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A Mechanically Strong Inner Core Implied by Deformation of Silicon-bearing Alloys

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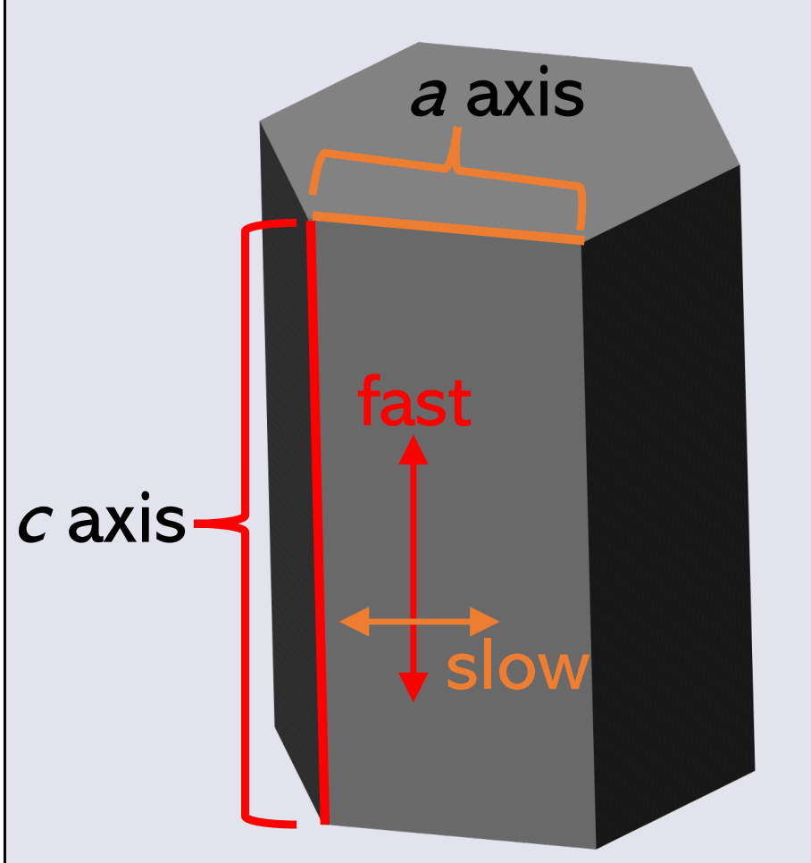
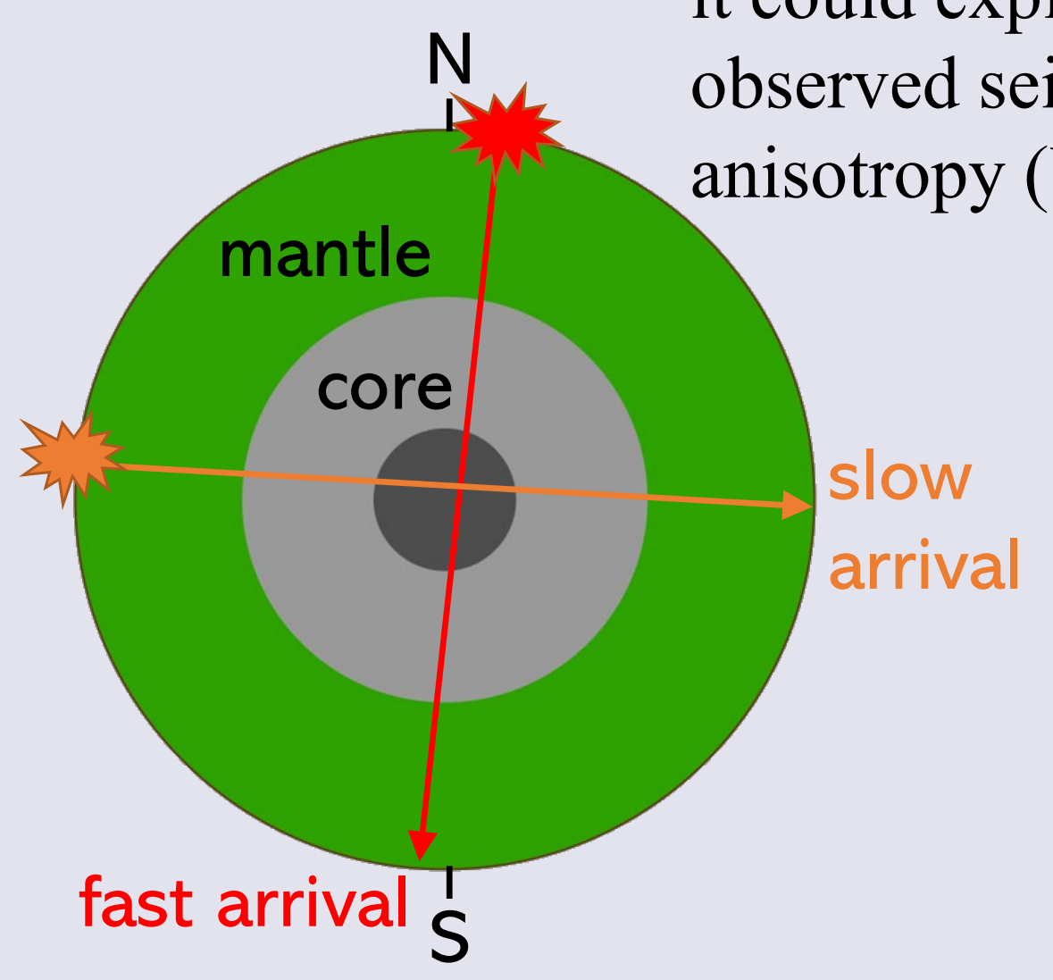
1. Background

- Seismic waves travel through the inner core ~3% faster North-South compared to East-West [1].
- Fe is hcp-structured in the inner core [2], so this anisotropy is interpreted as evidence for alignment of inner core crystallites with Earth's rotation axis.
- Previously, deformation had only been measured on alloys without light elements [3,4,5]. We wanted to know if a realistic composition would be sufficiently malleable and possess the correct deformation texture to explain the anisotropy.



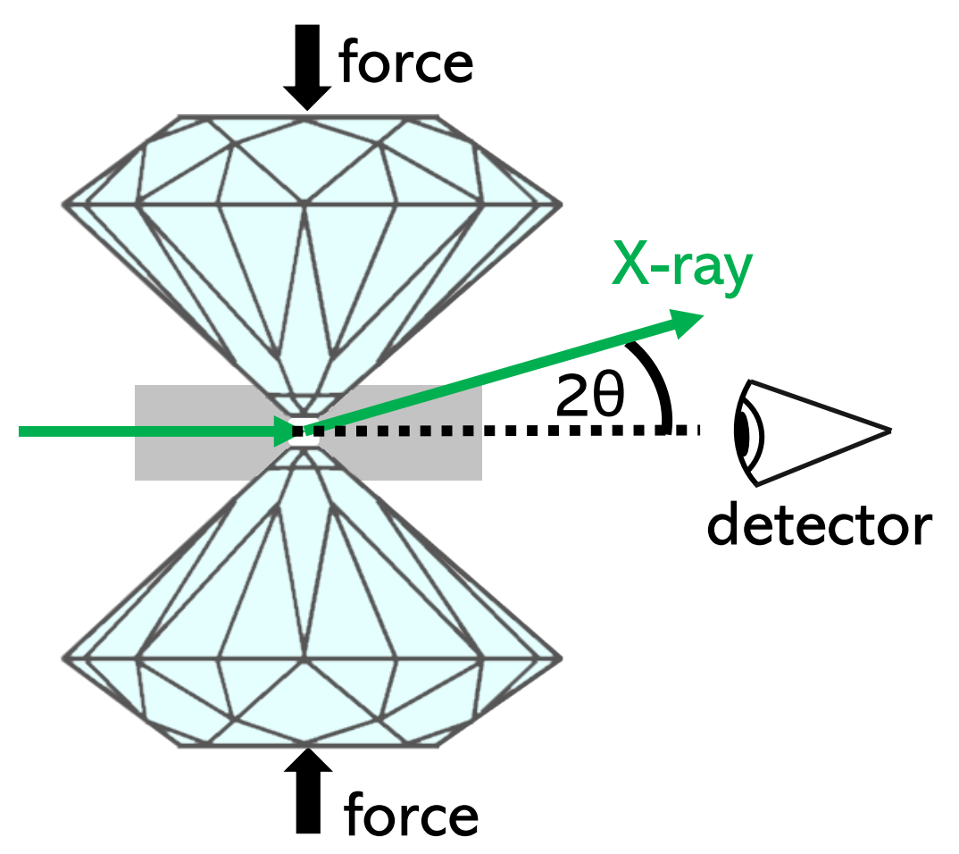
Crystallites of hcp Fe are seismically fast parallel to their *c* axes (**left**).

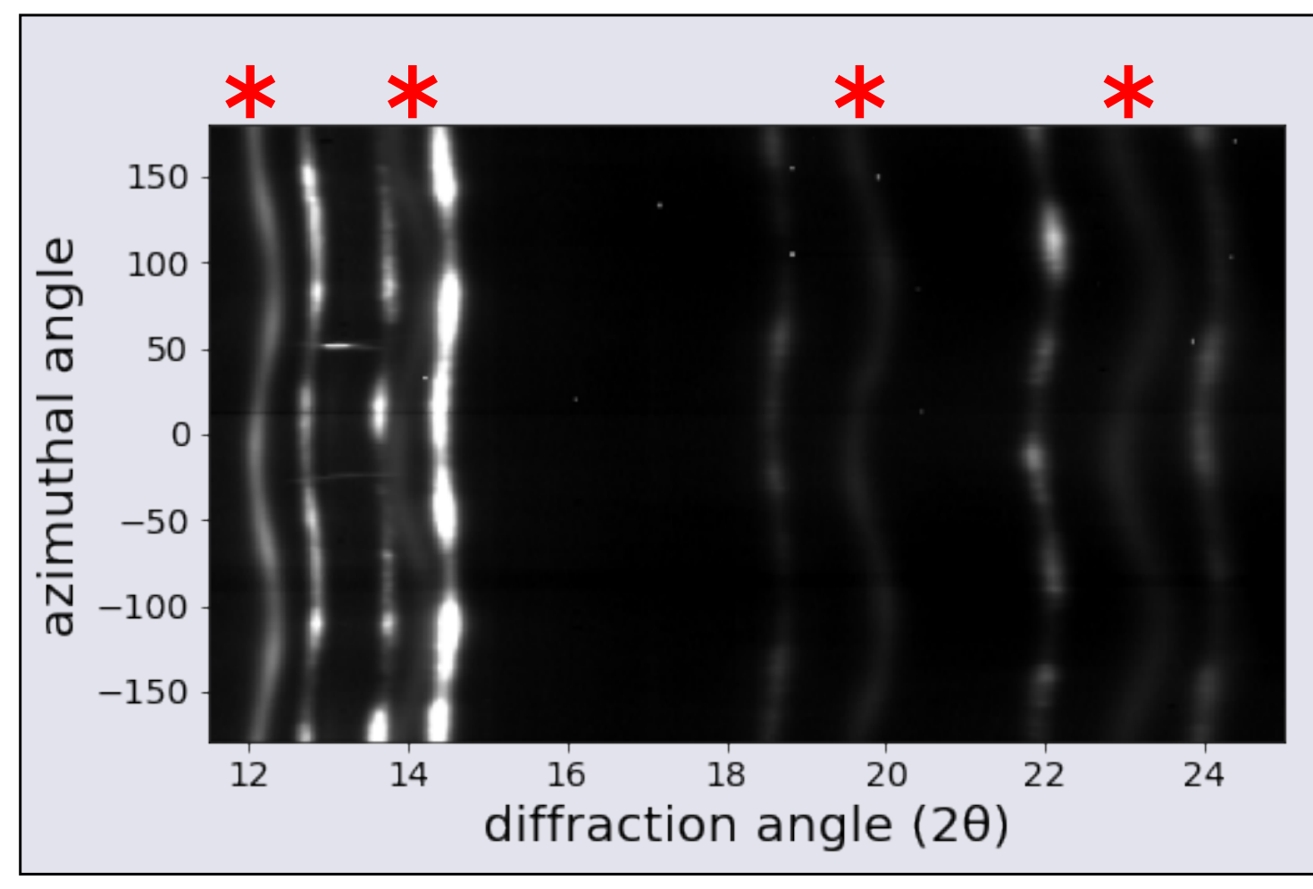


If the *c* axes of inner core alloy crystallites were aligned North-South by plastic flow, it could explain the observed seismic anisotropy (**below**).

2. Radial X-ray diffraction

- We performed deformation experiments on hcp Fe–Ni–Si alloys (up to 6 wt% Ni and 10 wt% Si) up to 60 GPa and 1650 K.
- Diamond anvil cell compression is inherently uniaxial. Radial X-ray diffraction (**right**) measures the lattice planes experiencing maximum deviatoric stress.
- We quantified the material strength of Fe–Ni–Si alloys (i.e., how difficult they were to deform) and their deformation textures (i.e., do their *c* axes align).





Unrolled radial diffraction pattern showing peaks from the alloy sample and pressure standard (Pt, red asterisks).

Sinusoidal peak deformation indicates elastic stress (related to material strength), and brightness variations indicate plastic deformation (related to texture).

References & acknowledgements

1. Deuss (2014) *Ann. Rev. Earth Planet. Sci.* 42: 103–26.
2. Tateno et al. (2015) *EPSL* 418: 11–19.
3. Singh et al. (1998) *Journ. App. Phys.* 83: 7567.
4. Reagan et al. (2018) *PEPI* 283: 43–47.
5. Gleason & Mao (2013) *Nature Geos.* 6: 571–574.
6. Merkel et al. (2013) *Acta Mater.* 61: 5144–5151.
7. Morrison et al. (2019) *PEPI* 294: 106268.

- Parts of this work are published in Brennan et al. (2021) *JGR:SE* 126: e2020JB021077.
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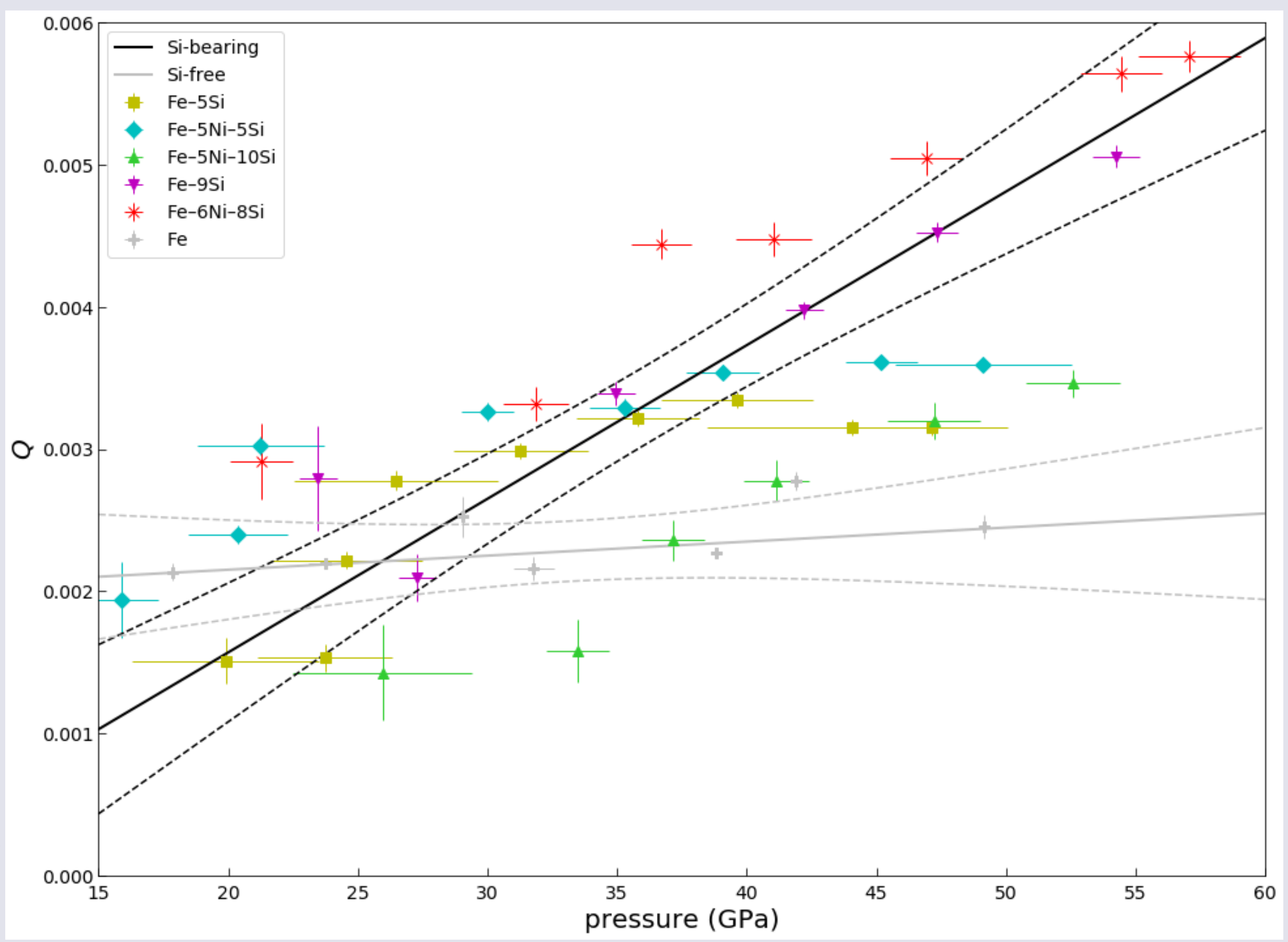
3. Alloy strength

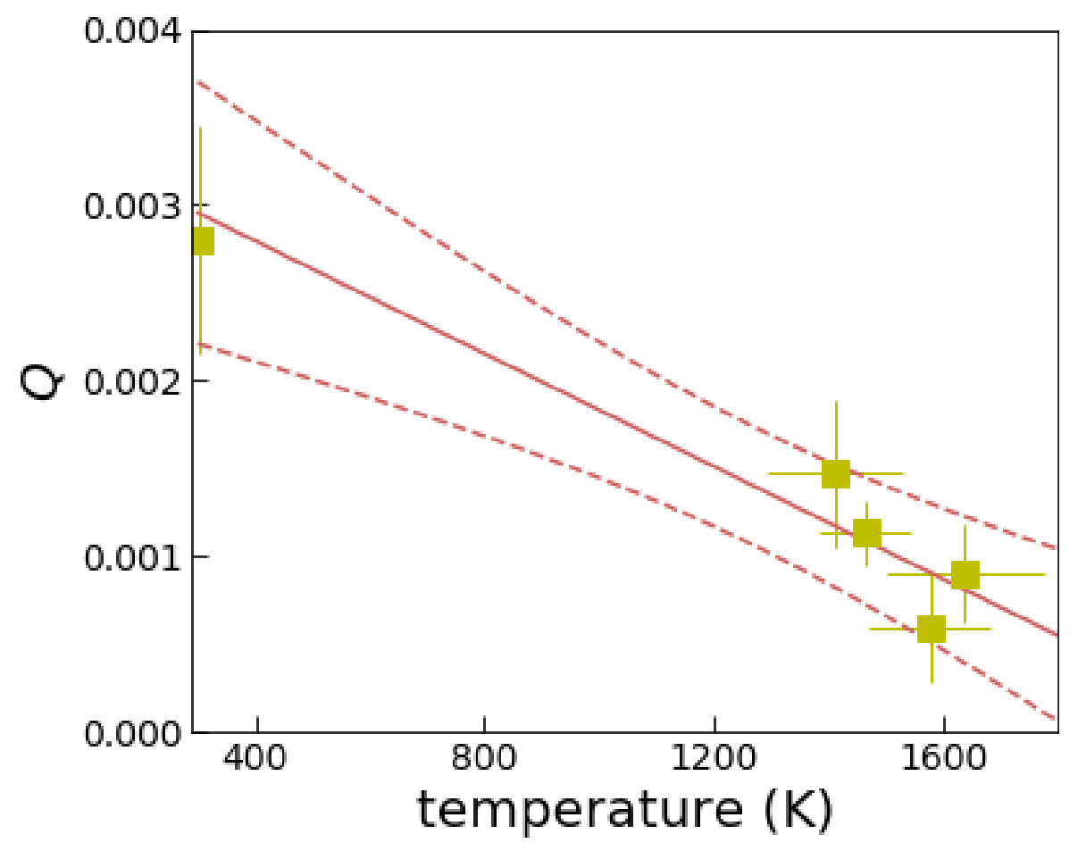
- Si-bearing alloys demonstrated a much greater increase in peak deformation with pressure compared to unalloyed Fe.
- We did not observe a significant compositional trend within the Si-bearing alloys. Fe–5wt% Ni–5wt% Si was unusually weak, but still stronger than Fe.

The peak deformation parameter Q varies as $t = 6GQ$, where t is yield strength and G is shear modulus [3].

Si-free (Fe):
$\partial Q/\partial P \approx 1.0 \times 10^{-5}\,\frac{1}{\text{GPa}}$, consistent with previous studies [4,5,6].

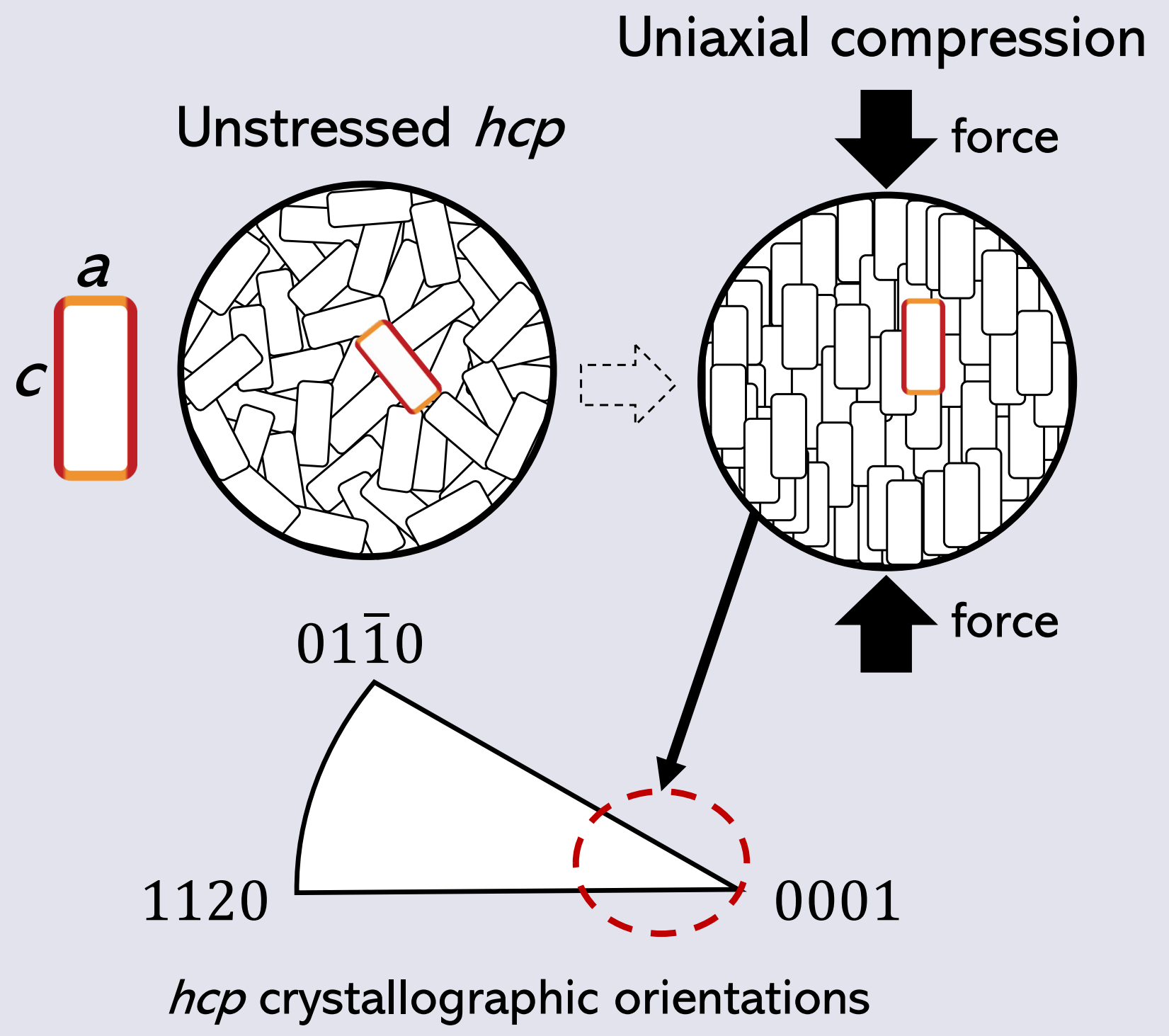
Si-bearing (Fe–Ni–Si):
$\partial Q/\partial P \approx 1.1 \times 10^{-4}\,\frac{1}{\text{GPa}}$, much higher than reported for any alloy without a light element.





- By heating one of the samples, we measured $\partial Q/\partial T \approx -1.6 \times 10^{-6}\,\frac{1}{K}$, consistent with the only other published value [6].
- Calculating material strength also required Fe–Ni–Si G values, which were obtained from NRIXS measurements of Si-bearing compositions [e.g., 7].

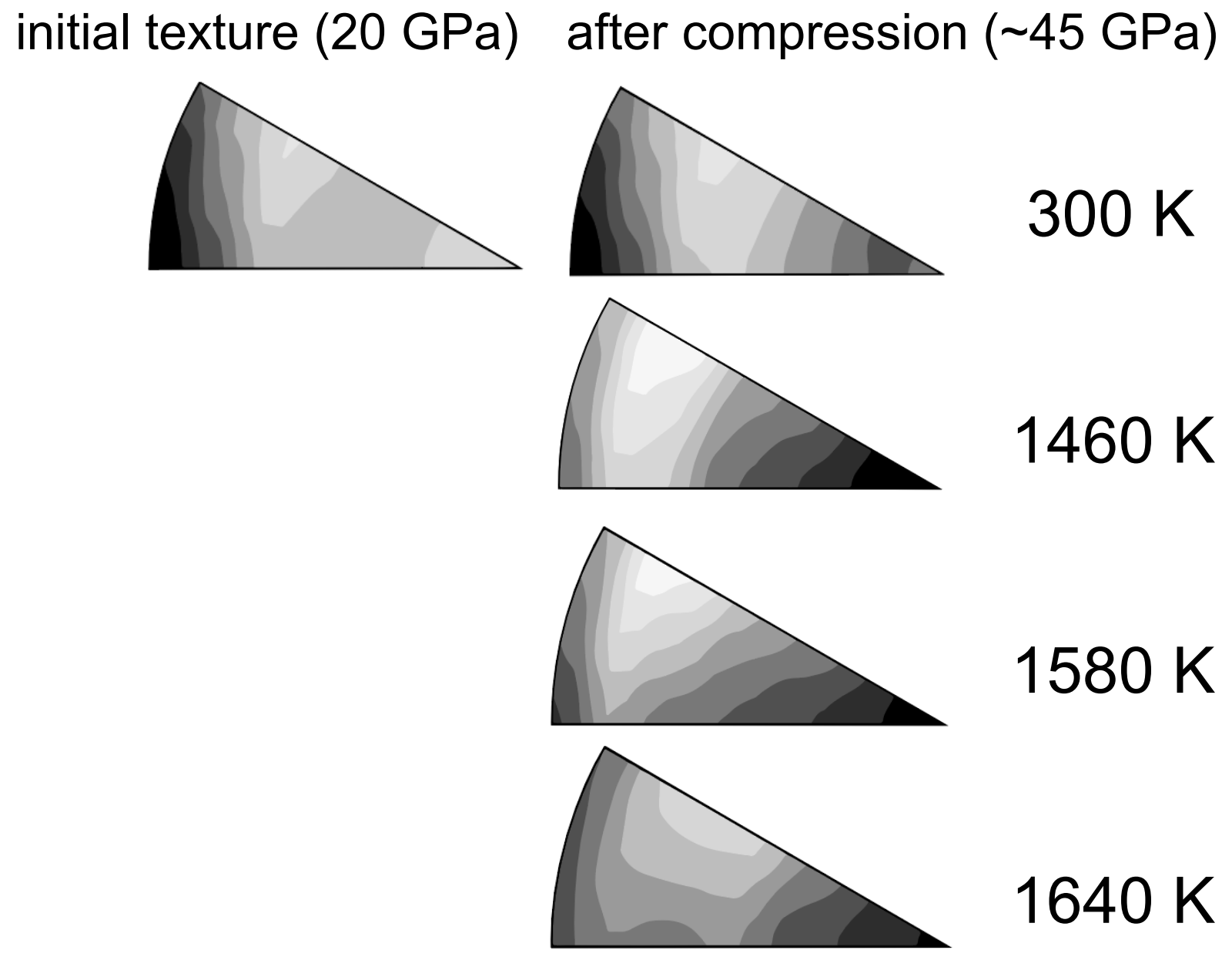
4. Alloy texture



Plastically deformed hcp crystallites tend to undergo basal slip and align their *c* axes with the compression direction (**top**).

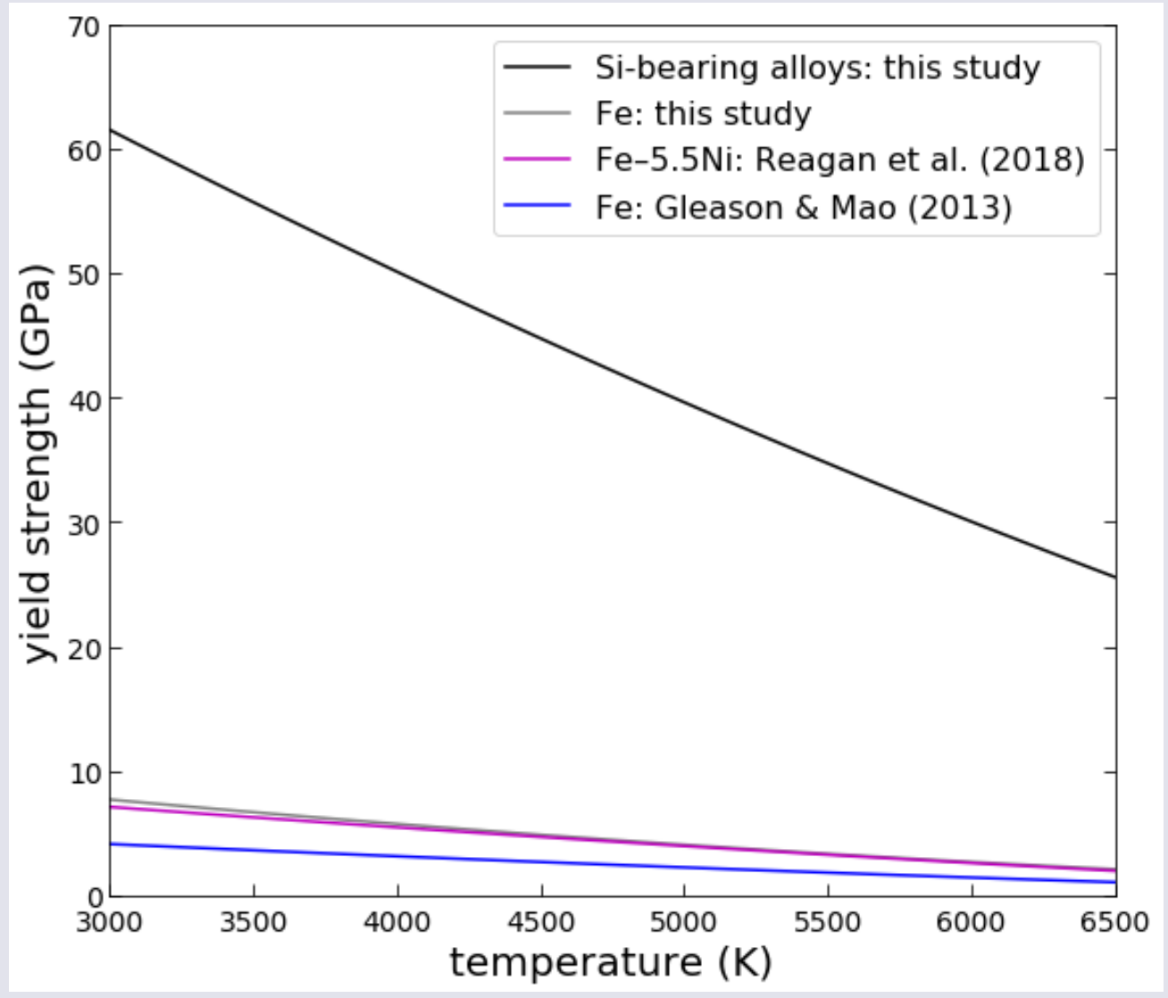
On an inverse pole figure (**bottom**), this texture corresponds to a 0001 maximum.

- At 300 K, the Si bearing alloys showed the expected texture, but also pyramidal slip (at $11\bar{2}0$) not seen in pure Fe.
- Upon heating, the intensity of this second maximum decreased, producing a texture consistent with *c* axis alignment in the inner core.



5. Implications

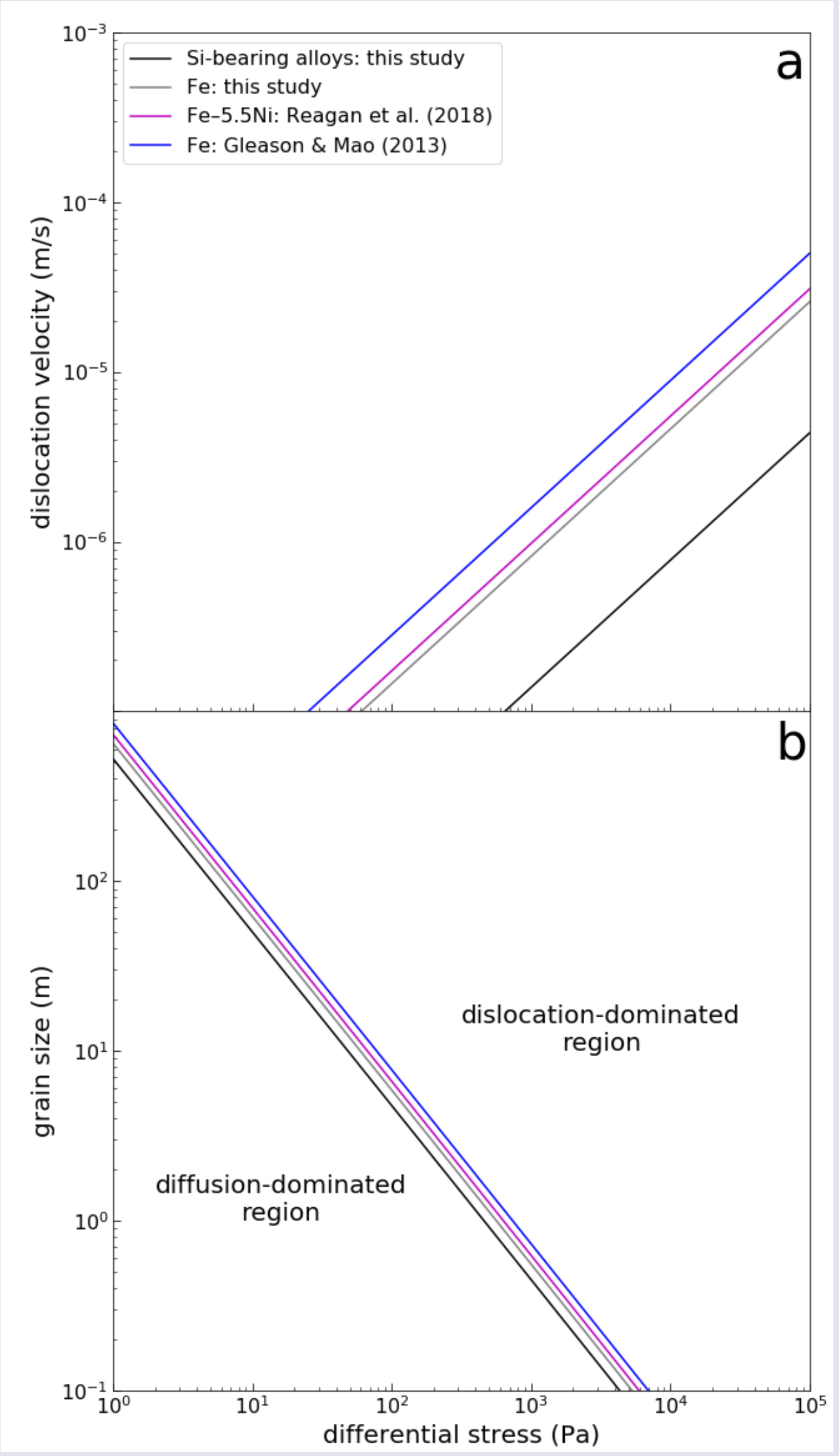
Inner core strength



Our pure Fe experiment reproduces previous measurements on Si-free alloys.

Our Si-bearing alloys are up to an order of magnitude stronger. This implies that they would require significantly more force in order to induce plastic deformation (and thus texturing) in the inner core.

Inner core deformation



An Si-bearing alloy is stronger and more viscous than an alloy without light elements and has less mobile lattice dislocations (**a**). Greater deviatoric stresses are needed to achieve the same strain rate (and degree of plastic deformation).

Deformation of a strong inner core could be dominated by diffusion of lattice defects. This would not result in texturing, meaning the observed inner core texture must have arisen from another process like preferential grain growth.

However, the inner core stress state and grain size are highly uncertain, as is the Si effect on shear modulus. A stronger alloy might even enhance dislocation-dominated deformation (**b**).

6. Summary

- Addition of a light element (Si) drastically increases the strength of Fe-rich alloys at high pressures.
- Compared to pure Fe, Si-bearing alloys may experience more pyramidal slip upon plastic deformation, but they can still produce the observed inner core anisotropy.
- A stronger inner core would reduce the effectiveness of dislocation creep, though the dominant mode of deformation is still highly uncertain.