Peach Springs Tuff: Its Bearing on Structural Evolution of the Colorado Plateau and Development of Cenozoic Drainage in Mohave County, Arizona: Discussion and Reply

Discussion

EARL M. P. LOVEJOY *Department of Geological Sciences, University of Texas at El Paso, El Paso, Texas 79968*

Young and Brennan (1974) presented geomorphic interpretations that differ from those of Hunt (1956, 1968, 1969) and myself (Lovejoy, 1973a, 1973b). I hope to show here that the surface on which the Peach Springs Tuff was deposited in the Colorado Plateau need not have been a *regionally* northeast-sloping surface, as Young and Brennan (1974, p. 87) conclude; the surface on which the tuff was deposited was not necessarily uniform or smooth; and the regional plateau infra-tuff topography could have been much like that of today along the edge of the Colorado Plateau.

The gradients between sites 38 and 40 and 36 and 41 (Table 1) on opposite sides of and parallel with the Hurricane fault should show the northeast slope, if any sets of points would, yet they are, respectively, 0.07 and 0.4 percent southwest. Of the points noted (excluding those in Milkweed Canyon, to be discussed below), only four show slopes to the northeast. Apparently the slope between sites 28 and 29 is due to local topography. The slopes between 41 and 31, 32, 34, and 35 are northeast, and those between 41 and 33 and 37 are southwest. Any post-tuff tilting accompanying plateau uplift would have subtracted from the original southwest gradients, although that amount would be minor, and therefore the southwest gradients mentioned above are less than the originals.

TABLE 1. GRADIENTS AND SLOPE DIRECTIONS BETWEEN SELECTED SITES OF YOUNG AND BRENNAN'S FIGURE 2 (1974)

Sites	Distance* (m)	Difference of elevation† (m)	Gradient (%)	Slope direction
13–14§	5,600	+305	5.4	West
16–17	3,700	-92	2.5	Southeast
16–18	4,800	-92	1.9	Southeast
21–22	5,500	+184	3.3	Southwest
24–25	1,000	0	0	Flat
25–26	2,100	-6	0.3	West
26–27§	8,400	-268	3.1	West
26–29§	7,900	-363	4.6	West
27–28	1,300	-15	1.2	North
28–29	800	-260	32.5	Northeast
29–33§	11,300	+710	6.3	Southwest
31–32	1,300	0	0	Flat
31–34	1,800	0	0	Flat
32–34	1,900	0	0	Flat
33–35	3,400	+49	1.5	Southeast
33–36	2,300	-61	2.7	Northeast
34–35	1,500	-12	0.8	Northeast
35–37	4,200	-79	1.9	Northeast
36–37	1,600	+30	1.9	South
36–41	18,600	+73	0.4	Southwest
38–39	15,100	+61	0.4	Southwest
38–40	16,100	+12	0.07	Southwest
40–41#	1,500	-49	3.4	West

* *All distances measured from Young and Brennan's Figure 2 (1974) in miles and converted to meters. Measured to nearest 0.1 mi, but may err by 0.1 mi. Computed to nearest 100 m.*

† *Difference in elevations taken in direction from first site number toward second site number; data from map.*

§ *Across major boundary fault of plateau.*

Across Hurricane fault.

Five lobes of the tuff shown on Young and Brennan's Figure 2 can be labeled the Mohon, Aquarius, Truxton, Milkweed Canyon, and North lobes.

According to Young and Brennan's map, the tuff of the Mohon lobe probably flowed southeast. If the flow had moved along a valley, its axial parts would be lower than its edges. Sites 17 and 18 form a level line normal to the lobe axis and flow direction; this line could be the central or axial part of the flow, and site 16 could represent its edge. Therefore, the present difference in elevation between 16, 17, and 18 may represent original differences due to the topography of the valley along which the ash flow moved.

The Aquarius lobe exhibits this aspect of axial minimum and rim maximum elevations. Sites 19 and 21, at equal elevations, are near the axis of the lobe. Sites 53, 22, and 23 are on the edge of the flow. The 3.3 percent slope southwest from 22 to 21 is not due to significant faulting, according to Young and Brennan's map. The surface is horizontal between 22 and 23. Sites 14 and 15 might be remnants of southeastward-moving ash flows that moved up gentle slopes on the divide between the southeast-moving Mohon lobe and the northeast-moving Aquarius lobe, where both flowed up gently sloping valleys.

The Truxton lobe exhibits an axial low at site 36, with rise toward the north rim at 31, 32, 34, and 35. Site 37 is nearer to the axis than to the north rim. Sites 33 and 30 lie between the axis and the south rim. Site 29 probably lay on the valley floor, and 27 and 28 outside the valley scarp (the escarpment formed by lateral erosion along the sides of the river valley).

The Milkweed Canyon lobe may represent maximum penetration of the flow onto the plateau, where the flow line was downwind, and downslope northeastward in the Basin and Range province up to the Colorado Plateau border, from the source near Kingman. Because there were no impediments in the path of this

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lobe except for the subdued plateau boundary cliffs (305 m lower than those of today), it had more momentum than the Mohon and Aquarius lobe flows, and it climbed onto the plateau through a gently sloping re-entrant north of Music Mountain. Site 43 represents the rim of the flow. Sites 44 and 46, at equal elevations, form a line normal to the direction of flow near the axis of the lobe. Sites 45, 47, 48, 49, and 51 represent remnants near the axis of the lobe that flowed northeast down the canyon that existed at the time of the ash flow. The important point is whether Milkweek Canyon drained into the Grand Canyon at the time of the flow, that is, whether the Grand Canyon existed then.

The North lobe (site 52) may represent another lobe, as shown on Young and Brennan's Figure 2, or a remnant of the Milkweed Canyon lobe, similar to site 42, that spread onto the Hualapai Plateau from the Milkweed Canyon flow near or west of site 46.

I believe, therefore, that tuff of the lobes noted flowed in broad, gently sloping valleys.

The close spatial relation of the Milkweed Canyon lobe with Milkweed Canyon is obvious. The tuff is inset in a canyon that had already been cut below the plateau rim at the time of tuff emplacement. This same close spatial relation exists in Truxton Valley, where the tuff also is inset in a canyon previously cut below the plateau rim on the same sequence of Paleozoic strata. The principal difference between Milkweed and Truxton Valleys is, however, the direction of their present and past slopes — Milkweed to the northeast and Truxton to the southwest. Equally obvious is the conclusion that the tuff is deposited and inset in northeast-sloping Milkweed Valley, just as it was deposited inset in southwest-sloping Truxton Valley. The evidence for the inset of the tuff in valleys at the Mohon and Aquarius lobes is equally convincing. Thus, three major lobes of the Peach Springs Tuff were emplaced and inset in southwest-sloping pre-existing valleys. This shows that the drainage at the border of the Colorado Plateau was southwesterly, as it is today, the result, I believe, of obsequent stream development on an already uplifted, northeast-tilted Colorado Plateau block. Indeed, the continuity of drainage since deposition of the tuff shows that the pre-tuff topography was much like that of the present; instead of supportive evidence for a major drainage change in the Colorado Plateau border, the evidence presented by Young and Brennan clearly indicates a continuity of drainage at the west edge of the Plateau throughout the past 17 m.y.

Peirce (1972) has shown that a deep basin exists beneath Red Lake and considered that a major fault lies along the northeastern side of Hualapai Valley with apparently at least 3,400 m of displacement. The 340-m displacement along the boundary fault of the Colorado Plateau in the past 17 to 19 m.y., which Young and Brennan (p. 84) have proven, thus represents perhaps less than 10 percent of the total displacement along the fault. Young and Brennan (p. 87) noted evidence of uplift and erosion along the edge of the plateau before eruption of the Peach Springs Tuff but concluded (p. 89) that "Prior to the post-tuff structural differentiation of these two provinces, the edge of the Colorado Plateau . . . appears to have been a structural boundary which had undoubtedly experienced some minor faulting during the regional upwarping. . . ." It is difficult to see that there has been only post-tuff structural differentiation of the two provinces, or that there has been only minor faulting of the plateau border. The evidence in Hualapai Valley does not support Young and Brennan's conclusion (p. 89) that "The eruption of the Peach Springs Tuff appears to have accompanied or immediately preceded most of the volcanism and block faulting . . . in Mohave County."

I agree with Young and Brennan that Milkweed and Peach Springs Canyons have always sloped northeast (Lovejoy, 1959, 1964, 1969). The evidence supplied by Young and Brennan does not contravene my view that the Colorado Plateau was uplifted primarily in Paleogene time (Lovejoy, 1959, 1964, 1973a, 1974) and that less than 25 percent of the total uplift occurred in Neogene time (Lovejoy, 1973a, 1973b). Their value of fault displacement of 340 m agrees with regional data (Lovejoy, 1973b), and that displacement is less than 25 percent of the total displacement manifest in Hualapai Valley, as noted by Peirce (1972). Obviously, the timing of total fault displacement cannot be determined by their data, but Peirce (1972) clearly showed that much more than "some deformation" preceded tuff emplacement. The evidence at Aquarius Mountain indicates a westward-sloping drainage off the rigid plateau block prior to tuff deposition 17 m.y. ago; obviously, broad structural uplift at one place in this rigid block must apply everywhere along this regional edge, thus corroborating my interpretation of Paleogene obsequent drainage development westward off the plateau edge. Northeast flow direction in Truxton Valley prior to 17 m.y. ago is not proven by their evidence. In the absence of conclusive evidence and precise data proving critical fault offsets of the tuffs in Truxton Valley, Young and Brennan's tuff-slope data show that the valley has always sloped southwest (as an obsequent valley) and ashflows could have climbed this valley.

Young and Brennan cited the theory of Colorado River development propounded by McKee and others (1967) but do not comment on the rejection of that theory by Hunt (1968), who demonstrated its fundamental failures.

Therefore, I submit three tentative conclusions: (1) Young and Brennan's evidence does not contravene my interpretation that less than 25 percent of total Plateau uplift occurred in Neogene time; (2) some well-developed, west-flowing, obsequent streams existed on the plateau edge at least 17 m.y. ago; (3) Young and Brennan and I agree that Milkweed and Peach Springs Canyon sloped northeast prior to 17 m.y. ago, as they do now, apparently into the Colorado River; (4) thus, a divide existed between the northeast-flowing streams and the southwest-flowing streams, and this divide has not migrated very far east in 17 m.y.

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Reply

RICHARD A. YOUNG
WILLIAM J. BRENNAN } *Department of Geological Sciences, State University of New York at Geneseo, Geneseo, New York 14454*

Lovejoy (1975) has raised four basic points that require clarification or elaboration: (1) What factors determine the elevation differences between Peach Springs Tuff outcrops on a local scale? (2) What is the nature of the evidence for the paleoslope and relief on the pre-tuff erosion surface? (3) What are the modes of emplacement of ash-flow tuff, in particular the Peach Springs Tuff? (4) What are the nature, amount, and timing of movements along the Hurricane–southern Grand Wash fault system?

ELEVATION DIFFERENCES

Many local differences in elevations of outcrops of tuff within individual canyons (lobes) are due, in part, to pre-existing elevation differences in the buried valleys, but some also result from abundant faults, which were too small to be shown on our Figures 1 and 2 (Young and Brennan, 1974). In many localities the outcrops consist of one or more remnants of tuff with clearly visible faults within or between the outcrops. The tuff serves as one of the few markers by which local displacement can be measured, especially in areas where Precambrian rocks are exposed. In some areas faulting is strongly indicated where the volcanic rocks are partly obscured by younger gravel, and tuff exposures exhibit significant local elevation differences. The elevation differences, for example, between sample localities 30, 33, and 36 (Young and Brennan, 1974, Fig. 2) were probably caused by faults that cannot be precisely delineated. Many of the visible faults are shown on the detailed maps by Young (1966). In other places, rotation and displacement of large blocks along multiple buried fault traces, as in the Truxton Valley between the Hurricane and southern Grand Wash faults, may have caused some of the apparent elevation "reversals" noted by Lovejoy. Some apparent slope reversals could be the result of the tuff having sufficient velocity to climb gentle slopes along the flanks of the main valleys. Because all sample locations are not along valley axes, some inconsistent elevation differences of small magnitude are to be expected.

The lobe of tuff north of the Aquarius Mountains apparently filled minor valleys that drained westward off the "plateau" escarpment, as demonstrated by imbrication in pre-tuff gravel and as noted by us (1974, p. 87, 89). However, the Cenozoic history of the area south of the Truxton Valley is different from that of the area to the north, regarding both the number of Tertiary units and the sequence of geologic events interpreted from deposits around the Truxton Valley and in canyons on the Hualapai Plateau.

PALEOSLOPE BENEATH THE TUFF

The strongest evidence concerning the pre–tuff erosion surface is the sequence of Tertiary events leading up to the onset of volcanism. The distribution, source, and paleocurrent directions of all geologic units in our Figure 5 (Young and Brennan, 1974) is well established, with the possible exception of the basal gravel near the head of Peach Springs Canyon. Nearly identical sections of Tertiary units occur in Peach Springs Canyon and Milkweed Canyon (Young, 1970). Except for some locally derived material, all the gravel units were transported in northeasterly directions along ancestral Milkweed and Peach Springs Canyons and most certainly through the Truxton Valley, where the Willow Springs Conglomerate covers most of the older deposits and precludes precise delineation of the main channel. Only a few outcrops of the basal arkosic unit containing gravel lenses were located in Peach Springs Canyon from 1962 to 1964. Because of extensive weathering, pebble roundness, and the high ratio of matrix to pebbles, imbrication measurements in the basal unit were considered insufficient to be conclusive. Considering the ideas that were current at that time, any incised northeast-trending channels would have required a pre–Grand Canyon drainage system flowing north across the modern Colorado River in rocks that are stratigraphically and topographically higher on the north side of the Grand Canyon. This evidence appeared to contradict most of the ideas concerning the development of the Grand Canyon as envisioned at that time.

Subsequent work in Peach Springs Canyon through 1974 has added to the evidence provided by the few earlier imbrication measurements. We now believe that all field evidence is consistent with northeast stream flow for the basal Tertiary deposits in Milkweed Canyon, Peach Springs Canyon, and the Truxton Valley, and by inference for the streams that cut the deep canyons that contain them. Since 1964, additional evidence from many other geologic studies concerning radiometric ages and the timing of the Cenozoic events around the Hualapai Plateau has helped to explain the northeast-flowing streams with respect to the regional geology (Lucchitta, 1972).

PREVIOUS CONCEPTS OF PRE–COLORADO RIVER DRAINAGE

McKee and others (1967) postulated a southwest flow direction for the basal gravel, in spite of some evidence to the contrary. However, Young stressed the possibility of northward drainage across the modern Colorado elsewhere (McKee and others, 1967, p. 56). Unfortunately, this initial uncertainty concerning the direction of stream flow for the basal Tertiary gravel, which is associated with the carving of the ancestral Peach Springs Canyon and the Truxton Valley, has been overemphasized by Hunt (1969), who suggested an alternative southwesterly course for a hypothetical ancestral Colorado River through Peach Springs Canyon prior to the Miocene volcanism. This is inconsistent with the field evidence in several important respects. The clasts in the basal gravel are not of Colorado Plateau provenance. The few paleocurrent measurements indicate northeast flow into Peach Springs Canyon from the Truxton Valley. Equivalents of all of the younger gravel units shown in our Figure 5 (Young and Brennan, 1974) were carried into the Truxton Valley and Peach Springs Canyon from the southwest or from around the rim of the Truxton Valley, eventually filling the valleys. Any postulated southwesterly stream flow is contradicted both by the regional dip of the Paleozoic rocks on the plateau and the evidence for marginal uplift adjacent to the plateau. The slope of the buried channel from a point near Hackberry into Peach Springs Canyon, as best as can be determined, is to the northeast (when corrections are applied for observable faults). Lucchitta (1972) also discussed the regional aspects of this problem and agreed with our conclusions.

The paleocurrent measurements in all other deposits beneath the volcanic rocks, which came predominantly from west of the plateau margin, demonstrate flow toward the northeast in Peach Springs Canyon, even if the evidence of paleocurrents, slope, and provenance for the oldest (basal) Tertiary gravels is disregarded. In his discussion of our paper, Lovejoy does not appear to have accepted the foregoing evidence that Peach Springs Canyon and the

Truxton Valley are a single, continuous old drainage system now filled by basal crystalline-bearing gravel and the Peach Springs Tuff, both of which are mostly covered by locally derived gravel.

Lucchitta (unpub. data) has found evidence for an outlet for pre–Colorado River drainage from Peach Springs Canyon across the modern Colorado River channel in the vicinity of the Hurricane fault. His hypothesis would require additional tilting of the Paleozoic rocks of only 0.5° to 1° to the northeast. The present geologic evidence indicates that in many places the southern and southwestern margin of the plateau was receiving debris shed from the higher Precambrian basement adjacent to it. Such widespread evidence for marginal uplift is consistent with the increase in the measured dip of Paleozoic rocks across the Hualapai Plateau in a southwesterly direction.

MODE OF EMPLACEMENT OF THE PEACH SPRINGS TUFF

The mode of emplacement of the Peach Springs Tuff and whether it was deposited across a regional surface of low relief is not resolved. There is no general agreement about the mechanisms of ash-flow tuff emplacement (Peterson, 1970). However, Boyd (1961, p. 413) noted that modern nueés ardentes–type eruptions generally do not produce welded tuff. We have documented that the Peach Springs Tuff has at its base a thin, nonwelded, bedded air-fall tuff layer that does not appear to have been noticeably scoured by the emplacement of the overlying welded tuff unit. The Peach Springs Tuff shows no abrupt changes in thickness and is restricted to partly preserved remnants of broad valleys in the edge of the plateau. It does not exhibit obvious field evidence of having overridden mountain ranges or having been "plastered" against escarpments or ranges. It might have climbed local gentle slopes.

Most of the mean paleomagnetic directions plotted in our paper were measured on samples collected from sites at which the tuff is nearly horizontal. Some outcrops are obviously faulted along the edge of the plateau and along the flanks of ranges, especially along the Cerbat and Peacock Mountains. Fault traces can be seen in the tuff and adjacent rocks. At some of our sites, the mean paleomagnetic directions were corrected for observed dips of as much as 8°, which appear in the field to be caused by faulting. If the dip corrections are removed, the mean paleomagnetic directions for these sites would be displaced farther from the mean direction of all the sites. This suggests that the dips are structural, rather than depositional, despite the fact that only a few sites with appreciable dips were sampled.

We believe that the tuff was emplaced as some type of fluidized flow or cloud, which was turbulent enough to prevent the formation of layering by density settling of large or dense clasts, as suggested by Fisher (1966). We do not believe that this thin unit could have traveled far through the air as a very low density cloud and still be welded with densities of as much as 2.35 g/cc at distances exceeding 80 km from the source. Nor did it travel fast enough at its base to scour the unconsolidated ash beneath it.

Large blocks of undeformed pumice (30 cm or more in diameter) are abundant near the eastern margins of the tuff, where the thin edge of the unit is more or less preserved. Ross and Smith (1961) suggested that the large blocks of pumice on the surface of an ash flow are rafted toward the margins and collect there. These observations argue against an extremely rapid event that could flow up over hundreds or thousands of meters of relief.

FAULTING ALONG THE PLATEAU MARGIN

The total amount and timing of faulting along the edge of the plateau cannot be precisely determined from our data. It seems clear that some deformation preceded deposition of the Peach Springs Tuff, as we pointed out. The measurement of displacement is complicated by the existence of several tilted fault blocks that are parallel to the plateau margin, similar to the type of block faulting near the mouth of the Grand Canyon. This can be seen at sites 8 through 13 and sites 27 through 29, as well as in subsurface borings (Young and Brennan, 1974). We agree with Peirce (1972) that a major fault (or faults) may underlie the Hualapai Valley. The deposition of 1,500 to 3,000 m of fill in the Hualapai Valley, noted by Peirce (1972), and the equivalent amount of fault displacement could both have occurred since deposition of the Peach Springs Tuff. No deep wells have yet penetrated volcanic rocks in the center of the valley south of Red Lake where the tuff should be present. If the block faulting and formation of basin topography along the edge of the plateau are as old as Lovejoy suggests, the tuff should be preserved in the subsurface in the Hualapai Valley, and not removed by erosion. This indicates that offset of the Peach Springs Tuff by faulting may be much greater than the observable 300 m along the edge of the plateau and that displacement across several parallel fault blocks could be involved.

Evidence on the Hualapai Plateau, especially near Milkweed Canyon, suggests that structural deformation caused the disruption of the drainage related to the basal Tertiary gravel. This resulted in ponding in canyons and deposition of coarse fanglomerates along channel margins, as well as temporary severance of the source of the pebbles of crystalline rocks coming from the west. We infer from field relations that pre-tuff movement occurred along the southern Grand Wash Cliffs as well as along structures on the Hualapai Plateau to disrupt the early drainage incised in the Paleozoic rocks.

SUMMARY

Lovejoy's detailed calculations of slopes beneath the tuff using our data are subject to many uncertainties with regard to the significance and origin of the elevation differences. The main evidence for northeast-flowing drainage in Peach Springs Canyon and the Truxton Valley immediately prior to deposition of the tuff is clear, and it is independent of the evidence provided by the tuff itself. The exact timing, total amount, and nature of plateau marginal faulting or deformation is incompletely understood in the area of this study, but it may be significantly greater than observed displacement of the Peach Springs Tuff. Young (1974) suggested that Precambrian structural control may be a factor in the location of the southernmost end of the Hurricane fault where it intersects the Cottonwood Cliffs.

We believe that many of Lovejoy's interpretations concerning the pre-tuff terrain, the significance of local slopes and local faulting, and the importance of the pre-tuff gravel units and drainage directions can best be refuted only by visiting the large numbers of localities indicated in our original Figure 2 and viewing all the Tertiary deposits.

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