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Geologic Setting, Depths of Emplacement, and Regional Distribution of Fluid Inclusions in Intrusions of the Central Wasatch Mountains, Utah

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Abstract

Nine mid-Tertiary calc-alkaline stocks, a subvolcanic porphyry system, and coeval volcanic rocks are exposed in a 45-km-long east-trending belt across the central Wasatch Mountains, Utah. The intrusions vary systematically from west to east in texture, style of emplacement, extent of contact metamorphism, hydrothermal alteration, and mineralization. Pressure-depth estimates based on metamorphic mineral assemblages, stratigraphic reconstructions, and fluid inclusion data indicate a regular variation in paleodepths ranging from about 11 km on the west to less than 1 km on the east. These data indicate that the central Wasatch Mountains have been tilted down to the east about 20° during the late Cenozoic. Fluid inclusion populations in igneous quartz also vary systematically with paleodepth; high-salinity (halite-saturated) fluid inclusions are present in the eastern porphyry stocks and in the upper parts of the Alta and Clayton Peak stocks in the center of the belt but are absent in the deeper parts of the Alta and Clayton Peak stocks and in the Little Cottonwood stock on the west side of the belt. In the Alta and Clayton Peak stocks, nearly planar high-paleosalinity horizons, presently dipping 15° to 20° east, separate rocks containing high-salinity fluid inclusions (above the high-paleosalinity horizon) from those lacking such fluid inclusions. Comparison of fluid-inclusion populations in igneous and vein quartz in the Alta and Clayton Peak stocks indicates that high-salinity fluids predated most of the vein-forming hydrothermal activity and provide the earliest record of fluids to circulate in these stocks. High-salinity fluids probably formed either by boiling of fluids released during the late stages of crystallization in the parts of the intrusions where pressure was less than about 1,300 bars or by exsolution of immiscible high-salinity brines from the crystallizing magmas. Most hydrothermal mineralization associated with the intrusions, including Ag-Pb-Zn ores in the Park City district, are associated spatially with parts of the intrusions where high-salinity fluids were present. The major exception is the porphyry molybdenum system in the eastern part of the Little Cottonwood stock, which probably was at too great a depth (approximately 7 km) to form high-salinity brines and is dominated by low-salinity CO_2-rich fluids.

Introduction

IN THE central Wasatch Mountains, Utah, a mid-Tertiary series of nine calc-alkaline granitoid stocks, a subvolcanic porphyry system, and coeval volcanic rocks are exposed in an east-trending belt that is the westward extension of the Uinta arch (Figs. 1 and 2). Important Ag-Pb-Zn replacement and fissure ores in the Park City district are spatially and temporally related to porphyry stocks (Barnes and Simos, 1968; Bromfield et al., 1977), and scattered base and precious metal mineralization is associated with several other stocks (Calkins and Butler, 1943; James, 1978; Bromfield and Patten, 1981).

Variations in texture, style of emplacement, hydrothermal alteration, and mineralization in these intrusions led Lawton et al. (1980) to suggest that successively deeper levels of erosion may be present from east to west across the range. Studies of fluid inclusion populations in igneous and vein quartz, presented here, suggest that there are systematic variations in the types of fluid inclusions in these intrusions that may be related to variable erosional levels.

This paper briefly summarizes the regional setting of the Wasatch intrusions and estimates for their depths of emplacement. The regional distribution of fluid inclusion populations in igneous quartz is presented and their relationship to depths of emplacement of the stocks is discussed.

Geologic Setting of Intrusions in the Central Wasatch Mountains

The central Wasatch Mountains, called the Cottonwood area by Crittenden (1977), has undergone a long and varied sedimentary and structural history dating from at least the middle Proterozoic through the early Tertiary prior to the igneous events that are the focus of this study. Metamorphic and sedimentary rocks ranging from middle (?) Proterozoic through late Mesozoic are exposed in the central Wasatch Mountains (Boutwell, 1912; Calkins and Butler, 1943; Crittenden et al., 1952; Bromfield, 1968; Crittenden, 1977). Middle Proterozoic metasedimentary and minor meta-igneous rocks are unconformably overlain by late Proterozoic quartzite, shale, and tillite. The

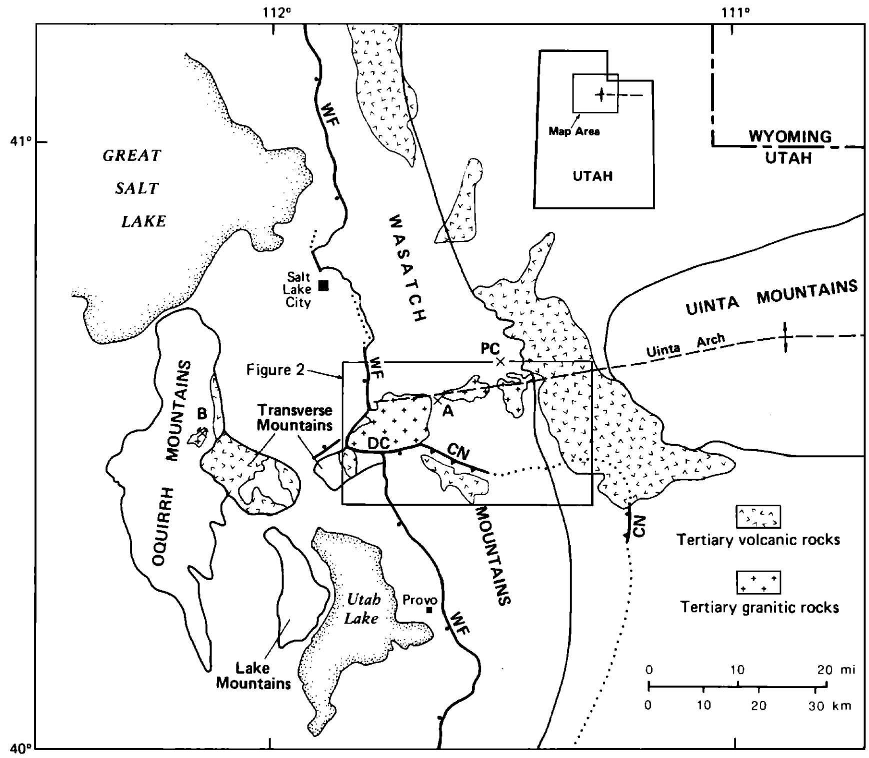


FIG. 1. Location map of the central Wasatch Mountains and surrounding region showing the distribution of middle Tertiary igneous rocks and major structures. Geology simplified from Hintze (1980). A = Alta, B = Bingham mine, CN = Charleston-Nebo thrust, DC = Deer Creek fault, PC = Park City, and WF = Wasatch fault zone.

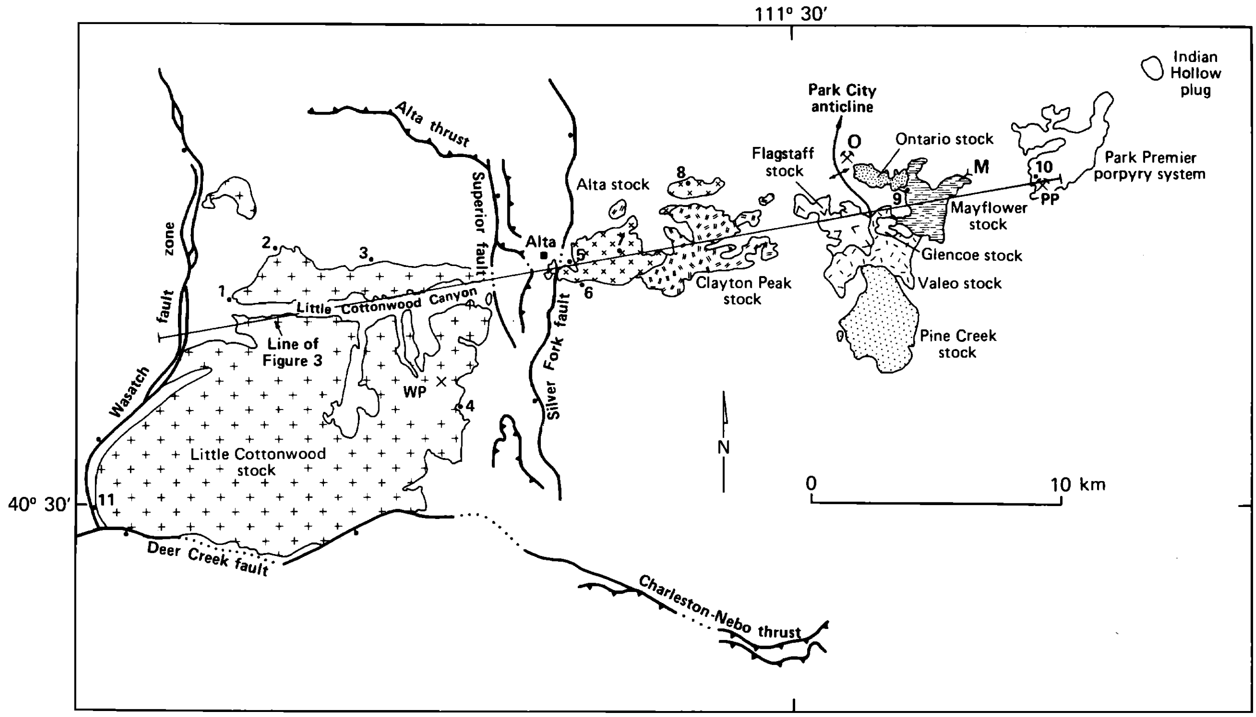


FIG. 2. Generalized geologic map of the Wasatch intrusions showing major mines, areas of hydrothermal alteration, and location of pressure-depth estimates in Table 2. M = Mayflower mine, MP = Mayflower-Pearl fault zone, O = Ontario mine, PP = Park Premier mine, WP = White Pine Fork molybdenum prospect.

late Proterozoic rocks are unconformably overlain by Paleozoic and Mesozoic miogeoclinal shelf sediments that include quartzite, shale, and carbonate rocks. The Cottonwood area was the hingeline of the Cordilleran miogeocline from at least late Proterozoic through late Paleozoic time, resulting in a relatively thin autochthonous cratonic section and a thick allochthonous miogeoclinal section that were juxtaposed by late Mesozoic-early Tertiary thrust faults (Crittenden, 1977).

Pre-middle Tertiary structure is dominated by east-directed thrust faults in the north-trending Sevier orogenic belt and uplift along the west-trending Uinta arch (Fig. 1; Crittenden, 1977). Sevier thrust faults placed thick sections of Paleozoic miogeoclinal sedimentary rocks over their thin cratonal equivalents. Three major thrust faults have been identified in the central Wasatch Mountains: the Alta, Mount Raymond, and Charleston-Nebo thrusts (Figs. 1 and 2). Much of the Ag-Pb-Zn mineralization in the Cottonwood district is localized in the Alta thrust (Calkins and Butler, 1943).

The Uinta arch is the other major pre-middle Tertiary structural feature in the central Wasatch Mountains. It is a major anticline that can be traced from the northwestern corner of Colorado to the west side of the Wasatch Range (Fig. 1). In the central Wasatch Mountains, this fold plunges about 30° eastward (Eardley, 1968; Bromfield and Patten, 1981). Most of the intrusions in the Wasatch Mountains were emplaced along the axis of this structure (Fig. 1). Crittenden (1977) suggests that most of the post-Paleozoic uplift along the Uinta arch occurred in three or four episodes during Early (?) Cretaceous to Paleocene time. Several major secondary folds developed along the flanks on the Uinta arch during uplift including the Park City anticline, a north-northwest-trending anticline or dome that is the dominant structural feature in the Park City district. The Park City anticline was important in localizing several of the porphyry stocks that were not intruded along the core of the Uinta arch. It also acted as a structural control for replacement Ag-Pb-Zn mineralization in the district (Fig. 2; Bromfield, 1968).

Post-Middle Tertiary Structures in the Central Wasatch Mountains

High-angle normal faults are the main post-middle Tertiary structures that affect the Wasatch intrusions. The Wasatch Mountains mark the eastern edge of the Basin and Range province and are bounded on the west by the Wasatch fault, a regional north-trending frontal fault system (Fig. 1). Relative to Salt Lake Valley, the Wasatch Range has been uplifted along this fault as much as 11 km during late Tertiary to Holocene time (Zoback, 1983; Parry and Bruhn, 1986, 1987). Potassium-argon and fission-track dating along the Wasatch fault indicate that uplift of the Wasatch Mountains may have begun as early as 17 m.y. ago, although most uplift has occurred in the past 10 m.y. (Crittenden et al., 1973; Naeser et al., 1983; Parry and Bruhn, 1986). A second north-trending fault that cuts the intrusive rocks is the Silver Fork fault (Fig. 2). This fault cuts the Alta stock and has a down to the west throw of 600 to 1,600 m (Calkins and Butler, 1943).

A second major orientation of faults that cut the Wasatch intrusions trends east-west. These faults include the Deer Creek fault along the south side of the Little Cottonwood stock and the Mayflower-Pearl fault zone in the Mayflower stock (Fig. 2). These faults may have been active during emplacement of the intrusions, and precious and base metal mineralization in the Mayflower mine occurs in quartz veins in the Mayflower-Pearl fault zone (Barnes and Simos, 1968).

Igneous Rocks in the Wasatch Mountains

Nine phaneritic to microcrystalline porphyry stocks are exposed along the core of the west-trending Uinta arch across the central Wasatch Mountains (Fig. 2). Coeval volcanic breccias and lavas (Keetley Volcanics) crop out on the east side of the range. They are intruded by a subvolcanic porphyry system in the Park Premier mine area and by a volcanic neck in Indian Hollow (Fig. 2). Potassium-argon dating of igneous biotite and hornblende indicate that the igneous rocks crystallized during Eocene to Oligocene time, about 43 to 31 m.y. (Crittenden et al., 1973; Bromfield et al., 1977; B. D. Turrin and D. A. John, unpub. data, 1987). Potassium-argon dating of hydrothermal minerals in the Park City district suggest that hydrothermal alteration and mineralization are broadly contemporaneous with intrusion of the porphyry stocks in the district and extrusion of the Keetley Volcanics (Bromfield et al., 1977).

Intrusive rocks consist of three phaneritic stocks in the western part of the range (Little Cottonwood, Alta, and Clayton Peak stocks), six porphyry stocks in the Park City district in the center and eastern side of the range (Flagstaff, Ontario, Mayflower, Glencoe, Valeo, and Pine Creek stocks), a subvolcanic porphyry complex on the east side of the range consisting of five small stocks (collectively called the Park Premier stock) intrusive into the coeval Keetley Volcanics, and a volcanic neck surrounded by a radial dike swarm (Indian Hollow plug; Fig. 2). The Keetley Volcanics consist of intermediate composition volcanic breccias, flows, and minor amounts of volcaniclastic sediment (Woodfill, 1972). Both the Little Cottonwood and Alta stocks consist of multiple intrusions with interior, somewhat more siliceous, porphyry phases. Major textural, compositional, petrographic, and alteration features of the intrusive and extrusive rocks are summarized in Table 1 and briefly discussed below. Additional data are given in John (1987) and references therein.

The textures of the stocks vary considerably from west to east ranging from the medium to coarse grained, coarsely porphyritic (2- to 6-cm microcline megacrysts) texture of the Little Cottonwood stock; through the fine- to medium-grained, nearly equigranular textures of the Alta and Clayton Peak stocks; to porphyries in the Park City district that have distinctly porphyritic textures with microgranular groundmasses; to the Park Premier stock that consists of several distinct porphyry phases with microaplitic to aphanitic groundmasses.

Mineralogy and major and trace element analyses indicate that the igneous rocks in the Wasatch Mountains are calc-alkaline, mostly metaluminous, I-type granitoids (John, 1987). Hornblende and biotite are the dominant mafic silicate minerals; clinopyroxene and minor orthopyroxene are present in several of the stocks; magmatic muscovite is absent. Magnetite is the dominant or only Fe-Ti oxide mineral. Phenocrystic sphene is present in several of the stocks. Modal compositions range from diorite to monzogranite (using the IUGS classification; Streckeisen, 1976), although the bulk of the exposed rocks are granodiorites. The silica content ranges from about 49 to 71 percent, but most of the rocks contain 60 to 70 percent SiO_2. With the exception of the Clayton Peak stock, individual intrusions have fairly restricted compositional ranges.

Hydrothermal alteration and mineralization, both within the stocks and in the surrounding wall rocks, are quite variable across the range. The largest area of hydrothermal alteration is an uneconomic porphyry Mo-Cu system near the eastern margin of the Little Cottonwood stock in the White Pine Fork area (Fig. 2), where abundant disseminated and fracture-controlled pyrite and local stockwork quartz veins (± muscovite, K-feldspar, pyrite, molybdenite, chalcopyrite) occur over an area of about 6 km^2 (Sharp, 1958; Bromfield and Patten, 1981). Small Fe-Cu skarns and Ag-Pb-Zn replacement bodies in Paleozoic carbonate rocks are associated with the Alta and Clayton Peak stocks, which exhibit only minimal hydrothermal alteration. In the Park City district, Ag-Pb-Zn replacement and fissure ores in Paleozoic carbonate rocks are spatially associated with the Ontario stock, but there is only minor vein mineralization within this stock (Erickson and Garmoe, 1974). The Mayflower stock is cut by several vein systems that contain major Au-Cu-Pb-Zn-Ag mineralization and are associated with argillic, sericitic, and potassic alteration (Nash, 1973, 1982; Villas and Norton, 1977). Mineralization in the Mayflower mine may be related to the younger Ontario stock, which has the same age as hydrothermal biotite in the Mayflower mine (Bromfield et al., 1977). The Park Premier stock has large zones of argillic, advanced argillic, sericitic, and quartz-sericite-albite alteration surrounding a small inner zone of stockwork quartz veins, actinolite-magnetite alteration, and low-grade disseminated Cu-Au-Mo mineralization (John, 1987, in press).

Depths of Emplacement of Intrusions in the Central Wasatch Mountains

Variations in the textures of the stocks, the extent of thermal metamorphic aureoles, the style of emplacement of the stocks, the ages and structural positions of the wall rocks, and the types of hydrothermal alteration and mineralization related to the stocks all suggest that successively deeper levels of exposure are present from east to west across the central Wasatch Mountains (Lawton et al., 1980). Estimates of depths of emplacement, briefly discussed below, are summarized in Table 2. A more detailed discussion of these estimates is given in John (1987).

Field relations

Field relations and megascopic and microscopic textures of the intrusions suggest that the eastern stocks—the Park City porphyries, the Park Premier stock, and the Indian Hollow plug—were emplaced at shallower levels of the crust than the western stocks—Little Cottonwood, Alta, and Clayton Peak stocks (Lawton et al., 1980). The Park Premier stock and the Indian Hollow plug intruded coeval volcanic rocks (Bromfield et al., 1977). These porphyries and the Park City porphyries contain textures and local flow foliation suggesting hypabyssal emplacement. Local deformation of the wall rocks along the margins of several of these intrusions suggest forcible emplacement (Bromfield, 1968; Bromfield et al., 1970, 1977). Chilled margins are present along contacts between several of the porphyries (Bromfield et al., 1977). Aplite and pegmatite dikes are absent except in the Ontario stock. Either the grade of contact metamorphism of the wall rocks is lower than farther west, or metamorphic effects are not evident around the porphyry stocks.

In contrast to the eastern porphyry stocks, volcanic rocks are absent in the vicinity of the western stocks. In general, the western stocks are coarser grained and more equigranular. Intrusive contacts are sharply discordant and show little evidence of forcible emplacement (Lawton et al., 1980). Metasedimentary wall rocks are cut by numerous dikes and are included as xenoliths in the margins of the stocks. Chilled margins are absent. Extensive thermal metamorphic aureoles were generated during emplacement of these stocks (Smith, 1972; Moore and Kerrick, 1976; Lawton, 1980; John, 1987). All these data suggest slower cooling rates probably caused by deeper levels of em-

TABLE 1. Summary of Igneous Rocks in

Stocks	Little Cottonwood	Alta	Clayton Peak	Flagstaff	Mayflower
Texture and groundmass size	Medium to coarse grained, porphyritic	Medium grained, equigranular to seriate porphyry	Fine grained, equigranular to porphyritic	Medium grained, seriate porphyry; groundmass ≤0.1 mm	Fine grained, seriate porphyry to medium grained equigranular
Modal composition[1]	Grd-qm	Grd-qmd	Di, qmd, grd	Not determined	D, qmd, grd
Color index	6–12	8–20	23–35	10–15	14–34
Phenocrysts	Ksp to 6 cm	Sparse plag, Ksp	Bt, Ksp to 1–2 cm	Plag, bt, hb, (qtz)	Plag, bt, hb, (qtz)
Mafic minerals	Bt, (hb), mt, sph	Bt, hb, (cpx), mt, sph, (ilm)	Bt, hb, cpx, (opx), mt, (ilm), (sph)	Bt, hb, mt	Bt, hb, (cpx), (opx), mt
Multiple intrusions	Yes	Yes	No	No	No
Aplite-pegmatite dikes	Abundant	Abundant	Present	Not observed	Not observed
Hydrothermal alteration	Weak-strong deuteric; local qsp	Weak-strong deuteric; local 2nd bt, qsp	Weak-strong deuteric; local secondary bt, act	Strong deuteric-propylitic	Weak-strong deuteric, potassic, argillic
Mineralization	Local stockwork qtz veins with Mo-(Cu); local scheelite on joints	Small Fe-Cu skarns; local Ag-Pb-Zn fissure ores	Small Fe-Cu skarns	None	Au-Ag-Cu-Pb-Zn veins

[1] Modal classification based on Streckeisen (1976)
Abbreviations: act = actinolite, bt = biotite, cpx = clinopyroxene, d = diorite, grd = granodiorite, hb = hornblende, ilm = ilmenite, Ksp = K-feldspar, mt = magnetite, opx = orthopyroxene, plag = plagioclase, qm = quartz monzonite, qmd = quartz monzodiorite, qsp = quartz-sericite-pyrite, qtz = quartz, sph = sphene

placement for the western stocks than for the eastern stocks.

Depth estimates using stratigraphic reconstructions

The depths of emplacement of the Wasatch intrusions can be crudely estimated by reconstructing the amount of stratigraphic cover present at the time of emplacement of the intrusions in the Eocene and early Oligocene. These reconstructions are subject to large uncertainties because of the complex late Mesozoic-early Tertiary structural history of the area (see discussion in John, 1987).

Two estimates for depths of emplacement of stocks in the Wasatch Mountains, based on stratigraphic reconstructions, have been previously reported. Wilson (1961) estimated 6,250 m of cover for the western part of the Alta stock (west of Brighton), based on stratigraphic thicknesses given in Crittenden et al. (1952). Nash (1973) estimated the depth of emplacement of the Mayflower stock to be about 900 to 1,200 m, assuming that most of the sedimentary cover younger than Triassic age had been removed by erosion and estimating a minimal volcanic cover of 305 m. Tertiary volcanic cover is likely to have been somewhat more that 305 m thick (see below).

A third estimate, with relatively small uncertainties, can be made for the Park Premier stock. These small intrusions intrude coeval volcanic rocks whose maximum known thickness, based on surface exposures and recent (1984) drilling by the U. S. Bureau of Reclamation, is about 500 m (Bromfield, 1968; Gary Dow, oral commun., 1984). An unknown thickness of volcanic rocks may have been removed by erosion, but it is unlikely that the volcanic cover greatly exceeded 1 km. Present exposures represent minimum depths of 500 m.

Pressure estimates using contact metamorphic assemblages

Broad metamorphic aureoles are present around the Little Cottonwood, Alta, and Clayton Peak stocks and are absent around the other stocks. Lawton (1980) and Kohlmann (1980) estimated lithostatic pressures of 3 and 4 kbars, respectively, for exposures at the mouth of Little Cottonwood Canyon along the western margin of the Little Cottonwood stock (Table 2). Bowman and Cook (1981) estimated pressures of 1.5 ± 0.5 kbars for the western part of the Alta aureole.

Additional pressure estimates were made by John (1987) at six locations along the margins of the Little the Central Wasatch Mountains, Utah

Ontario	Pine Creek	Valeo	Park Premier	Keetley Volcanics
Seriate porphyry; groundmass 0.2–1.0 mm	Medium grained, seriate porphyry; groundmass 0.05–0.10 mm	Medium to coarse grained, seriate porphyry; groundmass <0.01–0.25 mm	Fine to medium grained, seriate porphyry to porphyroaphanitic; groundmass <0.01–0.03 mm	Fine to medium grained, porphyritic pilotaxitic to hyalopilitic
Grd-qm	Not determined	Not determined	Not determined	Not determined
8–17	7–10	10–12	10–15	Approx. 10
Plag, bt, qtz	Plag, hb, bt, (qtz)	Plag, bt, hb, qtz	Plag, bt, hb, (cpx)	Plag, hb, cpx, (bt), (sph)
Bt, mt	Bt, hb, mt	Bt, hb, mt, (sph)	Bt, hb, mt, (cpx)	Hb, cpx, mt, (bt), (sph)
No	No	No	Yes	Several intrusions, plugs
Not reported	Not observed	Not observed	No	No
Not determined	Weak deuteric	Weak-strong deuteric-propylitic	Potassic, argillic, advanced argillic, phyllic, propylitic	Weak-strong deuteric-propylitic
Possible source of Ag-Pb-Zn ores in Park City district	None	Small Ag-Pb fissure ores	Disseminated Cu-Au-(Mo); peripheral Au-Ag	

Cottonwood and Alta stocks, using mineral assemblages and compositions of metamorphic minerals in pelitic rocks (Fig. 2 and Table 2). These pressure estimates were based on biotite, garnet, and cordierite compositions, Al_2SiO_5 phase relations, and the presence or absence of muscovite and K-feldspar (Table 2). Pressure estimates range from 3 kbars along the western side of the Little Cottonwood stock to 1.5 kbars on the western side of the Alta stock. See John (1987) for a more detailed discussion of these pressure estimates.

Depths of emplacement of the Wasatch intrusions and implications of late Cenozoic tilting

Table 2 summarizes quantitative and semiquantitative estimates of paleodepths and pressures of current erosional levels of intrusions in the central Wasatch Mountains. These pressure variations are strongly corroborated by qualitative data such as textures, styles of emplacement, and hydrothermal alteration and mineralization of the intrusions. Pressure estimates in Table 2 were converted to depths assuming lithostatic pressures for locations near the Little Cottonwood and Alta stocks.

Locations where pressure or depth were estimated (Fig. 2) are projected onto a cross section of the central Wasatch Mountains in Figure 3. The late Eocene preintrusion surface was approximated by fitting lines through points corresponding to depth estimates shown in Table 2. Although many uncertainties are present in these estimates, the increase in depth is fairly uniform across the range (Fig. 3), strongly suggesting that the central Wasatch Mountains have been tilted east about 20° after the emplacement of these intrusions. Apparent offset of the inferred late Eocene paleosurface on the Silver Fork fault is approximately 1,200 m, which agrees well with the 600 to 1,600 m of stratigraphic offset estimated by Calkins and Butler (1943, p. 62–63). The variation in present erosional levels (approximately 10–11 km) is much greater than can be explained by simple block faulting and downdropping of the eastern part of the central Wasatch Mountains along known faults.

The origin of the tilting and its north-south extent in the central Wasatch Mountains are unclear. However, the magnitude of tilting is comparable to that of other ranges in the Basin and Range province (Stewart, 1978, fig. 51), such as the amount of tilt in the Oquirrh Range immediately to the west (Einaudi, 1982). Discontinuous exposures of the late Eocene

TABLE 2. Pressure-Depth Estimates

Location (Fig. 2)	Mineral assemblages[1]	Fe/(Fe + Mg) biotite[2]	Fe/(Fe + Mg) cordierite[2]	Fe/(Fe + Mg) garnet[2]	T(°C)[3]	P_1(kbars)[4]	P_2(kbars)[5]	Other pressure and depth estimates[6]	Most reasonable estimate[7]
1	QBPKMASC	0.39–0.47	0.25–0.26			$2.3 \le P \le 3.7$	≥3.6–3.8	3–4 kbars (1)	3 kbars = 11.1 km
2	QBPMASC QBPKMASC	0.40–0.45	0.29–0.32			$2.3 \le P \le 3.7$	≥2.5		2.5 kbars = 9.3 km
3	QBAGC	0.80	0.68–0.69	0.95–0.96	625–660	≤1.6–2.1	≥2.4		2.0 kbars = 7.4 km
4	QBMKAGC	0.77–0.78	0.67–0.71	0.95–0.96	545–600	≤1.1–2.0	1.1–2.1		1.5 kbars = 5.6 km
5	QBKAG	0.52–0.53		0.82–0.84	634–663	≤1.3–1.9		1.5 kbars (2)	1.5 kbars = 5.6 km
6	QBKMAG	0.44–0.46		0.75	714–762	≤0.2–0.8		1.5 kbars (2)	1.5 kbars = 5.6 km
7								6.3 km (3)	6.3 km
8								≥0.75 kbars (4)	≥0.75 kbars = 2.8 km
9								1.3 km (5)	≥1.3 km
10								≥0.5 km (6) 0.035 kbars (4)	0.5–1.0 km
11								≥2.8 kbars (7)	≥2.8 kbars = 10.4 km

[1] A = andalusite, B = biotite, C = cordierite, G = garnet, K = potassium feldspar, M = muscovite, P = plagioclase, Q = quartz, S = sillimanite; all mineral assemblages also contain opaque minerals

[2] Representative mineral analyses given in John (1987, appendix 1)

[3] Temperatures calculated from garnet cores and biotites using equation (7) of Ferry and Spear (1978)

[4] P_1 = pressures estimated from Al_2SiO_5 phase relations of Holdaway (1971), muscovite + quartz stability of Chatterjee and Johannes (1974) and Kerrick (1972), and garnet-biotite temperatures where applicable

[5] P_2 = pressures estimated from cordierite compositions and stability relations calculated by Brown et al. (1985, fig. 2)

[6] (1) Lawton (1980) and Kohlmann (1980) from metamorphic mineral assemblages, (2) Bowman and Cook (1981) from metamorphic mineral assemblages, (3) Wilson (1961) from stratigraphic reconstructions, (4) this study from fluid inclusion homogenization data, (5) Nash (1973) from stratigraphic reconstruction, (6) this study from stratigraphic reconstructions, (7) Parry and Bruhn (1986) from secondary fluid inclusions

[7] See John (1987) for a more complete discussion

or Oligocene-age transverse volcanics (Crittenden et al., 1973) across the Wasatch Mountains south of the Deer Creek fault (Fig. 1) suggest that east-west tilting has not occurred in this part of the Wasatch Mountains and that tilting is bounded on the south by the Deer Creek fault. The northern extent of the tilting is unknown.

Eastward tilting of the central Wasatch Mountains explains several anomalous features: the porphyry molybdenum system located below the highest elevations in the eastern part of the Little Cottonwood stock becomes a cupola in the stock, and the Alta thrust, which presently dips gently eastward, is restored to a subhorizontal orientation that is consistent with its inferred movement from west to east (Calkins and Butler, 1943; Crittenden, 1977).

Fluid Inclusions in the Wasatch Intrusions

Fluid inclusions are common in both igneous and hydrothermal quartz in all of the intrusive rocks in the central Wasatch Mountains. Petrographic and heating and freezing studies of fluid inclusions in both types of quartz indicate that there are systematic variations in the types of fluids that circulated through the intrusions and were trapped as fluid inclusions. These variations appear to be closely tied to differences in the depths and pressures of emplacement and cooling of the intrusions. The differences in fluid inclusion populations also offer important insights into the evolutionary history of the hydrothermal systems generated by the cooling intrusions.

Previous studies of fluid inclusions in the Wasatch intrusions have been made by Nash (1973 and unpub. data), Kemp and Bowman (1984), and Parry and Bruhn (1986, 1987). Nash (1973, unpub. data) studied fluid inclusions in quartz veins in the Mayflower and Ontario mines. Kemp and Bowman (1984) studied fluid inclusions in exoskarn minerals formed along the edge of the Alta stock. Parry and Bruhn (1986, 1987) studied fluid inclusions trapped in cataclastites in the Wasatch fault zone along the western edge of the Little Cottonwood stock.

This study examines the distribution, types, and compositions of fluid inclusions in igneous quartz in all of the intrusions except the Mayflower and Ontario stocks. Only reconnaissance studies of fluid inclusions in the Pine Creek, Valeo, Glencoe, and Flagstaff stocks were made, however. Particular emphasis was placed on an attempt to define fluids trapped under magmatic conditions in igneous quartz. Unambiguous age relations between various types of fluid inclusions, using normal petrographic methods, could not be determined in most samples containing more than one type of fluid inclusion. Therefore, fluid inclusions were studied in both igneous and vein quartz in the Little Cottonwood, Alta, and Clayton Peak stocks, and in

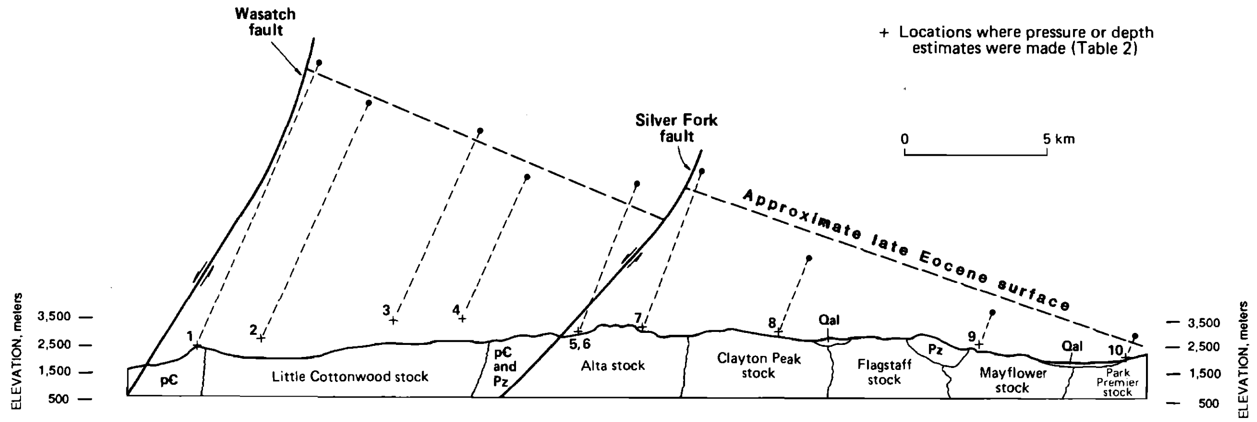


FIG. 3. Schematic cross section through the central Wasatch Mountains showing pressure-depth estimates of mid-Tertiary levels of present exposures given in Table 2. Line of section is shown in Figure 2. Several locations used for estimating pressure are projected onto this section and do not plot on the present surface. Depths were calculated assuming lithostatic pressure and average crustal density (1 kbar = 3.7 km).

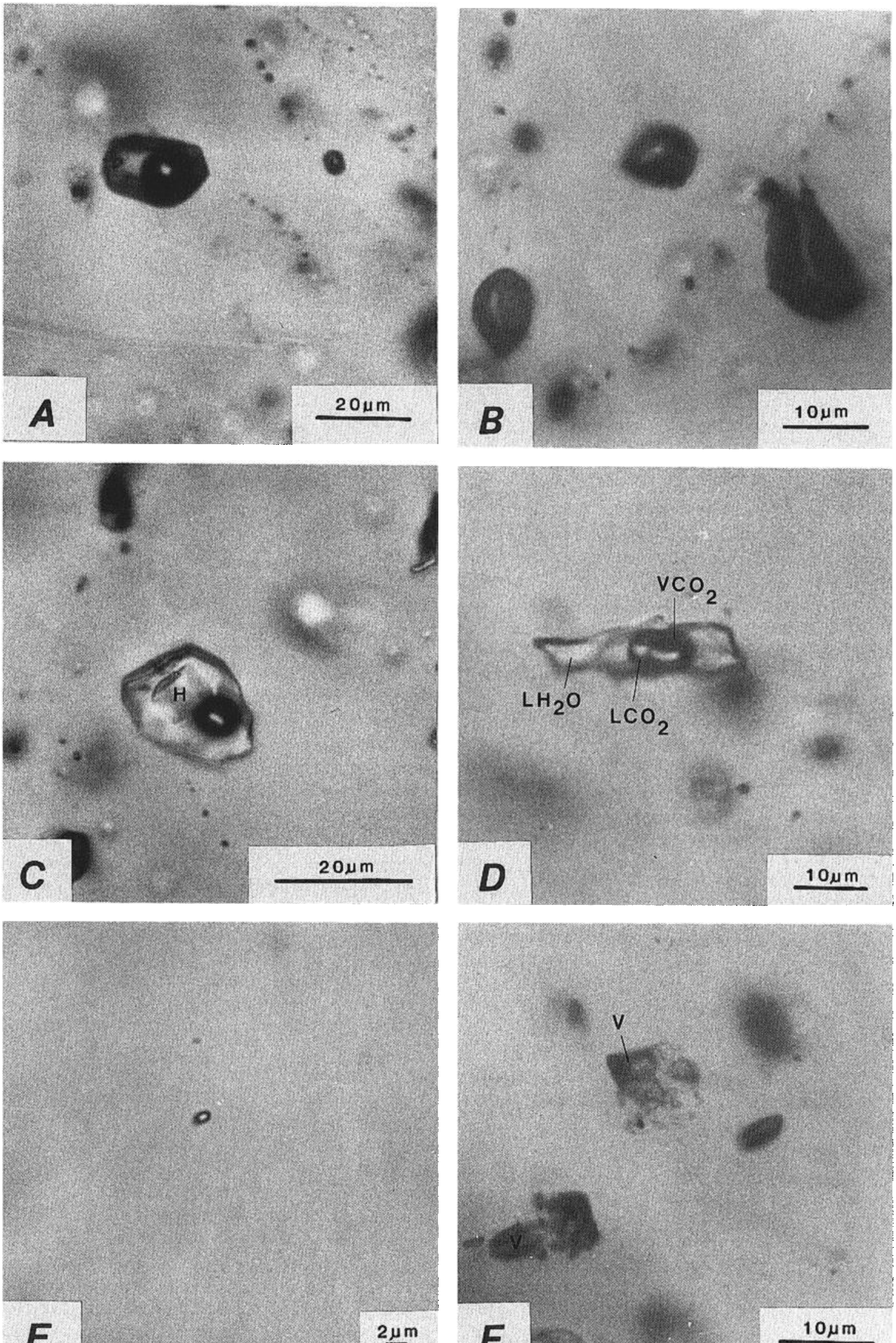
veins of various ages in the Park Premier stock to try to establish the relative ages of different types of fluids. About 600 samples of igneous rocks and veins were studied petrographically. Heating and freezing experiments were made on about 3,300 fluid inclusions from 53 samples from 52 locations. All microthermometric experiments were made on fluid inclusions trapped in quartz. Reconnaissance crushing experiments were made on most samples used in microthermometric studies to test for the presence of condensed gases. SEM studies of opened inclusions in selected samples were made to help identify daughter minerals. Experimental details are given in the Appendix and additional data are given in John (1987).

Petrographic characteristics of fluid inclusions in the Wasatch intrusions

Five major types of fluid inclusions were distinguished based on room temperature phase relations (Fig. 4). Type 1 inclusions are low- to moderate-salinity, liquid-rich fluid inclusions with a vapor bubble that is commonly between 5 to 30 vol percent (Fig. 4A). Type 2 inclusions are low-salinity, vapor-rich fluid inclusions with a vapor content generally greater than 80 vol percent (Fig. 4B). Based on crushing experiments, CO_2 is believed to be present in some of these inclusions. Type 3 inclusions are high-salinity fluid inclusions that commonly contain several birefrigent and/or opaque daughter minerals in addition to halite ± sylvite daughter crystals (Fig. 4C). These inclusions have a variable but generally small vapor content (≤30 vol %). Heating experiments indicate that high-salinity inclusions can be further divided into two types based on their homogenization behavior: type 3a are fluid inclusions in which halite dissolution occurs at temperatures less than or equal to the temperature of liquid-vapor homogenization, whereas type 3b are inclusions in which halite dissolution occurs at temperatures higher than liquid-vapor homogenization (halite homogenization). Type 3c inclusions are high-salinity inclusions that contain sylvite in addition to halite. Type 4 inclusions are mixed H_2O-CO_2 fluids with low to moderate salinities that generally contain three fluid phases at room temperature (Fig. 4D). They generally contain about 10 to 40 vol percent CO_2 (≤10 mole % CO_2 estimated using the method of Burruss, 1981). Type 5 inclusions are nearly pure CO_2, generally occurring as a single fluid phase at room temperature (Fig. 4E).

In addition to fluid inclusions, solid inclusions interpreted as altered silicate-melt inclusions are abundant in the eastern porphyry stocks (Flagstaff, Glencoe, Park Premier, Pine Creek, and Valeo stocks) in both plagioclase and quartz phenocrysts. These inclusions range from irregular to negative crystal-shaped cavities that are filled with small birefrigent crystals and brown clay (?) (Fig. 4F). They occur in regular distributions outlining crystal growth zones, in planar arrays cutting across growth zones, and in apparently random distributions.

Attempts were made to classify fluid inclusions into the usual categories of primary, secondary, and pseudosecondary using the criteria of Roedder (1967, 1984). In most samples, the origins of most fluid inclusions are ambiguous, because they are either extremely abundant or very sparse and because growth features are absent in most quartz crystals. In general, fluid inclusions that were clearly secondary were not studied on the heating-freezing stage. However, based on the large range in homogenization temperatures within single samples (see below) and on the subsol-


A
20µm
B
10µm
H
C
20µm
VCO2
LH2O
LCO2
D
10µm
E
2µm
V
V
F
10µm

idus pressure-corrected homogenization temperatures, it is obvious that most if not all fluid inclusions measured in igneous quartz are secondary. Paragenetic relations of most fluid inclusions in vein quartz are also unclear, and unequivocal evidence for the existence of primary inclusions cannot be demonstrated in most veins.

Regional distribution of fluid inclusion types

The distribution of fluid inclusion types is shown in Figure 5 and summarized in Table 3. Four major fluid inclusion populations are evident in the Wasatch intrusions. These are (A) abundant CO_2-rich inclusions (types 4 and 5) and liquid-rich (type 1) inclusions; (B) low- to moderate-salinity, liquid-rich inclusions (type 1); (C) high-salinity inclusions (types 3a, b, c) with liquid-rich (type 1) and locally vapor-rich (type 2) inclusions; and (D) vapor-rich inclusions (type 2) with subordinate liquid-rich (type 1) and high-salinity inclusions (types 3a, b, c). Population A is found exclusively in the deepest system, whereas population D occurs in the shallowest intrusions.

Several important points are evident from inspection of Figure 5 and Table 3.

1. CO_2-rich fluid inclusions (types 4 and 5) are limited to the Little Cottonwood stock and a few localities in the western part of the Alta stock. CO_2-rich inclusions are particularly abundant in the area of hydrothermal alteration and disseminated and vein molybdenite mineralization in the White Pine Fork area of the Little Cottonwood stock. There is no correlation between carbonate wall rocks and the presence of CO_2-rich inclusions.

2. High-salinity (type 3) inclusions are absent in the Little Cottonwood stock and the western parts of the Alta and Clayton Peak stocks except in the downdropped fault block of the Alta stock west of the Silver Fork fault and several topographic highs in the Alta stock. High-salinity fluid inclusions are present in the eastern parts of the Alta and Clayton Peak stocks and in all of the eastern porphyry stocks that contain quartz phenocrysts.

3. Vapor-rich (type 2) fluid inclusions are absent in all but one sample of the Little Cottonwood stock and in the western and central parts of the Alta and Clayton Peak stocks. A few vapor-rich fluid inclusions were found in one sample of the Little Cottonwood stock during a heating run, but these inclusions may have resulted from leakage of type 1 inclusions.

4. Vapor-rich fluid inclusions become increasingly abundant in the eastern stocks and are the volumetrically dominant type of fluid inclusion in the Park Premier stock forming approximately 80 percent of the fluid inclusions.

The approximate three-dimensional distribution of fluid inclusion types in the Alta and Clayton Peak stocks is shown in Figure 6. Fluid inclusion populations were divided into samples containing high-salinity fluid inclusions (populations C and D) and samples lacking high-salinity fluid inclusions (populations A and B). All samples containing high-salinity fluid inclusions also contain lower salinity liquid-rich (type 1) inclusions; many also contain vapor-rich (type 2) inclusions. This section was selected because it is approximately perpendicular to the axis of tilting of the central Wasatch Mountains.

There is an extremely regular distribution of fluid inclusion populations in these two stocks (Fig. 6). In the Alta stock east of the Silver Fork fault, the two sample populations may be separated by a horizon that dips about 15° to the east. With one exception, all samples lying east of, or above, this horizon contain high-salinity fluid inclusions, whereas with one exception all samples west or below this horizon lack high-salinity fluid inclusions. West of the Silver Fork fault, this horizon is apparently repeated in the four samples studied (Fig. 6). The offset of this horizon by the Silver Fork fault is about 1 km, which agrees well with the apparent offset of the preintrusion surface (approx. 1,200 m, Figs. 3 and 6) and with the stratigraphic offset (Calkins and Butler, 1943).

The distribution of fluid inclusions in the Clayton Peak stock is similar to that in the Alta stock, although the number of samples is smaller. Again the two fluid inclusion populations appear to be separated by a surface that dips about 20° east. These two horizons are subparallel, but the horizon in the Clayton Peak stock is about 600 m higher in elevation than the one

FIG. 4. Photomicrographs showing types of fluid inclusions in the Wasatch intrusions. A. Liquid-rich type 1 inclusion containing liquid plus a vapor bubble. Igneous quartz in sample S-38 from the Alta stock. B. Vapor-rich type 2 inclusions containing nearly 100 percent vapor. Quartz in a quartz-actinolite-magnetite vein in sample PP-13-462 from the Park Premier stock. C. High-salinity type 3 inclusion containing a cube of halite (H), vapor, and liquid. Igneous quartz in sample S-38 from the Alta stock. D. H_2O-CO_2 type 4 inclusion consisting of liquid CO_2 (LCO_2), CO_2 vapor (VCO_2), and H_2O-rich liquid (LH_2O). Igneous quartz in sample 79-WP-4 from the White Pine Fork area of the Little Cottonwood stock. E. Small type 5 inclusion of nearly pure CO_2. Igneous quartz in sample 79-LC-112 from the Little Cottonwood stock. F. Altered silicate melt inclusions consisting of numerous small birefrigent crystals and vapor bubble (V) in a quartz phenocryst in sample 79-PC-10b from the Pine Creek stock.

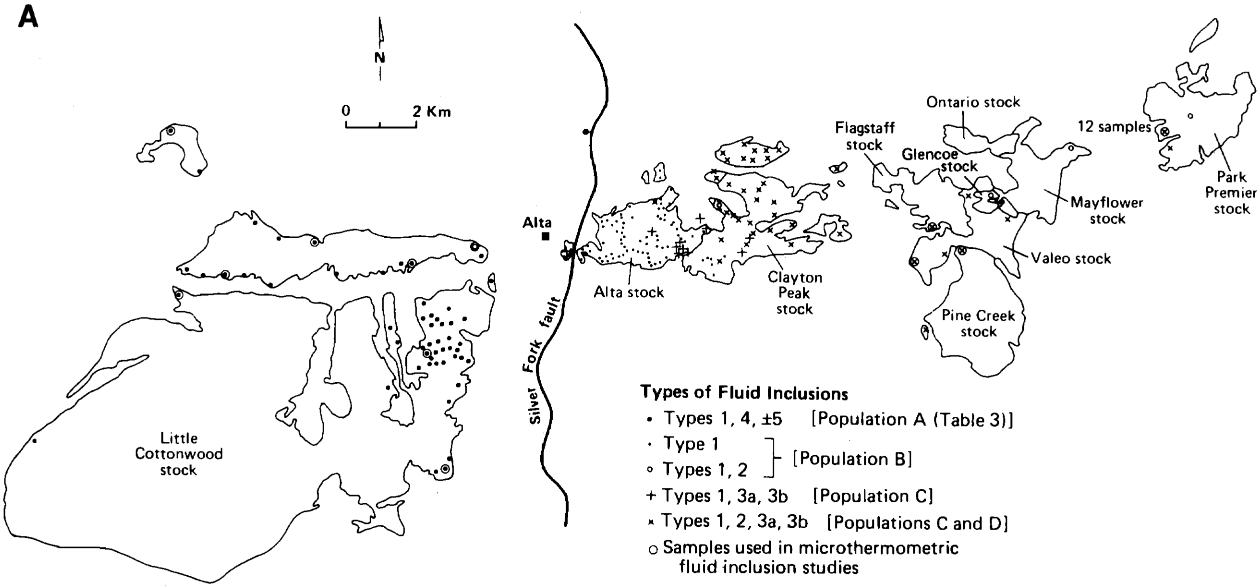


FIG. 5. A. Map showing the distribution of fluid inclusions in the Wasatch intrusions. Except for the Park Premier stock, only fluid inclusion populations in igneous quartz crystals are plotted. Many samples of the Little Cottonwood stock do not contain type 4 inclusions that are petrographically distinguishable in standard thin sections because of their extremely small size (<5μm). Based on heating and freezing experiments, type 4 inclusions are thought to be present in most of these samples.

in the Alta stock. A possible cause of this difference is discussed below. The one sample in the Clayton Peak stock that lies west of, and below, this horizon and contains high-salinity fluid inclusions is in close proximity to a part of the Alta stock that contains high-salinity fluid inclusions; the high-salinity fluid inclusions in this sample may be the result of trapping high-salinity fluids that flowed from the Alta stock into the older Clayton Peak stock.

TABLE 3. Summary of Fluid Inclusion Characteristics

Fluid inclusion population	Types of inclusions[1]	Locations	Approximate depths of formation[2]
A	1, 4, (5)	Little Cottonwood stock Western part of Alta stock	6–11 km
B	1	Little Cottonwood stock Western part of Alta stock Western part of Clayton Peak stock	5–11 km
C	1, 3, (2)	Eastern part of Alta stock Eastern part of Clayton Peak stock Park City porphyries	<5 km
D	2, (1, 3)	Park Premier stock	<1 km

[1] Inclusion types shown in parentheses are less abundant than other listed types

[2] Depths estimated from Figure 3

Timing of the trapping of fluid inclusions in the Wasatch intrusions

Most fluid inclusions studied in the Wasatch intrusions, particularly high-salinity type 3 inclusions, are believed to have been formed during cooling of the intrusions shortly after their emplacement from dominantly magmatically derived hydrothermal fluids. Four lines of evidence suggest this origin.

1. Early-formed skarn minerals along the margins of the Alta stock contain primary high-salinity fluid inclusions that are absent in retrograde skarn, indicating that high-salinity fluids formed early during skarn formation (Kemp and Bowman, 1984).

2. High-salinity fluid inclusions are ubiquitous in igneous quartz phenocrysts in the eastern parts of the Alta and Clayton Peak stocks but are virtually absent in hydrothermal quartz veins (see below). These veins are narrow (generally ≤5 mm wide), discontinuous, tensile fractures, filled with combinations of quartz, hornblende, K-feldspar, biotite, epidote, magnetite, pyrite, and chalcopyrite, that are similar to veins found in porphyry copper systems (Aiken, 1982; John, 1987). These features suggest that the veins were formed during cooling of the stocks shortly after their emplacement.

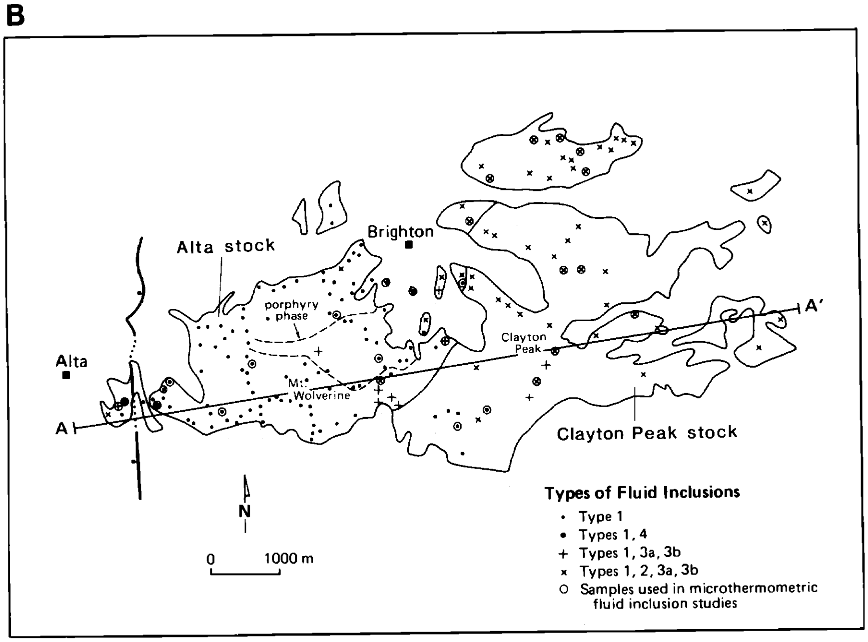


FIG. 5. B. Enlargement of the Alta and Clayton Peak stocks.

3. Reconnaissance stable isotope studies indicate that there has been little meteoric water introduced into the intrusions, suggesting that the fluid inclusions have dominantly magmatic water contents (Taylor, 1968; Kemp and Bowman, 1984; John, 1987). Quartz and K-feldspar phenocrysts in the Alta stock have normal igneous $\delta^{18}O$ values of 8.3 to 9.4 and 7.3 to 7.8 per mil, respectively. Biotites have $\delta D = -89$ to -109 per mil but become heavier with increasing water contents (increasing degree of chloritization).

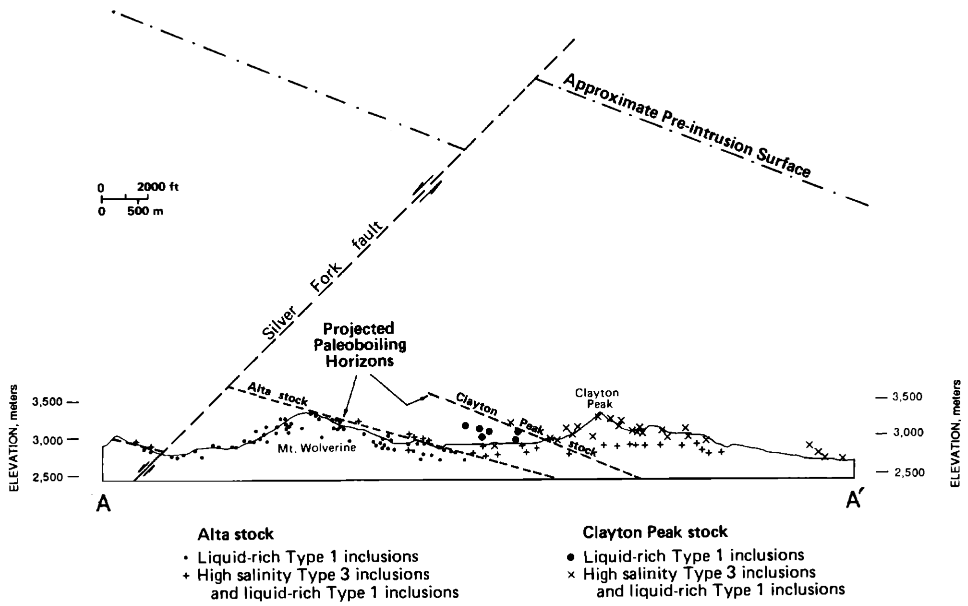


FIG. 6. Cross section showing the distribution of high-salinity (type 3) fluid inclusions in the Alta and Clayton Peak stocks. All samples contain liquid-rich (type 1) inclusions; many samples containing high-salinity inclusions also contain vapor-rich (type 2) inclusions. Line of section is shown in Figure 5B. Many sample locations are projected on this section and plot above or below the earth's surface. Inferred paleoboiling (high-paleosalinity) horizons are shown as heavy dashed lines. Late Eocene surface from Figure 3 shown as heavy dot-dash line.

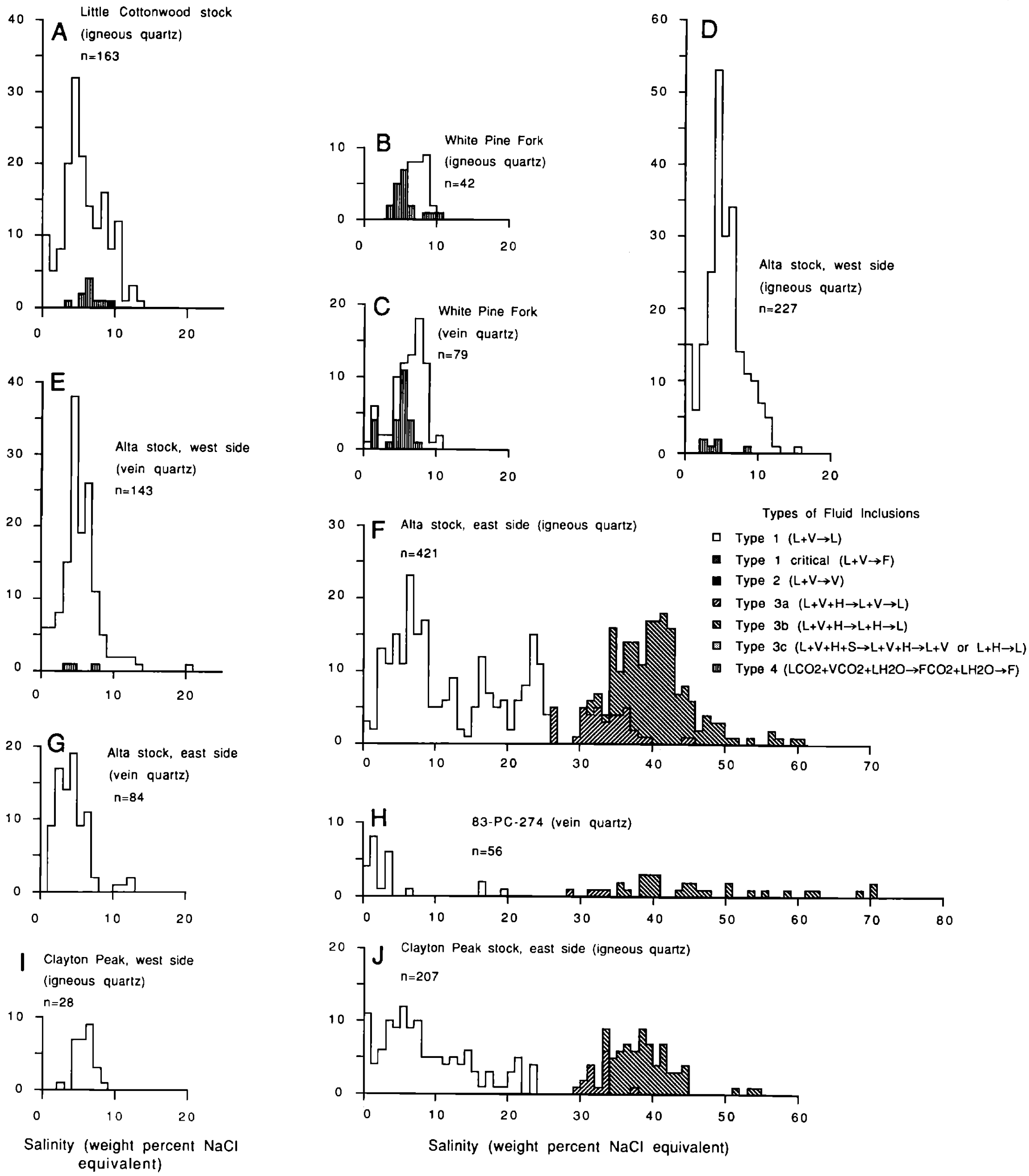


FIG. 7. Histograms summarizing fluid inclusion salinity data for the Wasatch intrusions. Arrows indicate fluid inclusions with salinities greater than the indicated values. F = supercritical fluid, FCO2 = supercritical CO_2 fluid, H = halite, L = liquid, LCO2 = liquid CO_2, n = number of fluid inclusion measurements, S = sylvite, V = vapor, VCO2 = CO_2 vapor. A. Igneous quartz in the Little Cottonwood stock. B. Igneous quartz in the White Pine Fork area of the Little Cottonwood stock. C. Quartz veins in the White Pine Fork area. D. Igneous quartz, western part of the Alta stock. E. Quartz veins, western part of the Alta stock. F. Igneous quartz, eastern part of the Alta stock. G. Quartz veins, eastern part of the Alta stock. H. Quartz + K-feldspar + hornblende vein in sample 83-PC-274 from the eastern part of the Alta stock. I. Igneous quartz, western part of the Clayton Peak stock. J. Igneous quartz, eastern part of the Clayton Peak stock.

Chlorites have $\delta D = -71$ to -75 per mil. These trends are consistent with equilibration with magmatically derived water (Nabelek et al., 1983) and are inconsistent with equilibration with meteoric water (e.g., Criss and Taylor, 1983).

4. K-Ar and fission-track ages of the Alta, Clayton Peak, and Little Cottonwood stocks indicate that these stocks had cooled to temperatures less than approximately 125°C at least 10 to 15 m.y. prior to the beginning of uplift of the Wasatch Mountains (see

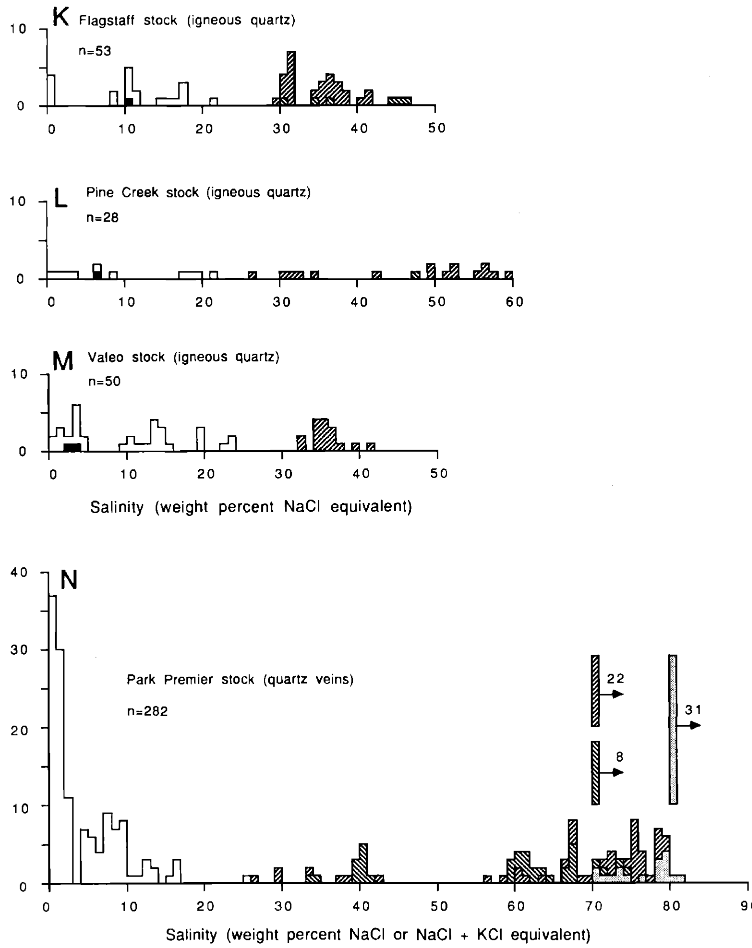


FIG. 7.(*Cont.*) K. Igneous quartz, Flagstaff stock. L. Igneous quartz, Pine Creek stock. M. Igneous quartz, Valeo stock. N. Quartz veins, Park Premier stock.

above). The high measured homogenization temperatures of fluid inclusions in these stocks (see below) indicate that the fluid inclusions must have been trapped prior to uplift of the stocks.

Heating and freezing experiments

Freezing points were measured for about 1,250 type 1, 2, and 4 fluid inclusions in 53 samples; the approximate salinities of these inclusions were calculated using the equation of Potter et al. (1978) for type 1 and 2 inclusions and the equation of Bozzo et al. (1975) for type 4 inclusions. Composite histograms showing salinities for each of the stocks are shown in Figure 7 and representative individual samples from the Alta stock are plotted in Figure 8. Eutectic melting temperatures were not routinely measured because of the small size of most of the fluid inclusions (generally ≤10 um).

There are regular differences in the salinities of type 1 fluid inclusions between different intrusions and between different parts of the Alta and Clayton Peak stocks (Figs. 7 and 8). Type 1 inclusions in the Little Cottonwood stock and in the western parts of the Alta and Clayton Peak stocks, which lack high-salinity (type 3) inclusions, have relatively restricted ranges in salinities with nearly all measured inclusions having salinities less than 12 equiv wt percent NaCl. Quartz veins in these rocks and in the eastern part of the Alta stock have similar salinities except for sample 83-PC-274, which contains high-salinity fluid inclusions (Fig. 7H). In the eastern parts of the Alta and Clayton Peak stocks, where high-salinity fluid inclusions are abundant, salinities of type 1 inclusions range from 0 wt percent NaCl to halite-saturated solutions (26 wt % NaCl). This range suggests that some type 1 inclusions may be the result of mixing relatively dilute fluids and high-salinity brines. Salinities of type 1 inclusions in the Valeo, Pine Creek, and Flagstaff stocks are similar to the eastern parts of the Alta and Clayton Peak stocks, but there are fewer data (Fig. 7). Nearly all type 1 inclusions in the Park Premier

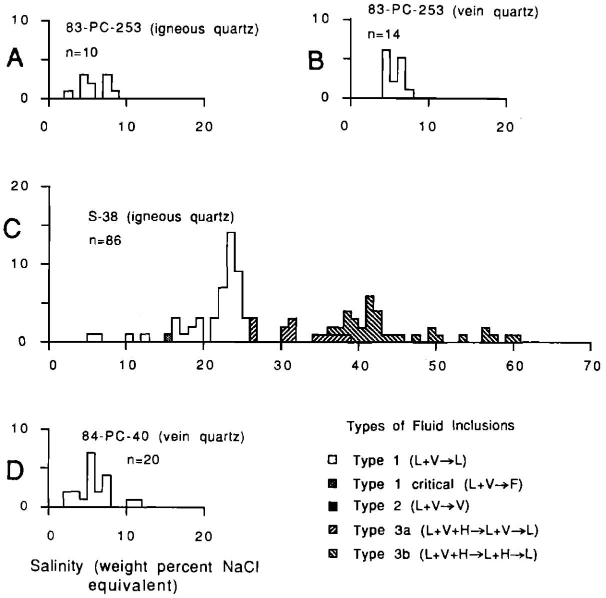


FIG. 8. Histograms showing fluid inclusion salinity data for representative samples from the Alta stock. A. Igneous quartz in sample 83-PC-253 from the west side of the Alta stock. B. Quartz + hornblende + K-feldspar + sphene vein cutting sample 83-PC-253 from the west side of the Alta stock. C. Igneous quartz in sample S-38 from the east side of the Alta stock. D. Sample 84-PC-40, a quartz + pyrite vein cutting sample S-38 from the east side of the Alta stock. Abbreviations same as in Figure 7.

stock have salinities less than 10 equiv wt percent NaCl (Fig. 7N).

Approximate minimum salinities of 530 high-salinity fluid inclusions calculated from halite dissolution temperatures (types 3a and 3b) using the equations of Potter et al. (1977) and Chou (1987), and from halite and sylvite dissolution temperatures (type 3c) using the data of Roedder (1984, fig. 8-25), are shown in Figure 7. Calculated salinities of these inclusions range from approximately 26 to >72 equiv wt percent NaCl (types 3a and 3b) and from 65 to >82 wt percent NaCl + KCl (type 3c). Maximum salinities of high-salinity fluid inclusions in the Alta stock tend to be higher than in the Clayton Peak stock (compare Fig. 7F and J), which may reflect higher temperatures of formation in the Alta stock (see below).

Homogenization temperatures are summarized in Figures 9 and 10. Homogenization temperatures show a considerable range within single samples (Fig. 10), within intrusions, and between intrusions (Fig. 9). Homogenization temperatures tend to be lowest in the Little Cottonwood stock and increase progressively to the east with decreasing depth of emplacement (see below). Pressure-corrected homogenization temperatures also tend to increase to the east (see below). In general, there is nearly a total overlap in homogenization temperatures of liquid-rich (type 1) and high-salinity (type 3) inclusions in the eastern parts of the Alta and Clayton Peak stocks (Fig. 9F and J). In these stocks most high-salinity fluid inclusions are type 3b that homogenize by halite dissolution after liquid-vapor homogenization. In contrast, high-salinity fluid inclusions in quartz veins in the Park Premier stock have much higher homogenization temperatures than liquid-rich (type 1) inclusions, and most high-temperature, high-salinity inclusions are type 3a or 3c (Fig. 9N).

Pressure and pressure corrections of homogenization temperatures

Evidence for the trapping of boiling fluids is absent in the Little Cottonwood stock and the western parts of the Alta and Clayton Peak stocks. Thus, measured homogenization temperatures of fluid inclusions in the Little Cottonwood stock and the western parts of the Alta and Clayton Peak stocks must be corrected for trapping pressures greater than liquid-vapor equilibrium. Vapor-rich (type 2) inclusions are absent in several igneous quartz samples and in quartz veins (except sample 83-PC-274) in the eastern parts of the Alta and Clayton Peak stocks (Fig. 5B). These relations suggest that type 1 and possibly type 3a inclusions were not trapped from boiling solutions and measured homogenization temperatures must be pressure corrected to estimate trapping temperatures. Type 3b inclusions homogenize by halite dissolution at temperatures greater than liquid-vapor homogenization and could not have trapped boiling fluids.

As discussed above, most fluid inclusions in these intrusions are believed to have been trapped during cooling of the intrusions shortly after their emplacement. Paleodepths of samples used in microthermometric studies were estimated from Figures 3 and 6 and range from about 11 km on the west side of the Little Cottonwood stock to about 3 km for the Flagstaff, Pine Creek, and Valeo stocks. These depths were converted to pressures assuming that fluid pressure was equal to lithostatic pressure and assuming a pressure gradient of 3.7 km/kbar. Fluid pressures may have been somewhat less than lithostatic pressure, but this is considered unlikely because of the relatively great depths of these intrusions.

Pressure-corrected homogenization temperatures are summarized in Table 4. Type 1 inclusions were pressure-corrected using equations of Zhang and Frantz (1987) for NaCl-H_2O fluids. Pressure corrections for type 3a and 3b inclusions were made by using the methods of Roedder and Bodnar (1980) and data from Urusova (1975), Haas (1976), and Potter and Brown (1977). Many type 3 inclusions had calculated densities much greater than the experimental data and pressure corrections could not be calculated. Type 4 inclusions were pressure corrected using data from Bowers and Helgeson (1983a, b). Type 5 inclusions were pressure corrected using data in Angus et al. (1976). Inspection of Table 4 shows that nearly all fluid inclusions studied had estimated trapping temperatures which are less than solidus temperatures of granites and granodiorites at pressure less than 4 kbars (Piwinski, 1973) and must have been trapped after the crystallization of the stocks. Pressure corrections calculated assuming lithostatic pressure are maximum values and could be significantly less if fluid pressures were less than lithostatic values.

Pressure estimates of igneous and hydrothermal events can be made by using fluid inclusion homogenization data at three localities (Fig. 2 and Table 2). Minimum pressures of 700 to 750 bars in the eastern lobe of the Alta stock (location 8, Fig. 2) are indicated by fluid inclusions in sample S-38 (Fig. 10C) that homogenize between 530° and 540°C and whose homogenization behavior suggests trapping near the critical point for a solution containing approximately 16 equiv wt percent NaCl (Sourirajan and Kennedy, 1962). In the Park Premier stock, coexisting liquid-rich and vapor-rich fluid inclusions in vein quartz homogenize at 199° to 260°C, temperatures which indicate maximum pressure of about 50 bars in the Park Premier mine area (location 10, Fig. 2). These veins formed during cooling of the stock and probably represent hydrostatic pressure (John, 1987, in press). Using fluid inclusion data, Parry and Bruhn (1986) estimated minimum pressures of 2.8 kbars for formation of cataclastic rocks in the footwall of the Wasatch fault where it cuts the Little Cottonwood stock (location 11, Fig. 2). This pressure corresponds to a minimum depth of 10.5 km assuming lithostatic pressure.

Relative ages of inclusion types

Samples of hydrothermally altered rocks from the porphyry Mo-Cu system in the White Pine Fork area of the Little Cottonwood stock showed few obvious differences in fluid inclusion populations between igneous and vein quartz (Figs. 7–10), suggesting that most fluid inclusions studied in igneous quartz were secondary and were trapped during subsolidus hydrothermal activity. Several type 1 inclusions in igneous quartz in one sample had significantly higher homogenization temperatures than type 1 inclusions in vein quartz, suggesting that they might have been trapped prior to vein formation. Pressure-corrected homogenization temperatures, however, still yield subsolidus temperatures (<610°C).

In the Alta stock, fluid inclusion populations in vein quartz are not obviously different from those in igneous quartz in the deeper western parts of the stock, where no high-salinity (type 3) fluid inclusions are present (Figs. 7–10). Pressure-corrected homogenization temperatures suggest that a few inclusions in igneous quartz were trapped at higher temperatures than inclusions in quartz veins (600°–740°C compared to ≤545°C, Table 4). In the shallower, eastern parts of the stock, where high-salinity fluid inclusions are ubiquitous in igneous quartz, high-salinity inclusions were found in only one vein (83-PC-274, Figs. 7H and 9H) and are absent in all other veins examined. It is not clear why high-salinity inclusions are present in this early vein and absent in all others, but it is evident that high-salinity fluids formed early in the hydrothermal history of this part of the stock and were

TABLE 4. Summary of Pressure-Corrected Homogenization Temperatures

Intrusion and type of sample	Number of samples	Type of inclusion	Range in maximum pressure-corrected homogenization temperatures[1]
Little Cottonwood; igneous quartz	7	1	380°–575°C
	4	4	>340°–500°C
	5	2	325°–400°C
Little Cottonwood-White Pine phase; igneous quartz	2	1	430°–605°C
	2	4	490°C
Little Cottonwood-White Pine phase; hydrothermal quartz	2	1	405°–430°C
	2	4	470°–500°C
Alta west part; igneous quartz	10	1	450°–740°C
Alta west part; hydrothermal quartz	7	1	465°–545°C
Alta east part; igneous quartz	10	1	410°–650°C
		3a	310°–570°C
		3b	≥250°–495°C
Alta east part; hydrothermal quartz	7	1	465°–560°C
	1	3a	410°C
	1	3b	≥550°C
Clayton Peak west part; igneous quartz	2	1	470°C
Clayton Peak east part; igneous quartz	6	1	465°–615°C
		3a	320°–440°C
		3b	≥340°–450°C
Flagstaff; igneous quartz	1	1	475°C
		3a	450°C
		3b	≥410°C
Pine Creek; igneous quartz	1	1	>600°C
		3a	>600°C
		3b	≥410°C
Valeo; igneous quartz	1	1	>600°C
		3a	>600°C

[1] Range in temperatures shown is the range in maximum temperatures in a group of samples in each intrusion
Pressure corrections made assuming lithostatic pressure

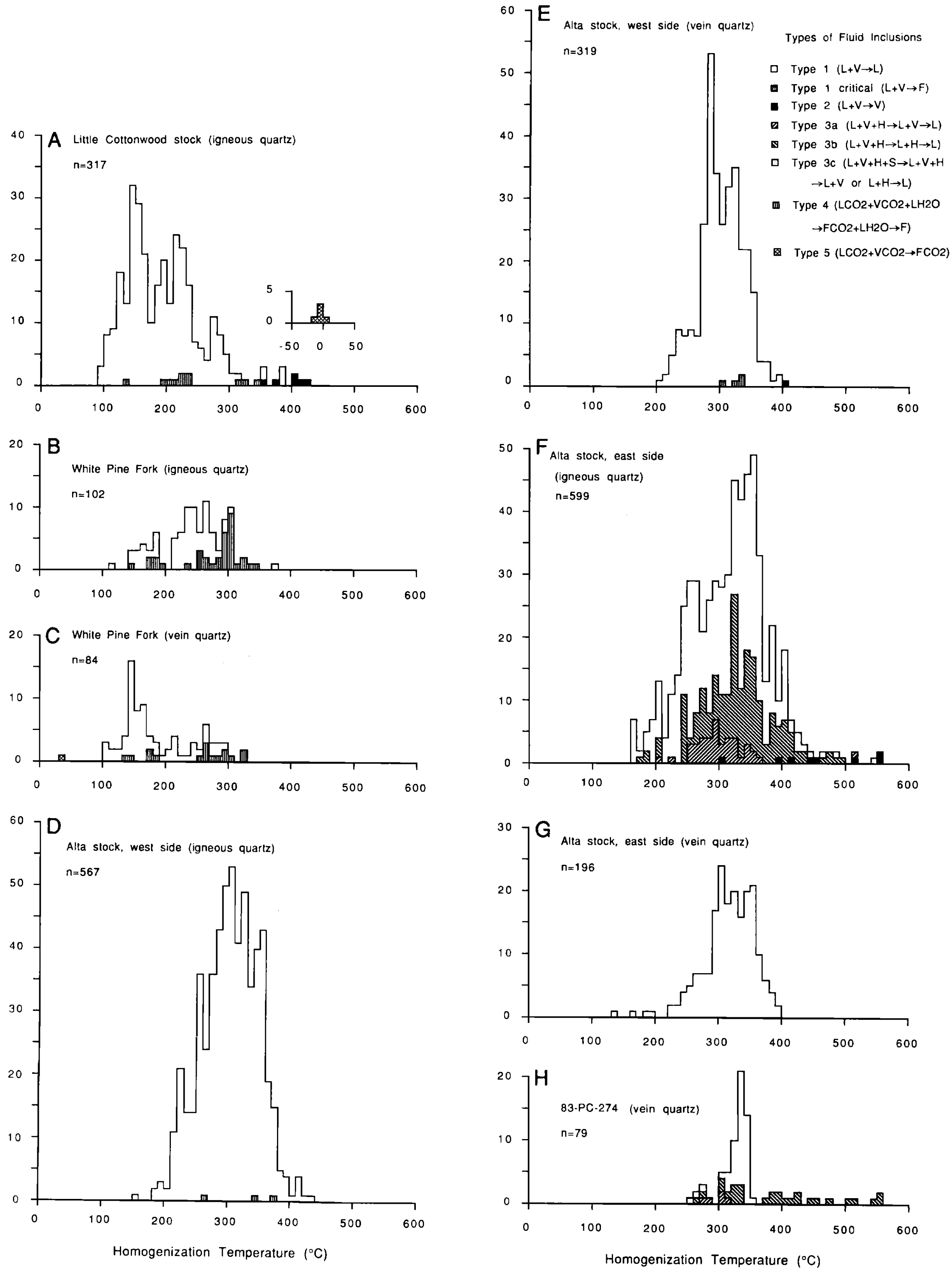
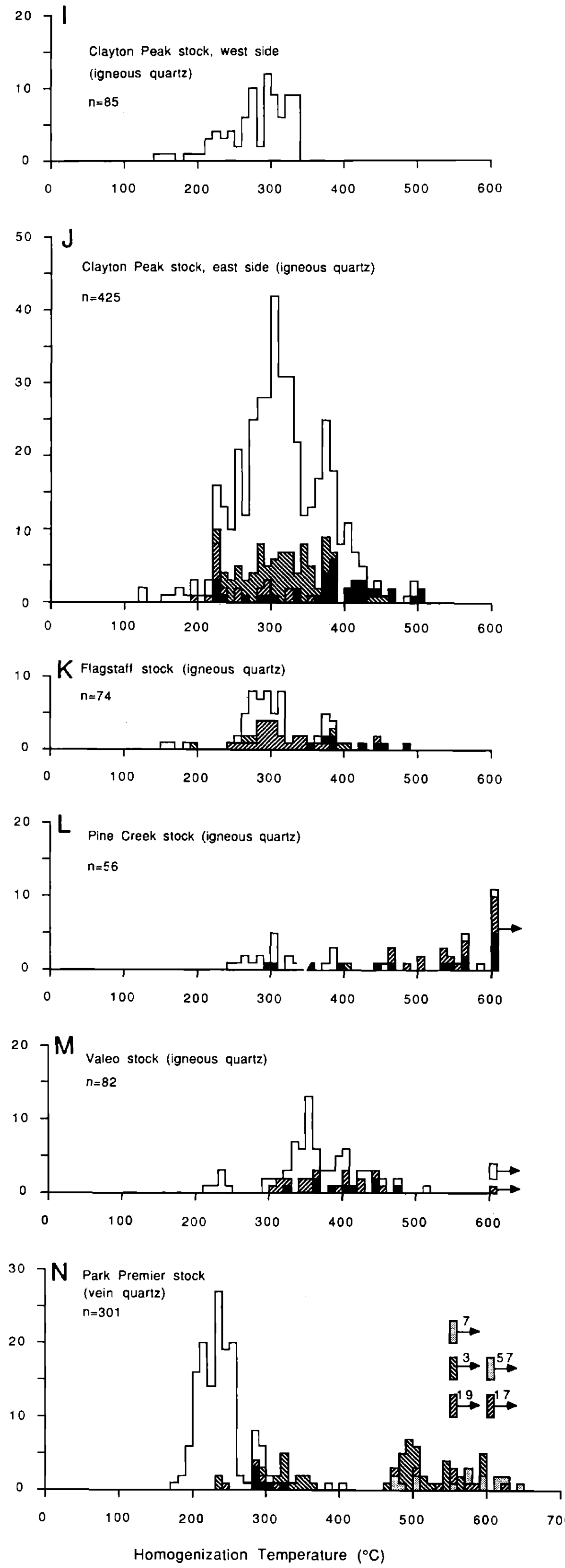


FIG. 9. Histograms showing measured homogenization temperatures of fluid inclusions in the Wasatch intrusions. A. Igneous quartz in the Little Cottonwood stock. B. Igneous quartz in the White Pine Fork area of the Little Cottonwood stock. C. Quartz veins in the White Pine Fork area. D. Igneous quartz, western part of the Alta stock. E. Quartz veins, western part of the Alta stock. F. Igneous quartz, eastern part of the Alta stock. G. Quartz veins, eastern part of the Alta stock. H. Quartz + K-feldspar + hornblende vein in sample 83-PC-274 from the eastern part of the Alta stock.



not widely distributed during its later hydrothermal history.

Fluid inclusions in the Clayton Peak stock are similar to those in the Alta stock. No obvious petrographic differences between fluid inclusions in vein quartz and those in igneous quartz were found in the deeper western parts of the stock, where only liquid-rich (type 1) fluid inclusions are present. However, in the shallower eastern parts of the stock, no high-salinity fluid inclusions have been found in vein minerals despite the fact that they are abundant in igneous quartz. Aiken (1982, p. 205) also noted that high-salinity fluid inclusions are absent in veins, but he also did not report high-salinity fluid inclusions in igneous quartz. These data suggest that high-salinity fluids formed early in the hydrothermal history of the Clayton Peak stock before the lower salinity fluids that formed the widely dispersed veins.

Fluid inclusion populations are quite complex in the Park Premier stock (John, 1987, in press). Homogenization data indicate that high-salinity fluid inclusions were trapped at much higher temperatures than the liquid-rich inclusions (Fig. 9N) suggesting that high-salinity fluids formed relatively early. High-salinity fluid inclusions are also limited to the central part of the system, where they are associated with stockwork quartz veins and low-grade porphyry Cu-Au mineralization.

Origin and implications of the distribution of high-salinity fluid inclusions in the Wasatch intrusions

The most striking feature about fluid inclusions in the Wasatch intrusions is the restriction of high-salinity (type 3) fluid inclusions to the upper parts of the Alta and Clayton Peak stocks and the shallower eastern porphyry stocks (Fig. 5). As discussed above, high-salinity fluid inclusions were trapped early in the hydrothermal history of the stocks. These data strongly suggest that the formation of high-salinity fluids was controlled in large part by variations in confining pressure during cooling of the stocks.

High-salinity fluids can form in the following ways: (1) by exsolution of an immiscible high-salinity brine (Roedder and Coombs, 1967; Cloke and Kesler, 1979), (2) by "boiling" (Burnham, 1979; Roedder, 1984), (3) by condensation or the vapor plume model (Henley and McNabb, 1978), (4) by effervescence (Bowers and Helgeson, 1983a; Trommsdorff et al., 1985), and (5) by solution of evaporites.

Stable isotope data for the Alta and Clayton Peak

FIG. 9. (*Cont.*) I. Igneous quartz, western part of the Clayton Peak stock. J. Igneous quartz, eastern part of the Clayton Peak stock. K. Igneous quartz, Flagstaff stock. L. Igneous quartz, Pine Creek stock. M. Igneous quartz, Valeo stock. N. Quartz veins, Park Premier stock. Abbreviations same as in Figure 7.

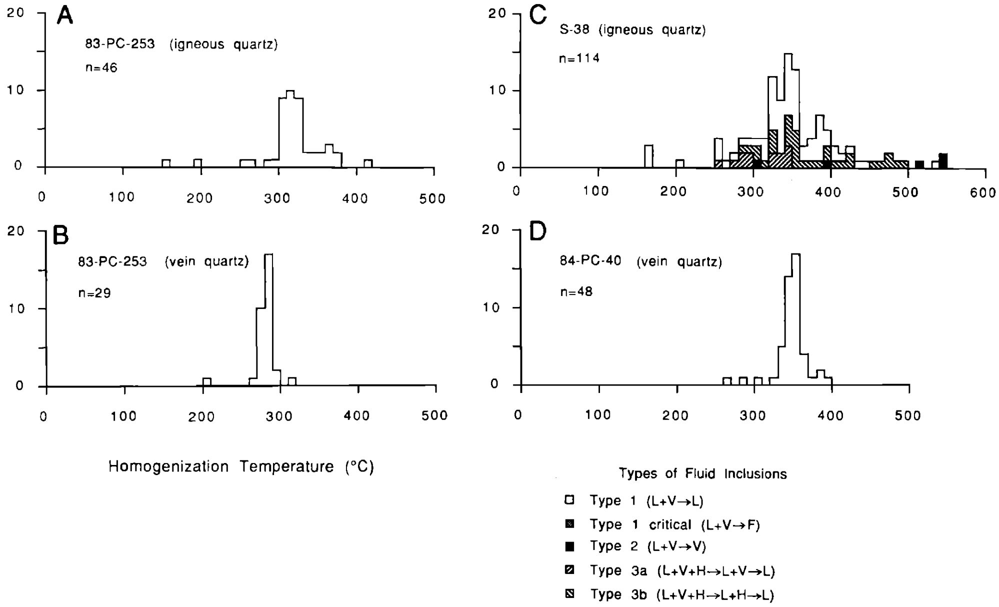


FIG. 10. Histograms showing measured homogenization temperatures of fluid inclusions in representative samples of the Alta stock. A. Igneous quartz in sample 83-PC-253 from the west side of the Alta stock. B. Quartz + hornblende + K-feldspar + sphene vein cutting sample 83-PC-253 from the west side of the Alta stock. C. Igneous quartz in sample S-38 from the east side of the Alta stock. D. Sample 84-PC-40, a quartz + pyrite vein cutting sample S-38 from the east side of the Alta stock. Abbreviations same as in Figure 7.

stocks indicate that these stocks have not reequilibrated with meteoric or metamorphic water (see above). Moreover, evaporites are not present in the sedimentary section of the central Wasatch Mountains. These relations suggest that flow of highly saline brines or CO_2-rich fluids from metamorphic wall rocks into the stocks was highly unlikely.

The lack of significant amounts of CO_2 in rocks with high-salinity fluid inclusions (CO_2 is present only in small amounts in vapor bubbles in some of the fluid inclusions) and in the deeper parts of the Alta and Clayton Peak stocks suggests that CO_2-H_2O-NaCl immiscibility did not cause the formation of high-salinity brines.

High-salinity (type 3) fluid inclusions appear to have been pervasive in igneous quartz in the upper parts of the Alta and Clayton Peak stocks. The distribution of these fluid inclusions cut across compositional zoning in the Clayton Peak stock and the contact between different intrusive phases in the Alta stock (Fig. 5B), which suggests that their presence is not due to compositional variations in the intrusions or to a particular intrusive phase. The lack of high-salinity fluid inclusions in veins in the Clayton Peak stock and their near absence in veins in the Alta stock also suggest that high-salinity fluids did not circulate widely along throughgoing fractures. Thus, it is unlikely that high-salinity fluids formed by condensation of a vapor plume rising up from the deeper parts of the stocks.

The most likely explanation for the formation of high-salinity fluid inclusions in the Wasatch intrusions is that magmatic fluids, or fluids that isotopically equilibrated with a magma at high temperatures, either boiled in the upper parts of the Alta and Clayton Peak stocks (paleodepths less than 4,600–5,200 m) and in the eastern porphyry stocks and formed high-salinity brines or that high-salinity brines were directly exsolved from the crystallizing magmas. Thus, the high-paleosalinity horizons in the Alta and Clayton Peak stocks, separating samples containing high-salinity fluid inclusions from samples lacking high-salinity fluid inclusions, may be thought of as high-temperature "paleoboiling" horizons.

Direct exsolution of an immiscible high-salinity brine from crystallizing granitic magmas has been demonstrated in plutonic blocks from Ascension Island (Roedder and Coombs, 1967; Harris, 1986) and has been suggested as the mechanism leading to formation of high-salinity brines lying on "halite trends" (Cloke and Kesler, 1979; Wilson et al., 1980). In the Alta and Clayton Peak stocks, most high-temperature, high-salinity fluid inclusions homogenize by halite dissolution after liquid-vapor homogenization (type 3b), indicating that the fluids were not vapor saturated and thus were not boiling at the time of trapping.

However, vapor-rich (type 2) fluid inclusions are present in most samples that contain high-salinity fluid inclusions (Fig. 5)—a fact which strongly suggests that boiling occurred at some time. The lack of vapor-rich fluid inclusions in quartz veins in these stocks suggests that boiling occurred prior to formation of the veins and may have been contemporaneous with formation of high-salinity brines.

Sylvite daughter crystals are rare in high-salinity inclusions in the Alta and Clayton Peak stocks, and fluid inclusions defining halite trends are not present. This fact suggests that high-salinity brines had low K/Na molar ratios ($\leq$0.2) which would not be in equilibrium with two feldspars (or granitic magmas) at magmatic or near-magmatic temperatures (Lagache and Weisbrod, 1977; Burnham, 1979; Cloke and Kesler, 1979). However, the K/Na molar ratio of high-salinity inclusions may not be an accurate indicator of the bulk composition of magmatic fluids, because if boiling has occurred near 700°C, K is preferentially partitioned into the vapor phase, lowering the K/Na ratio of the brine phase (Sterner and Bodnar, 1986). Silicate melt inclusions and mixed inclusions of high-salinity fluids and silicate melts similar to inclusions at Ascension Island (Roedder and Coombs, 1967) are also absent in the Alta and Clayton Peak stocks. These data suggest that boiling occurred early in the hydrothermal history of the Alta and Clayton Peak stocks, but it is not possible to determine if high-salinity brines formed by direct exsolution of an immiscible high-salinity brine from the crystallizing magmas with later boiling or by boiling of low- to moderate-salinity fluids released during crystallization of magmas.

Figure 11, based on Bodnar et al. (1985) and Chou (1987), shows a boiling model for the formation of type 3b high-salinity inclusions in the Alta and Clayton Peak stocks. Moderate-salinity fluids, probably approximately 5 to 10 equiv wt percent NaCl (Burnham, 1979, 1981), may have exsolved from the intrusions or have been introduced into the intrusions during the late stages of crystallization. In the upper parts of these stocks (point A), where, based on the estimated depths of emplacement shown in Figure 3, lithostatic pressure was less than about 1,250 to 1,400 bars, these fluids are in the two-phase liquid + vapor field and would immediately boil, separating into a high-salinity brine containing 40 to 60 wt percent NaCl and a low-salinity vapor containing about 2 to 4 wt percent NaCl (depending on pressure and temperature). If the high-salinity brine cools isobarically similar to that of A to C in Figure 11 and does not mix with the vapor phase, it will become vapor undersaturated and eventually cross the liquidus surface for a solution of this composition (L = L + NaCl) and begin precipitating halite. If the brine phase is trapped under P-T conditions between points B and C, the resulting fluid inclusions will homogenize by halite dissolution and will behave like the type 3b inclusions.

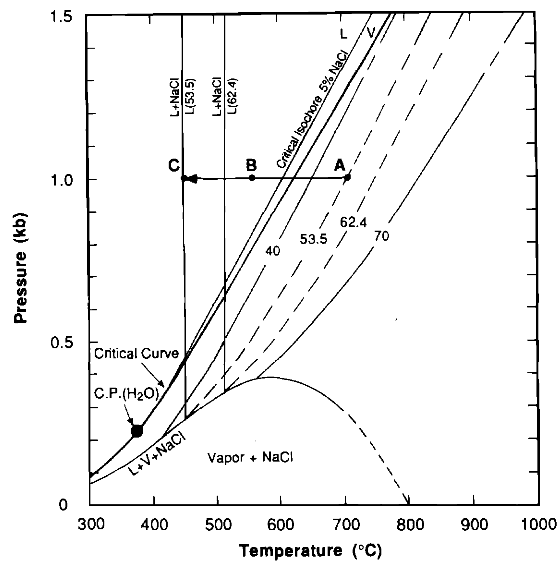


FIG. 11. Isoplethal P-T diagram for part of the H_2O-NaCl system showing compositions of high-salinity brines coexisting with a vapor phase, halite liquidus curves for 53.5 and 62.4 wt percent NaCl solutions, and a possible path for the formation of type 3b inclusions in the Alta and Clayton Peak stocks (see text). Diagram based on Gunter et al. (1983), Bodnar et al. (1985), and Chou (1987). C.P.(H_2O) = critical point of water, L = liquid, NaCl = solid NaCl (halite), V = vapor.

Temperatures of boiling and the formation of high-salinity fluids that were later trapped as type 3b fluid inclusions were estimated for 16 samples from the Alta and Clayton Peak stocks. Estimates were based on the maximum measured salinity in each sample, lithostatic pressures derived from Figure 3, and experimental H_2O-NaCl phase relations in Chou (1987). Temperature estimates range from 725° to 860°C (most $\leq$740°C) for the Alta stock and from 680° to 780°C (most $\leq$735°C) for the Clayton Peak stock. At lithostatic pressures taken from Figure 3, estimated boiling temperatures for the Alta stock are approximately similar to or slightly higher than the water-saturated solidus for natural granodiorites (Piwinski, 1973), whereas temperatures for the Clayton Peak stock are similar to or slightly lower than solidus temperatures for natural tonalite to granodiorite compositions. These data suggest that vapor saturation may have occurred at lower temperatures in the Clayton Peak stock than in the Alta stock, probably resulting from the lower magmatic-water content of the Clayton Peak stock, as shown by bulk compositions and mineral crystallization sequences (Aiken, 1982; John, 1987, and unpub. data). Thus, the differences in paleodepths compared to boiling in the two stocks (approximately 600 m higher in the Clayton Peak stock) may indicate an absence of fluids in the Clayton Peak stock at temperatures high enough to allow boiling at pressures greater than about 1,250 bars.

Type 3a inclusions may have formed by further cooling of the high-salinity brines and dilution by lower salinity fluids that formed vein quartz and were trapped as liquid-rich (type 1) inclusions. Type 1 fluid inclusions generally have maximum pressure-corrected homogenization temperatures greater than or equal to maximum homogenization temperatures of type 3a inclusions (Table 4). The source of the lower salinity fluids could have been (1) low-salinity fluids released from depths below the currently exposed intrusions, (2) the vapor phase formed during boiling that cooled without remixing with the brine phase, thus increasing its density until it crossed the critical isochore (Fig. 11), where it behaves as a liquid, or (3) meteoric or metamorphic fluids introduced into the intrusions at lower temperatures. Reconnaissance stable isotope studies indicate that large volumes of metamorphic or meteoric fluids did not enter the Alta or Clayton Peak stocks (see above); thus, type 1 inclusions probably represent magmatic water from sources 1 or 2.

Summary and Conclusions

A series of 11 mid-Tertiary calc-alkaline granitoid intrusions are exposed in a 45-km-long east-trending belt in the central Wasatch Mountains. Variations in textures of the stocks, style of emplacement, contact metamorphic aureoles, hydrothermal alteration, and related mineralization suggest progressively deeper erosional levels from east to west. Depths of emplacement based on contact-metamorphic mineral assemblages, stratigraphic reconstructions, and fluid inclusion data suggest that present exposures record nearly continuous variations in paleodepths ranging from <1 to about 11 km and that the central Wasatch Mountains have been tilted east about 20° subsequent to the emplacement of the intrusions. Reconstruction of the preintrusion surface suggests that the quartz monzonite (fluorine-deficient) type of porphyry molybdenum mineralization in the eastern part of the Little Cottonwood stock formed at depths near 7 km, Ag-Pb-Zn replacement and fissure ores in the Park City district formed at depths ranging from 2 to 3 km, and a low-grade porphyry copper-gold system in the Park Premier stock formed at depths of <1 km.

High-salinity fluids formed at depths less than about 4,600 to 5,000 m, probably either from exsolution of immiscible high-salinity brines by the crystallizing intrusions or from high-temperature boiling of fluids released during the late stage of crystallization of these intrusions. High-salinity fluid inclusions in igneous quartz in the Alta and Clayton Peak stocks and the inferred pressures suggest that high-salinity fluids may have formed at slightly higher temperatures in the Alta stock than in the Clayton Peak stock. Fluid inclusions trapped from these fluids are the oldest in these rocks and appear to predate formation of most of the veins in these stocks. However, pressure-corrected homogenization temperatures suggest that few if any fluid inclusions were trapped at magmatic temperatures. The general lack of fluid inclusions homogenizing at magmatic temperatures and the lack of silicate melt inclusions in the Alta, Clayton Peak, and Little Cottonwood stocks may be the result of recrystallization of these stocks with the concomitant loss of primary fluid inclusions (Roedder, 1984, p. 397).

The distributions of high-salinity fluid inclusions in the Alta and Clayton Peak stocks suggest that high-salinity fluids did not convectively circulate during subsolidus cooling of these intrusions. High-salinity fluids were probably absent when most veins formed in these stocks because pressure was too high to allow boiling and the formation of high-salinity fluids. The absence of boiling during formation of veins in the Alta and Clayton Peak stocks probably indicates that pressure values remained near lithostatic during subsolidus cooling of these intrusions. In contrast, in most porphyry copper systems, fluid-inclusion data suggest that pressure values dropped to near hydrostatic and that periodic boiling of hydrothermal fluids occurred during formation of the veins (e.g., Eastoe, 1978; Gustafson, 1978; Roedder, 1984, p. 439–453).

Most known mineralization in the central Wasatch Mountains is spatially associated with parts of the intrusions where high-salinity fluids were present (molybdenum mineralization in the Little Cottonwood stock is the notable exception); high-salinity fluid inclusions are present in veins in both the Mayflower and Ontario mines (Nash, 1973) and in the Park Premier stock. It is not clear, however, if any mineralization is genetically related to the high-salinity fluids.

The abundance of fluid inclusions with a relatively high content of CO_2 in the Little Cottonwood stock, especially in the area of molybdenum mineralization, is not easy to explain. Abundant CO_2 is apparently common in fluorine-deficient porphyry molybdenum systems (Theodore, 1982; Theodore and Menzie, 1984), but it is not clear if this is due to unusually CO_2-rich magmas, depth of emplacement, or other factors. In the Little Cottonwood stock, the concentration of CO_2 in the White Pine Fork area may have resulted in part from a concentration of volatiles in a cupola on the stock associated with somewhat more siliceous, late differentiates of the stock.

A major difference between largely barren stocks in the central Wasatch Mountains and more mineralized stocks in the Wasatch Mountains and in porphyry copper stocks is the lack of high-salinity fluids during hydrothermal vein formation in the barren stocks. In porphyry copper systems, high-salinity fluids generally form early, and high-salinity fluid inclusions are usually present in early veins (e.g., Chivas and Wilkins, 1977; Eastoe, 1978; Reynolds and Beane, 1985). This relationship suggests that long-lived and widespread circulation of highly saline fluids may be of critical importance in generating porphyry copper and silver-base metal replacement-type mineralization.

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APPENDIX

Methods of Fluid Inclusion Studies

All samples were studied initially under a petrographic microscope using standard thin sections. Doubly polished, thick sections (100–200 μm) of selected samples were then prepared for heating and freezing experiments. These samples were studied under a normal petrographic microscope before the section was broken into small chips for experimental studies. Generally 5 to 35 fluid inclusions were studied during a single heating run and 3 to 5 chips per sample were run. All cooling data were collected prior to heating runs and each chip was heated only once to minimize leakage and decrepitation of fluid inclusions. Chips from selected samples were also crushed in a bath of mineral oil while being observed through a microscope to detect expansion or contraction of vapor bubbles and the presence or absence of condensed gases.

All temperature data were collected on a Chaixmeca heating-freezing stage (Poty et al., 1976) modified to add insulation similar to that described by Cunningham and Carollo (1980). Numerous calibrations of the stage using natural and synthetic standards indicate an accuracy of ±0.5°C in the range −56.6° to 0°C and better than ±4°C in the range 0° to 398°C. Repeat freezing runs generally indicate a reproducibility of ±0.1°C for the melting point of ice. Repeat measurements of the temperature of liquid-vapor homogenization to liquid indicate reproducibility of better than 1.0°C. Heating rates during freezing runs were controlled by conductive interaction with room temperature air and averaged approximately 1.5°C/min near 0°C. Temperature increases during heating runs were generally maintained at 1° to 2°C/min.