P-T-fluid evolution of the Quetico basin: a metamorphic origin for Archean gold?

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CONTEXT

The fluid and metal source for gold deposits, especially Archean-aged, is highly debated.

Metamorphic devolatilization is a prevailing model:
- Supracrustal rocks experience dehydration reactions during prograde metamorphism
- Au-bearing phases (sulfides) break down and Au can be mobilized as S species
- Carbonates break down and release CO2 in the fluid
- Vertical structures (shear zones) allow focus and transport of fluid

This process can be investigated with **petrology, chemistry** and **phase equilibira modeling:**
- A quantitative pressure-temperature-composition approach (P-T-x)

The **Quetico subprovince, northern Ontario (Superior Province)**:
- ~2.7 Ga metasedimentary belt dominated by turbiditic wacke
- >1200 km strike-length across the western Superior craton

METHODOLOGY

Field and GIS analysis
- Compilation work: historical mapping, whole-rock, and geochronological data
- Transect-style isograd, structural, and stratigraphy mapping (~600 outcrops)

Thin-section and whole-rock analysis
- Optical microscopy: mineral assemblages and textures
- Scanning electron microscopy (SEM) and energy dispersive spectrscopy (EDS): mineral mapping and zoning profiles
- Electron probe micro analysis (EPMA): mineral chemistry
- Whole-rock chemistry by multivariate analysis: inductively coupled plasma optical emission/mass spectrometry for major and trace elements (ICPOES/ICPMS) and combustion furnace infrared spectrometry for H,C, and S.

Phase equilibria modeling
- Thermobarometry: pressure temperature (P-T) phase diagrams (pseudosections); isopleth convergence (solid solution mineral compositions); pure H2O fluid.
- Fluid evolution: composition-gradient (X-TP) phase diagrams; mixed H-O-C-S fluid, fixed fluid moles with stepwise fractionation

METAMORPHIC ZONES

Metamorphic zones defined by the first or last appearance of rock-forming minerals in pelitic rocks (isograds):

Increasing grade
- Chlorite-white mica (Chl-WM)
- Biotite (Bt)
- Garnet (Grt)
- Staurolite-andalusite (St-And)
- Cordierite (Crd)
- Sillimanite (Sil)
- Melt (Liq)
- Orthopyroxene (Opx)

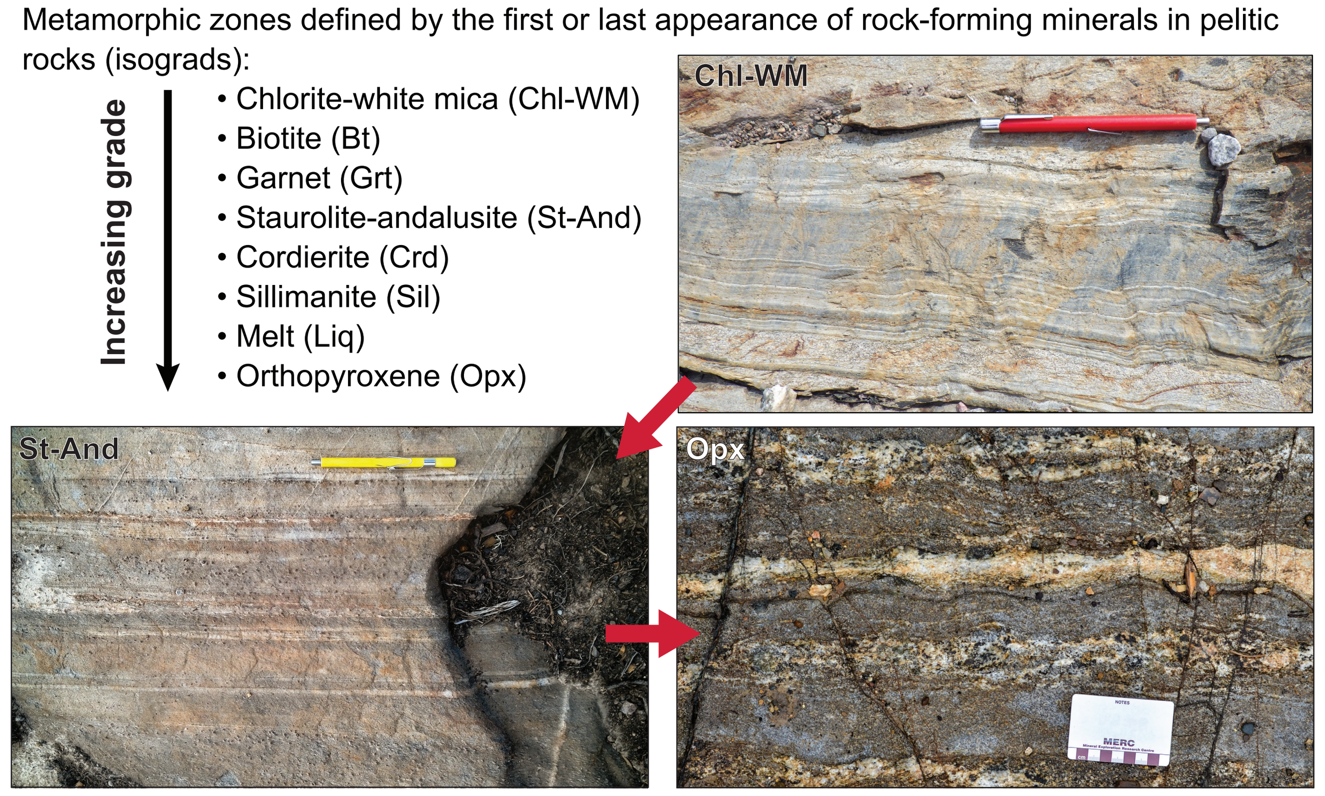

Fig. 2. Representative field photos of metasedimentary rock progressively metamorphosed through the different zones.

PROTOLITHS

Four groups of metasedimentary rocks are idenitified, based on mineral assemblages (+Ilm, Py, Po):

Pelite: Qz- and Pl- poor; Grt, Bt ± Ms, St, And, Crd, Sil, Opx

Semipelite: Qz- and Pl- rich; Bt ± Ep, Ttn, Grt, Crd, Opx

Calc-semipelite: Qz- and Pl- rich, Amp, Bt, ± Ep, Ttn, Grt, Opx

Mafic sediment: Qz- and Pl-poor, mainly Amp

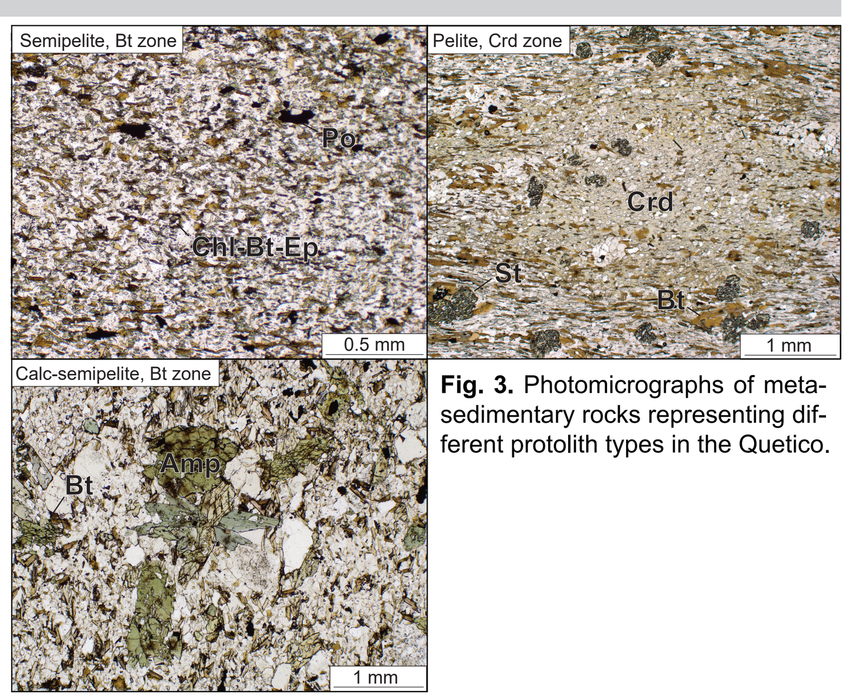

Fig. 3. Photomicrographs of metasedimentary rocks representing different protolith types in the Quetico.

COMPILATION BEDROCK MAP

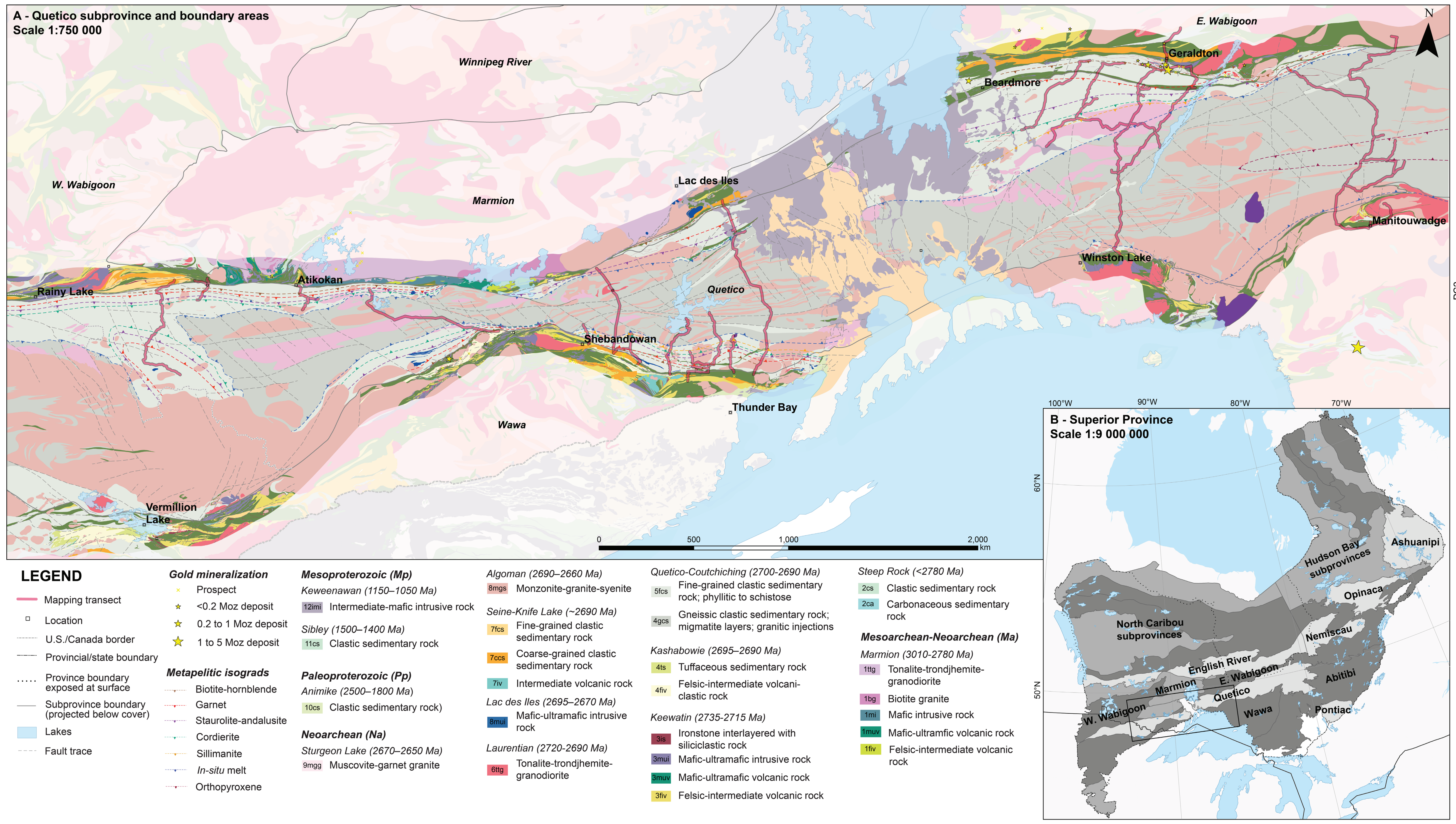

Fig. 1. A) Geological map of the study area in the central Quetico subprovince compiled from new and historical (Ontario Geological Survey) mapping. The legend and map units outside of the study area (whitened for clarity) are from (Montsion et al., 2018). B) Map of Superior Craton, Canada, with subprovince types: sedimentary (light grey), plutonic (grey), and volcanic (dark grey) (after Stott et al., 2010).

GARNET CHEMISTRY

Garnets from the Grt zone show a core-to-rim increase in Fe (almandine) and Mg (pyrope) and a decrease in Mn (spessartine) and Ca (grossular).

Garnets from Crd and Sil zone similar zoning profiles, apart from Mg (core-to-rim decrease).

Sample 1428A, Semipelite, Garnet zone

Sample 1702C, Pelite, Sillimanite zone

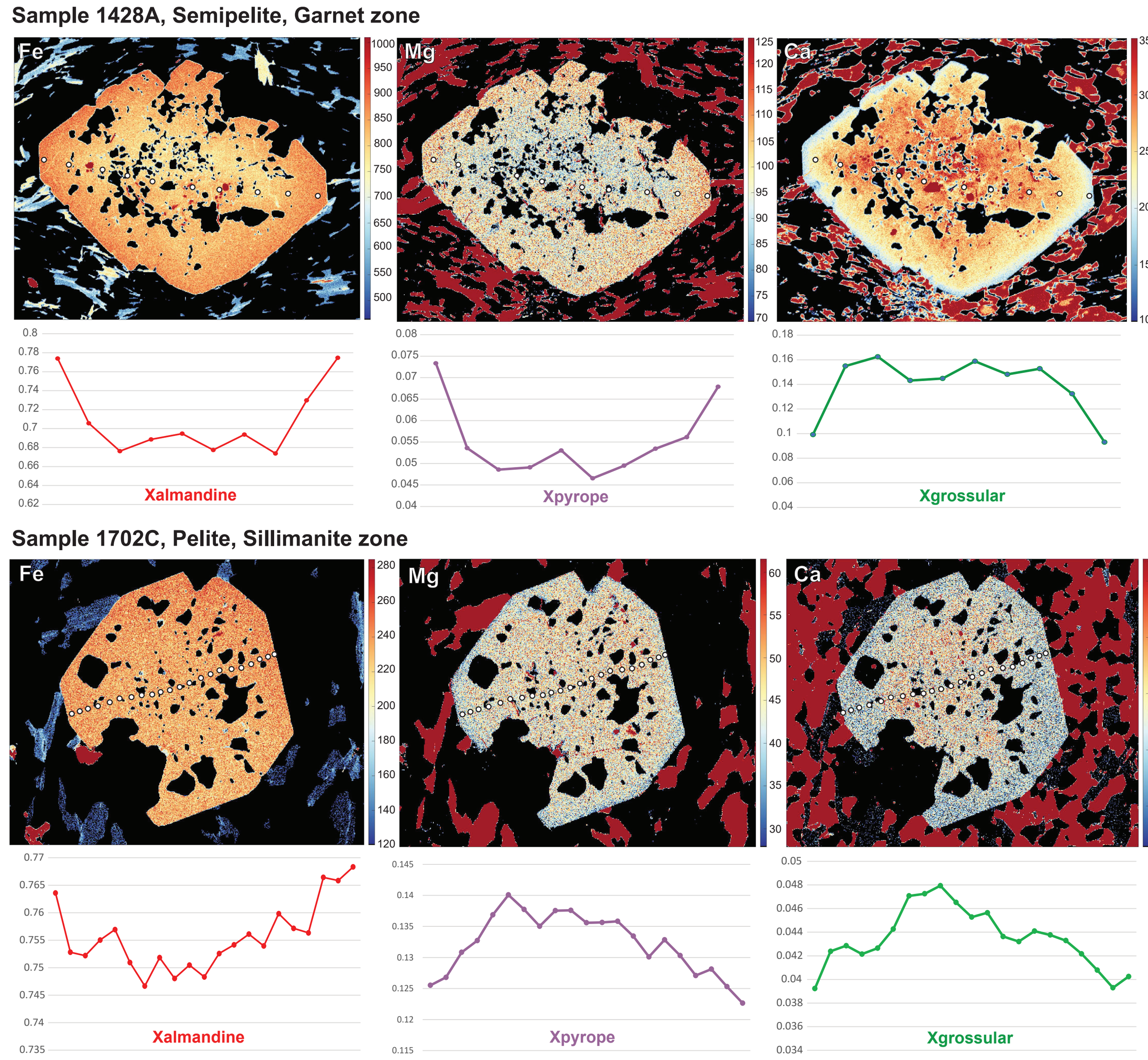

Fig. 4. Scanning electron microsope energy dispersive spectoscopy (SEM-EDS) element maps of a zoned garnet in the garnet zone (top) and sillimanite zone (bottom) with electron probe microanalysis (EPMA) transects showing end-member garnet chemistry.

ISOPLETH THERMOBAROMETRY

Garnet zone

Isopleths have a closest intersection at **~560 °C and 7 kbar**.
- In the Grt-Chl-Bt field (observed assemblage)

Zoning patterns in garnet are compatible with growth during increasing P-T (~20 bar/°C) followed by a sharp P-T decrease
- Clockwise P-T path
- Burial followed by decompression

Sillimanite zone

Isopleths have a closest intersection at **~600 °C and 4 kbar.**
- Near the Grt-St-Crd-Bt field (observed)
- Near And-Sil univariant reaction

Zoning patterns in garnet are compatible with growth along a decreasing P/T gradient
- Near-isothermal decompression over >3 kbar

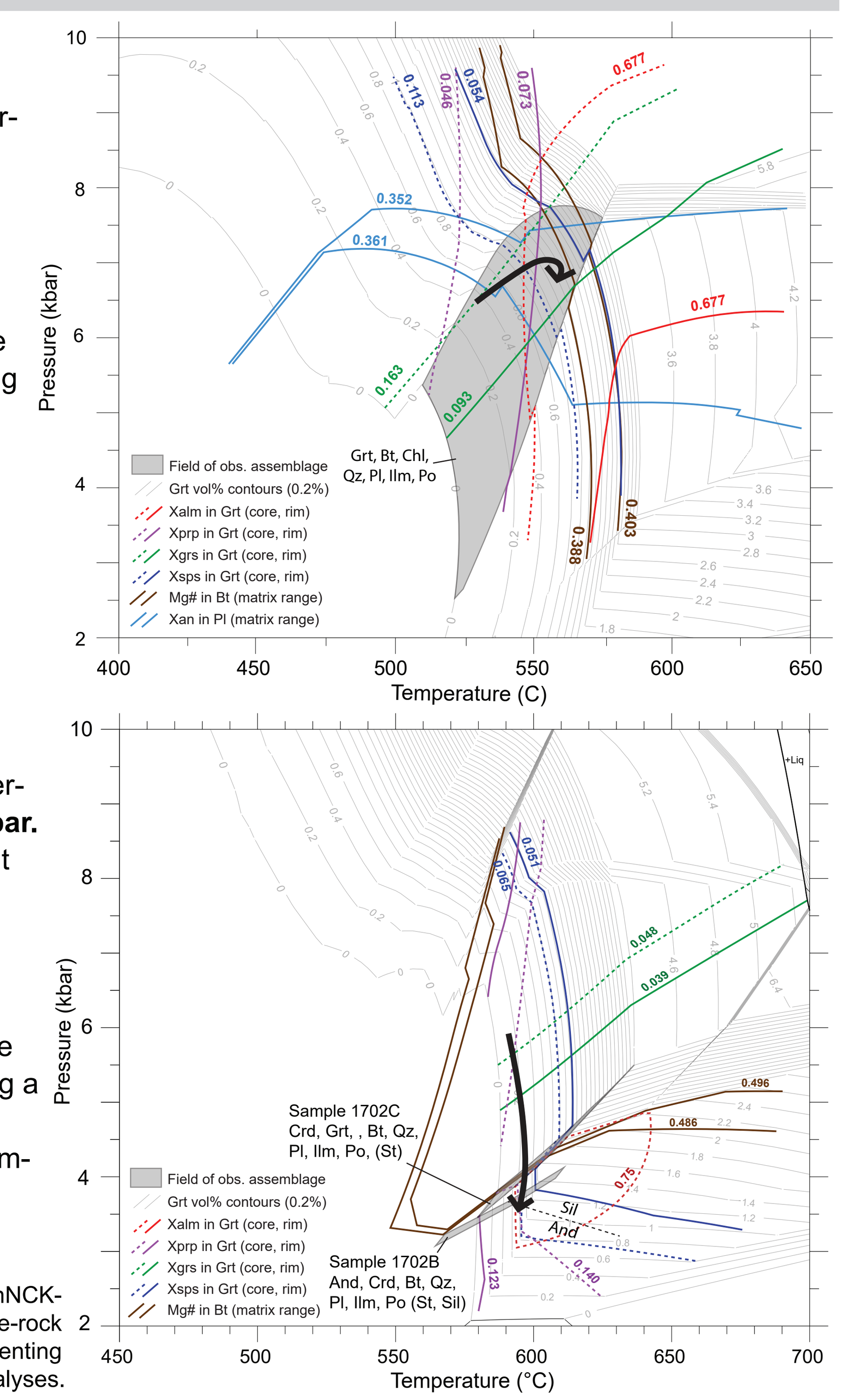

Fig. 5. Pseudosections in the MnNCKFMASHTOS system using whole-rock bulk compositions. Isopleths representing ranges in data from EPMA spot analyses.

WHOLE-ROCK CHEMISTRY

Principal component analysis (PCA) shows the opposing covariance of **K-Y-Fe** and **Ca-Na-Si** best describes the observed variability in pelitic compositions.
- Mechanism: hydraulic sorting of phyllosilicates and plagioclase-quartz crystals

H_2O decreases continuously with increasing grade; CO_2 decreases sharply near Bt isograd; SO_2 is not visibly affected.

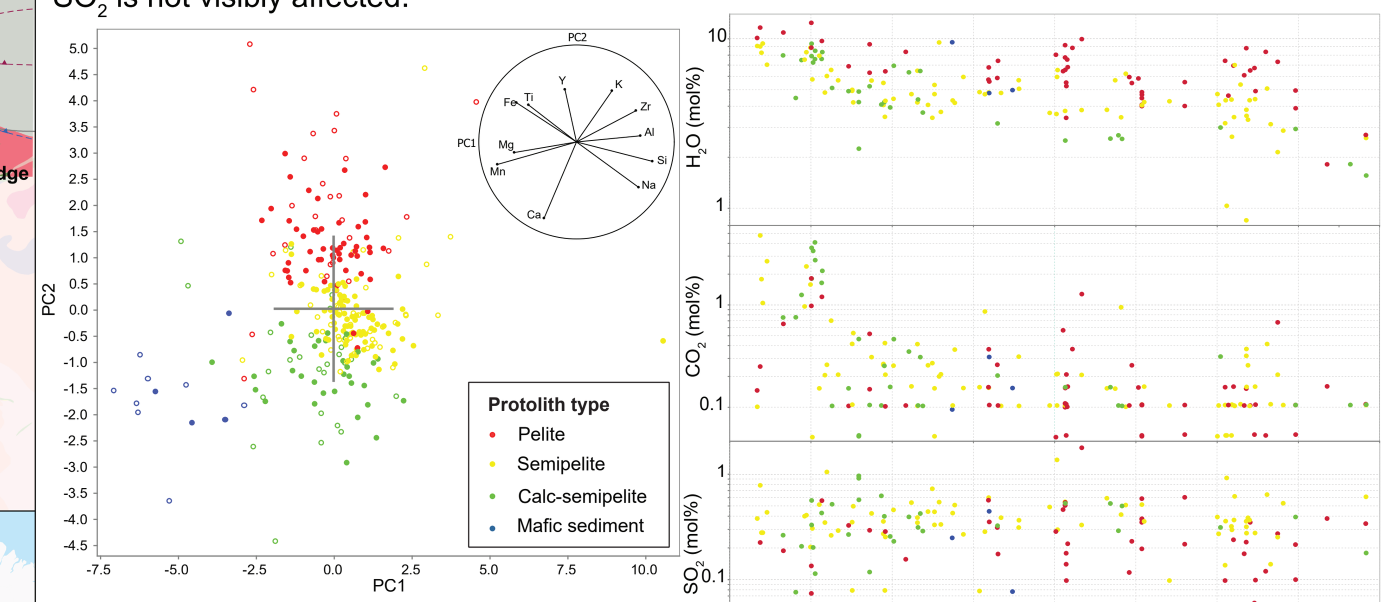

Fig. 6. A PC1-PC2 biplot of sedimentary rocks in the Quetico including new (full circles) and historical (empty circles) whole-rock data.

FLUID EVOLUTION

Fluid production is investigated along an inferred P-T vector of **400 °C (5 kbar) to 600C (7.5 kbar).**

At 400 °C, 5 kbar, calcite, chlorite, white mica, K-feldspar pyrite, and pyrrhotite are stable.
- Fluid is initially set to 1 vol% (1.27 mol)
- Fluid composition is **98.98%** H_2O, **1.00%** CO_2, and **0.03%** H_2S

At 505 °C, 6.3 kbar: calcite, chlorite and white mica breakdown; biotite and garnet are produced.
- Peak fluid production
- Fluid composition is **62.65%** H_2O, **37.27%** CO_2, and **0.1%** H_2S

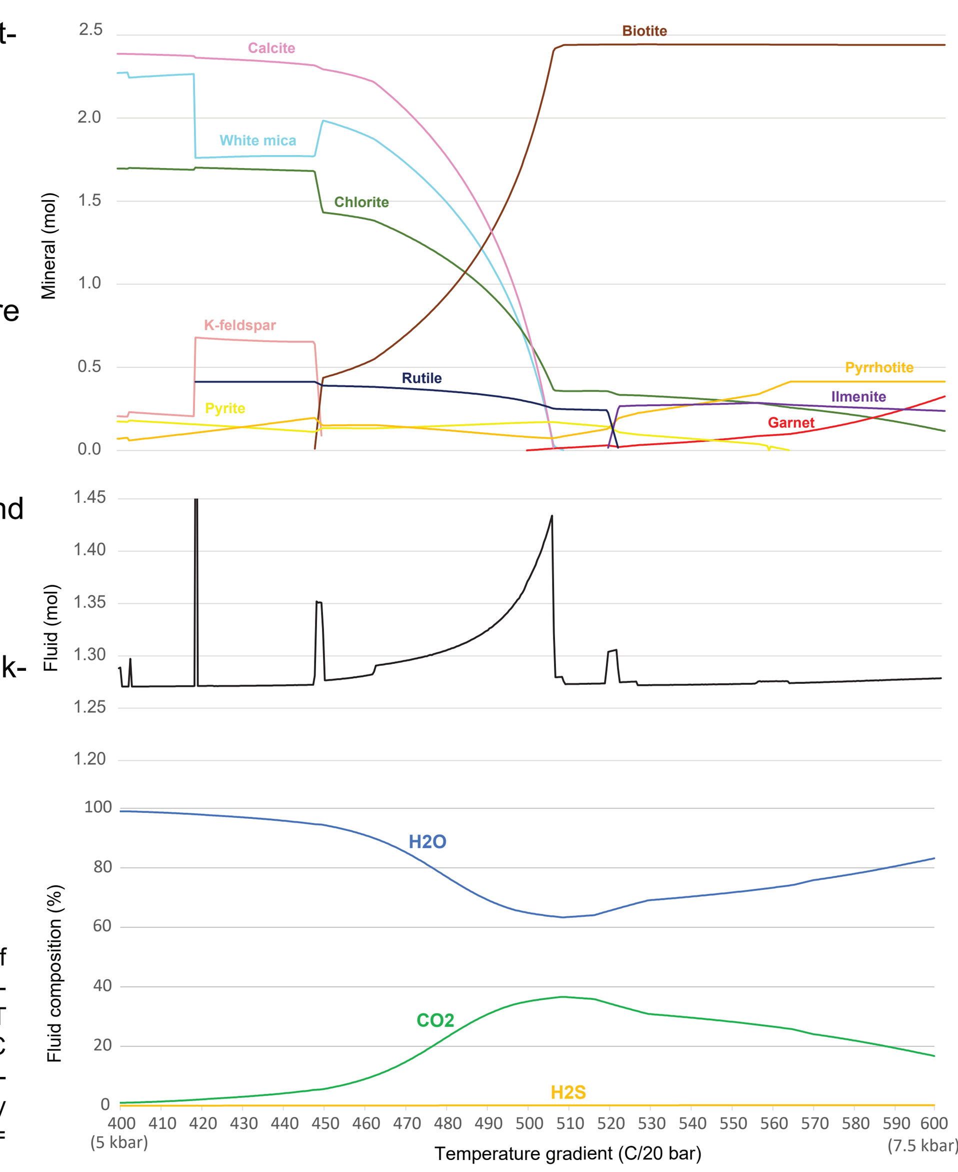

Fig. 6. Phase equilibria modeling of a semipelite in the MnNCKFMASH-TO-CS system along a fixed P-T gradient from 400C (5kbar) to 600C (7.5 kbar). Fluid composition is itteratively removed from the bulk every 0.4°C (500 steps) to maintain n_{fluid} = 1.27 mol.

SUMMARY AND IMPLICATIONS

(1) The sequence of metamorphic isograds is continuous across long axis of the Quetico, mirrored on northern and southern margins: similar tectonic evolution along both boundaries.

(2) P-T path follows a moderately high PT gradient, followed by sharp, rapid decrease in P: burial followed by isothermal decompression (diapiric rise of the Quetico core?).

(3) Peak fluid release occurred at around 500 °C, 6 kbar with a high X_{CO2} composition: fluid pH is buffered via bicarbonate equilibria, necessary for having Au in solution.

(4) Sulphide phases partially break-down continuously along P-T path: a small amount of H_2S is released into fluid; Au in sulphides may be exposed to fluid, potentially mobilised with a S species(?)

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