NGU Report 98.009

Fluid inclusions in post Late Devonian brittle faults in the Sunnfjord region, West-Norway: application to P-T estimates and geothermal gradient reconstruction's

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REPORT

Report no.: 98.009	ISSN 0800-3416	Grading: Open

Title:
Fluid inclusions in post Late Devonian brittle faults in the Sunnfjord region, West-Norway: application to P-T estimates and geothermal gradient reconstruction's

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Map-sheet name (M=1:250.000) Florø		Map-sheet no. and -name (M=1:50.000)	
Deposit name and grid-reference:		Number of pages: 11 Price (NOK): 30 Map enclosures:	
Fieldwork carried out:	Date of report: 19/2, 1998	Project no.: 2671.00	Person responsible: [signature]

Summary:
Previous structural analysis of post L. Devonian faults in the Sunnfjord region outlined the presence of four populations of faults (Braathen, 1998). In the present study, analysis of fluid inclusions hosted by minerals sealing populations 1, 2 and 4 faults are used as a first approach to estimate pressures and temperatures of major faulting episodes. Population 1 faults from Leknes contain primary fluid inclusions with saline aqueous solutions containing 5.8 wt% NaCl. Population 2 faults from Våge also contain aqueous inclusions with 11.5-12.5 wt% NaCl whereas population 4 faults from Atløy contain as much as 21.0 wt% NaCl with possible traces of FeCl. Fluid inclusions in population 1 and 2 faults formed at temperatures between 300° and 400 °C at 3-5 kbar pressure and population 4 formed at pressures <3 kbar and temperatures between 134 and 300 °C. Given these data, the geothermal gradient for L. Devonian to E. Carboniferous faulting when population 1 and 2 faults formed, was 20 - 25 °C/km.

Keywords: Fluid inclusions	Faults	Tectonics
Western Gneiss Region		

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1. INTRODUCTION

This report documents a first approach concerning the potential application of fluid inclusion studies in tectonic modelling of pressures, temperatures and geothermal gradients associated with post Late Devonian brittle faulting in the Sunnfjord region in West-Norway. With a record of 463 microthermometric measurements on fluid inclusions from three populations of brittle faults, it is possible to partially constrain the geothermal gradient during Late Devonian to Early Carboniferous faulting.

Previous studies of fluids migration along fault zones have documented that massive fluid flow coincides with major episodes of displacement because, during tectonically quiet periods, fractures rapidly clogs parallel with gradual sealing by minerals precipitating from the fault fluids. Because fluid inclusions were trapped during growth of these minerals, they provide concise information about P and T during major fault movements. With these data, it is possible to reconstruct the geothermal gradient and, if combined with $^{40}Ar/^{39}Ar$ geochronology and/or paleomagnetic- and fission track dating, the exhumation history of a given area can be approached.

2. GEOLOGICAL OUTLINE

The general geological setting of the Sunnfjord area is thoroughly reported elsewhere (Braathen, 1998) and the geological outline reported here are also extracted from Braathen. Four populations of post Caledonian brittle fault systems evolved after Early- to Middle Devonian extension associated with collapse of the Caledonian orogeny and formation of Devonian sedimentary basins in West Norway. Population 1 of the brittle faults are intimately associated with major reverse faults in the Kvamshesten and Solund basins. They developed during L. Devonian - E. Carboniferous contractional strain associated with N-S shortening and E-W extension contemporary with folding and major thrusting of the Devonian basins. Population 2 faults are associated with N-S lineaments, so-called master joints, and subordinate NE-SW together with NW-SE lineaments. Faults running sub-parallel to the N-S lineaments show normal movement and higher angle faults show oblique or strike-slip movements and, together, the overall geometry of population 2 is that of a conjugate strike-slip system and bisecting normal faults. Population 2 faults probably overlap with population 1 faults and, similarly, can be explained in a context of constrictional strain featuring horizontal NNE-SSW shortening and WNW-ESE extension. Population 3 faults developed during regional Permian E-W extension and features low angle normal faults composed of silicified green fault breccias. Population 4 faults includes the well known Red Breccia at Atløy and formed during a period of N-S extension on E-W striking normal faults. Probably, these faults are related to a regional L. Jurassic - E. Cretaceous extensional event.

3. ANALYTICAL METHODS

Physical and chemical properties of fluids migrating along brittle faults were constrained by utilising microthermometric analysis of fluid inclusions hosted in quartz and calcite which, together with epidote and rare phengite, seals the faults. The phase behaviour of individual fluid inclusions during heating was recorded with Linkam and Chaix Meca freezing-heating stages operated at Free University Amsterdam and University of Copenhagen, respectively. Observation of phase changes at sub-zero temperatures was done with a precision of ±0.1 °C whereas phase changes at higher temperatures were obtained with a precision of ±0.5 °C. A typical freezing-heating cycle would include simultaneous observation of 5-10 inclusions in the field of view, estimation of eutectic minimum melting of ice, which pretty much constrain major electrolytes dissolved in the aqueous inclusion, followed by final melting observations from which the total salinity is derived and, finally, observation of total homogenisation of the inclusion to a single fluid. Having these data, it was possible to calculate the total density and composition of the fluid inclusions and to predict their isochoric trace in P-T space.

4. FLUIDS IN FAULTS

In the present approach, fluid inclusion studies were implemented on population 1 faults from Leknes, population 2 faults from Våge and population 4 faults from Atløy (Red Breccia) (Fig. 1). Population 3 faults and the other fault localities shown on Fig. 1 are currently being processed for coming fluid inclusion studies.

4.1 Population 1 and 2 faults

Populations 1 and 2 faults are primarily sealed by quartz and epidote, but may also contain some white mica. Precise geothermometry remains to be completed, however, given the present mineral assemblage it is implied that temperatures did not exceed lower- to middle greenschist facies conditions i.e. 300 ° to 400 °C. *Population 1* faults from Leknes contain abundant primary fluid inclusions in quartz which precipitated on the sheltered side of steps running perpendicular to the maximum strain axis. Quartz formed at these settings, has characteristic fibrous crystals habits as they were growing parallel to the longest strain axis during offset along the faults. Fluid inclusions features sub- to anhedral negative crystal imprint and typically are 4-8 µm in diameter. During heating from -150 °C or lower, eutectic melting began at -23 to -22 °C and final melting of the last ice crystal would, on an average, occur at -3.6 °C (Fig. 2). Eutectic melting documents that the dominant salt species dissolved in the aqueous solutions is halite, and final melting imply a total salinity of 5.8 wt% NaCl (Tab. 1). After melting of ice, the fluid inclusions consists of liquid and a vapour bubble occupying ~3 vol% of the inclusion. Upon further heating the vapour bubble dissolves in the liquid phase and total homogenization is obtained at an average temperature of 137 °C (Fig. 3). Fluid inclusions in *population 2* faults from Våge also are hosted by quartz and compare with population 1 inclusions when it comes to shape, size and eutectic melting of ice. Final melting of ice occur at -8.4 to -9.6 °C which is commensurate with 11.5-12.5 wt% NaCl and total homogenisation occur with disappearance of the vapour bubble at 148-150 °C.

4.2 Population 4 faults

Observations of phase changes in fluid inclusions in the population 4 Red Breccia from Atløy (Fig. 1) was complicated by lack of transparent minerals in that the fault breccias are sealed by calcite and hematite. Only a few of the calcite crystals had satisfactory optical properties for fluid inclusion studies and, therefore, only 30 reliable measurements were obtained from 15 inclusions. All the fluid inclusions are primary and, therefore, constrain the temperatures at which the calcite cement formed.

Fluid inclusions are from <2 to 5 µm in diameter, sub- euhedral in shape and appear as aqueous two phase inclusions which, at room temperatures, comprise a vapour bubble coexisting with liquid. Meta-stable eutectic melting of ice at -28.8 to -29.9 °C suggests the aqueous fluids belong to the H_2O-NaCl system and final melting of ice at -15.6 to -19.1 °C implies moderate to high salinities commensurate with 19.3 to 22.0 weight percent NaCl (Tab. 1). A few inclusions demonstrated eutectic melting at -34.1 °C which indicates that either $FeCl_2$ or $MgCl_2$ is dissolved in the aqueous fluids in addition to NaCl. Given the presence of hematite in the Red Breccia, $FeCl_2$ is the most likely candidate. Final homogenisation occurred with dissolution of the vapour bubble in the liquid phase at an average temperature of 134 °C.

Table 1 Data from fluid inclusion analysis and isochore calculations

Locality	Host	Tmf-ice, °C	Th-total, °C	NaCl, wt%	dP/dT, bar/°C	# of inclusion
Våge 12	quartz	-8.4	148	11.5	20.6	70
Våge 15	quartz	-9.6	150	12.5	20.8	40
Leknes	quartz	-3.6	137	5.8	19.3	102
Atløy	calcite	-17.8	134	21	23.6	15

Tmf: final melting of ice, Th: total homogenisation, dP/dT: slope of isochore, #: number

5. DISCUSSION AND CONCLUSIONS

Because fluid inclusions, after total homogenisation, represent a closed system with constant volume, density and composition, they follow a linear isochoric path in P-T space (Figure 4). Average isochore paths were calculated for fluid inclusions at Leknes, Våge and Atløy utilising the equation of state expression developed by Bodnar and Vityk (1994) for the H_2O-NaCl system and which is integrated from experimental data at T<800 °C, P<6000 bar and salinities <70 wt% NaCl.

Isochores for fluid inclusions in population 1 and 2 faults largely follows the same path in P-T space and, as implied by the low- middle greenschist facies mineral assemblage, the fluid inclusions were trapped between 300° and 400 °C. A minimum pressure of ~3000 bars, can be derived from intercept between a 300 °C isotherm and the isochores for Leknes and Våge whereas the maximum pressure corresponds to ~5000 bars commensurate with interception of the 400 °C isotherm with the isochores. From these data, the geothermal gradient is defined as the slope of a line through the origin of the diagram and the P-T co-ordinates for trapping of fluid inclusions. Given these boundary conditions and assuming an average density of the overburden of 2.7 g/cm^3, it can be concluded that the geothermal gradient was 20°- to 25 °C/km during L. Devonian - E. Carboniferous faulting. A somewhat higher resolution is expected when more precise geothermometric data are available and, when fluid inclusion and mineral data for the other fault populations has been recorded, it is within reach to generate the time integrated geothermal gradient from L. Devonian to E. Cretaceous exhumation of the Sunnfjord region. Regarding population 4 faults at Atløy, it can only be concluded that they formed at lower P and T than population 1 and 2, i.e. at temperatures between 134° (=Th-total) and 300 °C at pressures lower than 3000 bar.

6. REFERENCES

Braathen A. 1998: Polyphase brittle faulting in the Sunnfjord region, western Norway: kinematic and timing. *Report, Geological Survey of Norway*, 98.007, 1-42.

Bodnar R. J. and Vityk O. M (1994) interpretation of microthermometric data for H_2O-NaCl fluid inclusions.

7. Figures

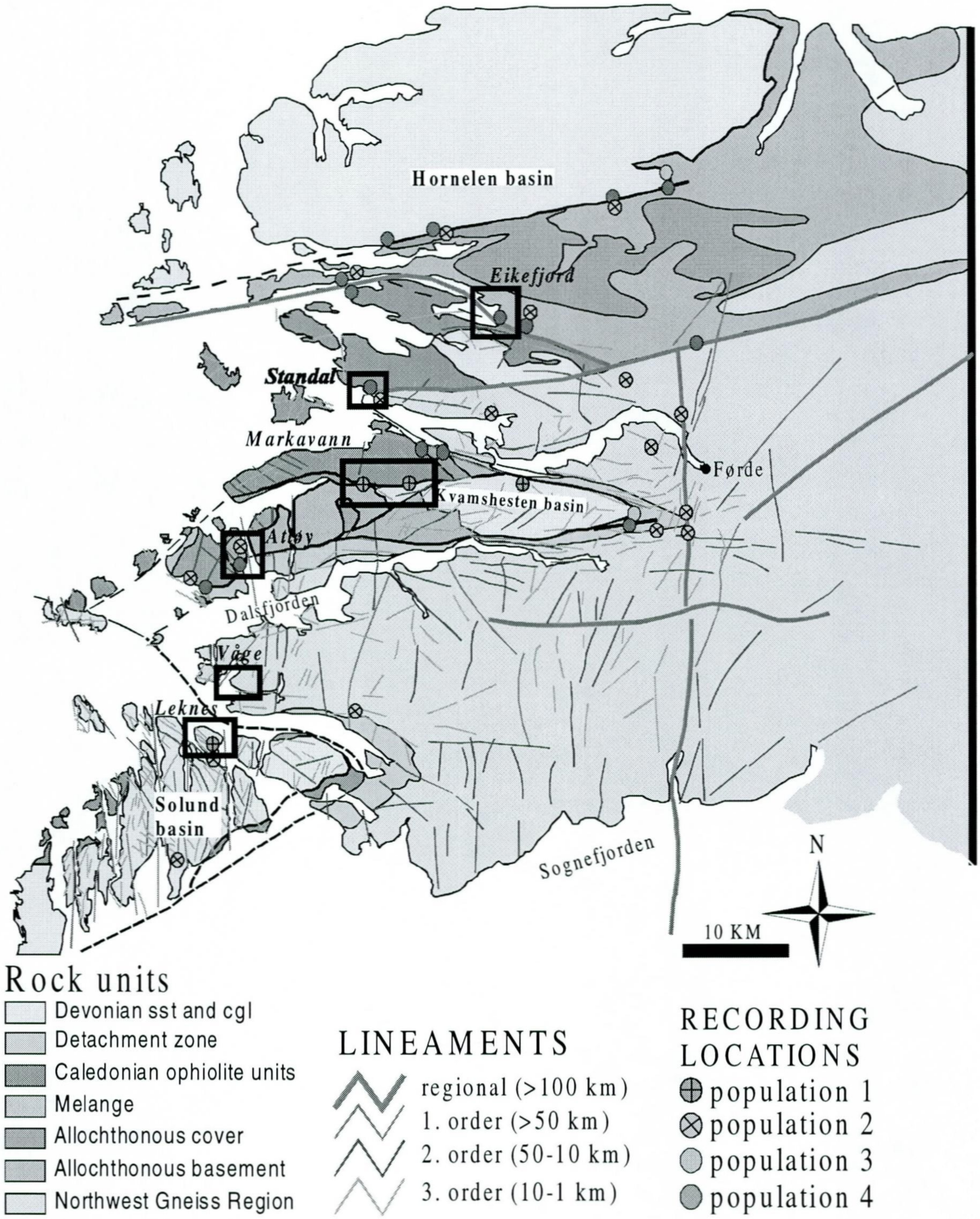

Figure 1 Geological setting of the studied area including fault localities (Black boxes). From Braathen (1998) where the same figure is available in colours.

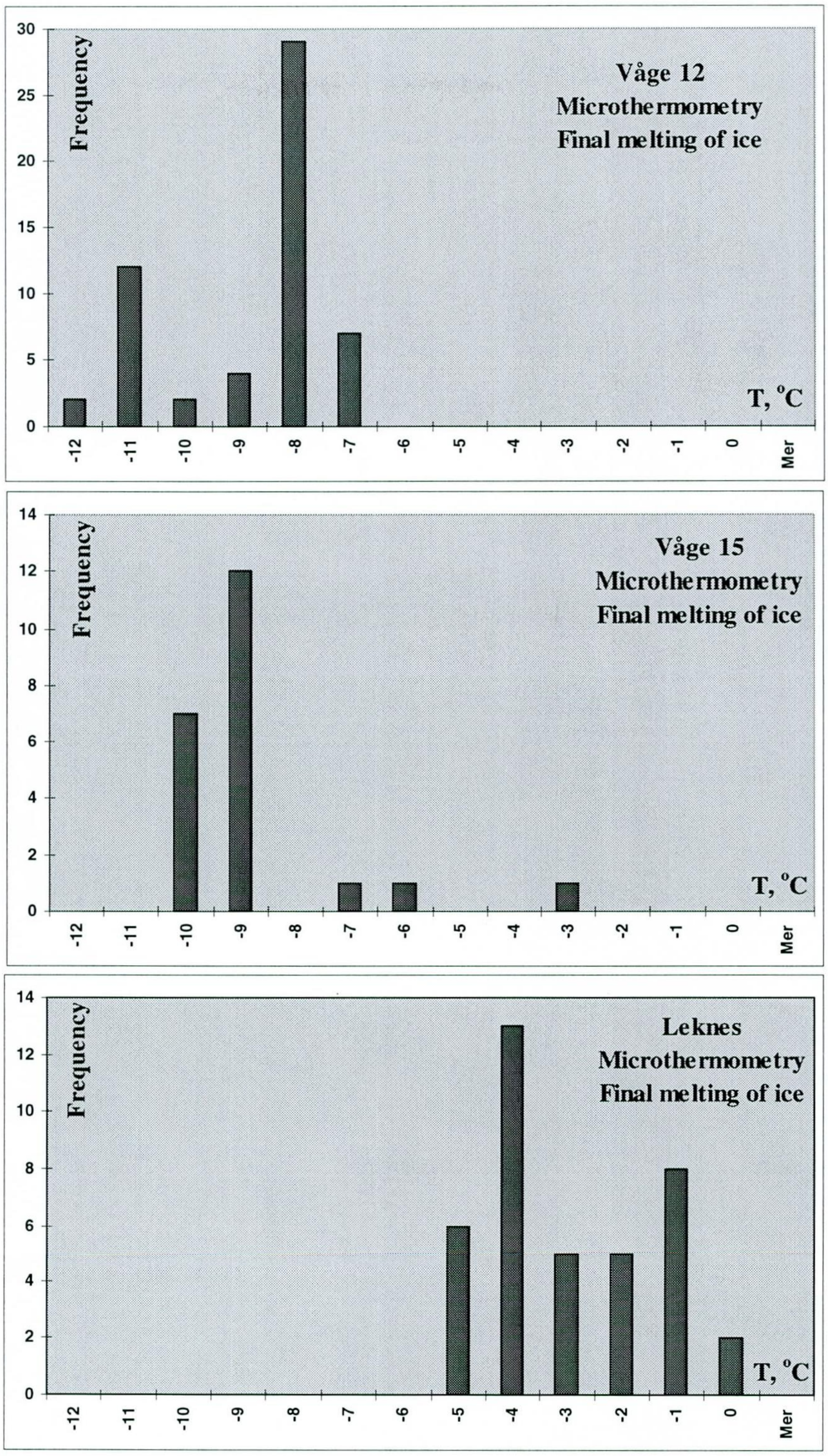

Figure 2 Final melting of ice in fluid inclusions.

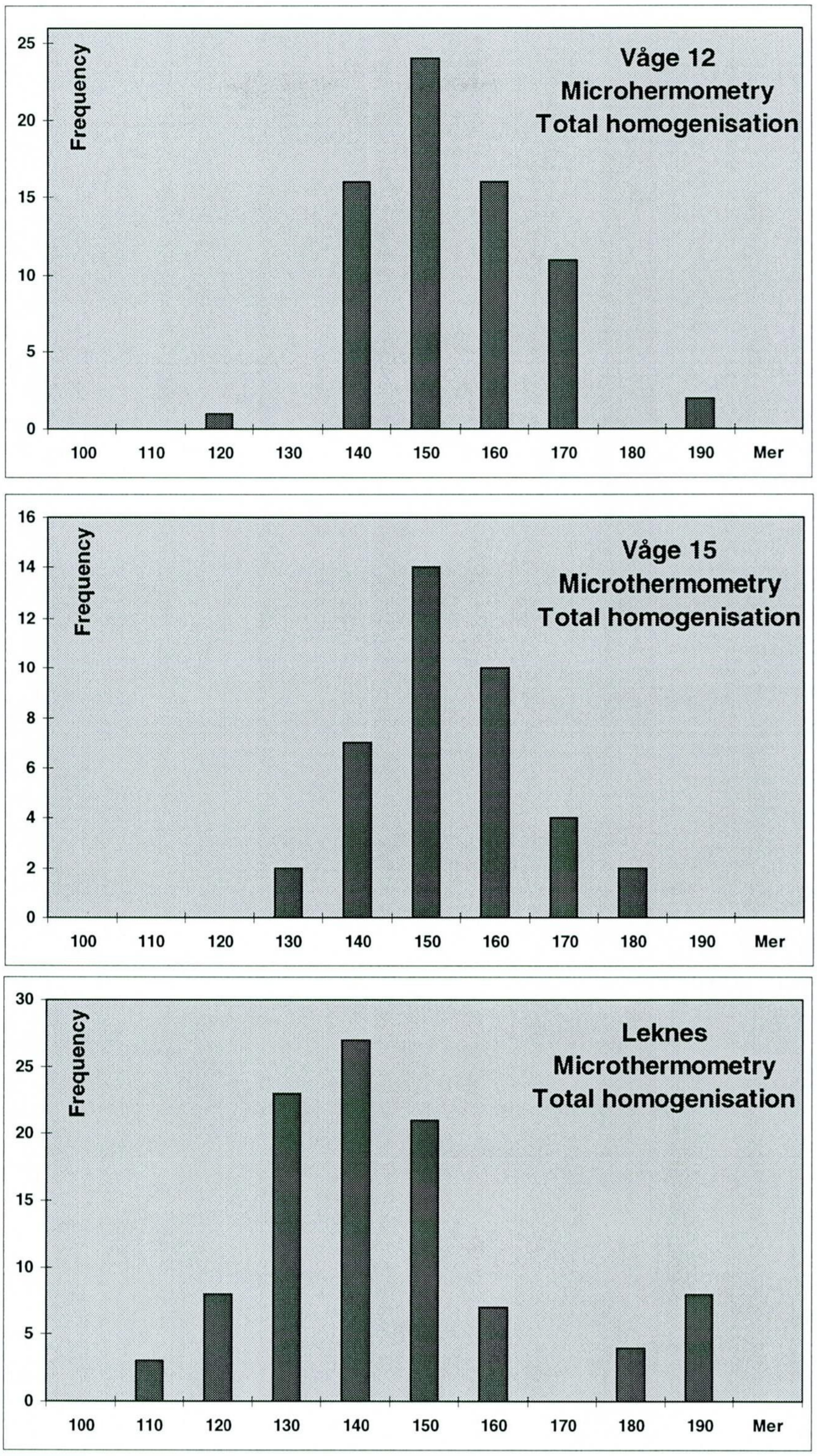

Figure 3 Total homogenisation of fluid inclusions in degree centigrade.

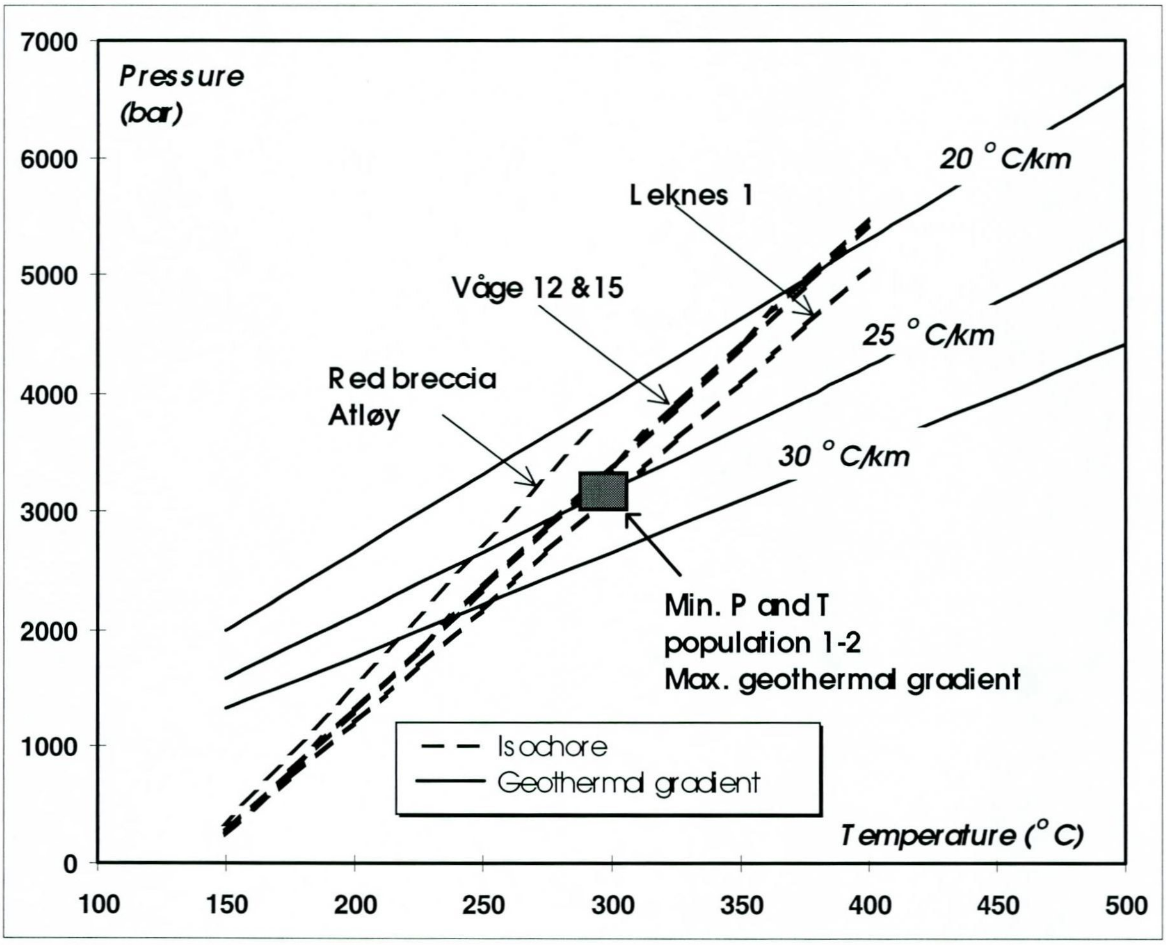

Figure 4 Construction of isochores and geothermal gradients based on fluid inclusion studies.