

The Iceland Deep Drilling Project: (III) Hydrothermal Fluid Geobarometry

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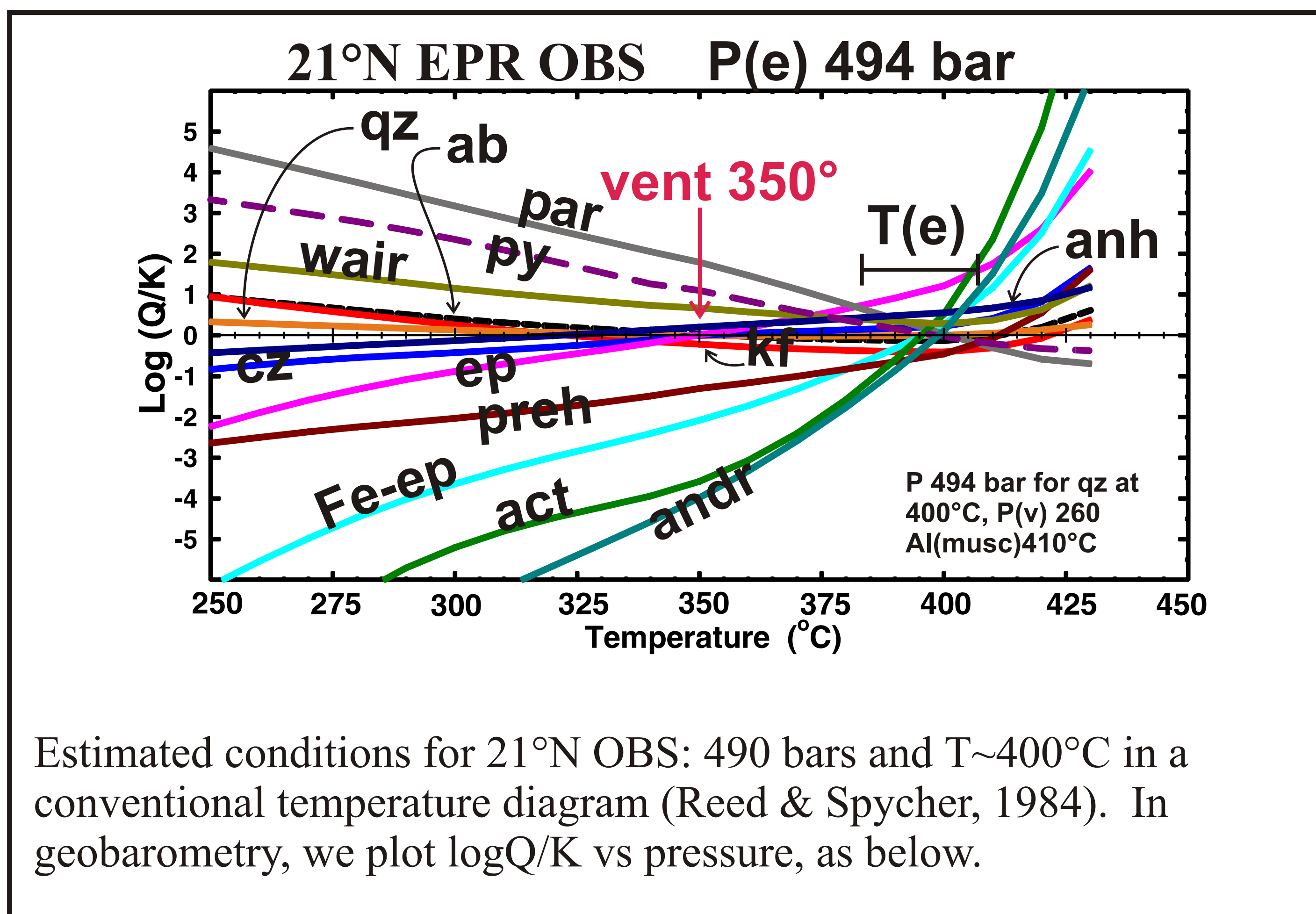
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How can we determine how deep black smoker fluids circulate and the temperature in the hydrothermal reservoir?

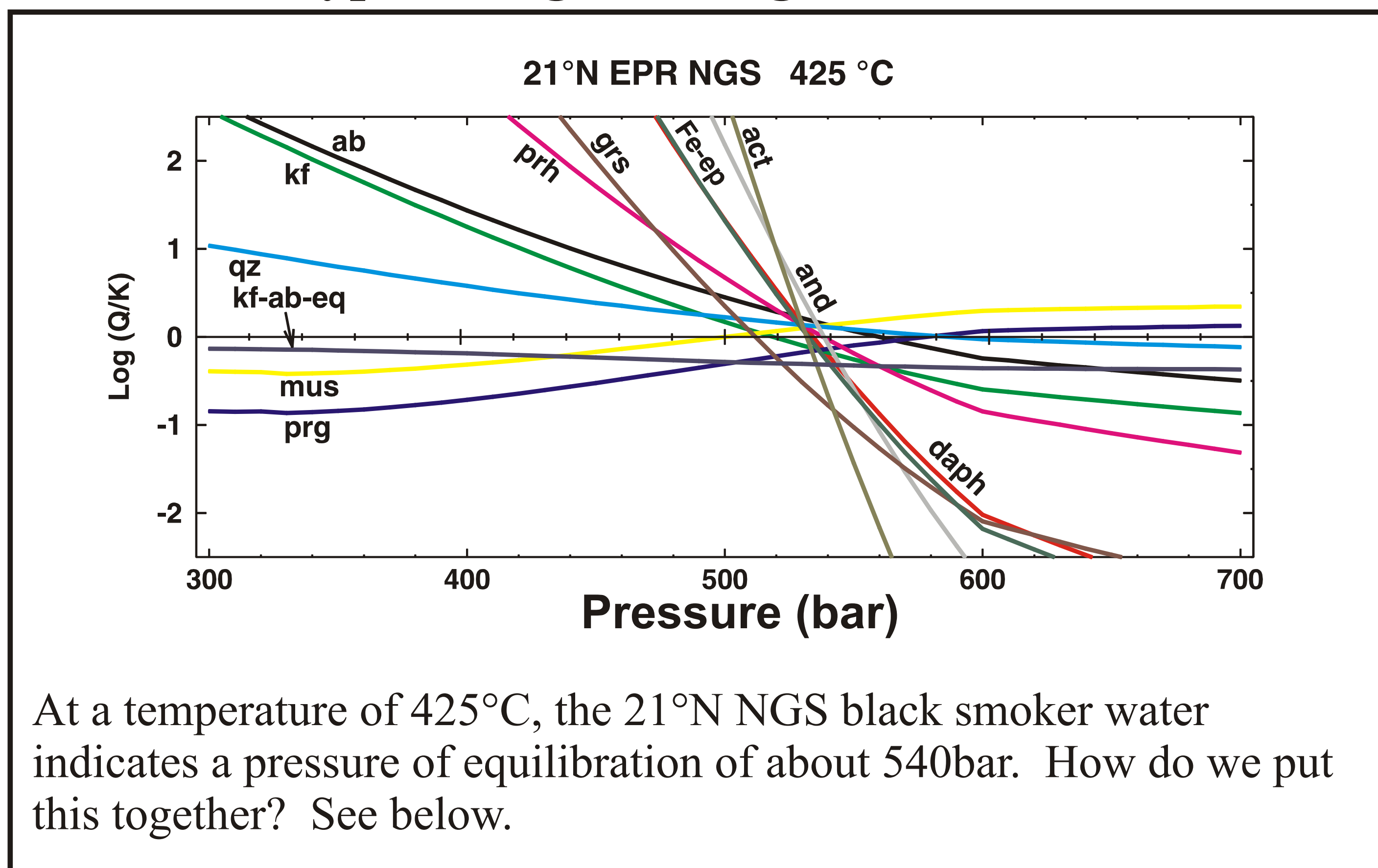
Purpose

In Iceland deep drilling we hope to find 450° to 500°C hydrothermal fluids that can be used to produce electricity. It is not clear whether a fluid reservoir with sufficient permeability exists to enable significant fluid production at such high temperature. If some deep ocean black smokers draw fluids from a reservoir at 450° to 500°C, that would verify the feasibility a natural very high-T reservoir. At high T in sub-sea-floor settings, pressure is great enough to affect estimates of temperature based on fluid chemistry, so we have devised a approach for simultaneously estimating temperature and pressure (and thereby depth) from fluid composition.

Conventional logQ/K diagram vs temperature



NEW type of logQ/K diagram vs PRESSURE



Principal findings for three smoker fluids

| | Measured Vent | | Estimated source | |
|------------|---------------|---------|------------------|---------|
| | T (°C) | P (bar) | T(°C) | P (bar) |
| Mark-1 MAR | 350 | 370 | 380-400 | 500 |
| 21°N OBS | 350 | 260 | 385-410 | 500 |
| 21°N NGS | 273 | 263 | 400-450 | 500-600 |

Geobarometry method

The composition of hydrothermal fluids depends on the temperature and pressure at which the fluid equilibrated with the alteration mineral assemblage in its host formation. Earlier studies show that natural hydrothermal waters *do* equilibrate with their mineral environment (e.g. Reed and Spycher, 1984). We must determine which minerals equilibrate under what conditions and whether any processes changed fluid composition between the deep fluid-rock environment and the analytical laboratory.

In earlier work, Karen Von Damm and others (e.g. Von Damm, et al, 1985, 1990, 1995, 1998) estimated pressure on the basis of quartz solubility by determining the pressure at which quartz equilibrates with measured smoker silica concentrations at a temperature estimated from an adiabatic decompression correction to the measured vent temperature.

In our study, we extend the mineral equilibrium approach to include feldspar, mica, zeolites, amphibole, garnet and chlorite and we use the assemblage to *determine simultaneously the pressure and temperature* of equilibration. This approach extends into the pressure regime the methods we previously developed for estimating temperature in geothermal and sedimentary fluids (Reed and Spycher, 1984; Pang and Reed, 1998; Palandri and Reed, 2001) by computing and plotting mineral saturation indices (log Q/K) as a function of temperature. We apply computer program SOLVEQ (Reed, 1998) with a new data base that enables calculation at arbitrary choices of pressure, data for which are derived from the recent compilations by Shock, et al (1997) and Holland and Powell (1998).

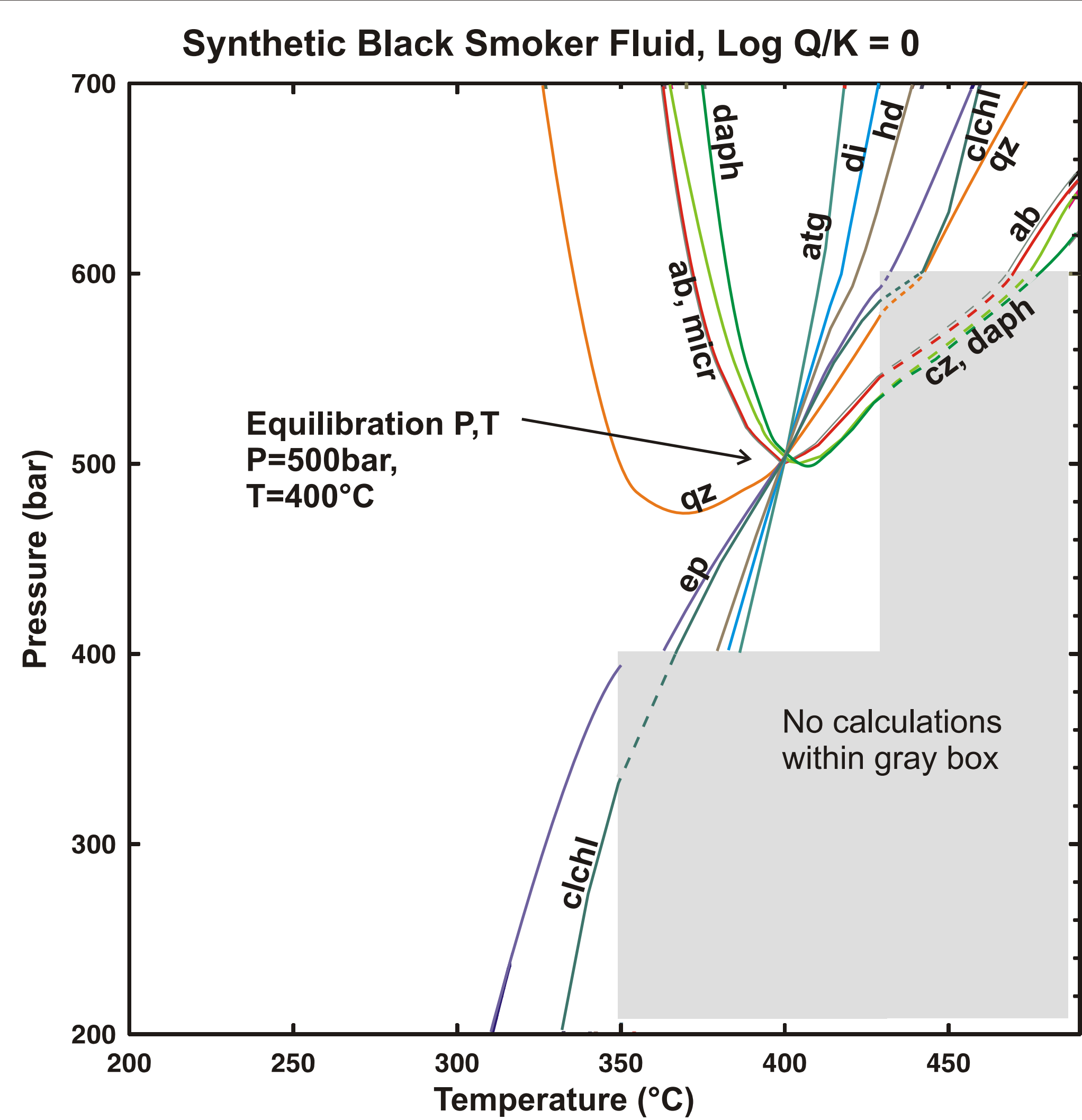
Synthetic fluid example

Simultaneous determination of pressure and temperature requires that we find the point in P-T-logQ/K space where the 3-D surfaces representing mineral logQ/K intersect each other and logQ/K=0. Since we know that the intersection of interest is at logQ/K=0, as shown in the conventional graphs to the left, we can simply graph the logQ/K=0 curves in P-T space to seek the point of intersection, if it exists. To illustrate the concept, we synthesized a test fluid by forcing it to equilibrate at 400°C and 500 bar with a set of alteration minerals, as shown in the graphs below.

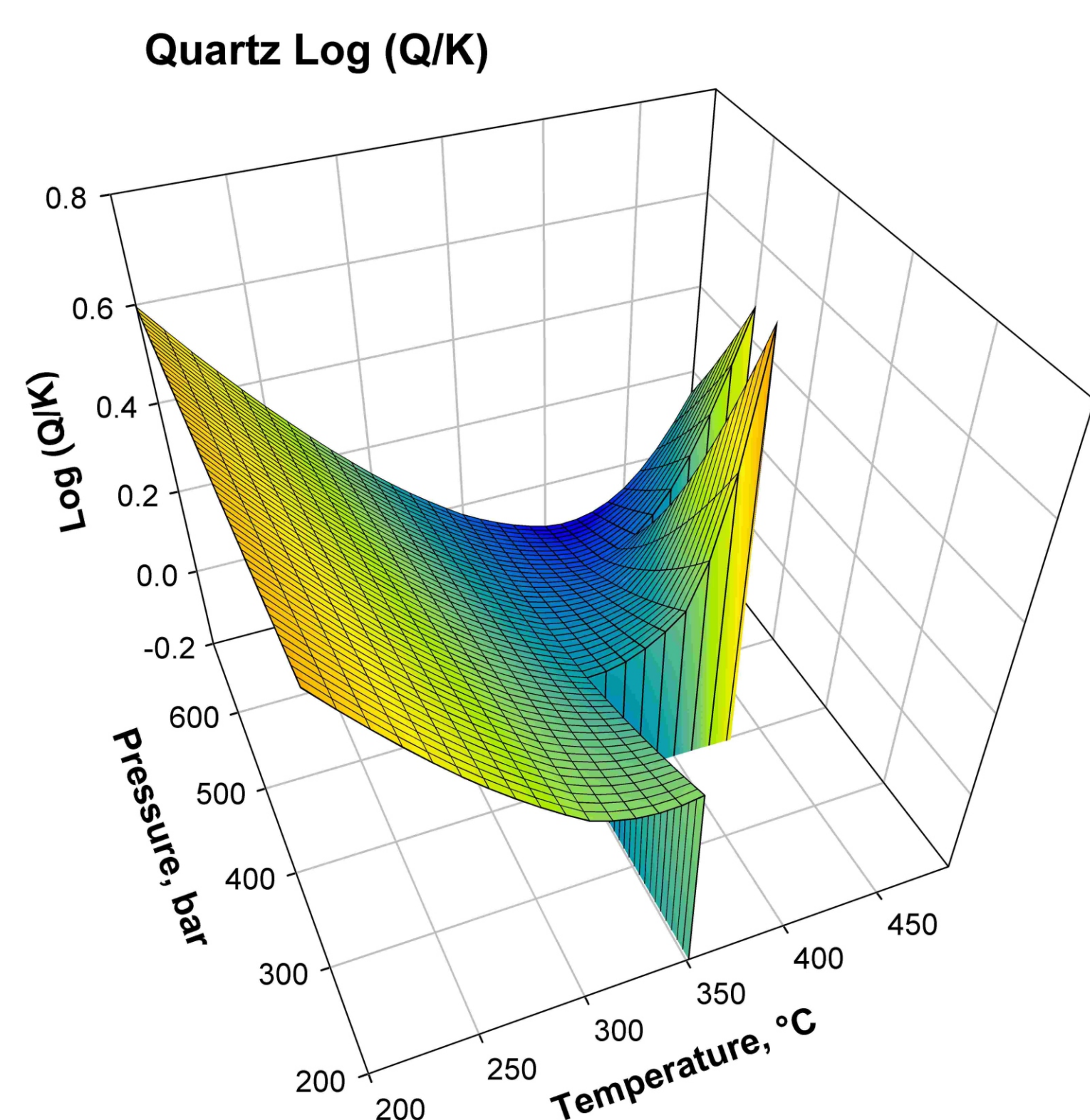
Mineral Abbreviations

ab, albite; act, actinolite; andr, andradite; anh, anhydrite; cz, clinozoisite; ep, epidote; kf, K-feldspar; musc, muscovite; par, paragonite; preh, prehnite; qz, quartz; wair, wairakite.

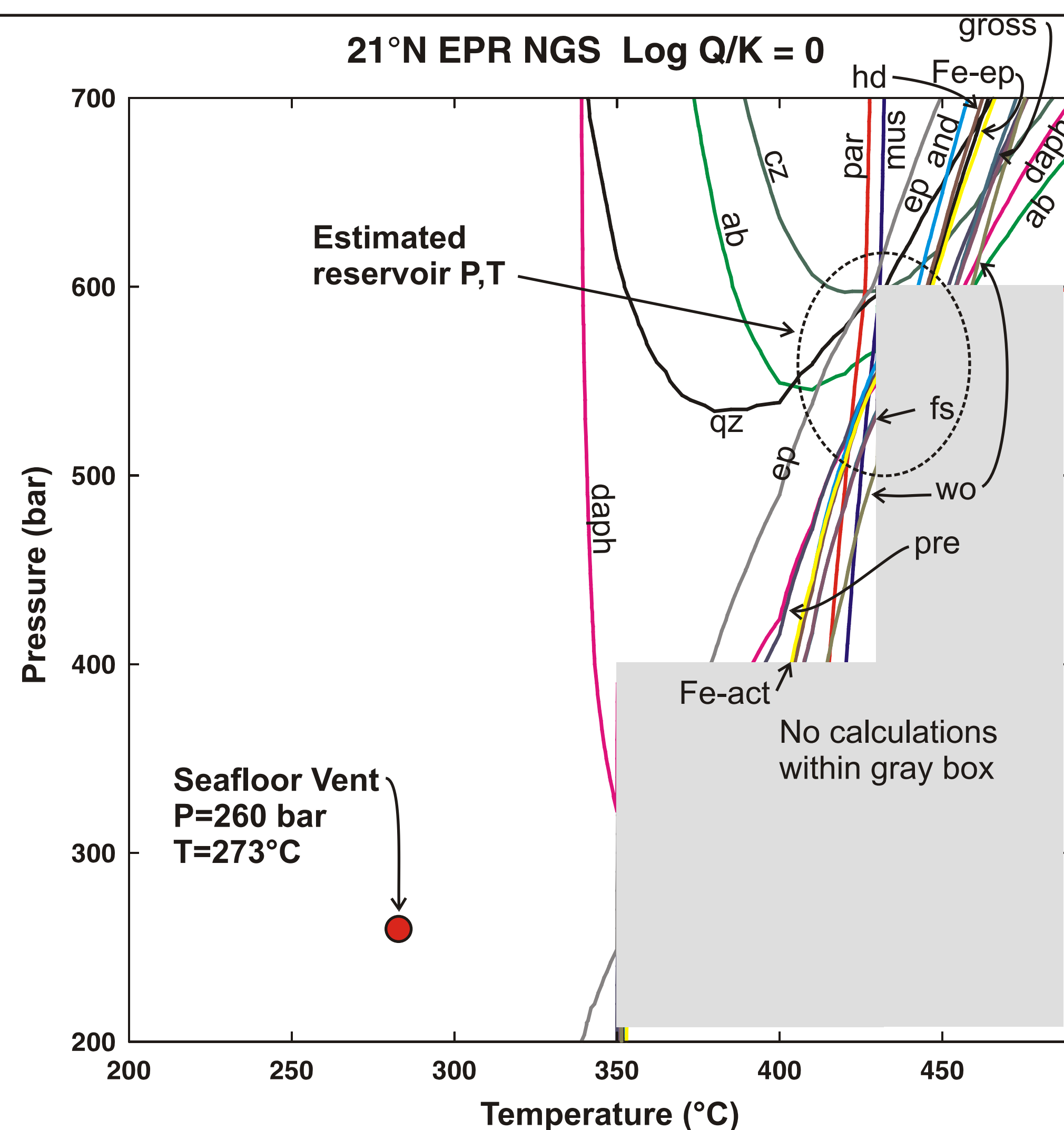
Black smoker compositions are from VonDamm et al (1985, 1990)



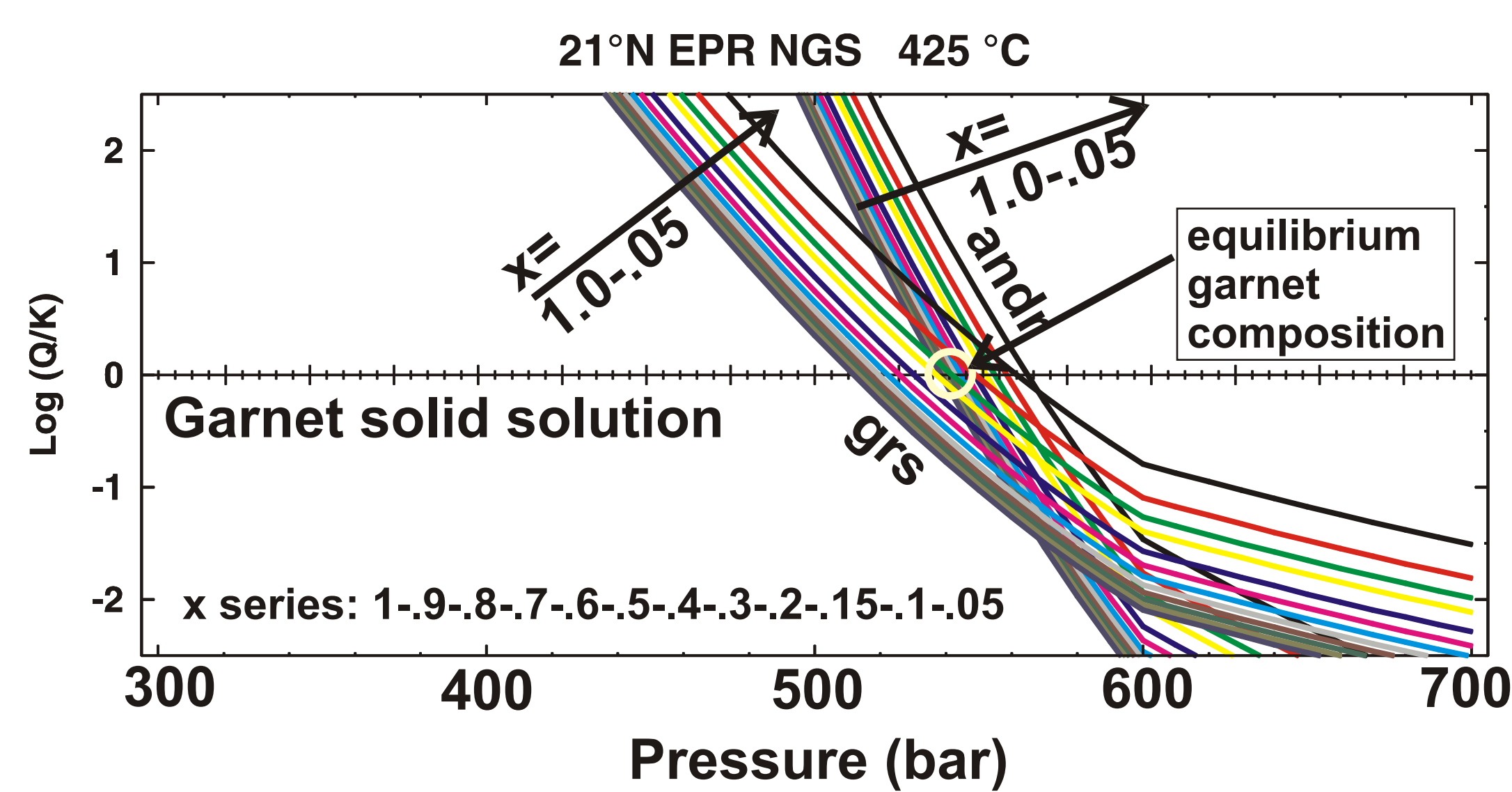
The logQ/K=0 slice through P-T-logQ/K space showing a synthetic water forced to equilibrate with chlorite, epidote, feldspars, clinopyroxene, quartz and antigorite. The perfect intersection of curves at the equilibration P-T illustrates the ideal.



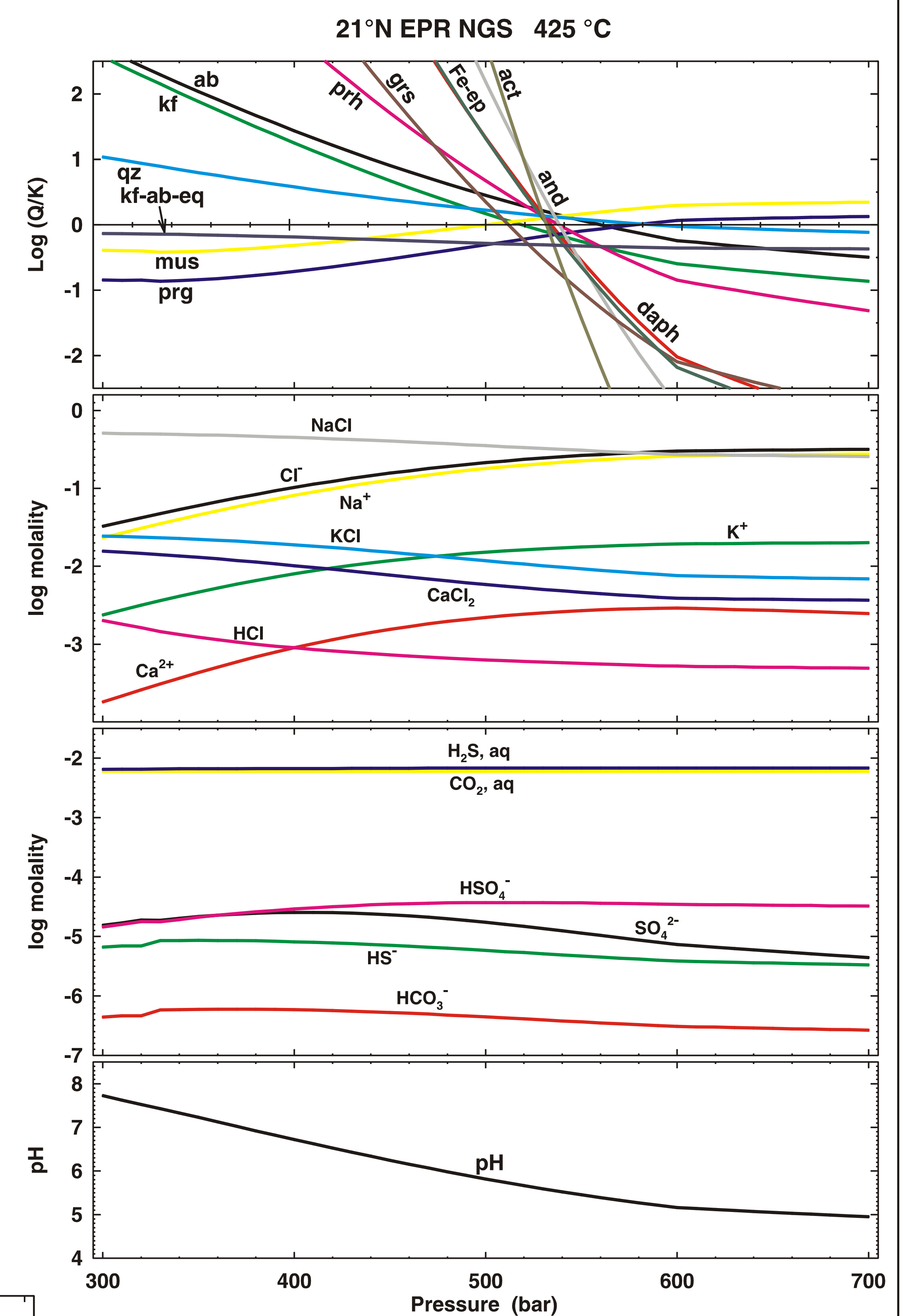
Quartz logQ/K surface in P-T space for the synthetic water forced to equilibrate with the minerals listed above. The intersecting curves in the P-T graph at the top are slices through P-T-logQ/K space as shown here for quartz.



The logQ/K=0 slice through P-T-logQ/K space showing the EPR 21°N NGS water. The intersection zone of common alteration minerals indicates likely reservoir conditions, P=500-600bar, T= 400-450°C, conditions substantially hotter and deeper than the vent P-T (red dot). (Bumps in some curves are numerical and plotting artifacts.)



21°N NGS fluid log Q/K of garnet solid solutions vs pressure at 425°C. The yellow circle marks where an equilibrium composition of grossularite and andradite form an andraditic solid solution at about 530bar. Ideal multisite mixing was applied in computing garnet activities.



Mineral logQ/K's and molalities of aqueous species vs pressure for the EPR 21°N NGS fluid. pH changes by more than 2 units between 300 and 600 bars owing to HCl dissociation at increased P. The pH change along with similar but smaller changes in major cations cause a significant effect of pressure on mineral solubilities.

Conclusion

Many black smoker fluids can be shown to have equilibrated with their mineral environment at a certain pressure and temperature, demonstrated by finding a "knot" where mineral logQ/K's go to a value of zero when plotted against P and T. In our previous studies of geothermal and sedimentary systems we found that fluids nearly universally equilibrate with their mineral environment where temperatures exceed 100°C. The new finding that such equilibrium can be demonstrated for black smokers is made possible by new thermodynamic data (Shock et al, 1997) at the elevated temperatures and pressures that apply to sea floor hydrothermal systems. The high pressure of sea floor systems makes it necessary to account for pressures well above the water liquid/vapor P-T curve.

By plotting only the logQ/K=0 values in P-T space we are able to simultaneously identify the pressure and temperature of equilibration, and to recognize the substantial departure of the vent P and T from the P and T of the

deep fluid reservoir. Typically the computed equilibration pressures exceed vent pressure by 100 to 250 bars, indicating fluid circulation to depths up to a few kilometers beneath the sea floor where temperatures are 30° to 100°C hotter than vent temperatures.

Further improvements in determination of fluid compositions and in reconstruction of fluids, including phase-separated fluids, will enable better constrained P-T estimates. Another necessary improvement is in the treatment of non-ideal solid solutions, resembling the garnet example above, which we treated as ideal on multiple sites.

On the question of the existence of very high temperature geothermal fluids in a setting like Iceland: the high temperatures we find for black smoker fluids show that we can be confident that fractured basalt is capable of sustaining substantial permeability at temperatures of at least 430°C, which is 100°C hotter than in currently producing geothermal systems.

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