Seismic Sources and Neogene Faulting in the Northern Front Range, Colorado, Source Area of the 1882 (M6.6) Earthquake; Collaborative Research with GEO-HAZ Consulting, Inc

Program Element II: Evaluate Urban Hazard and Risk.

Final Technical Report
Contract 02HQGR0094
National Earthquake Hazards Reduction Program
U.S. Geological Survey

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Project Goal

The goal of this project was to make a Late Cenozoic, interpretive fault map of the northern Front Range between I-70 and the Cache La Poudre River (Figure 1). The interpretive map would serve as a source for seeking evidence of Quaternary offset in the field. The assumption was that late Cenozoic movement on faults in the Front Range would disrupt widespread erosion surfaces and thus would be expressed strongly in the topography. The faults should not only show up as linear features, but should show differences in elevation of the disrupted surface on either side of the linears in order to be considered as a potential, late Cenozoic fault.

An additional goal of the collaborative effort was to attempt to locate the source of the 1882 M6.5 +/- 0.5 earthquake.

Software

Two different software packages were used in the interpretive process: ESRI ArcMap and Leica ERDAS Imagine. ArcMap was the primary software package for interpreting and compiling the interpretive results. ERDAS was used to rotate elevation models, to prepare elevation profiles, to create water levels, and to view aerial photographs in stereo.

Interpretive Tools

Within ESRI ArcMap, an extensive workfile was developed that ultimately comprised 89 different layers. A ten-meter DEM (Figure 1) was the base for the layers. Five renditions of the DEM were used: one with an elevation color ramp (Figure 2), and four with 90° sun-angle variations (45°, 135°, 225°, and 315°).

Shapefiles of all published faults in the area were created and made available to the public as CGS OF 03-04, *Published Faults of the Colorado Front Range* (Figure 3).

Thirty four, 1:24K geologic maps and the 1:50K map of Rocky Mountain National Park were scanned, geo-referenced, used, and also provided to the USGS Central Region for use in their Central Colorado Region Project (Figure 4). Shapefiles for the 1:500K map of Colorado were also available for use.

Six hundred and fifty nine NAPP Black & White aerial photo steropairs were scanned and geo-referenced. These provided a digital database that could efficiently be pulled up and viewed in stereo onscreen, in order to examine in detail features detected on the DEMs (Figure 5).

Seven hundred miles of stream profiles in the Front Range were obtained from Dr. R. Madole, USGS Emeritus. Knickpoints on these profiles were examined for correlation with mapped or interpreted faults. Additional layers that were used include: NAIP one-meter-resolution color photography-USDA (Figure 6) and LANDSAT Panchromatic Imagery prepared by D. Knepper –USGS (Figure 7).

Previous Mapping

Previous mapping that covered the entire Front Range (1:250K and 1:500K) indicated fairly sparse faulting (Figure 3). More detailed mapping was erratic in the way that faulting was portrayed. Some mappers showed many faults, whereas offsetting 1:24,000 maps showed virtually no faults (Figure 3). Moreover, there was no effort on these maps to differentiate Laramide faulting from post-Laramide faulting.

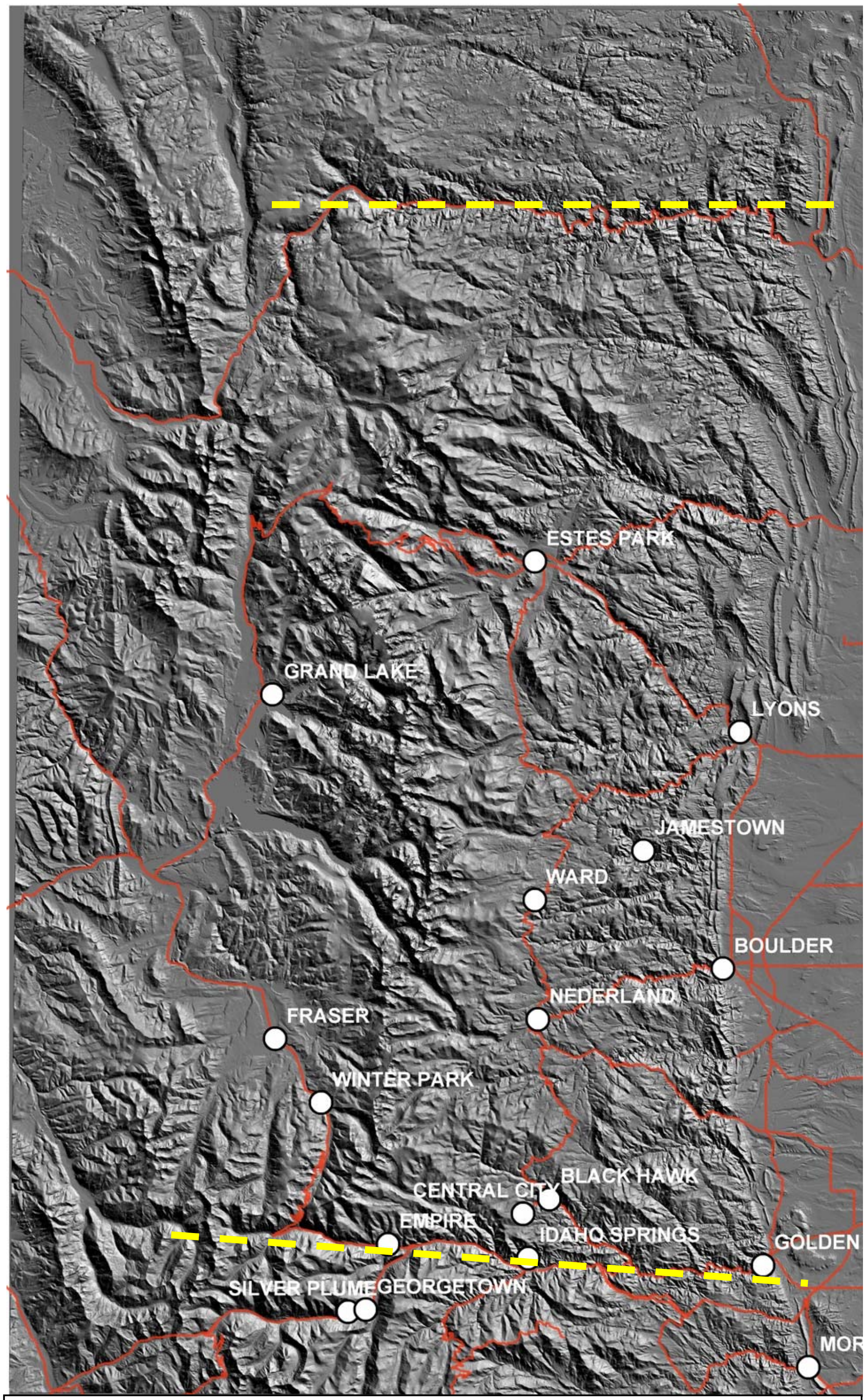

Figure 1 - DEM showing north and south boundaries of the project (yellow dashed lines), highways, and populated areas. Sun angle is from the northeast. Additional DEMs were used with SE, SW, and NW sun angles.

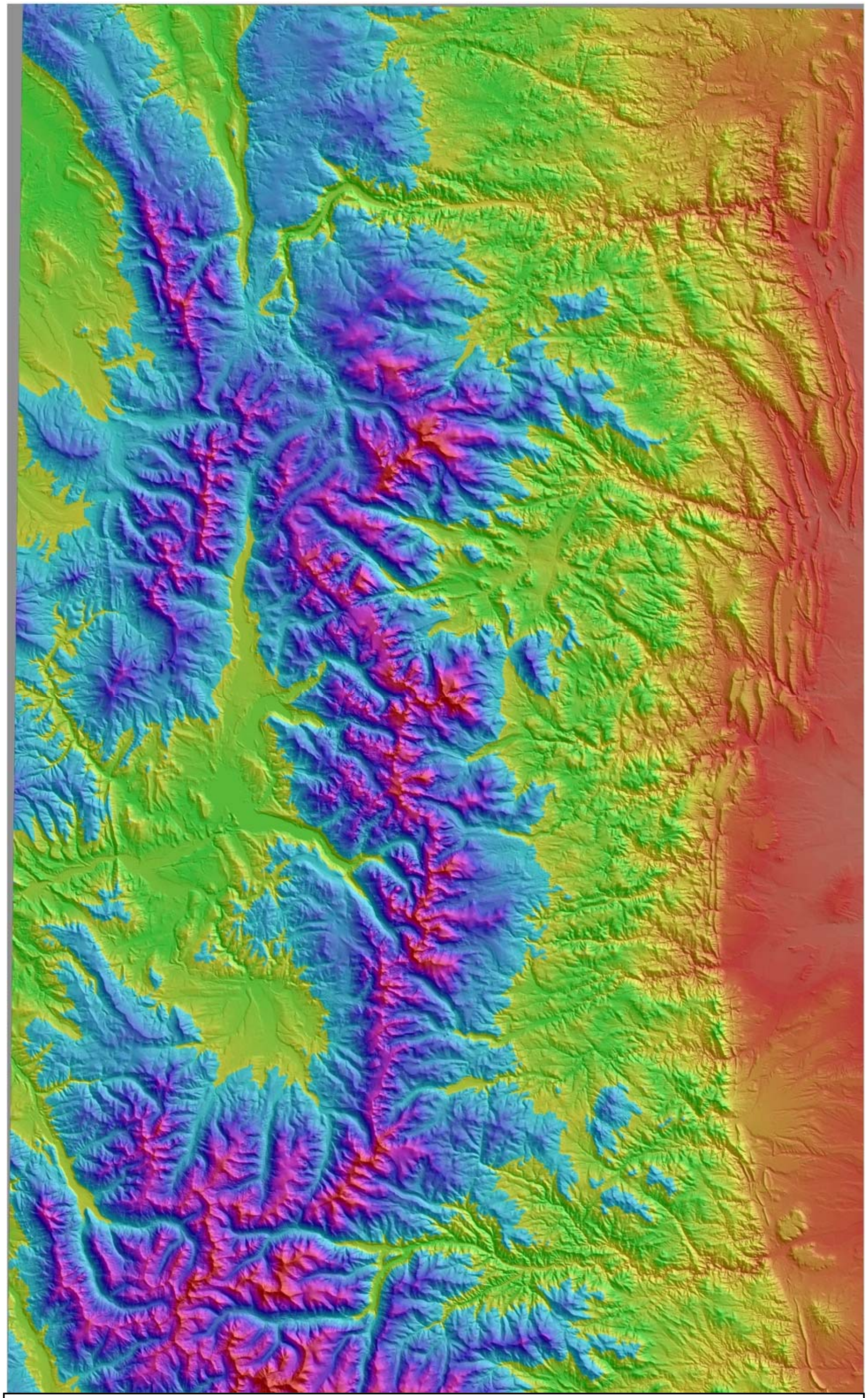

Figure 2 - DEM with color ramp for elevation. Sun angle is from the northeast.

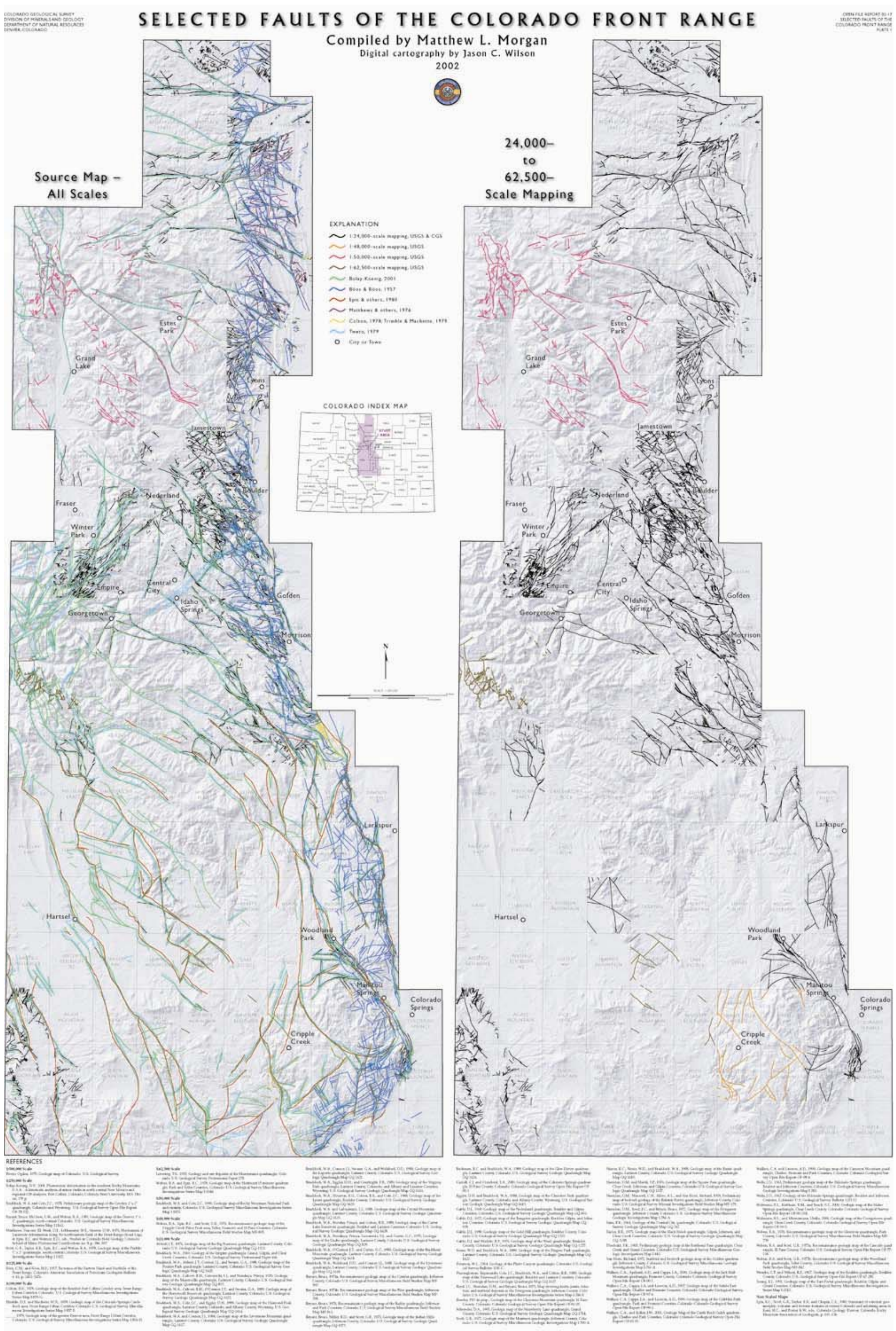

Figure 3 – Digital publication (OF 03-04) of shapefiles for published faults (at all scales) in the Front Range (2003)

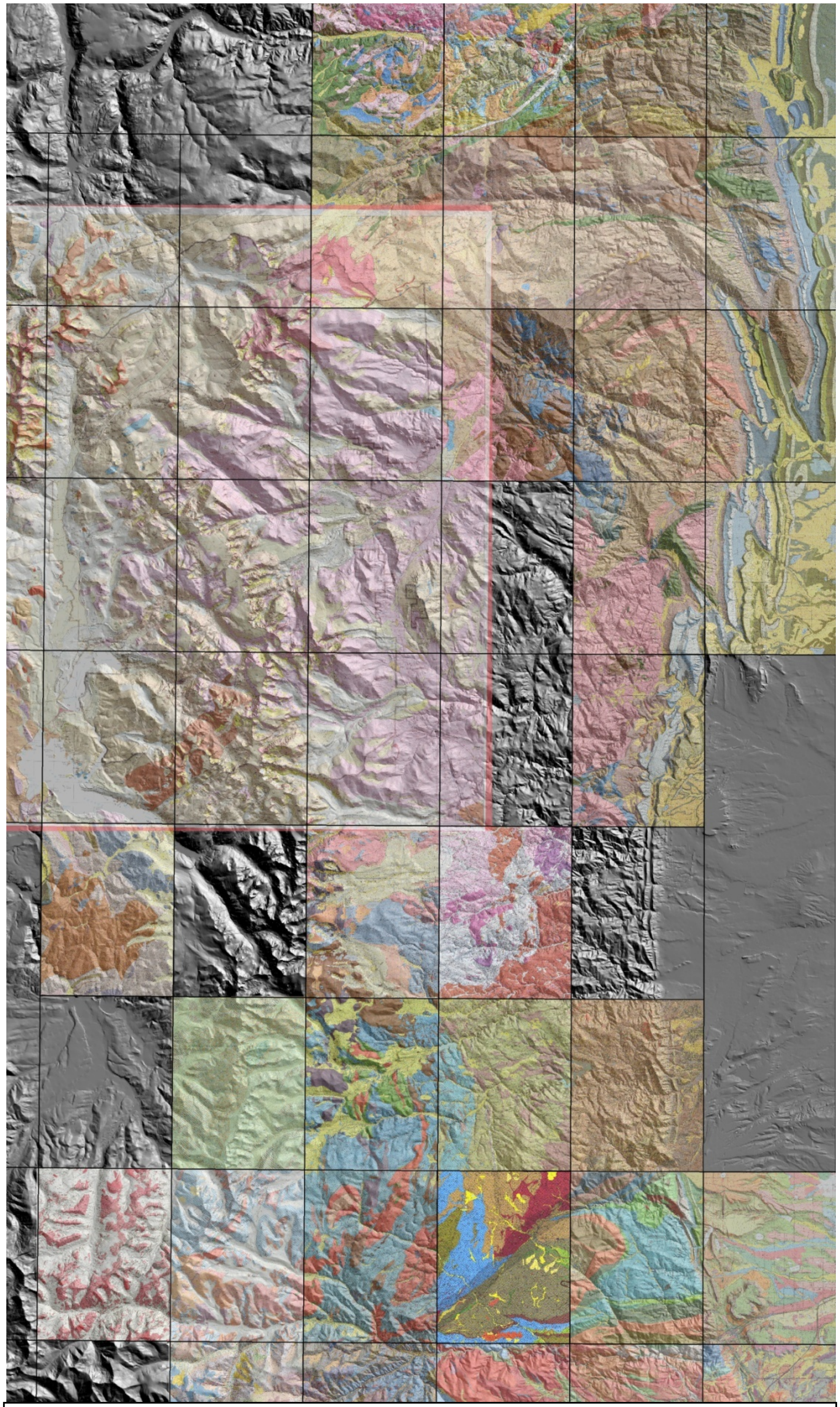

Figure 4 – Transparent, scanned 1:24K and 1:50K geologic maps draped on the ten-meter DEM

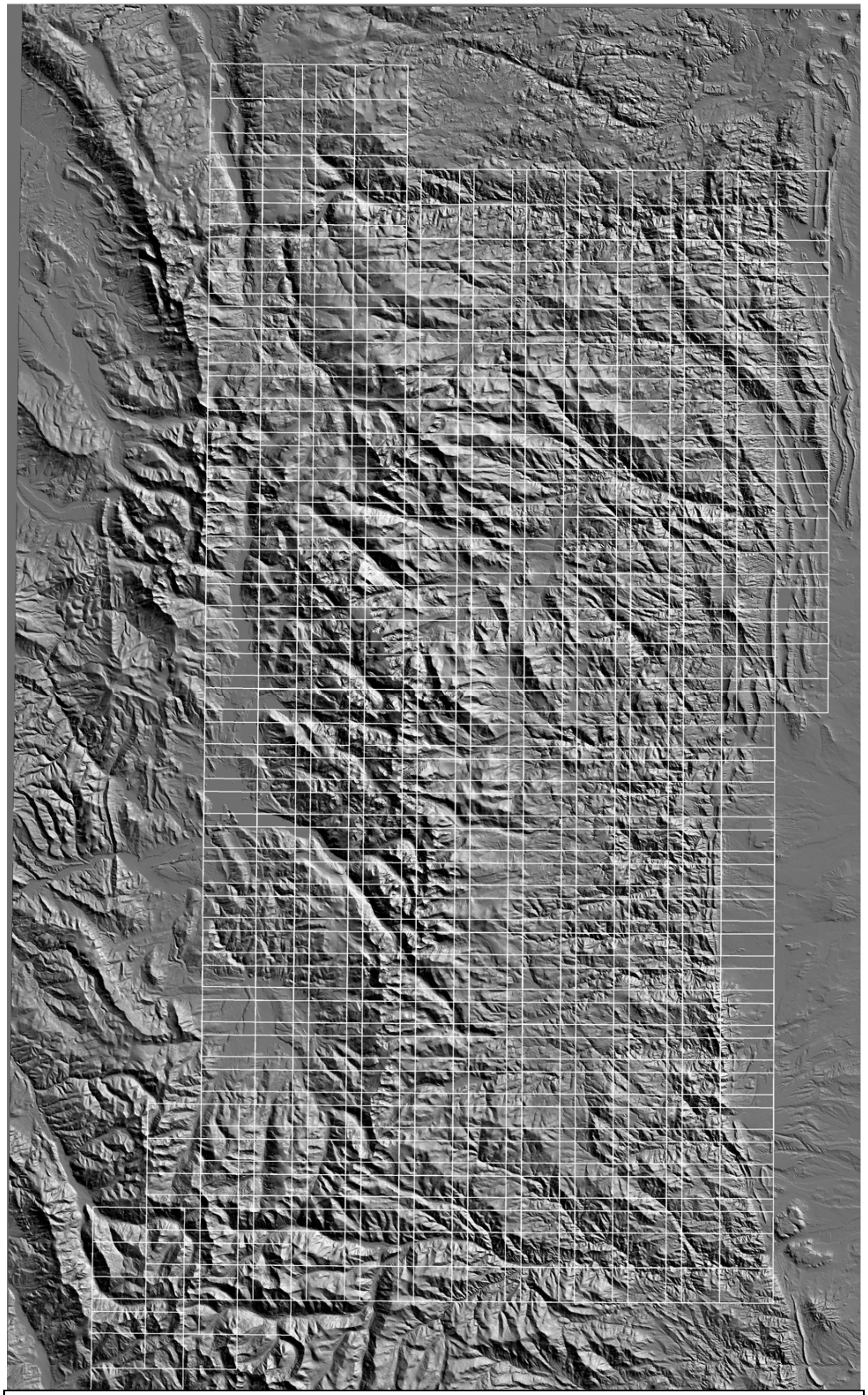

Figure 5 – Index for scanned, high-resolution stereopairs. This provided a quick way to recover photos and view them. When a feature of interest was located on the DEM, the correct steropairs for the detailed area were easily identified. They could then be retrieved and viewed in stereo in ERDAS Imagine.

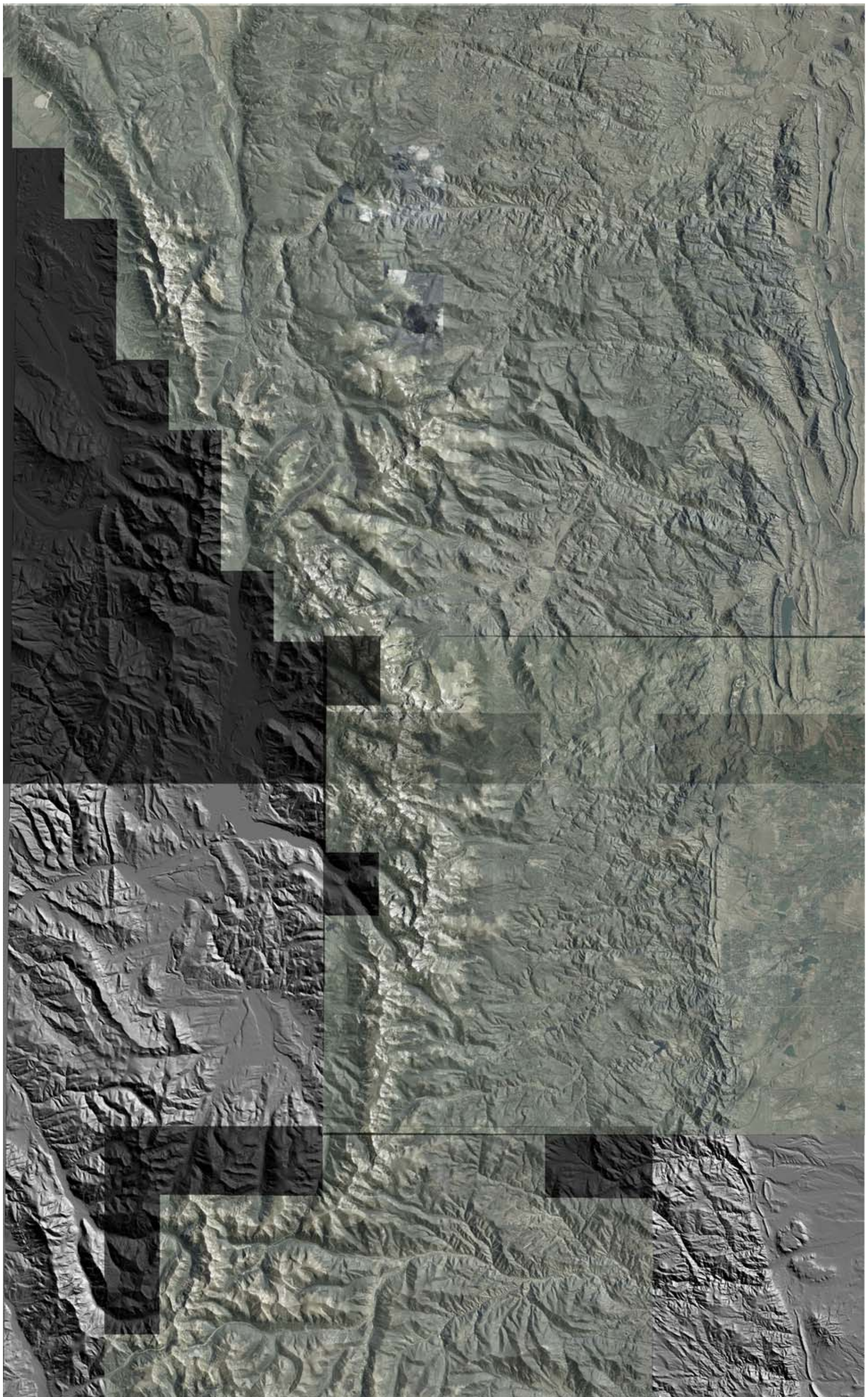

Figure 6 – Overlay of one-meter digital Photography (NAIP) from USDA.

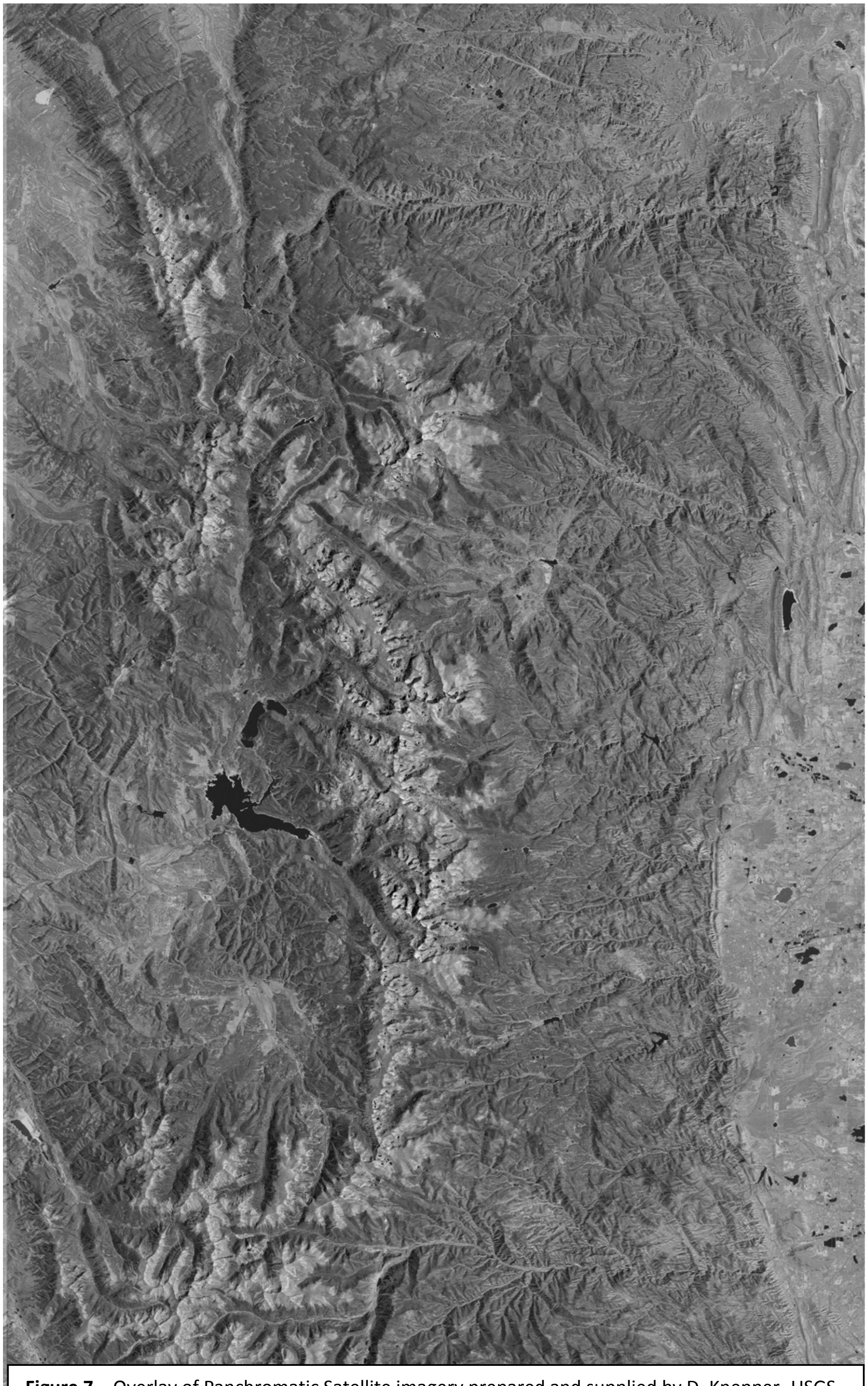

Figure 7 – Overlay of Panchromatic Satellite imagery prepared and supplied by D. Knepper- USGS.

Methodology

Erosion surfaces developed on Proterozoic rock in the northern Front Range are of at least three different ages: pre-Pennsylvanian, post-Laramide (Rocky Mountain Erosion surface), and post-27 mya (Figure 8). Layers showing the extent of erosion surfaces were prepared (Figure 9). The areas shown in light blue on Figure 9 are pre-Pennsylvanian in age because they have Pennsylvanian sedimentary strata resting directly on the surface and the structural attitude of the Pennsylvanian strata is the same as the attitude of the exposed surface on the Proterozoic rock. This surface and the overlying Phanerozoic strata were disrupted during the Laramide orogeny when the area was broken into discrete blocks that were differentially uplifted and tilted toward the east. No evidence of post-Laramide faulting was found in the area of these surfaces. Between the mountain front and the dashed red line on Figure 9, are areas colored in yellow that represent remnants of the widely recognized Rocky Mount Erosion surface (also referred to as the late Eocene erosion surface in older literature). Disruption of this surface by faulting is interpreted to be post-Laramide in age. West of the red dashed line on Figure 9 are surfaces shown in yellow that are interpreted to be Oligocene or younger in age. In two places this surface is developed on Oligocene volcanic strata dated at about 27 mya.

Interpretive linear maps were prepared from the grey-scale, four-sun-angle DEM's (Figure 10). Additionally, linear maps were prepared by two different workers in order to test possible investigator bias. Correlation was excellent between the maps prepared by the different investigators.

These linear shapefiles were then used as a guide to interpret the elevation-ramped DEM to prepare an interpretive fault map. If the topography indicated the possible presence of a fault, it was checked against the mapped faults and published geology. Many of the faults interpreted through the analysis of the DEM, correlated well with mapped faults. If there were no mapped faults present on the published geologic maps where an interpretation of a fault had been made with the DEM, then the geology was carefully checked to determine whether a fault could exist. In many instances, the mapped distribution of rock units was quite supportive of faulting, even though the author of the map had not interpreted one in that location.

Figure 8 – Arrow points to flat erosion surface on crest of Longs Peak (14,259 feet above sea level). Elsewhere in Rocky Mountain National Park, this surface is developed not only on Proterozoic rocks but also on top of a 27-myo ash flow.

The surface is faulted at Specimen Mountain and the ash flow is displaced about 200 feet.

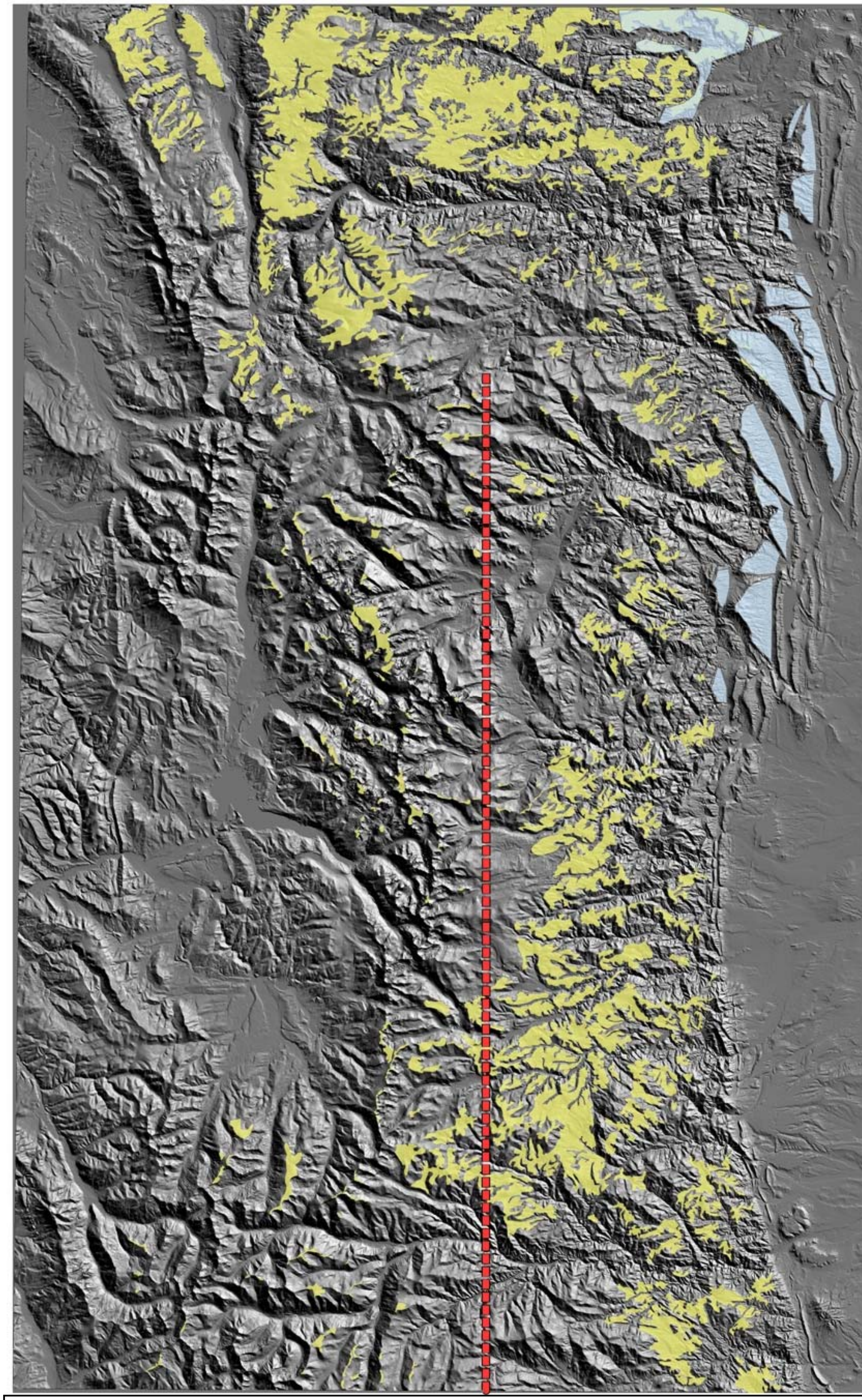

Figure 9 – Planar remnants of erosion surfaces. Blue are pre-Pennsylvanian surface deformed during the Laramide orogeny. Yellow are post -Laramide erosion surfaces. Red dashed line separates older Cenozoic surface on the east from younger surface on the west.

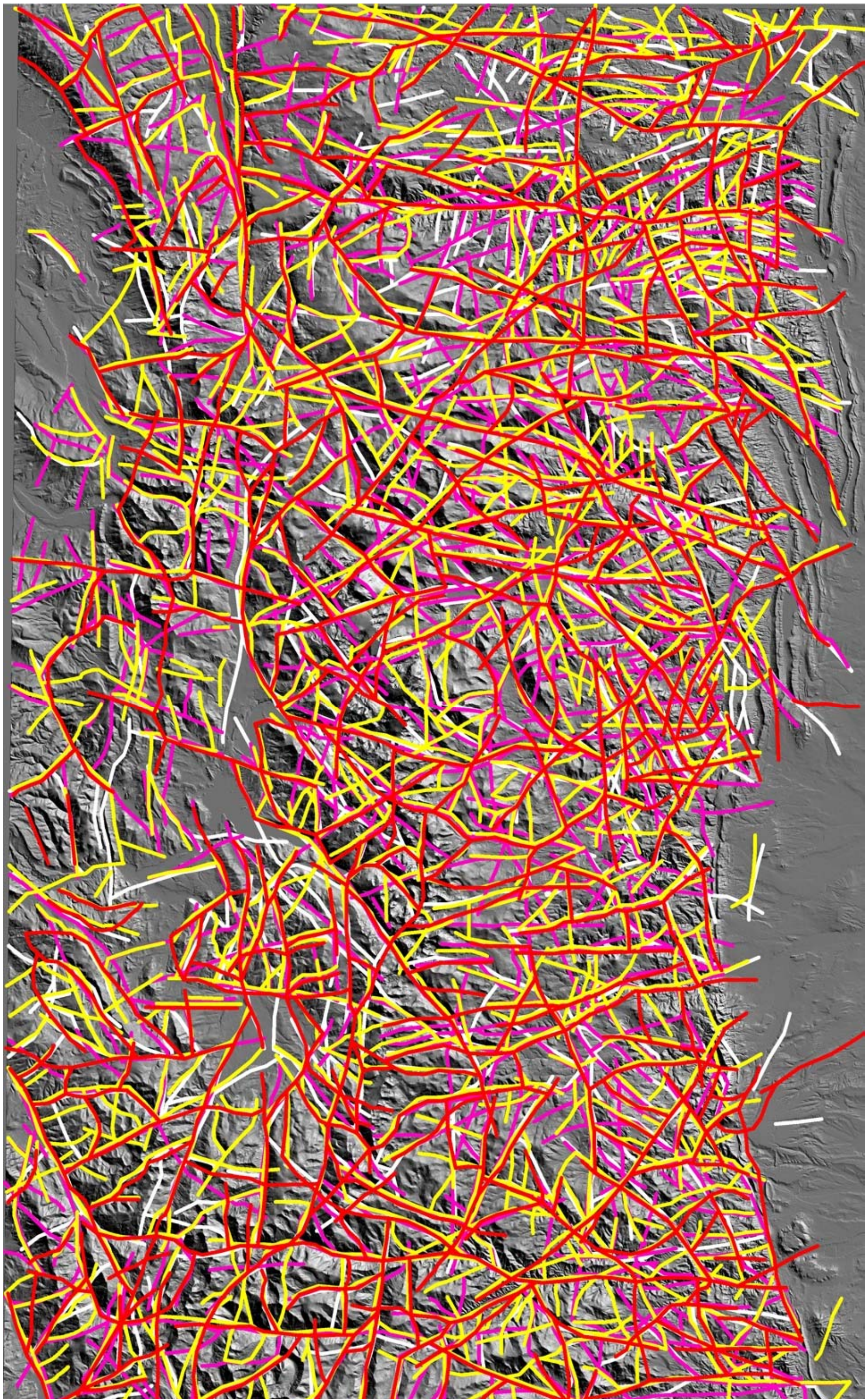

Figure 10 – Superposed linears mapped from the four, sun-angle DEMs. White lines are from the 45° DEM, red are from the 135°, pink from 225°, and yellow from 315°.

Results

Erosion Surfaces

Figure 11 shows an interesting relationship of the pre-Pennsylvanian erosion surfaces shown in blue on Figure 9. Figure 11 has an added water level at 7546 feet above sea level which is approximately where the easternmost exposure of the Rocky Mountain Erosion Surface begins. The water level was chosen to simulate what might have been covered by the Mio-Pliocene sediments of the Great Plains that presumably graded onto the Rocky Mount erosion surface in the Front Range. The Mio-Pliocene sediments of the Great Plains still presently grade onto the erosion surface in the Laramie range of Wyoming. However, Quaternary incision by the South Platte River system in Colorado has removed nearly all of the Mio-Pliocene sediments that presumably were present.

Note that all of the fault blocks along the eastern flank of the range are below the water level, i.e. would have been buried by the Mio-Pliocene sediments. That is why the pre-Pennsylvanian surface on tilted fault blocks is so well preserved. The faulting and folding associated with these fault blocks occurred during the Laramide orogeny. The structures were formed during the Laramide, buried by the post-Laramide sedimentation, and exhumed during the Quaternary incision. This accounts for their pristine geomorphologic expression. No evidence of post-Laramide faulting was found in this area.

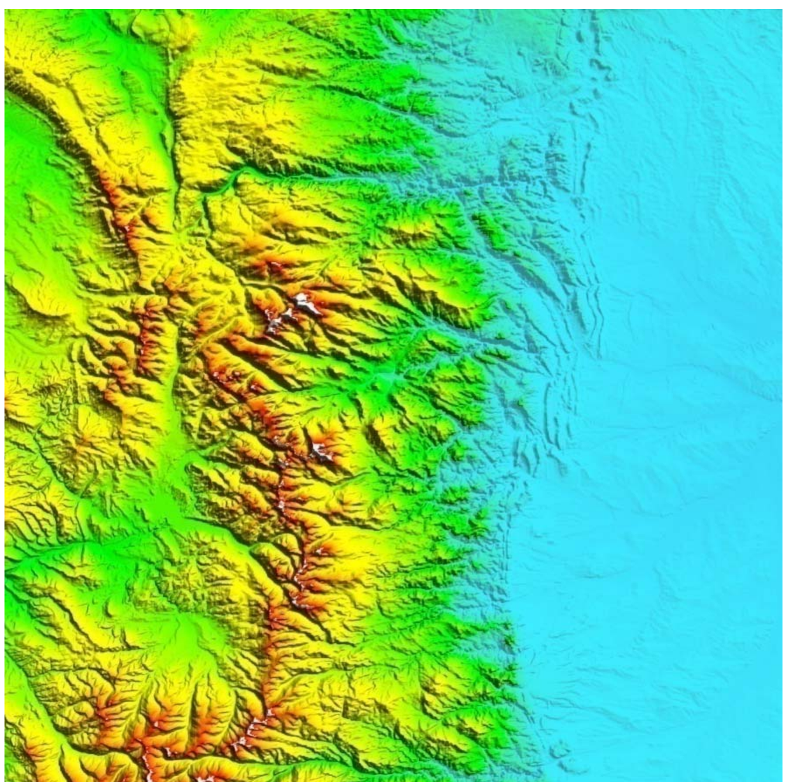

Figure 11 – DEM with water level (bluish area on eastern side) at 7546 feet above sea level which is approximately where the easternmost exposure of the Rocky Mountain Erosion Surface begins.

Figure 12 is a DEM with equal-elevation color bands. Note that the turquoise-colored band is much wider than the rust-colored band (white arrow) adjacent to it on the west. That is because the gradient is much less steep in the area of the turquoise color than in the area of the rust color. Indeed, at approximately the position of the rust colored band (white arrow), the gradient steepens dramatically

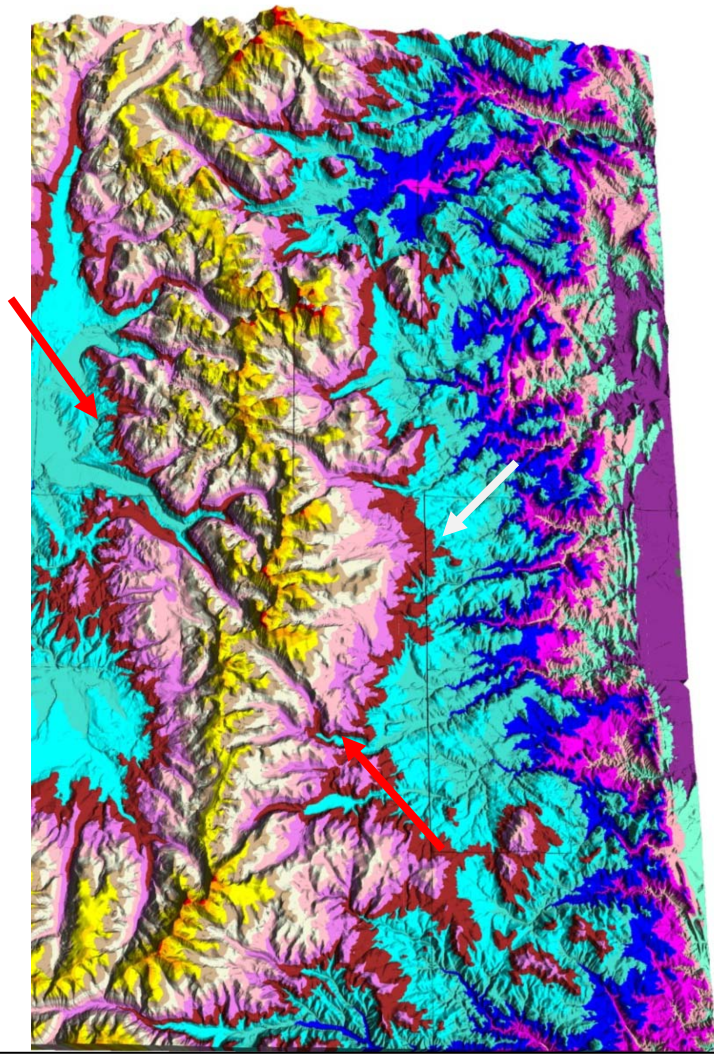

Figure 12 – DEM with equal-elevation color bands. White arrow points to abrupt increase in gradient. Red arrows indicate the Arapaho Pass lineament.

into the high peaks . The turquoise-colored area is approximately coincident with the area interpreted as the Rocky Mountain Erosion Surface (also referred to as the Late Eocene, Sherman, South Park, and sub-summit erosion surface).

Figures 13 & 14 show the mostly planar, gently-eastward-dipping remnants of the late Cenozoic erosion surfaces east and west of the red dashed line. The red dashed line marks a north-south boundary where slope gradients increase dramatically. The line extends from the base of Mount Evans on the south to the base of the Mummy Range on the north. To the west of the line, the erosion surface appears to be younger than 27 million years. East of the line the erosion surface appears to be mid-Cenozoic in age.

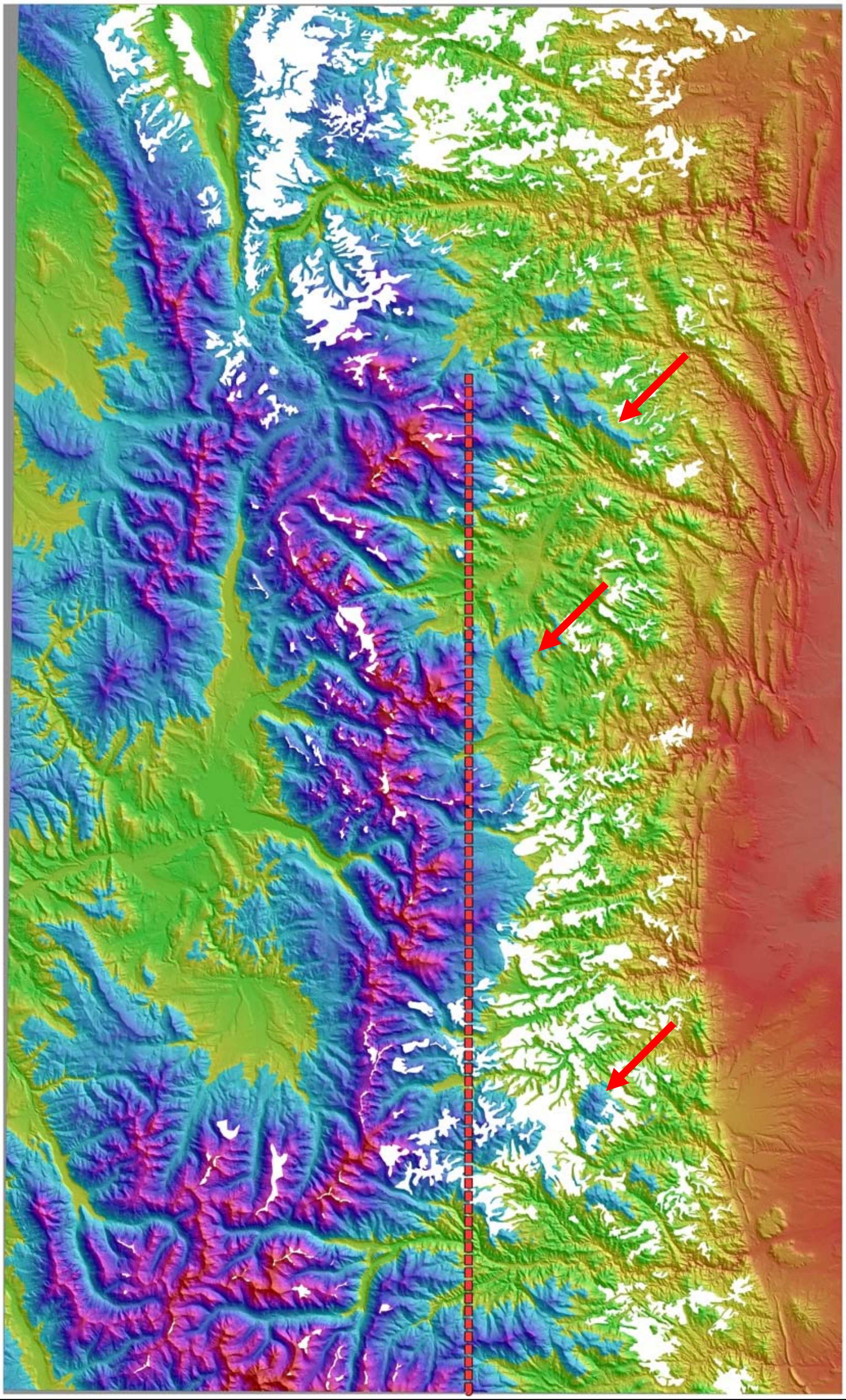

Figure 13 – DEM showing the mostly planar remnants of the Cenozoic erosion surfaces (white). The dashed red line is a proposed tectonic front with active mountain building to the west. Apatite fission-track data suggest that the western part of the Front Range has been uplifted more recently than the eastern part. The Front Range essentially dies out north of the red dashed line. The area of abundant planar surfaces north of the dashed line is ambiguous. The surfaces could be Cenozoic, pre-Pennsylvanian, or a combination of both. Arrows indicate significant topographic disruptions of the surface.

This line may mark a tectonic front, west of which, the high mountains have recently been uplifted. A careful look for Quaternary faulting along this line needs to be conducted, but unfortunately will probably require a LIDAR survey to be effective, such as currently is being conducted along the front of the Gore Range by USBR. A conservative approach would be to consider any fault west of the line as a potentially active fault that should be analyzed for potential seismic hazard.

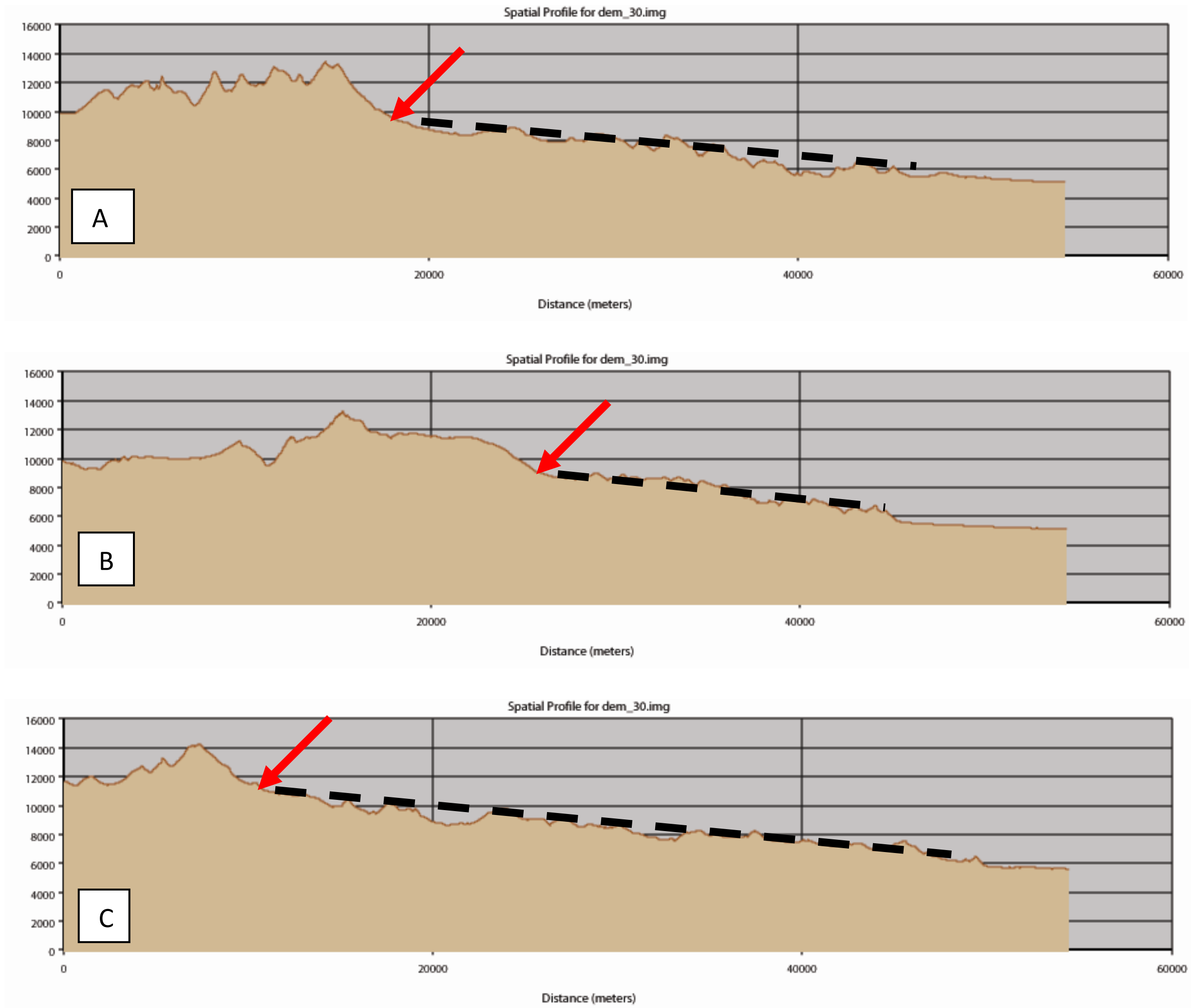

Figure 14 – East-west topographic profiles showing the nature of the Rocky Mountain erosion surface and the abrupt change in slope (red arrows) that is coincident with the dashed red line (proposed tectonic front) on Figure 13. A extends eastward from the vicinity of Long's Peak, B extends eastward from the vicinity of Niwot Ridge, and C extends eastward from the vicinity of Mount Evans.

The Rocky Mountain erosion surface (east of the red dashed line in Figure 13) is prominently disrupted in three different places: from north to south they are Tremont/Thorodin Mountain, Twin Sisters Peaks, and Storm/Lookout/Signal Mountain complex (red arrows, Figure 13). The geomorphic disruption (Figure 15) suggests the possibility of post-Laramide faulting in these areas. Two of these areas were examined in the field for evidence of young faulting. Faulting associated with the Storm/Lookout/Signal

Mountain geomorphic complex was examined by McCalpin under the collaborative grant (02HQGR0094). No evidence of Quaternary faulting was found.

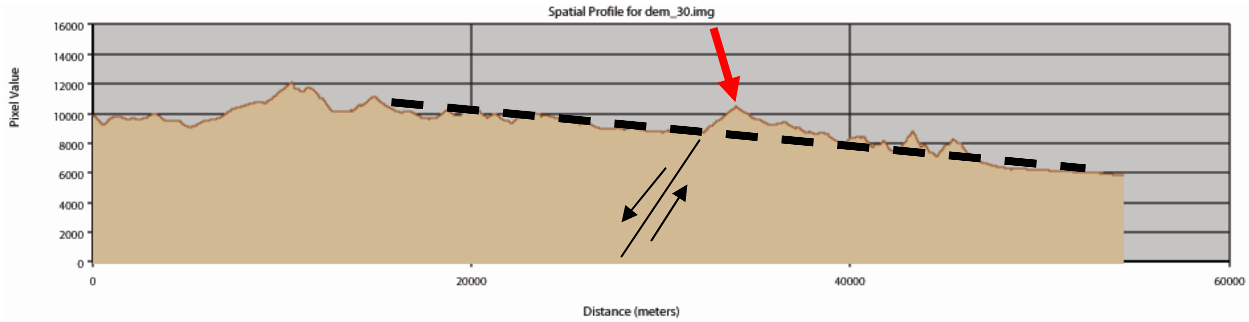

Figure 15 – East-west topographic profile through Thorodin Mountain (arrow) which rises 2,000 feet above the Rocky Mountain erosion surface. The geomorphic shape suggests a post-Laramide, uplifted fault block tilted toward the east.

The northeast trending fault indicated by the red arrow in Figure 16B Wallace studied in the field for evidences of faulting. A series of resistant granite knobs were found along the loci of the interpreted fault. Each of these knobs had a planar, near-vertical surface bounding its northwest face. This was highly suggestive of faulting. However, no conclusive evidence of faulting could be found. Which raises the issue of the character of post-Laramide faulting.

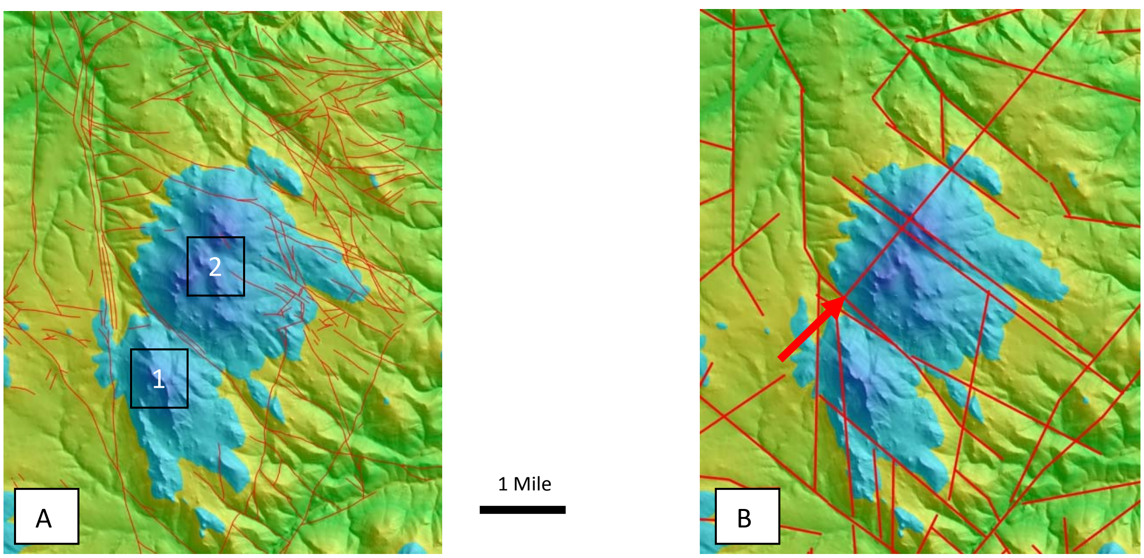

Figure 16 – DEMs of Tremont/Thorodin Mountain geomorphic anomaly. A.) Faults shown on 1:24,000 published geologic map. 1. Tremont Mountain and 2. Thorodin Mountain. B.) Larger interpreted faults from this study. Red arrow points to NE-trending lineament examined for evidence of faulting.

<u>Nature of post-laramide faulting</u>

Horizontal compressive forces were active during Laramide faulting. The basement was also under much higher confining pressure during the Laramide orogeny than during the post-Laramide period of faulting. Moreover, Laramide faults have existed for double the amount of time that post-Laramide faults have existed. Therefore, Laramide faults tend to be well cemented (Figure 17). Indeed, some Laramide faults stand out as resistant ridges, even being referred to as breccia reefs.

Figure 17 – Example of well-cemented Laramide fault breccia and gouge. This specimen was so well indurated that it could be removed from the field and transported to the office.

On the other hand, post-Laramide faulting occurred, and is occurring, as a result of extensional forces. The faults have existed for less than 20 million years and the confining pressure was much less than during the Laramide deformation. Therefore, these faults are rarely well cemented. Unfortunately, the only expression of a fault may be a small geomorphic anomaly. This is highlighted by a fault at the Henderson molybdenum mine which is located within the study area.

The Vasquez Pass fault displaces the 27-million-year-old ore body by 1280 feet. With good subsurface control, the mine geologists can accurately project the fault to the surface. Yet, a search of the projected surface location yields no breccia, no slickensided float, nor any other signs of a fault; nothing but a small geomorphic saddle (E. Geraghty, pers. comm.).

An example from the Central City/Black Hawk area illustrates the nature of the problem. A portion of North Creek has a very pronounced geomorphic and geologic expression that is strongly suggestive of an underlying fault (Figure 18 A & B). On the basis of geology and geomorphology, a fault was interpreted with the north side upthrown, as shown by the dashed black line on Figure 18-A. Although the published geologic map shows most of the valley overlain by alluvium, the interpreted fault does cross an area of bedrock (red arrow A, Figure 18A) which appeared to present an excellent area to test the interpretive technique in the field. The bedrock has a prominent notch through it, with sharp walls on either side (Figure 19). The notch has no in-place bedrock exposed, but is filled with blocks of granitic material. All of the relationships are compatible with a post-Laramide fault, but no definitive evidence could be observed. Similar notches formed over Laramide faults yielded abundant, in-place cemented breccias.

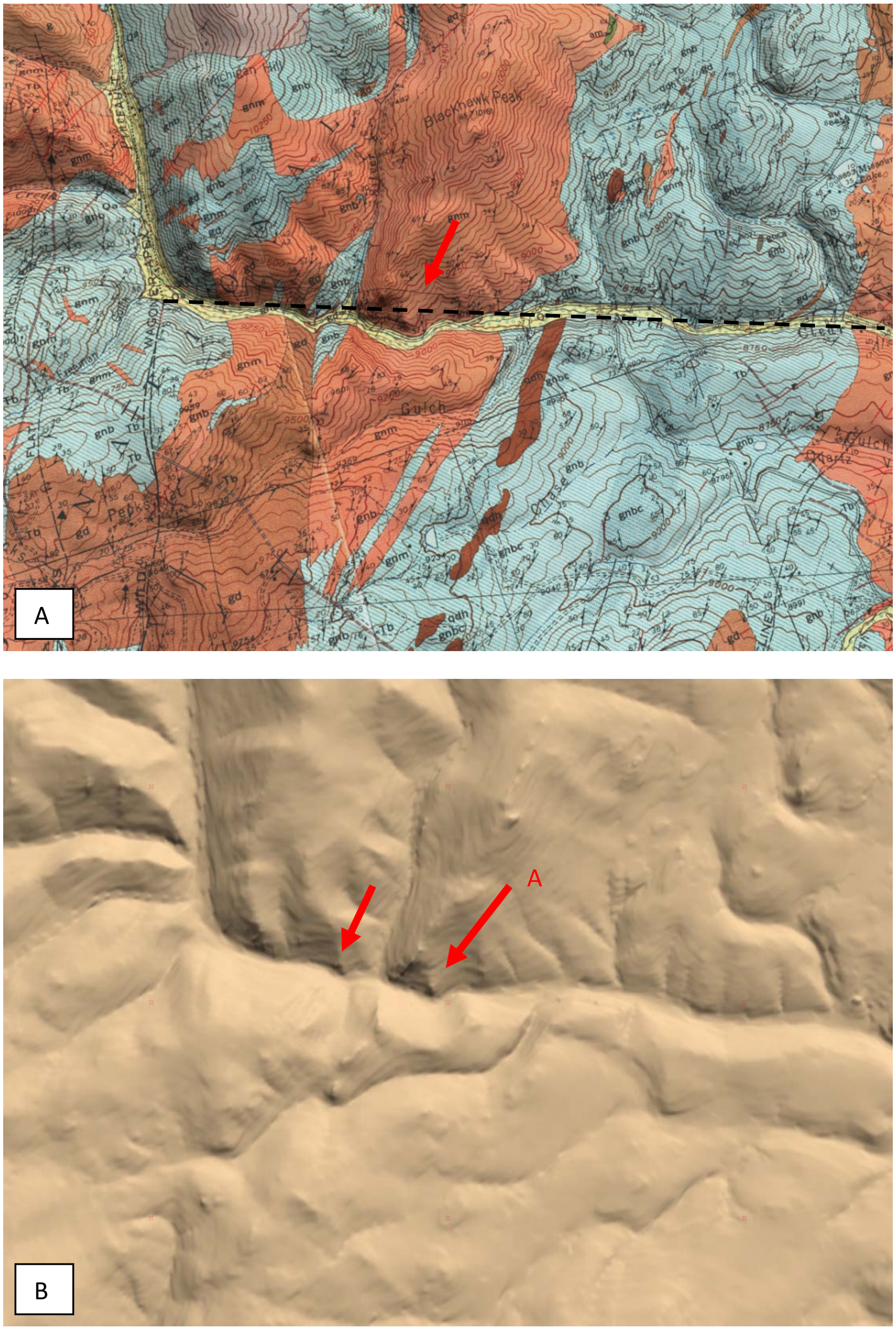

Figure 18 – Prominent lineament along North Creek approximately 2.5 miles northwest of Blackhawk. UTM 455348E ,4408376N,

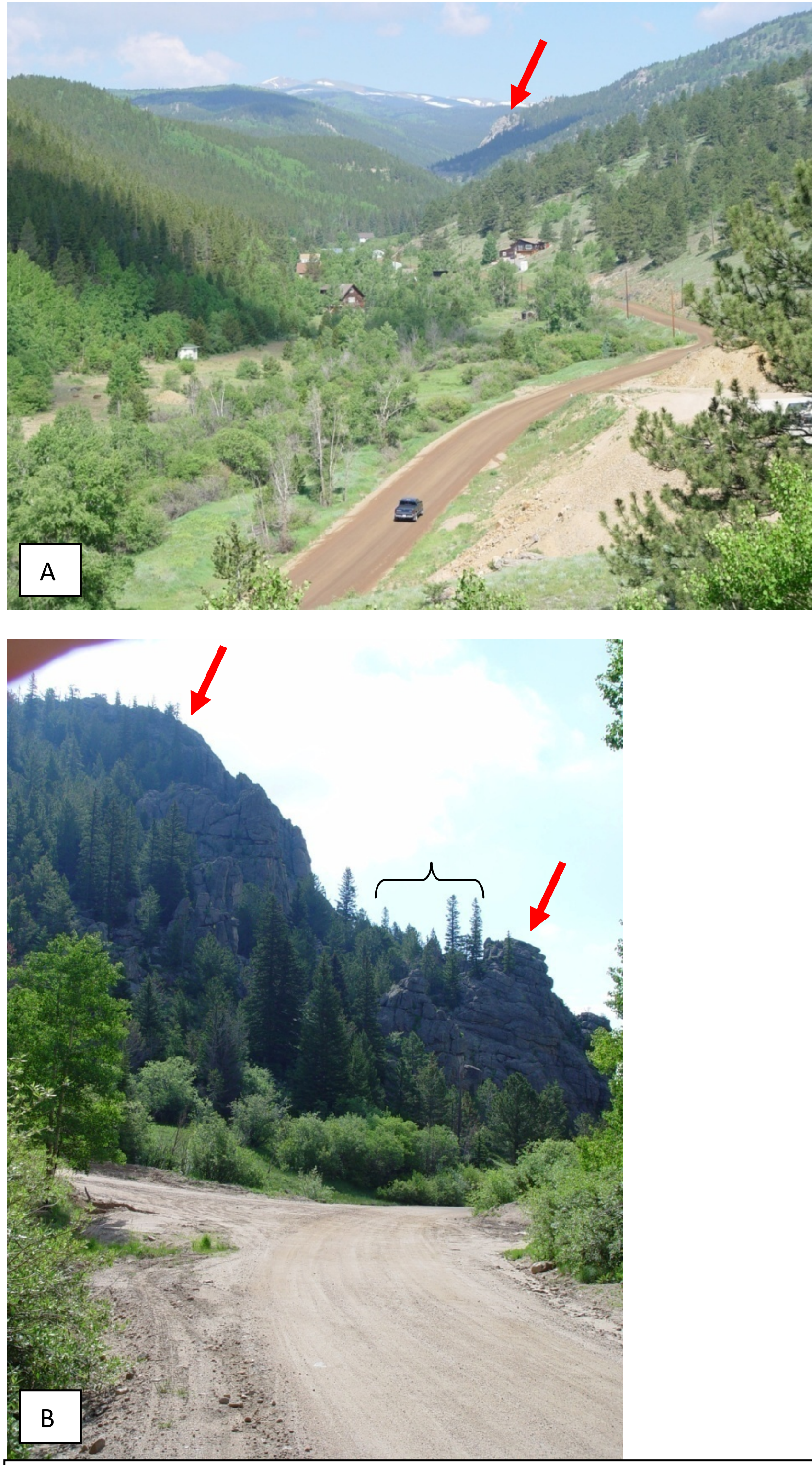

Figure 19 – A. View west-northwest along North Creek showing linear, alluvium-filled valley (UTM 455348E, 4408376N). Red arrow points to granite outcrop that lineament would have to cross. B. Prominent notch where interpreted fault would cut the granitic bedrock. Arrows point to resistant walls of granitic rock, bracket outlines notch filled with loose blocks of granitic material. The interpreted fault crosses another granite outcrop immediately behind the photographer with an identical notch filled with loose blocks.

Interpretive Late Cenozoic Fault Map

Figure 20 is an interpretive fault map of the Northern Colorado Front Range. It incorporates previously mapped geology (including faults), interpretation of offset of erosion surfaces, analyses of fault patterns where intensely mapped, analyses of detailed aerial-photography stereopairs, and new field investigations. Each of these interpreted faults displaces the topography in one way or the other. They may, or may not, coincide with mapped faults because many mapped faults may be Laramide in age and were not rejuvenated during post-Laramide deformation; and thus do not have the proper geomorphic expression to be considered as experiencing post-Laramide movement. Indeed, some of the largest and most prominent mapped shear zones do not have the proper geomorphic expression. Indeed, several large shear zones have no geomorphic expression at all.

Field investigations of Arapaho Lineament

A northwest-southeast trending lineament cuts across the northern Front Range near (but not exactly through) Arapaho Pass. This lineament is one of the longest and most prominent features in the northern Front Range. It appears to offset the spine of the range (Figure 12). It also cuts the Laramide-age Caribou stock. On the northwest end it appears to cross Pleistocene moraines.

Where the lineament cuts the crest of the range, pinnacles suggestive of brittle faulting are present in the saddle (Figure 21, UTM 443756E, 4430077N). However, investigations in the saddle where exposures were expected to be found, provided no evidence for, or against a fault, because the critical area was covered with talus.

At the northwest end of Arapaho Creek, the lineament is projected (Figure 22) to cross Pleistocene moraines (433201E, 4443915N). At this location is a major landslide complex (Figure 23) that could be faulting induced. Also, profiles along the Pinedale moraine suggest a strong possibility of ~200 feet of displacement across the lineament. Field investigations need to be conducted in this area.

Elswhere in the Arapaho Pass area, are other interesting features. West of the pass on the shore of Lake Dorothy is a small escarpment that appears to disrupt the ground surface (Figure 24). This escarpment trends into the lake and projects to an escarpment across the lake and up into a pinnacled saddle. Further studies are needed in this area.

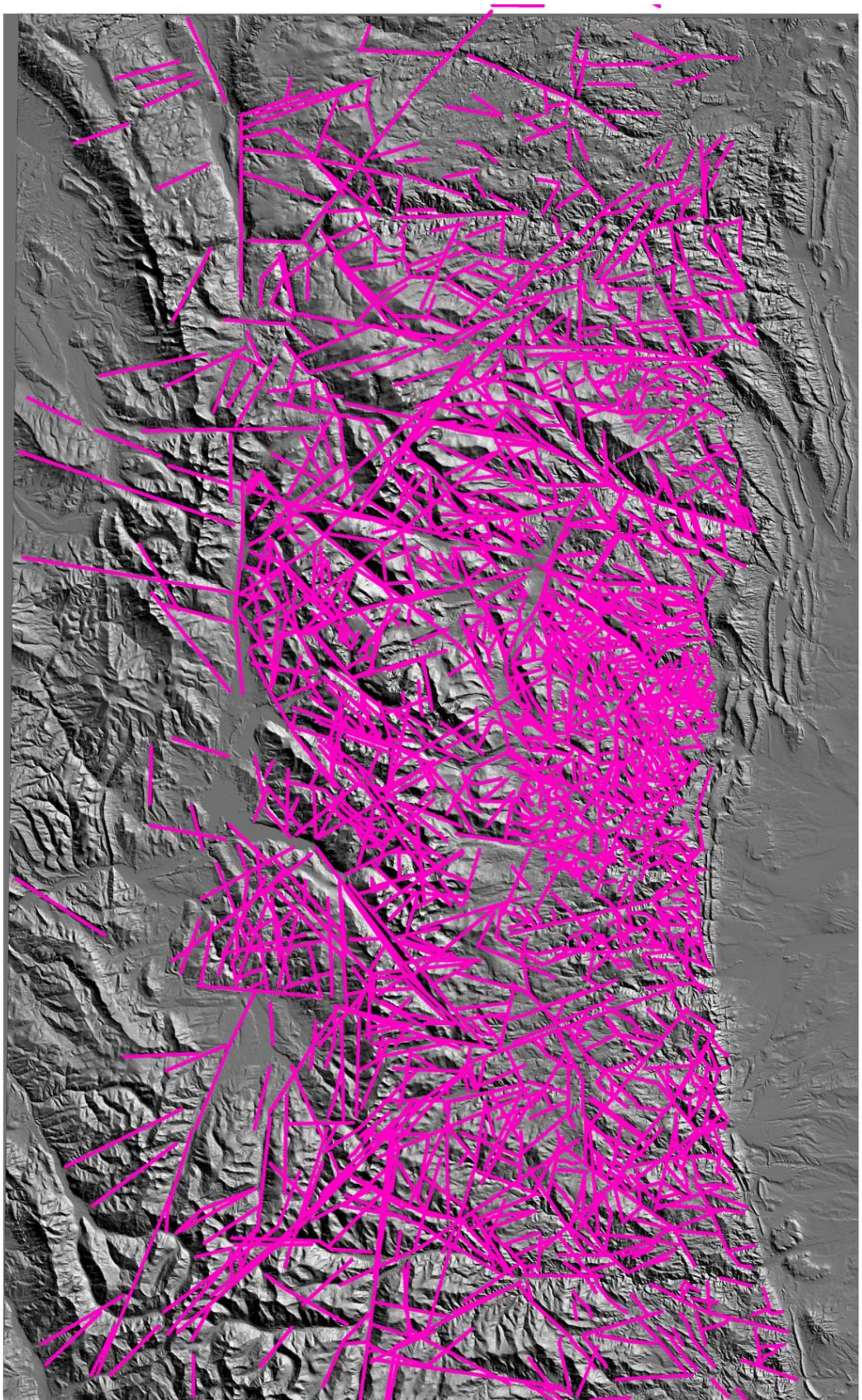

Figure 20 - Interpretive fault map of the northern Colorado Front Range. The purple faults are interpreted to have late Cenozoic displacement and thus disrupted one or both of the Cenozoic erosion surfaces.

Figure 21 - Location of possible ,late-Cenozoic fault (red arroe) covered with thick talus at crest of Front Range.

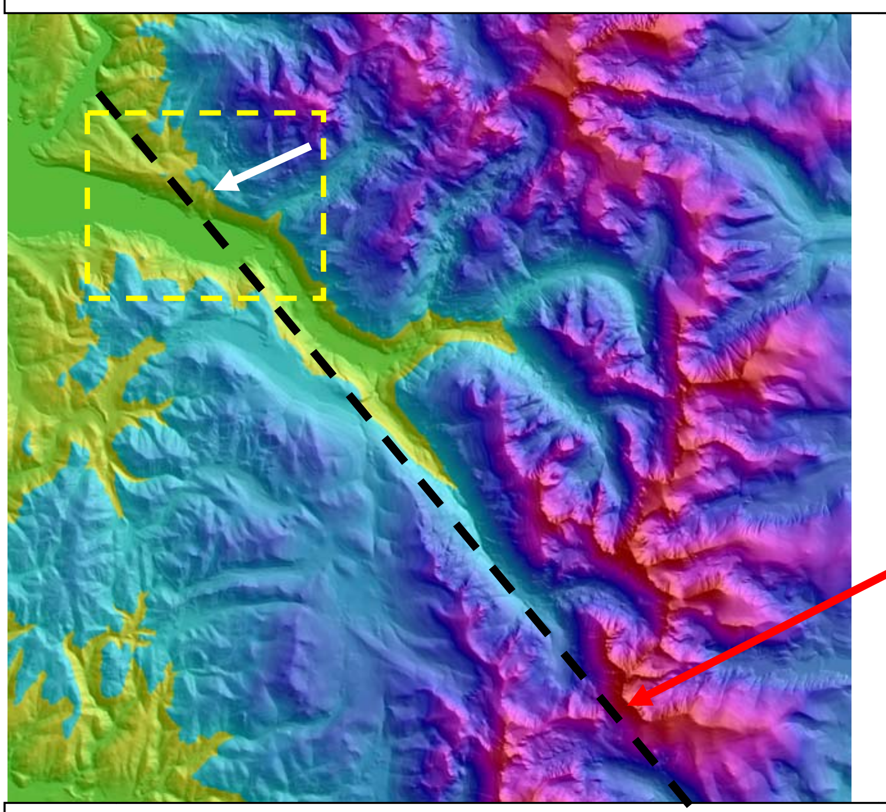

Figure 22 - Location of possible, late-Cenozoic fault (black dashed line) extending down Arapaho Creek to Lake Granby and crossing moraine at white arrow. Red arrow points to location of pinnacled saddle in Figure 21.

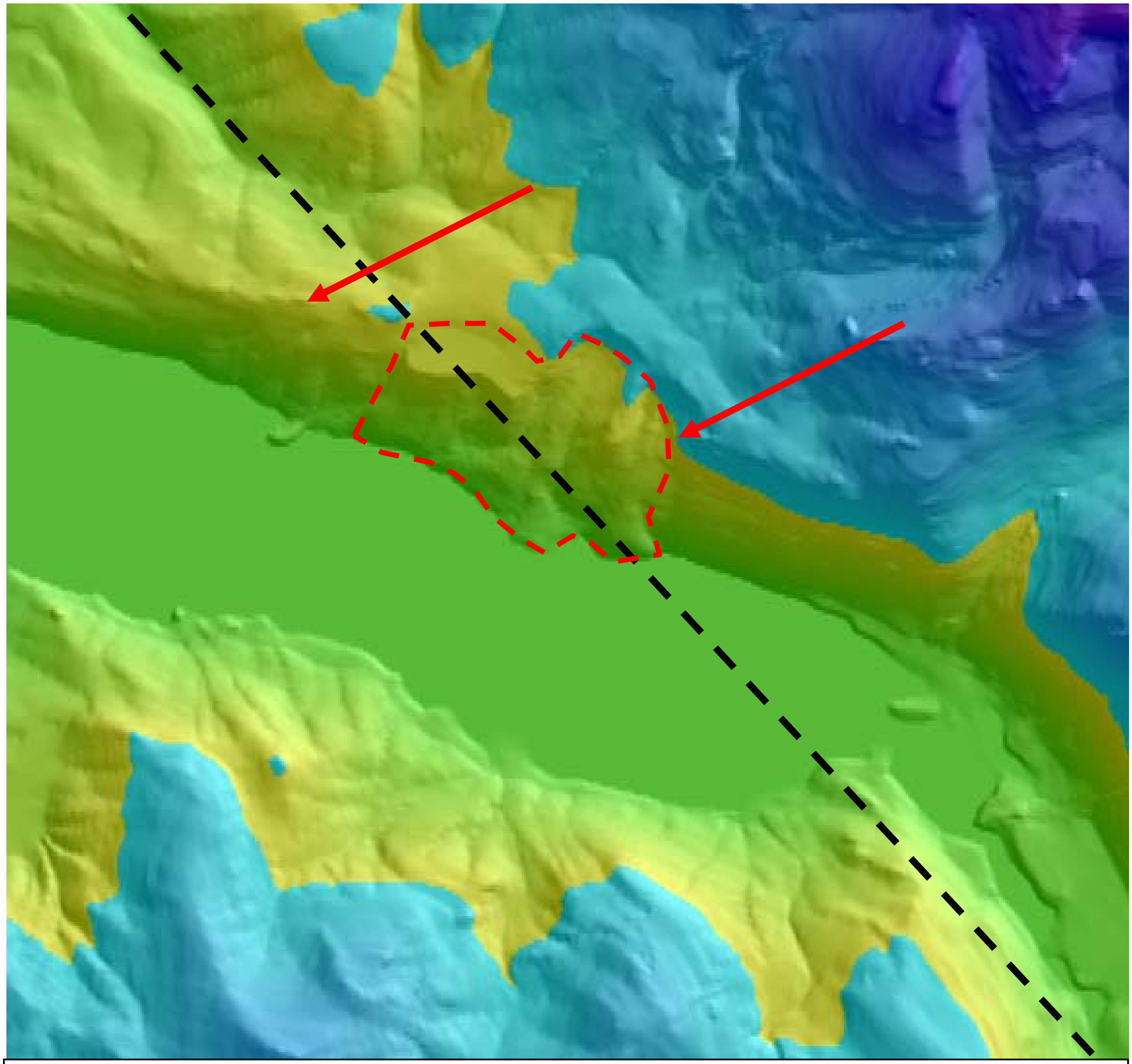

Figure 23 - Blowup of yellow box in Figure 22. Red dashes outline the landslide complex where the Arapaho lineament projects through the moraine. Although further documentation is required, the moraine appears to be offset ~200 feet between the two arrows.

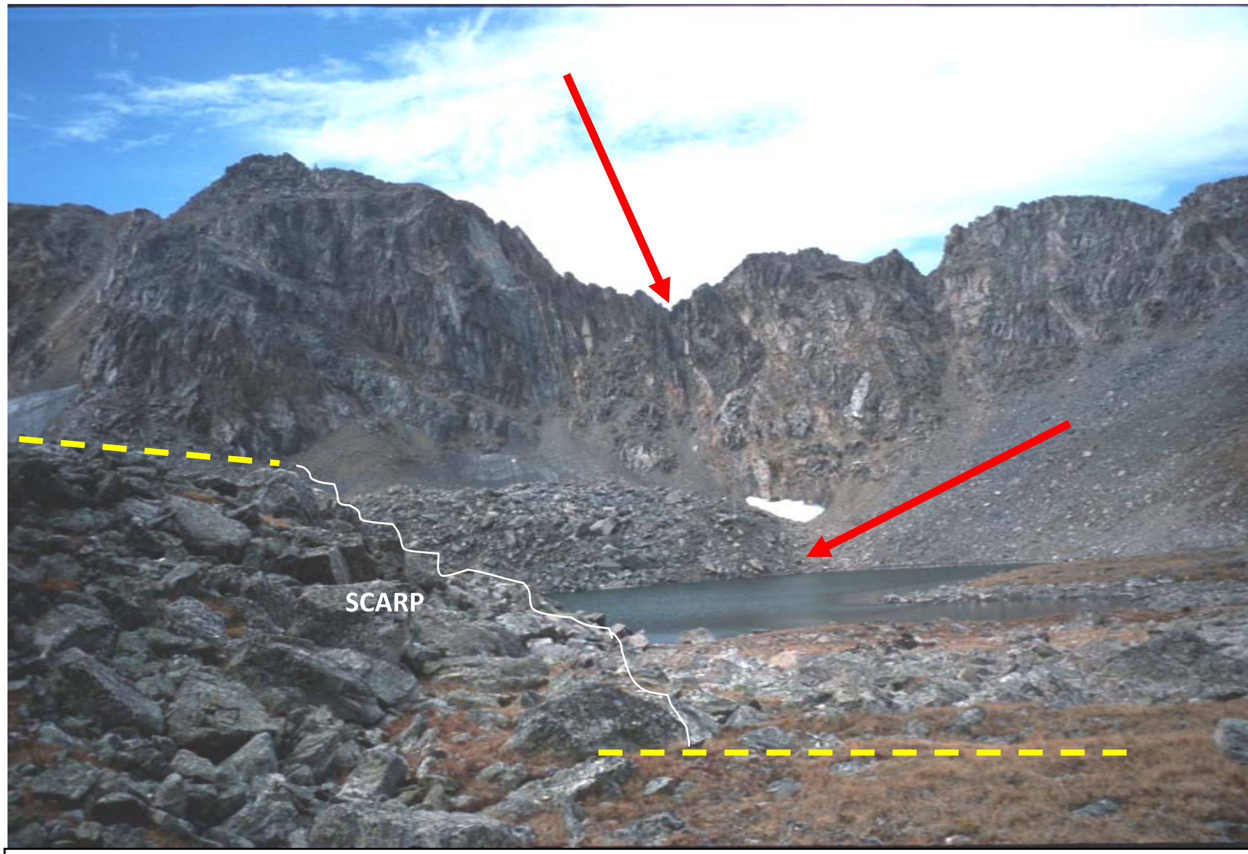

Figure 24 – View west across Lake Dorothy (441728E, 4429365N) showing displaced ground surface (yellow dashed lines). This small escarpment is in line with another escarpment across the lake and the notch at the crest of the range. The relationships here are suggestive of young, normal fault movement with displacement down on the right.

Source of the 1882 Earthquake

One of the goals of this collaborative project was to locate the source of the 1882 M 6.6 earthquake. An escarpment was located on the south side of Fall River in Rocky Mountain National Park that was in the area where the epicenter has been interpreted to be located (Figure 25). This escarpment was in solid rock and ran 2,000 feet up Sundance Mountain. From a distance, the scarp appeared to be quite fresh (lichen free) and thus a potential area to find preserved slickensides. However, a search of the scarp revealed no slickensides and suggested that the lichen-free faces were most likely a result of long lasting snow pack that killed any lichen growth.

However, the scarp bounds a massive landslide which is composed of mostly lichen-free boulders. The possibility that the slide was triggered by the 1882 earthquake remains to be tested. A cooperative study of this possibility is ongoing with Dr. R. Madole, USGS Emeritus.

Figure 25 – View south from Fall River road. Arrows point to fresh-looking scarp. Note the large, fresh rockslide covering the mountainside to the left.

Publications Resulting from this Study

Morgan, M. L. 2003, Published Faults of the Colorado Front Range: Colorado Geological Survey Open File Report 03-04, Denver, CO

Matthews, V., 2006, HOW EXTENSIVE IS NEOGENE FAULTING IN COLORADO?: Geological Society of America *Abstracts with Programs*, Vol. 37, No. 7, p. 476