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RAPID COMMUNICATION

Fault-fin landscape

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Abstract

The expression 'fault-fin landscape' is proposed for topography marked by sets of blade-like fins and walls of rock, controlled by deformation band shear zones, which project metres above upland surfaces of porous sandstone. Dramatic examples occur along monoclines of Navajo Sandstone in the Colorado Plateau region of southern Utah, USA. The fins express differential rates of erosion of porous (20–25 %) host sandstone relative to deformation band shear zones (<1 % to 5 % porosity), which are made highly resistant by collapse of porosity, cataclasis of quartz grains, and silica precipitation.

1. Character and control of fault-fin landscape

In the Colorado Plateau region of southern Utah, there are upland bedrock surfaces of Navajo Sandstone that display a bizarre topography which I call 'fault-fin landscape' (Fig. 1). The most dramatic of these landscapes occur in Navajo Sandstone in the Cottonwood Canyon area along the East Kaibab monocline and in the Sheets Gulch area along the Waterpocket fold (Fig. 2). Individual fins (including blades and walls) of resistant rock project upward as high as 12 m from the ground surface and extend tens to hundreds of metres in trace lengths (Figs 3 and 4). The fins occur by the dozens. Fin-like outcrops commonly occur as aligned elements that project upwards from a common structural trace. The co-linear fin alignments themselves, when viewed collectively, are arranged in sets and systems of preferred orientation, creating landscapes that resemble those due to the presence of swarms of resistant dykes.

Deformation band shear zones of tectonic origin control the fault-fin landscape. Development of deformation bands and zones of deformation bands is the preferred deformation mechanism in highly porous granular materials, including clean, well sorted, porous sandstones (Aydin, 1978; Aydin & Johnson, 1978; W. R. Jamison, unpub. Ph.D. thesis, Texas A & M University, 1979; Jamison & Stearns, 1982; Antonellini, Aydin & Pollard, 1994). Deformation bands and zones of deformation bands are tabular semi-brittle shear zones of cataclastic deformation that have accommodated faulting and strain of the porous sandstone host in which they occur. Well developed deformation band shear zones of tectonic origin in the Colorado Plateau always occur in close proximity to major discrete regional structures (Davis, 1995, 1996). The formation of such major structures is accompanied and, in part, accommodated by pervasive development of deformation band shear zones in porous sandstone lithologies.

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The structural origin of deformation bands and zones of deformation bands is described in detail by Aydin & Johnson (1978) and Antonellini, Aydin & Pollard (1994). The progressive development of millimetre-thick deformation bands of tectonic origin starts with collapse of pore space, proceeds with cataclastic reduction of quartz grains, and ends with a strain-hardening 'lock-up' after achieving a shear strain of up to 10 or so. Lock-up is followed normally by the initiation of a new deformation band alongside the first. In this way, zones of deformation bands are constructed, sometimes to thicknesses of metres. There may or may not be a loss of cohesion between the edge of a deformation band shear zone and the wall rock, although where displacement is on the order of metres there is usually evidence for fault-slip along the outer walls of the deformation band shear zone. Fault offset can be normal, thrust, strike-slip, and oblique.

Antonellini & Aydin (1994) have demonstrated that cataclastic deformation bands are marked by porosities that are approximately one order of magnitude less than that of the host rock, and permeabilities that are approximately three orders of magnitude less. For example, host rock porosities of 20 % to 25 % in the Navajo Sandstone are reduced to values of <1 % to 5 % within deformation bands (Antonellini & Aydin, 1994). Permeabilities in Navajo Sandstone host rock may range from 1000 md to 5000 md, whereas permeabilities measured perpendicular to cataclastic deformation bands in Navajo Sandstone may typically range from approximately 2 md to 20 md (Antonellini & Aydin, 1994). Reprecipitated silica, perhaps in part derived from pressure dissolution, tends to increase the cohesion of the zones. The toughness of deformation band shear zones, in contrast with host sandstone, sets the stage for the differential weathering and erosion that sculpts fault-fin landscape.

2. A closer look at outcrop expression

Individual fins project upward dramatically from the land surface, or more rarely, *outward* from canyon walls. In cross-sectional profile view the fins most commonly are triangular (see Aydin, 1978), with apical angles of approximately 50–55° (Fig. 5). The two flanks of the fins, which together define the triangular cross-sectional forms, are asymmetrical in their physical make up. One flank is simply shaped by weathering and erosion of unsheared sandstone host rock, complete with primary sedimentary structure such as bedding and cross-bedding. The other flank, which may often project higher above the opposite side as a thin blade, is the erosional remnant of the deformation band shear zone itself, composed of cataclastic fault rock, devoid, or nearly so, of any expression of the primary stratification of the sandstone. Tall thin blades sometimes bend

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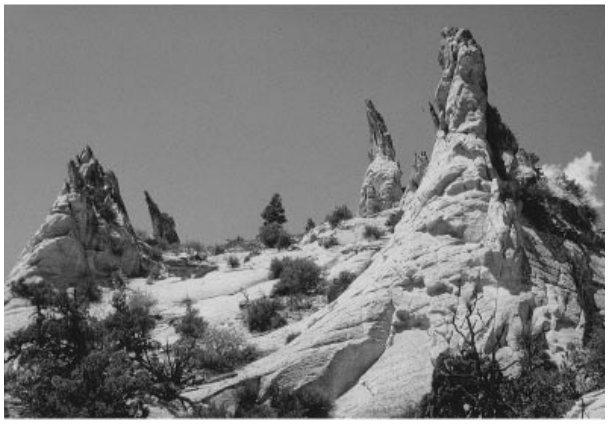


Figure 1. Fault-fin landscape in Navajo Sandstone along the East Kaibab monocline in the Cottonwood Canyon area of southern Utah. The fins are controlled by deformation band shear zones. Access to this locality from Kodachrome Basin State Park (see Fig. 2) is achieved by driving south along the Cottonwood Road, parking at the cattle guard (location Latitude 37 ° 26 ’ 48 ”, Longitude 111 ° 50 ’ 53 ”), and then hiking southwest into Cottonwood Canyon. Even from the road the fins are visible in the distance.

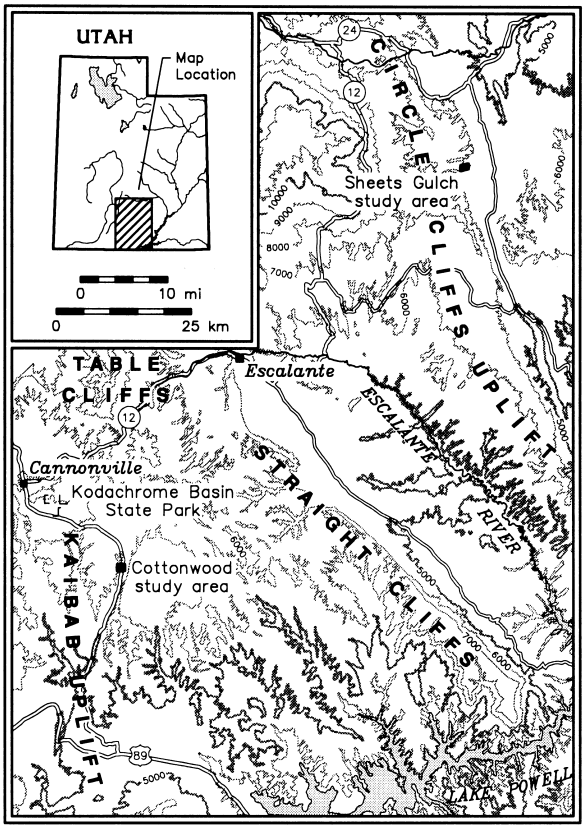


Figure 2. Map showing the locations of the Cottonwood Canyon area along the East Kaibab monocline, and the Sheets Gulch area along the Waterpocket fold.

or sag under their own weight. The surface of the deformation band shear zone tends to be smooth, not uncommonly stained by manganese, and splotched with lichen growth. Furthermore, the outer surface of the deformation band shear zone may be conspicuously slickensided and slickenlined. Viewed longitudinally in strike section, fault fins are crudely arcuate to triangular, with heights approximately the same or less than strike lengths. Tops of the arcuate fins may have a scalloped appearance, and not uncommonly they may be marked by windows where erosion has breached the thinnest parts of the fins.

In close-up cross-sectional view, the interior of a fault fin is marked commonly by a geometrically coherent network of thin (centimetre-scale) deformation band shear zone members that typically intersect at angles of approximately 50–55° (Fig. 6). If the deformation band shear zone is reverse-slip in nature, then the interior deformation bands subparallel to the overall orientation of the outer walls of the deformation band shear zone will also be reverse-slip (i.e. ‘synthetic’), whereas those interior deformation bands that are oblique will be normal-slip (i.e. ‘antithetic’). Where the host sandstone between the thin, closely spaced deformation band shear zones is weathered out by the effects of wind and water, the resulting structure is a honeycomb or boxwork form (see Fig. 6).

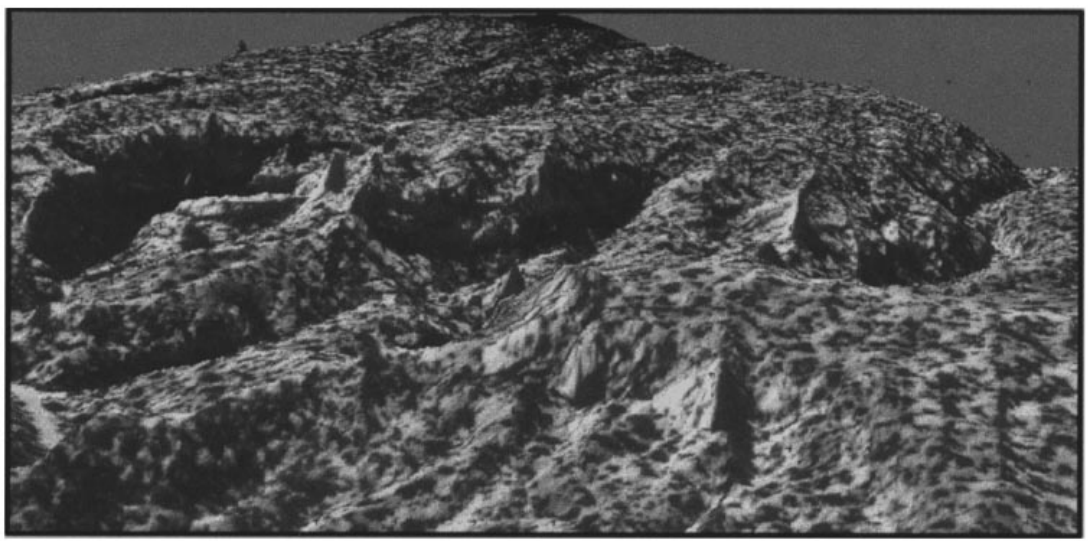


Figure 3. ‘Virtual’ image of deformation band shear zones and fault fins in the Cottonwood Canyon area along the East Kaibab monocline. Image created and provided by the Geology Division of Chevron Technology Company. View is to the southwest. Field of view is approximately 500 m.

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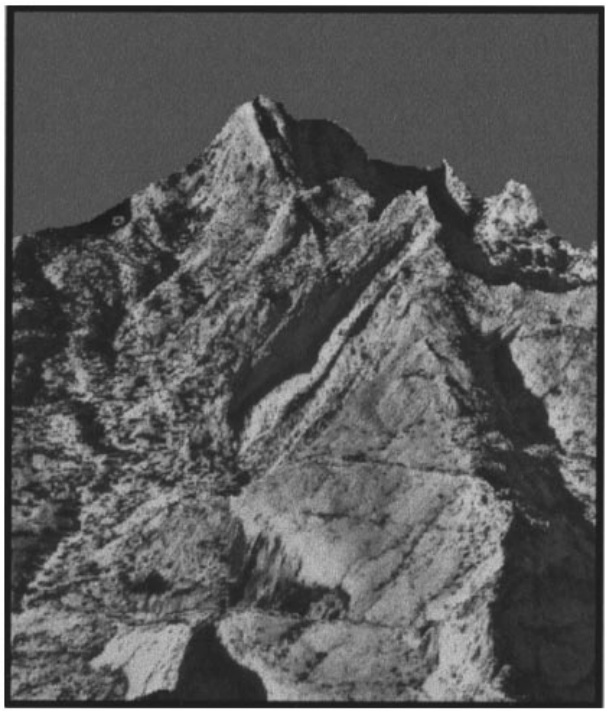


Figure 4. 'Virtual' image of deformation band shear zones and fault-fin landscape in the Sheets Gulch area along the Waterpocket fold. Note how parts of the canyon rim are controlled by thick deformation band shear zones. View is west-south west. Depth of image is approximately 1 km. Image created and provided by the Geology Division of Chevron Technology Company. The area captured within this figure is centered on Latitude 38 ° 07 ' 09 ", Longitude 111 ° 05 ' 44 ", and is easily accessible by driving south on the Notom Road from the vicinity of the Visitor's Center of Capitol Reef National Park. Turn west on the Oak Creek access road, which is marked on the Park map of roads and trails.

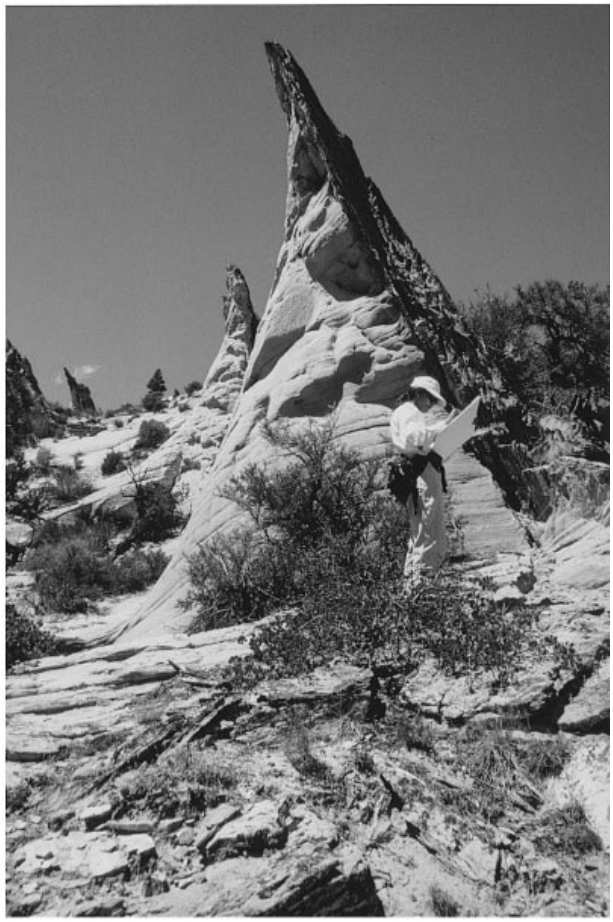


Figure 5. Profile view of fault fin in Navajo Sandstone in the Cottonwood Canyon area. One flank is controlled by a deformation band shear zone. The other flank is simply the repose angle of the sandstone. Pilar Garcia is doing the mapping.

3. Geomorphic expression of sets and systems of fault fins

The expression of fault fins and zones of deformation bands in topography can be seen especially clearly in 'virtual' images of the landscapes of parts of the Cottonwood Canyon and Sheets Gulch areas (see Figs 3 and 4). The deformation band shear zones within the Cottonwood Canyon locality are extensional, normal-slip; those within the Sheets Gulch locality are strike-slip. For purposes of detailed structural mapping, I subcontracted GPS surveying and low-altitude flyovers of the two study areas, thus creating the basis for producing very large scale (1 : 600) aerial photos and topographic maps. Using these data, the Geology Division of Chevron Petroleum Technology Corporation created the virtual images by draping scanned portions of the large-scale aerial photography over corresponding digital topography. The fine-scale topographic control (contour interval of 3 m in areas of >200 m topographic relief) afforded by GPS surveying (carried out by GEO-MAP, Inc.) permitted capturing the fault fins in the virtual images (see Figs 3 and 4).

Both virtual images reveal pronounced expressions of fault-fin landscape which has formed in the upland older landscapes. Within these upland surfaces, between deep-cut canyons, the easily eroded mudstone and siltstone lithologies of the Carmel Formation (Jurassic) have been erosionally denuded, leaving stripped structural surfaces of uppermost Navajo Sandstone and the deformation band shear zones contained therein. Weathering and erosion of the stripped upland surface have proceeded over sufficient duration to create a landscape that starkly reveals differential resistance to erosion.

The deformation band shear zones conspicuously express themselves in topography as long, continuous wall-like features (Fig. 3). They locally control the geometry of precipitous margins of deep canyons (Fig. 4). Where thick zones of deformation band shear zones trend at high angles to drainages, there is a correspondence between locations of the zones of deformation bands and the locations of dry waterfalls, plunge pools, and waterpockets. Positions of deformation band shear zones thus are evident in longitudinal profiles of stream courses. The locations of the traces of a thick deformation band shear zone may locally correspond with the exact locations of the confluences of drainages, reflecting the impediment that resistant deformation band shear zones impose upon headward migration of drainages. Evidence for stream piracy, which has been importantly controlled by the locations and orientations of especially thick and resistant deformation bands, can be seen from place to place in the topographic details of the landscape.

4. Scientific opportunities afforded by fault-fin landscapes

Fault-fin landscapes create scientific opportunities of both a practical and academic nature. The presence of finned landscape alerts us, in the most tangible ways possible, to the hydrogeologic modelling challenges of compartmentalized aquifer and hydrocarbon reservoirs. The largely impermeable zones of

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Figure 6. Close-up view of characteristic winnowed boxwork character of many of the deformation band shear zones. Conjugate centimetre-scale shear zones compartmentalize the host.

deformation bands serve to compartmentalize porous sandstone host rock, creating systems of seals and baffles that influence the distribution and flow paths of ground water or hydrocarbons (see Antonellini & Aydin, 1995). The clarity of exposure of the resistant deformation band shear zones makes it possible to assess the geometric/fractal character and petrophysical properties of these systems of structures, and to evaluate permeability flux (see, for example, Antonellini & Aydin, 1994, 1995, and Antonellini *et al.* 1994). In addition, fault-fin landscapes present opportunities to gauge rates of erosional denudation of plateau surfaces. Especially promising are fault fins that project 10 m or more above the surrounding landscape surface (see Figs 1 and 5). Such fins are expressions of differential rates of erosion of host rock versus deformation band shear zones. Such tall features might lend themselves to determining the actual differential rate of erosion through cosmogenic isotopic dating of the fin profiles. Close-spaced cosmogenic sampling/dating down the dip of especially suitable fault fins could provide critical data for estimating rates of vertical and lateral denudation of upland surfaces in the Colorado Plateau region. Results could be used as a guide to establishing rates of erosional denudation of upland surfaces within the Colorado Plateau tectonic province.

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