

**FLUID INCLUSION AND STABLE ISOTOPE
STUDY OF THE BIDJOVAGGE AU-CU DEPOSIT
AND OTHER COPPER DEPOSITS ON
FINNMARKSVIDDA, NORWAY**

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INTRODUCTION

During the past two years fluid inclusion and stable isotope studies of the Bidjovagge Au-Cu deposit and surrounding areas of copper mineralization on Finnmarksvidda, have been pursued at the University of Oslo. The area surrounding the Bidjovagge is an excellent area to study fluids and mineralization at different crustal levels. A series of mineralized areas, including the Bidjovagge deposit, provide a cross-section from deeper amphibolite facies- to shallower upper greenschist facies-hosted mineralization. This comparison study of fluids and mineralization may result in an increased understanding of Proterozoic shear zone-hosted gold-copper mineralization, and hopefully, criteria for successful exploration for Bidjovagge-type mineralization. Promising results of analysis have been interpreted to produce a genetic models for mineralization and fluid evolution. These results are to be presented in two parts, namely

- Gold transport and deposition at the Bidjovagge deposit
- Comparison of Bidjovagge with copper mineralization in the region.

The first part, concerning gold transport and deposition at the Bidjovagge deposit, is presented as an article entitled "Fluid composition of Proterozoic gold and copper deposits: An example from the Bidjovagge gold-copper deposit, Finnmark, northern Norway." The second part, concerning fluid evolution and mineralization on a regional scale, will be outlined in this report and an article is in preparation.

REGIONAL FLUID STUDY

Aside from Bidjovagge, numerous samples for fluid inclusion study have been collected, over the past 3 field seasons, from areas such as Dælljadas, Object 43, Ucca-vuovdas, Masi River, and areas directly west of the Bidjovagge field (Fig. 1). Generally, we may consider Dælljadas to represent Cu + U mineralization in the deepest crustal level within amphibolite phases rocks, and the shallowest copper mineralization may be represented by Object 43 hosted in upper greenschist facies rocks. Areas such as Bidjovagge, Ucca -vuovdas, and the Masi River albitization area may be considered to represent mineralization and/or alteration *in-between*, hosted within upper greenschist facies rocks.

Dælljadas

At Dælljadas, a copper and uranium anomaly, pegmatites intrude mafic greenstones. The pegmatites are assumed to be related to mineralization. Quartz from the pegmatite has been sampled for fluid inclusion investigation. Fluids are dominated by liquid CO₂, H₂O and salt. Tentatively these fluid inclusions are broken into 4 types.

- DÆ-Type 1: Single phase: liquid CO₂ + an undetermined minor second component (probably nitrogen or methane).
- DÆ-Type 2: Two phase inclusions: Liquid CO₂ (±N or CH₄) + slightly saline H₂O of varying ratios.
- DÆ-Type 3: Multiphase-Crystal dominated: Carbonate crystals ± small salt crystals + H₂O ± CO₂ (±N or CH₄).
- DÆ-Type 4: Single and double phase H₂O dominated: Slightly saline (≈ 5% NaCl eq.) H₂O ± H₂O vapour. Probably secondary inclusions.

Bidjovagge-Copper

Mineralizing fluids related to the chalcopyrite-carbonate veins which fill brittle structures and cross-cut earlier gold-copper mineralization at Bidjovagge have been studied by means of fluid inclusion analysis in minor quartz occurrences, and stable isotope analysis of carbonates. Fluids thus far observed are composed of lower salinity water and, in places, also methane. These inclusions are divided in three groups.

- BCu-Type 1: Two phase inclusions: Medium salinity (≈ 20% NaCl eq.) H₂O + vapour. Occasionally small salt crystals are found. (Fig. 2a)
- BCu-Type 2: Single phase liquid CH₄.
- BCu-Type 3: Double phase CH₄ + low salinity H₂O: Occur in chalcopyrite filled veinlets crosscutting syeno-diorites intruding black schists. (Fig. 2b)

The BCu-Type 1 fluid inclusions (Fig. 2a) are much less saline than inclusions related to earlier gold mineralization (Ettner et al.). Heating of BCu-Type 1 fluid inclusions results in fluid-vapour homogenization between 100 and 200°C (Fig. 3). Minor salt crystals present generally melt around between 160 to 200°C (Fig. 3).

Seven carbonate samples have been analyzed for oxygen and carbon isotope values. All but one of the samples display $\delta^{13}\text{C}$ values between -2.5 and -4‰, and $\delta^{18}\text{O}$ values lie between 10 and 15‰ (Fig. 4). These values plot within the trend shown for gold mineralization (Ettner et al.).

Ucca-vuovdas

Both drill core and outcrop samples from Ucca-vuovdas, an area of copper mineralization, are in presently being investigated. Unfortunately, most samples collected from Ucca-vuovdas for fluid inclusion analysis are too small or disturbed for fluid inclusion analysis, but recent work on two samples collected, in June 1992, from drill hole UV-13 have revealed promising results. The samples are from the 40 to 50 m zone with minor gold mineralization veinlets containing a quartz + carbonate + magnetite < chalcopyrite < pyrite < rutile assemblage. Two fluid inclusion types appears to be of significance in the samples studied.

UV-Type 1: Single phase liquid CO_2 + impurity. The CO_2 is slightly impure containing a undetermined gas, probably N or CH_4 .

UV-Type 2: Multiphase-Crystal dominated: Salt crystal + saline H_2O + gas bubble (H_2O vapour or CO_2) $\pm$ carbonate.

Masi River albitization area

A large area of albitic alteration along the Masi River is of interest because of similar alteration found at Bidjovagge, Ucca-vuovdas, and Object 43. Samples have been collected from quartz-carbonate-pyrite veins that occur within the albitic felsite for fluid inclusion analysis. Fluid inclusions display similar fluid compositions to the previously described areas, being composed of highly saline H_2O and CO_2 (with a minor contaminant, i.e. nitrogen or methane). Two important fluid inclusion groups are found in these veins.

MR-Type 1: Single phase liquid CO_2 : The CO_2 is slightly impure containing a undetermined gas, probably N or CH_4 .

MR-Type 2: Multiphase-Crystal dominated: Salt crystal + saline H₂O + vapour or CO₂ bubble ± carbonate ± unidentified daughter crystal.

Object 43

Several samples for fluid inclusion studies from the copper mineralized area of Object 43 have been collected by Stein Lønne during his Cand. Scient studies. Quartz veins sampled occur within altered (albitized, tourmalinized, and carbonatized) greenstones and metasediments. Fluid inclusions found consist of mainly of high salinity H₂O, but minor amounts of nitrogen have been found. These fluid inclusions can be divided into three types.

O43-Type 1: Multiphase-Crystal dominated: Salt crystals ± carbonate crystal + daughter crystal (tourmaline ?) H₂O + vapour. (Fig. 2c)

O43-Type 2: Single phase liquid nitrogen: May be in only minor occurrences (Fig. 2d)

O43-Type 3: Single H₂O dominated: Slightly saline. Probably secondary inclusions.

A temperature estimate based on fluid inclusion heating (Fig. 3) may be around 300°C, although "necking-down" or inhomogenous trapping of inclusions may have resulted in measurements in excess of 300°C.

PRELIMINARY CONCLUSIONS

Salinity

Highly saline water occurs in all of the areas discussed, including fluid inclusions related to the Bidjovagge-Au mineralization (Ettner et al.), except for Bidjovagge-Cu and Dælljadas where slightly saline water is present. Based on microthermometric data, salts most likely present include both NaCl and CaCl₂, and although not identifiable, KCl or other salts may be present. Calculated salinities of these inclusions range between 30 to 45 wt %, (eq. NaCl). Salinities at Bidjovagge-

Cu and Dælljadas are generally below 27 wt. %, although slightly more saline inclusions exhibiting small salt crystals occur occasionally.

In relationship to Bidjovagge-copper, homogenization temperatures, of low salinity H₂O + vapour inclusions, plotted against final ice melting temperatures (dependent on salinity) (Fig.5) indicate that salinities decrease with decreasing temperature. This relationship may be explained by fluid mixing with cooler, less saline meteoric water (Shepherd et al., 1985). The occurrence of large copper mineralized veins, found only at Bidjovagge in respect to the other areas discussed may explain the indication of the introduction of meteoric water. Wide, open fissures could allow for the introduction of meteoric water.

The presence of synorogenic granitic and diabase intrusives in the Kautokeino greenstone belt, sometimes occurring along shear zones, presents the possibility that the magmas were a source of the saline H₂O. Salinities (Cl content) of fluids expelled from granitic melts is dependent on factors such as melt composition (i.e. Cl, F, K/Na, SiO₂ and CO₂ content), pressure and temperature (Webster, 1992), and would therefore probably vary between different granitic bodies. Lower salinity water found within quartz in pegmatite at Dælljadas may represent low Cl fluids produced from a granitic melt which did not allow for extensive exsolution of Cl.

If intrusives such as the Dælljadas pegmatites were the source of fluids for these other areas discussed, salinity of the fluid may have increased during ascent through shear zones. Possible reasons for an increase in salinity during ascent of the fluid along shear zones may be due to either addition of salts from metasediments, especially carbonates and evaporites (i.e. Crawford and Hollister, 1986), or hydration of wall rocks (Trommsdorff and Skippen, 1987; Kullerud, *in preparation*). Because Cl has a strong affinity for the fluid phase, so therefore removal of H₂O, by the hydration of wall rock, would increase the salinity of the fluid (Trommsdorff and Skippen, 1987; Kullerud, *in preparation*).

CO₂

Fluid inclusions rich in CO₂ have been found in abundance at Bidjovagge-Au (Ettner et al.), Ucca-vuovdas, Masi River, and Dælljadas. The presence of minor carbonate daughter crystals in inclusions at Object 43 indicate that a minor amount of CO₂ was, or is, present. At Bidjovagge, large chalcopyrite-carbonate veins indicate that CO₂ was present in the fluids, although it is absent in the fluid inclusions.

This division of two groups of abundant vs. minor/absent CO₂ corresponds with crustal depth and metamorphic grades of the deposits. If we assume that the parent fluid consisted of H₂O with abundant dissolved CO₂, trapping of this fluid would correspond to inclusions found at Bidjovagge-Au, Ucca-vuovdas, Masi River, and Dælljadas, while phase separation could result the general loss of CO₂, seen in

inclusions at Object 43 and Bidjovagge-copper. Phase separation can occur as a result of temperature drop, pressure drop and fluid contamination (i.e. addition of salt or CH_4) (Fig. 6). Phase separation would not completely separate CO_2 from the water, thus providing CO_2 for carbonates to form in the veins and as daughter crystals in fluid inclusions.

CH_4

Methane has been found at Bidjovagge both in inclusions related to gold (Ettner et al.) and inclusions related to copper. The presence of a second gas, contaminating CO_2 , has been established for Dælljadas, Ucca-vuovdas and Masi River, although further Raman microprobe work is needed to confirm if the contaminant is CH_4 . Methane has not yet been found at Object 43.

The abundance of methane at Bidjovagge has been suggested to be a result of extensive fluid interaction with the black schists (Ettner et al.). This interaction appears to have been very important for gold and copper precipitation at Bidjovagge by drastically reducing the oxygen fugacity of the fluid and, therefore, reducing the stability of the metal complexes (Ettner et al.). Recognition of methane in the fluid at other areas of mineralization may indicate that similar processes occurred.

Nitrogen

Nitrogen has only been found at Object 43 thus far. Previous fluid inclusion studies have described fluids dominated by nitrogen in very low to high grade metamorphic rocks (i.e. Crawford and Hollister, 1986). Sources of nitrogen found in low grade metamorphic rocks, such as at Object 43, have been suggested as breakdown of organic matter, or breakdown of NH_4^+ bearing minerals (i.e. biotite, muscovite and potassium feldspar) (Kreulen and Schuiling, 1982; Crawford and Hollister, 1986). Therefore, the presence of nitrogen at Object 43 may represent alteration or metamorphic processes, rather than the nature of the mineralizing fluids.

Temperature and Pressure Estimates

Based on salt melting temperatures, differences in temperatures of trapping between Bidjovagge-gold (Ettner et al.) and Object 43, are not very pronounced. Temperatures for Bidjovagge-gold are estimated between 275 to 375°C (Ettner et al.) and around 300°C at Object 43. Although salt melting temperatures have not been measured at Masi River or Ucca-vuovdas, based on salt contents, trapping temperatures are not anticipated to be much different.

Isochores have been calculated for both Bidjovagge-copper (BCu-Type 1) and Object 43 (O43-Type 1) inclusions (Fig. 7). Different salinities and temperatures of homogenization were adapted from microthermometric data for the calculation of the

isochores. In figure 7, the maximum temperatures of salt melting are plotted as vertical isotherms, 260°C for Bidjovagge-Cu, and 325°C for Object 43, and where these isotherms cross the isochores, corresponding isobars are drawn. It is not yet clear whether the fluid trapping occurred as a homogeneous fluid or a heterogeneous fluid + salt crystal. From Figure 7, if homogeneous trapping occurred, it appears that maximum trapping pressures for Bidjovagge-copper is approximately 1.6 kbars or slightly higher, whereas maximum pressures for Object 43 are higher, at around 2.1 kbars or slightly higher. If heterogeneous trapping of salt crystals and H₂O occurred, then these temperatures and pressures represent maximum values of fluid trapping.

It was argued by Ettner et al. that temperatures for fluid trapping related to Bidjovagge-gold were approximately 300 to 375°C and between 2 to 4 kbars. Considering pressures and temperatures for trapping of Bidjovagge-gold, Object 43, and Bidjovagge-copper, there appears to be a distinct change in pressure and subtle changes in temperature (Fig. 7). Of these three mineralizations discussed, Bidjovagge-gold appears to be the deepest and hottest, and Bidjovagge-copper appears to be the shallowest and coolest, while Object 43 appears to lie between the two end members.

Stable Isotopes

Stable isotope data from carbonates at Bidjovagge suggest that mineralizing fluids were related to fluids responsible for gold mineralization, but were in somewhat more equilibrium with the wall rocks. This may have occurred during mixing of less reactive water, possibly of meteoric origin.

Proposed Model

Water rich in salt (NaCl + CaCl₂) and CO₂ appears to have moved up along shear zones and was responsible for alteration and mineralization in the Kautokeino greenstone belt. The fluids studied are in agreement with differences between mineralized areas, in the Kautokeino greenstone belt, in metamorphic grade (and implied crustal depth of formation) and the structural fabric of the shear zones. Based on fluid studies, these areas of mineralization and alteration, can be divided into two groups:

- 1.) Hotter CO₂-rich saline H₂O
- 2.) CO₂-poor saline H₂O

The hotter CO₂-rich saline H₂O occurs in deposits located within higher grade metamorphic terrains where shear zones display ductile to brittle fabric (i.e. Bidjovagge-gold, Dælljadas, Masi River, Ucca-vuovdas). Fluids studied which are CO₂-poor saline H₂O occur within lower grade metamorphic terrains where shear zones exhibit brittle fabric (i.e. Bidjovagge-copper, Object 43). Additionally, it may

be generally said that gold mineralization occurs in ductile shear zones within higher grade metamorphic terrains dominated by hotter CO₂-rich saline H₂O, and copper mineralization occurs within brittle structures in lower grade metamorphic terrains dominated by CO₂-poor saline H₂O.

The fluids observed suggest that the fluid evolved during ascent alone deeper ductile shear zones to shallower brittle shear zones in the crust. Fluids evolved by including an increase in salinity and the loss dissolved CO₂. Phase separation of dissolved CO₂ may have occurred due to decreasing pressure or temperature, or contamination by salts or methane. The presence of less saline water at Bidjovagge-copper suggest that in some areas meteoric water infiltrated the shear zones, probably along open brittle fractures in the shallower crust.

Mineralization styles, of the areas discussed, appears to have been controlled by changes in conditions and the nature of the transporting fluid. The transporting ability of the fluids appears to have been affected by the decrease of pressure and temperature, phase separation of CO₂ and change in salinity, as it moved up along shear zones. These changes may have allowed for more gold mineralization at deeper crustal depths in more ductile regimes, and copper mineralization in shallower brittle regimes.

Water interaction with black shales resulted in the production of methane, such as is seen at the Bidjovagge deposit. As argued by Ettner et al., the oxygen fugacity of the fluid was lowered resulting in gold and copper precipitation. Recognition of CH₄ in other areas of mineralization, such as Object 43, Uccavovdas and Masi River may indicate that similar processes have occurred.

IMPLICATIONS FOR EXPLORATION

Application of the proposed model towards exploration for Bidjovagge-type deposits may be applied on both a regional and local scale. As mineralization appear to be synorogenic (Bjørlykke et al., 1992), deposits appear to correspond to metamorphic grade (crustal depth of mineralization). Since Bidjovagge occurs along the boundary between higher grade (amphibolite facies) and medium grade (upper greenschist facies) metamorphic regions (Fig. 1), areas of similar metamorphic grade are potential areas of gold mineralization.

Models of shear zones show that styles of deformation are dependent on crustal depth and temperature (Sibson, 1977), and therefore related to metamorphic grade discussed above. Structural fabric, displayed by the shear zone which hosts gold mineralization at Bidjovagge, is composed of both ductile and brittle deformation (Fig. 8), indicating a certain depth and temperature of deformation and mineralization. Shear fabric, may therefore be used as an exploration tool, on a local

scale, to make a general determination of the depth of deformation, relative to Bidjovagge.

Continued fluid inclusion work may also be useful as an indirect tool for testing the potential of areas. Previous workers have used fluid inclusion studies to some success for the exploration of mineral deposits (Roedder, 1977). This method is somewhat cumbersome and time consuming, and may therefore be best used in advanced stages of prospect analysis.

The presence of methane has been shown to be significant during the mineralization at Bidjovagge, as argued by Ettner et al.. Therefore as previously discussed, the presence of methane in other areas under investigation would suggest that similar processes may have occurred. Recognition of methane may be accomplished by the cumbersome method of fluid inclusion analysis, or by a much more efficient method of gas chromatography of gas extracted from crushed samples. This method has been used by Mulshaw (1992) as an attempt exploration for base metal deposits that were associated with hydrocarbons and organic matter and may easily be applied to exploration for Bidjovagge-type deposits.

CONTINUING WORK

Fluid inclusion investigations are continuing in order to further characterize the fluids responsible for mineralization within the Kautokeino greenstone belt. Continued analysis of gas-rich inclusions, by means of Raman microprobe analysis, is needed to detect the possible presence of CH₄, or other gasses at Masi River, Dælljadas and Object 43. This work along with the results discussed in this report will be written as a article for publication. Also, work on the Bidjovagge deposit to further describe the fluids responsible for gold mineralization, is continuing. More carbon and oxygen isotope analysis of carbonates from Bidjovagge are in process at the isotope laboratory at the University of Bergen. Also, characterization of the water, at Bidjovagge, will be investigated by oxygen and hydrogen isotope analysis of biotite. A comprehensive synthesis of this work, along with the work of the post doctorate fellow Dr. Nie Fengjun and Kjell Nilsen is being planned.

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Figure Captions

Figure 1: Simplified geologic map of the Kautokeino greenstone belt emphasizing metamorphic grade. Mineralized and altered areas are marked with boxes. After Sandstad (1992) and Krill et al., 1988.

Figure 2: Photomicrographs of fluid inclusions from Bidjovagge-copper and Object 43. Scale bar = 0.05 mm. a.) BCu-Type 1 inclusions: low salinity H_2O + vapour. b.) BCu-Type 3: double phase CH_4 + low salinity H_2O . c.) O43-Type 1: multiphase-crystal dominated (salt crystals $\pm$ carbonate crystal + daughter crystal + H_2O + vapour). d.) O43-Type 2: single phase liquid nitrogen.

Figure 3: Histogram of fluid homogenization and salt melting temperatures measured at both Bidjovagge-copper and Object 43.

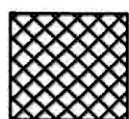
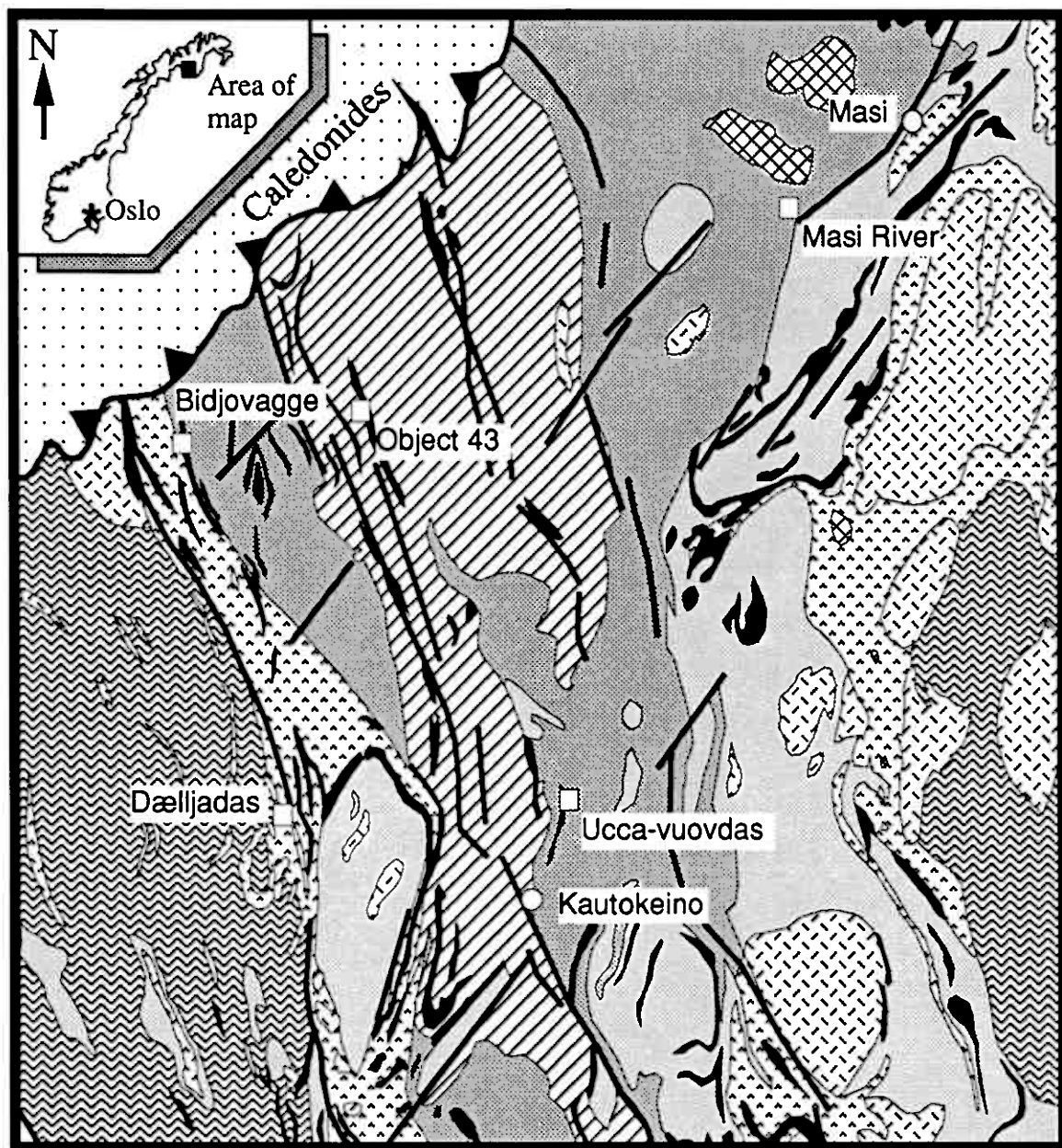
Figure 4: Stable carbon and oxygen isotopes from carbonates in the Bidjovagge deposit. Carbon isotopes are standardized to PDB and oxygen to SMOW.

Figure 5: Homogenization temperatures versus final ice melting temperatures from inclusions from Bidjovagge-copper (BCu-Type 1). Lower final ice melting temperatures indicate higher salinities in a NaCl - CaCl_2 solution.

Figure 6: Miscibility of CO_2 in H_2O plotted versus temperature. Fine lines at bottom of diagram indicate solvii for pure H_2O and CO_2 at separate pressures. The three upper solvii indicate solubility for impure systems, as indicated. Diagram constructed from compilations of Walsh et al. (1988) and Crawford (1981).

Figure 7: Pressure versus temperature diagram with calculated isochores from Bidjovagge-copper and Object 43 plotted. Possible limits of fluid trapping for Bidjovagge-copper and Object 43 are bounded by stripped lines.

Figure 8: Schematic model of a shear zone with structural styles, modelled for the Abitibi greenstone belt by Colvine (1989) and adapted for the Kautokeino greenstone belt. Deposits and fluids discussed are displayed relative to the shear zone.



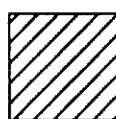
Metagabbro



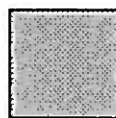
Sandstone/
Quartzite
(Masi Fm.)



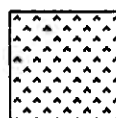
Basement
Gneiss



Greenstone
& Sediments
low grade (≈lower
greenschist facies)



Greenstone
low to medium grade
(≈greenschist facies)



Greenstone
medium grade
(≈amphibolite facies)

0 10 km



Faults/
Shear Zones

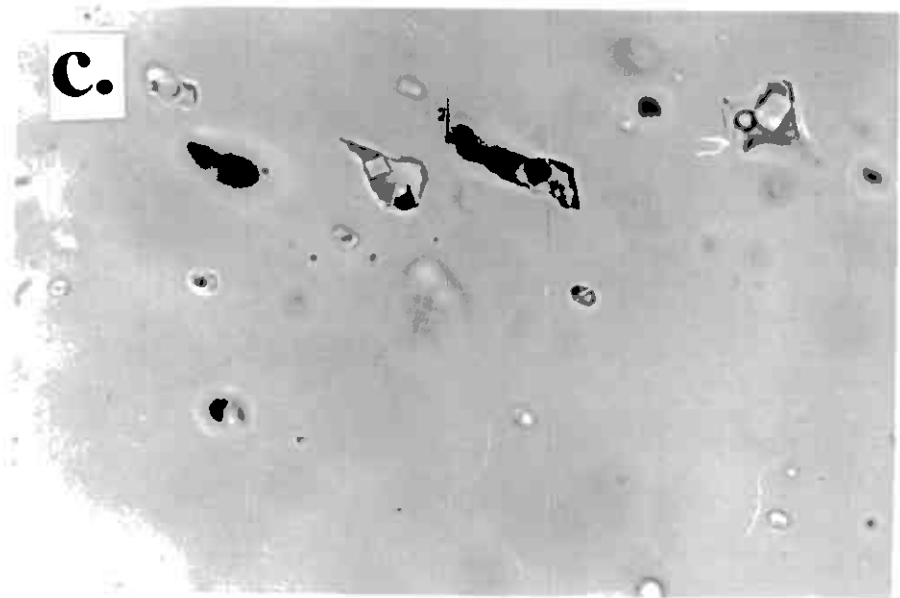
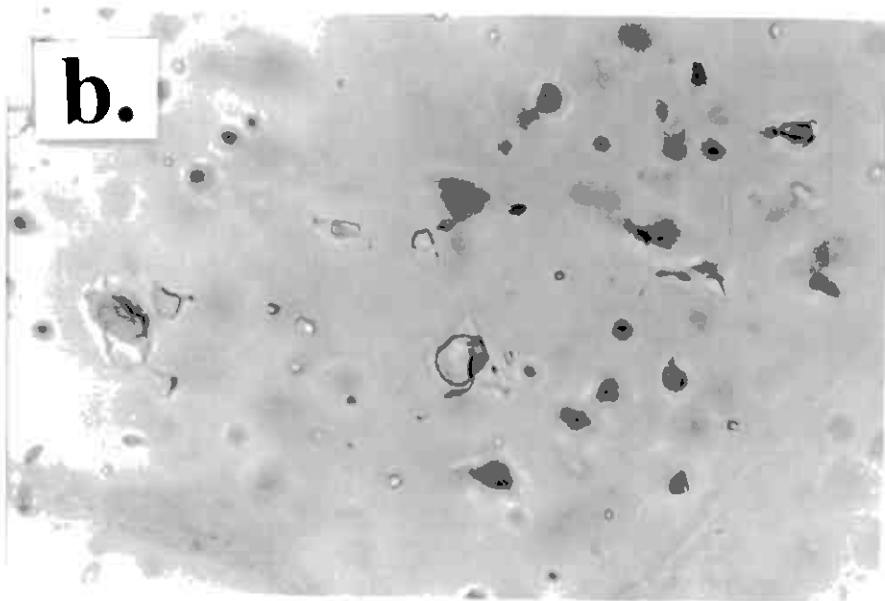
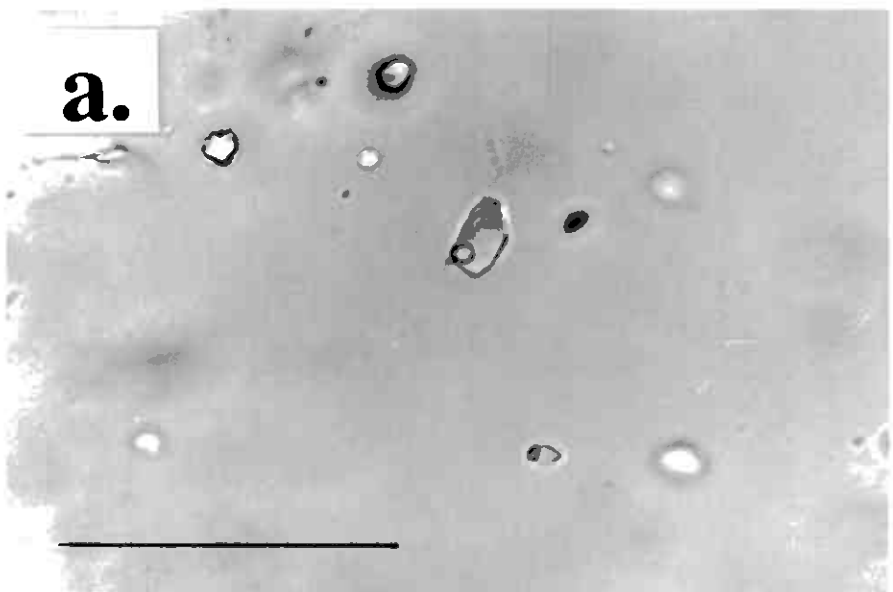


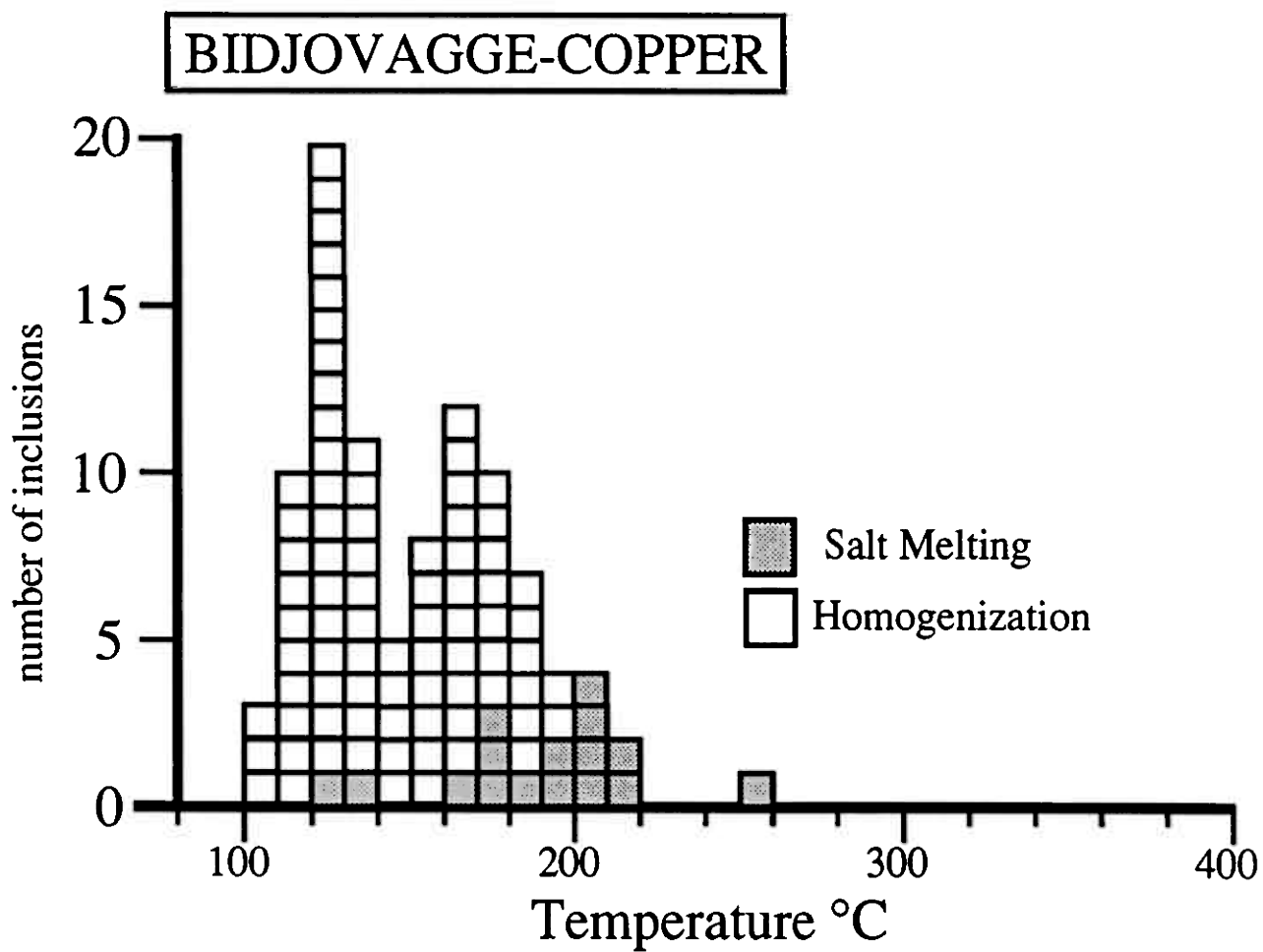
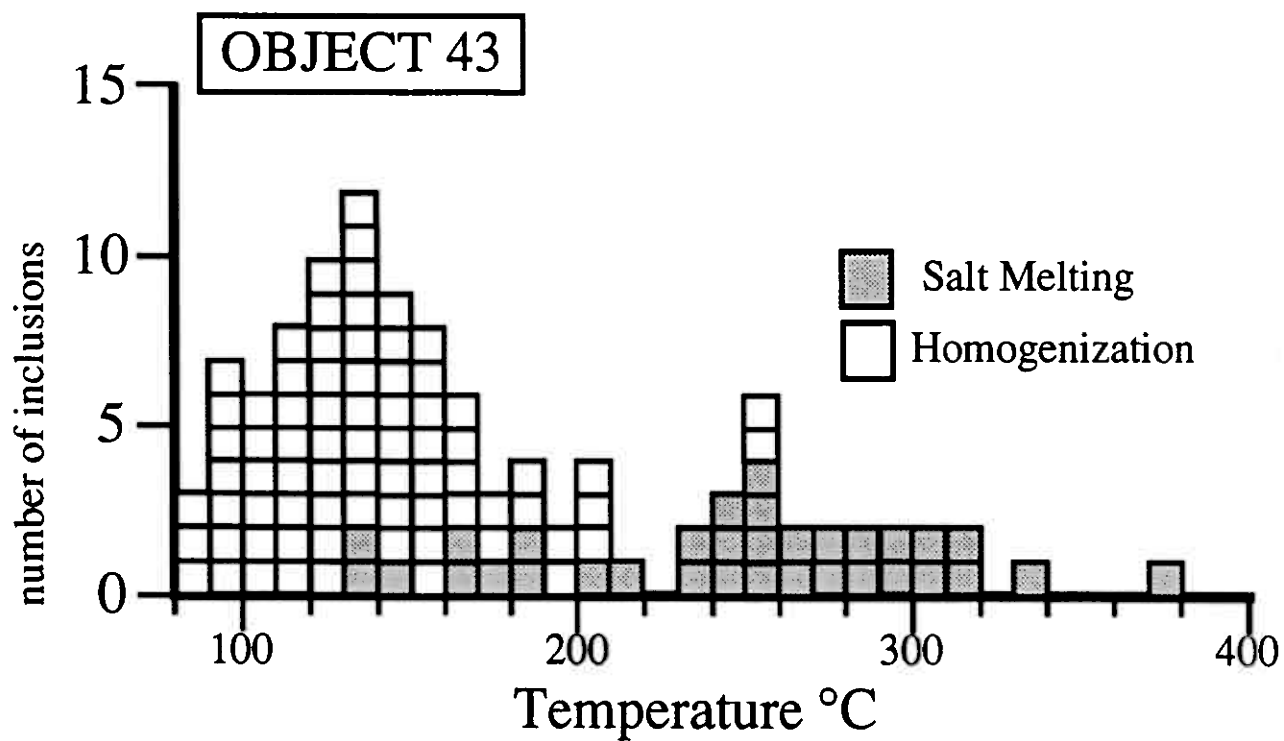
Diabase
Intrusives

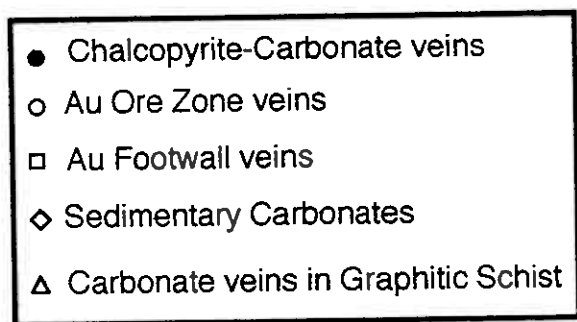
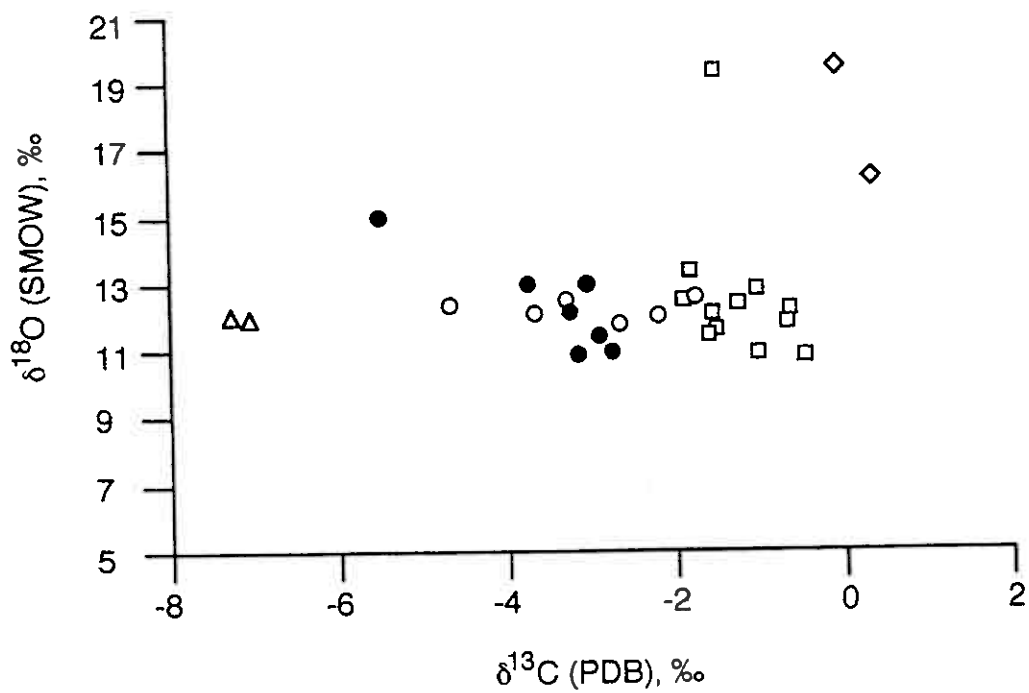


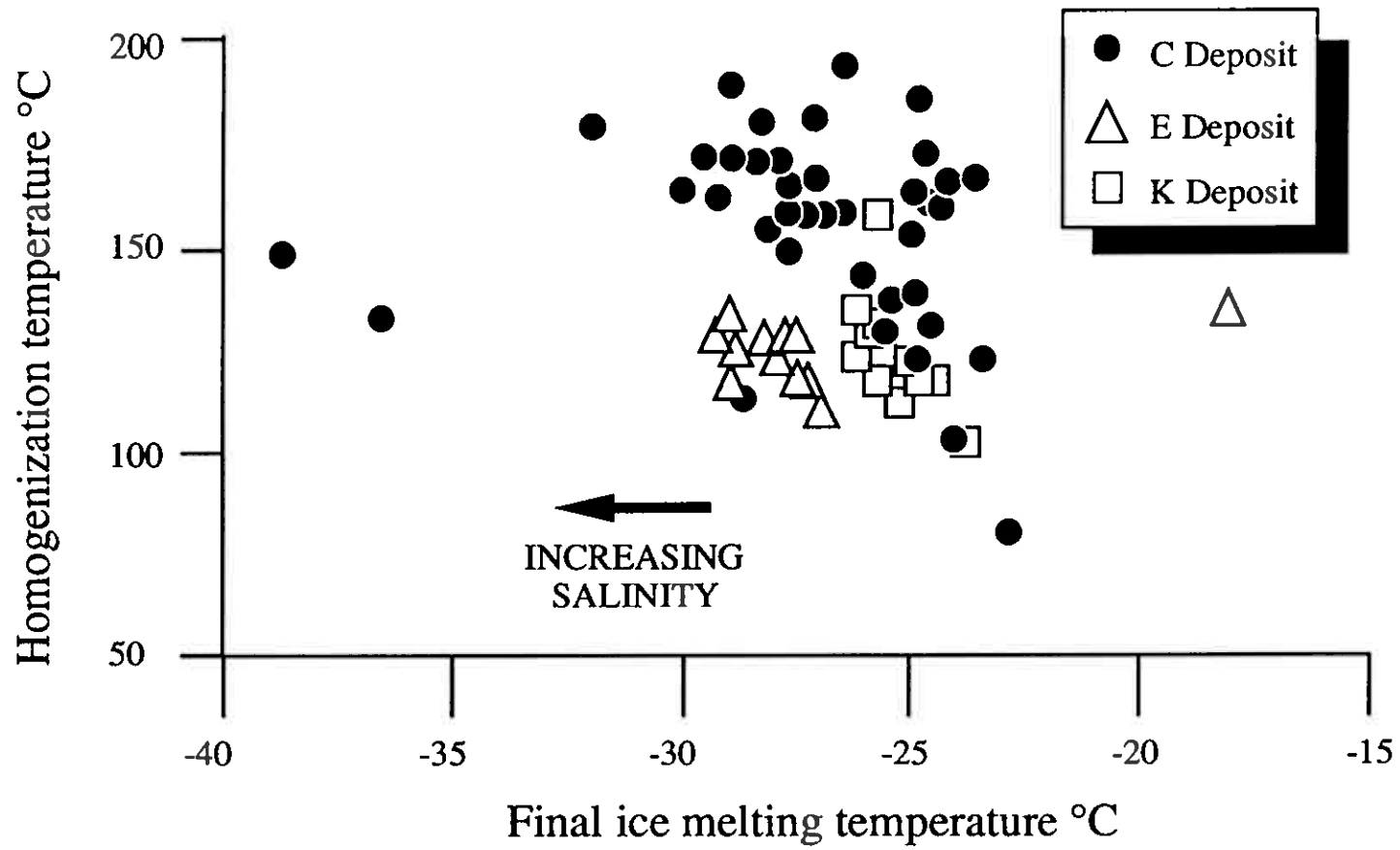
Granitic
Intrusives

Fig. 1









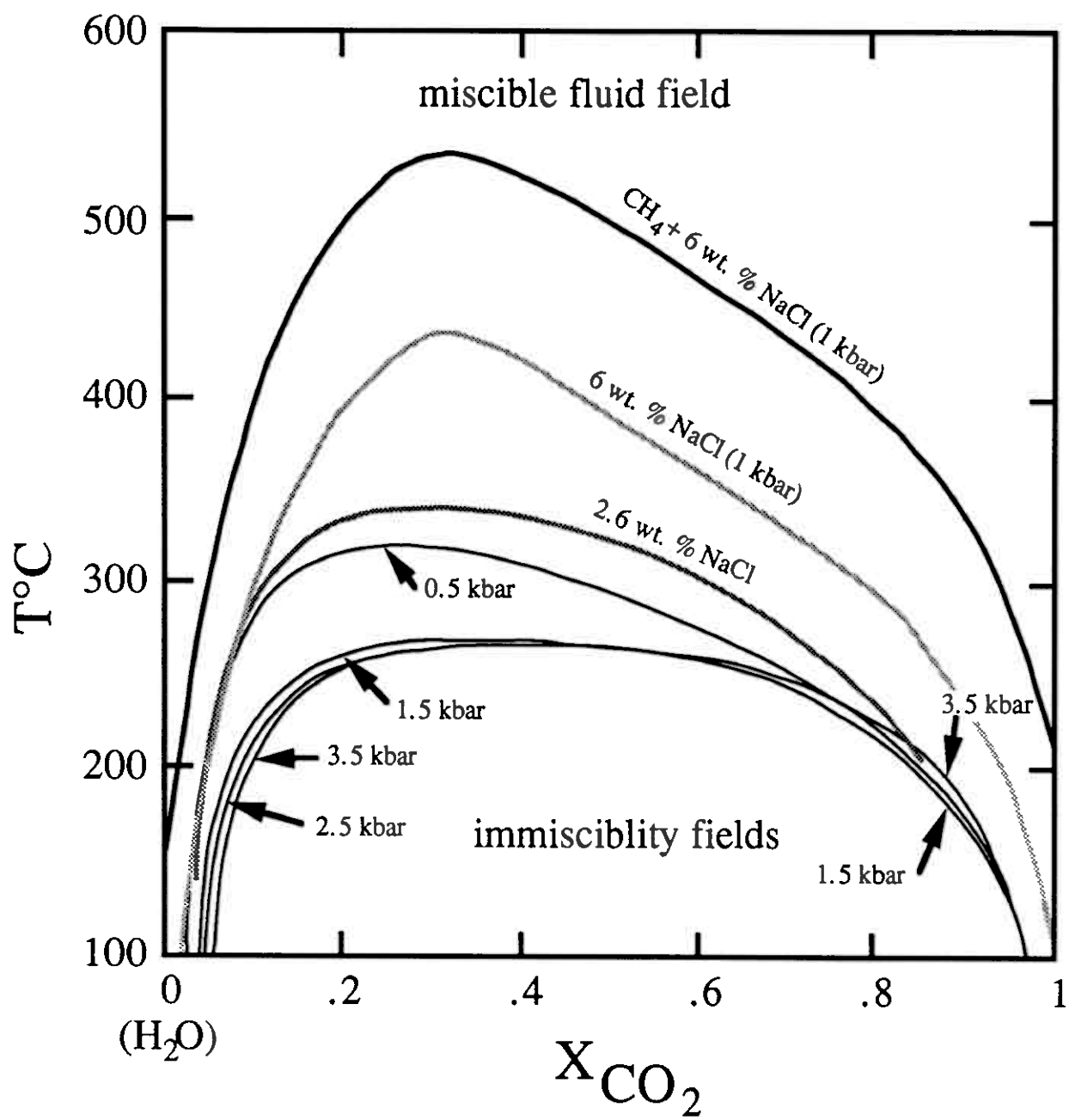


Fig. 6

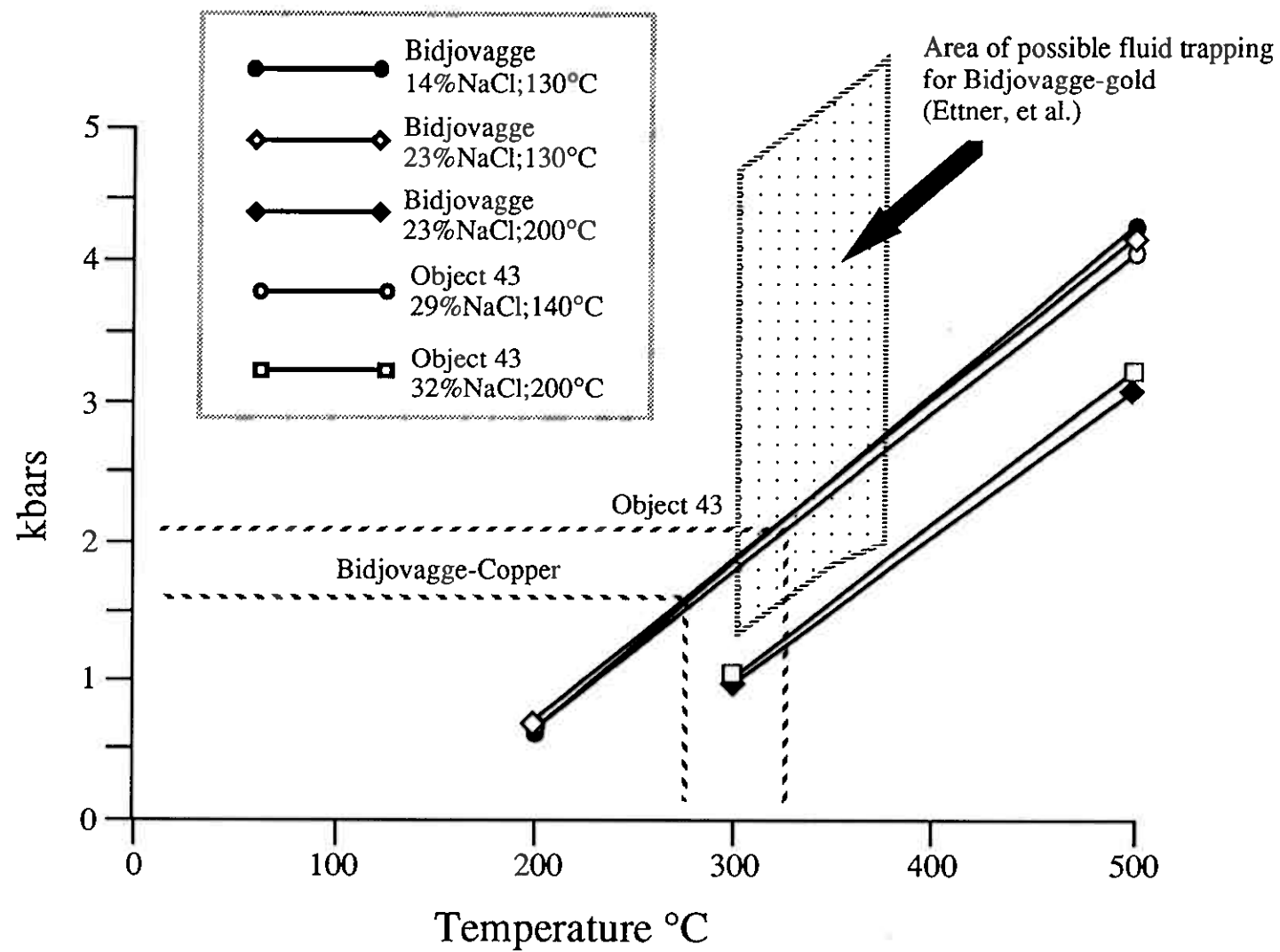


Fig. 7

