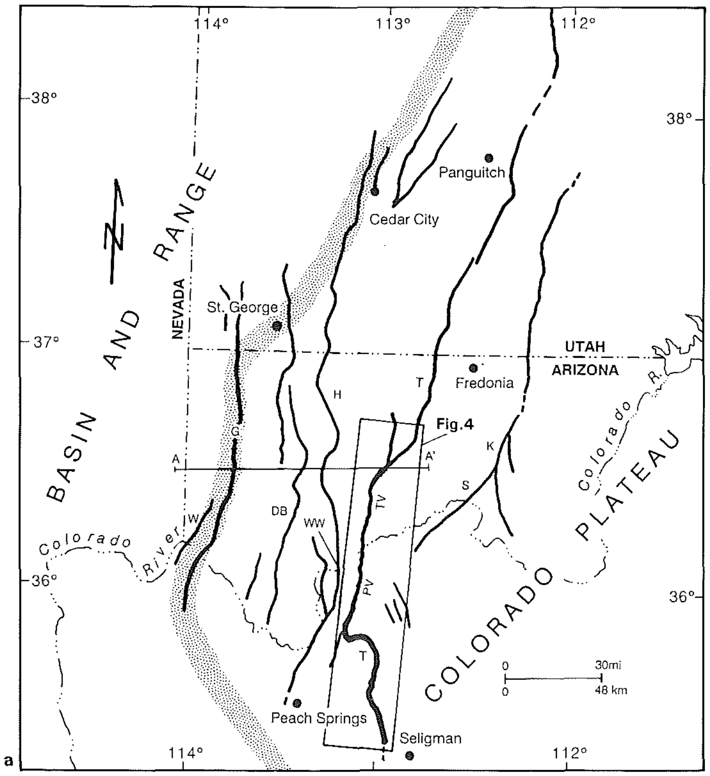
The Toroweap Fault: One of the Most Active Faults in Arizona

*by Garrett W. Jackson**
Arizona Geological Survey

Striking cliffs slice across northwestern Arizona. These fault-generated escarpments define the transition between two physiographic zones, the Basin and Range Province to the west and the Colorado Plateau to the east (Figure 1). Geophysical evidence suggests that the margins of the Colorado Plateau are foundering as the main body of the plateau is uplifted (Morgan and Swanberg, 1985) and that the Basin and Range Province may be expanding at the expense of the plateau (Keller and others, 1979).

The behavior of the faults that formed the escarpments is enigmatic because datable, displaced surficial materials are commonly absent. Displaced Quaternary alluvium, basalt flows, and cinder cones, however, are evident along the Hurricane and Toroweap faults on the North and South Rims of the Grand Canyon.



Documentation of displacement rates, prehistoric earthquake (paleoearthquake) magnitudes, and fault segmentation is, therefore, possible. A section of the Toroweap fault near the Grand Canyon is particularly useful in determining the behavior of active faults in northwestern Arizona. Recent analysis of the faulted materials (Jackson, 1990) has shed some light on how tectonically active this area may be.

GEOLOGIC SETTING

The Toroweap fault, which extends more than 480 kilometers (km), is a plateau-bounding, high-angle normal fault with up to 560 meters (m) of vertical displacement in northwestern Arizona. It was first recognized by Powell (1875) and has been studied by such famous geologists as Dutton (1882) and Davis (1901, 1903). Based on studies of displaced basalt flows, Koons (1945) inferred that movement had occurred along the fault during the Quaternary period, less than 1.6 million years (m.y.) ago. Huntoon (1977) suggested that movement had occurred less than 10,000 years ago (during the Holocene) along the fault in Prospect Valley.

The most recent study of the Toroweap fault (Jackson, 1990), summarized herein, covers a section between Seligman and Pipe Springs, Arizona. Stratigraphic displacement varies significantly along this length, ranging from 250 m on the South Rim to a few tens of meters at the northernmost end of Toroweap Valley. The earliest movement on the fault occurred during the Precambrian, or more than 570 m.y. ago, when it was a normal fault. Compression during the Laramide orogeny (80 to 40 m.y. ago) reactivated the fault in the opposite sense, displacing Precambrian rocks but folding Paleozoic (245- to 570-m.y.-old) rocks. Compression ceased in the early Tertiary and was replaced in the late Tertiary (about 20 m.y. ago) by extension (Wenrich and others, 1986).

QUATERNARY GEOLOGY AND GEOMORPHOLOGY

The evolution of Toroweap and Prospect Valleys, the valleys that drain to the Colorado River along the Toroweap fault, has been strongly influenced by Quaternary tectonic activity.

Toroweap Valley on the north side of the Grand Canyon is a gentle, broad valley with steep alluvial fans derived from cinder

* Current address: B & V Waste Science & Technology, 3600 Port of Tacoma Rd., Suite 304, Tacoma, WA 98424-1046.

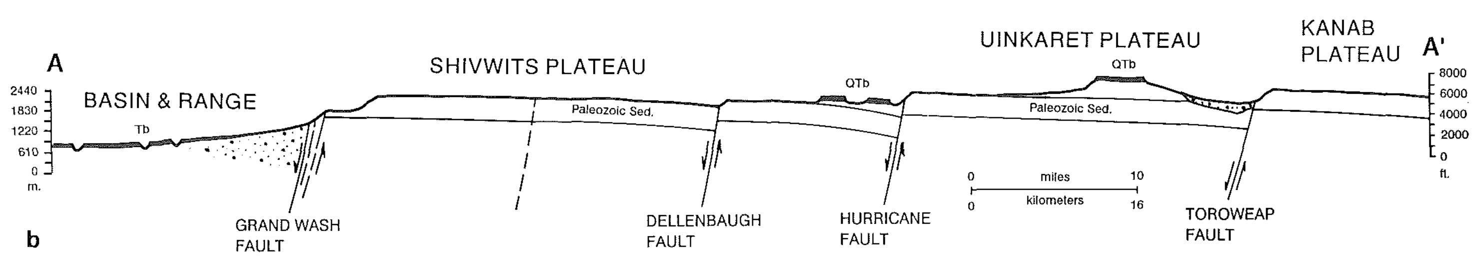


Figure 1. (a) Location map with selected normal faults. Stipple pattern shows the approximate physiographic boundary between the Colorado Plateau and Basin and Range Provinces. W = Wheeler fault; G = Grand Wash fault; DB = Dellenbaugh fault; H = Hurricane fault; WW = Whitmore Wash area; T = Toroweap fault; TV = Toroweap Valley; PV = Prospect Valley; K = Kaibab fault; S = Sinyala fault. Scale = 1:1,900,800. After Best and Hamblin (1978) and Reynolds (1988). (b) Cross section of the western Colorado Plateau (after Best and Hamblin, 1978). QTb = Quaternary and Tertiary basalts; Tb = Tertiary basalts. Each fault has an associated escarpment.

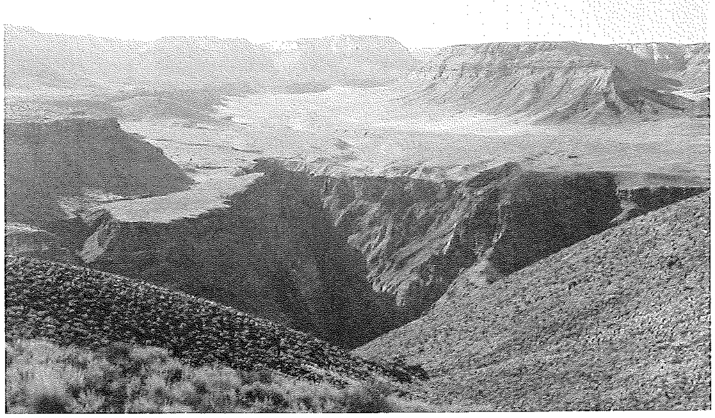


Figure 2. View of Prospect Valley toward south from North Rim of Grand Canyon. Inner Gorge of Grand Canyon is in foreground. Prospect Canyon (center), which is part of the Inner Gorge, has eroded along the Toroweap fault, cutting through Quaternary basalts and cinder cones that filled a previous canyon. The Toroweap-Aubrey Cliffs (left and on horizon) consist of two escarpments. The upper snow-covered cliffs are capped by the Kaibab Limestone. The lower cliffs are capped by the Esplanade Sandstone. The fault is at the base of the lower cliffs. The presence of two escarpments is unique to the northern 10 km of Prospect Valley and is probably related to pre-lava-flow canyon incision.

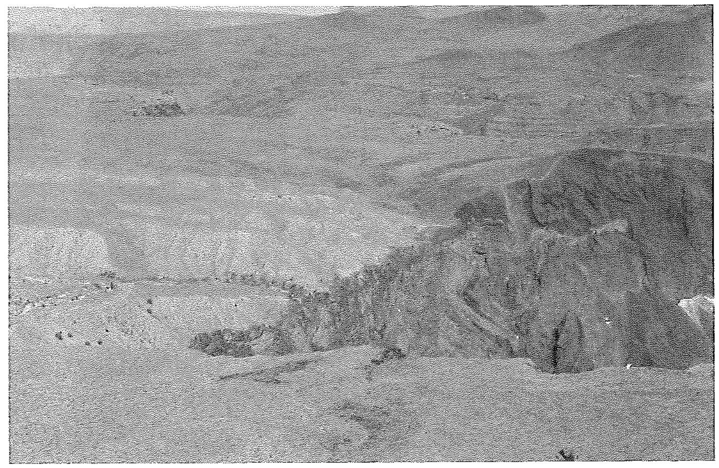


Figure 3. View toward west from top of Esplanade escarpment. Prospect Canyon (center) has eroded past Prospect Wash, creating a 400-m knickpoint. The cinder cone (right) is cut by this incision. The cinder cone once obstructed stream flow, impounding alluvium. Subsequent erosion of the cinder cone allowed Prospect Wash to incise. The wash now flows on canyon-filling basalt.

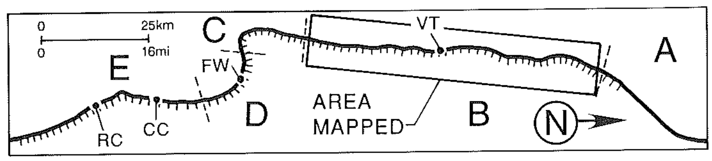


Figure 4. Map of study area. Large letters are segments of the fault; dashed lines separate segments. RC = Rhodes Canyon; CC = Crater Canyon; FW = Frazier's Well; VT = Vulcan's Throne. Box encloses the mapped area. Hachures indicate part of fault for which escarpment sinuosity indices were calculated.

cones and lava flows on the west. Sinuous, vertical cliffs form the escarpment on the eastern side of the valley. In the southern part of the valley, the cliffs are deeply embayed, and alluvial fans emanating from them are broad and gently sloping.

Toroweap Valley probably was once similar to the many adjacent side canyons of the Colorado River. These tributary canyons are steep, narrow, and very deep. Sinuosity of escarpments is usually an indicator of tectonic activity; lower sinuosities indicate higher displacement rates. It is likely, however, that most of the sinuosity of the cliffs is an artifact of earlier canyon cutting. The valley is broad and flat today because it was filled with a succession of lava flows from the Uinkaret volcanic field, starting about 1.2 m.y. ago (McKee and others, 1967). The lavas filled the ancestral valley to a level below the top of the Esplanade Sandstone and dammed the Colorado River several times (McKee and Schenk, 1942). Since the time of lava extrusion, the river has cut completely through several hundred meters of lava dams, plus an additional 15.2 m through Paleozoic rocks.

The latest stage of volcanism is marked by the emplacement of cinder cones near the river. Most notable is Vulcan's Throne, which lies perched near the Inner Gorge. The emplacement of these cinder cones, along with late-stage lava flows and faulting, blocked drainage of Toroweap Valley into the Inner Gorge. Some incision of the valley-filling basalts has occurred, but the Quaternary sediments of the valley remain undissected. Very low stream gradients suggest that the drainage is in equilibrium or is slightly aggradational.

Prospect Valley's present form is quite different from that of Toroweap Valley (Figure 2). Lava also filled the ancestral valley, presumably at about the same time it filled Toroweap Valley, to a level about 150 m below the latter. A wedge of alluvium about 30 m thick was deposited on top of the basalts. These sediments overlap the remnant of a cinder cone at the head of the modern Prospect Canyon (Figure 2), indicating that Prospect Valley was at least partially blocked by cinder cones, as Toroweap Valley is today. Sediments are much thicker on the downthrown side of the fault, indicating syndepositional faulting. Since then a new canyon has eroded through the cinder cone 1.5 km from the Colorado River (Figure 3). The axial drainage, Prospect Wash, has cut completely through the alluvium and now flows on the basalts. This wash does not coincide with the head of Prospect Canyon. The head of the canyon has eroded to the south, beyond the outlet of Prospect Wash. Erosion along the fault plane and canyon walls appears to affect canyon evolution more than fluvial erosion caused by streams such as Prospect Wash.

BEHAVIOR OF THE TOROWEAP FAULT

Segmentation

Variation in stratigraphic displacement along the fault indicates varying rates of displacement. The fault may be divided into five segments based on total displacement, escarpment sinuosity, and Quaternary displacements (Figure 4). Segment A is relatively inactive. No recent displacements are present; escarpment sinuosity is relatively high, and total displacement is only about 76 m. Segment B is the most active segment. It is about 45 km in length and has total displacements of 150 to 265 m. Sinuosity is very low. In addition, at least three surface-rupturing earthquakes have occurred during the late Quaternary; the most recent event occurred about 3,000 years ago (Jackson, 1990). Segment C is a short segment characterized by low sinuosity and high total displacement (up to 280 m), but it lacks evidence of Quaternary displacement. Segment D is bounded by two bends in the fault and is highly sinuous. Total stratigraphic displacement ranges from about 54 m to about 122 m. Many stream terraces and alluvial fans cross the trace of the fault, but no evidence of Quaternary displacement exists. To the south is segment E. Total displacement is moderate, at about 137 m, and the sinuosity of the escarpment is very low. Quaternary alluvium has been displaced; the last surface-rupturing event occurred about 5,000 years ago (Jackson, 1990). Segment E appears to be very similar to segment B.

Temporal Variations in Displacement Rates

Jackson (1990) estimated vertical displacement rates on segment B using estimated ages of faulted basalt flows and geomorphic surfaces. These rates seem to have increased during the Quaternary

(Figure 5). The displacement rate from 3,000 to 40,000 years ago is estimated at 110 m/m.y. This rate is based on soil age estimates derived from measured carbonate content and an assumed carbonate accumulation rate (Jackson, 1990). A basalt flow in northern Toroweap Valley is displaced 36 m. An age estimate of about 635,000 years was obtained on the flow by K/Ar analysis, yielding an average displacement rate of about 56 m/m.y. since the middle Pleistocene. Near Vulcan's Throne, a 203,000-year-old basalt displaced 15 m (Anderson and Christensen, 1989) yields an average displacement rate of 74 m/m.y., which is intermediate between the other two rates. The apparent recent increase in displacement rate suggests that the Toroweap fault is accommodating more extension and that earthquakes are occurring more frequently.

Longer term displacement rates are probably even lower. The timing of initial normal faulting in this part of the Colorado Plateau is uncertain. Normal faulting in southwestern Utah began about 8 to 10 m.y. ago (Anderson and Mehnert, 1979), whereas the main phase of faulting in the Lake Mead area occurred 6 to 10 m.y. ago (Hamblin and Best, 1970; Lucchitta, 1979). In the area southwest of segment E, the main phase of Basin-and-Range-style faulting did not begin until the Miocene (less than 24 m.y. ago). Total displacement of Paleozoic rocks at the Grand Canyon is about 193 m. If one assumes that movement began on the Toroweap fault 8 to 10 m.y. ago, the average displacement rate is 16 to 24 m/m.y. Recent displacement rates thus seem to be significantly higher.

Paleoearthquakes on the Toroweap Fault

Displacement rates represent the cumulative effect of discrete surface-rupturing earthquakes. The magnitudes of paleoearthquakes can be estimated by measuring

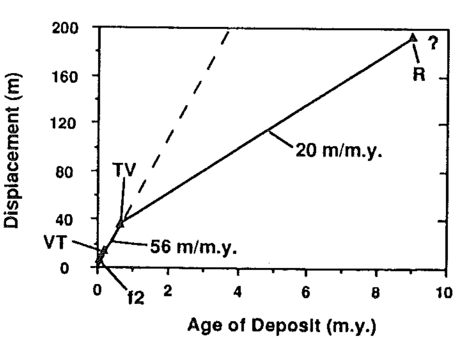


Figure 5. Variation in displacement rates with time. Dashed line shows extrapolated late Quaternary displacement rate (see text). The two lines suggest that either the rate has dramatically increased during the Quaternary or faulting began much more recently than previously thought. Either conclusion suggests that Basin-and-Range-style tectonism encroached onto the plateau during the latest Cenozoic. TV = Toroweap Valley basalt; VT = Vulcan's Throne basalt; f2 = late Pleistocene alluvial surface; R = regional inception of faulting and displacement at the Colorado River.

surface-rupture parameters and comparing them to the parameters of earthquakes with known magnitudes (Hanks sand Kanamori, 1979).

Jackson (1990) calculated the magnitude of the most recent paleoearthquake on segment B of the Toroweap fault. Using the seismic source-moment method, an average displacement of 2.2 m, a segment length of 53 to 62 km, and a depth of faulting of 15 km, Jackson (1990) estimated that the magnitude was between 7.1 and 7.2. This magnitude is equal to or slightly higher than that of the 1989 Loma Prieta earthquake in the San Francisco Bay area (Wallace and Pearthree, 1989).

An earthquake of magnitude 7.1 could seriously damage manmade structures and trigger rockfalls and landslides. The potential of a similarly sized earthquake occurring on segment B in the near future is probably low, however. The most recent earthquake occurred approximately 3,000 years ago, based on Jackson's (1990) scarp slope analysis. The relatively low displacement rate along the fault suggests that the interval between large earthquakes is long. The next earthquake along segment B, therefore, will probably not occur for several thousand years. The threat to human life and property is also relatively low because the region is sparsely inhabited. Residents in areas as far away as Hoover Dam and Las Vegas might feel an earthquake generated along the Toroweap fault, but the extent of potential damage is unknown.

The potential for earthquakes along other segments of the Toroweap fault and along other faults in northwestern Arizona remains a matter of speculation. This area, however, probably has the highest potential of any area in Arizona (Menges and Pearthree, 1983).

Regional Faulting Migration

Increasing displacement rates on the Toroweap fault may indicate a progressive breakup of the Colorado Plateau, as hypothesized earlier (Morgan and Swanberg, 1985; Wong and Humphrey, 1986). Migration of faulting has been documented in other areas along the margins of the plateau. In south-central Utah, faulting shifted uniformly from the Basin and Range Province (9 m.y. ago) to the Sevier fault (7.6 to 5.4 m.y. ago) to the Paunsagaunt fault (less than 5 m.y. ago; Rowley and others, 1981). In southwestern Utah, the rate of displacement during the Pliocene and Quaternary along major normal faults increased from west to east across the Colorado Plateau margin (Hamblin and others, 1981).

In the western Grand Canyon area, faulting seems to be migrating diffusely to the east as western faults become less active. In addition to increases in displacement rate on the Toroweap fault, escarpment sinuosities along major normal faults generally decrease from west to east. The age of the youngest faulted unit generally decreases from west to east as well.

A young fault-bounded depression lies east of the Aubrey Cliffs (segment E; Billingsley and others, 1986). This feature, along with low to moderate seismic activity in the eastern Grand Canyon area (Bausch, 1989; Brumbaugh, 1989), may represent continued migration of faulting to the east.

REFERENCES

Anderson, R.E., and Christensen, G.C., 1989, Quaternary faults, folds, and related volcanic features of the Cedar City 1° x 2° quadrangle, Utah: Utah Geological and Mineral Survey Miscellaneous Paper 89-6, 29 p.

Anderson, R.E., and Mehnert, H.H., 1979, Reinterpretation of the history of the Hurricane fault in Utah, *in* Newman, G.W., and Goode, H.D., eds., Basin and Range Symposium: Rocky Mountain Association of Geologists, p. 145-166.

Bausch, Doug, 1989, Grand Canyon earthquake swarm, September 1988: Arizona Geology, v. 19, no. 1, p. 9-10.

Best, M.G., and Hamblin, W.K., 1978, Origin of the northern Basin and Range Province: Implications from the geology of its eastern boundary, *in* Smith, R.B., and Eaton, G.P., eds., Cenozoic tectonics and regional geophysics of the western Cordillera: Geological Society of America Memoir 152, p. 313-340.

Billingsley, G.H., Wenrich, K.J., and Huntoon, P.W., 1986, Breccia pipe and geologic map of the southeastern Hualapai Indian Reservation and vicinity, Arizona: U.S. Geological Survey Open-File Report 86-458B, 26 p., scale 1:48,000, 2 sheets.

Brumbaugh, D.S., 1989, Summary of earthquake activity in Arizona for 1988: Arizona Geology, v. 19, no. 1, p. 8.

Davis, W.M., 1901, An excursion to the Grand Canyon of the Colorado: Harvard University, Museum of Comparative Zoology Bulletin, v. 34, p. 107-201.

_____ 1903, An excursion to the Plateau Province of Utah and Arizona: Harvard University, Museum of Comparative Zoology Bulletin, v. 38, p. 135-161.

Dutton, C.E., 1882, The Tertiary history of the Grand Canyon district: U.S. Geological Survey Monograph 2, 275 p.

Hamblin, W.K., and Best, M.G., 1970, The western Grand Canyon district: Guidebook to the geology of Utah, no. 23: Utah Geological Society, 155 p.

Hamblin, W.K., Damon, P.E., and Bull, W.B., 1981, Estimates of vertical crustal strain rates along the western margins of the Colorado Plateau: Geology, v. 9, p. 293-298.

Hanks, T.C., and Kanamori, H., 1979, A moment magnitude scale: Journal of Geophysical Research, v. 84, p. 2348-2350.

Huntoon, P.W., 1977, Holocene faulting in the western Grand Canyon, Arizona: Geological Society of America Bulletin, v. 88, p. 1619-1622.

Jackson, G.W., 1990, Tectonic geomorphology of the Toroweap fault, western Grand Canyon, Arizona: Implications for transgression of faulting on the Colorado Plateau: Arizona Geological Survey Open-File Report 90-4, 67 p.

Keller, G.R., Braile, L.W., and Morgan, P., 1979, Crustal structure, geophysical models and contemporary tectonism of the Colorado Plateau: Tectonophysics, v. 61, p. 131-147.

Koons, E.D., 1945, Geology of the Uinkaret Plateau, northern Arizona: Geological Society of America Bulletin, v. 56, p. 151-180.

Lucchitta, Ivo, 1979, Late Cenozoic uplift of the southwestern Colorado Plateau and adjacent lower Colorado River region: Tectonophysics, v. 61, p. 63-95.

(continued on page 10)