicts the widely accepted Onorato-Simonds model** of impact melt cooling

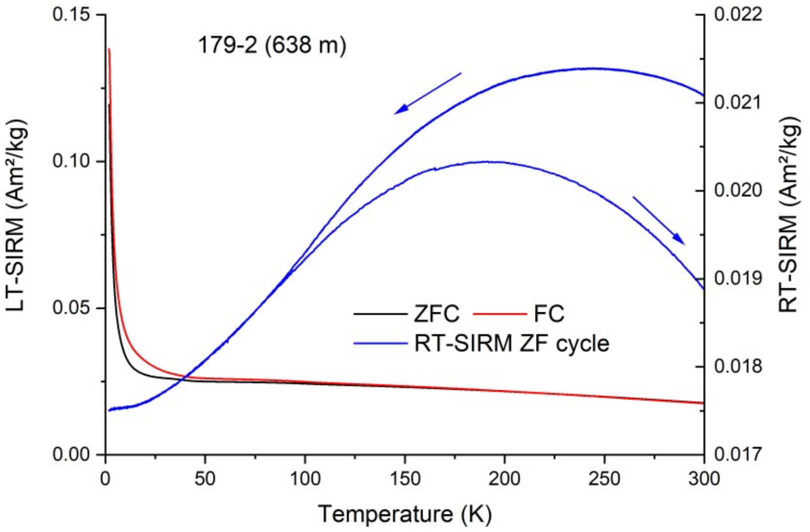
→ Rock magnetism provides a powerful, independent tool for reconstructing impactite formation conditions

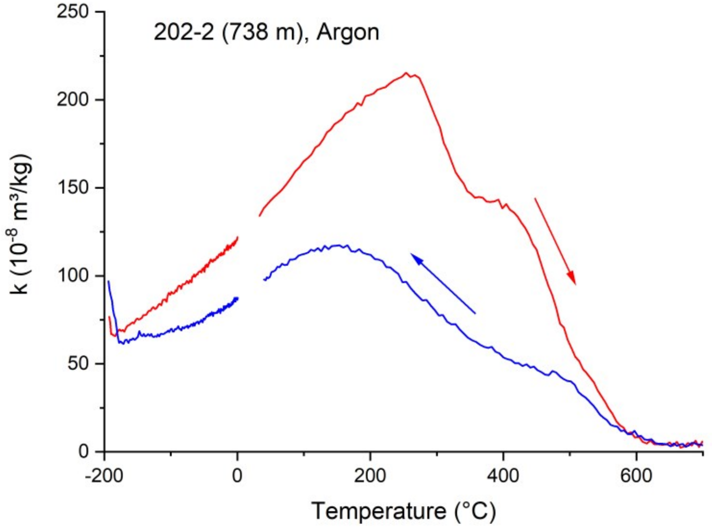
Thank You !

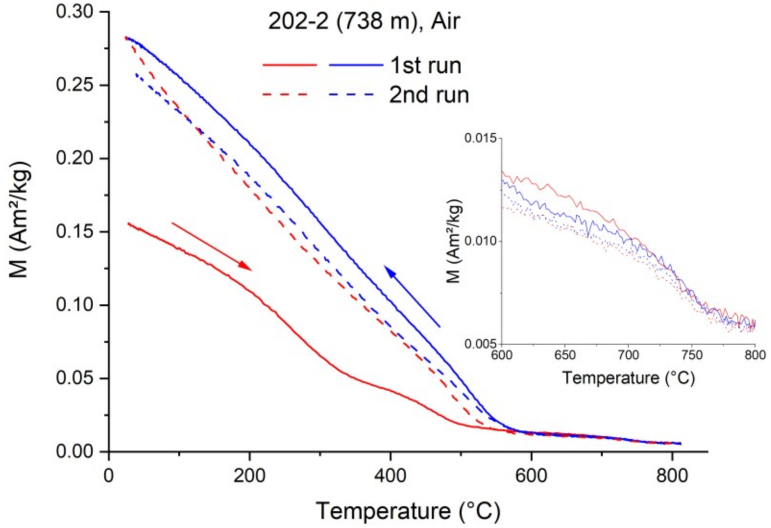
Questions?

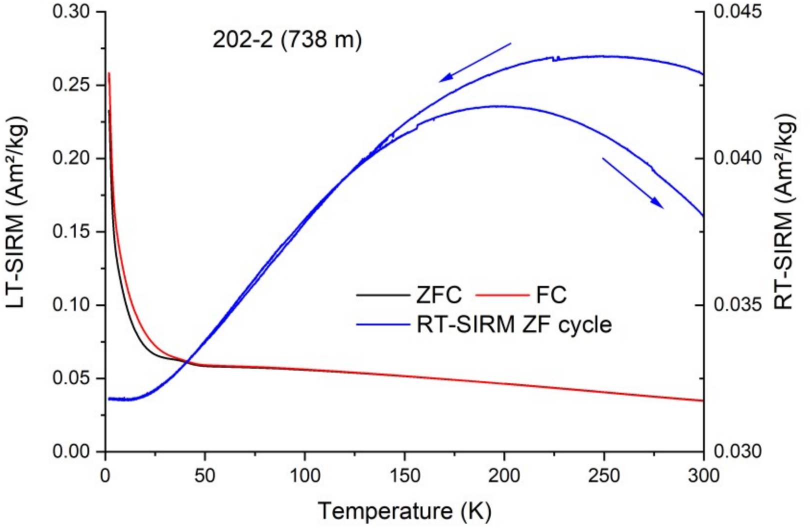

179-2 (638 m), Argon
k (10⁻⁸ m³/kg)
0
20
40
60
80
100
120
-200
0
200
400
600
Temperature (°C)


179-2 (638 m), Air
1st run
2nd run
M (Am²/kg)
0.00
0.05
0.10
0.15
0
200
400
600
800
Temperature (°C)
M (Am²/kg)
0.006
0.007
0.008
0.009
600
650
700
750
800
Temperature (°C)


179-2 (638 m)
ZFC
FC
RT-SIRM ZF cycle
LT-SIRM (Am²/kg)
0.00
0.05
0.10
0.15
RT-SIRM (Am²/kg)
0.017
0.018
0.019
0.020
0.021
0.022
0
50
100
150
200
250
300
Temperature (K)


202-2 (738 m), Argon
k (10⁻⁸ m³/kg)
0
50
100
150
200
250
-200
0
200
400
600
Temperature (°C)


202-2 (738 m), Air
1st run
2nd run
M (Am²/kg)
0.00
0.05
0.10
0.15
0.20
0.25
0.30
0
200
400
600
800
Temperature (°C)
M (Am²/kg)
0.005
0.010
0.015
600
650
700
750
800
Temperature (°C)


202-2 (738 m)
ZFC
FC
RT-SIRM ZF cycle
LT-SIRM (Am²/kg)
0.00
0.05
0.10
0.15
0.20
0.25
0.30
RT-SIRM (Am²/kg)
0.030
0.035
0.040
0.045
0
50
100
150
200
250
300
Temperature (K)

Magnetic characteristics of HT and LT tagamite layers in the drillhole 11475 section, Boltysh impact structure

Tagamite type	Depth, m	Layer thickness, m	M_{rs}/M_s	B_{cr}/B_c	B_{cr}, mT	Domain structure	T_C, °C
LT 1	585-626	41	0.16-0.24	1.7-2.0	16-25	PSD to MD > SD	500-600
LT 2	627-638	11	0.25-0.37	1.5-1.8	23-27	PSD to MD > SD	500-550, 350
Non-contrast HT	647-684	37	0.35-0.41	1.6-2.3	80-190	SD > SP	400-550
Contrast HT	685-733	48	0.02-0.15	7-50	70-189	SP >> SD	≤300
LT 2	737-744	7	0.25-0.37	1.5-1.8	23-27	PSD to MD > SD	500-550, 350, 770
HT–NHT layers	746-785	39	See above	–	–	SD + SP	–
LT 2	786-791	5	See above	1.5-1.8	23-27	PSD to MD > SD	500-550, 350
LT 1	870-890	20	0.16-0.24	1.7-2.0	16-25	PSD to MD > SD	500-600