Structural aspects of fluid-rock interactions in detachment zones

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ABSTRACT

Metamorphic core complexes and associated detachment faults of the North American Cordillera represent gently dipping, normal-displacement shear zones (detachment zones) along which hot, deeper levels of the crust were transported upward and outward from underneath a brittlely distended upper plate. Structures that formed during the ductile-to-brittle evolution of detachment zones can be used to reconstruct the relative magnitudes of fluid pressure and deviatoric stress at different levels within the shear zones. Mylonitization, which occurred along deeper segments of detachment zones below the brittle-ductile transition, was locally accompanied by tensile failure, indicative of low deviatoric stress and high fluid pressure. This condition persisted into the earliest phases of brittle deformation, after which shear fractures formed due to both a reduction in fluid pressure and an increase in deviatoric stress. Brittle deformation of upper-plate rocks occurred largely under conditions of low fluid pressure.

Structural and geochemical data suggest that normal displacement on detachment zones results in establishment of two fluid systems: (1) an upper-plate system driven by convection and dominated by meteoric and connate fluids at near-hydrostatic pressures and (2) a system within deeper levels of the shear zone, where fluids are largely derived from igneous sources and fluid migration is aided by dilatancy pumping. The late phases of normal displacement on detachment zones structurally juxtaposed rocks affected by the two fluid systems and locally caused the shear-zone rocks to be overprinted by mineralization related to the upper-plate fluid system.

INTRODUCTION

Metamorphic core complexes of western North America are characterized by metamorphic and plutonic rocks that are overprinted by gently dipping mylonitic fabrics and by superimposed brittle structures associated with regional, low-angle normal faults, referred to as detachment faults (Crittenden et al., 1980). Detachment faults underlie highly faulted and brittlely distended upper-plate rocks and have accommodated as much as 50 km of normal displacement during Tertiary extension (Wernicke, 1981, 1985; Reynolds and Spencer, 1985). Mylonitic fabrics and detachment-related, brittle structures within core complexes represent the ductile-to-brittle evolution of gently dipping, normal-displacement, crustal-scale shear zones (Davis et al., 1986), hereafter referred to as detachment zones. According to an evolving-shear-zone model, detachment faulting and associated brittle deformation occur in the upper levels of a detachment zone, but grade downdip along the zone into ductile deformation that produces mylonites (Wernicke, 1981; Davis, 1983; Reynolds, 1985; Davis et al., 1986). Normal displacement on detachment zones results in mid-crustal rocks being transported upward and outward from beneath a cover of fracturing, upper-crustal rocks and through the brittle-ductile transition where they begin being brecciated and retrogressed into chloritic breccia and microbreccia and cut by one or more detachment faults. During uplift, fault-related fabrics became increasingly localized to structurally higher levels of the lower plate, so that a discrete detachment fault is commonly underlain by successively thicker zones of microbreccia, chloritic breccia, and mylonitic rocks (Davis et al., 1986).

Displacement on detachment zones is accompanied by formation of two classes of fractures: those formed by tensile failure and those formed by shear or extensional-shear failure. Extension fractures are generally planar or smoothly curved due to later deformation, occur in parallel sets, and contain vein fillings with local fiber lineations. Shear fractures generally occur in sets that intersect at acute angles and are marked by striations, brecciated selvages, or other evidence of fracture-parallel displacement.

These two types of fractures reflect the interplay between fluid pressure and deviatoric stress (Secor, 1965; Phillips, 1972; Etheridge, 1983; Etheridge et al., 1984). According to the law of effective stress (Hubbert and Rubey, 1959) and a composite Coulomb-Griffith failure envelope with cohesive strength equal to twice the tensile strength for intact rock (Brace, 1960), extension fractures can form only when effective mean (confining) stress is low and deviatoric stress is less than or equal to four times the tensile strength of the rock (Fig. 1). In order to lower effective mean stress to the point where tensile failure can occur at depth, fluid pressure must exceed the minimum principal compressive stress (σ_3) by an amount equal to the tensile strength of the rock. For a normal-fault environment where σ_3 is subhorizontal, tensile failure can occur in the top 1 km of the crust with only hydrostatic fluid pressures, but it requires increasingly higher fluid pressures with depth (Fig. 2; Secor, 1965; Sibson, 1981). The formation of extension fractures at depths of more than 1 km is therefore a clear indication of high fluid pressures. Elevated fluid pressures also permit shear fractures to develop at lower deviatoric stress than in a dry environment, but still at higher deviatoric stress than that indicated for tensile failure (Fig. 1).

In this paper, we have applied these principles of fracture formation to evaluate the levels of fluid pressure and deviatoric stress during the ductile-to-brittle evolution of detachment zones. The results are consistent with present models for the rheology of continental crust and indicate that the brittle-ductile transition approximately coincides with the boundary between a deeper regime of transient(?) high fluid pressure and low deviatoric stress, and a shallower regime of generally lower fluid pressure and higher deviatoric stress.

STRUCTURES AND FLUID FLOW WITHIN UPPER-PLATE ROCKS

Upper-plate rocks above detachment faults are commonly fractured, brecciated, and cut by numerous low- to high-angle normal faults. The presence of normal faults and shear fractures indicates that the greatest principal compressive stress (σ_1) was vertical and that fluid pressure was generally insufficient to cause tensile failure. The presence of clastic dikes and mineral-filled extension veins in the top 1 km of the upper plate is accountable simply by hydrostatic fluid pressure (Fig. 2).

The larger normal faults within the upper plate were probably originally continuous from the detachment fault to the surface. These faults would have served as fluid-migration pathways during detachment faulting, providing they were kept open by ongoing faulting and not sealed by minerals precipitating from circulating fluids. A high connectivity of fluid-migration pathways in the upper plate during detachment faulting would ensure that fluid pressures remained near-hydrostatic, which is consistent with the abundance of shear fractures. Fluids within the upper plate would have been dominated by meteoric and connate fluids associated with syntectonic basins, although an influx of deep-level, igneous-derived fluids from the lower plate is also probable.

Displacement on gently dipping detachment zones resulted in steepened geothermal gradients as hot, lower-plate rocks were transported upward, toward the surface (Reynolds, 1980; Spencer and Welty, 1986). At sufficiently high rates of displacement, the lower plate cannot cool to ambient temperatures by conduction alone; this results in hydrothermal convection systems in the permeable upper-plate rocks. Another major source of heat to drive fluid convection in the upper plate would be synkinematic Tertiary intrusions, some of which were intruded, mylonitized, and subsequently brecciated, all in a short time span of 1–5 m.y. (Reynolds et al., 1986). This igneous activity must have caused at least localized steepening of the geothermal gradients and convective fluid flow.

STRUCTURES AND FLUID PRESSURES WITHIN DETACHMENT ZONES

Structures formed during the ductile-to-brittle evolution of detachment zones are preserved in rocks below the detachment fault. The earliest formed fractures in lower-plate rocks are steeply dipping extension fractures that are synmylonitic to late mylonitic and perpendicular to the stretching lineation and the direction of tectonic transport (Reynolds, 1985). These fractures vary from numerous microscopic extension gashes to larger, throughgoing quartz veins and dikes. In

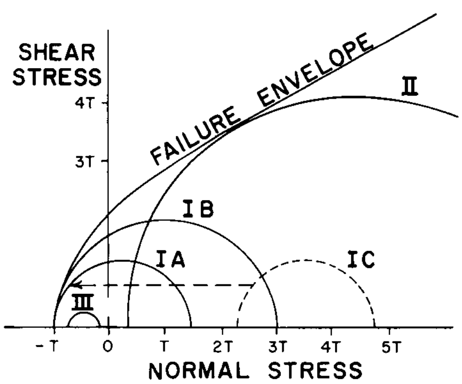

Figure 1. Coulomb-Griffith failure envelope and stress circles for tensile failure (IA), maximum deviatoric stress for tensile failure (IB), and shear failure (II). Circle IC represents nonfailure stress conditions that can result in tensile failure by increasing fluid pressure, which decreases effective stress, as represented by movement of stress circle to left (after Secor, 1965; Etheridge, 1983). For normal-fault environment (σ_1 vertical), fluid pressure cannot exceed lithostatic pressure (σ_1) unless deviatoric stress is less than tensile strength (T) of rock (circle III).

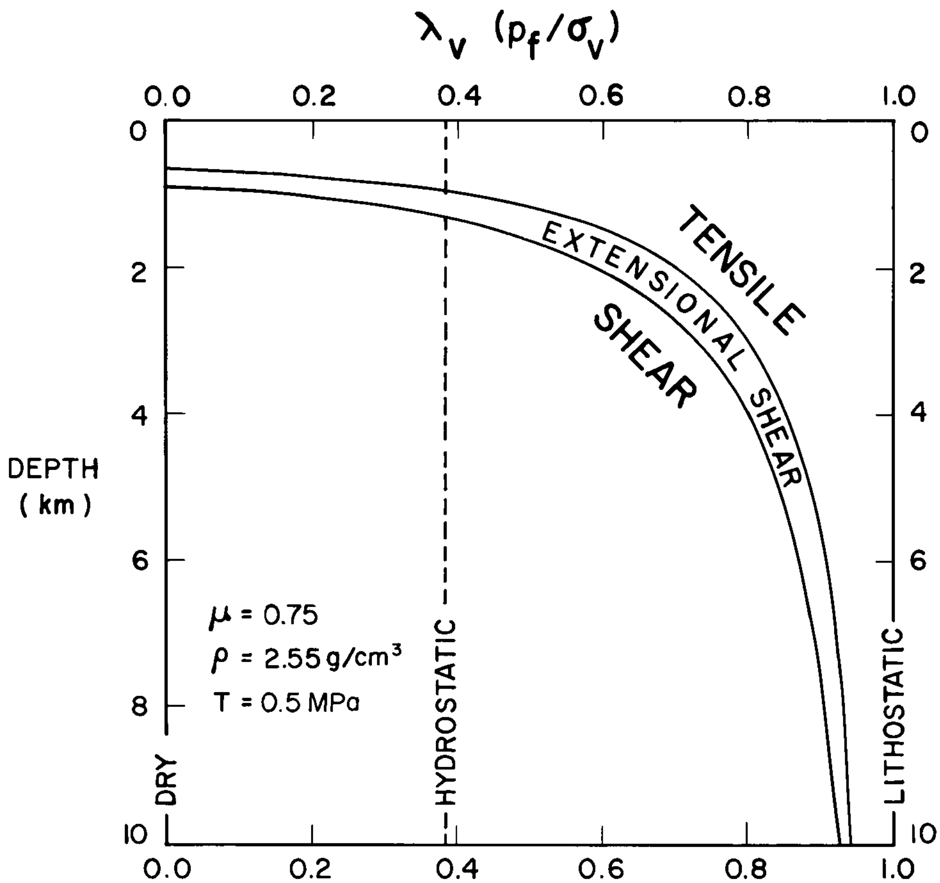

Figure 2. Curves showing ratio of pore-fluid pressure (p_f)/vertical compressive stress (σ_v) required for tensile and extensional shear failure at depth in normal-fault environment where σ_1 is vertical. Graphs are derived from equations defining failure envelope in Figure 1 for tensile strength (T) of 0.5 MPa, density (ρ) of 2.55 g/cm^3, and coefficient of friction (μ) of 0.75 (see Secor, 1965; Sibson, 1981). Note that when σ_1 is vertical, tensile failure can occur at shallow depths with only hydrostatic fluid pressures.

many cases, thin mylonitic shear zones nucleated along quartz veins or other extension fractures. The presence of these synmylonitic and late mylonitic fractures indicates that the rocks were simultaneously deforming by ductile mylonitization and transient brittle fracture, although on different time scales.

Inasmuch as these fractures formed by tensile failure, at least some stages of mylonitization must have occurred under conditions of small deviatoric stress and transient increases in fluid pressure relative to σ_3. This relative increase in fluid pressure was, in the case of the dikes, due to magma injection. The emplacement of dikes provides an "instantaneous" sample of ambient stress conditions during mylonitization because the time of emplacement and cooling of a dike is short (Jaeger, 1969) compared with the time required to form mylonites. The subvertical attitude of most extension fractures indicates that σ_3 was subhorizontal and that fluid pressures did not exceed the vertical compressive stress (lithostatic load), unless deviatoric stress was less than the tensile strength of the rock (circle III, Fig. 1). The local presence of subhorizontal, late mylonitic extension fractures may indicate that deviatoric stress was indeed low enough that fluid pressures intermittently exceeded lithostatic load as proposed by Coney (1980).

Extension fractures continued to form during the initial phases of brecciation associated with detachment faulting. These fractures are steeply dipping, are oriented perpendicular to transport direction during detachment faulting, and have been filled with chlorite, epidote, quartz, or igneous dikes. The presence of these structures implies that deviatoric stress remained low and fluid pressure remained high in the lower plate during this earliest phase of brittle deformation.

In the South Mountains detachment zone of central Arizona, these extension fractures are cut by numerous shear fractures that occur within the breccia zone beneath the detachment fault (Reynolds, 1985). The shear fractures are commonly striated and occur in conjugate sets with a subvertical acute-angle bisectrix. They reflect an increase in deviatoric stress and a decrease in fluid pressure.

The overall evolution of structures within detachment zones is consistent with an early period of ductile deformation where deviatoric stress was low and fluid pressure locally exceeded σ_3. This phase persisted during at least the late stages of mylonitization and continued intermittently into the earliest phases of brecciation and detachment faulting. It was followed by a decrease in fluid pressure and an increase in deviatoric stress, as evidenced by the formation of shear fractures and late-stage mylonites with very fine-grained, recrystallized quartz. This increase in deviatoric stress is consistent with an evolving-shear-zone model for detachment zones (Davis et al., 1986) and recent models of the depth-dependent rheology of continental crust (Brace and Kohlstedt, 1980; Sibson, 1982), which would predict that deviatoric stress would rise as the lower plate is drawn upward through the strongest part of the crust at the brittle-ductile transition.

Within detachment zones, the transition from dominantly ductile to dominantly brittle behavior of the lower plate approximately coincided with a change from transient high fluid pressure to relatively lower fluid pressure. In the ductile regime, high fluid pressure and plastic behavior of rocks would have prohibited buildup of large deviatoric stress until the onset of brittle deformation increased fracture permeability and permitted the escape of overpressured fluids. The change from ductile to brittle deformation also coincided with an increase in the volume of water interacting with the rocks, on the basis of a marked increase in the amount of retrograde metamorphism.

FLUID FLOW ALONG DETACHMENT FAULTS

There is a relative lack of throughgoing faults in the lower plates of detachment zones, except for postdetachment, high-angle faults and the breccia zones directly beneath detachment faults. The connectivity of observable fluid-migration pathways is low, which implies that most of the lower plate was characterized by lower permeability than the upper plate, although not so low as to totally restrict all fluid flow (Fyfe et al., 1978; Etheridge et al., 1983). Because the magnitude of fluid flow is strongly controlled by permeability, lower permeability implies a lower level of fluid circulation within the lower plate than within the upper plate. This conclusion is consistent with the limitation of significant retrograde metamorphic reactions, many of which require water to proceed, to strongly mylonitic or highly fractured zones where water had access to the rocks. A limited quantity of fluids in the lower plate is also consistent with oxygen and hydrogen isotopic data that reflect low water/rock ratios during deformation (Kerrich et al., 1984; Smith and Reynolds, 1985). Cooling of the lower plate would take place by a combination of conduction and advective heat transfer caused by fluid migration along the shear zone and into the upper plate.

Fluid flow during mylonitization within a shear zone is likely because ductile deformation results in a large increase in dynamically maintained permeability (Urai, 1983; Etheridge et al., 1983). In addition, a reduction in effective confining pressure due to high fluid pressure will further increase permeability (Brace et al., 1968; Etheridge et al., 1984). This increased permeability of ductilely deforming rocks within a detachment zone relative to adjacent less deformed rocks would tend to focus fluid flow into the shear zone, the direction of net fluid flow within the shear zone being generally updip, toward lower pressure. Focusing of fluid flow along shear zones (Beach, 1976; Fyfe et al., 1978) explains why synmylonitic retrogression is more pervasive in zones of high shear strain than in the less deformed wall rocks, even though all lower-plate rocks underwent the same drop in pressure and temperature as they were uplifted. Structural control of fluid flow became especially pronounced during the latest stages of mylonitization, when penetrative plastic deformation was superseded by formation of thin ductile-brittle shear zones enriched in quartz segregations and retrograde minerals.

The relatively short, discontinuous nature of most tension gashes in mylonitic rocks implies that the amount of overpressured fluid was limited, or else fluid pressures would have resulted in longer, throughgoing fractures. More throughgoing dilatant fractures formed only during dike emplacement and during the latest stages of mylonitization, which probably reflects an increase in the amount of available fluid.

The presence of transient, high fluid pressures during mylonitization requires limited connectivity of fluid pathways and no connectivity with areas of low fluid pressures. Deposition of quartz and other minerals from circulating fluids may help seal fluid pathways and permit a buildup in fluid pressure (Fyfe et al., 1978; Etheridge et al., 1983; Parry and Bruhn, 1986). The late stages of mylonitization were characterized by increased deposition of quartz in dilatant fractures and as irregular pods and segregations. Because at moderate pressures the solubility of quartz diminishes with decreases in temperature or pressure (Kennedy, 1950), fluids ascending along the shear zone would deposit quartz as they cool and decompress, thereby tending to seal fractures and other potential fluid pathways. Such sealing of fluid pathways by mineral precipitation may account for the fact that upper-plate rocks above the deeper parts of detachment zones were evidently intact enough to effectively seal fluid pressures within the zone. An increase in fluid pressure along the detachment zone due to such sealing could decrease the effective normal stress and initiate slip on faults (Coney, 1980; Sibson, 1985a).

The style of fluid flow along the shear zone would have changed with the onset of fracturing and brecciation associated with detachment faulting. Within the brittlely deforming segments of a shear zone, fluid flow is driven by pressure gradients caused by dynamically produced dilatancy and by temperature-related density variations of the fluid. Fluid pockets may be moved back and forth along the zone, depending on the way in which local failure develops and maintains dilatancy. This process, termed dilatancy pumping (Etheridge, 1983; Lister et al., 1986), occurs when dilating fault zones draw pore fluid from the country rock because of microcracking during the buildup of stress and then rapidly expel the fluids because of collapse of dilatancy during one or more seismic events (Sibson, 1977, 1981, 1985b).

Within detachment zones, the back-and-forth movement of fluids caused by dilatancy pumping will occur within the context of an overall flow up the fault zone due to vertical gradients in dilatancy, pressure, and temperature. Dilatancy pumping and overall updip fluid flow will both be most active at high rates of displacement on the fault because of increases in the connectivity of fluid pathways, the frequency of dilatancy creation-collapse cycles, and the thermal contrast between rocks on either side of the shear zone. The overall motion of fluid up the detachment zone implies a flux of deep-seated fluids from the deeper, mylonitically deforming segments of the shear zone into the chloritic breccia zone and eventually into the upper-plate fluid system. Some fluid ascending the shear zone will be removed from the fluid regime by retrograde hydration reactions.

TWO REGIMES OF FLUID BEHAVIOR

Structural data presented above suggest that fluid pressure within the deeper levels of detachment zones locally exceeded the least principal compressive stress. In contrast, fluid pressure in all but the lowest parts of the upper plate was generally lower, probably at near-hydrostatic levels. These differences in fluid pressure require that two regimes of fluid behavior existed during evolution of the detachment zones and that these regimes were, in part, isolated from one another (Fig. 3).

Fluids in the two regimes would be derived from very different sources and have strongly contrasting chemistries. Highly faulted upper-plate rocks have significant fracture permeability and would have contained abundant meteoric and connate fluids, including both reducing and oxidizing brines in syntectonic sedimentary basins (Beane et al., 1986; Wilkins et al., 1986). In contrast, the shear-zone fluid system involved less oxidized, deep-level fluids (Kerrich et al., 1984; Smith and Reynolds, 1985) that migrated both up the shear zone and back and forth within the zone because of dilatancy pumping (Fig. 3). The amount of *igneous-derived* fluid ascending the deeper, ductile segments of a detachment zone could be substantial above large, synkinematic Tertiary plutons. The amount of newly liberated *metamorphic* fluid entering a detachment zone from depth was probably minor because most lower-plate metamorphic rocks underwent pre–shear-zone prograde metamorphism and the associated loss of water. Also, the entire ductile-to-brittle continuum of deformation along detachment zones was accompanied by retrograde metamorphism, which involves hydration reactions rather than prograde, dehydration reactions.

Detachment faults represent an abrupt geochemical boundary; upper-plate rocks are generally reddish because of abundant hematite and secondary potassium feldspar, whereas the footwall breccia zone is commonly greenish because of epidote and chlorite. This geochemical boundary is largely structural. Most upper-plate hematitic alteration and K-metasomatism occurred at shallow crustal levels because of alkaline basin brines (Chapin and Lindley, 1986; M. Roddy, 1986, written commun.), whereas brecciation and retrogression of the lower plate began at depths near the brittle-ductile transition. The juxtaposition of reddish and greenish rocks along a detachment fault does not, therefore, require that the fault effectively isolated oxidized and reducing fluids.

The basic differences in the mechanisms driving fluid transport in the two systems imply that only one-way connection between the two fluid systems is possible. Deep-seated fluids migrating up the shear zone may bleed into the upper-plate circulation system, but the upper-plate fluids may not penetrate down into the ductile segments of the shear zone, against the overall upward-directed fluid flow. Dilatancy pumping and thermally induced convection could, however, draw upper-plate fluids into the brittle segments of the detachment zone, especially where the upper-plate rocks are most fractured and permeable.

Fluid flow along detachment zones resulted in widespread alteration and hydrothermal mineralization in both upper- and lower-plate rocks adjacent to the zone (Wilkins et al., 1986; Spencer and Welty, 1986). Mineralization occurred during the late stages of detachment faulting, after formation of most of the lower-plate chloritic breccia and many upper-plate normal faults. The general restriction of mineralization to within several hundred metres of detachment zones demonstrates the ability of the zones to channel fluid flow. Fluid-inclusion homogenization temperatures for detachment-related mineralization are commonly 200 to 325 °C (Wilkins et al., 1986), even in veins within syndetachment sedimentary and volcanic rocks; this demonstrates that hot fluids were able to ascend along the detachment zone from significant depths. The mineralizing fluids were evidently chlorine-rich, upper-plate basin brines (Wilkins et al., 1986) that were drawn into the permeable parts of the detachment zone, heated, and then driven upward along the zone.

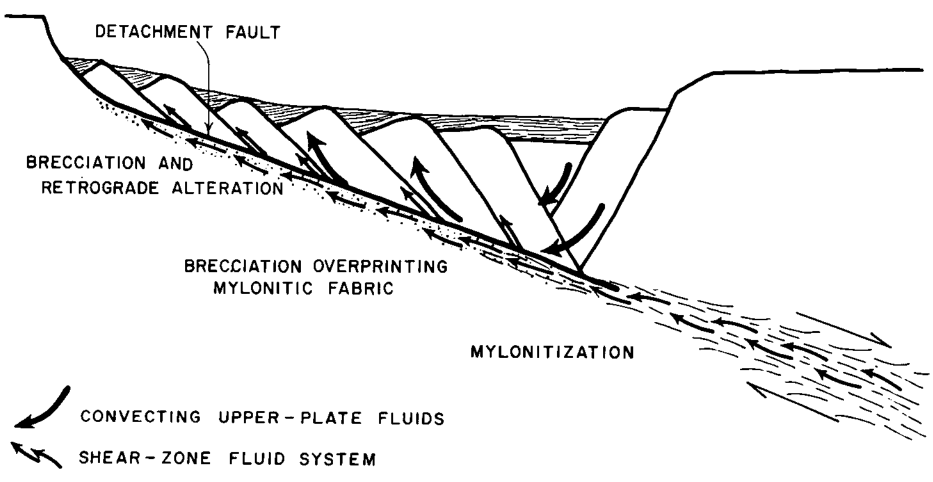

Figure 3. Schematic cross section showing regimes of fluid flow associated with detachment zone.

CONCLUSIONS

Considering the structural aspects of fluid-rock interaction during the evolution of gently dipping detachment zones lends insight into the variation in fluid pressure and deviatoric stress with depth along major shear zones. Mylonitization occurs below the brittle-ductile transition under conditions of transient, high fluid pressure and low deviatoric stress, whereas higher levels of crustal shear zones are characterized by lower fluid pressure and higher deviatoric stress (Etheridge et al., 1984; Parry and Bruhn, 1986).

Normal displacement on detachment zones was accompanied by the establishment of two fluid-circulation systems—one within upper-plate rocks and another along deeper levels of the shear zones. The upper-plate fluid system involved meteoric or connate fluid that probably remained at near-hydrostatic pressure because normal faults provided open channelways to the surface. Circulation systems in the upper plate were driven by the thermal contrast between the hot lower plate and the cooler upper plate, and by igneous activity.

In contrast, fluids within the deeper, shear-zone regime were derived at depth and were overpressured to levels that intermittently exceeded σ_3 by an amount equal to the tensile strength of the rock. Fluid migration up the detachment zone was controlled by gradients in temperature, pressure, and dilatancy. Passage of the shear-zone rocks through the brittle-ductile transition was accompanied by a drop in fluid pressure and a rise in deviatoric stress, resulting in the formation of shear fractures. The change from ductile to brittle processes coincided with an increase in the volume of fluids interacting with and retrogressing the lower-plate rocks.

Shear-zone fluids bled into the upper-plate circulation system and thereby underwent a drop from lithostatic to near-hydrostatic fluid pressure and an eventual change in redox state as they encountered oxidizing fluids and rocks in the higher levels of the upper plate. Conversely, upper-plate fluids, including basin brines, were locally drawn into brittle segments of detachment zones, heated, and expelled up the zones, causing hydrothermal alteration and mineralization. Continued displacement on detachment zones resulted in the structural juxtaposition of rocks affected by the two fluid regimes and caused lower-plate, shear-zone rocks to be locally overprinted by mineralization related to the upper-plate fluid system.

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