

## Metamorphic fluids in the Notch Peak contact-metamorphic aureole: Evidence from fluid inclusions

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### ABSTRACT

Fluid inclusions were examined in 13 samples from wollastonite-zone rocks, calc-silicate skarns, and granites from the Notch Peak, Utah, contact-metamorphic aureole using microthermometric techniques. All inclusions are aqueous, with no evidence for the presence of CO<sub>2</sub> or daughter crystals. Homogenization temperatures range from 280 to 110 °C, and melting temperatures range from +2 to –28 °C. Calculated trapping temperatures, at 2-kbar total pressure, range from ~250 to 475 °C, and calculated salinities range from 0 to 15 eq wt% NaCl. Wollastonite-zone inclusions have the highest homogenization temperatures of the rocks studied and have salinities of ~5 eq wt% NaCl. Granite sample inclusions have similar salinities but have homogenization temperatures in the range of 200 to 140 °C. Skarn samples have inclusions that are generally more saline than the other two sample groups and that have homogenization temperatures lower than ~180 °C. The low melting temperatures and lack of daughter crystals indicate that the solute consists of divalent salts, most likely CaCl<sub>2</sub>, in addition to NaCl. The lack of CO<sub>2</sub> is consistent with metamorphic fluid compositions indicated by mineral assemblages. Even though the calculated trapping temperatures and pseudosecondary or secondary nature of most inclusions indicate that the fluid was trapped after the peak of metamorphism, the compositions indicate that the trapped fluids could be the late metamorphic fluid.

### INTRODUCTION

The physical and chemical processes in most metamorphic terranes are conducted in the presence of a fluid phase. In most terranes, however, the only remaining evidence of the fluid is seen in fluid inclusions and mineral assemblages in the rocks. As a result, the composition, changes in the composition, and flow pathways of fluids must be inferred from mineral equilibria, from fluid inclusions, or from isotopic systematics.

Many authors have studied fluid inclusions in order to provide constraints on the conditions of metamorphism and to provide insight into fluid-rock interaction and subsequent fluid-phase evolution (see Roedder, 1984, for a list of some of these studies). Our petrologic and geochemical studies of the contact-metamorphic aureole of the Notch Peak stock, Utah (Hover-Granath et al., 1983; Nabelek et al., 1984; Labotka et al., 1988b), have shown that calcareous argillites and argillaceous limestones were metamorphosed in the presence of an extremely H<sub>2</sub>O-rich fluid (despite the loss of ~20 wt% CO<sub>2</sub>) that requires the interaction of as much as 13 rock masses of H<sub>2</sub>O with the lithologic units. Estimates of the amount of externally derived fluid require accurate determination of the fluid composition. This is generally determined by phase equilibria, and errors can greatly affect the calculated amount of infiltrated fluid (Wood and Graham, 1986). As an example of potential problems in determining the composition of a metamorphic fluid, Ferry (e.g., 1976) found that carbonate rocks in a regional metamorphic terrane

in Maine were infiltrated by large amounts of an H<sub>2</sub>O-rich fluid, causing extensive decarbonation. However, Ahrens et al. (1985) found that fluid inclusions in these rocks are CO<sub>2</sub>-rich. In light of this apparent inconsistency in determining fluid composition, our study compares the compositions of fluid inclusions with those determined by mineral equilibria in the Notch Peak aureole. We wish to determine whether the metamorphic fluid phase was trapped, whether the fluid-inclusion compositions are consistent with mineral equilibria, and whether processes such as gas-phase separation could account for the very H<sub>2</sub>O-rich fluid in the Notch Peak aureole.

### GEOLOGIC SETTING AND PETROLOGY

Notch Peak is located in west-central Utah (Fig. 1) in the middle of the House Range, a north-trending fault-block mountain range that is typical of the Basin and Range province. A simplified geologic map of a portion of Notch Peak, after Hintze (1974), is in Figure 1. During Jurassic time, the Notch Peak granitic stock intruded and metamorphosed limestones, argillaceous limestones, and calcareous argillites of Cambrian age. The petrology and geochemical evolution of the Notch Peak stock have been extensively studied by Nabelek et al. (1986). The metamorphosed units at Notch Peak include (from oldest to youngest) the Marjum Formation, the Weeks Limestone, and the Orr Formation. Metamorphism at Notch Peak has been studied by Hover-Granath et al. (1983), Nabe-

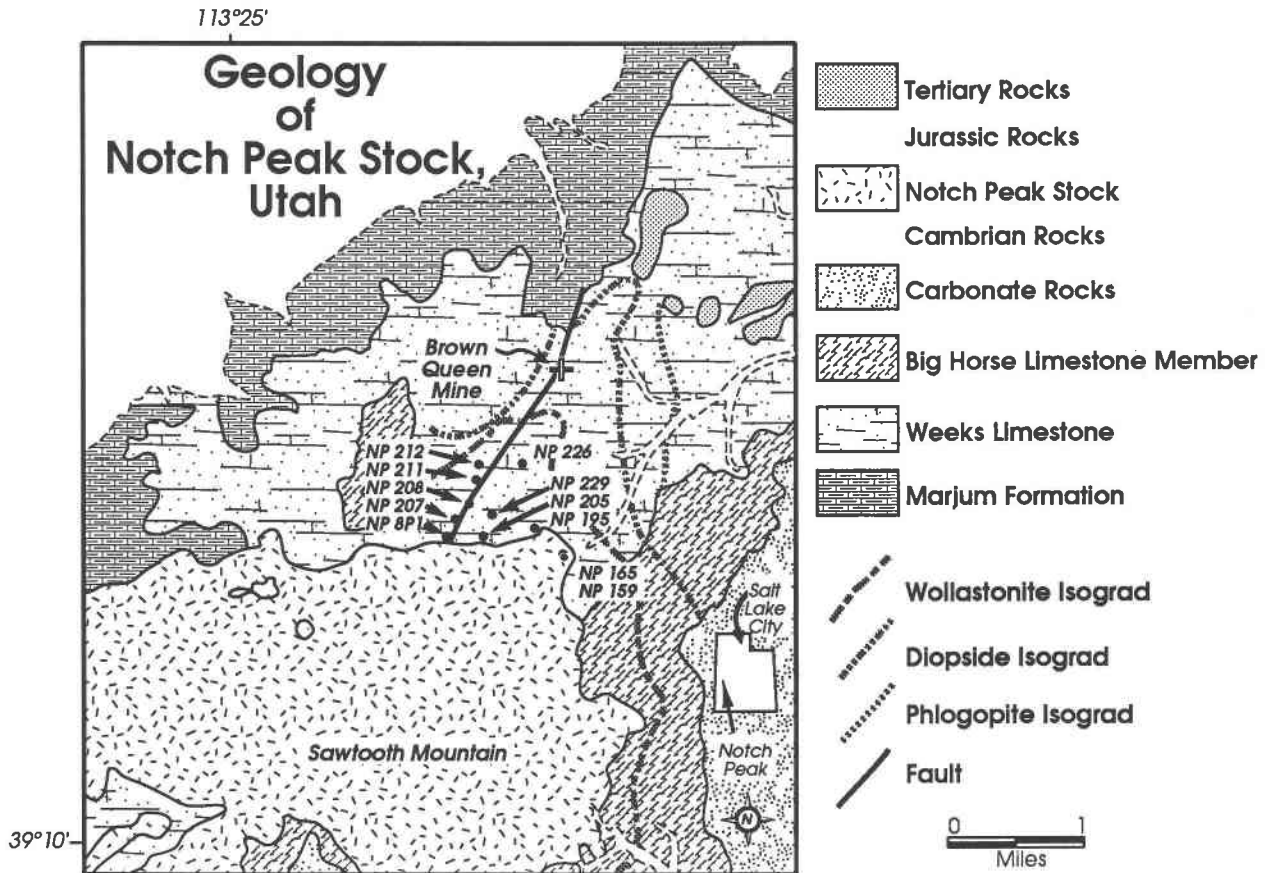


Fig. 1. Generalized geologic map of a part of the Notch Peak quadrangle, Utah, simplified from Hintze (1974). Wollastonite, diopside, and phlogopite isograds are mapped in the Weeks Limestone. The wollastonite and diopside isograds in the Big Horse Limestone Member are based on assemblages in calcareous argillites (Hover-Granath et al., 1983). The phlogopite isograd was not mapped in the Big Horse Limestone Member.

lek et al. (1984), Labotka et al. (1988a, 1988b), and Novick (1988). Detailed petrographic descriptions of the rocks, locations of the isograds, and the geochemistry of the rocks are included in those reports.

The isograds shown in Figure 1 are based on reactions that occurred in argillaceous limestones in the Weeks Limestone and in the overlying Big Horse Limestone Member of the Orr Formation, as described in the studies of Hover-Granath et al. (1983), Labotka and Nabelek (1986), and Novick (1988). Metamorphism is first manifested in the phlogopite zone, marked by the coexistence of phlogopite + muscovite + chlorite in rocks bearing calcite + quartz. At higher metamorphic grades, diopside appears at the diopside isograd in the assemblage diopside + K-feldspar + calcic plagioclase. Wollastonite and vesuvianite appear at the wollastonite isograd, at the expense of quartz and calcic plagioclase. Grossular is abundant in the Big Horse Limestone Member, but is only rarely found in the Weeks Limestone. Scapolite is widespread within the Weeks Limestone, first appearing near the diopside isograd, but is less common in the Big Horse Limestone Member. Scapolite typically contains 1.0 to 1.5 wt% Cl.

Assemblages in the argillaceous limestones indicate that metamorphism occurred over a temperature range from about 600 °C at the contact with the stock to less than 400 °C in the phlogopite zone. The wollastonite isograd is, in part, polythermal, but in most of the aureole it formed at ~465 °C. At this temperature and at a pressure of 2 kbar, the fluid composition must have been  $X_{\text{CO}_2} \approx 0.004$ . At the wollastonite isograd, the argillites were nearly completely decarbonated, releasing  $16 \pm 4$  wt%  $\text{CO}_2$ . Fluid inclusions were examined to determine whether their compositions are consistent with the petrologic estimate of the fluid composition and whether there is any evidence for separation of a  $\text{CO}_2$ -rich phase from the aqueous fluid.

#### SAMPLES

Fluid inclusions from three types of rocks were examined in this study. The inclusions occurred in (1) wollastonite-zone Weeks Limestone, (2) skarn samples collected in areas adjacent to the Notch Peak stock, and (3) granitic rocks from the Notch Peak stock. Diopside-zone and lower-grade samples were examined to see whether there were any significant differences in fluid inclusion

compositions from the higher-grade samples, but there were no inclusions of sufficient size to obtain meaningful data. Sample localities are shown on Figure 1.

Inclusions, both solid and fluid, are abundant in all the minerals present in the rocks of the Weeks Limestone at Notch Peak. Pseudosecondary fluid inclusions found in quartz, feldspar, and vesuvianite grains gave the most reproducible results. These are also the easiest minerals for measuring the temperatures at which phase changes occurred. Secondary inclusions are present in planes that crosscut those of pseudosecondary nature. Primary inclusions are also present but are rare.

Rocks in the wollastonite zone are typified by the presence of vesuvianite, wollastonite, diopside, and scapolite. Vesuvianite occurs as large, poorly formed grains surrounded by fine-grained wollastonite and diopside. Diopside grains may also be found as large, radiating crystals. Scapolite grains are present as idioblastic, inclusion-filled crystals. These critical minerals are typically set in a fine-grained calcite and feldspar matrix. Garnet is also present in some samples.

Skarn samples, which appear to have formed during the waning stages of metamorphism, were examined to ascertain the compositions of fluids after the peak of metamorphism. These rocks are characterized by large euhedral grossular garnets, diopside, hedenbergite, and hornblende, with minor occurrences of vesuvianite, rutile, chlorite, and ilmenite. Quartz and calcite are also present, filling spaces between garnets.

The granite samples were studied to determine whether  $\text{CO}_2$  was present in the fluids expelled from the stock. Granite samples contain subequal amounts of quartz, plagioclase, and K-feldspar, with minor amounts of biotite. The feldspar and quartz crystals are poorly formed and may be as large as 5 mm in size. Samples collected closer to the contact between the granite and the Weeks Limestone are finer grained and contain more K-feldspar than other rocks collected from the stock. Zircon and ilmenite are present as accessory minerals.

Determination of melting and homogenization temperatures was done on a Fluid, Inc. gas-flow heating and freezing stage. The unit was checked against a known standard for reliability several times during the course of this study. Calculation of salinities and isochores was performed using Nicholls and Crawford's (1985) FORTRAN program HALWAT, with the corrections described by Brown and Lamb (1986). Trapping temperatures were calculated using a pressure of 2000 bars as estimated from the overburden present at the time of emplacement of the stock (Hover-Granath et al., 1983). Results of the heating and freezing studies of inclusions are in Figure 2. Tabulated values of homogenization and melting temperatures, salinities, and mineral assemblages can be found in Novick (1988) and are summarized in Appendix 1.<sup>1</sup>

<sup>1</sup> A copy of Appendix 1 may be ordered as Document AM-90-430 from the Business Office, Mineralogical Society of America, 1625 I Street, N.W., Suite 414, Washington, D.C. 20006, U.S.A. Please remit \$5.00 in advance for the microfiche.

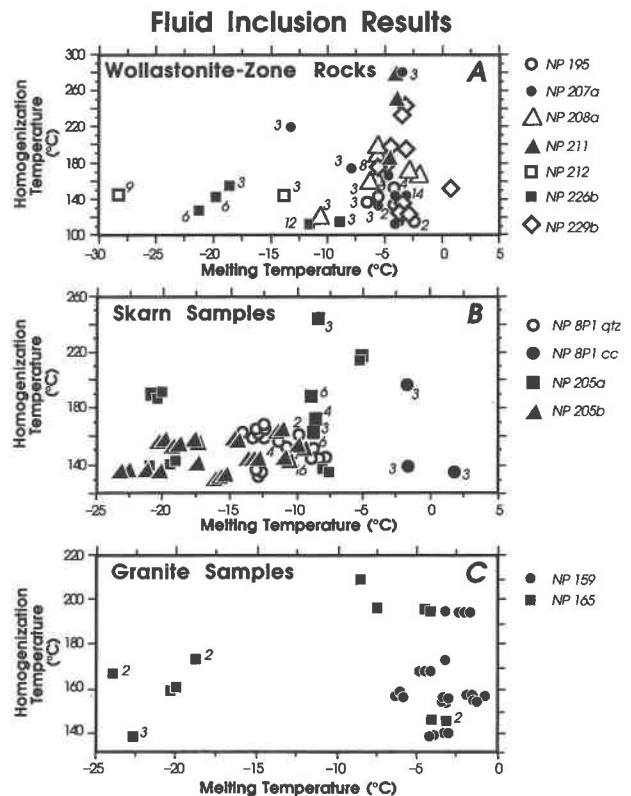


Fig. 2. Results of heating and cooling experiments on inclusions in the three sample groups: (A) wollastonite-zone rocks, (B) skarn samples, and (C) granite samples. Each sample is indicated by a different symbol, listed at the right-hand side of the diagram. The numbers next to some points indicate multiple inclusions with coincident values. The data can be found in Appendix 1 (see footnote 1).

## RESULTS

Summary diagrams of data for each of the sample types are in Figure 2. These diagrams show the homogenization temperature versus the melting temperature for each inclusion studied.

All inclusions in all samples contain an  $\text{H}_2\text{O}$ -rich fluid, with little or no  $\text{CO}_2$ . Daughter crystals were not observed in any inclusion. Inclusions in wollastonite-zone rocks, shown in Figure 2A, are pseudosecondary and occur mostly in vesuvianite, although some were observed in feldspar. The inclusions have homogenization temperatures in the range 120 to 280 °C. Eutectic temperatures could be determined for some larger inclusions and are mostly in the range of -28 to -38 °C; values as high as -20 and as low as -50 °C have been observed. Melting temperatures of most inclusions cluster near -5 °C, but are as low as -28 °C. There is no correlation between homogenization and melting temperatures, except that most inclusions with melting temperatures lower than -10 °C have homogenization temperatures lower than 160 °C. Calculated salinity values are in the range 5 to 15 eq wt% NaCl, with most inclusions having values of ~5%. Trapping temperatures, assuming a pressure of 2 kbar, range

from ~250 to 475 °C, with most inclusions having values of ~300 °C.

Inclusions in skarn samples were observed in calcite and quartz grains, and all appear to be pseudosecondary. Homogenization and melting temperatures are shown in Figure 2B. Homogenization temperatures range as high as 250 and as low as 130 °C, with most having values between 140 and 180 °C. Melting temperatures range from -23 to -7 °C, with a few near 0 °C, and measured eutectic temperatures range from -20 to -38 °C. There is no relation between melting and homogenization temperatures. Calculated salinities fall mostly in the range of 10 to 15 eq wt% NaCl, and calculated trapping temperatures span the range from 430 to 250 °C, with most inclusions giving a value of ~280 °C.

Inclusions in granite samples, illustrated in Figure 2C, show a much narrower range in homogenization temperatures than the skarn and wollastonite-zone samples do, ranging from ~200 to 140 °C. Observed melting temperatures of most inclusions fall in a narrow range from -5 to 0 °C, although a few show distinctly lower melting temperatures, between -25 and -17 °C. Calculated salinities are low, mostly in the range 0 to 5 eq wt% NaCl, and trapping temperatures appear to be ~300 °C.

Inclusions in wollastonite-zone rocks show the greatest range in homogenization and melting temperatures. The melting temperatures of most wollastonite-zone inclusions are similar to those of most granite samples; however, most skarn samples have inclusions that appear to be more saline than inclusions in other rock types. All inclusions have calculated trapping temperatures lower than the peak metamorphic temperatures, consistent with the secondary or pseudosecondary nature of the inclusions. Even though the trapped fluids appear to be younger than the peak metamorphic fluids, none of the inclusions contains detectable CO<sub>2</sub>, which is consistent with fluid compositions indicated by the metamorphic assemblages.

#### DISCUSSION AND CONCLUSION

The wide range of homogenization temperatures for inclusions is similar to ranges reported in many of the skarn studies listed by Roedder (1984). This wide range of temperatures probably reflects the capture of inclusions over a long period of time during cooling of the pluton.

Roedder (1984) indicated that a narrow range in salinities is typical of skarn deposits. This finding is contrary to the results found in this study; all sample groups show a wide spread in salinities, although most skarn inclusions have lower melting temperatures than most granite or wollastonite-zone inclusions.

The saline inclusions, those with melting temperatures lower than -7 °C, generally have homogenization temperatures lower than 180 °C. It is possible that the observed range in salinities is the result of leakage or necking of the inclusions, but there is no obvious petrographic evidence for leakage or other changes in volume of the

inclusions. The low-melting inclusions in the wollastonite-zone samples may have resulted from a late change in density, but the skarn samples appear to have trapped fluids that were generally more saline than those trapped in the wollastonite-zone samples.

Trommsdorff and Skippen (1986) discussed how a wide range in the fluid salinities could have been caused by fluid effervescence. If the H<sub>2</sub>O-CO<sub>2</sub>-NaCl fluid infiltrating the carbonate rocks had become immiscible before the inclusions were filled, two types of inclusions would be found: an H<sub>2</sub>O-NaCl-rich group and a CO<sub>2</sub>-rich group. However, a CO<sub>2</sub>-rich group of inclusions was not found. Labotka et al. (1988b) showed that fluid-phase immiscibility could have occurred only before the major metamorphic reactions and that peak-metamorphic fluid compositions could not have been derived by loss of a low-density, CO<sub>2</sub>-rich phase. Therefore, neither fluid-inclusion nor petrologic data supports the formation of a range in salinities by effervescence.

The skarns may have formed from more saline late fluids, exotic to the metamorphic fluid or from the metamorphic fluid that evolved to more saline compositions by ion exchange with the host rocks. The low melting and eutectic temperatures of the saline inclusions and the lack of daughter crystals indicate that the dissolved salts include something other than NaCl. Aqueous MgCl<sub>2</sub> solutions have eutectic temperatures of -35 °C and CaCl<sub>2</sub> solutions have eutectic temperatures of -50 °C. Both are geologically reasonable constituents in the metamorphic fluid. Dissolution of calcite in a chloride solution, for example, would increase the CaCl<sub>2</sub> content of the solution. This process would occur upon cooling only if the pressure also decreased. Late formation of a solid hydrous phase would result in increased salinity of the fluid, if the fluid is unsaturated. Many metamorphic rocks containing grossular and wollastonite show zones of alteration made of prehnite (Hover-Granath et al., 1983). The altering fluid would, as a result, be enriched in salts. Although the exact mechanism of increasing salinity from that of the peak metamorphic fluid to that of the skarn-forming fluid cannot be determined uniquely, the evolution in composition of a single fluid over the cooling of the aureole, rather than introduction of a late exotic fluid, is a plausible explanation of the data.

Labotka and Nabelek (1986) and Nabelek et al. (1988) have demonstrated that aqueous fluids flowed through the north-trending fault shown in Figure 1. The effect was to extend the wollastonite and diopside isograds much farther north than elsewhere in the aureole. The fluids apparently were relatively oxidizing because graphite, which is abundant in the Weeks Limestone, is absent in the vicinity of the fault. Fluid inclusions in rocks collected near the fault, NP 207, NP 208, NP 211, and NP 212, do not have melting or homogenization temperatures that are distinct from other inclusions in wollastonite-zone rocks. There seems to be no distinct effect of the relatively open channel way on the composition of the fluids.

Petrologic studies of the contact-metamorphic rocks in

the Notch Peak aureole indicate equilibration with a large volume of an externally derived aqueous fluid. The fluids in inclusions in wollastonite-zone rocks, skarns, and granite samples appear to have been trapped after the peak of metamorphism. Even so, they too have H<sub>2</sub>O-rich compositions with no detectable CO<sub>2</sub>. The trapped fluids may indeed be the metamorphic fluid.

The bulk of the wollastonite-zone and granite sample inclusions appear to have salinities of about 5 eq wt% NaCl. Some inclusions in these samples and most skarn sample inclusions have greater salinities than 5%. The lack of daughter crystals and low eutectic temperatures indicate that solute includes salts other than NaCl. CaCl<sub>2</sub> is a likely constituent. The skarn-forming fluids probably evolved from the metamorphic fluid instead of being ex-otic infiltrates.

The water-rich nature of the fluid does not appear to have resulted from effervescence and escape of a CO<sub>2</sub>-rich phase. There is no evidence for CO<sub>2</sub>-bearing inclusions, and if effervescence occurred, none of the CO<sub>2</sub> phase was trapped.

Fluid inclusions from rocks at Notch Peak provide data that are consistent with indications of metamorphic fluid compositions from mineral equilibria. Although data from these inclusions do not prove the presence of a H<sub>2</sub>O-rich fluid phase during metamorphism, the fluids in the inclusions could reasonably have been derived from an aqueous metamorphic fluid.

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