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Active breaching of a geometric segment boundary in the Sawatch Range normal fault, Colorado, USA

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Abstract

The northwest-trending Sawatch Range normal fault system is the principal range-bounding fault of the northern Rio Grande Rift of central Colorado. It displays a geometric segment boundary in the form of a prominent en échelon step at the Chalk Cliffs, a zone of highly fractured and hydrothermally altered quartz monzonite. There, the modern fault geometry suggests that the Sawatch Range fault is presently breaching the boundary. Immediately north of the Chalk Cliffs, the range front fault is active whereas immediately south, the range front fault is inactive. Instead, it is replaced by a north-trending break that transects much of the boundary.

The Chalk Cliffs also display a four-stage history of faulting and alteration/mineralization that appears to track the boundary's evolution. First-stage chlorite-filled faults and second-stage laumontite-filled faults affect the entire boundary and likely pre-date the breach. They record a change of fluid chemistry during oblique extension associated with the boundary's early history. Third stage, calcite-filled fractures are generally restricted to the eastern half of the boundary, between the breaching fault's projection into the Chalk Cliffs and the active range front fault. These fractures probably coincide with initiation of the breach. Modern (fourth stage) hydrothermal activity occurs at, and slightly beyond, the eastern edge. This coincidence of hydrothermal events with changes in large-scale fault geometry illustrates how normal fault zones, through breaching, can simplify their geometries and localize associated deformation and hydrothermal activity.

1. Introduction

Geometric segment boundaries characterize large normal fault systems (e.g. Bruhn et al., 1987; Jackson and White, 1989; Anders and Schlische, 1994). Typically, these boundaries are marked by discontinuous, en échelon fault traces or abrupt strike changes in the fault. Where the fault surfaces are discontinuous, these boundaries offer the chance to observe the processes that control growth of the fault across the zone. These processes are important because segment boundaries that persist through time may localize and/or arrest earthquake ruptures, localize hydrothermal mineralization, and influence basin development and sedimentation patterns (Gawthorpe and Hurst, 1993; Jackson and Leeder, 1994).

Although en échelon boundaries show a range of specific geometries, they can be described as either 'soft-linked' or 'hard-linked' (Gibbs, 1984; Walsh and Watterson, 1991). Soft-linked boundaries are those defined by a zone of distributed deformation between the faults rather than by a discrete breaching fault; typically they consist of a 'relay ramp', which connects the footwall of one fault with the hanging wall of the other. By contrast, hard-linked boundaries contain a fault surface which directly links the bounding faults. Soft-linked boundaries may become breached through time to become hard-linked boundaries (e.g. Peacock and Sanderson, 1994; Trudgill and Cartwright, 1994;

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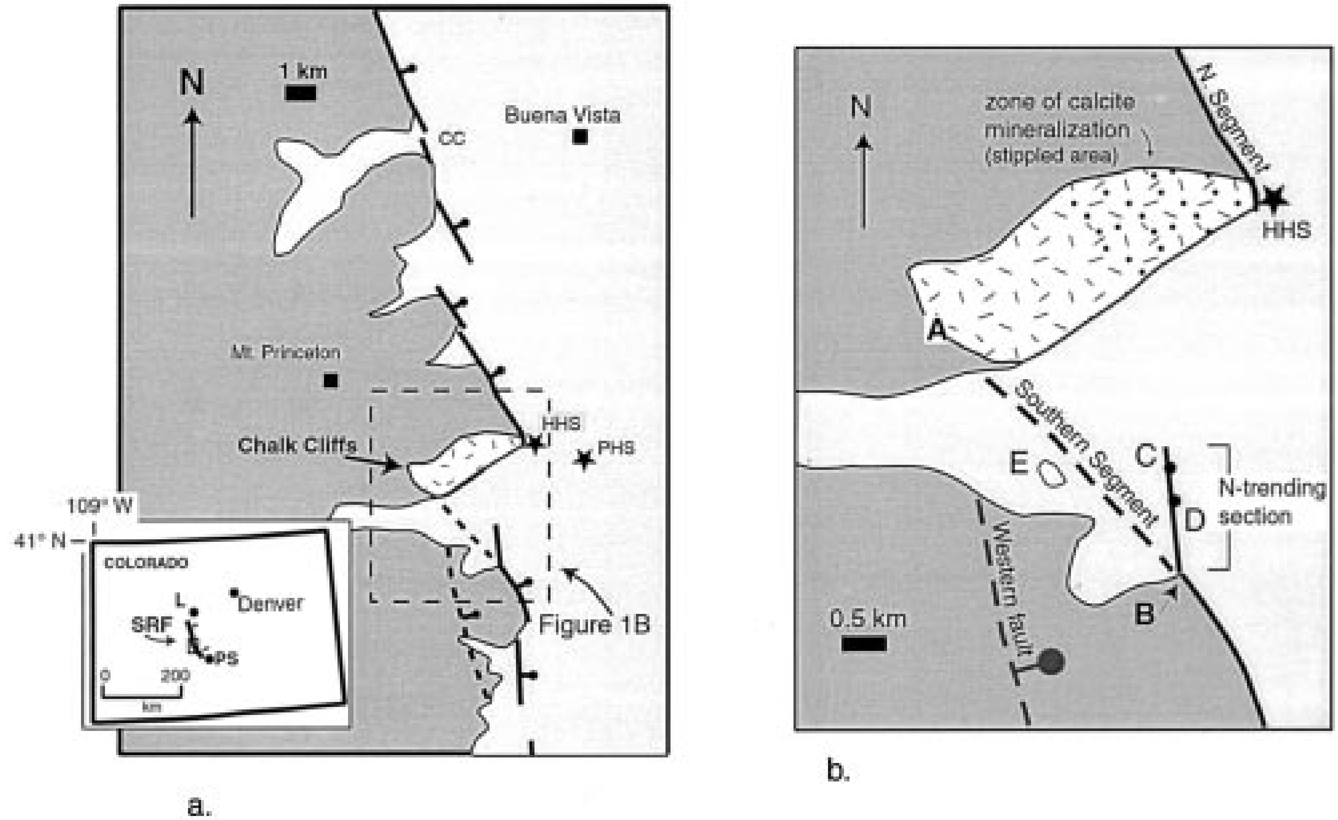

Fig. 1. Maps showing location and geometry of major faults at Chalk Cliffs. Except for Chalk Cliffs area (white), gray background indicates bedrock; off-white indicates Quaternary material. Quaternary breaks exist where fault is mapped through Quaternary. (a) Sawatch Range fault near Chalk Cliffs as it appears on maps by Scott et al. (1975) and Colman et al. (1985). Inset shows location in Colorado. (b) Detailed map of Chalk Cliffs with older extension of the southern segment mapped. On this map, gray 'bedrock' consists entirely of quartz monzonite of Mount Princeton batholith. Letters A–E refer to points in text. Abbreviations for (a) and (b) are as follows. (a) Inset: L, Leadville; PS, Poncha Springs; SRF, Sawatch Range fault. (a) Main figure: CC, Cottonwood Canyon; PHS, Mount Princeton Hot Springs. (b) HHS, Hortense Hot Springs.

Dawers and Anders, 1995). If the breaching fault cuts across the boundary diagonally, the principal fault zone can straighten and simplify its geometry.

The Sawatch Range normal fault, in the northern Rio Grande Rift of Colorado, extends northwards from near Poncha Springs, Colorado for approximately 75 km to the vicinity of Leadville (Colman, 1985; Colman et al., 1985). The southern half of its length is marked by numerous right-stepping, en échelon fault surfaces. Most of the boundaries between these fault surfaces are <1 km wide, but at the Chalk Cliffs, the boundary is approximately 3.5 km wide and exerts an obvious control over the location of the range front (Fig. 1). Additionally, this boundary is the site of at least four distinct episodes of hydrothermal activity.

The Sawatch Range fault appears to be in the process of breaching the boundary at Chalk Cliffs. The early and structurally deeper, soft-linked history of this boundary is recorded by the first two alteration and structural events within the Chalk Cliffs. The later history is reflected by an eastward shift in ongoing hydrothermal activity and Pleistocene–Holocene faulting. Breaching of the boundary is therefore simplifying the local structural geometry, and as a consequence, redu-

Fig. 2. Photograph of the Chalk Cliffs, looking northward. Photograph shows approximately the eastern two thirds of the area. Eastern edge of the Chalk Cliffs are bounded by the northern segment.

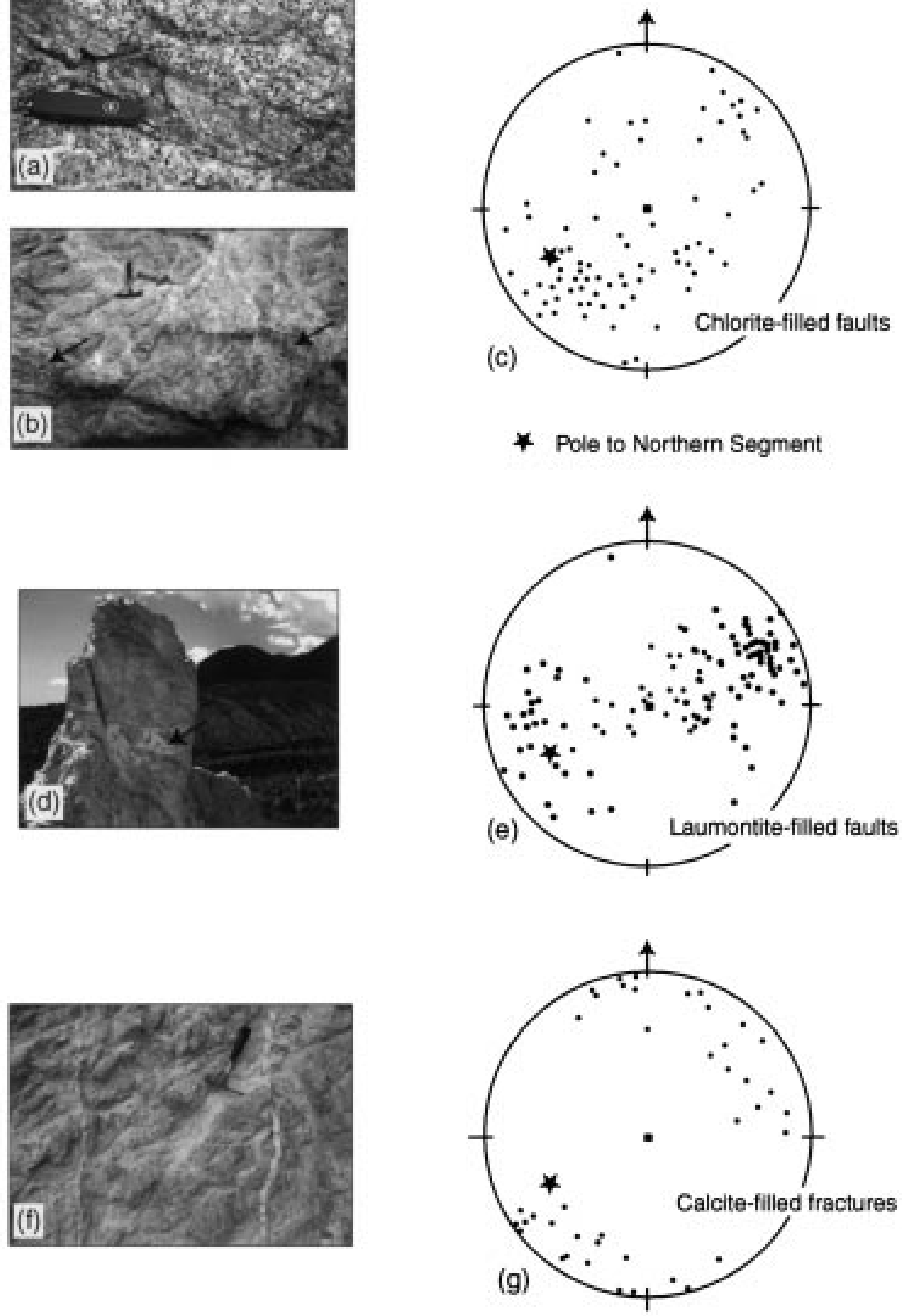

Fig. 3. Photographs and stereographic projections of fault and fracture data. Star in each stereo plot shows pole to the northern segment. (a) Narrow chlorite cataclastic shear zone. (b) Low-angle diffuse zone of chlorite alteration, offset by laumontite-filled fault. Arrows mark top of the chlorite zone on both sides of the fault. (c) Plot of poles to chlorite-filled faults. (d) Low-angle laumontite-filled fault (arrow) offset by high-angle laumontite-filled fault. (e) Plot of poles to laumontite-filled faults. (f) Photograph of near-vertical calcite-filled extension fractures. Inclined fractures in this photograph display laumontite alteration. (g) Plot of poles to calcite-filled extension fractures.

cing the area affected by fault-related hydrothermal activity and fracturing.

2. The Chalk Cliffs and Sawatch Range fault

The Chalk Cliffs form a 250-m-high east-trending erosional scarp along Chalk Creek in the Sawatch Range of Colorado (Figs. 1 and 2). They lie directly behind, and so are in the footwall of, the northern fault segment of the boundary. The Chalk Cliffs consist of quartz monzonite of the Eocene–Oligocene Mount Princeton batholith that has been extensively fractured and hydrothermally altered. Two of the dominant alteration minerals, laumontite, and its partially dehydrated variety, leonhardite, form chalky coatings on many of the faults and fractures (Sharp, 1970). The name 'Chalk Cliffs' probably stems from the white color of the rock and these coatings.

The Sawatch Range fault (Fig. 1), which bounds the range front to the northeast and southwest of the Chalk Cliffs, experienced approximately 3000 m of normal slip since about 23 Ma (Tweto, 1978; Shannon et al., 1987; Kelley, 1991). The fault shows much evidence for recent activity in the vicinity of the Chalk Cliffs and near Cottonwood Canyon to the north, including its coincidence with the break in slope at the range front, and fault scarps in latest Quaternary (Bull Lake and Pinedale) glacial deposits (Scott, 1975; Scott et al., 1975; Kirkham and Rogers, 1981). Moreover, trenching by Ostenaa et al. (1981) near Chalk Creek and at Cottonwood Canyon found evidence for up to five slip events in the last 150–200 ka, including one during the last 3 ka.

3. Faulting and mineralization at the Chalk Cliffs

The Chalk Cliffs display at least three generations of faults and fractures that can be distinguished by their accompanying alteration or mineralization and cross-cutting relations (Miller and Hooper, 1997). As a rule, chlorite-filled faults are cut by laumontite-filled faults, which are cut by calcite-filled faults and fractures. Other common minerals in faults and veins are well-crystallized epidote, which locally accompanies chlorite, and quartz, most prevalent in later structures. These observations contrast with those of Emslie (1991) who interpreted the laumontite alteration as the last event, after formation of the laumontite-filled faults, and after the calcite mineralization.

Each generation of faults and/or fractures displays at least two styles or orientations. The chlorite-filled, first generation structures consist of either narrow (1–30 cm), well-defined zones of foliated cataclasites (Fig. 3a), or broad (50 cm–2 m) diffuse zones of mineralization and local cataclasis (Fig. 3b). On average, these faults strike northwestward, slightly more westerly than the bounding range-front fault, and dip dominantly northeastward (Fig. 3c). Slip directions on these faults are poorly defined but preliminary observations suggest they are dominantly normal.

The second generation, laumontite-filled structures consist of well-defined, steeply northeast- and southwest-dipping faults, numerous wide (25 cm–2 m) gently dipping shear zones and closely spaced, steeply dipping fractures (Fig. 3d). The distinction between the gently and steeply dipping faults, however, is somewhat arbitrary, given their continuous range of dip angles (Fig. 3e). Additionally, these faults show mutually cross-cutting relations to suggest they formed contemporaneously. They typically strike more northerly than the range-frontal fault and show normal separations with both dip-parallel and oblique striations. Near the northeast edge of the Chalk Cliffs, laumontite-filled faults typically dip about 55° northeastward, subparallel to the range-frontal fault, and show normal separations.

The third generation, calcite-filled structures, consist of extension fractures and rare steeply dipping faults which cut across or re-occupy zones of laumontite alteration (Fig. 3f). The extension fractures typically range from about 0.5 to 15 cm in width and locally show fibrous fillings and separations of older features consistent with mode I fracturing. The strikes of these structures, although variable, are generally oblique to, and more westerly than, the range front (Fig. 3g).

The faults, fractures, and associated chlorite and laumontite alteration described above characterize the Chalk Cliffs from Hortense Hot Spring southwestward to location A on Fig. 1(b). Within that region, however, the local intensity of faulting, fracturing and alteration can vary markedly. In several places, it can be described as penetrative when viewed at the outcrop scale, whereas in some localities fault zones and associated fractures are spaced as far as 10 m apart. Calcite mineralization is most intense on the east side, marked by the stippled region on Fig. 1(b), and present only sporadically to the west.

Faulting and alteration at the Chalk Cliffs can be tied to the structural evolution of the Sawatch Range fault. The host rock itself is only about 40 Ma (Shannon et al., 1987) whereas the Sawatch Range fault has been active since about 23 Ma (Tweto, 1978; Shannon et al., 1987; Kelley, 1991). Kelley (1991) found evidence for a local thermal event, which probably drove much of the hydrothermal alteration, between 5 and 15 Ma. Spatially, the alteration at Chalk Cliffs is related to the segment boundary. The chlorite and laumontite alteration occupies the entire boundary whereas the calcite mineralization is generally restricted to the eastern half (Fig. 1b). At the east-

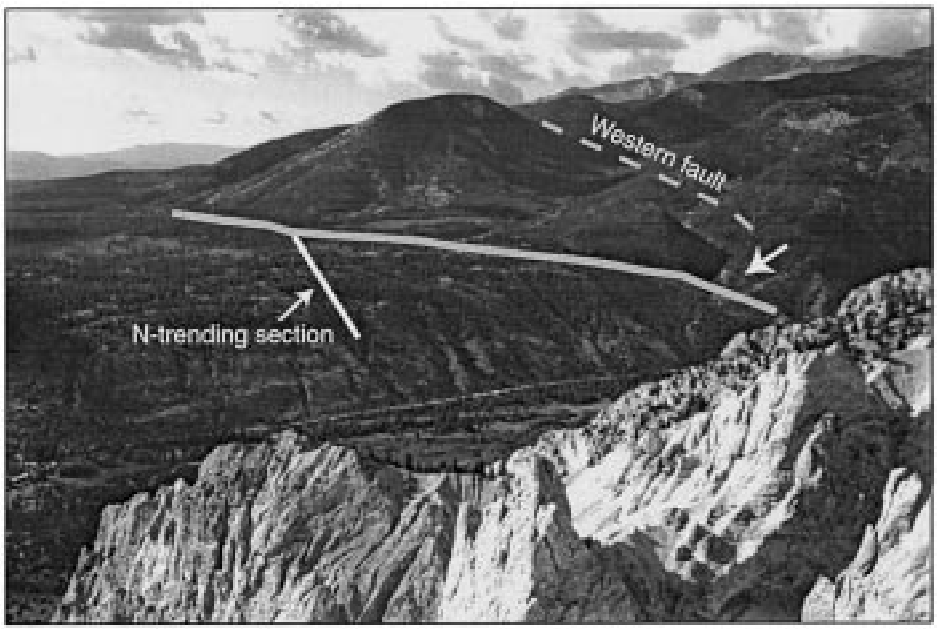

Fig. 4. Photograph of southern segment, north-trending section, and Western fault as described in text. View is towards the southwest, looking over part of the Chalk Cliffs.

ern edge of the Chalk Cliffs, adjacent to the Sawatch Range fault, laumontite-filled faults form surfaces that are subparallel to the fault, suggestive of alteration and minor faulting concurrent with slip on the range front. As calcite fractures cut the laumontite zones, the calcite reflects an even later event on the fault.

4. Geometry and evolution of the segment boundary

Figs. 1 and 4 show the geometry of the segment boundary at Chalk Cliffs. Hereafter, 'southern segment' will refer to that part of the Sawatch Range fault which lies south of Chalk Creek; 'northern segment' will refer to the part of the fault north of Chalk Creek. Scott et al. (1975) and Colman et al. (1985) show that the southern segment turns northward at location B on Fig. 1 and leaves the range front. This north-trending part of the fault will be described as the 'north-trending section'. Additionally, a north-trending fault, labelled 'western fault' on Fig. 1(b), lies within the footwall of the southern segment. The 'western fault' probably predates the southern segment as it shows less topographic expression, lies within the range rather than at its front, and is everywhere buried beneath Quaternary deposits (Scott et al., 1975).

Although not suggested by mapping of Scott et al. (1975) or Colman et al. (1985), some workers interpreted the northern and southern segments as offset by an east-trending fault (Limbach, 1975; Crompton, 1976; Arestad, 1977). That interpretation is not favored here because the cliffs, which owe their structural history to the evolution of the range front, display virtually no minor east-trending strike-slip or normal faults (Fig. 3).

Recent faulting on the north-trending section is confirmed by the presence of fault scarps in late Pleistocene deposits (Scott et al., 1975; 4) and by the trenching studies of Ostenaa et al. (1981) at locations C and D on Fig. 1(b), respectively. Projection of this north-trending section into the Chalk Cliffs defines the modern segment boundary as only about 1 km wide. Significantly, it also shows that much of the alteration and faulting of the Chalk Cliffs extends west beyond the limits of the present-day boundary.

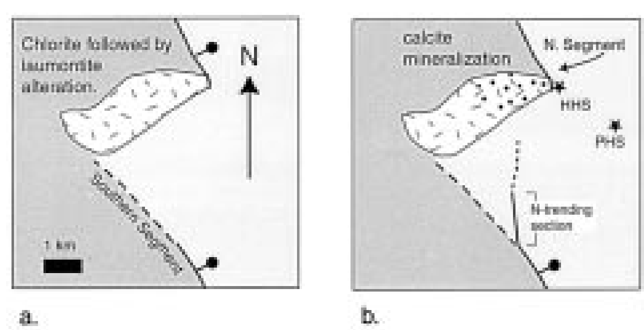

Fig. 5. Proposed sequence of events at Chalk Cliffs. (a) Faulting, accompanied by chlorite and then laumontite alteration, occurs in the soft-linked boundary between southern and northern segments. (b) Formation of the north-trending section begins to breach the boundary. This event coincides in time with the switch to calcite mineralization (stippled area). Locations of present-day hot springs (HHS, Hortense Hot Springs; PHS, Mount Princeton Hot Springs) suggest that since calcite mineralization, activity has shifted even further eastward.

In addition to the north-trending section, the Sawatch Range fault also probably extends beyond location B northwestward to Chalk Creek, along the dashed line of Fig. 1(b). However, this part of the fault appears to be inactive as Scott et al. (1975) mapped unfaulted Quaternary deposits in this area. This geometry maintains a relatively straight fault trace at the base of the abrupt slope break and projects the fault trace into the Chalk Cliffs at location A, the approximate western limit of intense faulting and alteration in the Chalk Cliffs. Further evidence for this extension of the fault comes from the presence of highly faulted and altered quartz monzonite along its trace (Fig. 1b, location E). Moreover, a prominent northwest-trending valley that may be partly fault controlled lies along its projection at the western edge of the Chalk Cliffs (Fig. 1b, location A). However, the fault must terminate in the vicinity of location A because an unfaulted rhyolitic sill crosses the valley north of the Chalk Cliffs (Scott et al., 1975).

Given these observations, I propose that the north-trending section is presently breaching the segment boundary at Chalk Cliffs. Fig. 5 illustrates this process. Initially, faulting and chloritic alteration of the Chalk Cliffs formed in the soft-linked segment boundary between the southern and northern segments of the Sawatch Range fault; at later stages, faulting was accompanied by laumontite alteration (Fig. 5a). The boundary must therefore have persisted over the time period necessary to form both episodes of faulting and alteration. Furthermore, the boundary also controls the range front with approximately 1.5 km of relief. At the slow uplift rates ($\ll$1 mm/y) estimated for this part of the Rio Grande Rift (Colman, 1985), that much relief implies at least several million years of structural control.

Subsequent to laumontite alteration, the northwestern part of the southern segment ceased activity and became replaced by the newly formed north-trending section (Fig. 5b). Later calcite mineralization was focused towards the east side of the boundary, in the area between the north-trending section and the northern segment. Given the wide range of orientations for calcite-filled fractures (Fig. 3g), they probably formed as a consequence of local stresses driven by strain transfer between the two faults, rather than being directly attributable to either fault. Present-day hydrothermal activity now occurs at Hortense Hot Springs and Mount Princeton Hot Springs, both of which lie near the range front by the eastern edge of the boundary.

The presence of the western fault south of Chalk Creek suggests that this evolution might be traced to an even earlier stage. Although presently speculative, if the western fault initially bounded the southern range front, early faulting and chlorite alteration at Chalk Cliffs would reflect strain in the soft-linked boundary between it and the northern segment. Later faulting and laumontite alteration might then reflect the formation of the southern segment. Then, as in Fig. 5, propagation of the north-trending section began the process of breaching and coincided with calcite mineralization.

5. Discussion

Fig. 5 shows how deformation and alteration at Chalk Cliffs may track the evolution and breaching of the soft-linked segment boundary. Given the relative homogeneity of the rock, quartz monzonite, the processes operative during this evolution probably resemble processes active in other soft-linked boundaries. Most significantly, this example at Chalk Cliffs illustrates the interplay between faulting and hydrothermal activity. Additionally, the minor faults, which are well exposed at Chalk Cliffs collectively describe the transfer of strain through the segment boundary.

Fault zone geometry, in active and ancient faults, has long been known to control sites of hydrothermal activity (e.g. Sales, 1914; Guilbert and Park, 1986). The Chalk Cliffs show how simplification of fault geometry, through breaching of segment boundaries, may cause spatial changes in hydrothermal activity. Prior to the breach, minor faulting and hydrothermal activity affected the entire relay zone between the northern and southern segments of the Sawatch Range fault. As the boundary decreased in width through breaching, so did the zone of hydrothermal activity. Calcite mineralization affected only the eastern part of the Chalk Cliffs, and the modern hot spring activity is confined to, or lies east of, the range front.

The association of distinctive mineral associations with different fault types shows that as faulting progressed, the geochemistry of the system changed. The change from chlorite to laumontite mineralization may also reflect a decrease in temperature, as formation of crystalline epidote, which accompanied much of the chlorite, requires temperatures above 250°C (Reyes, 1990; Reed, 1994); laumontite, however, typically forms in the range of about 120–220°C (Coombs et al., 1959). This decrease in temperature could relate to unroofing of the footwall of the northern segment, or more likely, mark the end of the 5–15 Ma thermal event as defined by Kelley (1991).

Although the causes of variations in minor fault geometry and orientation at Chalk Cliffs are not yet defined, suggestions of mixed normal and oblique slip on the laumontite faults implies that the soft-linked boundary experienced extension oblique to the range front. If the chlorite faults are normal or normal-oblique, as might be expected in this setting, then they too suggest extension oblique to the range front. The amount and sense of this obliquity awaits a clearer understanding of the fault kinematics, but given the contrast in strike directions between the chlorite and laumontite faults, their expected obliquities with respect to the range-front fault are opposite, from left-lateral in the chlorite zones to right-lateral in the laumontite faults. During calcite mineralization, presumably after breaching was initiated, the sense of obliquity switched back to left-lateral.

6. Conclusions

Relations between active and inactive strands of the Sawatch Range normal fault at the Chalk Cliffs, Colorado, suggest that the fault is presently breaching a geometric segment boundary. Minor faults and associated hydrothermal alteration within the boundary document its structural evolution. Chlorite alteration accompanied the earliest faults, followed by laumontite alteration along later faults, and finally, calcite mineralization along predominantly extension fractures. As the chlorite and laumontite alteration affect the entire segment boundary, it is likely that they formed prior to breaching, when the Chalk Cliffs provided a soft link between the two bounding range-front faults. Calcite mineralization and present-day hydrothermal activity appear to temporally coincide with the growth of a north-trending breaching fault and affect progressively smaller areas on the east side of the boundary. Therefore, they reflect a narrowing of the boundary zone and overall simplification of the fault system.

In addition to tracking the gross evolution of the boundary, the alteration sequence and minor faults at Chalk Cliffs can fill in details regarding the boundary's history. Specifically, the change from chlorite to laumontite alteration indicates both a change in water chemistry and probable cooling of the zone during the soft-linked stage. The northwest trends of minor normal faults and extensional fractures at Chalk Cliffs indicates that the zone accommodated oblique extension between the bounding faults, and that the sense of this obliquity probably varied through time.

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