Included in 1997 CGS Geohazards Conference field trip guidebook

Seismicity and Quaternary Faulting near Ridgway, Colorado

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Introduction

As part of an ongoing dam safety evaluation program, the U.S. Bureau of Reclamation has conducted several seismotectonic studies in southwestern Colorado. This paper briefly describes the results of those studies that pertain to the vicinity of Ridgway, Colorado.

The Ridgway region lies near the boundary between the Colorado Plateau and Southern Rocky Mountains physiographic provinces. The Colorado Plateau is an uplifted crustal block bounded by extensional block-faulted regions of the Basin and Range province on the west, the Rio Grande rift zone on the southeast, and the Southern Rocky Mountains on the north and east. The Plateau is characterized by basement uplifts that formed primarily during the late Cretaceous to early Tertiary Laramide orogeny. Basement cores of these uplifts are concealed beneath pre-Cenozoic strata that are folded into gently dipping, broad, asymmetric anticlines. The Southern Rocky Mountains province is characterized by north to northwest-trending uplifts with exposed Precambrian crystalline cores. These basement-cored uplifts are typically bordered on the west and southwest by Laramide-age thrust faults.

An area covering a portion of western and central Colorado and northern New Mexico was defined for recent seismotectonic investigations (Figure 1). The area covers a specific portion of the Southern Rocky Mountains province but excludes the Colorado Plateau and Rio Grande rift seismotectonic provinces. This region encompasses basement-cored Laramide-age uplifts of the Uncompahgre Plateau, Uinta Mountains, and southwestern Rocky Mountains, but excludes the relatively undeformed Tertiary to upper Cretaceous rocks of the Colorado Plateau. Previous observations suggest the eastern margin of the Colorado Plateau is somewhat more seismically active than other areas of northern New Mexico and southern Colorado (House and Hartse, 1995). The region appears to be responding to east-northeast-directed minimum principal stresses (Zoback and Zoback, 1989). A similar area was defined by Kirkham and Rogers (1985) as the "Western Mountain" seismotectonic province.

Faulting near Ridgway

Late Cenozoic faults in the area generally show normal displacement parallel to the strike of pre-existing Laramide structures, and typically occur in the hanging walls of Laramide thrust faults. These relationships are consistent with models that propose reactivation of Laramide thrust faults as normal faults in the contemporary extensional tectonic setting. The distribution, orientation and kinematics of the late Cenozoic faults in the region, therefore, are strongly influenced by the regional structural fabric developed during the Laramide orogeny.

Several faults in and adjacent to the southern end of the Uncompahgre Plateau near Ridgway have been investigated in the course of regional seismotectonic evaluations (Sullivan et al., 1980; Weisser, 1982; Lettis et al., 1997). These faults include the Ridgway fault and associated branch faults, the Cow Creek fault, the Busted Boiler fault, and the Log Hill Mesa graben faults (shown on Figure 2).

The Ridgway fault is a 24-km-long, east-west-striking, down-to-the-south normal fault with 450 m of post-Cretaceous displacement. There is no evidence of late Quaternary surface displacement along the trace of the fault; middle and late Quaternary glacial and landslide deposits are undisplaced. However, microseismicity appears to be associated with the fault. Earthquake focal mechanisms (Figure 2) indicate that the present sense of slip on the fault includes a significant strike-slip component, which is consistent with the current stress regime. Based on the occurrence of microearthquakes, the Ridgway fault is considered potentially active, though it does not necessarily follow that the fault is capable of generating large earthquakes accompanied by surface rupture in the current stress regime.

The branch faults and the Cow Creek fault are generally north-striking faults that extend northward from the Ridgway fault north of Ridgway. The branch faults of Sullivan et al. (1980) and Weisser (1982) are referred to as the eastern and western Ridgway Quarry faults by Lettis et al. (1997). These faults were interpreted to be late Quaternary tectonic features by Sullivan et al. (1980) based on limited quarry exposures, but have been reinterpreted based on further field studies as landslide related by Lettis et al. (1997). Other than the ambiguous quarry exposures, there is no suggestion of late Quaternary surface rupture on these faults. The Cow Creek fault was discovered during construction of Ridgway Dam and was investigated in detail by Weisser (1982) because the fault is present in the right abutment and outlet works area of the dam. The Cow Creek fault is 4-6 km long and has experienced a total of 9-13 m of vertical, down-to-the-east normal displacement. Geologic mapping and interpretation of three backhoe trenches showed that the fault does not displace glacial outwash deposits of middle Pleistocene age (>130 ka). More so than the Ridgway fault, there appears to be a demonstrable association of microseismicity with the Cow Creek fault (Figure 4). Focal mechanism data are consistent with normal displacement (Figure 2).

The Busted Boiler and Log Hill Mesa graben faults extend northward from the Ridgway fault onto the Uncompahgre Plateau for 19 km and 10 km, respectively. The Busted Boiler fault shows < 30 m of displacement of the Cretaceous Dakota Group. It forms a 5- to 30-m-high west-facing escarpment along the eastern edge of a discontinuous 200-m-wide graben. The age of the scarp is unknown, but disruption of drainages and ponding of late Quaternary sediment suggest the fault is potentially active. The 1-km-wide Log Hill Mesa graben is bounded by well-defined scarps that offset Pleistocene pediment surfaces and may displace middle to late Pleistocene alluvial fans. Reconnaissance field studies suggest that younger deposits are undeformed.

Seismicity

The earthquake record in Colorado dates back to about 1870. The largest historical earthquakes in the region are the enigmatic event of November 7, 1882 (M_L 5.8 to 6.5) and two magnitude m_b 5.5 events, one of which occurred on October 11, 1960 near Ridgway in southwestern Colorado and the other on January 23, 1966 near the border of New Mexico and Colorado. Contemporary seismicity, based on somewhat improved seismographic coverage, indicates that earthquakes of small magnitude are widely distributed throughout the region and occur occasionally in swarms (e.g. the 1984 Carbondale and 1986 Crested Butte swarms (Wong, 1991), and the Front Range activity west of Denver (Butler, 1993)). In 1985, as part of the seismotectonic evaluations described above, the U.S. Bureau of Reclamation installed a seven-station seismic network in the vicinity of Ridgway prior to the construction of Ridgway Dam. The data from this network have been important in evaluating the occurrence of induced seismicity as well as understanding the current stress-field as manifested by microearthquakes. Figure 1 illustrates the seismicity (magnitudes greater than M_L 2.0) in the southern Rocky Mountains region. The general pattern is one of diffuse seismicity with localized zones of enhanced activity. The highest rates of seismicity are in the areas near Ridgway and along the Colorado-New Mexico border (near Dulce). As described above these are areas where significant, felt earthquakes have occurred in this century.

Detailed examinations of seismicity in the immediate vicinity of Ridgway suggests a relationship between observed microseismicity and previously identified faults in the area. Figure 3 depicts the seismicity located by the seismographic network in the period of 1985-1995 in the vicinity of Ridgway along with the faults identified as potentially active by recent investigations (discussed above). Some portion of the abundant seismicity in the immediate vicinity of the reservoir has been interpreted as potentially induced (Ake et al., 1994; Vetter et al., 1995). The most consistently active area for the entire decade of monitoring has been the area to the east beneath Cimarron Ridge. Much of this seismicity to the east of the reservoir (along Cimarron Ridge) is unlikely to be associated with the filling of Ridgway Reservoir as it was the inferred location of several felt events prior to the construction of Ridgway Dam. Activity to the west associated with the September 1994 M_L 4.6 earthquake is also unlikely to be related to the presence of the reservoir due to the large hypocentral distance from the reservoir. Figure 4 is a cross-section of the seismicity shown in Figure 3. The location of the 1994 earthquake sequence is obvious as is the seismicity to the east under Cimarron Ridge. The inferred down-dip extent of the Cow Creek fault appears to have associated seismicity as well. The majority of earthquakes in the area appear to be occurring in the 5-12 km depth range. This is a typical depth distribution for much of the western United States. The very near surface events shown beneath Ridgway Reservoir are inferred to be "ice quakes" as they all occurred during the winter months and had unusual seismic signatures.

Tectonic Stress Field From Focal Mechanisms

Recent compilations of focal mechanisms within the Southern Rocky Mountains province suggest generally normal faulting in response to NE-SW directed extension (Ely et al., 1986; Vetter et al., 1995; Wong, 1986). The focal mechanisms developed to date for the area (shown on Figure 2) support this broader observation. The well-constrained focal mechanism of the M_L 4.6 September 1994 event (shown on Figure 2) strongly suggests east-northeast-directed minimum principal stresses. The modern stress direction is in contrast to the E-W compression that seems to have prevailed during the Laramide uplift, which ended about 50 Ma (Zoback and Zoback, 1980).

None of the focal mechanisms published to date (either individually or in aggregate) are unambiguous enough to provide definitive constraints on the P- or T-axes in this area. We interpret the data from the Ridgway area as being a good indicator of the general behavior to be expected within the "Southwestern Mountain" region of Colorado. Based on most of the information available at the present time, the deformation currently occurring near Ridgway is mainly extensional in response to NE-SW (+/- 30 degrees) oriented least principal stresses. Earthquakes appear to be occurring on pre-existing faults (probably Laramide in age) favorably oriented in the current stress field. Hence, faults with north to northwest trend would be the most favorable candidates for reactivation. Probably not coincidently, most of the young faults in western Colorado (c.f. Figure 2 and faults of the Rio Grande rift) have a generally north to northwest trend.

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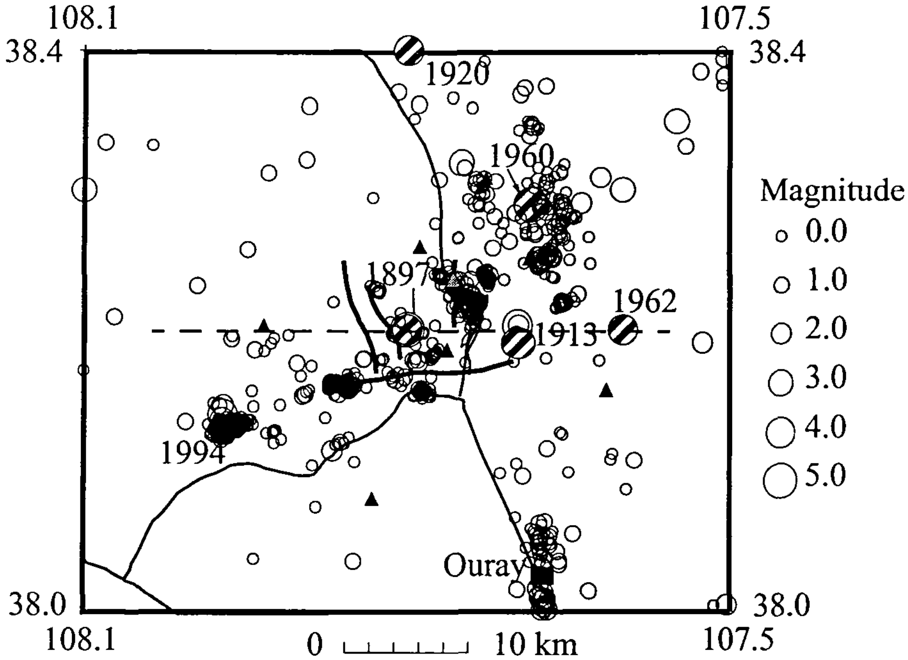

Figure 3. Seismicity in the Ridgway area. Approximate locations of historical events indicated by hatched pattern circles (800 events plotted). Seismograph stations indicated by dark triangles, faults by heavy dark lines. Line of section in Figure 4 shown by dashed line.

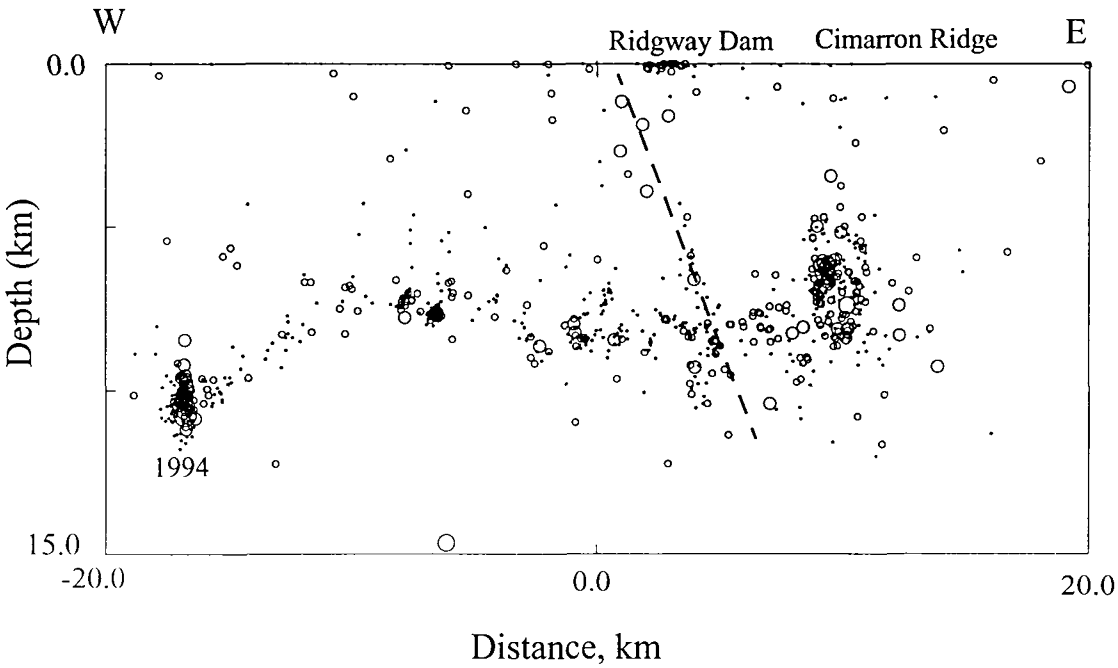

Figure 4. Cross section of seismicity in the Ridgway area. Position of Ridgway Dam indicated. Dashed line indicates approximate projection of Cow Creek Fault. Events at ~10 km depth to the west are associated with September 1994 M 4.6 event.

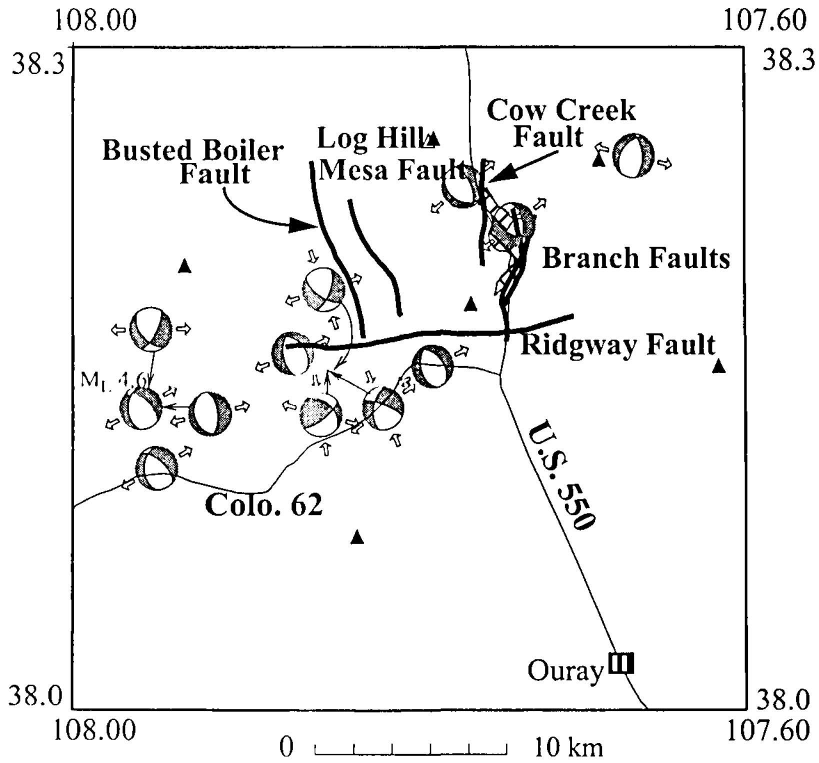

Figure 2. Better constrained focal mechanisms from Ridgway seismic network data, 1987-1994, shown with identified young faults in the area (heavy dark lines). Location of seismograph stations indicated by dark triangles, Ridgway Reservoir by cross-hatched pattern.

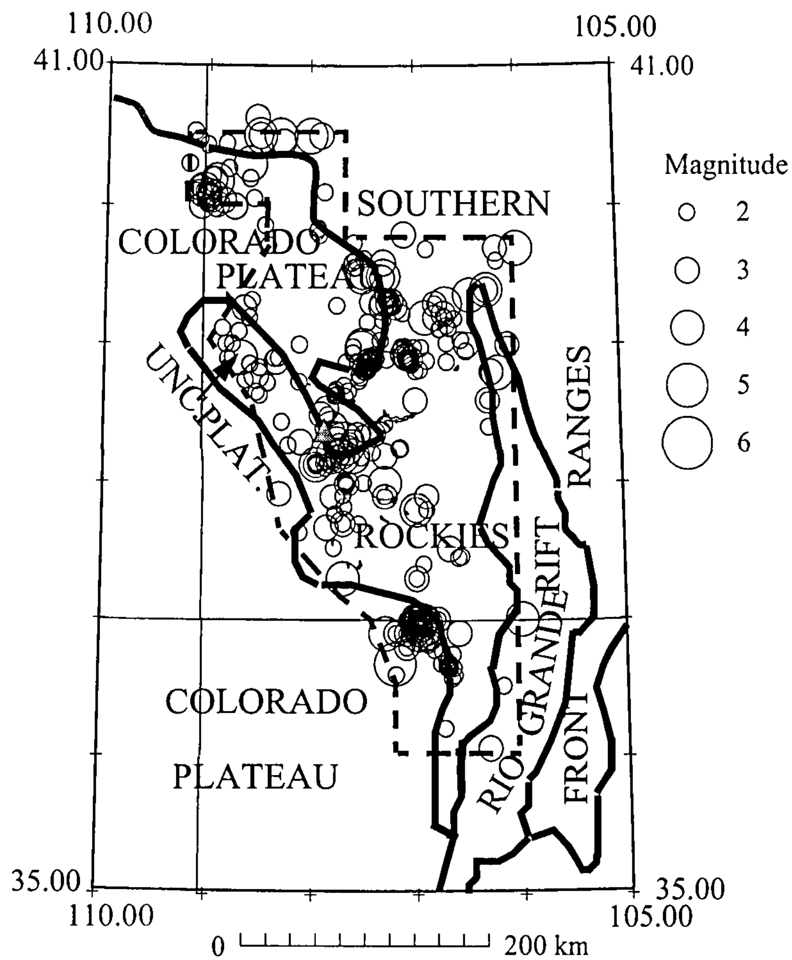

Figure 1. Physiographic provinces of southwestern Rocky Mountains and eastern Colorado Plateau. Study area indicated by dashed line, location of Ridgway Dam indicated by shaded triangle. Seismicity greater than M 2 plotted (421 events).