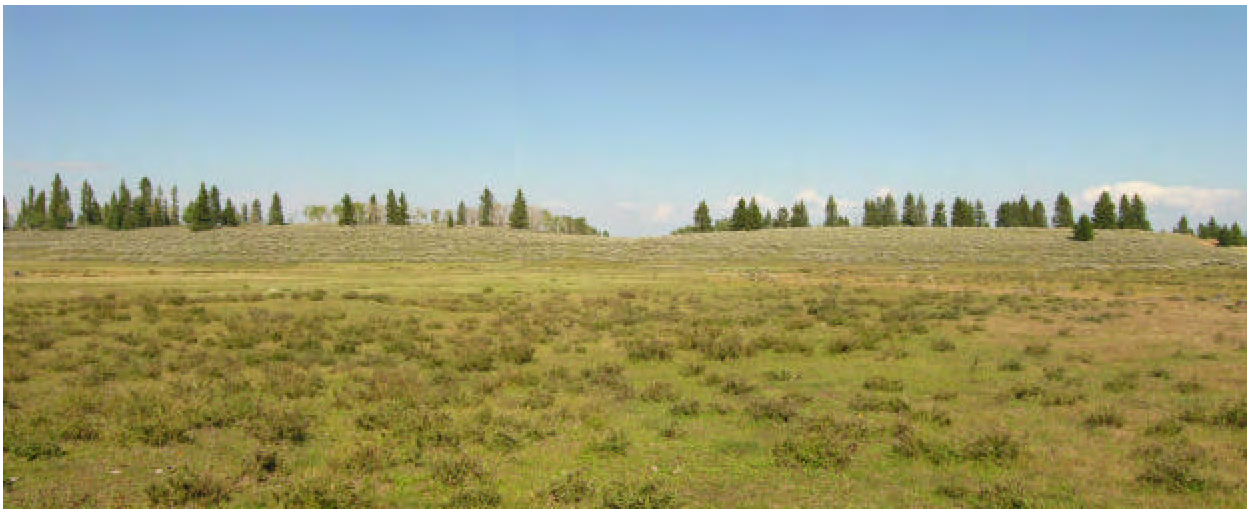
NEOTECTONICS OF QUATERNARY FAULTS Q20, Q22, AND Q23 IN THE CENTRAL UNCOMPAHGRE PLATEAU, COLORADO



Submitted to:
U.S. Bureau of Reclamation
Attention: Dean Ostenaa, 86-68330
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Denver CO 80225-0007

Submitted by:
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December 23, 2006

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October 8, 2006
Dec. 23, 2006

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1. ABSTRACT

Based on map compilation, photo interpretation, and limited field checking, there is a NW-trending zone of Quaternary faulting in the central Uncompahgre Plateau at least 32 km long that coincides with parts of previously-mapped faults Q20, Q22, and Q23 (Widmann et al., 1998). The youngest fault scarps identified are 1-12 m high, have steep scarp faces (slightly below the angle of repose), and in some cases truncate Quaternary landforms such as stream valleys. These late Quaternary fault scarps all lie at the toes of ca. 60-m high, NE-facing escarpments and form the margins of prominent grabens at the toes of the escarpments. Of the three prominent escarpments that have such grabens (Roubideau Creek fault, fault Q20/2270; Roubideau Ranch fault, fault Q22/2272; Old Paradox Road fault, fault Q23/2273), the first is clearly a monocline. Exposures are insufficient to prove that the other two escarpments are also monoclines, although I suspect they are.

In addition to these late Quaternary scarps, there are older scarps that disrupt the smooth plain of the Dakota dipslope. These scarps are at least partly erosional, but seem to be younger than the removal of the Mancos Shale from atop the Dakota-Burro Canyon sandstones on the plateau dipslope. One such area of scarps is the Donley-Garrison faults, a group of 7 faults that separates the Roubideau Ranch fault from the Old Paradox Road fault.

This mapping study has identified many late Quaternary and Quaternary (undivided) fault scarps, but many questions remain as to the age of the fault scarps, and whether they are fault scarps, fold scarps, or some combination of the two. McCalpin (2003) made some very preliminary estimates of scarp age to calculate recurrence intervals and slip rates for the Roubideau Creek fault, but these estimates were not supported by any numerical dates.

One of the key assumptions of McCalpin (2003) was that only the grabens and isolated antislope scarps were of Quaternary age, and the much higher 60 m-high monoclines were pre-Quaternary. This assumption was based on an inference that Quaternary deformation occurred at very low confining pressures, when the landscape looked essentially as it does today, so it must be expressed as brittle faulting. Accordingly, folding such as observed at Roubideau Creek was inferred to represent pre-Quaternary ductile deformation that required high confining pressures, which could only have occurred when there was still a thick cover of post-Dakota sedimentary rocks still covering the Plateau.

When the author presented a guest lecture at Utah State University on these faults in Fall of 2006, the two structural geologists there (James P. Evans, Suzanne Janecke) took exception to the inferences above. They argued that the entire monocline could also could have formed in Quaternary time, when the landscape looked like it does today. In other words, they thought that the monoclines could have formed as forced folds over a normal fault at or near the ground surface. Supporting evidence was cited in the paper by White and Crider (2006).

If their contention is true, it offers a way to compute the long-term Quaternary slip rate on these normal faults, since the monoclines began developing. Such a long-term slip rate could be compared to the short-term slip rates computed for smaller (2-10 m-high) fault scarps.

2. INTRODUCTION

2.1 Justification of Study

The justification for this study is described by the Statement of Work in USBR Purchase Order 06PG810275:

"*The Seismotectonics and Geophysics Group (86-68330) of the Bureau of Reclamation (Reclamation) has a requirement for specialized technical studies of potential seismic sources (the Roubideau Creek fault and other nearby faults) for Ridgway Dam.*

The Probabalistic Seismic Hazard Analysis (PSHA) for Ridgway Dam that was conducted in 2002 included several faults on the Uncompahgre Plateau west of the dam as likely sources of significant earthquakes near the dam. Earlier deterministic studies concluded that the north-striking faults on the Uncompahgre Plateau could have experienced late Quaternary activity, but provided little actual data. Because of the sparse information that was available about these faults, the slip rates that were used in the PSHA had broad limits.

86-68330 is presently re-assessing faults on the Uncompahgre Plateau in order to provide more information about the seismic hazard posed by these geologic structures to Ridgway Dam and to refine the slip rates on these faults. Few faults on the Uncompahgre Plateau have been studied in any detail to evaluate their seismogenic potential, which is difficult because of the low slip rates on these faults and the unique geomorphology of the region. Initial assessments to date have included geomorphic and trenching studies of the Busted Boiler and Log Hill Mesa faults. Results of these investigations indicate the need to expand the area of investigations to include several faults north and west of Ridgway Dam. 86-68330 will be conducting some of these investigations, but wishes to utilize previous work by others to the greatest degree possible.

Dr. James P. McCalpin has previously conducted a preliminary assessment of one of the faults of interest, the Roubideau Creek fault, for the Colorado Geological Survey. The results of that assessment are needed in expanded form, and in digital GIS format for inclusion in the ongoing 86-68330 studies. The combined results of the contracted and 86-68330 investigations will be used to develop a new PSHA for Ridgway Dam."

2.2 Scope of Work

The scope of work was also set out in P.O. 06PG810275, as follows: "*The Contractor will:*

(1) digitize existing mapping from the Preliminary assessment of neotectonics of the Roubideau Creek fault prepared for Colorado Geological Survey and ARCGIS 9 compatible files; [see McCalpin, 2003]

(2) conduct additional field checking and mapping of the Roubideau Creek fault to confirm the style of faulting associated with previously mapped lineaments; [Photogeologic mapping performed in Crestone, CO, August, 2006; field checking performed Sept. 4-12, 2006]

(3) conduct additional photogeologic and field mapping along CGS database faults Q20, Q22, Q23 and adjacent areas; [These fault designations are from Widmann et al., 1998. Photogeologic mapping was performed in Crestone, CO, August, 2006; field checking was performed Sept. 4-12, 2006]

(4) compile results of new mapping together with previous mapping into ARCGIS 9 compatible files,

(5) conduct 2-day field review with 86-68330 staff of mapping results and assessment of similar features mapped in adjacent areas by 86-8330; [field review held Sept. 13-14, 2006]

(6) document mapping results and field review observations in letter report; [this report].

2.3 Location and Physiography

Faults Q20 (Roubideau Creek fault), Q22, and Q23 lie in the central Uncompahgre Plateau west of Montrose, Colorado (Fig. 1). The Uncompahgre Plateau is dominantly a gigantic dip slope underlain by the resistant Dakota Sandstone and Burro Canyon Formation. The Plateau strikes about N30°W, is roughly 50 km wide and 160 km long, and slopes northeastwards from a high elevation of 10,000 feet on the west to 5000 feet on the east. The Roubideau Creek fault lies about in the center of the Uncompahgre Plateau, and crosses terrain with an average elevation of about 8500 to 9000 feet.

The Roubideau Creek fault (fault Q22 of CGS; fault 2270 of USGS) is located about 40 km west of Montrose, Colorado, on the west flank of the Uncompahgre Plateau of western Colorado (Fig. 1). The fault is located in (from west to east) the central parts of the Moore Mesa, Davis Point, and Dry Creek Basin 7.5' topographic quadrangles and trends on average N74°W. The Colorado Geological Survey on-line Database of Quaternary Faults and Folds (Widmann et al., 1998) lists the fault's end-to-end length as 20.47 km (Fig. 2), with the fault trace "taken from Williams (1964)." However, the fault trace shown in Williams (1964) is only 10 km long**.** Presumably, the additional 10.47 km of fault length shown by Widmann et al. (1998), which is dashed lines on the east and west ends, was taken from Lettis et al. (1996).

Faults Q22 (fault 2272 of USGS) and Q23 (fault 2273 of USGS) are zones of multiple faults that trend southeast from the Roubideau Creek fault toward the Busted Boiler and Log Hill Mesa faults. These faults occupy the southern parts of the 3 7.5' quadrangles listed above, but in addition enter into the 3 quadrangles to the south (from west to east, Ute, Antone Spring, and Pryor Creek.

The following summary of the geologic history of the Uncompahgre Plateau is taken from Kirkham and Rogers (1981):

" The Uncompahgre uplift rose during the Neogene from the crest of an older, much larger highland that was a prominent structural feature during the late Paleozoic (Cater, 1966). Distribution and thickness of late Paleozoic sedimentary formations derived from the highland suggest the ancient upwarp was bounded by large faults on the southwest, while the northeast limb, which extended farther east than the present uplift, gently dipped to the northeast (Cater, 1970). Structural relief along the southwestern flank during the Paleozoic may have been as great as 2440 m……….."

"The modern Uncompahgre uplift is a northeast-tilted block, structurally similar to its predecessor but much smaller. The southwestern flank and part of the northeastern flank near Grand Junction are bounded by abrupt, locally faulted monoclines (Lohman, 1965; Cater, 1970). Cater (1966, 1970) presents evidence suggesting the modern Uncompahgre uplift has experienced considerable movement during the Pliocene and Quaternary, and that many of the faults and monoclines which bound the uplift were activated during this period."

Williams (1964) maps numerous faults on the Uncompahgre Plateau, most of which trend NW-SE or WNW-ESE and dip very steeply (Fig. 1). The Roubideau Creek fault is mapped as being downthrown to the northeast, and presumably has a near-vertical dip, based on its straight mapped trace across Roubideau Canyon. The surface of the Plateau drops about 60 m down-to-the-northeast across the fault. If the Plateau surface is underlain by the same bed of the Dakota-Burro Canyon Fm. on both sides of the fault, then the Cretaceous beds are displaced about 60 m down-to-the-northeast.

2.4 Regional Geology and Tectonics

The Uncompahgre Plateau is dominantly a gigantic northeast-dipping dip slope underlain by the resistant Dakota Sandstone and Burro Canyon Formation. Major streams flow northeast and have incised canyons up to 300 m deep into the surface of the Plateau. These canyons, such as at Roubideau Creek (Fig. 1), expose the underlying Jurassic (Morrison) and Triassic (Chinle) Formations. The deepest canyons, such as Roubideau Creek, expose in their bottoms Precambrian basement rocks.

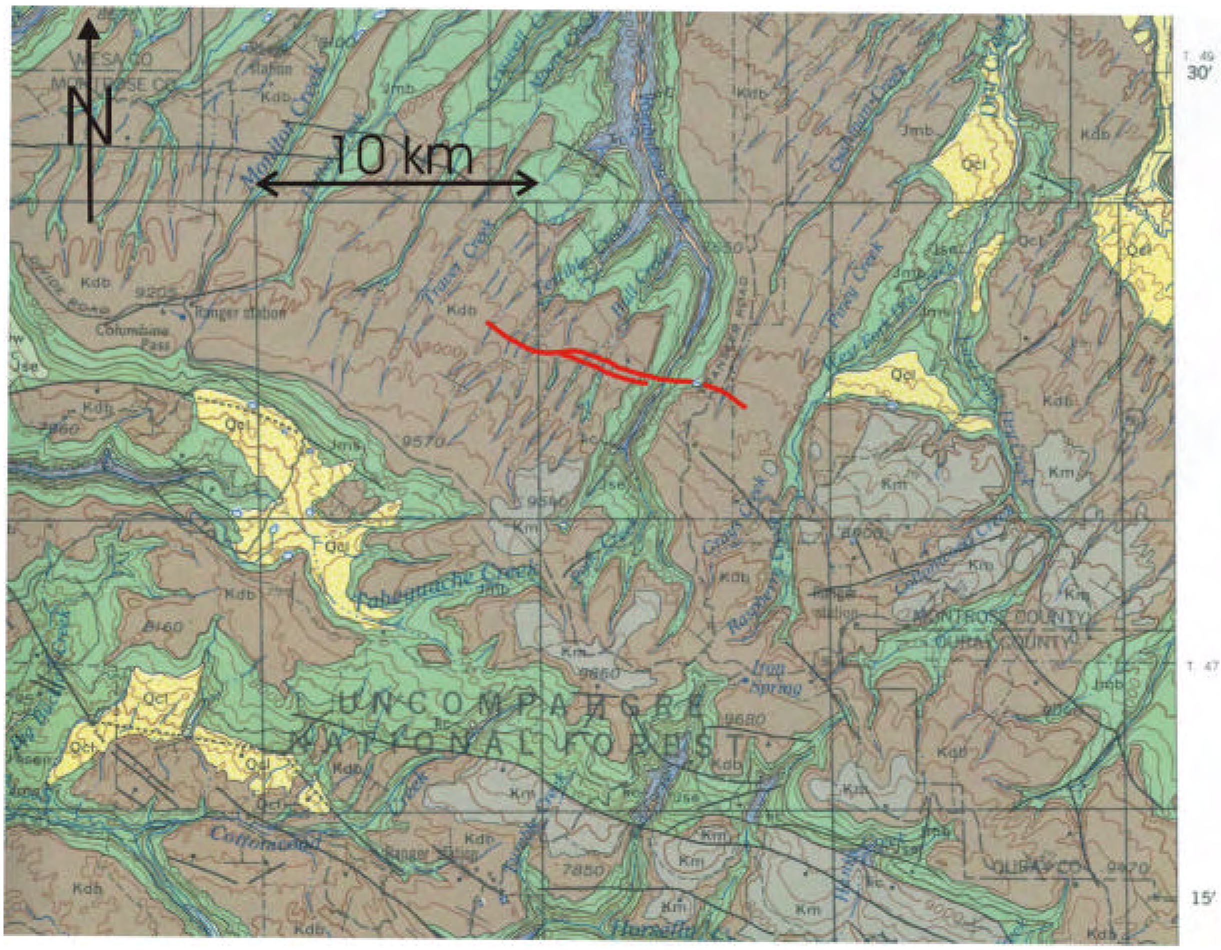

Fig. 1. Portion of the geologic map of the Moab 1° by 2° quadrangle (Williams, 1964; original scale 1:250,000). The Roubideau Creek fault is highlighted in red; note that its original mapped length is only half that shown in Fig. 1 (from Widmann et al., 1998). Most of the Plateau surface is underlain by map unit Kdb (in brown; resistant sandstones of the Dakota-Burro Canyon Formations), but small patches of the overlying Mancos Shale (unit Km, in gray) are preserved south and east of the fault. Incised canyons expose successively older rocks, including the Morrison Formation (in green; unit Jmb, Brushy Basin Member of the Morrison Formation; unit Jms, Salt Wash Member of the Morrison Formation: unit Jse, Entrada Sandstone; in blue, unit Trc, Chinle Formation). The Chinle Formation is directly underlain by Precambrian basement (unit PC, in pink).

2.5 Previous Work

The earliest mapping in the 6-quadrangle area studied herein was a 15' photogeologic map at 1:62,500 scale by Marshall (1959), which covered the area of the eastern 4 quadrangles (Davis Point, Dry Creek Basin, Anton Spring, and Pryor Creek). Marshall's map contained 1 fault, "definite"; 82 faults, "approximately located"; 7 faults, "probable"; and 47 "linear features (geologic significance uncertain from photointerpretation)." Marshall (1959) did not map any monoclines.

The study area was also covered by the 1:250,000-scale geologic map of the Moab 2° sheet compiled by Williams in 1964. In that map, the source mapping for the 4-quadrangle area described above was cited as Marshall (1959), and for the 2 quadrangles farther west, as "Pomeroy, J.S. and Marshall, C.H., unpublished photogeologic map." Despite this attribution, however, there are puzzling differences between Map I-283 and Map I-360.

(1) Map I-360 shows only 33 faults in the 4-quadrangle area, compared to the 90 faults shown on Map I-283 in that same area. This omission may have been justified by the need to condense to the smaller map scale of I-360 (1:250,000), but the 2/3 of the faults omitted are not always the shortest ones. The reason these omissions are relevant, is that Map I-360 is the main map basis for both the CGS and USGS Quaternary Fault and Fold Databases. Surprisingly, Marshall's (1959) Map I-283 is not cited by either fault database (see Appendices 1-8).

(2) For the northern strand of the Roubideau Creek fault (Q20) and the *Roubideau Ranch fault* (Q22a), I-360 shows an opposite sense of slip to that shown on Map I-283. There is no explanation for this discrepancy, which may be a drafting error.

(3) Some faults on I-360 are longer than their counterparts on I-283 (faults Q20, Q22b), but some are shorter (fault Q22a).

(4) One fault on I-360 (fault Q22c) is not mapped at all on I-283.

In 1978 through 1981, Sinnock (1978, 1981a, 1981b) published several general papers on the geomorphology of the Uncompahgre Plateau. Although his emphasis was not on structural geology, Sinnock was the first to map the large monoclines associated with the Roubideau Creek, Roubideau Ranch, and Old Paradox Road faults.

In addition to the discrepancies between the source maps, there are discrepancies between the source maps and the CGS/USGS Quaternary Fault and Fold Database, which are discussed more later. The CGS On-Line Fault and Fold Database is shown in Fig. 2a (http://geosurvey.state.co.us/CGS_Online/WEB/LoadMap.cfm). Here, the Roubideau Creek fault is shown in red (Q20, "Holocene") and other "Quaternary" faults in blue. Faults Q22 and Q23 lie SE of the Roubideau Creek fault, but are unnumbered on the map. The correlative map from the USGS On-Line Quaternary Fault and Fold Database (http://earthquake.usgs.gov/regional/qfaults/ is shown in Fig. 2b. On this map, the Roubideau Creek fault is 2270, the fault Q22 zone is 2272, and the fault Q23 zone is 2273. These two databases use a different color scheme to label lines, but the fault lines are identical. Black rectangles show the six 7.5' quadrangles described in this study.

For chronological comparison of these discrepancies, see Table 1. Fig. 3 is a map that graphically shows the differences between the source mapping of USGS Map I-283, USGS Map I-260, and the Quaternary Fault and Fold Database.

2.6 Acknowledgments

This study would not have been possible without the access provided by local landowners. In particular, I wish to thank Mr. Edwin Garrison of Montrose for permitting access to his ranch and the "Garrison ranch fault" (fault 2272C); Mr. Donald Duepree of Montrose for access to the Roubideau Ranch and the "Roubideau Ranch fault" (fault 2272A); and Mr. Dennis Gray of Montrose for access to his land containing the "Old Paradox Road fault" (fault 2273A).

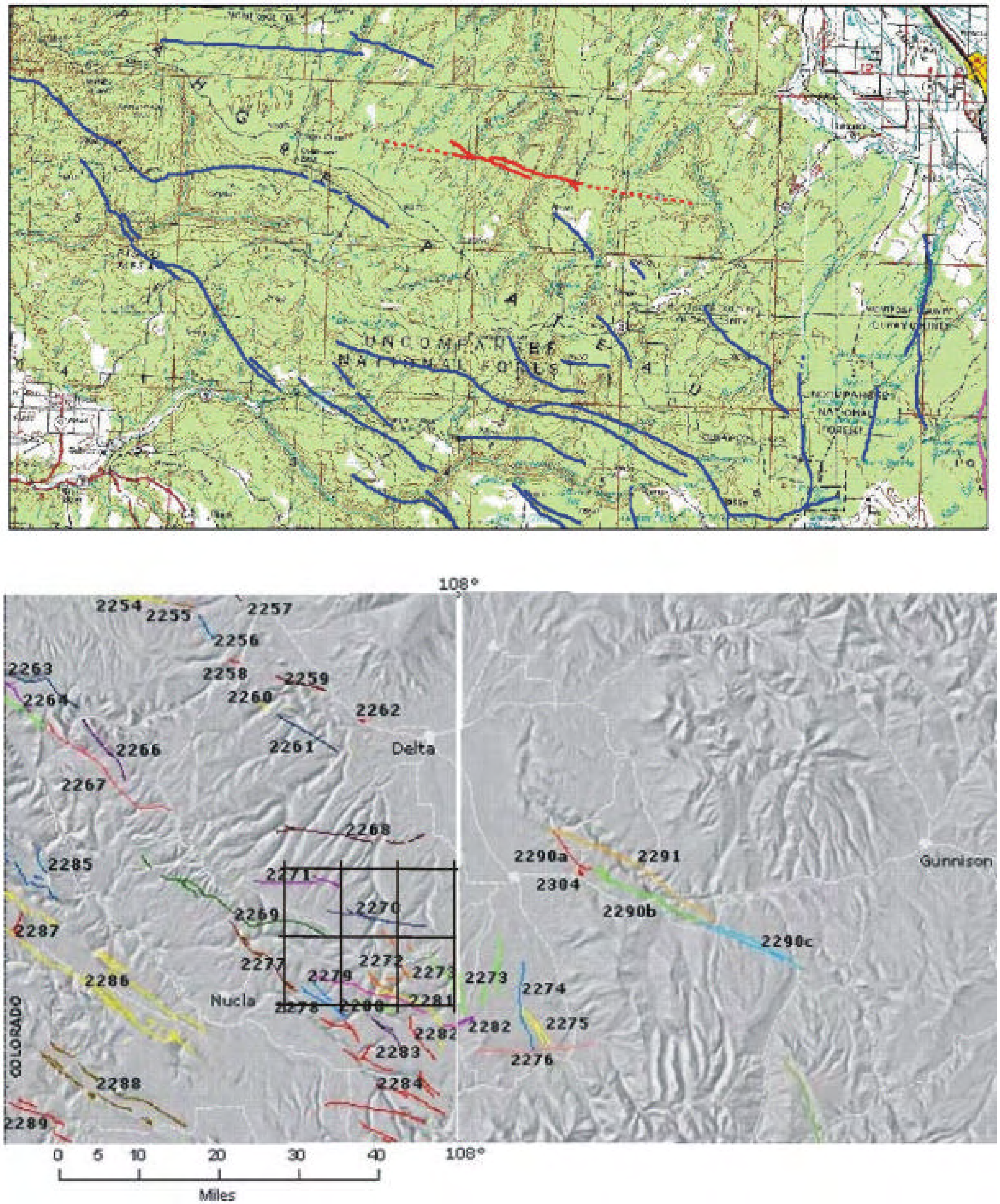

Fig. 2. Fault database maps. (a) Upper map from CGS On-Line Quaternary Fault and Fold Database of Colorado (http://geosurvey.state.co.us/CGS_Online/WEB/LoadMap.cfm). Roubideau Creek fault in red (Q20, "Holocene") and other "Quaternary" faults in blue. Faults Q22 and Q23 lie SE of the Roubideau Creek fault. (b) Lower map from USGS On-Line Quaternary Fault and Fold Database (http://earthquake.usgs.gov/regional/qfaults/). On this map, the Roubideau Creek fault is 2270, the fault Q22 zone is 2272, and the fault Q23 zone is 2273. Rectangles show the six 7.5' quads described in this study.

Table 1. Faults shown in CGS and USGS Quaternary Fault Databases, and how they were mapped in the original source maps.

CGS #[1]	CGS name[1]	**USGS #[2]**	My Scarp#[3]	Name[4]	USGS Map I-283 (Marshall, 1959)	USGS Map I-360 (compiled by Williams, 1964)[5]	Sinnock (1978; 1981a, b)[5]
Q20	Roubideau Creek fault	**2270**	2270-01 through 2270-22	Roubideau Creek fault	2 major strands mapped; N strand extends from Beach Creek to E of Transfer Road, is down-to-S, 6.1 km long; S strand goes from 108°15' to edge of Roubideau Canyon, is down-to-N, >4 km long; Total Fault Length >7.4 km	N strand was extended 0.8 km to SE, into Montrose County, along a lineament shown on Map I-283; was also **extended 2.2 km W** of 108°15', **for unknown reason**; **slip sense was changed to down-to-N** S strand was unchanged TOTAL FAULT LENGTH= 9.5 km	N strand is **changed back to a down-to-S fault, and extended SE** to the West Fork of Dry Creek, 1.5 km farther into Montrose County **S strand is mapped as the crest of a down-to-N monocline**, steeper at crest
Q22	Unnamed faults east of Roubideau Creek	**2272(A)**	2272-01 through 2272-09	*Roubideau Ranch fault*	Down-to-NE fault; the NW 2.4 km lies in Ouray County and is mapped as definite; the SE 3.2 km lies in Montrose County and is queried; Total Fault Length= 5.6 km	**Slip sense was changed to down-to-SW, for unknown reason; fault was shortened at both ends, to reduce TOTAL FAULT LENGTH to 4 km**	Mapped only in Ouray County, **as a down-to-NE monocline, steeper at crest**; 3.2 km long
		2272(B)	2272-13 to 2272-14	*Donley Camp fault*	Down-to-SE fault, 1.6 km long; has 2 parallel lineaments to NE and SW; terminates at a 2.4 km-long ENE-trending fault	SAME; parallel faults are not mapped; ENE-trending fault lengthened to 6.4 km long	SAME; parallel faults are mapped (SW one as the toe of a monocline); ENE-trending fault is curved to NNE to the N boundary of the Pryor Creek quadrangle
		2272(C)	No Q scarp	*Antone-Pryor fault*	Not mapped	Mapped as a down-to-SW fault; TOTAL FAULT LENGTH= 3.2 km	Fault mapped in same location as in I-360, but **slip sense changed to down-to-NE**
		2272(D)	No Q scarp	*Curved fault*	East half of fault, east of Red Canyon, is mapped as a straight "fault, probable"; no sense of slip; length 2.4 km	Fault is extended an additional 3.5 km west of Red Canyon; sense of slip down-to-N; length 6.2 km	Mapped similar to I-283, with no slip sense
		2272(E)	No Q scarp	*S of Divide*	Not mapped	**Mapped as "fault, approximately located"**; down-to-S; 4.1 km long (compared to Fault Database length of 3.0 km)	**Mapped as the eastern part of a much longer fault** that extends west into the Ute quadrangle; down-to-S
Q23	Unnamed faults SW of Montrose	**2273(A)**	2273-01	*Old Paradox Road fault*	Mapped as "fault, approximately located"; down-to-S; 9.5 km long	Same as in Map I-283	Same sense of slip as I-283 and I-360, but does **not map southeasternmost 2.2 km of fault; northeasternmost 3.2 km of fault is mapped at the toe of a NE-faicng monocline** (not mapped in I-283 or I-360)
		2273		Lie east of 108 degrees west longitude, so were not examined in this study			
		2273					
		2273					
		2273					

[1] from CGS On-Line Quaternary Fault and Fold Database, at http://geosurvey.state.co.us/CGS_Online/WEB/LoadMap.cfm
[2] from USGS On-Line Quaternary Fault and Fold Database, at http://earthquake.usgs.gov/regional/qfaults/. Capital letters in parentheses are used in this study, where the USGS fault number covers more than one fault trace.
[3] Scarp number used in this report. Each separate digitized line segment is assigned a unique number, even though the breaks between segments may simply represent erosion through a once-continuous fault trace.
[4] either the name used in the 2 databases cited above, or an informal name used for this report (*in italics*)
[5] **bold** type indicates a change from the previous published map

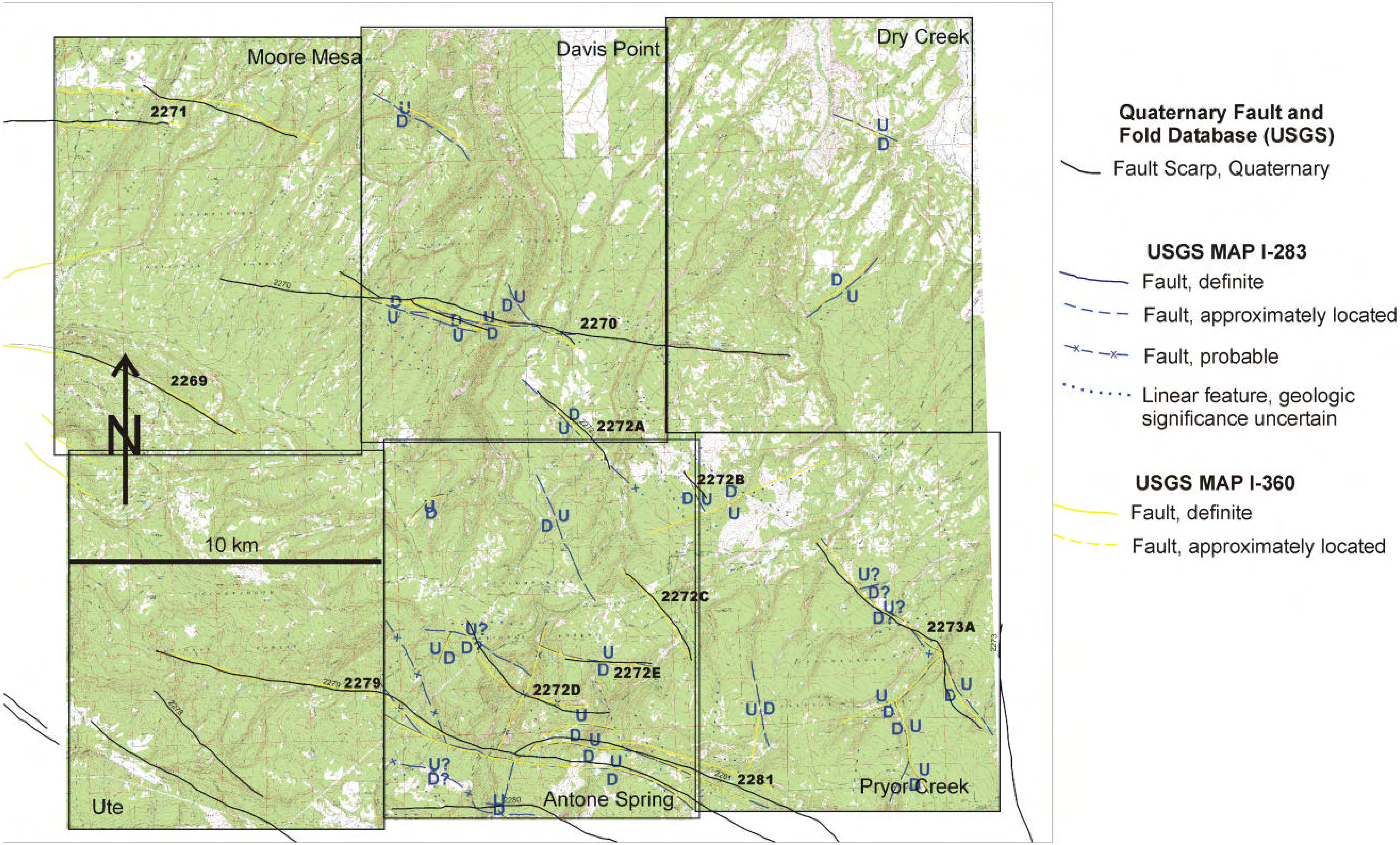

Fig. 3. Map showing the differences between faults on USGS Map I-283 (blue), USGS Map I-360 (yellow), and the USGS Quaternary Fault and Fold Database (black).

2.7 Overview of 2006 Mapping in This Report

The fault mapping in this report was based primarily on airphoto interpretation and limited field reconnaissance. Mapping is presented in 2 ways: (1) as figures within this report, and (2) as ESRI Shapefiles in UTM Zone 13, NAD27. In the figures and the Shapefiles, structures are subdivided as follows:

1—Fault scarp, late Quaternary (displaces late Quaternary deposits or forms a steep fault scarp)
2—Fault scarp, Quaternary (displaces either Quaternary deposits, or landforms of inferred Quaternary age)
3—Monocline crest and sides (large flexures in the caprock sandstones of the Plateau)
4—Eroded fault scarp, pre-Quaternary (anomalous linear slopes that face against the dip of the Plateau caprock, and have inferred fault saddles at their base)
5—Topographic Lineament (alignments of stream reaches, saddles in ridges, and other erosional features)
6—Photo Lineament (linear features on airphotos that have insignificant topographic relief; mainly vegetation linears)

Field checking concentrated on the Quaternary fault scarps, as shown in red on Fig. 4. All of the steepest of these Quaternary faults scarps (late Quaternary fault scarps) lie at the toes of large monoclines (Fig. 5). Fig. 5 shows all 4 of the 6 structure types mapped in this study (late Quaternary scarps are included within Quaternary scarps; eroded fault scarps are not shown).

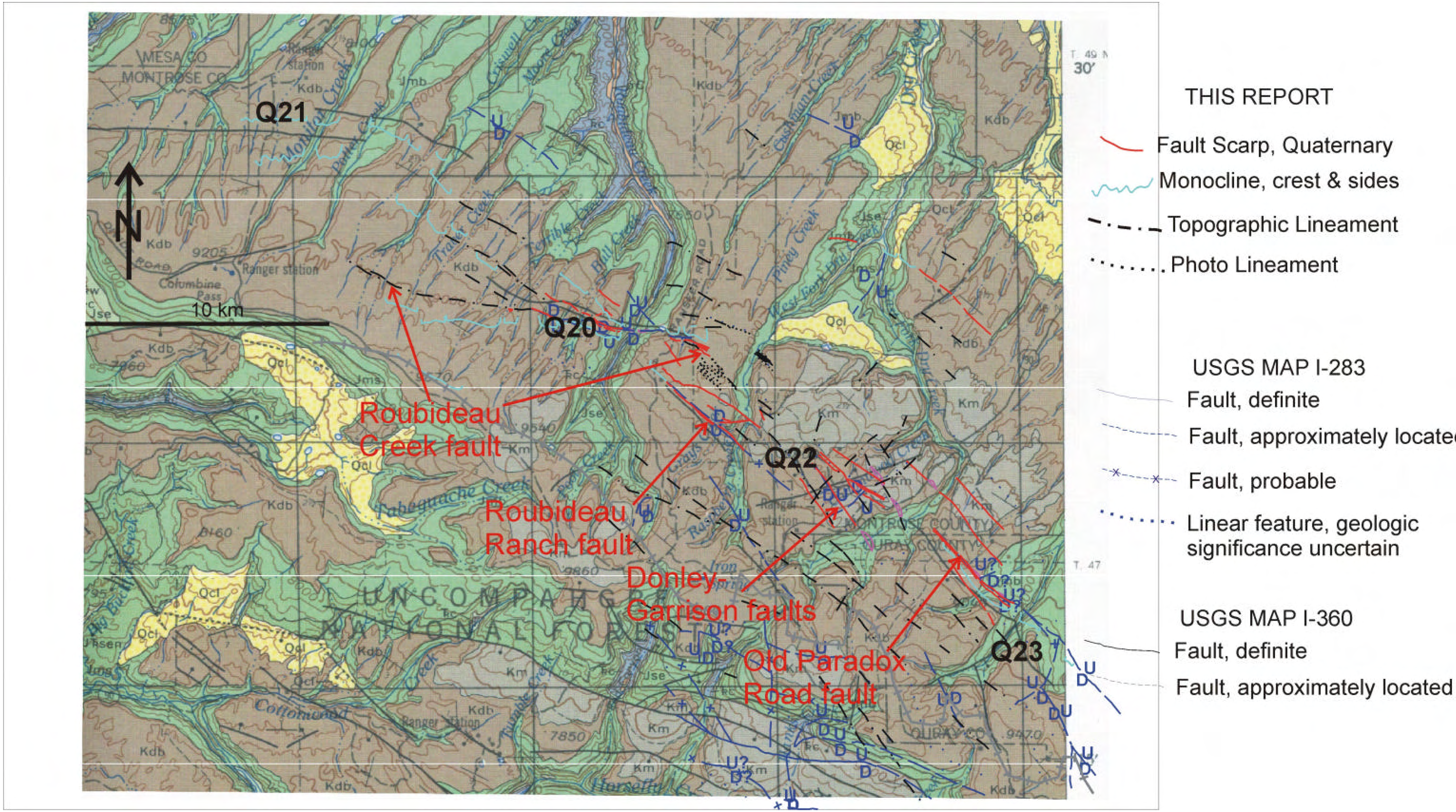

Fig. 4. Structures mapped in this study superimposed onto USGS Map I-360 (Williams, 1964).

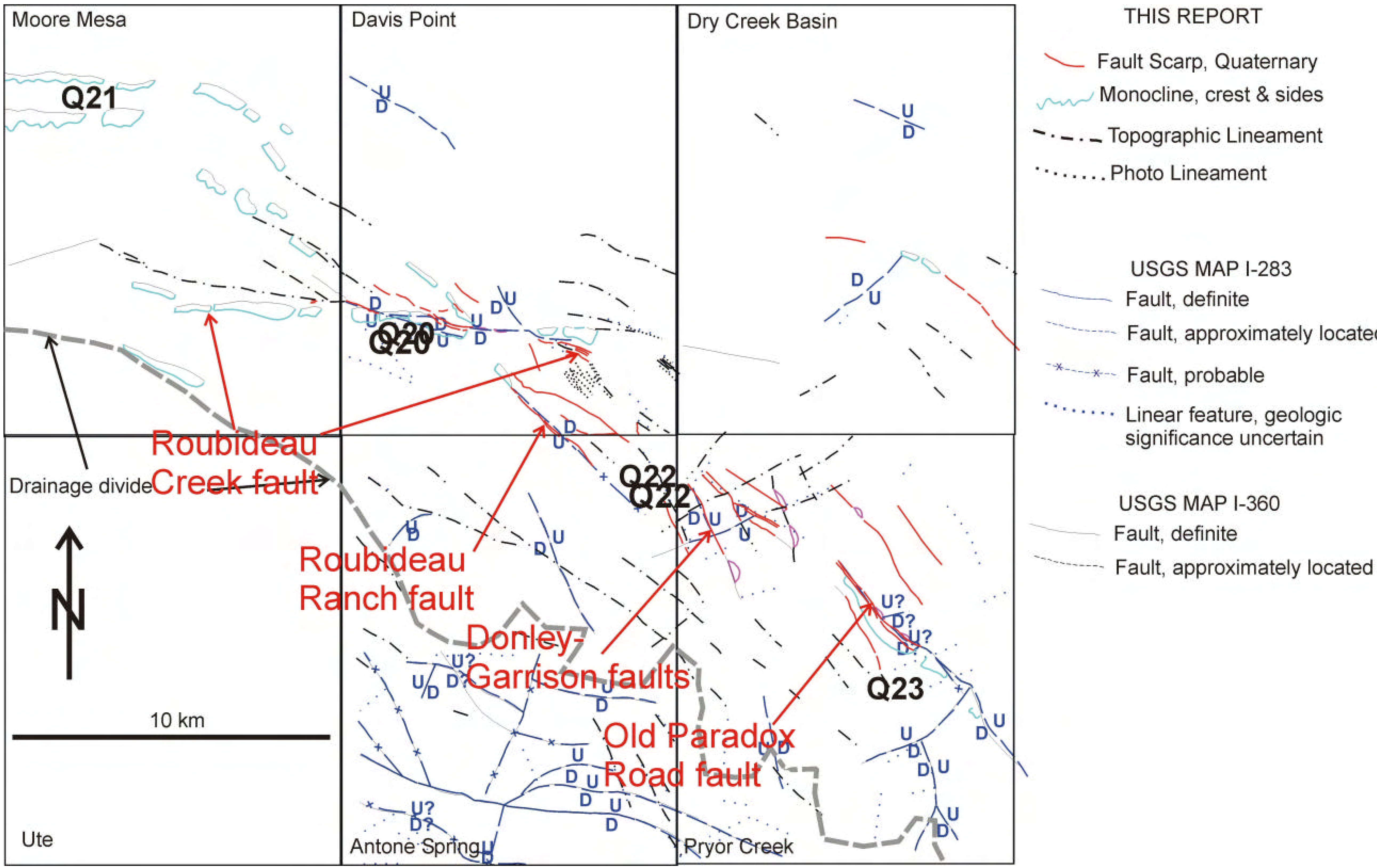

Fig. 5. Structures mapped in this study (Quaternary fault scarps; monoclines; topographic lineaments; photo lineaments), and in previous published mapping. Notably, the USGS mapping in 1959 (USGS Map I-283; Marshall, 1959) was photogeologic mapping with no field checking. In addition, USGS Map I-360 (Williams, 1964) was mainly a compilation, which cites Map I-283 as its source for mapping in the eastern 4 quadrangles, and unpublished photogeologic mapping in the western 2 quadrangles. Unexplained differences between the I-360 compilation and its I-283 source map are discussed in Table 1.

3. FAULT Q20 (Roubideau Creek fault; USGS no. 2270)

The Roubideau Creek fault was first mapped as an unnamed fault by Marshall (1959). He mapped two fault strands. The northern strand extends from Beach Creek (on the west) to slightly east of Transfer Road, east of Roubideau Canyon, for a total length of 6.1 km. Throw is down-to-the-South.

The southern strand extends from the western lip of Roubideau Canyon, westward to the western boundary of Marshall's map at 108°15'. Thus, its mapped length of 4.0 km is a minimum length; sense of throw is down-to-the-North. The combined length of both traces is at least 7.4 km long.

The next published geologic map to include the fault was the Moab 1° by 2° sheet, compiled by Williams (1964). For the area of the Roubideau fault, Williams (1964) cites his data source as Marshall (1959). On this compiled map the northern fault strand was extended 0.8 km to the SE, into Montrose County, along a lineament shown on Map I-283. The northern strand was also extended 2.2 km W of 108°15', beyond the mapping of Marshall (1959). The basis for extending the fault is not known. Most importantly, the slip sense of the northern strand was changed by Williams (1964) to down-to-N, the opposite of the slip sense shown by Marshall (1959). Again, the reason for this reversal is unknown. By comparison, Williams (1964) portrays the southern fault strand exactly as on Marshall's (1959) map. With the lengthening of the fault to the east and west, the total fault length on Williams' map is now 9.5 km.

Kirkham and Rogers (1981) were the first to suggest Quaternary movement on the Roubideau Creek fault, which they referred to as fault 82 (the fault was later named by Lettis et al., 1996). They wrote *"Fault number 82 lies in T48N, R13W and T48N, R12W and trends N70°W. Bedrock in the area consists of gently northeast-dipping Dakota Sandstone and Burro Canyon Formation, underlain by the Brushy Basin Member of the Morrison Formation. In places where the Brushy Basin Member lies at the surface, it is covered by abundant landslides, earthflows, and other types of slope failures largely of Quaternary age. Fault number 82 passes through the Brushy Basin Member and overlying Quaternary deposits at Roubideau Creek. Near the creek there is a scarp in the surficial landslide deposits that suggests fault movement since development of the Quaternary landslide complex*.

Recent movement on this fault appears to be downward on the southwest side. However, apparent drag in the bedrock suggests down-to-the-north displacement. This anomaly may be the result of a change in direction of movement or possibly due to scissors-type movement."

The Roubideau Creek fault was renumbered as fault Q20 by Widmann et al. (1998), and later numbered as fault 2270 by USGS, (http://earthquake.usgs.gov/regional/qfaults/) who adopted the mapping of Widmann et al (1998).

The fault trace as depicted by the CGS fault database and Widmann et al. (1998) can be subdivided into four geomorphic sections, which are discussed separately below. From west to east, these sections are the Traver Mesa section (7.3 km long), the Bull Creek section (4.2 km long), the Roubideau Canyon section (2.1 km), and the Roubideau Ranch section (4.9 km). This total length (18.5 km) does not include an additional 2+ km east of the West Fork of Dry Creek, where Widmann et al. (1998) mapped the fault as a dashed line, which is not shown as a fault by either Marshall (1959) or Williams (1964).

Note that this 18.5 km length is twice the length of the same fault as mapped on Marshall (1959; Map I-283) at >7.4 km or on Williams (1964; I-360) at 9.5 km. The source of the increased fault length is somewhat of a mystery, because Widmann et al (1998) state that: *"The trace used herein is from Williams (1964)",* although a comparison of those 2 maps shows that this is not true. Probably the additional 9 km of fault length added by Widmann et al (1998) came from unpublished mapping by Lettis et al (1996). For example, she cites her mapping source for the other faults in the area Q22 (2272) and Q23 (2273) as Lettis et al, 1996.

3.1 Mapping of the Roubideau Creek Fault in 2003 for CGS

The author was commissioned by the Colorado Geological Survey in 2003 to map the Roubideau Creek fault, with the goals of: (1) confirming or denying whether the fault had experienced Holocene faulting, as stated by Kirkham and Rogers (1981) and Widmann et al (1998), and (2) locating suitable sites for future paleoseismic trenching studies. The resulting 43-page report (McCalpin, 2003) concluded that the Roubideau Creek had experienced multiple episodes of Quaternary faulting, but that the Holocene fault scarp mapped by Kirkham and Rogers (1981) and cited as evidence for Holocene fault movement (Widmann et al., 1998), was a landslide scarp. The major observations and conclusions of that report are summarized below (italics).

3.1.1 STRUCTURE OF THE FAULT ZONE

All studies of the Roubideau Creek fault cited previously have called it a fault. But none of these studies have described the folding of Dakota-Burro Canyon Formation strata exposed in the cliffs on the west side of Roubideau Canyon, or the surface monocline that lies upslope from the mapped fault. (Fig. 6).

Both from a distant perspective (Fig. 6) and a close perspective, the Roubideau Creek fault appears to be a faulted monocline. Strata on the upthrown side are dragged down into the fault, while strata on the downthrown side are drug up toward the fault. Dips measured on cliff outcrops on the western wall of Roubideau Canyon range from 21° to 38° N.

The monocline is disrupted by several high-angle faults and shear zones, some of which are expressed as gullies cutting through the cliff band, and some of which are inferred to underlie the large gully that leads to the graben west of Roubideau Canyon. One fault plane exposed on the west side cliffs exhibited well-preserved slickensides on a fault plane that dipped 65 south, while bedding in the fault-bounded pinnacle dipped 38° north.

On another cliff promontory a shear zone was exposed at the top of the cliff. This zone is about 1 m wide and consists of closely spaced fractures on the centimeter to decimeter scale. Where fractures are closer than 1 cm apart the rock has a cataclastic texture. Fracture-bounded blocks in the zone typically display Lisegang banding, which is not seen elsewhere in the sandstone outcrop. Like the fault plane mentioned above, these shear zones dip steeply to the west, or toward the upthrown block.

Fig. 6. Photograph of the Roubideau Creek faulted monocline, looking west from Oak Hill on Transfer Road. The Roubideau Creek fault is at center, where a forested gully cuts through the band of cliffs. Monoclinal folding of the Dakota-Burro Canyon Formation can be clearly seen to the left and right of the gully.

These two areas of exposure suggest that the Roubideau Creek "fault scarp" is actually a faulted monocline. Most of the 60 m height of the escarpment can be attributed to plastic warping of Dakota sandstone down-to-the-north, with only 5-15 m of the height attributable to brittle normal faulting associated with the basal rejuvenated fault scarp and graben. Kirkham and Rogers (1981, p. 86-88) describe numerous monoclines and suspected Quaternary faults farther north on the flank of the Uncompahgre Plateau neat Grand Junction. In many places the monoclines graded into normal faults along strike.

A more classic interpretation of faulted monoclines comes from Powell (1873) who described a spectrum of fault-fold deformation from the Colorado Plateau (Fig. 7). Powell distinguished simple monoclines (Fig.76a) and normal faults (Fig. 7b) from hybrids that combine both folding and faulting (Fig.76c). In the latter case, multiple high-angle faults disrupt the core of the monocline, and the fault-bounded blocks rotate forward, as if toppling forward toward the downthrown block.

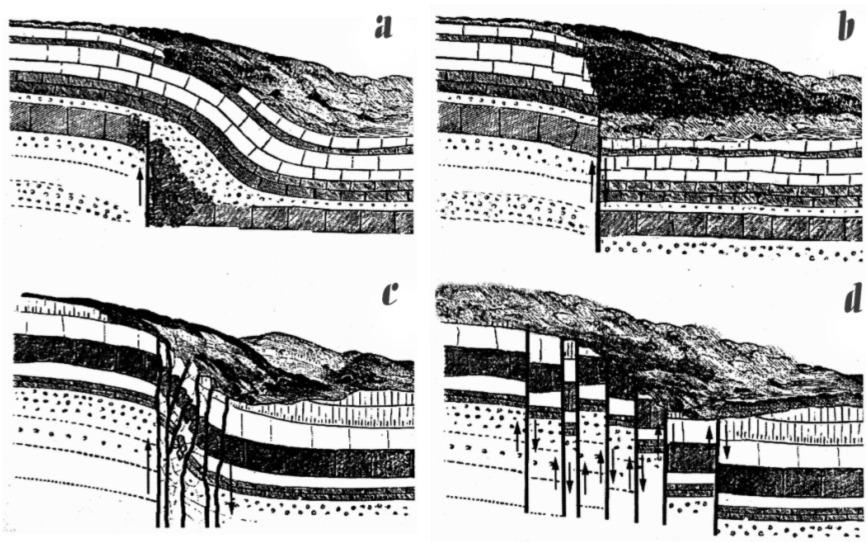

Fig. 7. Schematic cross-sections of faults and monoclines on the Colorado Plateau, from Powell (1873). (a) monoclinal (drape) fold overlying a vertical fault at depth; (b) single vertical fault; (c) faulted monocline with 5 major fault strands. Note the rotation of discrete fault-bounded blocks toward the downthrown block (toppling); (d) multiple vertical faults. The Roubideau Creek fault most resembles diagram (c).

Although Powell was describing faults believed to be Laramide in age, similar structures were documented by McCalpin (2005) on the 50-120 m-high fault escarpment of the Pajarito fault in northern New Mexico. The Pajarito fault "scarp" was found to be mainly an articulated monocline with a basal graben, which had formed since deposition of the 1.2 Ma Bandelier Tuff. This peculiar structural style was attributed to the rheology of a hard, dense welded tuff at the surface overlying weaker, unwelded tuffs. Faults propagating upward were expressed as diffuse ductile deformation in the unwelded tuffs, but were forced to break through the brittle caprock along discrete faults. A similar rheological argument could be made for the Roubideau Creek fault, which cuts hard Dakota sandstone overlying soft, ductile Morrison Formation.

However, at Roubideau Creek the contrast between ductile bending of hard sandstone strata versus formation of steep fault scarps and graben seems too great to accomplish simultaneously. A more reasonable explanation is that the monoclinal folding occurred as drape folding when the strata were buried to considerable depths, perhaps in the Laramide origeny. Thus the majority of the 60 m escarpment height could be explained as simple erosional stripping of a structural datum that was folded 50 million years ago. In contrast, the graben at the base of the escarpment clearly cuts the monocline and represents a younger deformation episode of completely different style.

One piece of evidence supporting this interpretation is an outcrop of Dakota sandstone north of the graben in the Bull Creek section. Here bedding dips 25° north, similar to the steepest dips measured in the core of the monocline elsewhere. Clearly this location was once in the core of the monocline, but has now been detached from beds of similar dip south of the graben by formation of the graben itself.

3.1.2 *PRELIMINARY ESTIMATES OF SLIP RATE, RECURRENCE, AND CHARACTERISTIC EARTHQUAKE MAGNITUDE*

3.1.2.1 Slip Rate

Preliminary slip rates can be estimated from the height of north-facing fault scarps in the Bull Creek section and from the ages of surfaces they displace. The smallest fault scarps on the southern margin of the graben display vertical surface offsets of 3.6 to 5.1 m, on Quaternary deposits or surfaces that are scarcely dissected by subsequent erosion. These colluvial deposits and incised valley levels probably date from the last major geomorphic reorganization of the landscape on the Uncompahgre Plateau, which in turn probably correlates with the latest glacial maximum of ca. 15-35 ka (Pinedale glaciation). In Table 3 below I use a conservative estimate of age of 25-35 ka for these displaced surfaces, which yields averaged vertical slip rates of 0.1 to 0.2 mm/yr.

Table 2. Scarp heights and slip rates for the Bull Creek section of the Roubideau Creek fault.

No.	Location	Scarp Height (m)	Surface Offset (m)	Maximum Scarp Angle (degrees)	Age of Faulted Surface (ka)	Slip Rate (average), mm/yr
1	Between Bull and E. Bull Creeks	9.0	5.1	28	25-35	0.15-0.20
2	North of stock pond	7.0	4.2	30	25-35	0.12-0.17
3	East of stock pond	-	3.6	32	25-35	0.10-0.14
4	East of stock pond	13	9.1	26	150	0.06

As is often the case, average slip rates estimated for older scarps are slightly lower than for younger scarps. If the 8-13 m-high scarps all along the base of the escarpment displace deposits correlatibe with the penultimate glaciation of the Rocky Mountains at ca. 150 ka (Bull Lake glaciation), then average slip rates are only 0.06 mm/yr.

3.1.2.2 Recurrence

Recurrence time between surface-rupturing earthquakes is difficult to estimate merely from geomorphic data, because the number of such events represented by a 3.6 m-high scarp, 5.1 m-high scarp, or 9.1 m-high scarp is unknown. One way to estimate the likely displacement per event on the Roubideau Creek fault is to measure the likely length of surface rupture and correlate that with a displacement per event. It seems very likely that several late Quaternary events ruptured the surface in at least the the Bull Creek section, the easternmost 1 km of the Traver Mesa section, and possibly the Roubideau Canyon section. That equates to a minimum distance of 5.2 km and a maximum of 7.3 km. It seems unlikely these same late Quaternary surface ruptures extended into the Roubideau Ranch, based on the lack of continuity of scarps. The upper bound of length is the 20.5 km listed by Widmann et al. (1998).

According to Wells and Coppersmith (1994), normal fault surface ruptures 5.2-7.3 km long correlate with average displacements of only 0.08-0.12 m and maximum displacements of only 0.13-0.21 m. These displacements are so small in relation to the scarp heights of 5-14 m that I suspect the ruptures were longer than 5-7 km, and the additional length of rupture has *been obscured by the dense forest. By comparison, surface ruptures 20.5 km long correlate with average displacements of 0.43 m and maximum displacements of 1.0 m.*

If we assume that the scarps associated with the graben in the Bull Creek section were formed by near-maximum displacements, then roughly 4 displacement events are required since 25-35 ka and 9 events since ca. 150 ka. These values yield average recurrence intervals of 6.25-8.75 ky and 16.7 ky, respectively. These recurrence values are very high for Colorado, being as short or shorter than those on the Sangre de Cristo fault, the state's most active fault (Widmann et al., 1998). Due to this apparent discrepancy, I suspect that the per-event displacements were significantly larger than 1 m.

3.1.2.3 Characteristic Earthquake Magnitude

The magnitude of characteristic earthquakes on the Roubideau Creek fault can be estimated from surface rupture lengths or from per-event displacements, but our estimates of those variables are highly uncertain and co-dependent. Ake et al. (2002) estimated the following: "A maximum magnitude of 6.5 is assigned to the fault based on fault length. Based on the estimate of a maximum vertical separation rate of 0.2 mm/yr, we estimate a broad range of slip rates, from 0.005-0.2 mm/yr." A magnitude of 6.5 is just barely above the surface rupture threshold for normal faults, and seems like a reasonable first approximation for a fault with a mapped length of Quaternary scarps of only 5-7 km. This magnitude estimate could be refined by site-specific data on per-event displacements, to be obtained by trenching.

3.2 Mapping of the Roubideau Creek Fault in 2006 (this study)

3.2.1 Monocline at Moore Mesa Road

The only new mapping I performed in 2006 on the Roubideau Creek fault as defined by CGS/USGS, was near the western end of the fault. At the western end of the fault as mapped by CGS/USGS (Fig. 8), the mapped fault trace lies 550 m north of an E-W-trending, 25 m-high escarpment. This is the section of the Roubideau Creek fault that lies in the Moore Mesa quadrangle and did not appear on either USGS Map I-283 (Marshall, 1959) or Map I-360 (Williams, 1964), but was added by Widmann et al (1998). I mapped a topographic lineament along this part of the fault, but have never field checked it.

The 25 m-high escarpment that lies south of (and parallel) to the mapped fault trace appears to be the western extension of the Roubideau Creek monocline studied in detail by McCalpin (2003). This part of the monocline is 5.4 km long and extends from Terrible Creek, west to N Road. The monocline is complex, composed of: (1) a larger, 300 m-wide, 25 m-high monocline, and (2) a steeper, 100 m-wide, 19 m-high smaller monocline at its base (Fig. 8).

I field checked this monocline where it crosses the Moore Mesa Road (Trail), 9.4 km west of Roubideau Creek. The purpose of field checking was to: (1) determine if smaller fault scarps existed at the base of the larger escarpment, as occurs farther east on the Roubideau Creek fault, and (2) to measure dip of Dakota-Burro Canyon bedding, to see if dips were anomalously steep compared to the ambient dip of the dipslope here (2.5°). I did not drive the additional ¼ mile farther north on the road to field check the fault location mapped by Widmann et al (1998), although I would have with additional field time.

The smaller monocline did not display any fault scarps. Instead, the ground surface of the monocline was roughly parallel to the dip of Dakota formation bedding planes. I measured one topographic profile across the lower monocline (Fig. 9a), where the monocline height was about 19 m and the vertical surface offset about 14.5 m (compared to an ambient dipslope angle of 2.5°). The steepest observed dips on this profile were in the upper half of the lower monocline, where the overall slope angle averaged 10°. However, locally the slope was steeper, paralleling the 13°-16° dips of bedding (Fig. 9b). At a point 70 m west of the profile, bedding dip increased locally to 25°, in an area of shallow slumping on the monocline face. This slumping was probably a dip-slope landslide caused by the steep dip at that location.

3.3 Potential for trenching studies on the Roubideau Creek fault

The best-preserved fault scarps are associated with the monocline and graben in the 1.3 km-long reach between Roubideau Canyon and East Bull Creek (Fig. 3). These scarps can be accessed by driving NW on the Divide Road, NE on the Long Creek Road (FR 520), and then SE on jeep roads 2 km to the graben. There are several sizes of scarps to choose from once at the graben. USBR personnel visited most of these potential trench sites with the author in August of 2005, associated with field reviews of USBR trenches across the Busted Boiler fault.

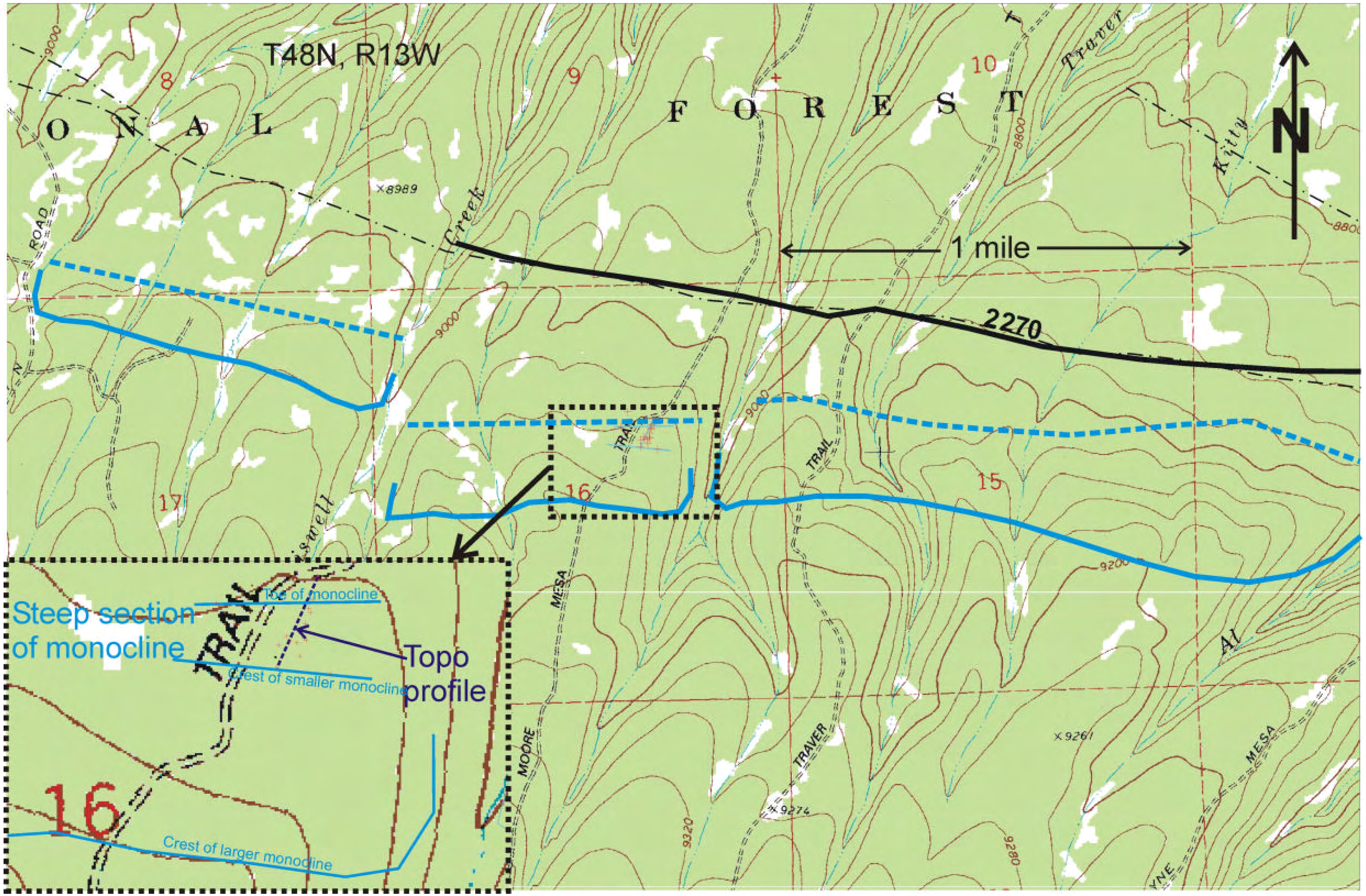

Fig. 8. Map of the western part of the Roubideau Creek monocline (solid blue line at crest, dashed blue line at toe). Thick black line shows location of Roubideau Creek fault (2270) from CGS/USGS Quaternary Fault and Fold Database. Dash-and-dot line shows topographic lineament mapped in this study. Inset shows the steeper part of the lower monocline section (parallel blue lines), and the topographic profile across that steeper section (dark blue dashed line). Red crosses are GPS waypoints.

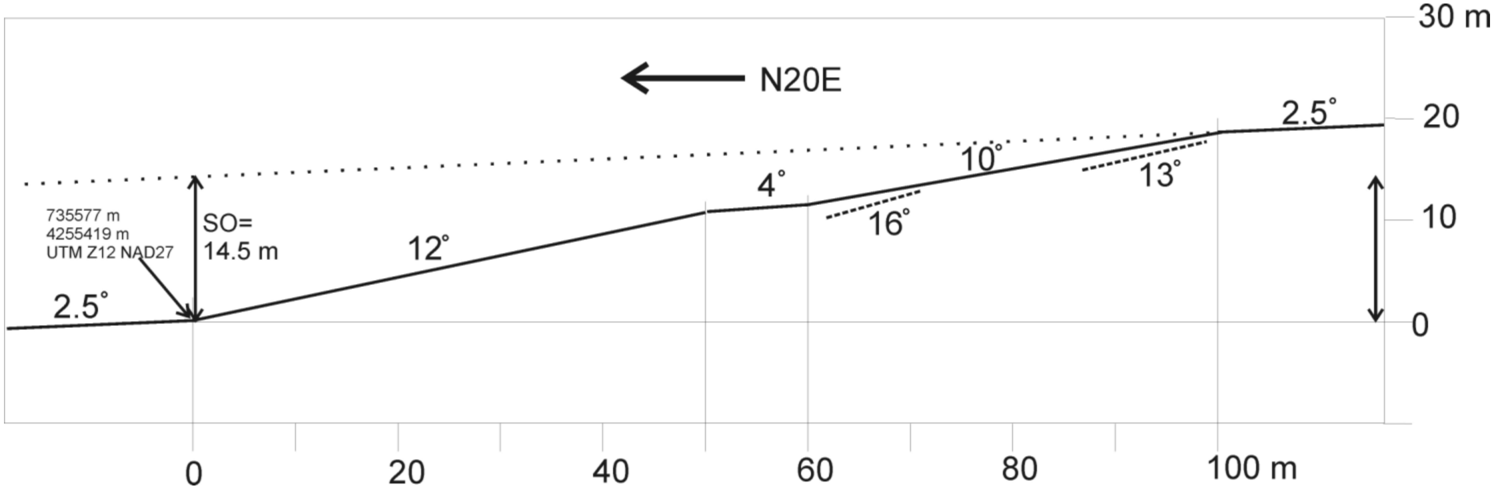

Fig. 9a. Topographic profile across the smaller monocline (solid line, with segment slopes in degrees), just east of Moore Mesa Trail. Bedding dips shown by dashed lines and associated dip angles.


Fig. 9b. Photograph of the slab of Dakota sandstone (at right center) on the scarp profile, with a dip of 16° to the NNE.

4. FAULT Q22 (unnamed faults east of Roubideau Creek)

Fault Q22 as defined by CGS (fault 2272 of USGS) is composed of 5 separate faults (Table 1 and Fig. 3), interpreted as Quaternary faults by Lettis et al (1996). None of the faults were named by either Lettis et al., CGS, or USGS. I have given informal names to these 5 faults in this report, for ease of discussion, as follows:

2272A Roubideau Ranch fault
2272B Donley Camp fault
2272C Antone-Pryor fault
2272D Curved fault
2272E S of Divide fault

The Boubideau Ranch fault contains impressive, steep scarps along most of its length, as does the Garrison Ranch fault, although those scarps are developed mainly in Dakota Formation bedrock. The other 3 faults did not appear to have fault scarps along them, based on my photointerpretation, and appeared to be mainly erosional features. As a result, I did not field check them and I do not discuss them further herein.

4.1 Roubideau Ranch fault (scarps 2272-01 through 2272-09)

In 2006 I performed additional mapping of the "Roubideau Ranch fault" for this study in two areas. On Sept. 7 and 10, 2006 I spent 2 days mapping fault scarps east of Roubideau Canyon at the base of a large monocline, both west of Transfer Road (scarp 2272-01), and east of Transfer Road in the Roubideau Ranch (scarps 2272-02 through -04). Fault scarp locations and heights are shown on Fig. 10, and in Table 3.

4.1.1 Monocline and fault scarp west of Transfer Road

I mapped scarps in detail in a 500 m-long stretch of the northeast-facing escarpment that lies between Transfer Road and a jeep road farther west. Here the scarp is roughly 15-20 m high and 100 m wide (Fig. 11a), but is composed of several elements. Near Transfer Road the scarp face is relatively broad and concave-upward, about 20 m high (Fig. 11b). Traced to the NW, the scarp splits into an upper and lower scarp, separated by a gentle bench. The lower scarp is about 15 m high near Transfer Road, but decreases to 6 m high 200 m NW of Transfer Road. After a short gap, the displacement continues as a second scarp trending N75W, which continues to the jeep road. This scarp steadily decreases in height to the NW, from 4 m high 250 m NW of Transfer Road to 0.5 m high just west of the jeep road, after which it dies out (Fig. 10).

The upper part of the escarpment is composed of a steep, 300 m-long scarp that extends from 60 m to 360 m NW from Transfer Road. This scarp is as much as 3 m high in the central portion, but rapidly decreases in height toward the NW and SE ends (Fig. 10). The highest central part is also the steepest part (Fig. 12).

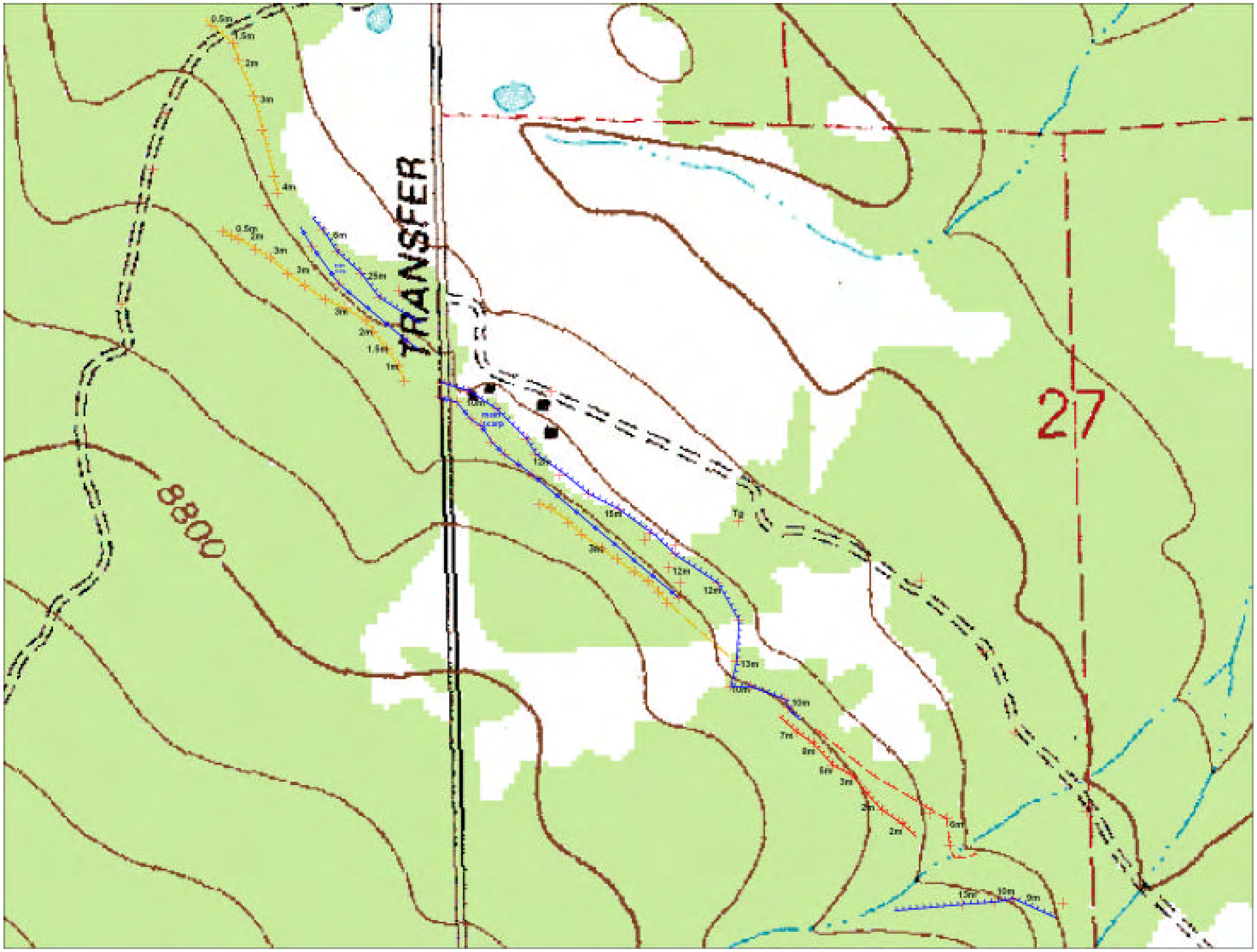

Fig. 10. GPS traverse map of NE-facing Quaternary fault scarps of the Roubideau Ranch fault (2272-01 through 2272-04) at the toe of the monocline near Transfer Road, on the eastern side of Roubideau Canyon. Antithetic faults are not shown. Main scarp in blue, with hachures at the toe and cross-tics at the crest; secondary scarps in red and orange. Scarp heights in meters, not corrected to vertical surface offset.

Table 3. Summary data for all Quaternary fault scarps mapped in this study. Scarp numbers match those in ESRI Shapefiles.

Scarp ID	central Uncompahgre Plateau NAME_	MY NUMBER	Fault Name	Length (m)	Scarp Height (m) Max	Avg	Vertical Sep. (m)	DownSide	Remarks
1	Fault Scarp, late Quaternary, D to N	2270-01	Roubideau Creek fault	164				N	Similar to 2270-02
2	Fault Scarp, late Quaternary, D to N	2270-02	Roubideau Creek fault	192				N	oversteepened at base, tension fissure at head; Fig. 21, McCalpin 2003
3	Fault Scarp, late Quaternary, D to N	2270-03	Roubideau Creek fault	808				N	fault is poorly expressed, does not form scarp at Long Creek Road
4	Fault Scarp, late Quaternary, D to N	2270-04	Roubideau Creek fault	265		10	5	N	Figs 9-10 in McCalpin, 2003; Forest Road 545, monocline 62 m high
5	Fault Scarp, late Quaternary, D to N	2270-05	Roubideau Creek fault	193				N	short arcuate scarp on trend of fault scarp; could partly be a landslide headscarp
6	Fault Scarp, late Quaternary, D to N	2270-06	Roubideau Creek fault	645				N	steep scarp and small forested graben at base of monocline; old jeep road in graben
7	Fault Scarp, late Quaternary, D to N	2270-07	Roubideau Creek fault	556				N	Figs. 13-14 in McCalpin, 2003
56	Fault Scarp, late Quaternary, D to N	2270-07a	Roubideau Creek fault	380		9	5.1	N	Fig. 11 in McCalpin, 2003
8	Fault Scarp, late Quaternary, D to N	2270-08	Roubideau Creek fault	544	13	10	12.7	N	Figs. 15-20 in McCalpin, 2003; best single- and multiple-event scarps
9	Fault Scarp, late Quaternary, D to N	2270-09	Roubideau Creek fault	148				N	poorly expressed scarp; could be erosional on a hard bed of Dakota Sandstone
10	Fault Scarp, Quaternary, D to S	2270-10	Roubideau Creek fault	617				S	not a sharp scarp; forms antithetic hinge zone on N side of backtilted area
11	Fault Scarp, Quaternary, D to S	2270-11	Roubideau Creek fault	725				S	not a sharp scarp; forms antithetic hinge zone on N side of backtilted area
12	Fault Scarp, late Quaternary, D to S	2270-12	Roubideau Creek fault	364				S	sharper version of 2270-10 and -11
13	Fault Scarp, late Quaternary, D to S	2270-13	Roubideau Creek fault	1387				S	main antithetic scarp of Roubideau Creek fault graben; does not displace young channel alluvium
14	Fault Scarp, late Quaternary, D to S	2270-14	Roubideau Creek fault	301				S	short antithetic scarp on N edge of meadow
15	Fault Scarp, late Quaternary, D to N	2270-15	Roubideau Creek fault	470	25			N	scarps at toe of monocline; offsets youngest alluvium in incised valley
16	Fault Scarp, Quaternary, D to S	2270-16	Roubideau Creek fault	996				S	not a sharp scarp; forms antithetic hinge zone on N side of backtilted area
17	Fault Scarp, Quaternary	2270-17	Roubideau Creek fault	513				none	erosional fault-controlled gully on S side of Oak Hill; continuation of Roubideau Creek fault
18	Fault Scarp, Quaternary, D to N	2270-18	Roubideau Creek fault	1177				N	N-Most fault of 4 at head of N-Facing monocline; E-ward continuation of Roubideau Monocline
19	Fault Scarp, Quaternary, D to S	2270-19	Roubideau Creek fault	473				S	N boundary of graben at head of N-Facing monocline; E-ward continuation of Roubideau Monocline
20	Fault Scarp, Quaternary, D to N	2270-20	Roubideau Creek fault	448				N	S boundary of graben at head of N-Facing monocline; E-ward continuation of Roubideau Monocline
21	Fault Scarp, Quaternary, D to S	2270-21	Roubideau Creek fault	839				S	S-Most fault of 4 at head of N-Facing monocline; E-ward continuation of Roubideau Monocline
22	Fault Scarp, late Quaternary, D to W	2270-22	Roubideau Creek fault	959				W	sharp antithetic scarp trends N75W across Transfer Road S of Oak Hill
23	Fault Scarp, late Quaternary, D to N	2272-01	Roubideau Ranch fault	473				N	scarps on complex moncocline (also 2272-02, 2272-03, 2272-04); Fig. 22, McCalpin, 2003
24	Fault Scarp, late Quaternary, D to N	2272-02	Roubideau Ranch fault	1897				N	composed of 10-15 m-high main scarp at base, and 3 m steep scarp at top
25	Fault Scarp, late Quaternary, D to N	2272-03	Roubideau Ranch fault	758				N	secondary step fault of Roubideau ranch fault
26	Fault Scarp, late Quaternary, D to N	2272-04	Roubideau Ranch fault	1290				N	SE part obscure; does not displace alluvium in Grays Creek
27	Fault Scarp, Quaternary, D to S	2272-05	Roubideau Ranch fault	305				S	short antithetic fault within the Roubideau Ranch graben
28	Fault Scarp, Quaternary, D to S	2272-06	Roubideau Ranch fault	383				S	short antithetic fault within the Roubideau Ranch graben
29	Fault Scarp, Quaternary, D to S	2272-07	Roubideau Ranch fault	4050				S	bounds Roubideau Ranch graben on N side; varies in height and preservation; Fig. 23, McCalpin, 2003
30	Fault Scarp, Quaternary, D to S	2272-08	Roubideau Ranch fault	1439				S	E-W fault within Roubideau Ranch graben; mimics trend of Roubideau Creek fault segments
31	Fault Scarp, Quaternary, D to S	2272-09	Roubideau Ranch fault	259				S	continuation of fault 2272-07
32	Fault Scarp, Quaternary, D to W	2272-10	Donley-Garrison faults	1574				W	1 of 4 subparallel, down-to-W faults that define N-tilted blocks of Dakota
33	Fault Scarp, Quaternary, D to W	2272-11	Donley-Garrison faults	1307				W	1 of 4 subparallel, down-to-W faults that define N-tilted blocks of Dakota
34	Fault Scarp, Quaternary, D to W	2272-12	Donley-Garrison faults	2594				W	1 of 4 subparallel, down-to-W faults that define N-tilted blocks of Dakota
35	Fault Scarp, Quaternary, D to N	2272-13	Donley-Garrison faults	1014				E	part of graben
36	Fault Scarp, Quaternary, D to W	2272-14	Donley-Garrison faults	2003				W	1 of 4 subparallel, down-to-W faults that define N-tilted blocks of Dakota
37	Fault Scarp, Quaternary, D to N	2272-15	Donley-Garrison faults	989				E	part of graben

38	Fault Scarp, Quaternary, D to N	2272-16	Donley-Garrison faults	1229				E	part of graben
39	Fault Scarp, Quaternary, D to S	2272-17	Donley-Garrison faults	1665				W	1 of 4 subparallel, down-to-W faults that define N-tilted blocks of Dakota
40	Fault Scarp, Quaternary, D to S	2272-18	Donley-Garrison faults	2374				W	1 of 4 subparallel, down-to-W faults that define N-tilted blocks of Dakota
41	Fault Scarp, Quaternary, D to S	2272-19	Donley-Garrison faults	1001				S	N extension of fault 2273-02
42	Fault Scarp, Quaternary, D to E	2273-01	unnamed	2405				N	no steep scarp; coincides with a slope break
43	Fault Scarp, Quaternary, D to W	2273-02	unnamed	3384				S	no steep scarp; coincides with a slope break
44	Fault Scarp, Quaternary, D to W	2273-03	unnamed	2103				S	antislope scarp on footwall above crest of monocline, like on Pajarito fault in NM (McCalpin, 2005)
45	Fault Scarp, Quaternary, D to W	2273-04	unnamed	459				S	extension of fault 2273-03
46	Fault Scarp, Quaternary, D to S	2273-05	unnamed	1302				S	westernmost segment of >7.5 kmdown-to-S fault scarp, not in Q Fault Database
47	Fault Scarp, Quaternary, D to S	2273-06	unnamed	786				S	other segment of same down-to-S fault scarp
48	Fault Scarp, Quaternary, D to S	2273-07	unnamed	537				S	other segment of same down-to-S fault scarp
49	Fault Scarp, Quaternary, D to S	2273-08	unnamed	391				S	other segment of same down-to-S fault scarp
50	Fault Scarp, Quaternary, D to S	2273-09	unnamed	1333				S	other segment of same down-to-S fault scarp
51	Fault Scarp, Quaternary, D to W	2273-10	Old Paradox Road fault	1220	2	1	1	SW	NW segment of the antithetic scarp of the Old Paradox Road graben
52	Fault Scarp, Quaternary, D to W	2273-11	Old Paradox Road fault	1072	4	1.5		SW	central segment of the antithetic scarp of the Old Paradox Road graben
53	Fault Scarp, Quaternary, D to W	2273-12	Old Paradox Road fault	1172				SW	SE segment of antithetic scarp of the Old Paradox Road graben; no young scarps
54	Fault Scarp, late Quaternary, D to E	2273-13	Old Paradox Road fault	2266	10	3		NE	main scarp at toe of Old Paradox Road monocline
55	Fault Scarp, late Quaternary, D to E	2273-14	Old Paradox Road fault	1457	10	3		NE	main scarp at toe of Old Paradox Road monocline

Fig. 11a. Photo of the escarpment of the Roubideau Ranch fault (aspen-covered slope in middle distance) west of Transfer Road (scarp 2272-01).

Fig. 11b. Telephoto view of the 15-20 m-high escarpment of the Roubideau Ranch fault, taken from the west shoulder of Transfer Road (scarp 2272-01).

Fig. 12. Photo of the steep upper scarp of the Roubideau Ranch fault, west of Transfer Road (scarp 2272-01).

The exact nature of the structure underlying the escarpment is unknown. Dakota Group bedrock outcrops only in a single place, on the lower face of the upper steep scarp near its center. However, that small outcrop was too poorly expressed to permit measurement of strike and dip of bedding. Therefore, it is not known whether the escarpment is actually a monocline, or a fault scarp, or some combination of both. The steepness and sharpness of the upper steep scarp, however, so suggest that the escarpment is a Quaternary structural feature, and not an exhumed structure or the product of differential erosion on a resistant bed in the Dakota Group.

4.1.2 Monocline and fault scarp east of Transfer Road

I also mapped scarps in detail in a 1.1 km-long stretch of the northeast-facing escarpment that lies east of Transfer Road (NW half of scarp 2272-02), in the Roubideau Ranch (SW1/4 Sec. 24, T48N, R12W). Here the scarp is roughly 10-15 m high and 50-70 m wide (Figs. 13a, 13b), somewhat steeper overall than the scarp west of Transfer Road. Like the scarp west of Transfer Road, the scarp here is also divided into a 10-15 m-high, lower scarp (labeled “main scarp” on Fig. 10) and a smaller but steeper, 3 m-high upper scar (Fig. 14).

Fig. 13a. Photo of the scarp of the Roubideau Ranch fault (scarp 2272-02) west of the ranch house at Roubideau Ranch.

Fig. 13b. Photo of the scarp of the Roubideau Ranch fault (scarp 2272-02) west of the ranch house at Roubideau Ranch.

Fig. 14. Panoramic photo of the upper scarp of the Roubideau Ranch fault (scarp 2272-02).

The main scarp and secondary scarp parallel each other until a point 520 m SE of Transfer Road (Fig. 10). At this point the main scarp curves 45° to the south in a reentrant, but the secondary scarp continues SE and intersects the main scarp. At this point, the 3 m-high secondary scarp can clearly be distinguished as a separate scarp element as it obliquely descends the larger, 13 m-high main scarp face. This distinctive geometry has been described previously on Quaternary normal fault scarps (McCalpin, 1983, Fig. 65). It is difficult to imagine how such a landform could be formed by erosional exhumation of old structures, or by differential erosion of strata.

4.1.3 Potential for Trenching Studies on the Roubideau Ranch fault

The longest and most continuous fault scarps on the Roubideau Ranch fault lie in the Roubideau Ranch, owned by Mr. Donald Duepree of Montrose. Based on my last conversation with Mr. Duepree, it is unlikely that he would give permission for trenching on his ranch.

Fortunately, shorter scarps nearly as well preserved exist west of Transfer Road, in the Uncompahgre National Forest. Access to the 10+ m lower scarp and the 1.5-3 m steep upper scarp would be relatively easy from Transfer Road, and from an older jeep Road that ascends the scarp just west of Transfer Road.

4.2 Donley-Garrison Faults (scarps 2272-10 through 2272-19)

The Donley-Garrison faults comprise a group of 10 parallel, NW-trending fault segments that lie in the northeastern corner of the Antone Spring quadrangle (2272-10, -11), and the northwestern corner of the Pryor Creek quadrangle (2272-12 through -19). These faults lie about halfway between the Roubideau Ranch fault/graben/monocline complex and the Old Paradox Road fault/graben/monocline complex. Each fault forms a prominent SW-facing scarp or a NW-trending graben that disrupts the ambient dipslope of the Dakota-Burro Canyon sandstones. The faults divide the Dakota caprock into NE-tilted panels about 600-1000 m wide and 2.5-3 km long.

The seven dominant fault segments are all down-to-the-SW, and all scarps are numbered herein from the SW (2272-10) to the NE (2272-19). Only one of these faults (scarp 2272-12, herein termed the "Donley Camp fault") appears in the CGS/USGS Database, because it was mapped as a down-to-the-SW fault by Marshall (1959) and Williams (1964). In the discussion below, I describe the fault scarps from SW to NE.

4.2.1 Scarps 2272-10 and 2272-11

These are the farthest SW scarps of the Donley-Garrison faults, and form a discontinuous down-to-the-SW fault in the NE corner of the Antone Springs quadrangle. Together these scarps are 2.9 km long (1574 m for 2272-10; 1307 m for 2272-11). I did not field check scarp 2272-10, and only briefly examined scarp 2272-11 from County Road 90 at Silesia Pond. At that location, the scarp is broad and gentle, and in fact the slope on the western side of Silesia Pond is more impressive than the slope on the eastern side. This contrast may indicate that Silesia Pond is located in a graben. I did not see any other obvious explanation for the existence of this pond when in the field, i.e., there is no obvious depositional dam to create the impoundment. If the pond is a structural feature resulting from fault movement, then it must be a Quaternary feature. In addition, the topographic depression that the pond occupies continues to the SW, where it forms an anomalous, broad meadow that contains the USFS Silesia Guard Station.

4.2.2 Scarp 2272-12 (the "Donley Camp fault")

The "Donley Camp fault" (scarp 2272-12) is the only one of the 10 scarp segments in the Donley-Garrison faults to be shown on the CGS/USGS Quaternary Fault and Fold database. This inclusion can probably be explained because it is the only one of my 10 scarp segments to appear on USGS Maps I-283 and I-360. I map the Donley Camp fault about twice as long in this study as was done on maps I-283, I-360, and the CGS/USGS Databases. This length was added to connect the well-preserved scarp section of the fault with a saddle in the ridge to the SE.

The Donley Camp fault forms an impressive SW-facing scarp about 1860 m long and 16 m high (Fig. 15); the additional southeastern 700 m of the mapped scarp has little topographic expression except as a saddle at the ridge crest. In the northern part of the scarp a 4 m-deep, flat-floored valley exists only on the upthrown side of the scarp, and flows 650 m to the NE where it enters the graben formed by scarps 2272-13 and -14 in the Garrison Ranch. This valley projects out into space to the SW when it reaches fault scarp, and has no counterpart of the downthrown side.

The geomorphic expression of the valley, and its absence on the downthrown side of the scarp, suggests that the scarp truncates the erosional valley and is thus younger than it. At the truncated valley the scarp is 12 m high, indicating that 12 m of vertical displacement has occurred since the valley was beheaded. I infer that the valley is a Quaternary erosional feature that developed after the Mancos Shale was removed from the dipslope here by erosion. Therefore, the 12 m of displacement must also be Quaternary.

The alternative explanation for the beheading of the valley would be erosional. In this explanation, tributary streams flowing along the SW side of the fault would have to downcut, work headward, and finally capture the NE-flowing stream. To accomplish this, such streams would have to have a gradient greater than that of the NE-flowing stream that got beheaded, and be graded to a lower base level. However, no such streams exist now on the downthrown (SW) side of the scarp, and in fact the beheaded stream is

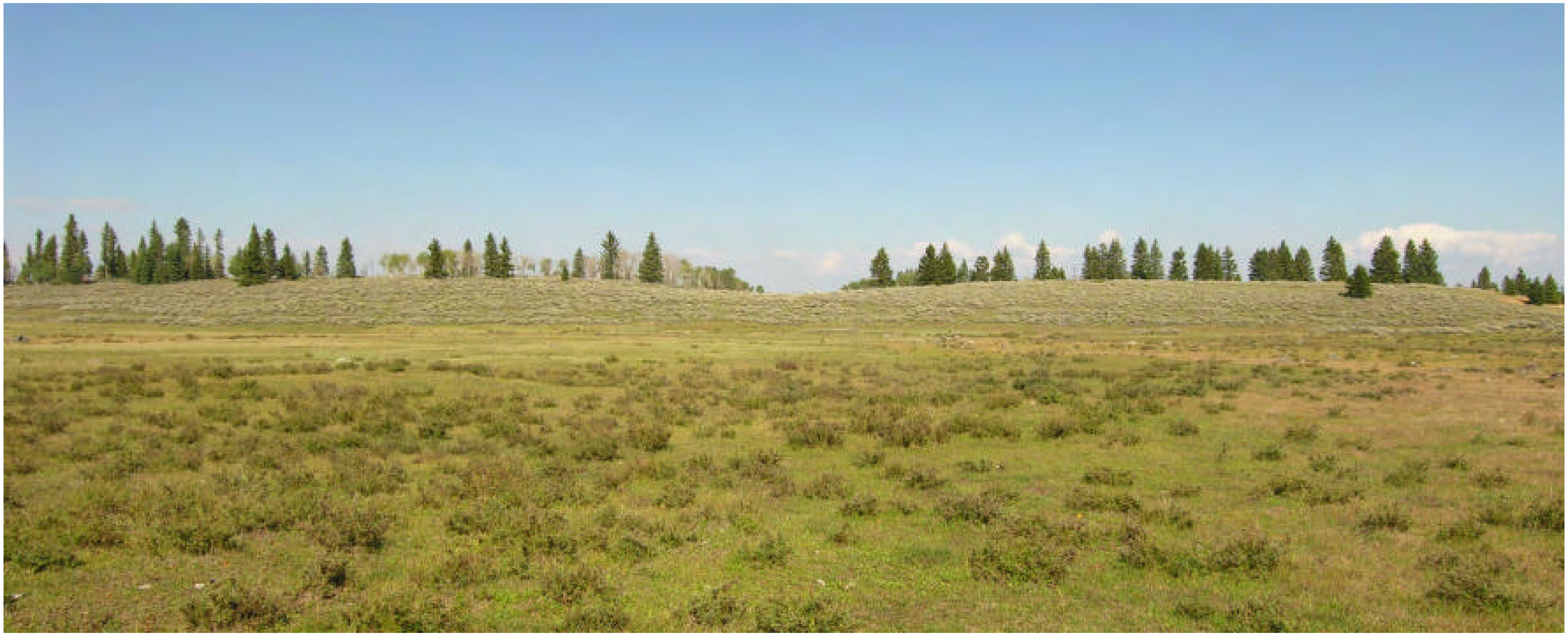

Fig. 15. View to the NE of the northern part of the Donley Camp fault scarp (scarp 2272-12). The boundary fence between the Donley Ranch (foreground) and the Garrison Ranch (background) runs N-S through the saddle at the center of the photo. That saddle marks the location of a valley that exists only on the upthrown side of the scarp, and flows 650 m to the NE where it enters the graben formed by scarps 2272-13 and -14 in the Garrison Ranch. The geomorphic expression of the valley, and its absence on the downthrown side of the scarp, suggests that the scarp truncates the erosional valley and is thus younger than it.

graded to a lower base level (the Garrison Ranch graben) than the insignificant streams on the SW side of the scarp. Therefore, I do not think that the beheading of the stream can be explained by simple erosion on the Uncompahgre Plateau.

4.2.3 Scarps 2272-13 and 2272-14 (the "Garrison Ranch faults")

Scarps 2272-13 and 2272-14 form a wide graben 1000 m long and 170 m wide, which contains the ranch buildings of the Edwin Garrison Ranch (Fig. 16). The northernmost part of NE-facing scarp 2272-13 is very steep (Fig. 17) and exposes in-situ Dakota sandstone on the steepest, unvegetated part of the scarp face. Bedding strikes parallel to the scarp (N50W) but dips 47°NE, in the direction of the scarp face. When these same beds are traced westwards 10-15 m from the scarp, the strike remains constant but dip decreases to 15°NE. This geometry suggests the scarp is underlain by a sharp down-to-the-NE fold in the Dakota sandstone.

A similar outcrop on the road to the Garrison Ranch, about 10 m E of the Garrison entrance gate on scarp 2272-14 on the opposite side of the graben, also shows that scarp is underlain by steeply folded Dakota sandstone. At that location (752714m E, 4248817m N, UTM Zone 12, NAD27), a roadcut into Dakota sandstone at the toe of scarp 2272-14 exposes bedding strikes of N00-05W (parallel to scarp 2272-14), and maximum dips of 50°-60°W near the base of the roadcut. However, dips visibly decrease toward the top of this exposure, indicating tight folding.

I did not observe either scarp 2272-13 or 2272-14 to displace Quaternary deposits or to create a scarp in them, although admittedly, Quaternary deposits are scarce on the Plateau here. For example, where scarp 2272-13 crosses the mouth of the beheaded drainage described earlier, where it enters the graben, there is no clear scarp across the alluvium of that valley. Likewise, there are no compound scarp landform elements in the colluvial apron along the base of scarp 2272-13. Due to the lack of evidence for late Quaternary displacements, I assign a Quaternary (undivided) age to these 2 scarps.

Fig. 16. View to the south, down the axis of the graben formed by scarps 2272-13 (right) and 2272-14 (left). GPS coordinate of camera position is 751794m E, 4250012m N, UTM Zone 12, NAD27.

Fig. 17. View on the northernmost part of scarp 2272-13, looking SW at the scarp face. GPS coordinate of unvegetated scarp face at center (shadowed) is 751631m E, 4249760m N, UTM Zone 12, NAD27. In-situ Dakota bedrock is exposed in shadowed area, bedding strike is N50W, dip 47NE (toward the viewer). Thus, although scarp face is very steep, it is not as steep as bedding. Pervasive fractures in Dakota sandstone strike N55W, 47SW, roughly perpendicular to bedding.

4.2.4 Scarps 2272-15 through 2272-17

Scarp 2272-15 is a 990 m-long, 3-4 m-high, NE-facing scarp that lies in the Donley Ranch, southwest of the access road to the Garrison Ranch (Fig. 3). The scarp trends N60W and lies 200 m SW of the graben formed by scarps 2272-16 and 2272-17. The scarp crosses the access road to the Garrison Ranch at UTM coordinates 753290m E, 4248250m N (Zone 12, NAD27), where it is 2 m high. The 200-220 m-wide zone between these scarp 2272-15 and the graben looks like a landslide, and contains an arcuate scarp at its head that contains a small pond at its base. Therefore, it is not clear whether the scarp is a primary fault scarp, or a secondary (exhumed) landform caused by the landslide mass pulling away from an old fault plane.

Scarps 2272-16 and 2272-17 form a long (1220 m) but narrow (70 m) graben along strike to the SE of the Garrison Ranch graben, in the Donley Ranch (Fig. 18). Part of this “graben” may be erosional, but the linear shape of the valley sides, and its alignment with the Garrison Ranch graben, also argue for a structural origin.

Fig. 18. View NW down the axis of the graben formed by scarps 2272-16 (on left) and 2272-17 (on right). GPS coordinates of camera location are 754238 m E, 4248071 m N, UTM Zone 12, NAD27, on the access road to the Garrison Ranch.

4.2.5 Scarps 2272-18 and 2272-19

I did not field check the NE-most scarps (2272-18, 2272-19) in the Donley-Garrison faults, so the following comments are based on examination of topographic maps and airphotos.

Scarp 2272-18 is a 2374 m-long, discontinuous, down-to-the-SW fault trending N60W. The main evidence for its existence is a saddle in the interfluve NW of Cottonwood Creek, and an aligned tributary valley head to the SE of Cottonwood Creek. The existence of 2 isolated hills on the NE side of the fault (elevations 8460, 8603 ft marked on topo map) suggest that the NE side of the fault is the upthrown side, as it is for most of the other Donley-Garrison faults. However, the geomorphic expression of this fault is mainly erosional (saddles, aligned stream courses), and it does not form a nice scarp like the other faults of this group do.

Scarp 2272-19 lies 1.6 km east of scarp 2272-18, and is really not part of the Donley-Garrison group. It is only discussed with them herein because it (like they) lies on the northern side of the East Fork Dry Creek, which forms the boundary between faults 2272 and 2273 as mapped by CGS and USGS. In fact, scarp 2272-19 appears to be a short, northwestward continuation of scarp 2273-02, which is discussed in the next section.

Based on my mapping and field checking, all 10 of these faults (scarps 2272-10 through 2272-19) have essentially the same geomorphic expression, and thus I infer they are all Quaternary faults or steep folds. However, there is no location where late Quaternary deposits are unambiguously displaced. Therefore, I assign an age to these scarps as Quaternary, undifferentiated.

4.3 Potential for Trenching Studies on the Donley-Garrison Faults (scarps 2272-10 through 2272-19)

Road access is quite good to many of the Donley-Garrison faults, so if landowner permission could be obtained, trenching is possible. For example, dirt roads parallel the toes of scarps 2272-11, -14, and -15. Roads cross scarps 2272-12, -13, and -15, and come very close to scarps 2272-16 and -17. In theory, it would be possible to bracket the age of latest fault movement by excavating a pair of trenches, one across unfaulted alluvium (if any) that traverses the fault trace, and a second across the scarp itself.

5. FAULT Q23 (Unnamed faults southwest of Montrose)

In the CGS/USGS Fault and Fold Database, fault Q23 (2273) is a group of 5 unnamed faults. Only one of these Q23 faults (my 2273A in Table 1 and Fig. 3; scarps 2273-10 through -12 in Table 2), lies in this study area (i.e., west of 108° W Longitude), and is discussed in this report. However, in the area of fault 2273, I mapped an additional 11 Quaternary fault scarp segments not included on the Quaternary Fault database (se Fig. 3 and ESRI Shapefiles).

In this text section, I describe all the Quaternary scarp segments in the area of fault Q23/2273 (scarps 2273-01 through 2273-14) in 2 geographic groups. First, scarps 2273-05 through-09 which form a zone of down-to-the-SW scarps in the south-central part of the Dry Creek Basin quadrangle. Second, scarps 2273-01 through -04, and 2273-10 through -14, which form a complex monocline/fault/graben system in the north-central part of the Pryor Creek quadrangle, across the Old Paradox Road (see Table 2 and ESRI Shapefiles).

5.1 Unnamed scarps 2273-05 through 2273-09

Scarps 2273-05 through 2273-09 form a discontinuous zone of 5 south- and southwest-facing scarps at least 7.4 km long (may extend east of 108°W Longitude, into the adjacent Montrose West 7.5' quadrangle). Scarps 2273-06 through 2273-09 form a continuous zone of scarps 3.4 km long, broken only by the incised valleys of NE-trending streams (Fig. 19). On the wider interfluves, the scarp is expressed as a low slope facing southwest, or opposite to the dipslope. The dipslope surface on the downthrown side of the scarp has been buried by fine-grained, locally derived sediments for a width of about 50-70 m. This band of finer Quaternary sediments gives rise to more grassy meadow-type vegetation than is typically found on the rocky, rubbly dipslope soils.

On narrower interfluves, the fault trace is marked by not only a small saddle, but by short NW- and SE-trending tributary valleys that connect with the more deeply-incised NE-trending valleys. Such saddles are also covered with locally-derived Quaternary slopewash sediments. On scarp 2273-08, these sediments are roughly 1 m thick based on roadcut exposures in the saddle, and the clasts derived from the underlying bedrock (residuum) are coated with thick rinds of calcium carbonate.

There are no good vertical exposures of the causative fault plane. However, the bed of a jeep road in the southern half of scarp 2273-08 exposes zones of crushed and sheared Dakota sandstone, with abundant fractures paralleling the mapped scarps (Fig. 20).

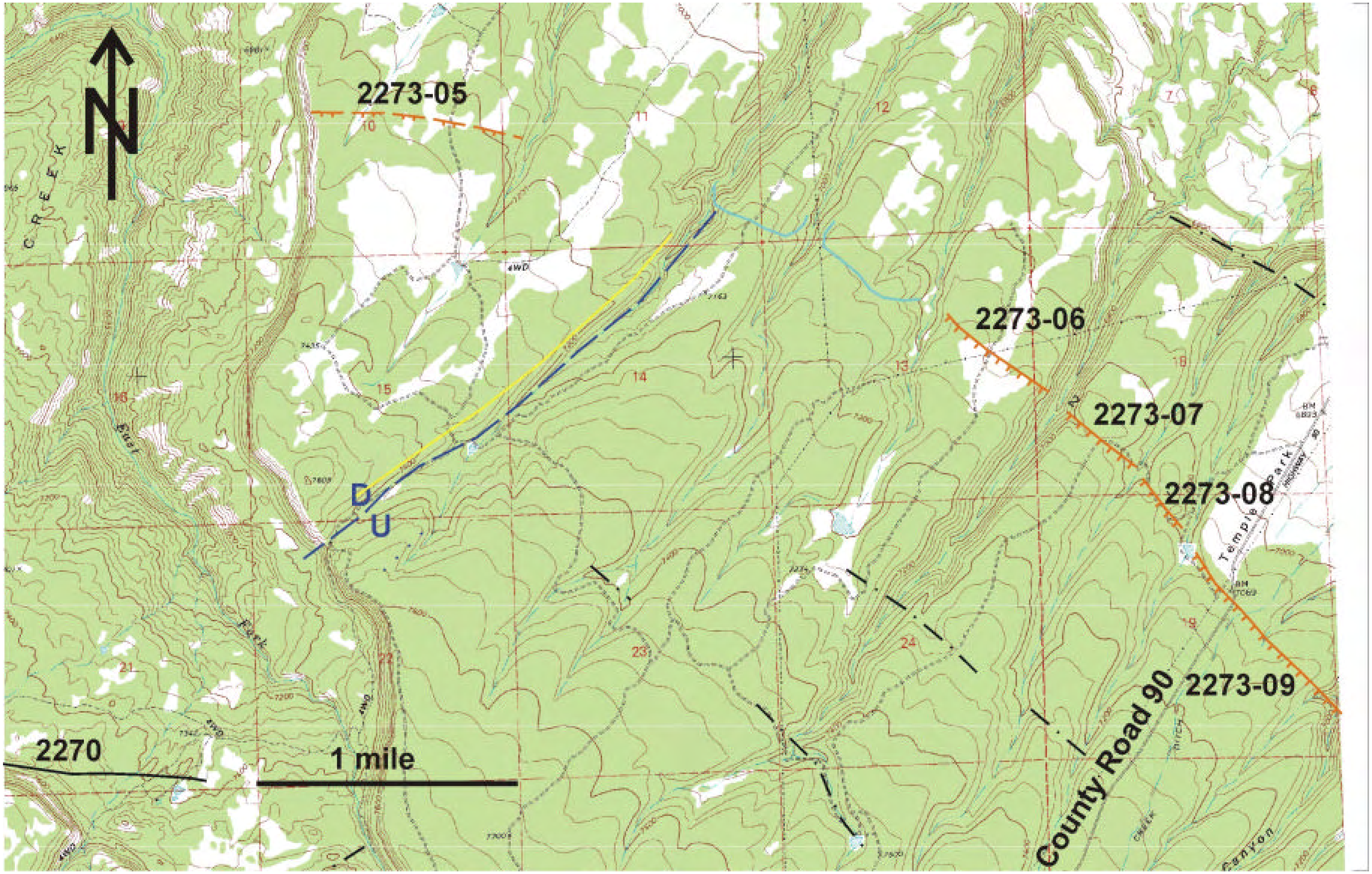

Fig. 19. Map of scarps 2273-05 through 2273-09 (orange; hachures toward downthrown side). Eastern end of the Roubideau Creek fault (2270) is at lower left. Blue, faults from I-283; yellow, faults from I-360; black dot-and-dash, topographic lineaments (this study). Base map is the Dry Creek Basin, CO 7.5' quadrangle. County Road 90 crosses scarp 2273-09 about 8 miles SW of Montrose.

Fig. 20. Photo of shear zones in the bed of a jeep road, as it ascends to the saddle on scarp 2273-08 from the SE. View is to the northwest. GPS location 760937m E, 4255028m E, UTM Zone 12, NAD27.

5.2 Old Paradox Road fault complex (scarps 2273-01 through 2273-04, and 2273-10 through 2273-14)

The only part of CGS/USGS fault 2273 that lies in this study area is a complex zone of 14 parallel scarps in the north-central part of the Pryor Creek 7.5' quadrangle (Fig. 3). These scarps all trend between N25-35W (roughly parallel to dipslope contours) and form a rhomboidal group 3.5 km by 3.5 km (Fig. 21). Compared to the 8.8 km length of fault 2273A shown on the CGS/USGS Database, I mapped Quaternary scarps only on the NW-most 3.8 km of the fault, between the East Fork Dry Creek and the West Fork Spring Creek. However, this was also the only part of 2273 that I field-checked.

The remaining 5 km of fault 2273A crosses rugged topography created by landsliding at the contact of the Dakota-Burro Canyon Formation and the underlying Morrison Formation. For example, in the 2 km stretch between the West Fork and Middle Fork of Spring Creek, the fault runs near or in a saddle that separates a detached hill from the remainder of the Dakota-Morrison escarpment. In the 3.2 km stretch between the Middle Fork and East Fork of Spring Creek, the fault is mapped up a structurally-controlled stream and saddle parallel to the escarpment face. Therefore, there may be small indicators of Quaternary fault movement on this 5 km stretch of the fault that I did not field check. Such indicators did not appear obvious on the aerial photographs.

The largest topographic feature of the fault complex is a NE-facing, 60 m-high, gentle flexural escarpment of the Dakota dipslope, very similar to the ones previously described along the Roubideau Creek (2270) and Roubideau Ranch (2272) faults. I will refer to this feature as the Old Paradox Road monocline (shown in blue on Fig. 21), although lack of good exposures precluded confirming that the structure is, in fact, a monocline. I merely assume it has an internal structure similar to that of the Roubideau Creek monocline, because it has a similar external form.

At the base of the monocline is a very narrow (60-100 m, except at SE end), 3.6 km-long graben (bounded by red lines 2273-10 through 2273-14 on Fig. 21). This graben is similar to the graben at the base of the Roubideau Creek monocline, except it is longer and narrower. Most of my field checking concentrated on mapping and measuring the scarps along this graben. These scarps are so narrow and steep that I infer late Quaternary movement on them.

The remaining scarps of the Old Paradox Road fault complex fall into two groups. Scarps 2273-03 and -04 are small antislope (SW-facing) scarps that lie above the crest of the monocline. I did not field check these scarps. These scarps resemble antislope scarps mapped by McCalpin (2005) above the crest of the Pajarito Fault monocline at Los Alamos, New Mexico.

Scarps 2273-01 and -02 bound a NW-trending, horst 1-1.3 km wide that lies1.3 km NE of the Old Paradox Road graben. Scarp 2273-02 is the antislope scarp on the SW side of the horst, and is discontinuous and quite gentle, resembling other antislope scarps such as 2272-05 through -09. Scarp 2273-01 is even more vague and discontinous, probably because it faces NE, in the direction of the dipslope. The horst

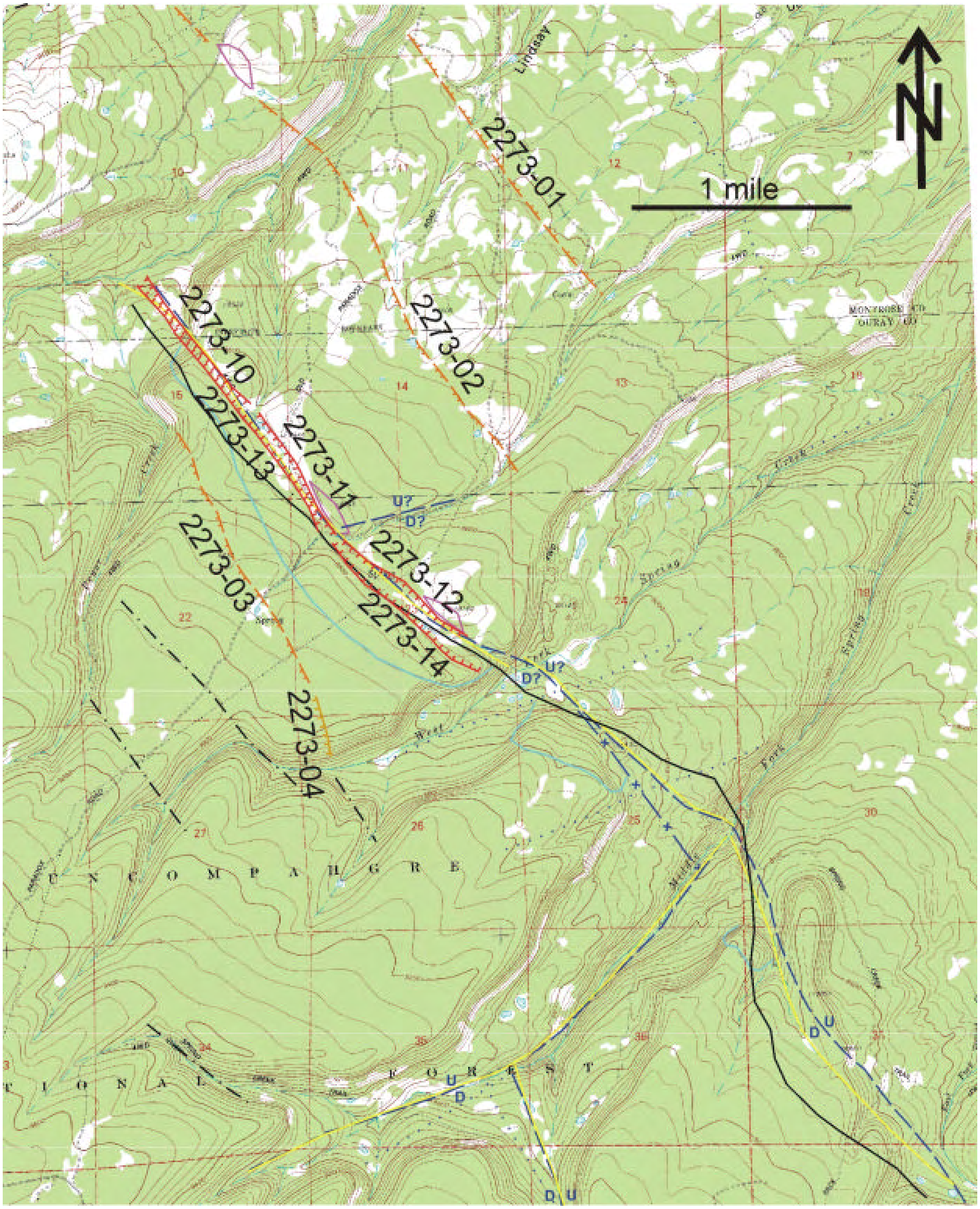

Fig. 21. Map of the Old Paradox Road fault complex. Black solid line, fault 2273 from CGS/USGS Fault Database; red lines, late Quaternary fault scarps; orange lines, Quaternary fault scarps; yellow lines, faults from USGS Map I-360; blue lines, faults from USGS Map I-283; black dash-and-dot, topographic lineament (this study). Base map is Pryor Creek quadrangle.

between these scarps is dominantly composed of Mancos Shale, in contrast to the rest of the dipslope which is capped by Dakota Sandstone. Due to the discontinuous and gentle nature of these scarps, I assume that movement occurred during the Quaternary, but not the late Quaternary.

5.2.1 Old Paradox Road graben

The Old Paradox Road graben is bounded by antithetic scarps 2273-10 through -12, and by synthetic scarps 2272-13 and -14 (Fig. 21). These scarps were mapped and numbered in a rather generalized way, based on clear breaks in the scarps at drainages, such as the drainage that separates 2273-13 from 2273-14 and contains the Old Paradox Road. However, at a more detailed scale each scarp is composed of smaller individual scarp segments that often display an *en echelon* pattern with ramps and stepovers (Fig. 22). This is especially true of the north half of scarp 2273-14. This pattern cannot be seen on the aerial photographs, due to the thick forest cover, and was discovered only during field GPS traverses.

In the following section I describe the characteristics of the fault scarps along the graben, concentrating on the higher, synthetic fault scarps 2273-13 and 2273-14.

5.2.1.1 Scarp 2273-13

Scarp 2273-13 comprises the northwestern half of the synthetic scarp of the graben, and extends from the Old Paradox Road northwest to the East Fork Dry Creek (Fig. 21). The scarp can be divided into 3 sections. The southern section trends NW from Old Paradox Road a distance of 630 m to an unnamed tributary drainage (Fig. 22). The central section trends an additional 515 m to the NW, to a large drainage that drains the graben toward the NE. The northern section trends an additional 400 m to the NW, to a saddle and then to the lip of the East Fork canyon.

The southern section contains two parallel scarps that are 90 m apart at the south end but widen to 180 m apart at the north end. The western scarp starts off at 6 m high near the Old Paradox Road, but then decreases irregularly as traced to the NW. At the corner of Sections 14, 15, 22, and 23, the scarp splits into 2 scarps (1.5 m and 2 m high), just behind the cabin owned by Alice Goodman of Montrose. This scarp soon dies out. The western 1.5 m-high, 250 m-long scarp also eventually dies out, and is replaced after a right step by a similar 160 m-long scarp that is 2.5 m high at either end, but up to 4 m high in the middle (Fig. 23). This scarp is typical of many scarps on the Old Paradox Road graben, being 100-200 m long, and increasing in height from zero at the ends to 3-4 m in the center. It also exposes NE-dipping slabs of Dakota Sandstone at its base, suggesting that the scarp is at least partly monoclinal in structure.

The eastern scarp of the southern section is 500 m long and bounds the western side of the grassy center of the graben. The scarp reaches a maximum of 3.5 m high in its northern part, but over most of its length it is 2-2.5 m high. The upthrown side of the scarp is also a very flat surface and appears to have been part of the graben floor at one time; it does not look like the toe of the monocline. If true, this implies that the eastern scarp is a “mid-graben” scarp developed at a later time than the initial graben. The downthrown side of the scarp is quite grassy and moist in its central section, suggesting that the water table is very close to the surface.

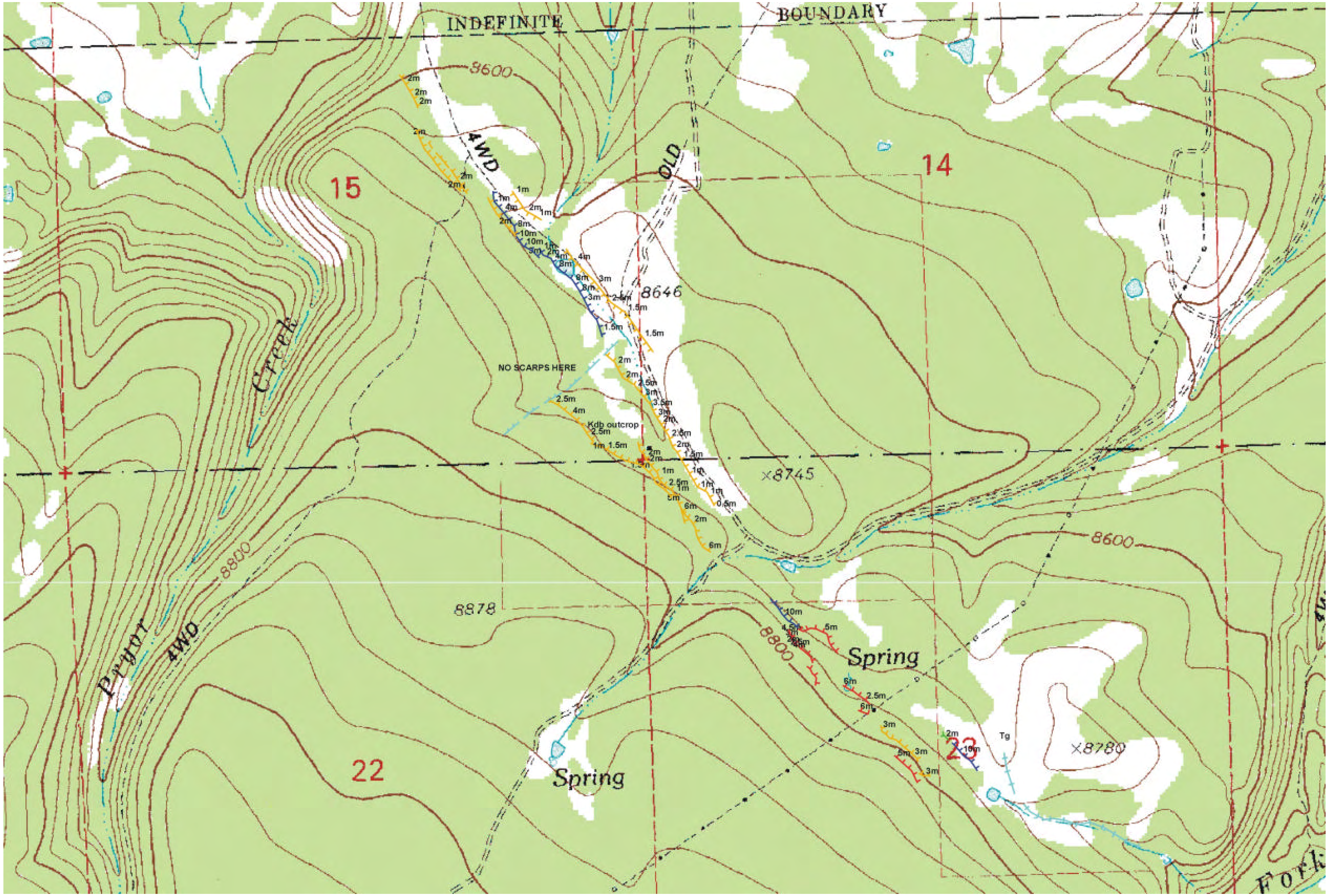

Fig. 22. GPS traverse map of Quaternary fault scarps of the Old Paradox Road graben. Main (highest) scarp in blue, secondary scarps in red and orange. Scarp heights in meters.

Fig. 23. Photo of scarp 2273-13, south section, western scarp, looking NW from waypoint 28 (756993m E, 4245445m N, UTM Zone 12, NAD27). Scarp height is approximately 3 m. Note outcrop of Kdb on lower scarp face at lower left. This location is shown on Figure 22 at the label “Kdb outcrop.” Bedding in Kdb dips to the NE, suggesting that the scarp here is at least partly monoclinal.

The central section of scarp 2273-13 contains the highest and most continuous scarps. The main synthetic scarp zone is composed of 2 scarps (blue in Fig. 22). The southern scarp is 300 m long and rises from 1.5 m high at its south end, to 8 m high in the center (opposite the stock pond; see Fig. 24), then rapidly decreases to 2m, 1m and then 0 m north of the stock pond. The northern scarp lies about 50 m to the SW of the southern scarp and overlaps it (in other words, a left-stepping en-echelon fault). The height of the northern scarp rises in exact proportion to the decline of the height of the southern scarp in the overlap zone, making a classic example of a ramp between en-echelon, left-stepping normal fault scarps. The northern scarp rises very rapidly in height to 9m then 10m, then declines rapidly to 8 m then 2-4 m, finally dying out after a total length of 220 m. As it dies out northward, a second scarp appears to the west about 2 m high, but that scarp too dies out after about 125 m total length.

The central section of scarp 2273-13 contains the deepest graben with the flattest floor (Fig. 24), which is nearly a closed topographic depression. The graben is asymmetrical, with a very steep western margin (scarp 2273-13) and a gentler, lower eastern margin (scarp 2273-11). The only indication of the internal structure of scarp 2273-13 is an outcrop of subhorizontal Dakota Sandstone at the toe of the scarp (Figs. 25, 26). This outcrop was exposed when the landowner dug away the thin colluvium at the toe of the scarp, probably to better develop at spring at that location. The existence of subhorizontal bedrock at the toe of the scarp is hard to reconcile with either a monoclinal or a fault scarp origin for this scarp. If the scarp were a monocline, one would expect any bedrock exposed at the toe to dip steeply NE. If the scarp were a fault scarp, one would expect the toe of the scarp to be covered with thick, scarp-derived colluvium. Without further field mapping and/or trenching, this ambiguity cannot be resolved.

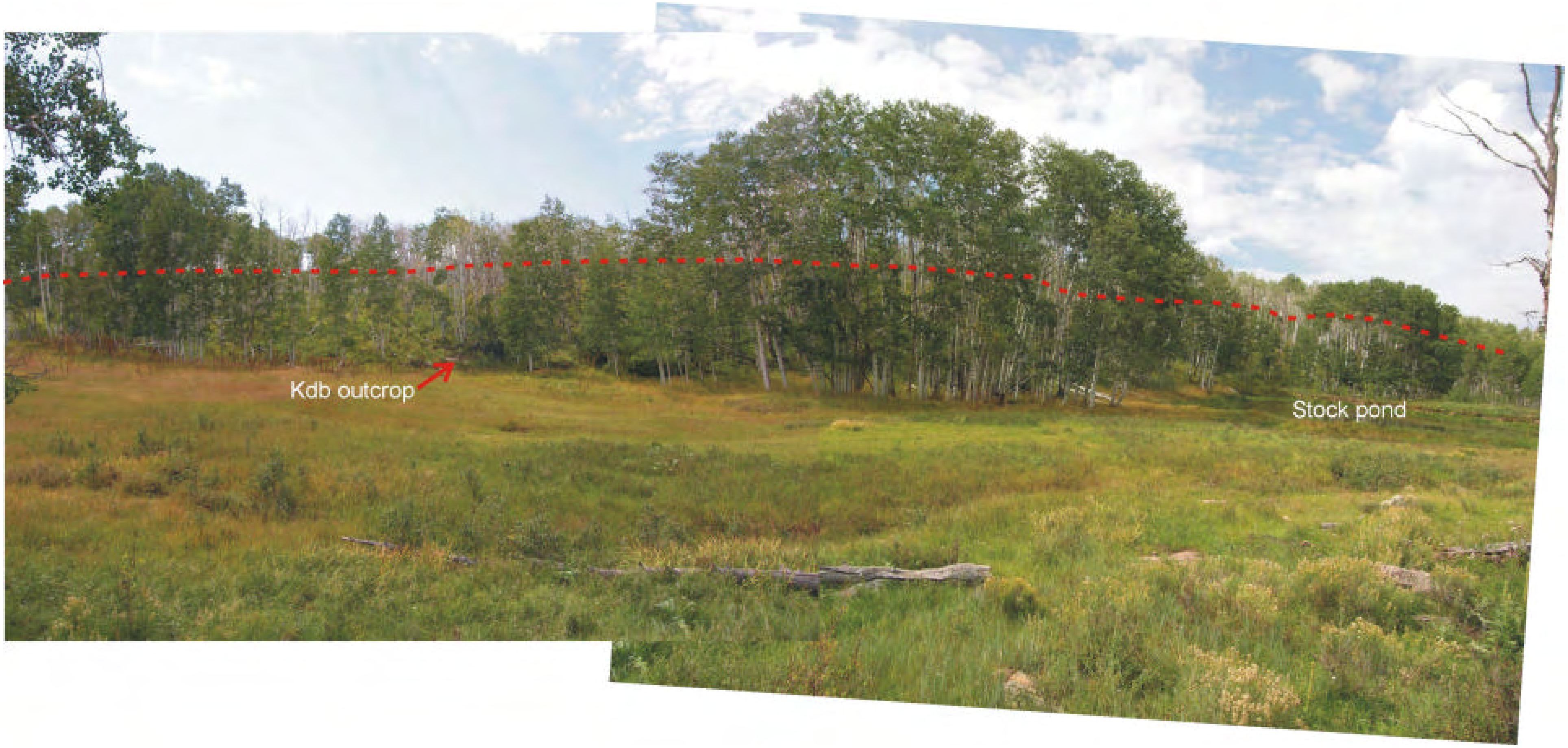

Fig. 24. Panorama of scarp 2273-13, central section, looking toward scarp to the west from across the graben. Red dashed line shows approximate crest of fault scarp, which averages about 8 m high here. Stock pond in middle of central section (shown on Fig. 22) is at far right center. GPS coordinates of the “Kdb outcrop” at the base of the scarp (left center) are 756999m E, 42455811m N, UTM Zone 12, NAD27.

Fig. 25. Photo of scarp 2273-13, central section, southern half, showing outcrop of Dakota Sandstone at the toe of the scarp. This outcrop was exposed when the landowner dug away the colluvium at the toe of the scarp, to develop a spring at the toe of the scarp. The runoof from the spring flows off the right side of the photo, to the stock pond.

Fig. 26. Close-up photo of the Kdb outcrop. Pack at lower left is 50 cm high.

The northern section of scarp 2273-13 bounds a very shallow graben that rises to a saddle. The individual synthetic scarps are a consistent 2 m high. On the antithetic side of the graben, the gentle slope cannot even be termed a scarp.

5.2.1.2 Scarp 2273-14

Scarp 2273-14 comprises the southeastern half of the synthetic scarp of the graben, and extends from the Old Paradox Road southeast to the West Fork Spring Creek (Fig. 21). The individual scarps that make up scarp 2273-14 are even shorter (50-100 m) and less continuous than the scarps of scarp 2273-13 (Fig. 22). A typical scarp is 70-80 m long, and rises from a height of zero at either end, to an average maximum height of 5-6 m in the center. In most cases, the displacement on one scarp dies out and is transferred to a parallel scarp to the east or west, in examples of either left or right stepovers.

5.3 Potential for trenching studies on scarps of 2273A

The best potential for trenching late Quaternary fault scarps of fault 2273A is in the Old Paradox Road graben. Access to the graben is reasonably good via the Old Paradox Road from the SW, or via private roads in the Dennis Gray property to the NE. Once in the graben, there are jeep trails along its length. However, almost all of the scarps lie in private land. Therefore, permission would have to be obtained for trenching.

Assuming that permission could be obtained, there are many potential trenching targets. The most obvious one is the mid-graben scarp that comprises the eastern scarp of the southern section of scarp 2273-13. This is the scarp that lies just east of the Alice Goodwin cabin. This scarp has 4 advantages as a trenching target: (1) it is relatively small (2-2.5 m high), so would not require a long or deep trench to confirm late Quaternary faulting, (2) it may be a single-event scarp, so internal stratigraphy would be simple, (3) the graben sediments on the downthrown side may contain datable organics, and (4) it should be one of the younger scarps, since it apparently postdates the initial formation of the graben. The only drawback to trenching this scarp would be inferred high groundwater level in the central part of the scarp. This could be avoided by trenching north of the scarp center.

There are many higher scarps on scarps 2273-13 and -14 that, based on their height (5 to 10 m), are presumably multiple-event scarps. These scarps could be trenched to determine the recurrence interval between surface faulting events. However, such trenches would have to be longer and deeper than the trench on the mid-graben scarp.

6. DISCUSSION

Based on map compilation, photo interpretation, and limited field checking, there is a NW-trending zone of Quaternary faulting in the central Uncompahgre Plateau at least 32 km long that coincides with parts of previously-mapped faults Q20, Q22, and Q23 (Widmann et al., 1998). The youngest fault scarps identified are 1-12 m high, have steep scarp faces (slightly below the angle of repose), and in some cases truncate Quaternary landforms such as stream valleys. These late Quaternary fault scarps all lie at the toes of ca. 60-m high, NE-facing escarpments and form the margins of prominent grabens at the toes of the escarpments. Of the three prominent escarpments that have such grabens (Roubideau Creek fault, fault 2270; Roubideau Ranch fault, fault 2272; Old Paradox Road fault, fault 2273), the first is clearly a monocline. Exposures are insufficient to prove that the other two escarpments are also monoclines, although I suspect they are.

In addition to these late Quaternary scarps, there are older scarps that disrupt the smooth plain of the Dakota dipslope. These scarps are at least partly erosional, but seem to be younger than the removal of the Mancos Shale from atop the Dakota-Burro Canyon sandstones on the plateau dipslope. One such area of scarps is the Donley-Garrison faults, a group of 7 faults that separates the Roubideau Ranch fault from the Old Paradox Road fault.

This mapping study has identified many late Quaternary and Quaternary (undivided) fault scarps, but many questions remain as to the age of the fault scarps, and whether they are fault scarps, fold scarps, or some combination of the two. McCalpin (2003) made some very preliminary estimates of scarp age to calculate recurrence intervals and slip rates for the Roubideau Creek fault, but these estimates were not supported by any numerical dates.

One of the key assumptions of McCalpin (2003) was that only the grabens and isolated antislope scarps were of Quaternary age, and the much higher 60 m-high monoclines were pre-Quaternary. This assumption was based on an inference that Quaternary deformation occurred at very low confining pressures, when the landscape looked essentially as it does today, so it must be expressed as brittle faulting. Accordingly, folding such as observed at Roubideau Creek was inferred to represent pre-Quaternary ductile deformation that required high confining pressures, which could only have occurred when there was still a thick cover of post-Dakota sedimentary rocks still covering the Plateau.

When the author presented a guest lecture at Utah State University on these faults in Fall of 2006, the two structural geologists there (James P. Evans, Suzanne Janecke) took exception to the inferences above. They argued that the entire monocline could also could have formed in Quaternary time, when the landscape looked like it does today. In other words, they thought that the monoclines could have formed as forced folds over a normal fault at or near the ground surface. Supporting evidence was cited in the paper by White and Crider (2006).

If their contention is true, it offers a way to compute the long-term Quaternary slip rate on these normal faults, since the monoclines began developing. Such a long-term slip rate could be compared to the short-term slip rates computed for smaller (2-10 m-high) fault scarps.

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8. Appendix 1
Complete Report for Roubideau Creek fault (Class A) No. 2270

Brief Report ||Partial Report

Compiled in cooperation with the Colorado Geological Survey

citation for this record: **Widmann, B.L., compiler, 1997, Fault number 2270, Roubideau Creek fault, in Quaternary fault and fold database of the United States: U.S. Geological Survey website, http://earthquakes.usgs.gov/regional/qfaults, accessed at 11/28/2006 08:34 AM.**

Synopsis	The Roubideau Creek fault is on the east flank of the Uncompahgre Uplift. It is marked by a northeast facing 80-m-high scarp, a smaller southwest-facing scarp, and a sag pond (Lettis and others, 1996 #4453). The fault dips northeast (Lettis and others, 1996 #4453), but the sense of movement is not well understood. Late Pleistocene to Holocene landslide deposits are offset by the fault near Roubideau Creek (Kirkham and Rogers, 1981 #792; Lettis and others, 1996 #4453).
Name comments	The Roubideau Creek fault is a west-northwest-trending fault southwest of Delta, Colorado. The fault extends from near Traver Creek on the west nearly to the East Fork of Dry Creek on the east. Roubideau Creek is the dominant drainage beetween these two creeks. Lettis and others (1996 #4453) referred to this fault as the Roubideau Creek fault. **Fault ID Comments:** Fault 82 in Kirkham and Rogers (1981 #792) and fault number Q20 of Widman and others (1998 #3441).
County(s) and State(s)	MONTROSE COUNTY, COLORADO
AMS sheet(s)	Moab
Physiographic province(s)	COLORADO PLATEAUS
Reliability of location	Good Compiled at 1:250,000 scale. *Comments:* The fault was mapped at a scale of 1:250,000 by Williams (1964 #2789) and Lettis and others (1996 #4453). The trace used herein is from Williams (1964 #2789).
Geologic setting	The Robideau Creek fault is a northeast-dipping normal fault (Lettis and others, 1996 #4453). Quaternary offset, however, seems to suggest down-to-the-southwest movement on the fault (Kirkham and Rogers, 1981 #792), implying reverse faulting at least during the Quaternary. The fault lies on the east flank of the Uncompahgre Uplift, which is a northwest-trending, east-tilted fault block.
Length (km)	21 *Comments:*

	This fault includes numerous strands that have a cumulative length of 26.1 km.
Average strike	N74°W
Sense of movement	Normal or reverse *Comments:* Lettis and others (1996 #4453) defined the fault as northeast-dipping and normal, but Kirkham and Rogers (1981 #792) formerly suggested reactivation during the Quaternary in a reverse sense.
Dip	*Comments:* Lettis and others (1996 #4453) defined the fault plane as northeast-dipping.
Paleoseismology studies	
Geomorphic expression	The Robideau Creek fault is marked by an 80-m-high northeast-facing scarp. The fault also aligns with another smaller scarp that is southwest-facing, and a sag pond is against this fault scarp. The smaller scarp and sag pond may be evidence of Quaternary activity on an antithetic fault in the hanging wall of the Robideau Creek fault (Lettis and others, 1996 #4453).
Age of faulted surficial deposits	Quaternary landslide deposits of late Pleistocene to Holocene age are offset along the fault trace (Sullivan and others, 1980 #2756; Kirkham and Rogers, 1981 #792; Lettis and others, 1996 #4453). Williams (1964 #2789) shows no offset of Quaternary deposits. The majority of the fault extends through Jurassic and Cretaceous bedrock.
Historic earthquake	
Most recent prehistoric deformation	Latest Quaternary (<15 ka) *Comments:* Kirkham and Rogers (1981) designated the fault as Quaternary. Colman (1985 #1953) mapped the fault as an inferred Pleistocene fault. Sullivan and others (1980 #2756) and Lettis and others (1996 #4453) indicated late Pleistocene to Holocene movement on the fault based on offset of young landslide deposits.
Recurrence interval	
Slip-rate category	Less than 0.2 mm/yr *Comments:* Lettis and others (1996 #4453) calculated a slip rate of <0.2 mm/yr based on a scarp height of 80 m and an age of about 500 ka or older.
Date and Compiler(s)	1997 Beth L. Widmann, Colorado Geological Survey

References	#1953 Colman, S.M., 1985, Map showing tectonic features of late Cenozoic origin in Colorado: U.S. Geological Survey Miscellaneous Geologic Investigations I-1566, 1 sheet, scale 1:1,000,000. #792 Kirkham, R.M., and Rogers, W.P., 1981, Earthquake potential in Colorado: Colorado Geological Survey Bulletin 43, 171 p., 3 pls. #4453 Lettis, W., Noller, J., Wong, I., Ake, J., Vetter, U., and LaForge, R., 1996, Draft report, Seismotectonic evaluation of Colorado River storage project-Crystal, Morrow Point, Blue Mesa dams, Smith Fork project-Crawford dam, west-central Colorado: Technical report to U.S. Bureau of Reclamation, Denver, Colorado, 177 p. #2756 Sullivan, J.T., Meeder, C.A., Martin, R.A., and West, M.W., 1980, Seismic hazard evaluation-Ridgway dam and reservoir site-Dallas Creek project Colorado: U.S. Water and Power Resources Service, Seismotectonic Section, report, 43 p. #3441 Widmann, B.L., Kirkham, R.M., and Rogers, W.P., 1998, Preliminary Quaternary fault and fold map and database of Colorado: Colorado Geological Survey Open-File Report 98-8, 331 p., 1 pl., scale 1:500,000. #2789 Williams, P.L., 1964, Geology, structure, and uranium deposits of the Moab quadrangle, Colorado and Utah: U.S. Geological Survey Miscellaneous Geologic Investigations I-360.

Appendix 2
Complete Report for Unnamed faults east of Roubideau Creek (Class B) No. 2272

Brief Report ||Partial Report

Compiled in cooperation with the Colorado Geological Survey

citation for this record: **Widmann, B.L., compiler, 1998, Fault number 2272, Unnamed faults east of Roubideau Creek, in Quaternary fault and fold database of the United States: U.S. Geological Survey website, http://earthquakes.usgs.gov/regional/qfaults, accessed at 11/28/2006 08:31 AM.**

Synopsis	This group of faults lies on the southern end of the Uncompahgre Uplift. Although there was no reported evidence of Quaternary offset along these faults, they were mapped as Quaternary faults by Lettis and others (1996 #4453 ; plate 2). They attributed the fault activity to salt tectonism, and thus are considered to be Class B structures. The most recent movement on the faults herein considered to have occurred during the Quaternary based on the work of Lettis and others (1996).
Name comments	This group of unnamed faults includes five faults that generally trend northwest at the southeast end of the Uncompahgre Uplift. **Fault ID Comments:** Fault number Q22 of Widman and others (1998 #3441).
County(s) and State(s)	MONTROSE COUNTY, COLORADO
AMS sheet(s)	Moab
Physiographic province(s)	COLORADO PLATEAUS
Reliability of location	Good Compiled at 1:250,000 scale. *Comments:* The faults were mapped at a scale of 1:250,000 by Williams (1964 #2789) and Lettis and others (1996 #4453). The fault traces used herein are from Lettis and others (1996 #4453).
Geologic setting	This group of faults is on the southeast end of the Uncompahgre Uplift, which is a northwest-trending, east-tilted fault block. These faults are down to the northeast and southwest, and are considered to be salt-related rather than tectonic features (Lettis and others, 1996 #4453).
Length (km)	12 *Comments:* This group of faults have a cumulative length of about 18.7 km.

Average strike	N50°W
Sense of movement	Normal
Dip	
Paleoseismology studies	
Geomorphic expression	No information is available about the Quaternary geomorphic expression of the fault.
Age of faulted surficial deposits	Faults in this group offset Jurassic to Cretaceous bedrock (Williams, 1964 #2789), but Quaternary deposits are not mapped along the faults. Although there is no evidence of faulted Quaternary deposits along these faults, Lettis and others (1996 #4453) concluded tahat they moved during the Quaternary, but are related to salt tectonism.
Historic earthquake	
Most recent prehistoric deformation	Quaternary (<1.6 Ma) *Comments:* Although there is no direct evidence for offset of Quaternary deposits along these faults, they were mapped as Quaternary faults related to salt tectonism by Lettis and others (1996 #4453 ; plate 2). Faults associated with the Uncompahgre Uplift are often considered to have experienced Quaternary movement. Based on the timing of abandonment of Unaweep Canyon from the Uncompahgre plateau Cater (1966 #2671) indicated uplift began in the mid-Pliocene and continued into the Pleistocene resulting in as much as 640 m of differential uplift.
Recurrence interval	
Slip-rate category	Less than 0.2 mm/yr *Comments:* Widmann and others (1998 #3441) placed this structure within the <0.2 mm/yr slip-rate category.
Date and Compiler(s)	1998 Beth L. Widmann, Colorado Geological Survey
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Appendix 3
Complete Report for
(Class B) No. 2273

Brief Report ||Partial Report

Compiled in cooperation with the Colorado Geological Survey

citation for this record: **Widmann, B.L., compiler, 1998, Fault number 2273, Unnamed faults southwest of Montrose, in Quaternary fault and fold database of the United States: U.S. Geological Survey website, http://earthquakes.usgs.gov/regional/qfaults, accessed at 11/28/2006 08:35 AM.**

Synopsis	This group of faults lies on the south end of the Uncompahgre Uplift. Although there was no reported evidence of Quaternary offset along these faults they were mapped as Quaternary faults by Lettis and others (1996; plate 2). They attributed fault activity to salt tectonism, and thus are considered to be Class B structures. The most recent movement on the faults herein considered to have occurred during the Quaternary based on the work of Lettis and others (1996 #4453).
Name comments	This group of unnamed faults includes five generally north-south-trending faults at the south end of the Uncompahgre Uplift. The faults are west of Highway 550 between Montrose and Ridgway. **Fault ID Comments:** Fault number Q23 of Widman and others (1998 #3441).
County(s) and State(s)	MONTROSE COUNTY, COLORADO OURAY COUNTY, COLORADO
AMS sheet(s)	Montrose Moab
Physiographic province(s)	COLORADO PLATEAUS
Reliability of location	Good Compiled at 1:250,000 scale. *Comments:* The faults were mapped by Steven and Hail (1989 #2747) at a scale of 1:100,000, and by Williams (1964 #2789), Tweto and others (1976 #2774), and Lettis and others (1996 #4453) at 1:250,000 scale. The fault traces used herein are from Lettis and others (1996 #4453).
Geologic setting	This group of faults is on the southeast end of the Uncompahgre Uplift, which is a northwest-trending, east-tilted fault block. Faults in this group are downthrown to the west and southwest, and are considered to be salt-related rather than tectonic features (Lettis and others, 1996 #4453).
Length (km)	9 *Comments:* This group of faults have a cumulative length of about 38.5 km.

Average strike	N7°W
Sense of movement	Normal
Dip	
Paleoseismology studies	
Geomorphic expression	There is no geomorphic expression of Quaternary offset along these faults according to Lettis and others (1996 #4453).
Age of faulted surficial deposits	This group of faults offset the Cretaceous Dakota Sandstone and Mancos Shale (Williams (1964 #2789; Tweto and others, 1976 #2774; Steven and Hail, 1989 #2747). The faults are almost entirely within Cretaceous rocks with less than 5 percent extending through or beneath Quaternary deposits. Although there is no evidence of faulted Quaternary deposits along these faults, Lettis and others (1996 #4453) concluded they moved during the Quaternary.
Historic earthquake	
Most recent prehistoric deformation	Quaternary (<1.6 Ma) *Comments:* Although there is no direct evidence of faulted Quaternary deposits along these faults, they were considered to be Quaternary faults by Lettis and others (1996 #4453; plate 2). They concluded that fault activity is due to salt tectonism.
Recurrence interval	
Slip-rate category	Less than 0.2 mm/yr *Comments:* Widmann and others (1998 #3441) placed this structure within the <0.2 mm/yr slip-rate category.
Date and Compiler(s)	1998 Beth L. Widmann, Colorado Geological Survey
References	#4453 Lettis, W., Noller, J., Wong, I., Ake, J., Vetter, U., and LaForge, R., 1996, Draft report, Seismotectonic evaluation of Colorado River storage project-Crystal, Morrow Point, Blue Mesa dams, Smith Fork project-Crawford dam, west-central Colorado: Technical report to U.S. Bureau of Reclamation, Denver, Colorado, 177 p. #2747 Steven, T.A., and Hail, W.J., Jr., 1989, Geologic map of the Montrose 30' x 60' quadrangle, southwestern Colorado: U.S. Geological Survey Miscellaneous Geologic Investigations I-1939. #2774 Tweto, O., Steven, T.A., Hail, W.J., Jr., and Moench, R.H., 1976, Preliminary geologic map of the Montrose 1° x 2° quadrangle,

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