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TECTONIC, HYDROTHERMAL AND GEOMORPHIC CONTROLS ON ALTERATION SCAR FORMATION NEAR QUESTA, NEW MEXICO

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Abstract—Alteration scars are iron-oxide and clay-rich areas of badlands topography that form by processes of landsliding, slumpage, rockfall and direct erosion by water. Scars form in regions of high slope angle where the rock has been weakened by hypogene (primary) and supergene (secondary) alteration, and rift-related tectonic events. Low-angle fault zones related to Oligocene extension were preferentially pyritized by meteoric-hydrothermal systems related to subjacent magmatic activity. Late-Miocene to present uplift of the eastern margin of the Rio Grande rift exposed these tectonically weakened, high pyrite zones, resulting in the formation of alteration scars. High slope angles form: (1) in headwater portions of tributary drainages, (2) at a slope break in the cross-canyon profiles caused by later entrenchment of the canyon and (3) along the rift-front escarpment. Mudflows that emanate from the scars pose significant geologic hazards and strongly influence the down-canyon profile of the Red River drainage.

INTRODUCTION

Alteration scars are landforms characterized by steep slopes, a lack of soil, iron oxide staining and clay formation, rapid erosion and common slumping and landsliding. Scars are the most visible geologic features of the Questa–Red River region (Fig. 1) and are significant in that they represent source areas for mudflows that pose a substantial geologic hazard and have significantly altered the topographic form of the Red River drainage. On a less significant scale, runoff from these scars has high concentrations of iron oxides and clay minerals. During times of high precipitation, waters from these scars turn the Red River orange, giving the river its name.

Historically, these scars were thought to have been caused by low-temperature fumerolic alteration related to breccia pipes and/or tectonic breccias formed during the waning stages of volcanic activity (Schilling, 1956; Ishihara, 1967; Clark and Read, 1972). Recent geologic mapping by the authors has led to the re-interpretation of these scars as resulting from landsliding, and other erosional processes that are enhanced in regions where the rock has been weakened by faulting and supergene (secondary) weathering of pyrite. This paper discusses our current understanding of the geologic controls on development of the alteration scars and considers the effects of these alteration scars on their local environment.



FIGURE 1. Photograph of the Red River drainage looking ENE, showing the moly mine shafts (lower left), Cottonwood Park area (lower middle), open pit mine dumps (fore- to middleground) and alteration scars on the northern canyon wall (middle- to background). Mid-slope break in the cross-canyon profile, at about the elevation of the lower trend of scars, is interpreted to result from Pliocene to Quaternary renewed tectonic uplift of the Sangre de Cristo range. Meadow at bottom of photo is caused by the Goat Hill Gulch debris apron, immediately downstream.

GEOLOGIC SETTING

The Questa–Red River area is in the late-Oligocene Latir volcanic field, in the southern portion of the Questa caldera (Fig. 2). Latir field volcanism was synchronous with early Rio Grande rift extension, characterized by high extensional strain in local regions as at Questa (Lipman, 1981, 1988; Morgan et al., 1986; Meyer, 1988). Early rift extension was followed by the late Miocene to present modern rift system, characterized by lesser extensional strain and development of the modern rift basin and rift flanking uplifts (Chapin, 1979; Tweto, 1979; Lipman and Mehnert, 1979).

The region contains a Proterozoic basement of meta-igneous and meta-sedimentary rocks overlain by early-Tertiary sediments and finally by the late-Oligocene Latir volcanic field (Lipman, 1983, 1988). The Latir volcanic field is largely intermediate in composition and covers a 1200 km^2 area in north-central New Mexico. Latir field volcanism culminated in the formation of the Questa caldera, a 14-km-diameter caldera that was the source of >500 km^3 of Amalia Tuff (Fig. 3) (Lipman, 1983, 1984, 1988; Lipman et al., 1986; Lipman and Reed, 1989; Johnson et al., 1989). The southern structural boundary of the

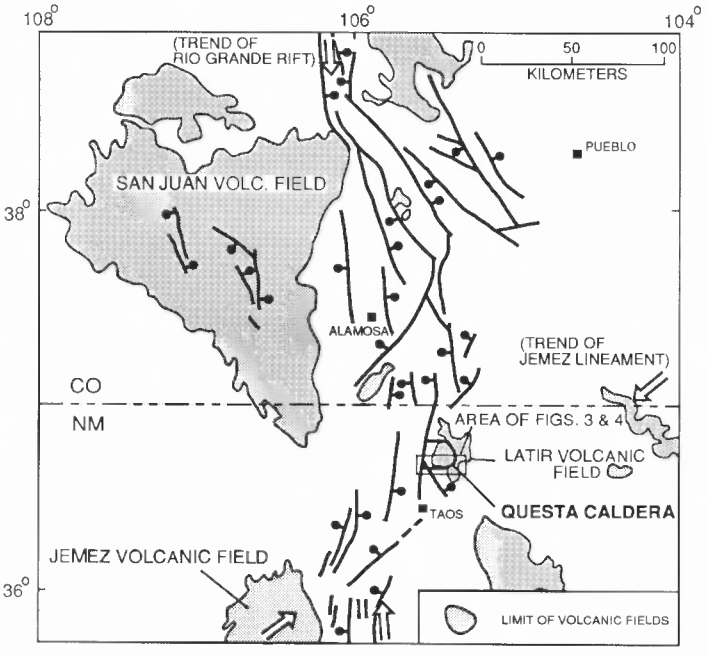


FIGURE 2. Regional location map of the Latir volcanic field and the Questa caldera.

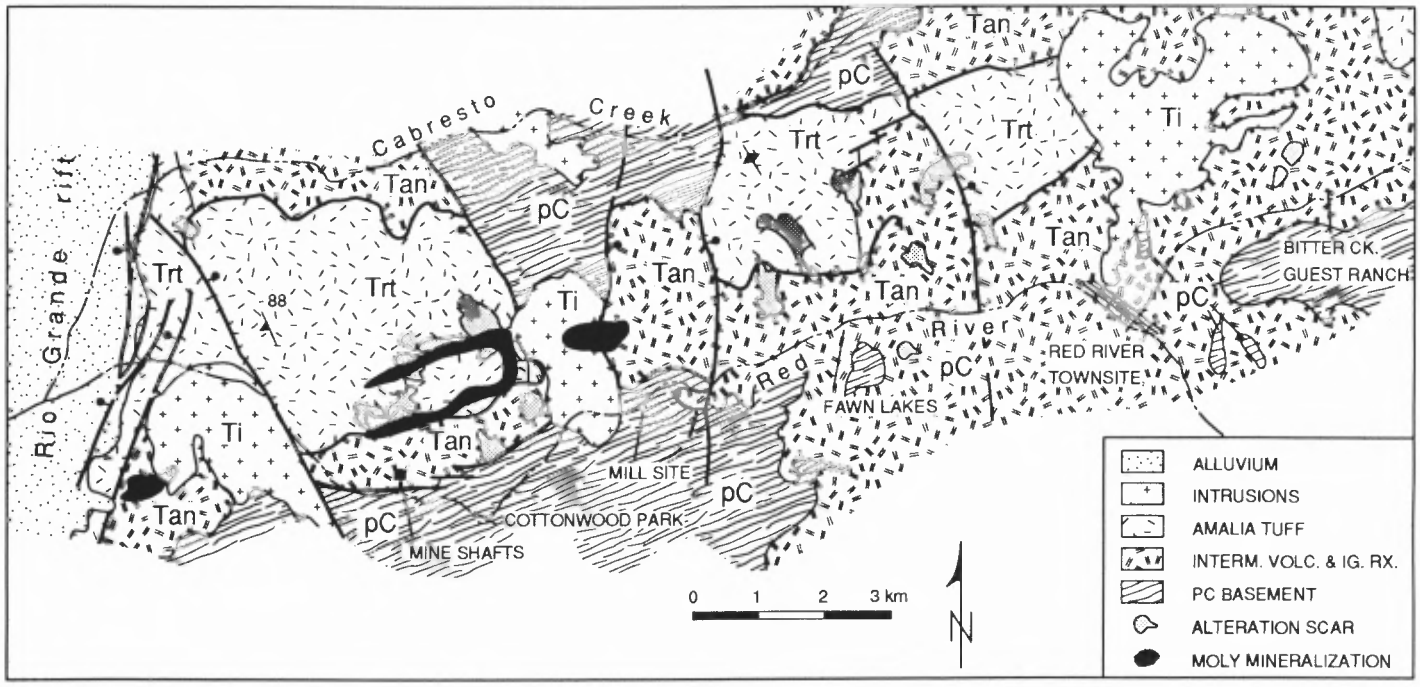


FIGURE 3. Generalized geologic map of the southern caldera area.

caldera approximately corresponds to the course of the Red River between Red River townsite and the rift front near Questa (Fig. 2).

Early rift extension accelerated immediately following caldera collapse, resulting in the 90° westward tilting of the entire southern caldera region (Fig. 3). Tilting is believed to have been accomplished by domino-style rotation of normal faults to low angles and westward tilting of the intervening stratigraphy (e.g., Proffett, 1977; Chamberlin, 1983). Low-angle fault zones are pervasive throughout the Questa–Red River region and served as conduits for intrusions, molybdenum mineralization, pyritization, and as zones of weakness for later landsliding and scar formation.

Plutons were intruded along the southern caldera margin immediately following the period of accelerated extensional faulting (Hagstrum and Lipman, 1986). These plutons are responsible for molybdenum mineralization and hydrothermal alteration in the district (Leonardson et al., 1983). Meteoric-hydrothermal systems related to these intrusions deposited pyrite in regions made permeable by early rift-related low-angle faults. High pyrite zones (>3% pyrite) were favored sites for later landslide activity and scar development.

Late Miocene to present rifting uplifted the Sangre de Cristo Mountains along high-angle normal faults at the eastern margin of the modern rift basin (Fig. 3). Uplift and erosion exposed the Latir volcanic system to deep caldera/upper batholith crustal levels (Lipman, 1984) and exposed hydrothermally altered and tectonically sheared zones that subsequently developed into the alteration scars. Erosion increased during the Pliocene(?) due to local acceleration of range-front faulting combined with dissection along the Rio Grande system and climatic change (Menges, 1987, 1988). Increased uplift resulted in facet benches along the Rio Grande rift-front and a "valley-in-valley" cross-canyon profile to the Red River and Cabresto Creek drainages (Menges, 1988; Kelsey, 1988).

ALTERATION SCARS

Alteration scars at Questa are areas of badlands topography (Fig. 1) where a dominance of mass transport processes inhibit soil development. There are approximately 20 alteration scars at Questa (Fig. 4) ranging in size from <0.1 km^2 to approximately 0.5 km^2. The scars are aligned along two parallel trends (Fig. 4). The northern trend lies along the southern side of the Cabresto–Red River divide, and contains generally larger scars (scars #3, 7, 8 and 9 of Fig. 4 and Table 1). The southern trend lies approximately midway between the northern trend of scars and the Red River drainage (scars #4, 5, 6, 10 and 11 of Fig. 4 and Table 1). The only scars not falling in or between these two trends are June Bug scar, south of the Red River drainage, and Questa scar, at the eastern margin of the Rio Grande rift valley (Fig. 4).

The alteration scars occur in densely welded intracaldera tuff (10%), intracaldera megabreccia facies of the tuff (30%), caldera floor andesite (15%), quartz latite intrusions (40%) and in the sub-volcanic batholith (5%) (Fig. 3). Alteration scars commonly occur in low-angle fault zones, which are related to early-rift tilting of the volcanic sequence.

Secondary earth materials in the alteration scars include colluvium and ferricrete. Colluvium forms by rockfalls from over-steepened portions of the scar margins and interior (Fig. 5). Ferricrete is an iron oxide and silica-cemented rock that forms in regions of seepage from shallow-source waters that recharge from higher portions of the scar. These waters become silica saturated through evaporation, resulting in deposition of an iron-rich silica cement. Highly permeable colluvial deposits are commonly cemented during this process and form striking ferricrete breccias.

Alteration scars are characterized by supergene alteration of rocks with high (usually >3%) original pyrite content. Primary high-pyrite

TABLE 1. Features of major alteration scars of the Questa–Red River region.

number	name of scar	high pyrite? (>3%)	low angle faulting?	direction of slope	comments
1	Questa	N	Y	W	39 degree slope
2	Goat Hill Gulch	Y	Y	S	
3	Pit	Y	Y	S	largely mined out
4	SE Truck Shop	Y?	Y?	S	covered by dumps
5	S Truck Shop	Y?	Y?	S	covered by dumps
6	SW Hansen	Y	Y	S	
7	Hansen	Y	N	S	
8	Straight Creek	Y	Y	S	
9	Hottentot	Y	Y	S	
10	SE Straight Ck.	Y	Y	S	
11	SE Hottentot	Y	Y	S	
12	June Bug	Y	Y	N	39 degree slope
13	Mallette	Y?	Y	S	
14	Lower Bitter Ck.	Y	?	S	
15	Bitter Creek	Y	?	S	

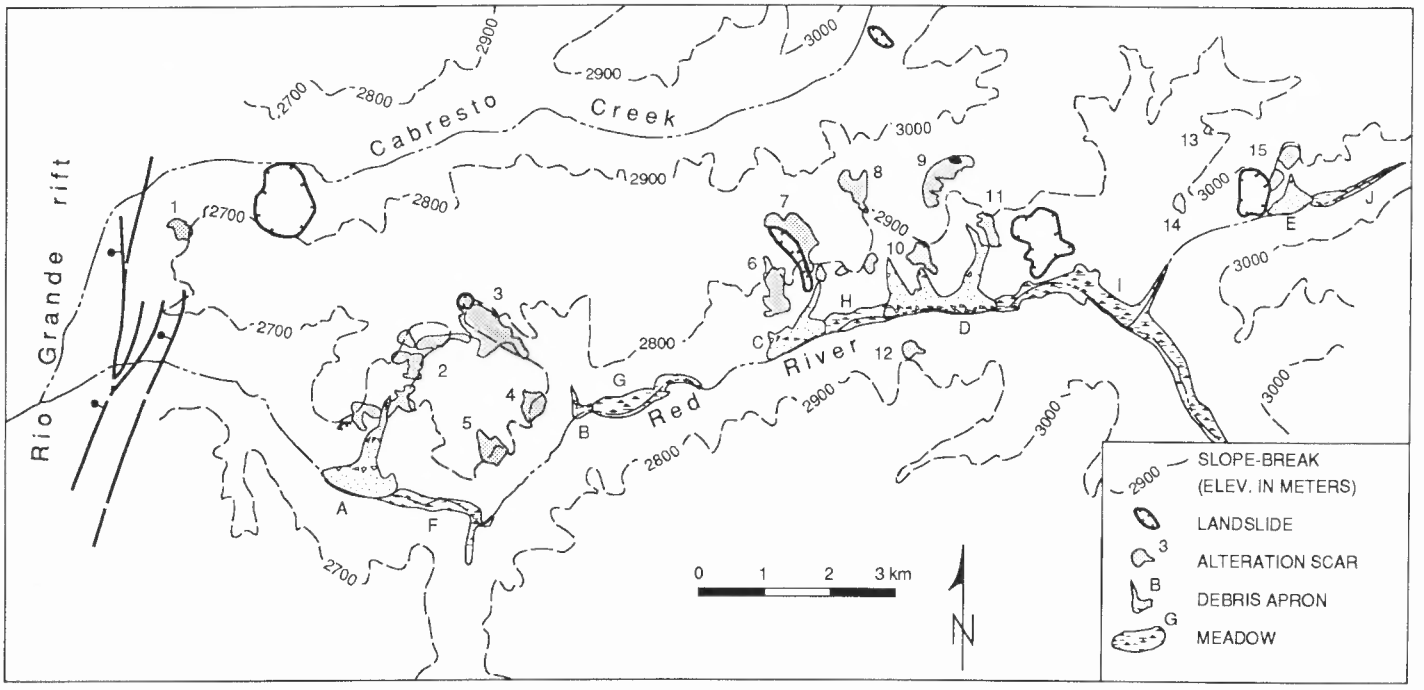


FIGURE 4. Location map of landslides, scars, debris aprons and associated meadowlands in the Questa–Red River region. Approximate slope-break in the cross-canyon profile (Figs. 1 and 6) is shown with a dashed line. A = Goat Hill Gulch debris apron, B = Sulfur Gulch debris apron, C = Hansen scar debris apron, D = Hottentot/Straight Creek debris apron, E = Bitter Creek debris apron, F = Cottonwood Park meadowland, G = Moly mill meadowland, H = Fawn Lakes meadowland, I = Red River town site, J = Bitter Creek Guest Ranch meadowland. Names of major scars are located in Table 1.

mineral assemblages include quartz-sericite-pyrite, pyrite-kaolinite and pyrite-chlorite-epidote-calcite. Supergene alteration of these rocks produces abundant iron oxides, silicification, gypsum and clay minerals including illite, montmorillonite, kaolinite and probable supergene sericite. Supergene montmorillonite is much more abundant in scars with intermediate composition host rocks as a consequence of increased availability of Ca, Fe and Mg cations (S. Conlon, unpubl. report, 1983).

The above mineralogy is interpreted to result from supergene reaction of cold-oxygenated surface waters with a pyrite-bearing host. Earlier ideas relating scar alteration to late-volcanic stage, fumarolic activity (Ishihara, 1967) are discounted by the lack of alteration in drill holes below about 150 m depth and the lack of minerals typically associated with vapor phase transport.

Controls on scar formation

A number of geologic factors control development of alteration scars at Questa. In order of decreasing significance, the major controls are slope angle, tectonic fracturing, pyrite content and vegetative cover.



FIGURE 5. Photograph of colluvium in a scar in Goat Hill Gulch.

A slope angle in excess of 25° is a primary requirement for generation of all alteration scars in the region. Slope angles less than 20° do not contain the driving force required for the initiation of mass-wasting processes. High slope angles in the Questa area are located in three settings: (1) along the topographic divide between Red River and Cabresto Creek drainages, (2) at the slope break between the inner and outer valleys of the Red River canyon and (3) along the fault escarpment of the Rio Grande rift front.

High slope angles along the Red River–Cabresto Creek divide are interpreted to result from steepening of individual drainages as their headwater regions are approached (Fig. 6B). Steep gradients in headwater portions of drainages are a part of the typical concave-upward profile of graded streams (Easterbrook, 1969). The relatively large size of the "divide" scars suggests that these scars may be older than other scars of the district, possibly predating Pliocene uplift and "valley-in-valley" profile development. "Divide" scars form the northern belt of alteration scars at Questa (Fig. 4).

High slope angles occur at the junction between a gentler outer valley and a steeper, incised inner valley that formed during an accelerated period of uplift of the rift-related range (Figs. 4 and 6C) (Menges, 1987, 1988). At this slope break, the steeper inner valley is attempting to widen and become gentler at the expense of the outer valley, and landslide potential is at a maximum (Kelsey, 1988). "Slope-break" scars are numerous and relatively small and form the southern belt of alteration scars at Questa (Fig. 4).

High slope angles along the eastern margin of the Rio Grande rift occur as escarpments to rift-bounding normal faults. Tectonic oversteepening along the fault plane of high-angle normal faults is responsible for the westernmost scar in the district (Fig. 4) and resulted in a probable landslide block south of Red River that offsets a molybdenum mineralized zone. Gravity sliding of this block into the rift resulted in preservation of the mineralized zone, which otherwise would have been eroded had it remained exposed on the rift escarpment.

Tectonic fracturing is a second critical factor in development of alteration scars at Questa. Extreme fracturing and shearing is closely associated with the low-angle fault zones prevalent throughout the Questa–Red River region. As much as 90% of the scars occur along these fault

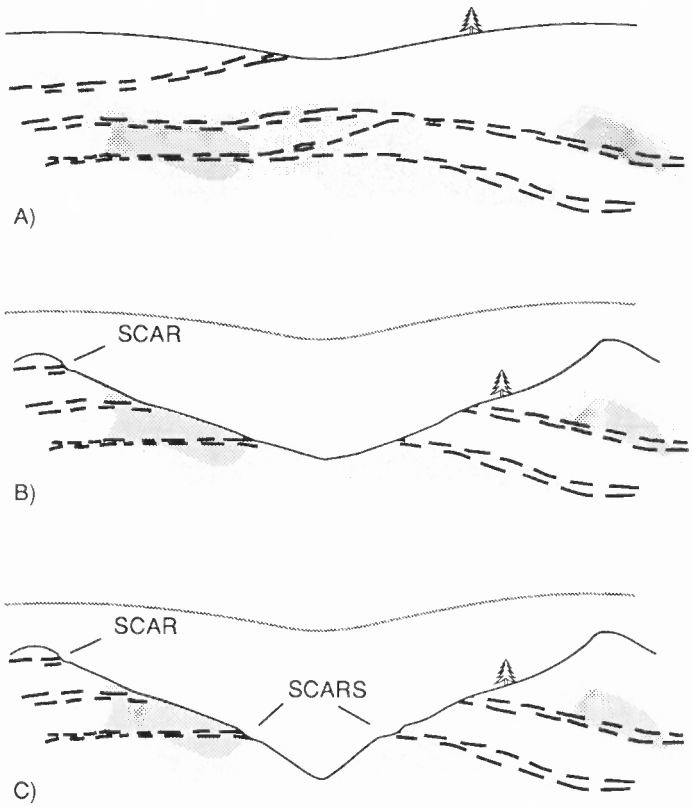


FIGURE 6. Schematic cross-sectional development of the alteration scars. A, Postcaldera low-angle faulting and subsequent pyritization (stipling). B, Erosion and scar formation in faulted and pyritized regions near the Cabresto–Red River divide (ridge on left). C, Pliocene to recent incision and scar development in faulted and pyritized regions near the slope-break in between the inner and outer canyons.

zones, which locally are up to 300 m thick (Figs. 6 and 7, and Table 1). Tectonic fracturing increases permeability, promoting pyrite deposition, and weakens the rock, enhancing the later mass-wasting process (Fig. 6). Scars that do not exhibit low-angle faulting are fractured by either sympathetic low-angle fractures, or high-angle fractures and faults.

High pyrite content is another important factor in the formation of scars at Questa. Pyrite contents of 3–5% are common in scar areas, whereas pyrite contents near 1% are typical throughout most of the region (Table 1). Pyrite weathers in the near surface environment to form iron oxides and sulfates. Acidic water generated from oxidation of pyrite reacts with feldspar minerals in the rock to form clay minerals, which have very low shear strength when saturated with water.

Only the Questa scar, located on the eastern fault escarpment of the Rio Grande rift (Fig. 4), has near background levels of pyrite. This scar has an unusually high slope angle (Table 1), suggesting a probable inverse relationship between pyrite content and slope angle needed for mass transport processes and scar development.

Vegetative cover may be another important factor in scar formation at Questa. A high proportion of scars at Questa are on south-facing slopes, which have a lower density of forest cover than north-facing slopes. The only scar that is on a north-facing slope is the June Bug scar (Fig. 4, Table 1), and it has a higher slope angle than scars on south-facing slopes. A higher slope angle may be necessary to overcome the stabilizing effects of increased vegetation, suggesting a direct relationship between vegetative cover (or degree of north facing) and slope angle required for development of a scar.

Stages of scar development

As erosion progresses through regions that are structurally and mineralogically favorable for scar development, the resultant scars pass through stages of initiation, growth and eventual decay as stable slope angles are obtained and revegetation occurs (Fig. 8). Scars are believed to be initially exposed by landsliding in regions that are oversteepened by headward erosion of drainages (Fig. 8A). Initial landslides will only turn into scars in regions that have sufficient tectonic shattering and/or pyrite content for mass-wasting processes to continue. Regions of initial landsliding that do not have sufficient tectonic fracturing and/or pyrite content for mass-transport processes to continue, regain their slope stability and become revegetated (e.g., landslide areas not associated with scars on Fig. 4).

Initially formed scars grow by processes of landsliding at their margins, and by landsliding, slumpage and erosion of their interiors (Fig. 8B). Growth of scars by landsliding occurs at a high proportion of scars at Questa (Fig. 4). Erosion of scar interiors occurs at a very rapid rate, as drill roads in scars that are 20–25 years old are locally dissected by as much as 10–15 m. Other processes of scar growth include rockfall along escarpments and local down-slope creep of saturated ground.

As the scar grows, some portions of the scar begin to reach stable slope angles. At this time (Fig. 8C) some areas of the scar may be enlarging, while other portions of the scar have reached stable slope angles and are beginning to revegetate.

Finally, slope stability is obtained either by erosion down to stable slope angles or by erosion through all available incompetent ground. At this stage, isolated outcrops of more resistant rock may remain in a region that has otherwise reached slope stability (Fig. 8D). The only indication that a scar ever existed in this region may be the existence of extreme clay, silica and iron oxide alteration and possible ferricrete formation in intervening outcrops.

Down-slope effect of alteration scars

A large number of small-scale landslides and slumps form during periods of heavy precipitation under conditions of water saturation. Saturation results from spring snow melt combined with spring rains or, more commonly, from numerous consecutive days of summer rains. The effect of water saturation is to: (1) break down the gypsum cement that often fills fractures and forms a hardpan coating when the surface is dry, (2) cause expansion and weakening of the supergene clay component of the rock, (3) add extra weight to oversteepened regions and (4) increase pore pressure, which decreases the shear strength of the slope.

The water-saturated landslides and slumps mix with sediment-laden surface runoff from other parts of the alteration scars to form active mudflows. The mudflows run down-slope until they deposit their detritus in debris aprons located at the junctions of side streams with the Red River (Fig. 4). A number of Forest Service campgrounds west of the Red River townsite are located in the lower portions of debris aprons in particularly hazardous locations. Mudflows often wash across State Highway 38, resulting in temporary closures. In 1982, mudflows from the Hansen scar area resulted in a fatality to a motorist.

The debris aprons consist of interbedded mixtures of alluvial and mudflow deposits. The buildup of these debris aprons impedes the flow of the Red River and pushes the stream channel to the southern side of the canyon (Fig. 4). Upstream of the aprons, the river becomes stagnant and meadowlands form, such as those located at the Red River town site, Fawn Lakes, the moly mill site, immediately downstream from Cottonwood Park and in the Bitter Creek drainage at the Bitter Creek Guest Ranch (Figs. 1, 3, 4 and 9).

The effect of the debris aprons on the Red River can clearly be seen on a profile of the drainage (Fig. 9). Gradients in debris-apron regions are in excess of 0.028, whereas gradients in regions between debris aprons are generally lower (Fig. 9). Areas immediately upstream from debris apron blockages have the lowest gradients and typically contain upward-steepening profiles as the next upstream debris apron is approached (Fig. 9).

CONCLUSIONS

Alteration scars at Questa form by mass wasting and erosional processes in regions of low shear strength and high slope angles. Low

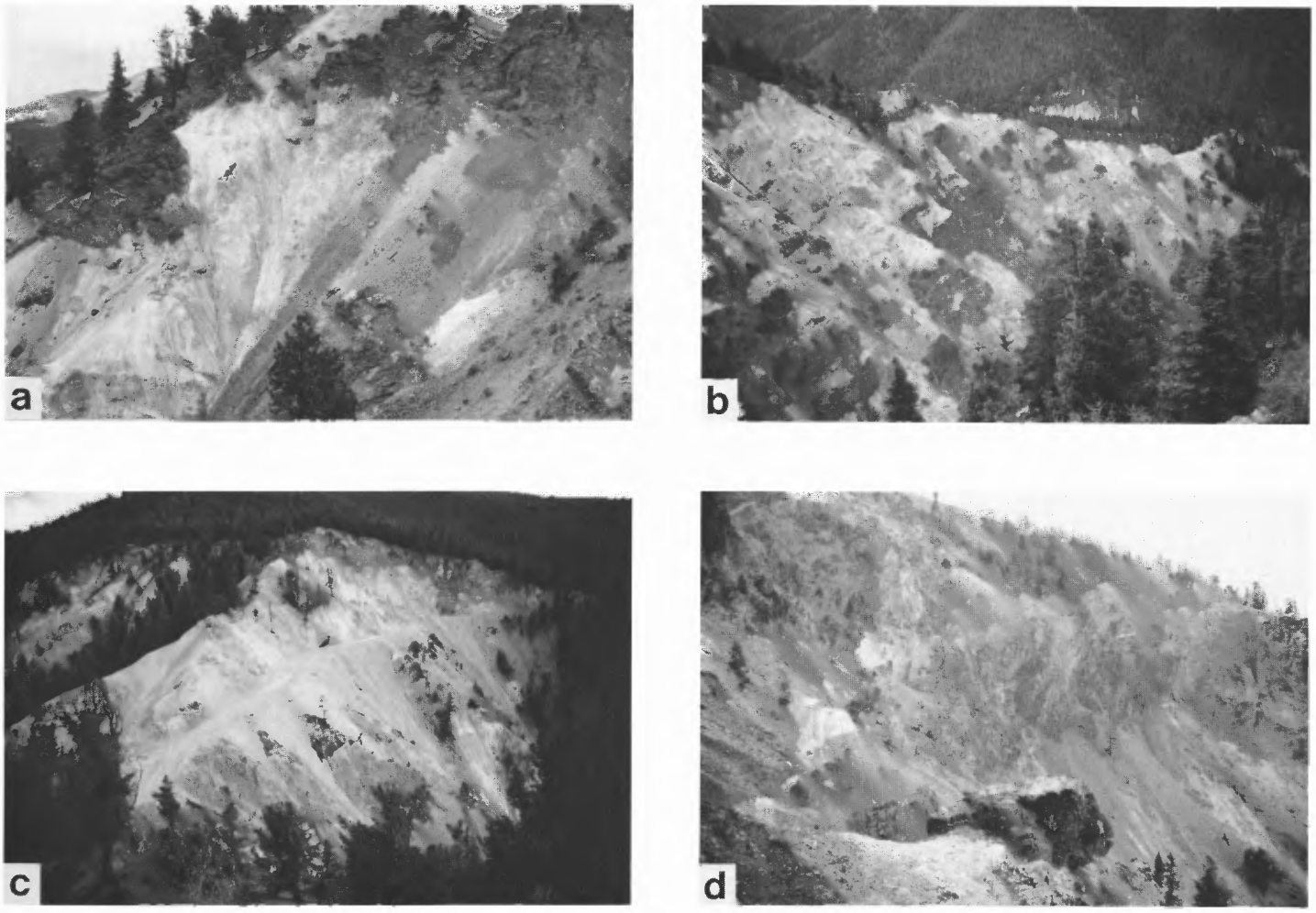


FIGURE 7. Low-angle faulting and fracturing in scars of the Questa–Red River region. A, Questa scar looking NE. B, SW Hansen scar looking E. C, Straight Creek scar looking SW. D, Hottentot scar looking E.

shear strength results from late Oligocene magmatic, tectonic and hydrothermal activity and supergene weathering. High slope angles are caused by the late Tertiary development of the Rio Grande rift zone. The scars are not fumarolic, as the clay and iron oxide mineralogy results from supergene reaction of oxygenated surface waters with pyrite-bearing host rocks.

The scars occur in two ENE-trending belts where high slope angles formed in regions of low shear strength. The northernmost belt is located near the Cabresto–Red River divide in oversteepened headwater regions of tributary drainages to the Red River. The southernmost belt is located at a slope break in the cross-canyon profile of the Red River valley, where a locally oversteepened inner valley is widening at the expense of the gentler outer valley.

Major controls that favor scar formation include steep slope angle, strong tectonic shearing, high pyrite content and low vegetative cover. Significant mass-wasting processes include landsliding, slumping and

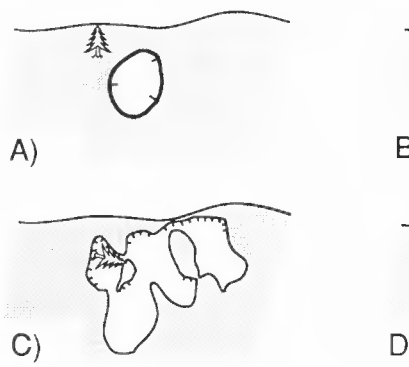


FIGURE 8. Plan-view schematic of the evolutionary stages of a scar through time. A, Initiation by landsliding. B, Growth by landsliding and other mass transport and erosive processes. C, Growth in some areas, stable slope development and revegetation in other areas. D, Complete slope stability and revegetation.

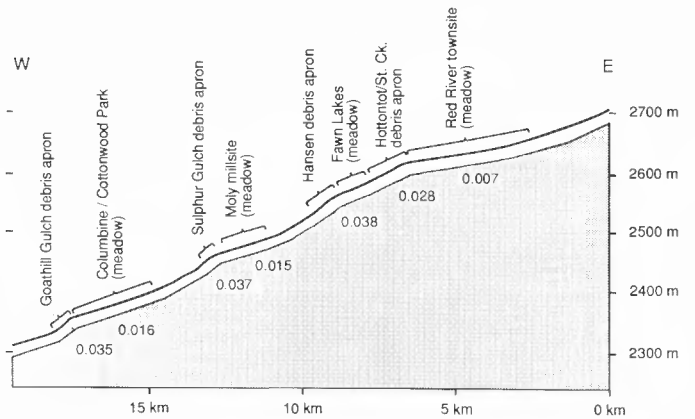


FIGURE 9. Down-stream profile of the Red River drainage demonstrating the strong influence of debris aprons on gradients immediately upstream.

rockfall. Direct erosion of scar interiors by rainwater and snowmelt occurs at very rapid rates.

The scars pose a hazard to the region as a significant number of roads, buildings and campsites are located on debris aprons deposited by mudflows that originated from the scars. The debris aprons cause stagnation of flow in the Red River drainage and the formation of upstream meadows. It is an interesting contrast that these fertile, serene meadowlands owe their existence to the sterile, hazardous scars.

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