Fluid flow and metasomatism in a subduction zone hydrothermal system: Catalina Schist terrane, California

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ABSTRACT

On Santa Catalina Island, southern California, blueschist to amphibolite facies metasedimentary, metamorphic, and meta-ultramafic rocks show veining and alteration that reflect fluid flow and mass transfer at 25-45 km depths in an Early Cretaceous subduction zone. Synkinematic and postkinematic veins record fluid transport and metasomatism during prograde metamorphism and uplift. Vein and host-rock mineralogy and whole-rock compositions demonstrate large-scale chemical redistribution, especially of Si and alkali elements. Veins and host rocks trend toward isotopic equilibrium with aqueous fluids with \( \delta^{18}O_{\text{SMOW}} = +13^\circ/2 \pm 1^\circ/00 \). The likely source for these fluids is in lower temperature, sediment-rich parts of the subduction zone. Carbon isotope systematics support this conclusion and indicate the influence of an organic C source. Quartz solubility relations indicate the importance of fluid-flow paths in chemical redistribution during subduction. These results document large-scale fluid flow and the complexity of possible metasomatic and mechanical mixing processes at intermediate levels of subduction zones. The record of subduction-zone mass transfer in the Catalina Schist is compatible with the record inferred for deeper depths from geochemical and petrologic studies of arc magmatism.

INTRODUCTION

Subduction zones are sites where volatiles and other crustal materials are recycled to the upper mantle and play an important role in arc magmatism, geochemical cycles, energy budgets, and mantle evolution. Metasomatism has been called upon in both geochemical and petrologic models to facilitate the large-scale hybridization that leads to arc magmatism (see Wyllie and Sekine, 1982; Gill, 1981). Investigators of subduction-related terranes mention abundant veins and other metasomatic features (e.g., Ernst, 1965; Fye and Zardini, 1967; Moore et al., 1981; Moore, 1984). Isotopic studies of subduction complexes (Taylor and Coleman, 1968; Magaritz and Taylor, 1976; Nelson, 1985) indicate extensive fluid-rock exchange and fluid mobility. Studies of accretionary complexes suggest massive fluid flow at shallow levels (<15 km) in subduction zones (Moore et al., 1987; Vrolijk et al., 1988).

Although shallow parts of accretionary complexes are commonly well exposed, reconstruction of processes at deeper levels depends on a fragmentary record in high-pressure metamorphic terranes and inference drawn from theory and indirect products of subduction (e.g., arc magmatism). The Catalina Schist subduction complex, exposed on Santa Catalina Island, southern California (Fig. 1), contains an unusually complete and coherent sequence of high-pressure metamorphic rocks which consists of tectonic units of metamafic-metasedimentary, and meta-ultramafic rocks that range in grade from blueschist to amphibolite facies (Platt, 1976). The units are juxtaposed along low-angle faults, resulting in an inverted metamorphic gradient; structurally lowest blueschist facies rocks are overlain by greenschist facies rocks, which are overlain by the structurally highest amphibolite facies rocks (Fig. 1). The proportion of metasedimentary rocks decreases with increasing metamorphic grade (~70% of blueschist unit; ~10% of amphibolite unit) and is compensated by increasing metamafic and, especially in the amphibolite unit, meta-ultramafic rocks. The ultramafic melange in the amphibolite unit (Fig. 1) contains variably metasomatized and mechanically incorporated mafic and ultramafic blocks (rare sedimentary blocks) and is believed to represent a zone of mechanical and metasomatic mixing near the slab-mantle interface. The amphibolite unit also contains coherent schistose metasedimentary and metamafic rocks (Fig. 1). Migmatitic textures and felsic pegmatites in the amphibolite unit indicate high-pressure, high-\( \text{MgO} \) partial melting (Sorensen and Barton, 1987; Bebout and Barton, 1988).

Field and petrologic evidence, together with geochronology (K-Ar, 98-112 Ma; U-Pb, 112-114 Ma; see Mattinson, 1986), suggest that all units of the Catalina Schist were metamorphosed during a single Early Cretaceous subduction episode. Bailey (1941) first mapped the

Figure 1. Generalized geologic map of Santa Catalina Island (~40 km southwest of Los Angeles), showing exposures of Catalina Schist (after Platt, 1976). Insets show location of island and present structural juxtaposition of units of Catalina Schist along traverse shown by line.

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rocks and suggested the probability of metasomatic processes. Petrologic studies by Platt (1976) and Sorensen (1986) indicated peak metamorphic conditions of 7-12 kbar and 350-750 °C. Platt (1976), to explain high inferred temperatures for the Catalina Schist compared with those for other subduction complexes, suggested that the rocks were metamorphosed during early stages of subduction.

The Catalina Schist offers an unusual opportunity to study fluid flow and mass transfer at intermediate levels of a subduction zone (25-45 km depths). This paper presents field, petrologic, and geochemical observations from the Catalina Schist that document large-scale fluid movement and associated mass transfer during subduction-zone metamorphism.

**EVIDENCE FOR FLUID AND MASS TRANSFER IN THE CATALINA SCHIST**

All units of the Catalina Schist contain features that demonstrate fluid and mass transfer during various stages of metamorphism. These features include veins, reaction zones between disparate lithologies, changes in bulk composition, and changes in isotopic composition. Individual icecaps commonly show multiple veining or alteration events. Table 1 puts the field evidence into the context of the metamorphic and deformational histories of the rocks by using textural and petrologic criteria. In Table 1, the units are further subdivided to distinguish variable metamorphic grade within areas mapped in Figure 1 as the blueschist and greenschist units (lawsonite-albite parts of blueschist unit; glaucophane-greenschist and epidote-amphibolite parts of greenschist unit; Sorensen, 1986). Although the ultramafic meltage hanging-wall complex contains mineral parageneses that represent retrograde metamorphism relative to presumed predissolution upper mantle conditions, the highest grade (amphibolite facies) assemblages are referred to as prograde.

Fluids are inferred from isotopic and petrologic studies (i.e., stability of shchene, lawsonite, epidote in veins; cf. Moore, 1984) to have been aqueous. Sorensen and Barton (1987) reported low-salinity H₂O + CH₄-bearing fluid inclusions in mafic blocks and pegmatites in the ultramafic meltage. Quartz veins in the blueschist unit commonly contain abundant H₂O-rich inclusions of similar low salinities. Vein compositions and alteration trends in host rocks record the relative mobilities of elements in fluids during subduction. Abundant quartz-bearing veins in slab-derived units and inferred enrichment of Si in the ultramafic meltage indicate large-scale Si mobility. Abundant albite-bearing veins in all units, felsic pegmatites in the amphibolite unit, and Na-amphibole-bearing veins in the blueschist unit indicate at least local mobility of Na, Al, and Si. Similarly, enrichments of many trace elements in veins and pegmatites (e.g., large-ion lithophile elements [LILE]) indicate their mobility; altered mafic rocks commonly show enrichments in the same elements. In the ultramafic meltage, mineral zonations in veins that crosscut ultramafic blocks and whole-rock compositional trends in the meltage matrix indicate at least local mobilities of Ca, Na, K, and many trace elements, consistent with findings of Sorensen (1988) for rinds on mafic blocks.

**Veining Relations**

Veins and their metasomatic envelopes are ubiquitous features of all units, typically comprising 0.1% to 10% of the outcrop, locally exceeding 50%. Some areas of pervasive bulk compositional change reflect coalescence of vein envelopes. Veins may either prograde or retrograde and synkinematic or postkinematic (Table 1). Prograde veins contain mineral assemblages (generalized in Table 1) diagnostic of the highest grade of metamorphism preserved in the host rocks. Retrograde veins contain minerals requiring lower temperature (+ pressure [P]) conditions than their host. Many veins (~35%) lack diagnostic assemblages (e.g., contain only calcite, quartz, albite), but can commonly be placed in sequence by crosscutting relations or stable-isotope temperature estimates. Vein (and pegmatite) mineralogy and geology

### TABLE 1. SUMMARY OF FIELD EVIDENCE FOR METASOMATISM, CATALINA SCHIST

<table>
<thead>
<tr>
<th>Unit</th>
<th>Lithology</th>
<th>Host-rock assemblage</th>
<th>Petrologic</th>
<th>Textural</th>
<th>Synkinematic*</th>
<th>Postkinematic†</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lawsonite-Albite</td>
<td>Sedimentary</td>
<td>Qtz + Ab + Cal + Lws + WM</td>
<td>+ Pp + Graph + Carb</td>
<td>Pp + Qtz + Carb + Ep</td>
<td>Qtz + Carb + Lws</td>
<td>Pp + Qtz + Carb + Ep</td>
</tr>
<tr>
<td>Mafic</td>
<td></td>
<td>Ab + Chl + Lws + Qtz + Carb + Actin</td>
<td></td>
<td>Qtz + Carb + Lws</td>
<td>Actin + Chl + Carb + Ab</td>
<td>Qtz + Carb + Lws</td>
</tr>
<tr>
<td>Bluechist</td>
<td>Sedimentary</td>
<td>Qtz + Ab + Cal + Lws + Na-amp + WM + Graph + Carb</td>
<td></td>
<td>Na-amp + Qtz + Ab</td>
<td>Pp + Qtz + Carb</td>
<td>Na-amp + Qtz + Ab</td>
</tr>
<tr>
<td>Mafic</td>
<td></td>
<td>Ab + Chl + Na-amp + Lws + Qtz + Carb</td>
<td></td>
<td>Na-amp + Lws + Ab</td>
<td>Pp + Qtz + Carb</td>
<td>Na-amp + Lws + Ab</td>
</tr>
<tr>
<td>Glaucophane</td>
<td>Sedimentary</td>
<td>Qtz + Ab + WM + Na-amp + Qtz + Chl + Graph + Ep</td>
<td></td>
<td>Qtz + Chl + WM + Ep</td>
<td>Pp + Qtz + Carb</td>
<td>Qtz + Chl + WM + Ep</td>
</tr>
<tr>
<td>Glaucophane-Greenschist</td>
<td>Mafic</td>
<td>Na-amp + Ep + Ab + Carb</td>
<td></td>
<td>Eps + Na-amp + Ab + Gl</td>
<td>Carb + Na-amp + Ab</td>
<td>Eps + Na-amp + Ab + Gl</td>
</tr>
<tr>
<td>Greenchist</td>
<td>Sedimentary</td>
<td>Qtz + Cal + WM + Ab + Ep</td>
<td>+ Graph + Actin</td>
<td>Qtz + Actin + Ep + Chl</td>
<td>Pp + Ab + Qtz</td>
<td>Qtz + Actin + Ep + Chl</td>
</tr>
<tr>
<td>Mafic</td>
<td></td>
<td>Actin + Ab + Chl + Ep + Qtz + WM</td>
<td></td>
<td>Actin + Ab + Ep + Chl</td>
<td>Pp + Ab + Qtz</td>
<td>Actin + Ab + Ep + Chl</td>
</tr>
<tr>
<td>Epidote-Amphibolite</td>
<td>Sedimentary</td>
<td>Qtz + Ab + WM + Ep + Graph + Bt + Bt</td>
<td></td>
<td>Pp + Qtz</td>
<td>Qtz + Chl</td>
<td>Pp + Qtz</td>
</tr>
<tr>
<td>Mafic</td>
<td></td>
<td>Ab + Ep + Cal + WM + WM + Bt</td>
<td></td>
<td>Qtz + Pp + Ab + Chl + Actin</td>
<td>Pp + Ab + Qtz</td>
<td>Qtz + Pp + Ab + Chl + Actin</td>
</tr>
<tr>
<td>Amphibolite</td>
<td>Sedimentary</td>
<td>Qtz + Plag + WM + Bu + Gl + Ky + + Graph + Zois + Hbl</td>
<td></td>
<td>Qtz + Plag + WM + Ky</td>
<td>Qtz + Pt + Chl</td>
<td>Qtz + Plag + WM + Ky</td>
</tr>
<tr>
<td>Mafic</td>
<td></td>
<td>Mg-Hbl + Zois + Plag + Gl + Qtz</td>
<td></td>
<td>Chl + WM + (v + r)</td>
<td>Chl + WM + (v + r)</td>
<td>Chl + WM + (v + r)</td>
</tr>
<tr>
<td>Ultranatric</td>
<td>Sedimentary</td>
<td>Chl + Actin + Anh + Tc + Ens + Qtz</td>
<td></td>
<td>Plag + Zois + Qtz</td>
<td>Pp + Ab + Actin</td>
<td>Plag + Zois + Qtz</td>
</tr>
<tr>
<td></td>
<td>Mafic</td>
<td>Ormph Cpx + Qtz</td>
<td></td>
<td>Cpx + Anh</td>
<td>Lws (replacement)</td>
<td>Cpx + Anh</td>
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<tr>
<td></td>
<td></td>
<td>?</td>
<td></td>
<td>?</td>
<td>?</td>
<td>?</td>
</tr>
</tbody>
</table>

Note: Units listed in order of increasing grade; veins unless otherwise specified. Qtz = quartz; Ab = albite; Chl = chlorite; WM = white mica; Pp = pumpellyite; Carb = carbonate (usually calcite) except ankerite; dolomite/negritis in ultramafic melts; Na-amp = sodic amphibole; Lws = lawsonite; Graph = graphite; EP = epidote; Actin = actinolite; Hbl = hornblende; Plag = plagioclase; Grt = garnet; Bt = biotite; Kyo = kyanite; Mg-hbl = magnesiohornblende; Zoi = zoisite; Cpx = clinopyroxene; Anh = anthophyllite; Tc = talc; Ens = enstatite; Ormph = Cpx = amphibolite clinopyroxene.

Common vein accessory minerals include apatite, sphene, graphite, white mica, and, in the lawsonite-albite and blueschist units, stilpnomelane. Sphene occurs in mafic host rocks of all units. Conodont to fabric elements in host-rock or otherwise related to prograde deformation. Veins and replacement. **Cross-cut fabric elements in host-rock. Leucosomes and pegmatites representing partial melting of mafic and sedimentary rocks.

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chemistry correspond to host-rock composition. Within less siliceous (mafic and ultramafic) lithologies, veins rarely contain quartz and generally show the clearest metasomatic envelopes. For example, in the ultramafic melange, envelopes of prograde veins in serpentine-rich zones show zonations from siliceous assemblages of talc ± anthophyllite ± actinolite nearest veins, to anthophyllite ± enstatite-bearing assemblages, to dunite compositions (now serpentinitized) farthest from vein centers. In metasedimentary rocks, quartz-bearing veins rarely have obvious envelopes; however, some Na-ambibole-bearing veins have albite- or quartz-bearing and/or graphite-absent envelopes. Graphite-bearing veins and pegmatites are largely restricted to graphite-bearing metasedimentary rocks. Pegmatites in the amphibolite unit have distinct compositions that reflect variable hosts (Bebout and Barton, 1988); pegmatites from metasedimentary exposures have higher LILE, $\delta^{18}O\text{,}$ and light rare-earth elements (REE) than those from metamorphic exposures.

Vein textural relations are complex. Many of the mineralogically prograde and some of the mineralogically ambiguous veins are synkinematic, showing variable transposition into the fabric or composing part of the fabric. For example, in the blueschist-unit metasedimentary rocks, abundant quartz ± calcite ± Na-ambibole veins fill spaces between boudins in psammitic layers; intervening pelitic beds apparently flowed and contain only later, crosscutting quartz ± calcite ± pumpellyite veins and variably transposed albite ± graphite veins. Prograde veins in mafic lithologies of up to epidote-amphibolite grade tend to be developed in fractures that crosscut weakly foliated to unfoliated hosts, suggesting brittle behavior of the rocks during prograde metamorphism. Prograde veins in some exposures show little deformation and cut across fabrics, and thus are locally postkinematic. Prograde veins may show retrograde features, but retrograde veins are usually distinct from prograde features. Retrograde veins are rarely deformed; they have sharp, planar margins and crosscut maximum-grade fabrics and prograde veins. Prograde and retrograde veins occasionally contain open space. Many exposures contain veins along which prograde minerals in host rocks show retrograde hydration and/or replacement. Other veins show evidence of inward mineral growth from vein walls, or contain minerals that topotaxially overgrow prograde host-rock minerals. Textural evidence, particularly open-space textures and primary fluid inclusions, and vein-related metasomatism require substantial fluid infiltration with $P_{\text{fluid}} \sim P_{\text{total}}$. Vein and petrological evidence alone, however, is insufficient to demonstrate the overall extent and scale of fluid flow.

**Evidence for Whole-Rock Major- and Trace-Element Mobility**

Many of the Catalina rocks show changes in major- and trace-element bulk composition from likely protolith compositions. Textures, mineral assemblages, or isotopic signatures require that some of these changes took place during high-P metamorphism; locally, evidence points to earlier alteration, probably on the sea floor. Whole-rock compositions were measured (>150 samples) by X-ray fluorescence (XRF) and instrumental neutron activation (INAA; this study; Sorensen, 1986, 1988).

Metamorphic rocks in all units show evidence for metasomatism. High-pressure sodic-potassic metasomatism is indicated in blueschist metaconglomerates by replacement textures and whole-rock compositions of gabroic and dioritic clasts (cf. Fyfe and Zardini, 1967; Moore et al., 1981). Many exposures of metamorphic rocks in all units show whole-rock enrichments in Na, light REE, and LILE such as K, Ba, and Rb relative to mid-ocean ridge basalt (MORB) protoliths (this study; Sorensen, 1986; e.g., up to 1.5 wt% $K_2O$ and ~5 wt% $Na_2O$). Identification of high-P alteration in metamorphic rocks is complicated by uncertainties regarding the nature and extent of pre-subduction alteration (e.g., Alt et al., 1986). Shifts to more radiogenic $^{87}Sr/^{86}Sr$ in metamorphic rocks of all units could represent exchange with seawater, perhaps at the mid-ocean ridge (M. D. Barton et al., in prep.). Pervasive compositional alteration in metasedimentary rocks is more difficult to document because of variable protolith compositions and extensive mechanical mixing (± local chemical redistribution) accompanying ductile deformation. For the most part, chemical changes are unambiguous only in vein envelopes and igneous clasts.

Most of the whole-rock compositional changes in metasedamic and metasedimentary rocks do not require mass transfer from beyond the boundaries of their unit and thus do not prove large-volume fluid flow to facilitate mass transfer. The ultramafic melange in the amphibolite unit is an exception. Mass-balance studies of the melange matrix (using XRF and INAA whole-rock major- and trace-element data) indicate its derivation through chemical mixing of ultramafic and mafic rocks and massive addition of Si by infiltrating fluids. Some compositional variations in the melange (e.g., Al, Cr) can be explained by chemical mixing, suggesting relative immobility of these elements; mechanical mixing models suggest a roughly 2:1 molecular proportion of ultramafic to mafic rocks for the melange matrix as a whole. Other compositional variations suggest either redistribution within the melange (e.g., Ca, Na, LILE) or wholesale addition from an external reservoir (e.g., Si, O-, H-, C-isotope systematics). Mass-balance calculations, assuming immobile Al and Cr, indicate that mixture of metamorphic blocks (wt% $SiO_2$ = 50% on anhydrous basis) with dunitic protolith (~40 wt% $SiO_2$) was insufficient to silicify the melange matrix (present average wt% $SiO_2$ ~ 55%), necessitating an external Si source. Significant addition of high-Si materials such as sediment (including chert) is discounted on the basis of field evidence and other geochemical trends. Large parts of the melange resemble (in mineralogy and bulk composition) metasomatic assemblages developed at the rims of mafic and ultramafic blocks in the melange, suggesting complex evolution of the melange through combined mechanical and metasomatic proc-

**Figure 2. Calculated water $\delta^{18}O$ for prograde vein and host-rock mineral and whole-rock data, using fractionation data in Friedman and O'Neil (1977); $n$ = number of samples.**

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esses. Nd isotopic data for variable metasomatized mafic blocks require addition of a sedimentary component (M. D. Barton et al., in prep.) compatible with the stable-isotope evidence (presented below).

O-, H-, and C-Isotope Systematics

Stable-isotope systematics indicate extensive fluid-rock exchange and large-scale fluid flow from lower temperature to higher temperature parts of the subduction zone. More than 350 silicate, carbonate, and carbonaceous mineral separates and whole-rock samples were analyzed for δ18O, δD, and δ13C by conventional methods.

O-isotope fractionations between coexisting prograde vein minerals are generally consistent with petrologically inferred peak metamorphic temperatures. Calculated water δ18O_MSW, using prograde vein data and the petrologically estimated temperatures (Fig. 2), indicate equilibration of veins in all fluids with aqueous fluids of remarkably uniform δ18O of +13% to +17%.

With the exception of some metasomatised rocks and less metasomatized matrix and blocks in the ultramafic melange, host rocks show shifts in δ18O with grade that parallel those of vein minerals. For example, metacherts are strongly shifted from initial compositions (+25% to +35%) toward equilibrium with the vein-forming fluids (+17% in blueschist unit; +14% in amphibolite unit). For all units, calculated water δ18O_MSW values, using vein and host-rock mineral data, range from −20% to 0% (cf. Magaritz and Taylor, 1976).

The δ13C_PDB (Pee Dee belemnite) values for poorly crystalline carbonaceous matter in the lowest grade metasedimentary rocks (−24% to −27%) are consistent with an origin of organic matter. Vein graphites from blueschist metasedimentary rocks have δ13C values that match those of graphite in the host rocks (−25%).

Amphibolite unit pegmatites contain graphite with δ13C (−25% to −18%) similar to values for graphite in metasedimentary rocks (all units, −27% to −18%). Carbonate veins from blueschist unit metasediments also have light δ13C values (−13% to −6%) compatible with formation from fluids equilibrated with the carbonaceous matter. Carbonate veins in mafic rocks range widely in δ13C (−7% to +2.5%); veins with heavier values may have formed during low-T sea-floor alteration. Ankerite dolo
tite in the amphibolite unit ultramafic melange (δ13C of −10% to −9%) would be in C-isotopic equilibrium at 650 °C with CO2 of δ13C of −8% to −7%, similar to that calculated for calcite veins in low-grade metasediments (−10% to −3%).

The calculated range in fluid δ18O most closely approximates isotopic equilibrium in inferred metamorphic temperatures with the abundant low-grade metasedimentary rocks (e.g., for blueschist unit, whole-rock δ18O = +12% to +15%; quartz δ18O = +15% to +18%; quartz-water fractionation of −4.1% at 400 °C; Friedman and O'Neil, 1977). This suggests that the fluids that metasomatized higher grade units of the Catalina Schist were derived in lower temperature sediment-dominated parts of the subduction zone. This interpretation is consistent with the C- and H-isotope data. The range in calculated fluid δD suggests an evolved seawater source, from isotopically modified pore water or through more complex dehydration processes.

MODEL FOR VEINING AND METASOMATISM IN THE CATALINA SCHIST

The model of fluid flow and metasomatism envisioned for the Catalina Schist is shown in Figure 3A. Metamorphic and metasedimentary rocks represent metamorphosed, subducted oceanic crust + sediment; the ultramafic melange of the amphibolite unit is a zone of mechanical and/or metasomatic mixing of hanging-wall and slab-derived rocks near the slab-mante
t interface. Mildly satitic fluids derived from slab evolved chemically and isotopically as they interacted with rocks in the slab; the dominant mechanism of fluid subduction (entrained as pore fluid or in minerals) remains uncertain. Some of the slab-derived fluids interacted with the amphibolite unit ultramafic melange, introducing large amounts of Si, H, and O and redistributing other elements within the melange (e.g., path 2, Fig. 3A). This conclusion is sup-
ported by O-, H-, and C-isotope systematics. Abundant quartz-bearing veins suggest high mobility of Si in slab materials, and silicic mineral assemblages and mass-balance constraints would suggest massive addition of Si to the ultramafic melange. Quartz solubility rela
tions (see Walther and Helgeson, 1977) indicate the passage of large volumes of aqueous fluid to precipitate the abundant quartz veins. Si and δ18O shifts in ultramafic rocks require fluid-rock ratios (oxygen-equivalent basis) of >5:1; δ18O shifts in cherts require fluid-rock ratios of >10:1.

The C-, O-, and H-isotope data suggest that higher-grade units were infiltrated by fluids equilibrated with metasedimentary rocks at temperatures like those inferred for the blueschist unit (300–450 °C); however, the fluid source could have been substantially deeper than recorded by the present exposures. Thermal models of subduction zones (e.g., Anderson et al., 1978) demonstrate that, even during early stages of subduction, large domains exist at these temperatures to great depths (greater than the depths inferred for the Catalina blueschist unit).

Arguments for some low- to high-temperature fluid flow based on the isotope data for the Catalina Schist have more general implications for chemical redistribution in subduction zones. Figure 3B shows quartz solubility as a function of temperature and pressure and two generalized fluid flow paths that ascending fluids might encounter in an active subduction system. For the case of updip fluid flow parallel to the subduction thrust, ascending fluids would encounter P-T:

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**Figure 3.** A: Model for fluid flow and metasomatism in Catalina Schist, showing schematic fluid-flow paths 1 and 2 and inferred mobility of aqueous fluid, Si, and isotopic components. Mafic (stippled) and ultramafic (patterned) blocks are rocks from slab and mantle wedge, respectively, incompletely incorporated into kilometre-scale shear-zone melange near slab-mantle interface. B: Quartz solubility in water (in wths; contours labeled at top of figure) as function of temperature and pressure (Walther and Helgeson, 1977). Also shown are stability fields for blueschist (B), green
cschist (G), and amphibolite (A) units (Sorensen, 1986; this study). Arrows 1 and 2 are fluid-flow paths discussed in text.

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conditions dictated by the prevailing geothermal gradient (path 1, Fig. 3, A and R; cf. Peacock, 1987), resulting in flow from regions of higher to lower quartz solubility, which should lead to silica precipitation, perhaps as quartz veins. Fluids along flow paths with strong vertical components (vertical rising toward hanging wall; path 2, Fig. 3, A and B) would warm, potentially leaching rather than adding silica to rocks (possibly represented by quartz-poor vein assemblages). Silica leached along such flow paths in the slab could be removed through interaction with low-Si ultramafic assemblages near the slab-mantle interface (e.g., Fig. 3A).

CONCLUSIONS

The Catalina Schist contains field, petrologic, major- and trace-element, and isotopic evidence for large-scale fluid flow and complex metamorphic and mechanical mixing processes during subduction-zone metamorphism at 25–45 km depths. The evidence for mass transfer in the Catalina Schist is consistent with experimental solubility data and theoretical predictions of element mobility under subduction-zone pressure-temperature conditions (see Walther and Helgen, 1977; Tatsumi et al., 1986). Veining and alteration in other subduction complexes (e.g., Ernst, 1965; Frye and Zardini, 1967; Taylor and Coleman, 1968; Magaritz and Taylor, 1976; Moore et al., 1981; Moore, 1984; Nelson, 1985; Vrolijk et al., 1988) show similarities in style with the record of metasomatism in the Catalina Schist. Although isotopic homogenization of the Catalina Schist requires extensive fluid-rock exchange, necessitating some pervasive fluid flow, the Catalina and other rocks suggest the particular importance of fracture-controlled fluid flow in subduction zones. This study demonstrates that such transport may occur on a large scale, in some cases perpendicularly to structures from lower to higher temperature, potentially hanging-wall, parts of subduction zones. Fluid P-T flow trajectories may determine large-scale chemical redistribution patterns during subduction.

Veining and alteration histories in subduction-related metamorphic complexes fingerprint metasomatism at various depths (0 to ~60 km) in subduction zones and may yield information regarding geochemical cycles of many components (H₂O, Si, halogens, alkali elements, C, radiogenic isotope signatures, etc.) thought to be recycled to the upper mantle via subduction. Comparabilities exist between the record of subduction-zone metasomatism in the Catalina Schist and the record obtained through study of arc lavas (cf. Gill, 1981; Wylie and Sekine, 1982; Tatsumi et al., 1986). This study documents large-scale mobility of Si in aqueous C-O-H fluids and, together with the studies of Sorensen (1988) and S. S. Sorensen and J. N. Grossman (in prep.), at least local-scale mobility of many other elements, including Al, alkali elements (Na, K), Ca, and many trace elements (e.g., Sr, Rb, Cs, Ba, light REE, P) in fluids and silicate liquids. Pegmatites in the amphibolite unit of the Catalina Schist have many characteristics inferred for a slab-derived "fluid" component in the generation of arc magmas (M. D. Barton et al., in prep.; high-Si, LILE-enriched, high field strength element-depleted, light REE-enriched, radiogenic Sr-isotope compositions; cf. Gill, 1981). Metasomatism in the Catalina Schist may be indicative of the scale and complexity of fluid and mass transfer processes that operate at greater depths in subduction zones, including those that contribute to the geochemical evolution of arc-magma source regions.

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