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Orientation Piezometry: Quantifying Non-Hydrostatic Stress from Mineral Chemistry

BENJAMIN HESS[1] AND JAY AGUE[2]

[1]University of Oxford
[2]Yale University

Mineral chemistry underpins geothermobarometry and reconstruction of tectonic processes. Yet most thermodynamic approaches assume hydrostatic pressure, even though subduction zones, shear zones, and collisional orogens experience non-hydrostatic stresses that can exceed hundreds of MPa. How stress influences mineral compositions and whether mineral chemistry can directly record stress remains a fundamental question.

The thermodynamic framework of Larché and Cahn[1] indicates that multicomponent, elastically anisotropic minerals do not have a single equilibrium composition under non-hydrostatic stress. Instead, equilibrium compositions vary systematically with crystallographic orientation relative to the stress field. Grain-to-grain chemical variation in a monomineralic aggregate can therefore reflect stress magnitudes and directions.

Here, we present a quantitative framework for extracting paleo-stress information from mineral compositions termed "orientation piezometry"[2]. Two complementary inverse modeling approaches are introduced. (1) A coupled orientation piezometer integrates crystallographic orientation data and mineral chemistry to recover the full stress tensor. (2) A decoupled orientation piezometer uses only the observed compositional spread among grains to estimate differential stress and can be used even when expected orientation–composition relationships are decoupled (e.g., by grain rotation).

Synthetic clinopyroxene and feldspar datasets demonstrate that differential stresses of a few hundred MPa generate measurable grain-scale compositional variations (~0.04–0.05 mole fraction). Inverse modeling recovers principal stresses with uncertainties of only a few to tens of MPa for realistic analytical precision. Even when orientation-composition relationships are decoupled, differential stress magnitudes can be robustly estimated from the spread of mineral compositions.

Orientation piezometry provides a thermodynamic bridge between mineral chemistry and rock mechanics. By enabling stress to be quantified directly from solid-solution compositions, this approach opens new opportunities to evaluate stress magnitudes in shear zones, subduction complexes, and deep crustal rocks. More broadly, incorporating stress into compositional analysis offers a new pathway for reconciling metamorphic pressure estimates with geodynamic models and for rethinking the relationship between pressure, depth, and tectonic stress in Earth's interior.

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[1] Larché, F., & Cahn, J. (1985). *Acta metallurgica*, *33*(3), 331-357.

[2] Hess, B., & Ague, J. (2024). *Journal of Geophysical*