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MORPHOLOGY OF A POSTGLACIAL FAULT SCARP ACROSS THE YELLOWSTONE (WYOMING) CALDERA MARGIN AND ITS IMPLICATIONS

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We have mapped, profiled and manually sampled for dating a postglacial fault scarp (the "Eagle Bay Fault") across the Yellowstone (Wyoming) rhyolitic caldera boundary to determine the age and extent of the faulting as part of a broader study of vertical deformation in the Yellowstone Lake basin. The results imply similar rates of scarp evolution in cool, humid, forested terrain as in warm, arid grasslands; Holocene propagation of normal faulting into the Yellowstone caldera; and seismic hazard in Yellowstone National Park from local, large ($M_s > 7$) extensional earthquakes as well as moderate ($M_s = 6$) volcano-tectonic seismicity.

Yellowstone Tectonism

The most obvious feature of Quaternary tectonism in Yellowstone National Park (Fig. 1) is the plexus of faults indicating resurgent doming of the 0.6 Ma rhyolitic caldera. The ring fractures of that eruption are largely obscured by later rhyolite flows or submerged by Yellowstone Lake, which crosses the SE corner of the caldera. The region has experienced historic volcano-tectonic doming within the caldera (Pelton and Smith, 1982), as well as extensional faulting outside it (e.g., Smith and Sbar, 1974; Fig. 1). The strongest expressions of regional tectonism in the greater Yellowstone area are the Madison/Centennial/Hebgen region of normal-fault-bounded ranges to the west and the Teton Range, to the south of Yellowstone National Park. The regional trend is, however, evident in Yellowstone as well, as alternating N-S ridges and basins (e.g., the Arms of Yellowstone Lake) with accumulated relief of nearly 1 km. Quaternary faults are mapped or inferred as bounding these features (USGS, 1972). Specifically, Richmond (1974) mapped a N-S trending, down to the east, normal fault (herein termed the Eagle Bay Fault) which he observed to cut postglacial lacustrine terrace deposits at the east end of the Flat Mountain Arm of Yellowstone Lake (Fig. 1). The Eagle Bay Fault, which may have been responsible for a swarm of small earthquakes in 1989 (Fig. 1; Peyton and Smith, 1990) was examined in detail as a part of a deformed shoreline study (Meyer and Locke, 1986; Locke and Meyer, manuscript in preparation).

The purpose of the deformed shoreline study is to determine the postglacial history of deformation within the Yellowstone caldera. The Eagle Bay fault was examined to help date the associated shorelines, to evaluate scarp evolution under very different conditions than has been reported previously, to examine the interaction between local volcano-tectonism and regional extension, and to assess the seismic hazard associated with regional extension in Yellowstone National Park.

Method

Twenty-seven profiles across the fault scarp were surveyed to 1-cm vertical precision at 0.5-m slope distance increments at two locations (Fig. 2), in order to analyze scarp morphology (e.g., Crone and Omdahl, 1987). Slope angle was

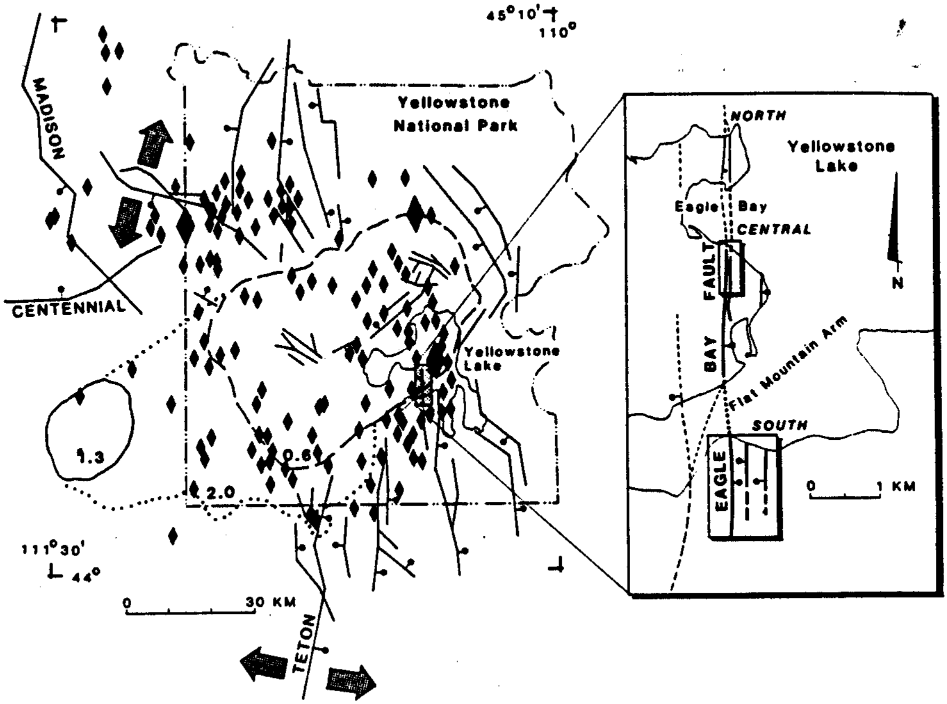

FIG. 1. Location of the study area in Yellowstone Park, relative to schematic extensional (line segments, ball on downthrown side) an caldera collapse (solid, dashed, and dotted lines, ages in Ma) structures. Arrows show sense of regional stress (from Stickney and Bartholemew, 1987). *Inset* shows faulting as mapped by Blank *et al.* (1974: light symbols) and remapped in this study (heavy lines) in the Eagle Bay area: further insets show locations of Figure 2. Representative seismicity (1989; $0 < M < 4$, diamonds) from Peyton and Smith (1990). Large diamonds indicate approximate locations of observed 1989 earthquake swarms.

calculated every 0.5 m over a 1-m slope distance to reduce the effect of local variability. The scarps were formed in well-sorted, cohesionless beach sand and pebble gravel, and show the form typical of scarps in colluvium elsewhere, with steeper midslopes on taller scarps (Fig. 3). Most (21) of the profiles were surveyed to the point where no elevation change occurred over 1 m distance, i.e., far-field slope goes to zero (cf. Hanks and Andrews, 1989).

Two approaches have been used for morphologic dating: an empirical approach constrained by radiocarbon dates (e.g., Bucknam and Anderson, 1979) and a mathematical model (diffusion; e.g., Nash, 1980, 1984; Hanks et al., 1984; Andrews and Hanks, 1985), which also requires calibration. In this paper we use an empirical disequilibrium approach (Howard, 1965; Graf, 1977) as a compromise between the existing methods. Disequilibrium models, like the diffusion model, assume an exponential decrease in the rate of change with time as the degree of disequilibrium decreases, but do not implicitly require conservation of material.

DISCUSSION

Regression analysis of maximum scarp angle versus the logarithm of scarp height (following Bucknam and Anderson, 1979, and others) for 15 scarp profiles in the central area (Figs. 2a and 4a) shows a statistically significant relationship ($p < 0.001$). There is no clear evidence of aspect affecting that

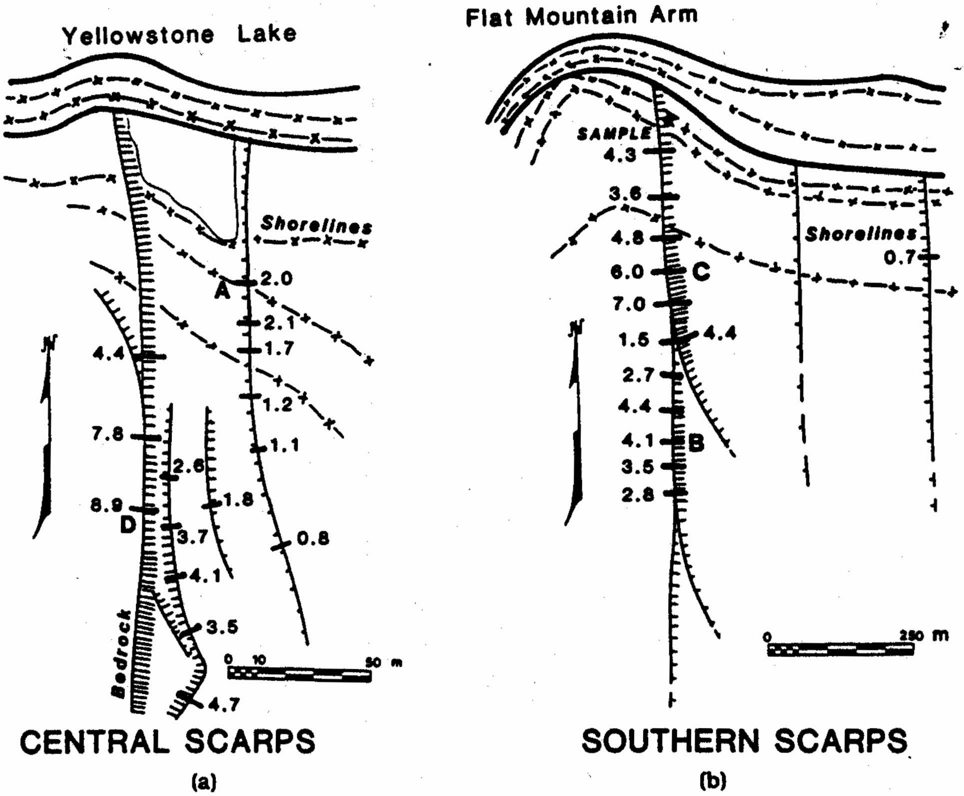

FIG. 2. Locations of scarp profiles in the (a) central and (b) southern areas. Letters indicate sample profiles shown in Figure 3. Hachures are on the downthrown side, increasing length and decreasing spacing imply scarp height, and numbers indicate surface offset (m). Note difference in horizontal scales. See text for discussion of shorelines.

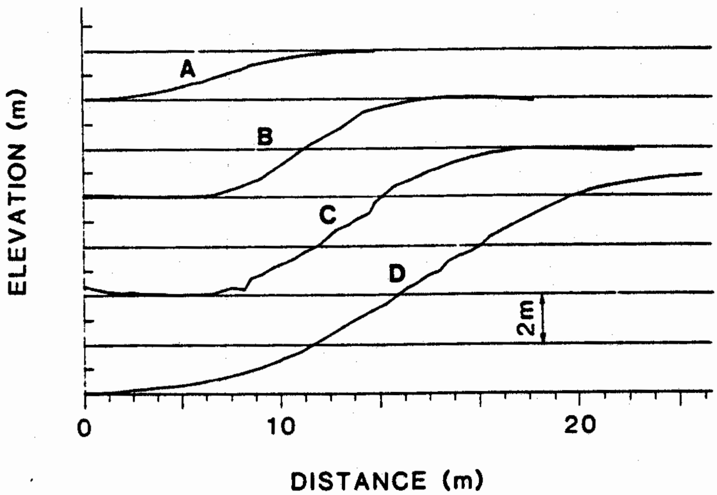

FIG. 3. Examples of surveyed scarps. See Figure 2 for locations.

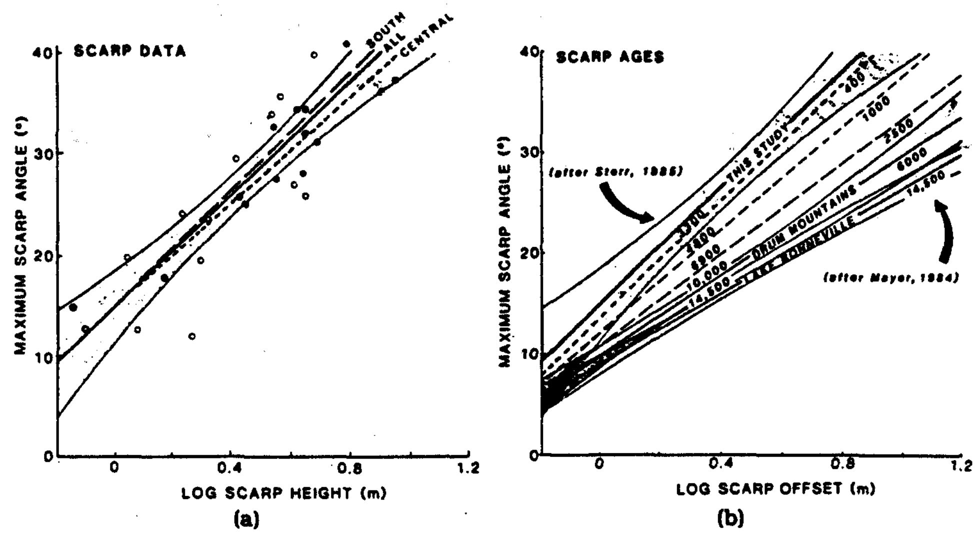

FIG. 4. (a) Regression of maximum scarp angle against the common logarithm of scarp height for scarps in the central area (open symbols and dotted line) and southern area (closed symbols and dashed line). Solid line and error bars (95% confidence interval) represent composite data. (b) Estimated morphologic ages of Eagle Bay Fault scarp from composite regression line, disequilibrium model, and assumed ages for older scarps (see text). Decreasing dash length implies increasing uncertainty. Error bars represent 95% confidence interval.

relationship (cf., Pierce and Colman, 1986). A similar analysis for 12 scarps in the southern area (Fig. 2b and 4a) yields a statistically similar regression. The implication is clear: that the scarps in the two areas are of the same age, thus that the aggregate data set ($r^2 = 0.71$) can be used for age estimates. The conclusion of a single rupture event is supported by the observations that each scarp segment is cut by Holocene shorelines at the same elevation above present lake level (thus of the same age), and that fault offset is independent of pre-fault shoreline elevation (Fig. 2) (thus multiple offsets have not occurred since deglaciation).

The scarp steepness/offset relationship is subparallel to that observed (corrected for far-field slope by Hanks *et al.*, 1984) for lakeshore (Lake Bonneville) and tectonic (Drum Mountains) scarps from the Great Basin, but steeper for a given height (Fig. 4b). Assuming a logarithmic decrease in the rate of scarp degradation with both time and scarp height, comparable rates of scarp evolution, and the ages of 14,500 and 6000 years for the Lake Bonneville and Drum Mountains scarps, respectively (after Mayer, 1984; Hanks *et al.*, 1984), yields an approximate age of 400 years for surface rupture on the Eagle Bay Fault (Fig. 3b). Alternatively, using an age of 10,000 yr for the Drum Mountains scarp (after Sterr, 1985) and retaining the other assumptions yields an age of about 3300 yr for the Eagle Bay scarp (Fig. 3b).

Clearly, there is no *a priori* reason for expecting that the rate of scarp evolution in Yellowstone—in beach sediments, under lodgepole pine, and in a cold subhumid climate—should be the same as the rate in the Great Basin—in gravelly colluvium, under sagebrush, and in a temperate semiarid to arid climate. We can test the possible scarp ages using approximate radiometric ages and crosscutting relationships with the lacustrine terraces. The scarp cuts a shoreline which has a minimum radiocarbon age of about 3500 yr and a maximum obsidian-hydration date of 4800 yr (Locke and Meyer, manuscript in preparation) and is cut by lower shorelines which have a maximum ^{14}C age of 620 yr BP.

We dug a pit into the scarp in the southern area (Fig. 2). In the uniform gravel neither the fault plane nor offset units were evident. A sample of charcoal from 1 m depth in crudely slope-parallel scarp colluvium yielded an accelerator ^{14}C date of 4540 ± 40 yr BP (ETH-3987). Either of the morphological ages (3300 or 400 yr) is acceptable relative to the ages of the shorelines, however, the older morphologic age is more consistent with the colluvium date. In either case, the rate of scarp evolution in beach sediments, under lodgepole pine, at a mean annual temperature near 0°C is similar to that reported in the colluvium of warmer, more arid settings. This similarlity may reflect fundamental disequilibrium processes, but may also result from coincidental interaction among the several environmental variables.

There are several noteworthy aspects of this faulting. First, the trace of the scarp, shown by the morphological analysis (Fig. 3) to represent a single rupture event, is apparently continuous for 10 km and possible more (under Yellowstone Lake to the north: USGS, 1972; Richmond, 1974). This trace crosses the interpreted caldera boundary (Fig. 1; e.g., Richmond, 1974). Evidently the caldera is sufficiently cool that regional extension, perpendicular to the caldera margin, can propagate into the caldera across or beneath its bounding faults.

A second point of interest is the lack of accumulated offset along the fault which is evident in the far-field slope data. There is no topographic evidence of repeated Holocene or Quaternary movement along the present fault, which might imply that the regional stress field has only recently generated brittle fracture within the caldera.

Finally, the offset along this fault is large. In the southern part of the central scarp region, a graben in bedrock shows up to 15 m of throw and > 5 m of net offset. This displacement is greater than that observed in the $M_s = 7.3$ Borah Peak earthquake of 28 October 1983 (maximum scarp height 5 m; Crone, 1987). The offset observed in Yellowstone is incompatible with a fault length of as little as 10 km (based on western U.S. earthquake ground ruptures: Bonilla *et al.*, 1984). The scarp dies out at the southern edge of the mapped area (although it might step westward to the fault trend inferred by USGS, 1972), supporting the inference of northwards continuation of the fault beneath Yellowstone Lake (USGS, 1972). The scarp height is also suggestive of the potential of $M_s > 7$ earthquakes (Bonilla *et al.*, 1984). Alternatively, the unusually high scarp may reflect a local anomaly of crustal thickness or strength. R. B. Smith (oral comm., 1986) has cited an $M_s = 6$ earthquake of volcano-tectonic origin as perhaps the greatest natural hazard in Yellowstone National Park: this scarp implies that a larger earthquake ($M_s > 7$) caused by regional extension may pose a greater hazard to the region. Unfortunately, the lack of evidence for multiple rupture events makes recurrence interval estimation for such earthquakes impossible.

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