# GEOLOGICAL FIELD TRIP

In Conjunction with *THE COLORADO SCIENTIFIC SOCIETY*
Symposium on the "Geology of the Front Range"

## "Laramide and Precambrian Geology and Tectonics of the Central Front Range"

### *with Emphasis on Laramide Tectonics and Precambrian Accretion of Colorado*

Trip Leaders:
Dr. Robert J. Weimer, Prof. of Geology Emeritus, CSM
Lisa R. Lytle, Ph.D. Geology Candidate, CSM
Dr. Thomas L. Davis, Prof. of Geophysics, CSM
Thomas R. Fisher, Ph. D. Geology Candidate, CSM

Sunday **APRIL 4, 2004** - 8:00am to 5pm

*COLORADO SCIENTIFIC SOCIETY*
*FRONT RANGE FIELD TRIP*
*APRIL 4, 2004*

*DEDICATED TO THE MEMORY OF BILL BRADDOCK*

# GEOLOGY AND GEOPHYSICS OF THE MOUNTAIN FLANK, JEFFERSON COUNTY

**BY: ROBERT J. WEIMER AND THOMAS L. DAVIS**

# LARAMIDE FRONT RANGE UPLIFT AND THE GOLDEN FAULT

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## Abstract

The history of the Front Range Uplift is recorded in 5000 feet of late Cretaceous and early Tertiary strata in the west-central Denver Basin. In the Golden—Green Mountain area, the un-roofing and flank deformation of the uplift occurred as two main events during the approximate interval of 71 to 63 Ma. First, the central core of the range was uplifted out of the Cretaceous seaway and eroded to the Precambrian. Sediment was deposited in the adjacent subsiding Denver Basin as the upper Pierre Shale (marine), Fox Hills Sandstone (shoreline) and Laramie Formation (delta plain). Braided streams then deposited conglomerates of the Arapahoe Formation with chert and igneous pebbles, followed by volcanic-derived sediment and flows in the Denver Formation. Angular unconformities with up to ten degree discordance are present at the base and top of the Arapahoe Formation.

During the second main event, the above formations were deformed to near vertical dip on east flank of the Front Range Anticline and broken by the Golden fault zone.. Large boulders in the Green Mountain Conglomerate, possibly indicating maximum stream gradients, were deposited in early Paleocene.

In the type locality at Golden, Colorado, the Golden Fault has been a subject of debate for over a century. Through the use of structural, stratigraphic and geophysical observations, the Golden Fault geometry is now largely known. Of significance is the documentation that the originally defined Golden fault plane is accompanied by an east branch (imbrication) mapped as the Basin Margin Fault. Between the two fault planes is a narrow zone of

near vertical deformed strata that represents the limb of the Front Range fold.

Factors related to the geometry of the Golden fault zone are as follows:

o The Golden Fault has been mapped for about 18 miles where surface exposures of the Pierre Shale in the foot wall of the reverse fault are in contact with the Pierre or older rocks in the hanging wall.

o Although the dip of the fault plane is controversial, two trenches across the fault trace, one and one-half miles south of Clear Creek indicate a west dip. Where the fault trace crosses the Clear Creek Valley at Golden, a contour map on the fault plane indicates an approximate 35 degree west dip. One half mile west of the mountain front, the dip increases to 45 degrees or more, where the fault plane passes beneath an 1854 ft well drilled in the Precambrian near an oil seep.

o Modeling of a four and one-half mile seismic line in Golden Gate Canyon and of gravity data suggest a 50 to 60 degree west dip from two to three miles west of the mountain front where Precambrian rocks are faulted over the sedimentary rocks in the foot wall.

o Maximum throw along the Golden Fault is estimated to be 10,000 feet in the area between I-70 and U. S. 6, from one to four miles south of Clear Creek.

o The Basin Margin branch places strata with 50 to 70 degree dip on the west side of the fault trace in contact with strata with 5 degrees or less on the east side. The throw of the fault is generally less than a few hundred feet.

Documentation of the geometry and zone of flank deformation in the Golden area is important to understanding the geological history of the area, the structural style of deformation, and the economic resources in the area.

# Laramide Mountain Flank Deformation and the Golden Fault Zone, Jefferson County, Colorado

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## Abstract

The Front Range - Denver Basin couplet is divided into an undeformed basin block and an uplifted mountain block, with an intervening rotated, deformed zone. The overall form is an anticline with a steeply dipping and faulted east flank.

Over the last 12 years, a series of seismic lines have been acquired across the deformed zone of the Front Range which reveal the underlying fold-fault geometry and Laramide tectonic history. Common structural elements occur in the seismic lines which relate the discordant dip between the surface outcrops and subsurface borehole data in the Denver Basin. The structure is primarily the result of east-directed compression during the Laramide Orogeny.

The Golden Fault zone changes structural style along the mountain front as illustrated by numerous published geologic maps and cross sections. Surface mapping indicates the mountain front fault decreases in dip from the area of maximum dip and displacement near the city of Golden to a slightly lower angle dip both to the north and south where it dies out. The dip of fault planes varies from approximately 50°W to 70° W. The fault traces are generally in the Pierre Shale, or where older formations are juxtaposed on the Pierre. The mapped length of the fault zone is 24 mi.

Steep dip and variation in formation thicknesses across the fault zone complicate the construction of geologic cross sections and distort the seismic mapping. The integration of geologic cross sections with the seismic data constrains the seismic interpretation and gives a reasonable range of fault plane dip. Further refinement of the fault geometry will require improved seismic data acquisition along with more sophisticated data processing and modeling.

## Introduction

A major geologic anomaly is present at Golden, Colorado where approximately 9000 ft of late Paleozoic and Mesozoic rocks are missing from the outcrop, although the strata are generally present 8 mi to the north and south. Recognizing this discontinuity in a detailed cross section, Lakes (1889) attributed the absence of strata either to a fault, or an unconformity. Seven years later in a monograph on the Denver Basin, Emmons, Cross, and Eldridge (1896) advanced the unconformity interpretation and described the geology as onlap of strata onto a structural high in the Golden area that persisted from the late Pennsylvanian to the late Cretaceous. The Golden Fault zone, now recognized to explain the mountain flank anomaly, was first proposed by Ziegler (1917) and has been accepted by investigators since.

Oil seeps in the Precambrian and Phanerozoic outcrops, in the hanging wall of the fault system, encouraged exploratory drilling in the 1950s. The logs of these wells, together with well-exposed surface outcrops and two modern seismic lines, provide exceptional control for unraveling the Laramide fold-thrust geometry of the east flank of the central Front Range. The geology and seismic of three key reference areas (Turkey Creek, Deer Creek, and Rocky Flats—Coal Creek Canyon) are described in this paper.

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# Guide to the Petroleum Geology and Laramide Orogeny, Denver Basin and Front Range, Colorado

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Including a Field Guide to the
Central Denver Basin

By
Robert J. Weimer and
Stephen A. Sonnenberg

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**Colorado Geological Survey**
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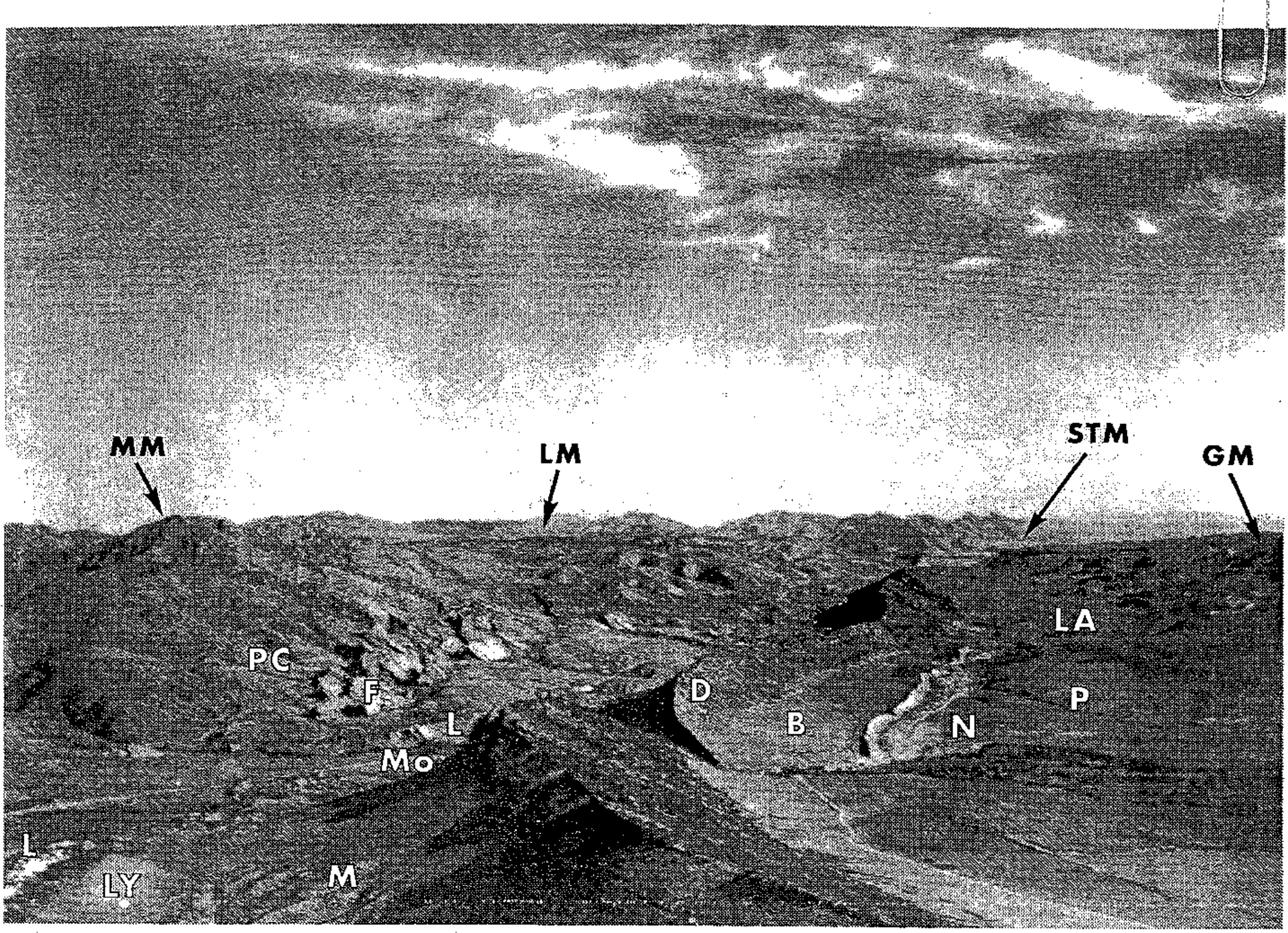
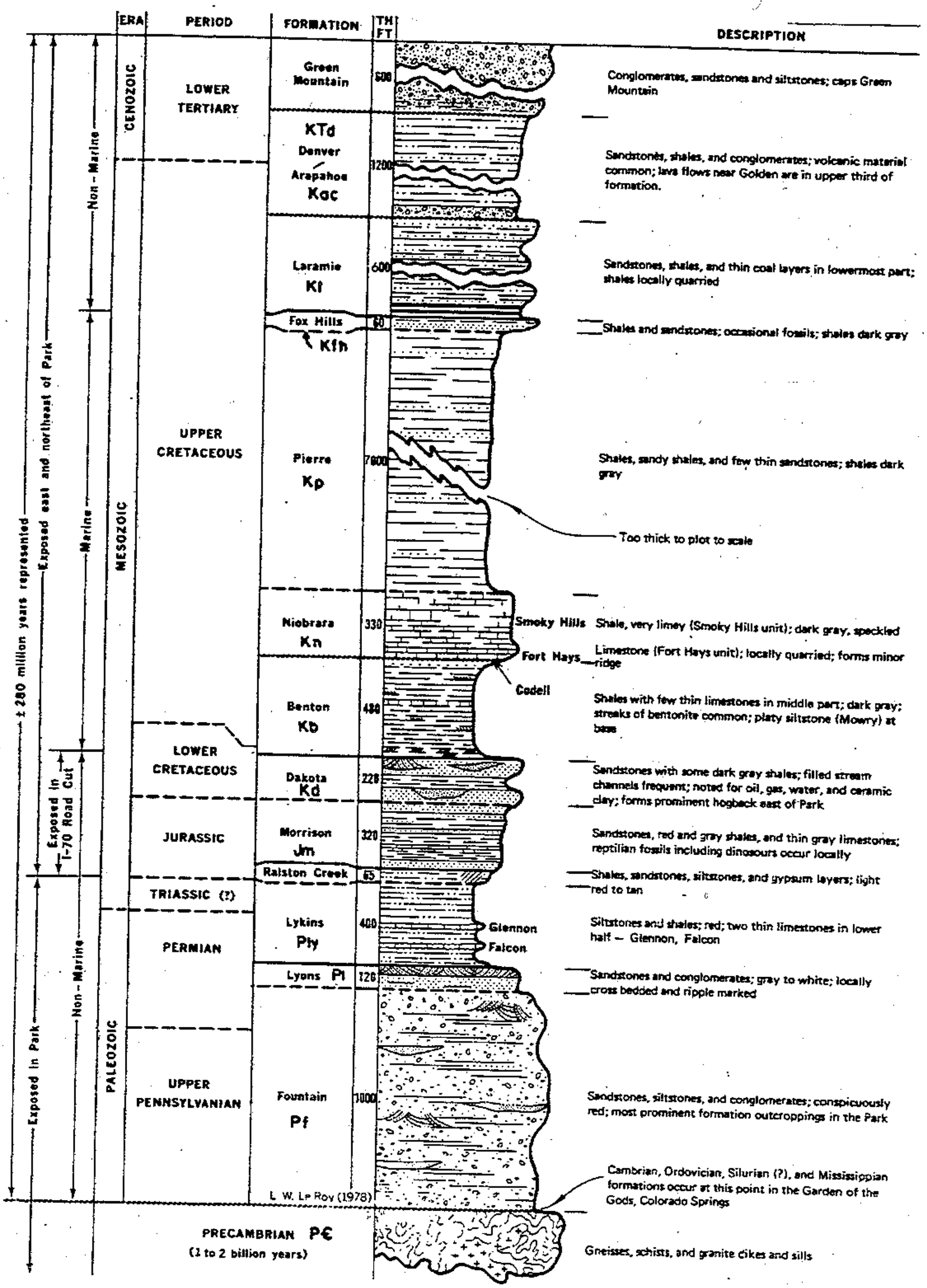


View of the eastern edge of the Front Range looking north-northwest from south of Morrison, Colorado. Town of Morrison (Mo) is west of prominent water gap in Dakota Group Sandstones in foreground:
Photo by T.S. Lovering, U.S. Geological Survey.

| | |
|---|---|
| PC | Precambrian metamorphics |
| F | Fountain Fm. |
| L | Lyons Fm. |
| LY | Lykins Fm. |
| M | Morrison Fm. |
| D | Dakota Group |
| B | Benton Fm. |
| N | Niobrara Fm. |
| P | Pierre Fm. |
| LA | Laramie Fm. |
| MM | Mt. Morrison |
| LM | Lookout Mtn. with erosional surface |
| STM | South Table Mountain |
| GM | Green Mountain |

# GENERALIZED STRATIGRAPHIC SECTION

Golden-Morrison Area
Jefferson County, Colorado



| ERA | PERIOD | FORMATION | TH FT | DESCRIPTION |
|---|---|---|---|---|
| CENOZOIC | LOWER TERTIARY | Green Mountain | 500 | Conglomerates, sandstones and siltstones; caps Green Mountain |
| | | KTd Denver / Arapahoe Kac | 1200 | Sandstones, shales, and conglomerates; volcanic material common; lava flows near Golden are in upper third of formation. |
| MESOZOIC | UPPER CRETACEOUS | Laramie Kl | 600 | Sandstones, shales, and thin coal layers in lowermost part; shales locally quarried |
| | | Fox Hills Kfh | 60 | Shales and sandstones; occasional fossils; shales dark gray |
| | | Pierre Kp | 7800 | Shales, sandy shales, and few thin sandstones; shales dark gray |
| | | Niobrara Kn | 330 | Smoky Hills: Shale, very limey (Smoky Hills unit); dark gray, speckled<br>Fort Hays: Limestone (Fort Hays unit); locally quarried; forms minor ridge |
| | | Benton Kb | 480 | Shales with few thin limestones in middle part; dark gray; streaks of bentonite common; platy siltstone (Mowry) at base |
| | LOWER CRETACEOUS | Dakota Kd | 220 | Sandstones with some dark gray shales; filled stream channels frequent; noted for oil, gas, water, and ceramic clay; forms prominent hogback east of Park |
| | JURASSIC | Morrison Jm | 320 | Sandstones, red and gray shales, and thin gray limestones; reptilian fossils including dinosours occur locally |
| | | Ralston Creek | 65 | Shales, sandstones, siltstones, and gypsum layers; light red to tan |
| | TRIASSIC (?) | | | |
| PALEOZOIC | PERMIAN | Lykins Ply | 400 | Siltstones and shales; red; two thin limestones in lower half — Glennon, Falcon |
| | | Lyons Pl | 120 | Sandstones and conglomerates; gray to white; locally cross bedded and ripple marked |
| | UPPER PENNSYLVANIAN | Fountain Pf | 1000 | Sandstones, siltstones, and conglomerates; conspicuously red; most prominent formation outcroppings in the Park |
| | | | | Cambrian, Ordovician, Silurian (?), and Mississippian formations occur at this point in the Garden of the Gods, Colorado Springs |
| PRECAMBRIAN P€ (1 to 2 billion years) | | | | Gneisses, schists, and granite dikes and sills |

**Figure 3.** Stratigraphic section, Golden-Morrison area (from Weimer and LeRoy, 1987).

## INTRODUCTION TO FIELD TRIP

The following quotations from Tweto (1975, p. 2) best summarize the origin and use of the term "Laramide".

> *The Laramide system of mountain ranges extends along the summit of the Rocky Mountains far northward in British America, and southward into Mexico . . . In the United States it occupies the summit region of the mountains, between the line of the Wasatch Archean and the Front Range . . . The rocks involved were those of all Paleozoic and Mesozoic time, Cambrian beds making the bottom, and the Laramie, or the uppermost formation of the Cretaceous, the top.*

"In these words, Dana (1895, p. 359) introduced the term "Laramide," which subsequently has come into wide and varying usage. The name was clearly derived from "Laramie formation," a term that, in Dana's time, had been applied widely as a synonym of "Lignite group" to coal-bearing strata above fossiliferous marine Cretaceous rocks through much of the Rocky Mountain West. Two factors unknown to Dana have served to make a rather vague definition more ambiguous: (1) the term "Laramie formation" as originally applied in many areas was later found to include strata ranging in age from pre-Laramie Cretaceous to Eocene, and (2) various units of the Rocky Mountains were found to differ appreciably in date of origin. In 1910, the U.S. Geological Survey restricted the application of the term "Laramie Formation" to the Denver basin, and in 1939 the restricted unit was designated as entirely Cretaceous in age. Meanwhile the descendant term "Laramide" has flourished, but owing to the misconception inherent in the original definition, it has come to have many connotations. Hence, the term is only a convenient wastebasket except when the usage is defined. In this paper, which refers only to the Southern Rocky Mountain portion of the Rocky Mountain System, in Colorado and adjoining parts of New Mexico and Wyoming, the term "Laramide" is applied to orogenic events that occurred between late Campanian Cretaceous and late Eocene time. Other parts of the Rocky Mountains had different time frames of orogeny, and even within the restricted area considered here, the movements of major tectonic elements started and ended at different times within the limits just named."

Following Tweto's analysis, if an area were to be designated as a type locality, for the Laramide, it would include the region traversed by this field trip.

The Front Range uplift and Denver basin form one of the best known couplets in the southern Rocky Mountains to study mountain uplift and adjacent basin subsidence during the Laramide. Both crustal blocks have been extensively analyzed to unravel their structural, stratigraphic, and volcanic and intrusive history.

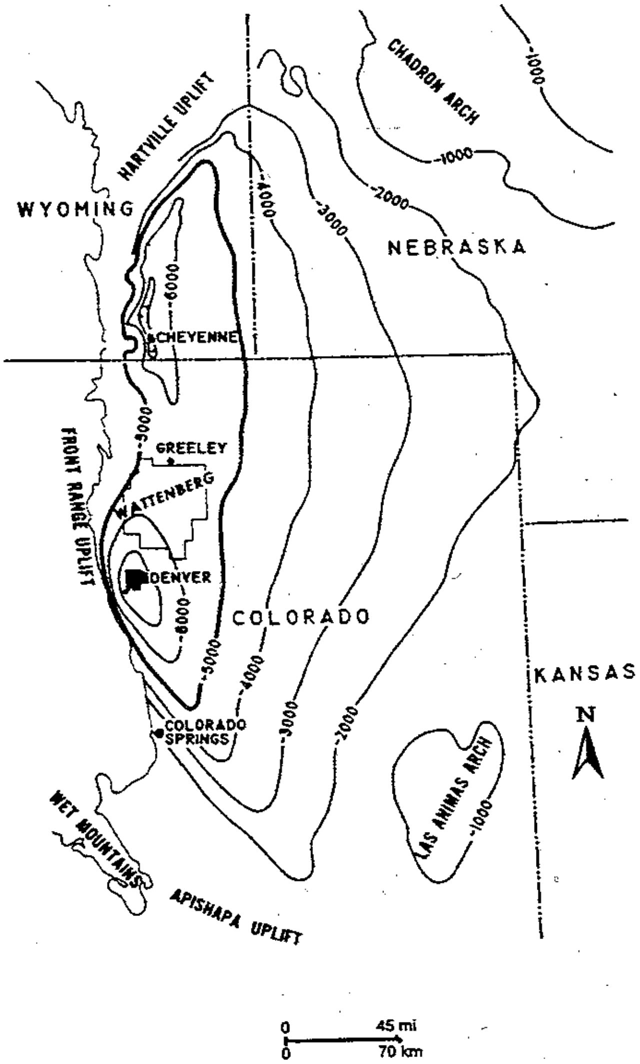


**Figure 2.** Structure contour map on top of Precambrian for Denver Basin and related structural features (from Matuszczak, 1973). Contours are in feet.

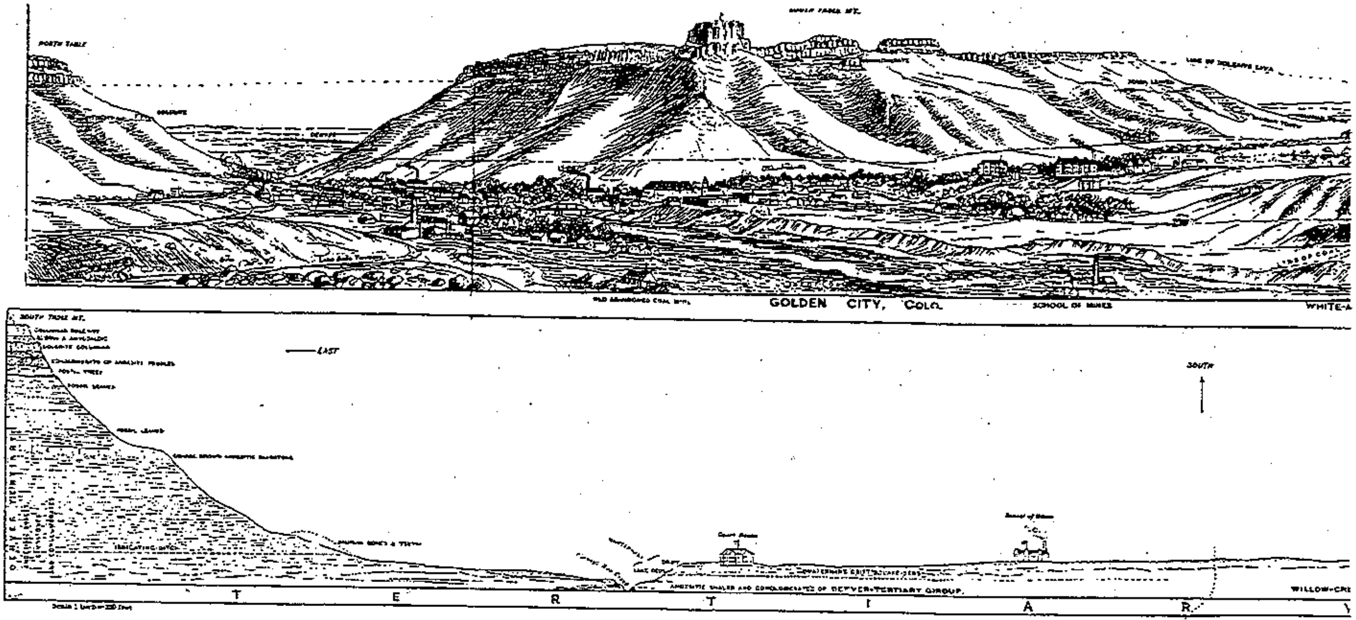
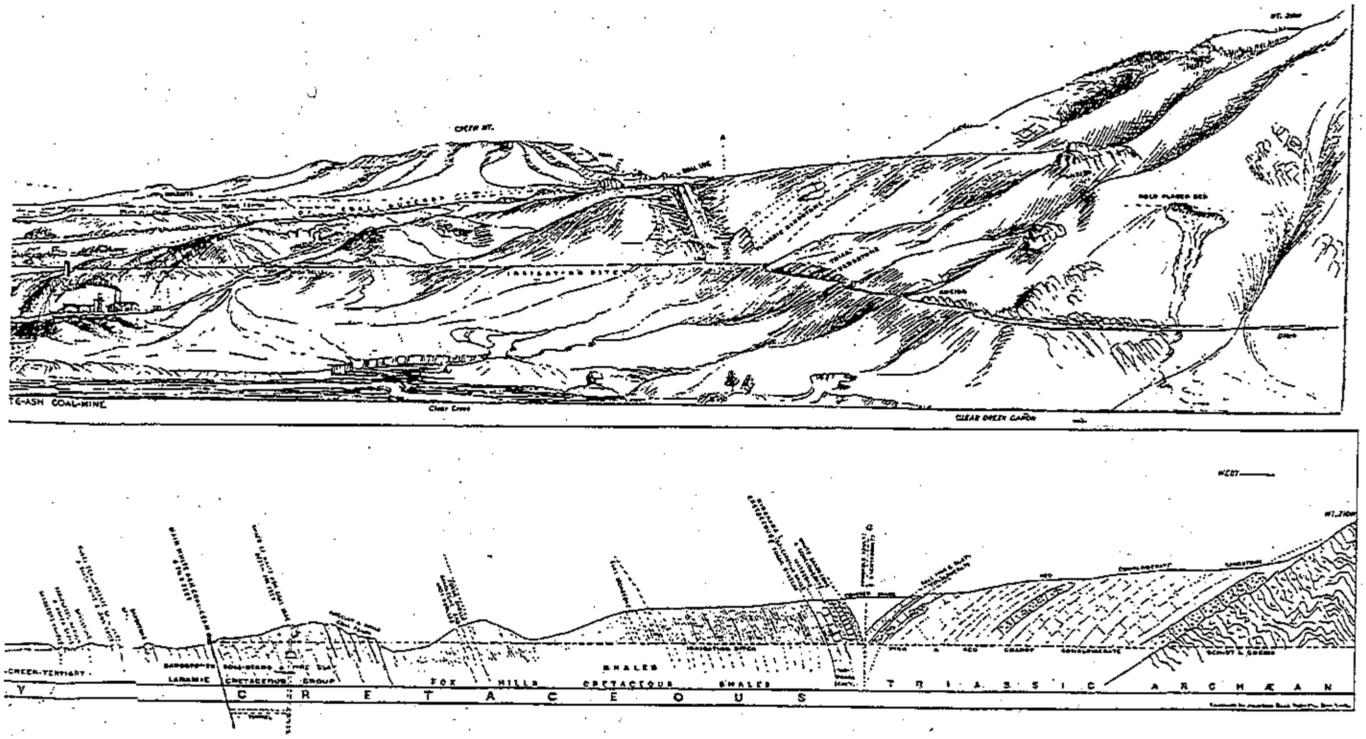


Figure 22. Sketch of geologic and geographic features of the greater Golden area (Lakes, 1889).



## STOP _

## COLORADO SCHOOL OF MINES CAMPUS

### (Clay Pits along 12th Street)

Geology was among the first courses taught at the Colorado School of Mines when it opened in 1874. With the booming mining activity in the Colorado mineral belt, and the coal and clay mining along the foothills, a legacy of geoscience instruction and applied research was established that continues until today.

The unique geology surrounding the greater Golden area is an important part of Mines' heritage. E. L. Berthoud and Arthur Lakes were the first geology professors, and the geology building and the library, respectively, were named after them. Lakes, who also taught drawing, published a magnificent sketch of the region in 1889 (Figure 22).

The purpose of this stop is to traverse across the abandoned clay pits and to discuss the tectonics and sedimentation of the Laramide recorded in the latest Cretaceous and early Tertiary formations.

### Structure

Steeply dipping Paleozoic and Mesozoic rocks form a narrow 1 mi (1.6 km) band cut in the middle by the Golden fault (Figure 23). About 6000 ft (1830 m) of the Cretaceous section is cut out by the fault (Figure 24). Between the Precambrian and the fault, strata dip from 35 to 70° E. in the rotated central block of Stops 3 and 4. East of the fault the strata in the Clay Pits are nearly vertical to overturned (Figure 24) and strike N. 35° W. The Basin Margin fault marks the change from the steep dip to 2 to 4o dips of the Denver basin block of which the lava-capped Table Mountains are a part. The low southeast dip of Table Mountain and Green Mountain is illustrated by a structure contour map (Figure 25) on the second lava bed and equivalents by Reichert (1954). The position of the Basin Margin fault is plotted on the diagram from the mapping illustrated by Figure 23 (Weimer, 1976).

The Basin Margin fault is now believed to be a branch of the Golden fault. The trace of the Golden fault is within the thick Pierre Shale and the maximum throw is in the Golden area. By mapping faunal zones within the Pierre Shale, Scott and Cobban (1965) demonstrated that the Golden fault has no discernible displacement 8 mi (13 km) to the south at the Turkey Creek nose and 12 mi (19.2 km) to the north at Rocky Flats. It is my belief that, where the Golden fault disappears, the main displacement shifts eastward, and the Basin Margin fault becomes the break along which the main block rotation and uplift occurred instead of the Golden fault.

## Stratigraphy

The upper Pierre, Fox Hills, Laramie and Lower Arapahoe formations (Figure 3) are exposed by clay pit excavation along the west margin of the Colorado School of Mines (CSM) campus. Excavations for buildings temporarily exposed the Denver Formation, which does not have natural outcrops on the campus. A geologic map of the area is presented on Figure 26 and a structure section on Figure 24. At present, the best exposures are of the Laramie and lower Arapahoe formations at the north end of the area just south of 12th Street and Brooks Field.

Faulting influences the stratigraphy of the area. A minor fault, believed to be a syndepositional growth fault, places the Laramie Formation against Pierre Shale and cuts out the Fox Hills Formation along the northwest side of the clay pits area. Because of the faulting, the exposed portion of the Laramie Formation varies from 350 ft (108 m) along 12th Street to 570 ft (174 m) south of 19th Street. In addition, the Fox Hills Sandstone reappears along strike of the strata. Marker beds within the Laramie Formation illustrate the manner in which the Fox Hills and lower Laramie strata are cut out by the faulting. The individual marker beds of shale or sandstone seem to diverge, indicating northward thickening of zones in the lower Laramie toward the fault. Although the fault trace curves, the present attitude of the fault plane has a strike varying from N. 10o W. to N. 20o W. and a dip of 65o E. at the surface. Arrows along the fault trace indicate the south component of movement which is shown by drag in the Pierre Shale. The movement indicated by the drag is in conflict with the dominant eastward movement of the major Golden fault, possibly confirming different ages for the faults.

The formations record the last regression of the Cretaceous shoreline seaway and the initiation of uplift of the Front Range.

## Pierre Shale

Exposures of the Pierre Shale and Fox Hills Sandstone are limited. The Pierre consists of dark gray shale with minor thin laminae of tan-weathering, limonitic siltstone, and silty, very fine-grained sandstone. The shale contains a sparse foraminiferal assemblage, similar to that reported by LeRoy (1946, p. 85) from the upper 120 ft (37 m) of the Pierre:—"the foraminifera Haplophragmoides occurs in considerable numbers. Robulus, Gyroidina, Globigerina, Eponides and Gumbelina have been observed in small numbers." These fossils, together with specimens of Sphenodiscus coahuilites and Baculites clinolobatus Elias collected 250 ft (76 m) below the top of the Pierre, indicate marine neritic conditions of sedimentation. In addition, the clay assemblage of the Pierre is dominantly montmorillonite, suggesting marine or brackish sedimentation. The B. clinolobatus zone is indicated by Cobban et al., (1994) to have an age about 70 Ma.

## Fox Hills Sandstone

The Fox Hills Sandstone is tan to yellow, fine-grained, subrounded, friable, glauconitic, feldspathic, calcareous sandstone with thin beds or laminae of siltstone and gray montmorillonitic claystone. Stratification consists dominantly of subparallel laminations or thin beds which occasional ripple laminations; no large-scale cross-stratification was observed. Mica and transported flattened grains of carbonaceous material are abundant along bedding planes. Penecontemporaneous deformational structures are present but confined to a few thin layers in the lower Fox Hills. Indistinct burrows are present but rare. The exposed thickness of the Fox Hills near 12th Street is 40 ft (12 m); however, the exact thickness is questionable because of difficulty in placing the lower transitional contact with the Pierre and the faulting near the upper contact with the Laramie. The thickness may be as great as 75 ft (23 m). A 50-ft (15 m) thick tongue of the Pierre Shale occurs above the Fox Hills along 12th Street. An upper Fox Hills Sandstone, usually present in a normal facies order, has been faulted out. The Fox Hills is interpreted as a shoreline and delta front sandstone.

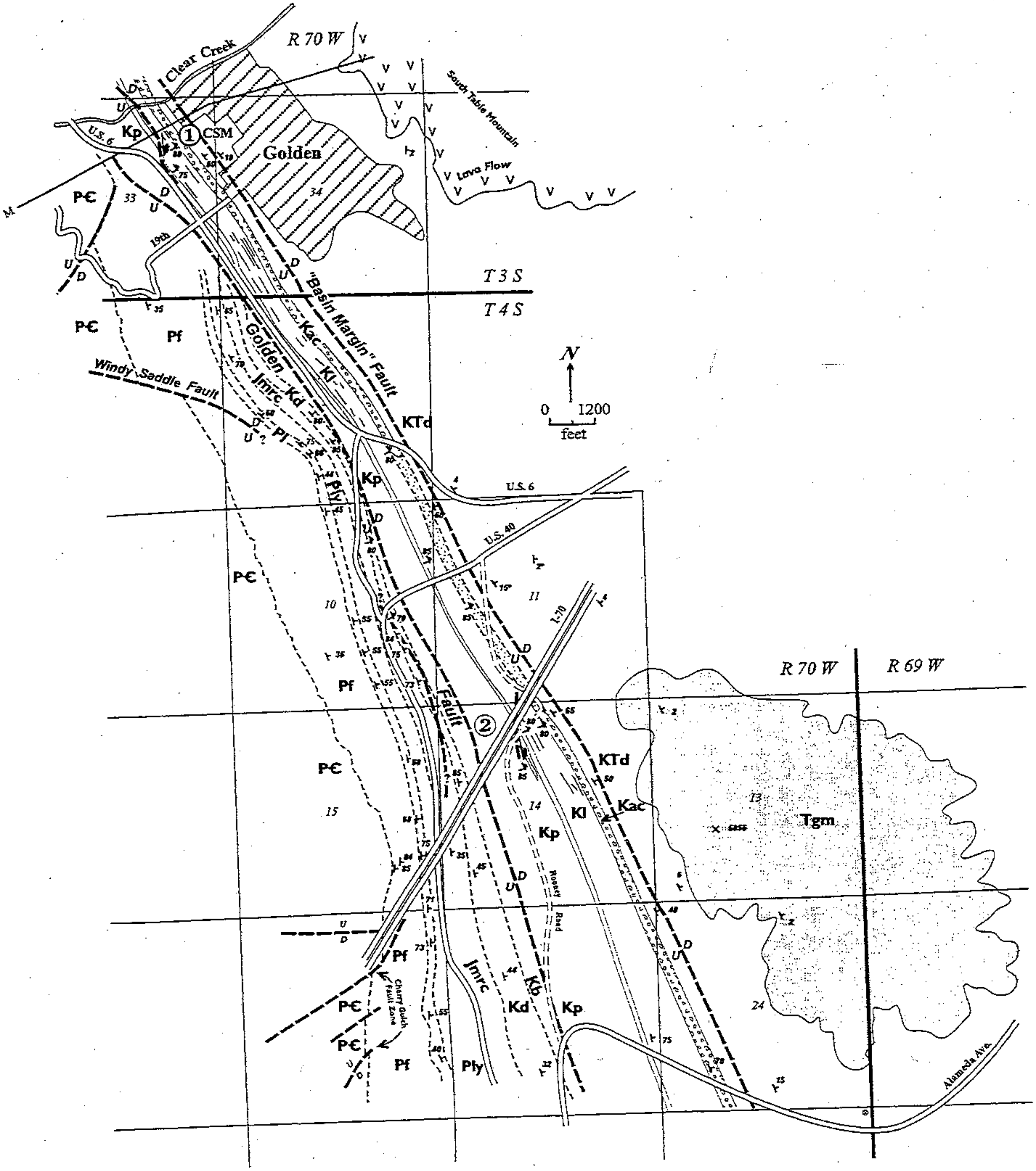


Figure 23. Bedrock geologic map from Golden to I-70 with reference sections 1 and 2.

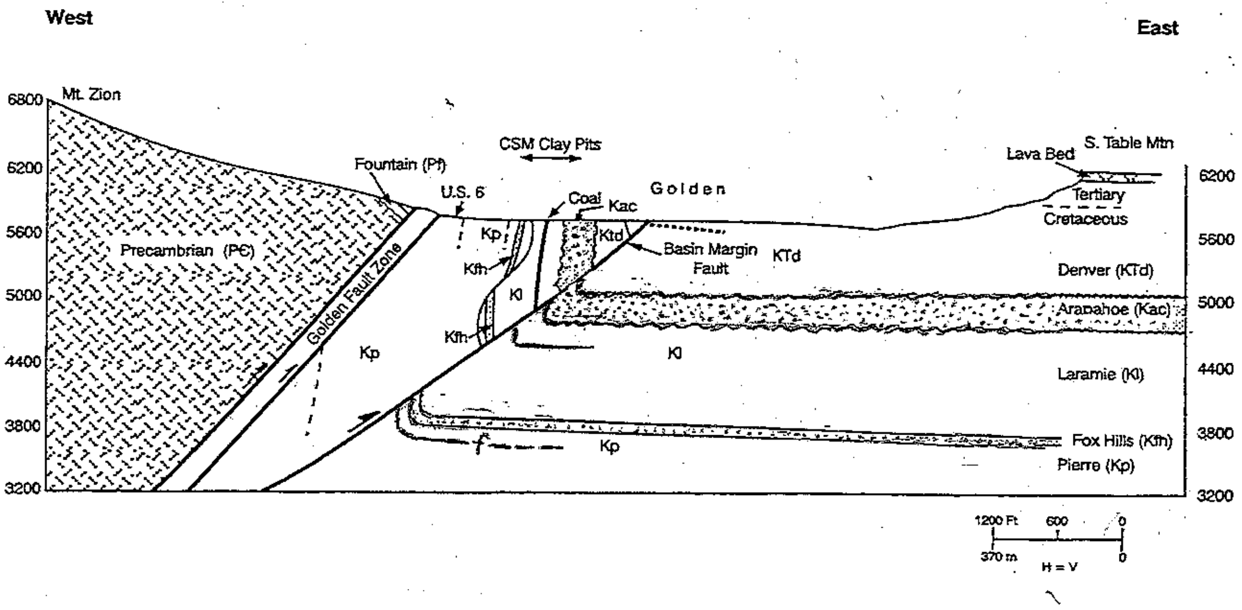


**Figure 24.** East-west structure cross section with CSM clay pits and campus area.

## Laramie Formation

As elsewhere along the mountain front, the Laramie Formation can be divided into two units: a lower unit containing equal quantities of sandstone, siltstone, and claystone with thin coal layers; and an upper unit of dominantly claystone, with minor units of sandstone and siltstone.

The lower Laramie is approximately 190 ft (58 m) thick near 12th Street and consists of 4 major sandstone units which alternate with mineable kaolinitic claystone. The thickness of each individual sandstone and claystone unit varies from 20-40 ft (6-12 m). The sandstones are light gray to buff, fine- to coarse-grained, poorly sorted, subangular, silty; and contain grains of black chert, clay, mica and carbonaceous material. The sandstones have a scour base and commonly contain abundant clay clasts and log imprints. In the lower part, grain size decreases upward from medium and coarse to fine.

The kaolinitic claystone units of the lower Laramie contain several lithologies. Light- to medium-gray blocky weathering claystone is the dominant lithology, with lesser quantities of dark gray to black carbonaceous claystone and thin coal streaks. Several

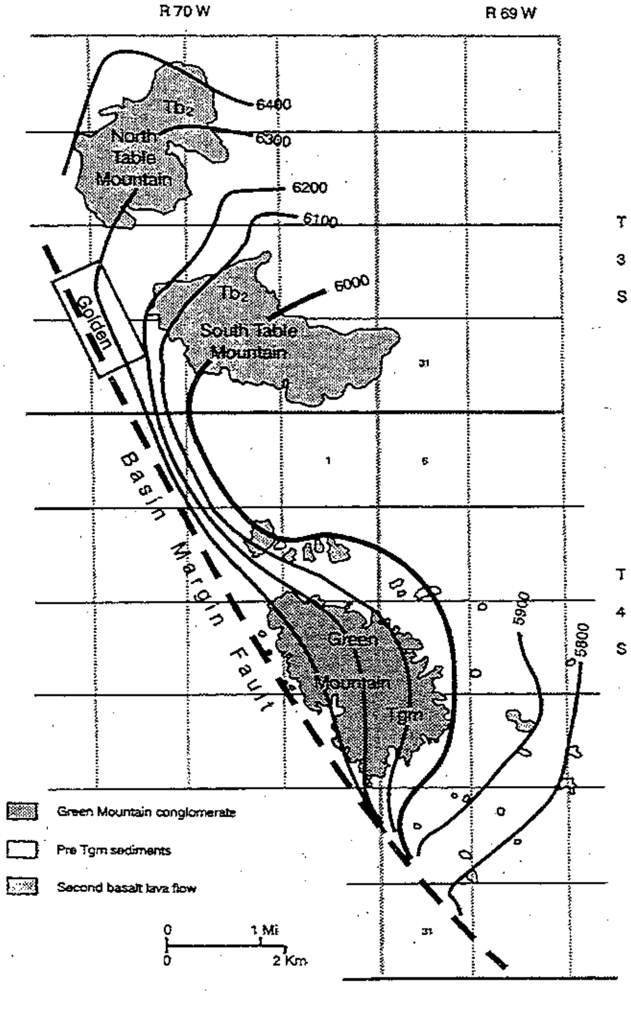


**Figure 25.** Structure contour map (in ft) on the base of Tertiary basalt flow 2, Golden-Green Mountain area (modified from Reichert, 1954).

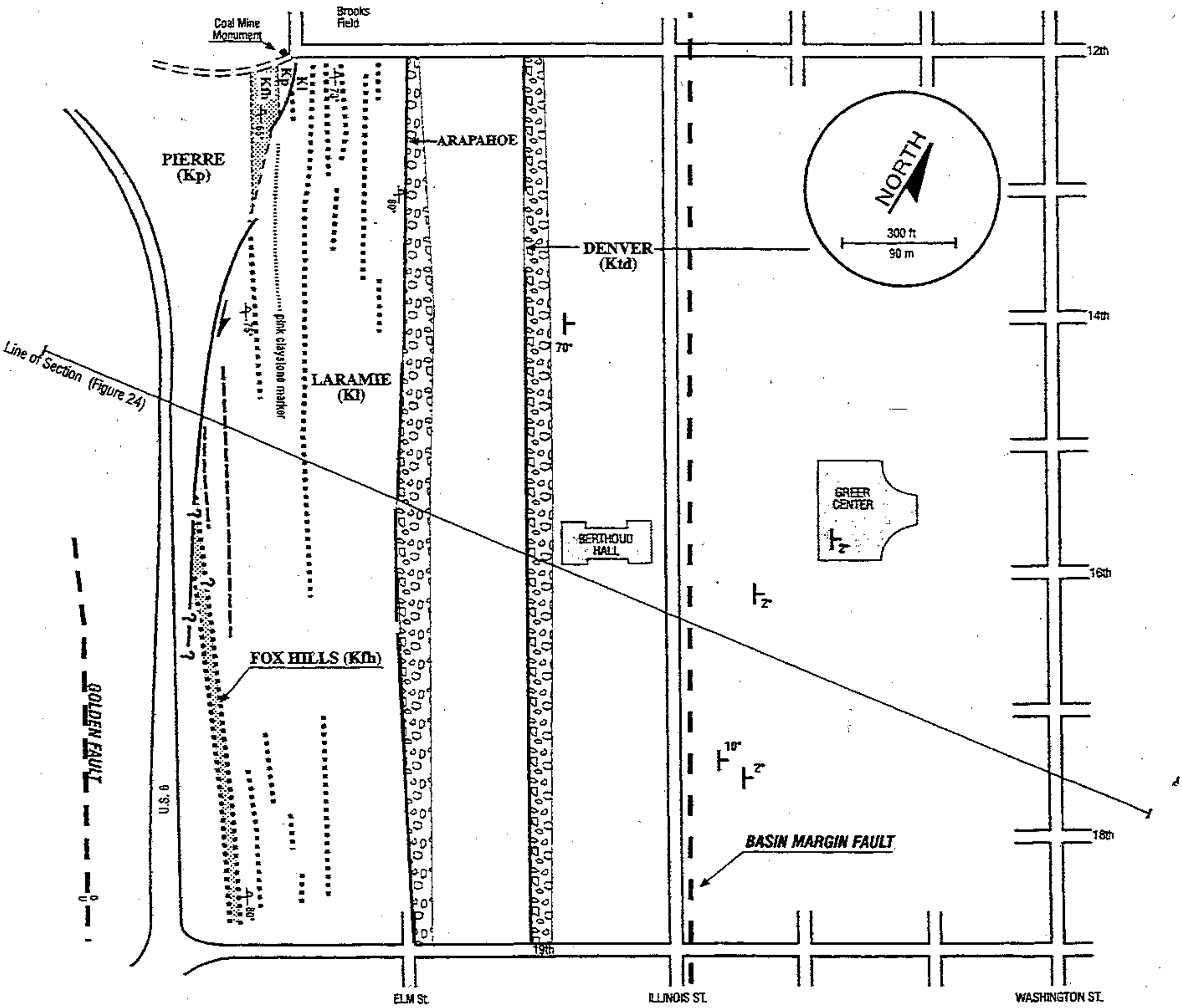


**Figure 26.** Bedrock geologic map of CSM clay pits and campus area. Sandstones within the Laramie Formation are dotted lines; intervening intervals are claystone.

thin layers are pink to light red and yellow to tan in color. Iron-rich concretionary siltstone layers (ironstone) from 1-4 in. (2 to 10 cm) thick are common. The claystone is generally structureless; however, the light gray claystone rarely contains conchoidal fractures with grooving and polishing similar to slickenslides. These breaks are referred to as "clay skins" and are caused by the expansion of root systems.

A monument near the shaft of the old White Ash coal mine is located at the west end of 12th Street. According to Eldridge (in Emmons et al., 1896, p. 335), "the collar of the shaft was 135 ft (41 m) west of the main worked seam, and at the 600-ft (184 m) level is still 39 ft (12 m) to the west". The main coal seam was reported to be 8 ft (2 m) thick; and, a second worked seam, 10-20 ft (3-6 m) below, as 3 ft (1 m) thick. These seams were mined, with a few gaps, to a distance of 1 mi (2 km) north of Clear Creek (the Loveland mine). The monument commemorates a mine tragedy that occurred when sudden flooding caused the death of 10 men and forced abandonment August 20, 1889. The White Ash coal mine was one of the first worked in Colorado.

The upper Laramie at this locality (12th Street) is approximately 160 ft (49 m) thick and is similar in lithology to the lower Laramie, except that the sandstone units are much thinner (less than 15 ft (5 m) thick), and are finer grained. No coal or carbonaceous shale are associated with the upper Laramie claystone, and some parts of the claystone show fine laminations instead of having a uniform blocky appearance.

Fossils found in the Laramie Formation are plant or tree impressions and dinosaur trackways (Lockley and Hunt, 1995). The trackways found at the base of the lowermost sandstone and in sandstone near the top confirm the shallow water depth of the splay sandstones. These fossil data and the lithologies indicate a freshwater origin for the Laramie Formation with deposition in delta plain environments.

## Arapahoe Formation

The lower Arapahoe Formation is one of the most distinctive lithologic units in the area. Approximately 110 ft (33 m) of the formation is exposed in the clay pits area. The lower 80 ft (24 m) are composed dominantly of conglomerate and conglomeratic arkosic sandstone, with minor layers of gray claystone and siltstone. The upper 30 ft (9 m) of exposed beds consist of light gray, soft mudstone and light gray to buff, fine- to medium-grained friable sandstone. Measurements elsewhere along the outcrop suggest a thickness for the Arapahoe of between 300 (92 m) and 400 ft (122 m).

The conglomeratic sandstone rests on a sharp scour surface (unconformity) on the Laramie Formation. Numerous clay clasts as large as 2 ft (.6 m) in diameter, and log imprints and load casts are present in the lower few feet of the lowermost conglomerate. Pebbles in the conglomerate layers are dominantly gray to black chert; but minor quantities of quartz, quartzite, and igneous and metamorphic rocks are present. The pebble diameter is as much as several in. (cms), although the dominant size is less than 1 in. (2.5 cm). The dominance of chert pebbles led earlier workers to call this lower conglomerate the "flint-chert phase". The Arapahoe was deposited in fluvial environments with the conglomeratic sandstone as part of a braided channel complex.

## Denver Formation

The Denver Formation is not exposed in the Clay Pits or on the CSM Campus. In excavations and exposures to the south (Figures 27 and 28) the lower few feet (cms) of the Denver Formation consist of greenish-brown, fine- to coarse-grained, hornblende-augite, andesite-rich, clayey sandstones with local lenses of conglomeratic sandstone that contain andesite porphyry pebbles as much as 0.5 in (1 cm) in diameter. The main lithology of the Denver is dark brown and yellow brown sandy mudstone layers which are intercalated with fine- to coarse-grained conglomeratic sandstone. The basalt flows, capping the Table Mountains, are in the upper few hundred feet of the formation. The volcanic-rich sandstones are distinctively different from the arkosic sandstones and conglomerates and the lighter-colored mudstones of the underlying Arapahoe Formation. This abrupt lithologic change reflects introduction of large quantities of volcanic material into the drainage basin which was the source for the sediments in the Denver Formation. The total thickness of the Denver is estimated to be between 900-1200 ft (275-340 m). The environments of deposition were a fluvial complex of channels and overbank deposits.

Lithologic variations and historic changes in terminology for the Denver Formation are reported by LeRoy (1946) and Reichert (1954). Age dating was summarized by Brown (1943), with the Cretaceous-Tertiary boundary placed about 300 ft (92 m) below the lava beds on the southeast slope of South Table Mountain (Figure 24).

## Early Laramide Fault Movement

An important question is when did Laramide movement first occur on the mountain flank fault systems? A comparison has been made between the thickness and facies changes of the combined Laramie and Fox Hills formations in the hanging wall (outcrop area) and the foot wall (well data, Denver basin area) of the Basin Margin fault (Figures 27 and 28, Weimer, 1973). An isopach map of the interval shows a 30 to 70 percent increase in thickness across the fault. These changes are plotted on structural sections across the fault at Golden and the Leyden mine 6 mi (9.7 km) to the north (Figures 24, 27 and 29).

A stratigraphic restored section along 8 mi (13 km) of outcrop from Golden to Alameda Parkway shows thickness and lithologic changes (Figure 28, Weimer, 1973) related to faulting. Syndepositional faults at the CSM clay pits and Rooney Road sections, as well as a possible unconformity at the base of the Arapahoe, appear to control the thickness variations in the outcrop sections and are inferred to control changes from the

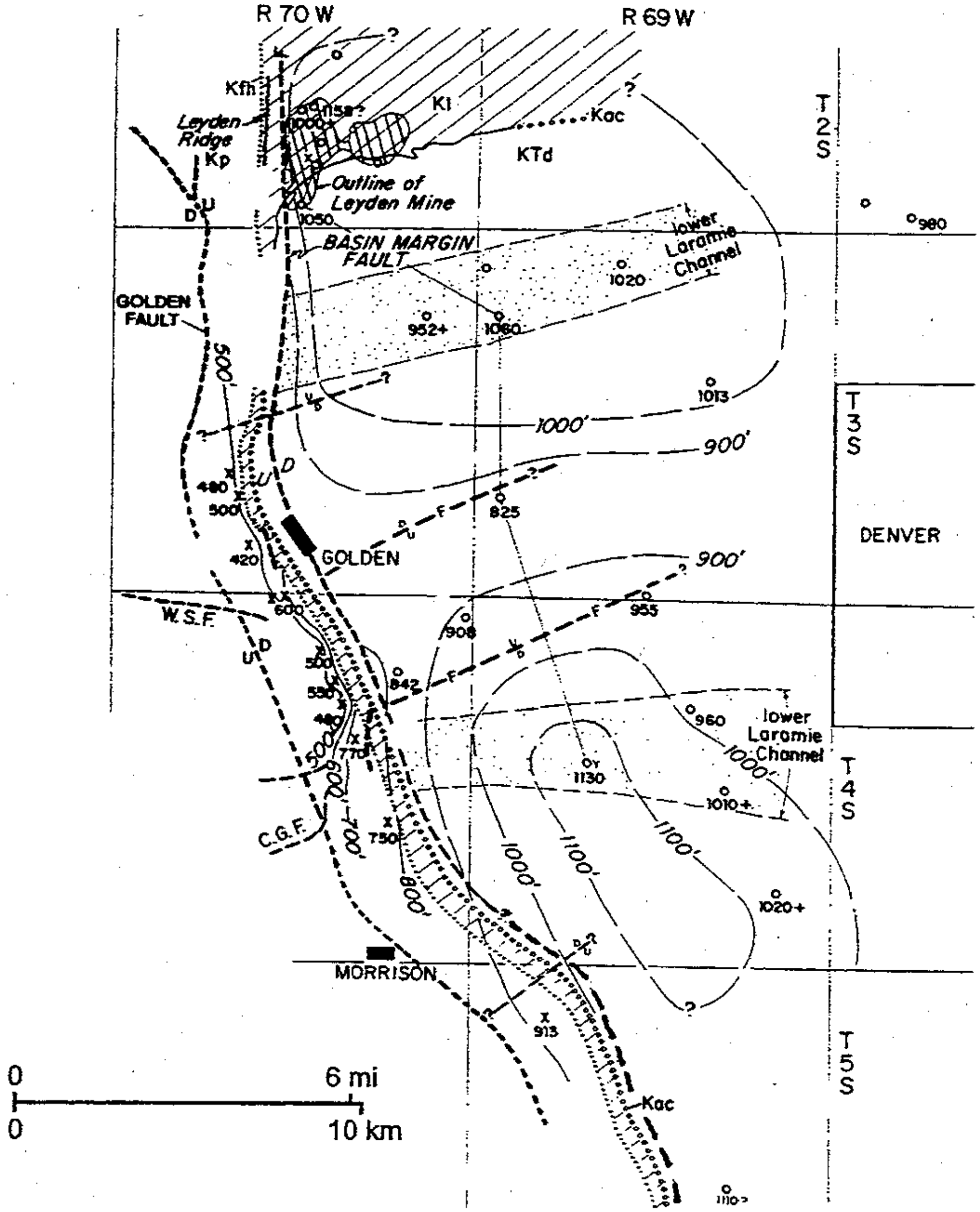


**Figure 27.** Geologic map and isopach map with combined thicknesses (in ft) of Laramie and Fox Hills formations. Fault patterns are indicated with trace of Golden fault restored to estimated original position before uplift of Front Range (from Weimer, 1976).

outcrop to the subsurface in a similar manner. The thinnest sections in the outcrop appear to be over a horst block bounded by the Windy Saddle fault (W.S.F.) and the Cherry Gulch fault (C.G.F.) (Figure 28). Moreover, channel sandstones in the lower Laramie and Arapahoe appear to be thicker in the downthrown portions of the faults (Figures 27 and 28).

On the west flank of Green Mountain, step-like changes in eastward dips occur (Reichert, 1954; Smith, 1964) that suggest angular unconformities. The dip changes in ascending formations are as follows: upper Arapahoe 80° to 90°; middle Denver (unit with volcanic flows) 50°-60°; upper Denver 15°-20°; and Green Mountain 2°. Limited observations suggest that

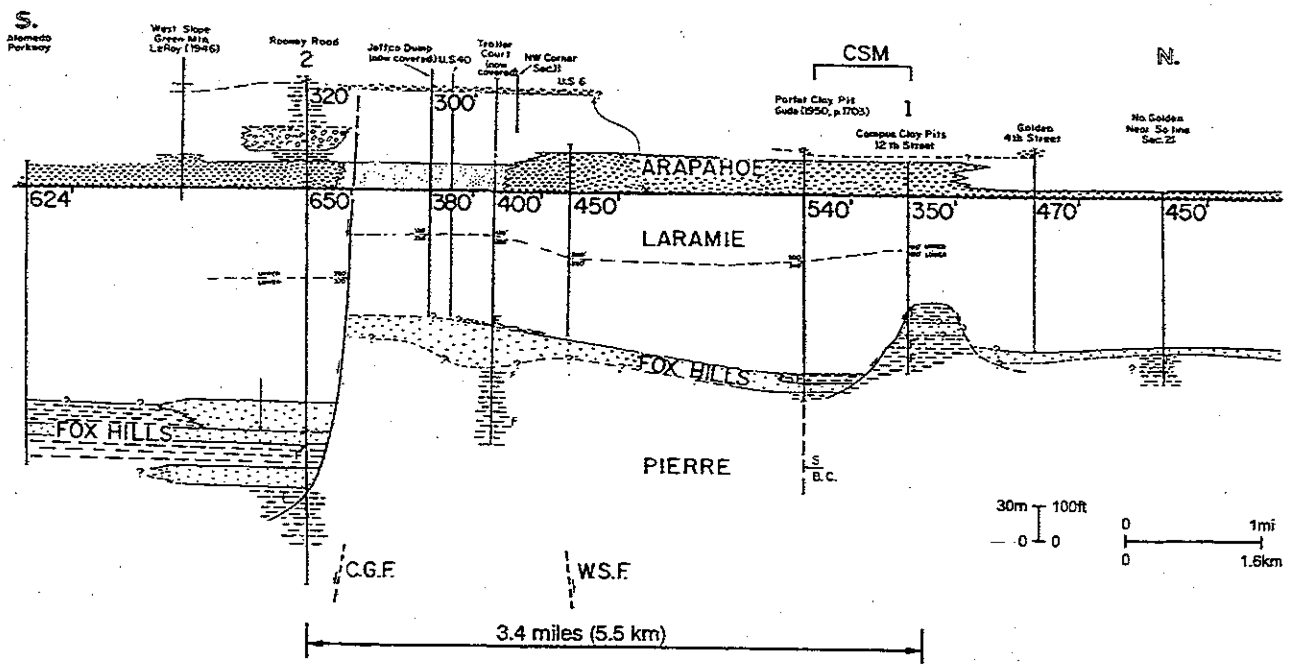


**Figure 28.** Stratigraphic restored section from north Golden to Alameda Parkway. Numbers are measured thicknesses for Laramie and Arapahoe formations from outcrops. Faunal zones in Pierre Shale--S = Sphenodiscus; B.C. = Baculites clinolobatus (from Weimer, 1976).

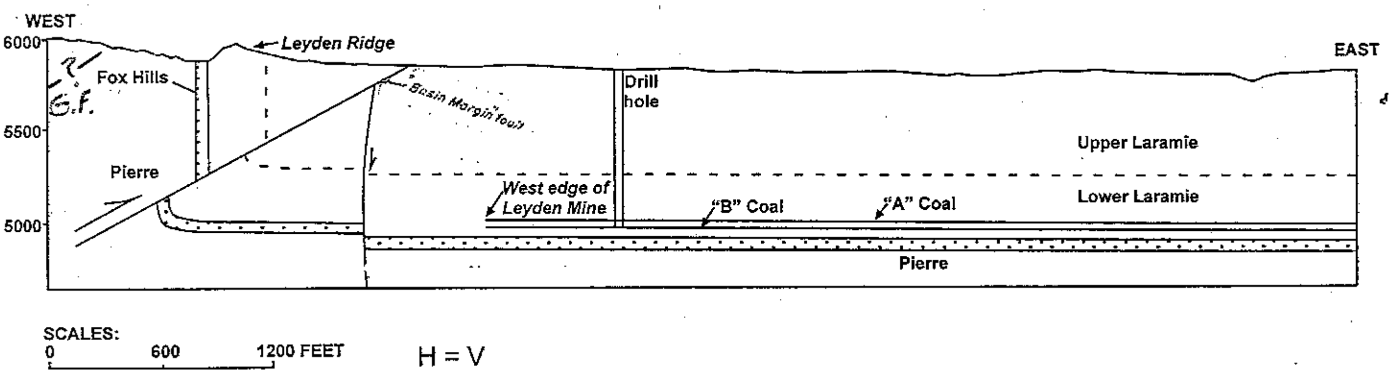


**Figure 29.** East-west structure cross section along Leyden Gulch relating outcrop and Basin Margin fault to Leyden Coal Mine (T. 2 S., R. 70 W.; refer to Figure 27). Golden fault location from Van Horn (1976).

G.F.

an angular unconformity exists between the Arapahoe and Denver formations. The Basin Margin fault marks the change from steep to shallow dip within the Denver. The 10° to 20° dip may be related to drag on the east side of the fault. Episodic structural movements, perhaps more than noted, with tilting, erosion and deposition seem most likely. Similar dip changes occur across the CSM Clay Pits and Campus area (Figure 24).

Step-like dip changes are also reported by Kluth and Nelson (1988) in the Air Force Academy area on the flank of the Rampart Range 50 mi (80 km) to the south, and related to angular unconformities. The ages of the unconformities on the flank of the Front Range-Green Mountain area are about the same as those reported at the Air Force Academy, Late Maestrichtian and Early Paleocene, and may reflect the start of mountain flank deformation from Colorado Springs to Boulder.

## Main Phase of Laramide Deformation

The Front Range uplift and associated deformation have been portrayed in structural cross-sections and by discussions by many authors over the past 40 years (e.g. Boos and Boos, 1957; Berg, 1962; Grose, 1972; Davis and Young, 1977; Tweto, 1983; Jacob, 1983; Erslev, 1993). The authors believe the uplift to be the result of east-directed stress. Over the past 107 years, there have been at least 14 published and unpublished cross sections across the east flank of the Front Range from Jarre Canyon to Boulder. Dip interpretations of the Golden fault, and other similar flank faults, have varied from low angle thrust to high angle reverse fault. The cross-sections in this report show the dip of the Golden fault and the Basin Margin fault to be 40 to 45° with a steepening at depth under the Front Range. It seems likely that the fault plane dips are variable along the entire Front Range.

The volcanic events recorded in the stratigraphic section and fossils are crucial to the timing of the main uplift. The Laramide volcanism of the Front Range is summarized by Larson and Drexler (1988) (Figure 30). The age of the Table Mountain flows and the Ralston sill are bracketed as being emplaced 64 to 66 Ma. Dating of stocks in the Colorado mineral belt (COMB) range in age from 60 to 70 Ma and were probably the source for the flows. The heat source for the large Wattenberg thermal anomaly, in alignment with the COMB, is thought to be a complex of intrusives in the basement under the Denver basin (Myer and McGee, 1985) either associated with late Cretaceous-Paleocene intrusions, or possibly the younger Oligocene intrusions of the Front Range (Mutschler, et al. 1987). The giant Wattenberg gas field occurs within this anomaly.

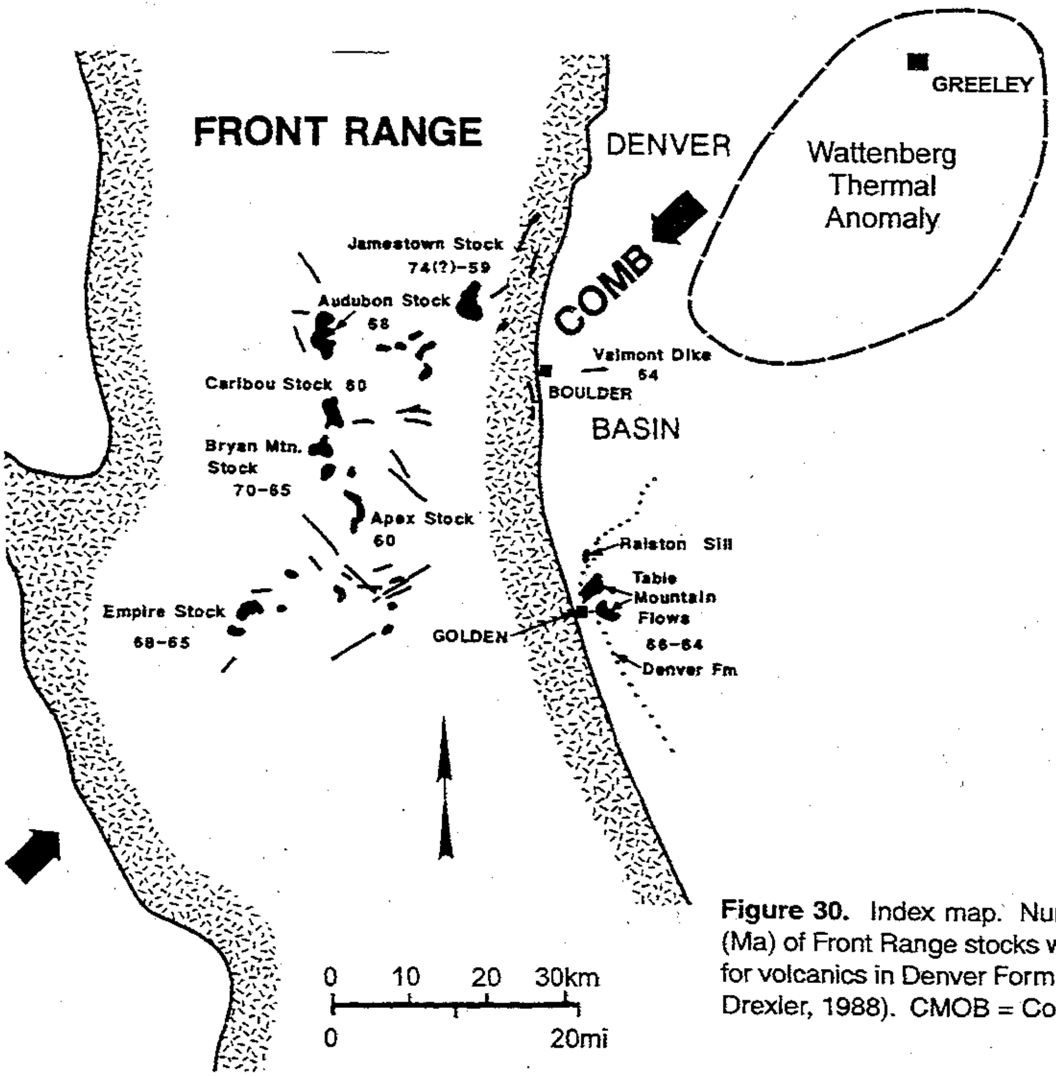


**Figure 30.** Index map. Numbers represent ages (Ma) of Front Range stocks which could be sources for volcanics in Denver Formation (from Larson and Drexler, 1988). CMOB = Colorado Mineral Belt.

Physical evidence for the impact event at the K/T boundary has not been found where the boundary was identified by Brown (1943) based on fossil evidence on South Table Mountain. Regional radiometric dates by Obradovich (1993) yields an age for the K/T boundary of 65.4 + 0.1 Ma, a date consistent with the other data from the Golden area. Furthermore, no discernible unconformity exists at K/T boundary in this area.

The Ralston sill (aka dike) was intruded into the Pierre Shale west of the Golden fault (Van Horn, 1957). Paleomagnetic data indicate that the sill and enclosing strata were rotated to the present attitude by movement on the fault (Hoblitt and Larson, 1975). Moreover, the Table Mountain flows, or related volcanic conglomerates, were reported by Reichert (1954) as having 20° to 40° east dips near the base of the west slope of Green Mountain, indicating post-flow structural movement.

By use of plant and mammal fossils, strata below the Table Mountain flows were dated by Brown (1943) as early Paleocene. The Green Mountain Conglomerate, which lies above the flows, is also dated as Paleocene by Brown (Reichert, 1954, p. 27) and as Early Paleocene with possible Middle Paleocene strata in the upper part (Soister and Tschudy, 1978). Boulders from 3 to 6 ft (1 - 2 m) in diameter are reported in the Green Mountain conglomerates and interpreted as indicating "the maximum period of orogenic intensity in the Front Range west of Golden" (Reichert, 1954).

The above data indicate that the main phase of Laramide activity started in the early Paleocene. This phase terminated before development of the late Eocene erosional surface discussed at Stop 2 on Lookout Mountain. In the southern Front Range coarse sediment, in the main body of the Dawson Arkose, 1000 ft - 300 m thick, was shed eastward into the Denver basin during Early to Middle Eocene, a record suggesting continued uplift during this period of time (Soister, 1978). However, the late Paleocene and Early to Middle Eocene history of the Golden area is uncertain because no rocks of this time interval are now present. The absence of lower Tertiary in all of northeast Colorado may reflect renewed structural movement on the Transcontinental arch, either causing non-deposition, or the removal of strata after deposition of the Eocene rocks, and before the White River Formation (Oligocene) was deposited on the Laramie or older formations (Meade, 1976, Tweto, 1979).

A study of clay mineralogy by Elliott et al. (1991) in the central Denver basin reveals that the age of illitization, about 60 Ma, is coincident with the late Laramide structural development of the basin. If upwarping occurred along the Transcontinental arch it would post-date this 60 Ma event. Such warping might have been concurrent with the strike changes, suggesting downwarping observed in the outcrop band of the Late Cretaceous and Tertiary formations (including the faults) between Leyden Ridge (north of Golden) and Turkey Creek (south of Morrison) (Figure 27).

## Summary

In summary, the Laramide started during upper Pierre deposition (70 to 71 Ma) with the first conglomerate phase, the Arapahoe, being deposited between 66 to 67 Ma. Introduction of volcanic rocks occurred 66 to 64 Ma, an interval that includes the Cretaceous-Tertiary boundary. The main phase of uplift and mountain flank deformation was in early Paleocene, probably extending into the Early and Middle Eocene, within the time interval 64 to 50 Ma. Poorly defined unconformities may occur within this interval reflecting periodic uplift and cessation of sedimentation. Broad warping along northeast trends may have also occurred in the 60 to 50 Ma interval. Orogenic movements ceased before the formation of the late Eocene erosional surface.

## STOP

## MARSHALL COAL AREA

## (East Side of Intersection, CO 93 and 170)

The first coal mined in Colorado was at the Marshall coal field, 4 mi (6 km) southeast of Boulder (from historic markers in area). Discovered by William Kitchens in 1859, the land is marked by foundations of mine structures, spoil piles, mine shaft depressions and sunken earth reflecting the pillar-and-room mines below. Coal was mined from 1859 until 1945, and several shallow coal seams that caught fire during operations are still burning.

The coal-bearing Laramie Formation known from this locality and the Golden area was part of Dana's (1895) first description of the Laramide Orogeny.

The Marshall field is at the southwest end of a more extensive coal mining area extending northeast 40 mi (65 km), known as the Boulder-Weld Coal Field (Colton and Lowrie, 1973). Several seams occur in the lower Laramie Formation and mines are located

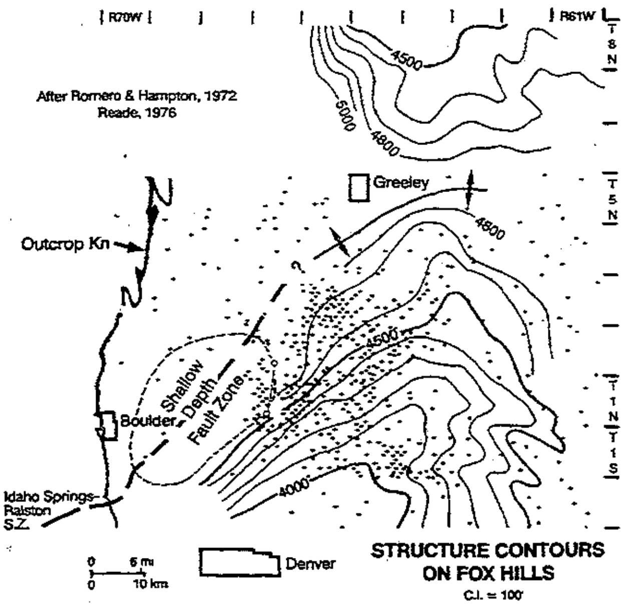


**Figure 31.** Structure contour map (in ft) on top of Fox Hills Sandstone. Shallow depth fault zone of Boulder-Weld coal field and axis for Greeley arch are indicated. Outcrop is for Niobrara Formation (Kn).

generally in graben areas of shallow depth horst-graben fault structures (Figures 31 and 32). A regional structure map, contoured on the top of the Fox Hills Sandstone (base of the Laramie Formation), shows the location of a shallow depth fault zone in which the main mines occur on the northwest flank of a southern sub-basin of the Denver basin (Romero and Hampton, 1972). An anticlinal arch, probably an extension of the fault zone, separates this sub-basin from the Cheyenne sub-basin to north (Kirkham and Ladwig, 1979 and Reade, 1976). The arch, known as the Greeley arch, is expressed in the Fox Hills and Laramie formations but is not present on structure contour maps of the Hygiene and Muddy (J) Sandstone (Weimer and Sonnenberg, 1989).

The horst-graben structures (Figure 32) are known from surface mapping of the Louisville quadrangle (Spencer, 1961), from compilation of mine maps and drill holes (Colton and Lowrie, 1973), from mapping and drill hole data from the Rocky Flats Plant (T.2S., R.70W.), Ebasco Team (1993), and from drill holes in the Spindle oil field (Kittleson, 1992). Even with this remarkable set of subsurface data disagreement still exists as to what happens to the faults at depth.

Faults associated with the shallow depth zone cut the upper Pierre, Fox Hills, Laramie and Arapahoe formations. The width of the fault zone varies from 6 to 10 mi (9.6 - 16 km) (Figure 32). The following summary describes the main features of the fault zone:

- Graben blocks constituting most of the fault zone have a low dip to the southeast (Spencer, 1961).
- Horst blocks display the following:
- 2 to 4 mi (3.2 - 6.4 km) long and 0.25 to 0.5 mi (0.4 to 0.8 km) wide
- appear as slices that wedge out both to north and south; may flair out into grabens with horsetail pattern of faults;
- trends change from northeast in T.1S., R.70W. to nearly north in Ts.1-2N. and Rs.67-68W.
- some have rotation being higher on southeast side;
- most of structural relief is related to upward movement of horst blocks
- Fault planes generally have a high angle dip (Spencer, 1961) and have both normal and reverse movement. Reverse faults repeat section in Ts.1 and 2N., Rs.67 and 68W. (Kittleson, 1992).
- Throw on the faults range up to 350 ft (108m);
- Steeper dips may occur as drag close to fault planes;
- Syndepositional fault movement has resulted in thicker coal beds in the grabens compared to the horsts (Weimer, 1973).
- Faulting started in the upper Pierre and ended post-Arapahoe and before regional tilting (Figure 31).

The northeast-trending faults are cut off by the Basin Margin Fault that marks the eastern edge of the mountain front rotated block (Figure 32). Based on surface mapping, a seismic line and quarry in T.2S., R.70W. (Figure 32), and core hole data, the Pierre, Fox Hills and Laramie formations in the uplifted and rotated block dip 60 to 70° E. and strike north-south. The Boulder-Weld fault zone within the Denver basin block appears to be older than the mountain front deformation.

The structural trend from Marshall to Greeley has been noted by many authors to be on a projection of the major Idaho Springs-Ralston shear zone of Precambrian age (e.g. Spencer, 1961, Tweto and Sims,

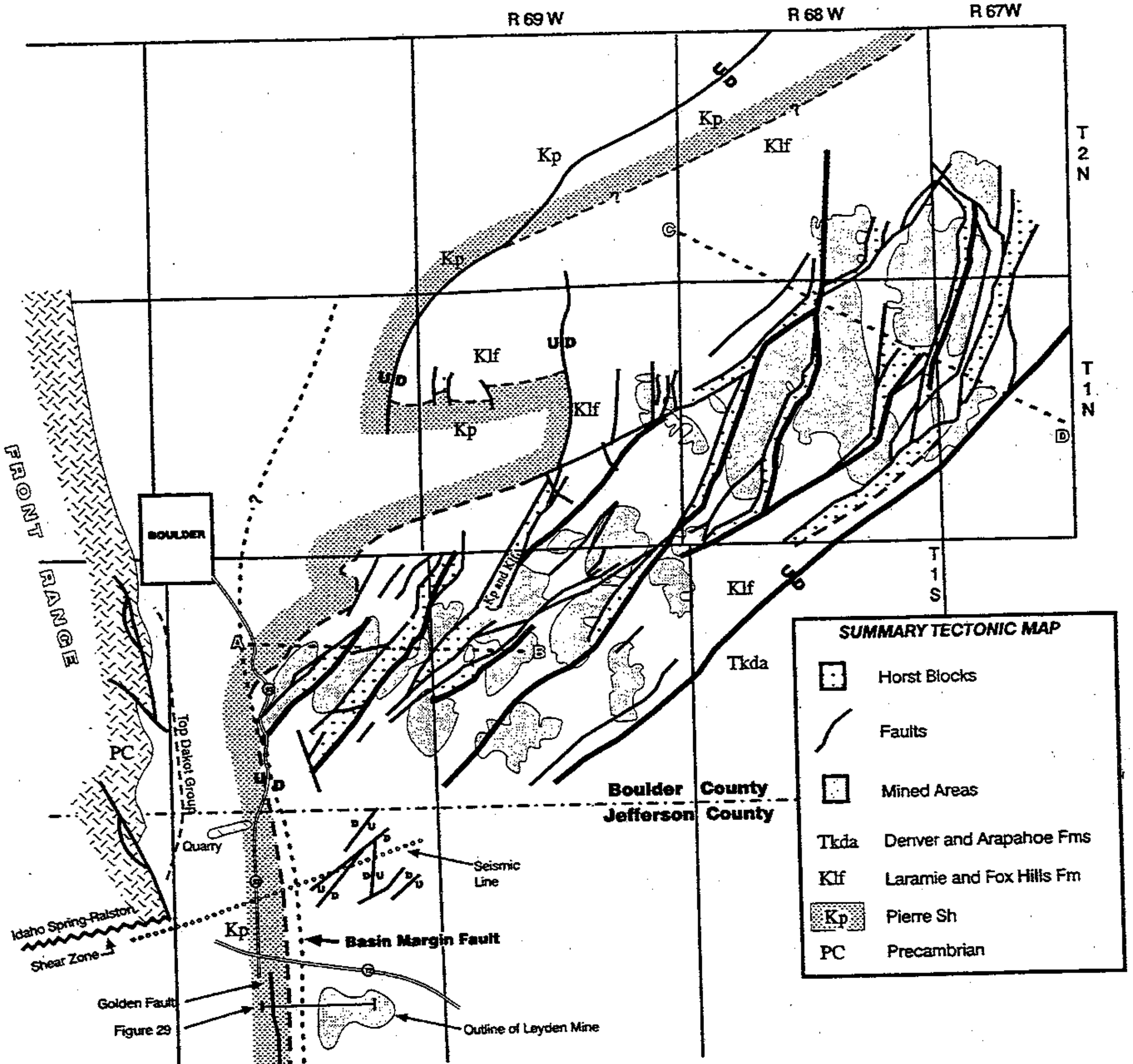


**Figure 32**. Fault map of Boulder-Weld coal field (modified after Colton and Lowrie, 1973; Spencer, 1961; Amuedo and Ivey, 1975; Kittleson, 1992 and Ebasco Team, 1993). Mountain front faults from Wells, 1967. North end of Golden fault from Van Horn (1976).

1963, Haun, 1968, Weimer, 1978, 1980) (Figure 31). A major argument against a projection of the shear zone into the basin is the lack of offset in the Phanerozoic strata (Pierre Shale and older) on the mountain front by wrench faulting (note contact on top of Dakota Group without fault offset (Figure 32) (from Wells, 1967). However, if the faulting was post-Arapahoe but before the mountain uplift, and fault movement was strike-slip, then offset of strata might not be discernible. Work in progress leads me to believe that this is the case. A difficult problem is how to relate the shallow faulting to recurrent movement on the basement shear zones. Interpretations have ranged from no direct tie to projecting all of the main faults to the basement. Moreover, if the shallow faults are related to wrench movement on the Idaho Springs-Ralston basement shear zone, then a north offset of the shear zone may have occurred along the Basin Margin fault.

Seismic data interpreted by Davis (1974) and Davis and Weimer (1976) suggested that the faults within the Boulder-Weld fault zone become listric at depth, passing into bedding planes, and do not project below the Hygiene level of the Pierre. Later work in the basin suggested a genetic relationship between listric faulting and basement faults (Davis, 1985). Generally, the faults have been interpreted as normal. However, reverse faulting, causing repeated section, was recognized in the Spindle oil field in unpublished work by Sonnenberg and Weimer in 1983, and a decollement thrust style repeating sections was published by Kittleson (1992). There is also the unaddressed problem of what caused the regional bulge in the Pierre Shale to form the Greeley arch. High resolution seismic across the fault zone is needed to resolve differences in interpretations.

For the present, the best explanation to explain the disharmonic nature of the surface to subsurface structure is the integration of data into wrench fault models, either as the palm tree structures of Sylvester (1988, p. 1686) and/or the flower structures related to a convergent wrench fault style by Harding (1990). The style of wrench faulting may change along the major fault zone. A paper describing the deformation by wrench faulting at different Cretaceous stratigraphic levels in the Denver basin is now in press (Weimer, 1996).

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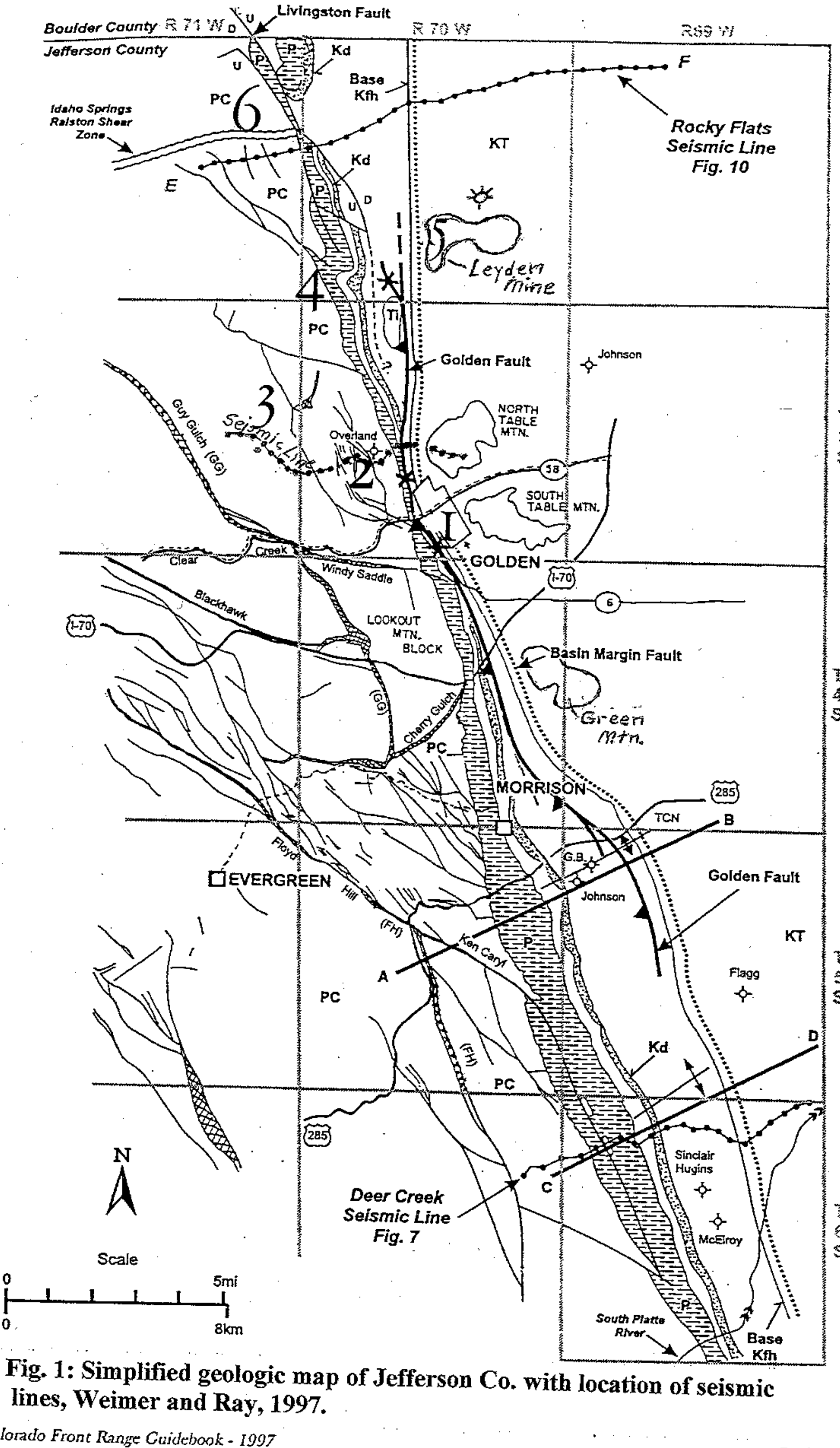


FIGURE 2. Simplified geologic map and compilation of faults in the Jefferson County mountain front area. From Tweto (1979 and 1980), Trimble and Machette (1979), Sheridan et al. (1972), and geologic quadrangle maps. Symbols for stratigraphic units are on Figure 3. X's in T2 and 3S, R70W mark three localities where trenches across the Golden Fault were excavated by Dames and Moore (1981). Ti = Tertiary intrusion (Ralston sill a.k.a. Ralston dike).

**Fig. 1: Simplified geologic map of Jefferson Co. with location of seismic lines, Weimer and Ray, 1997.**

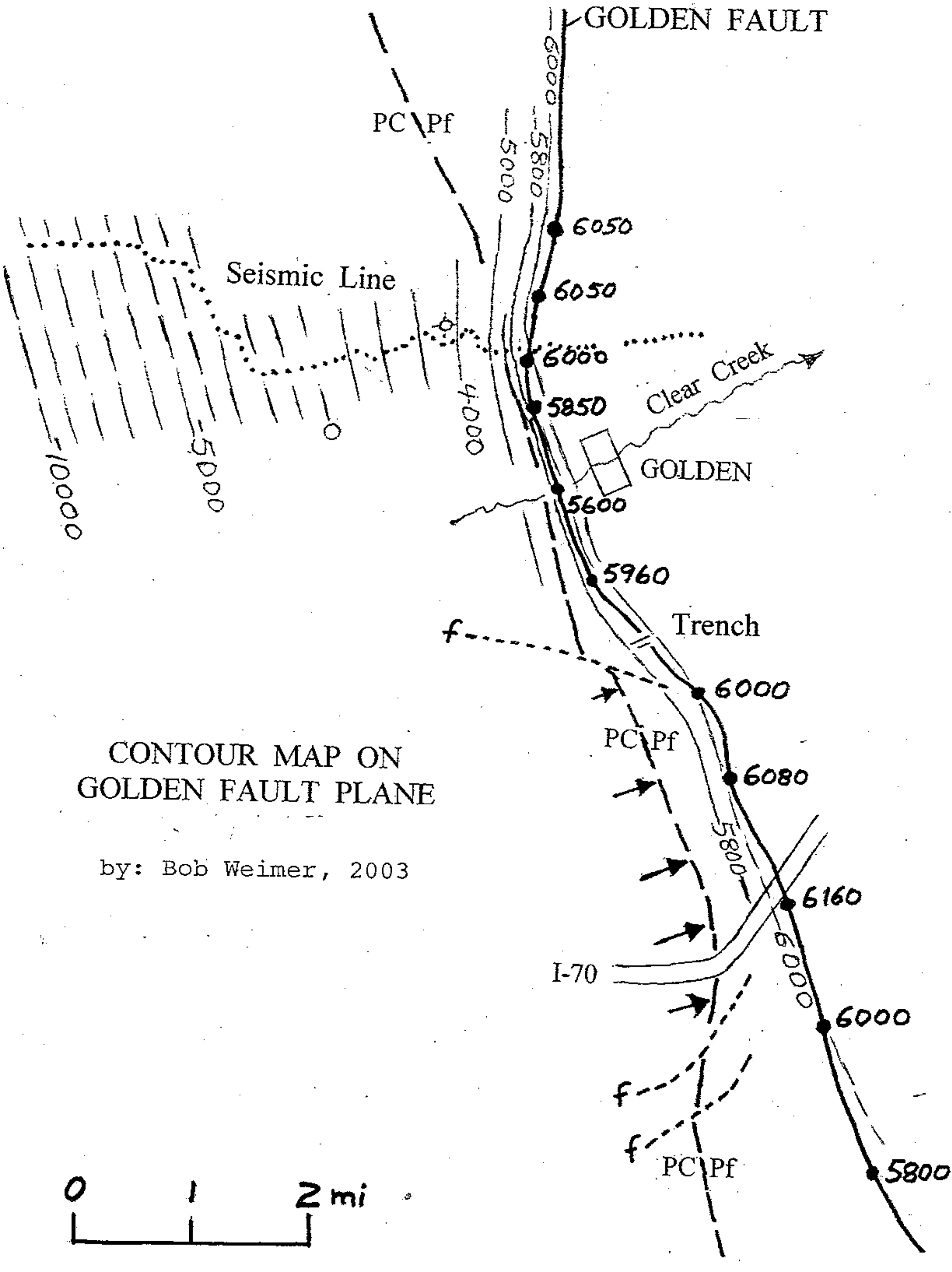


**Fig. 2: Contour map on Golden fault plane.**

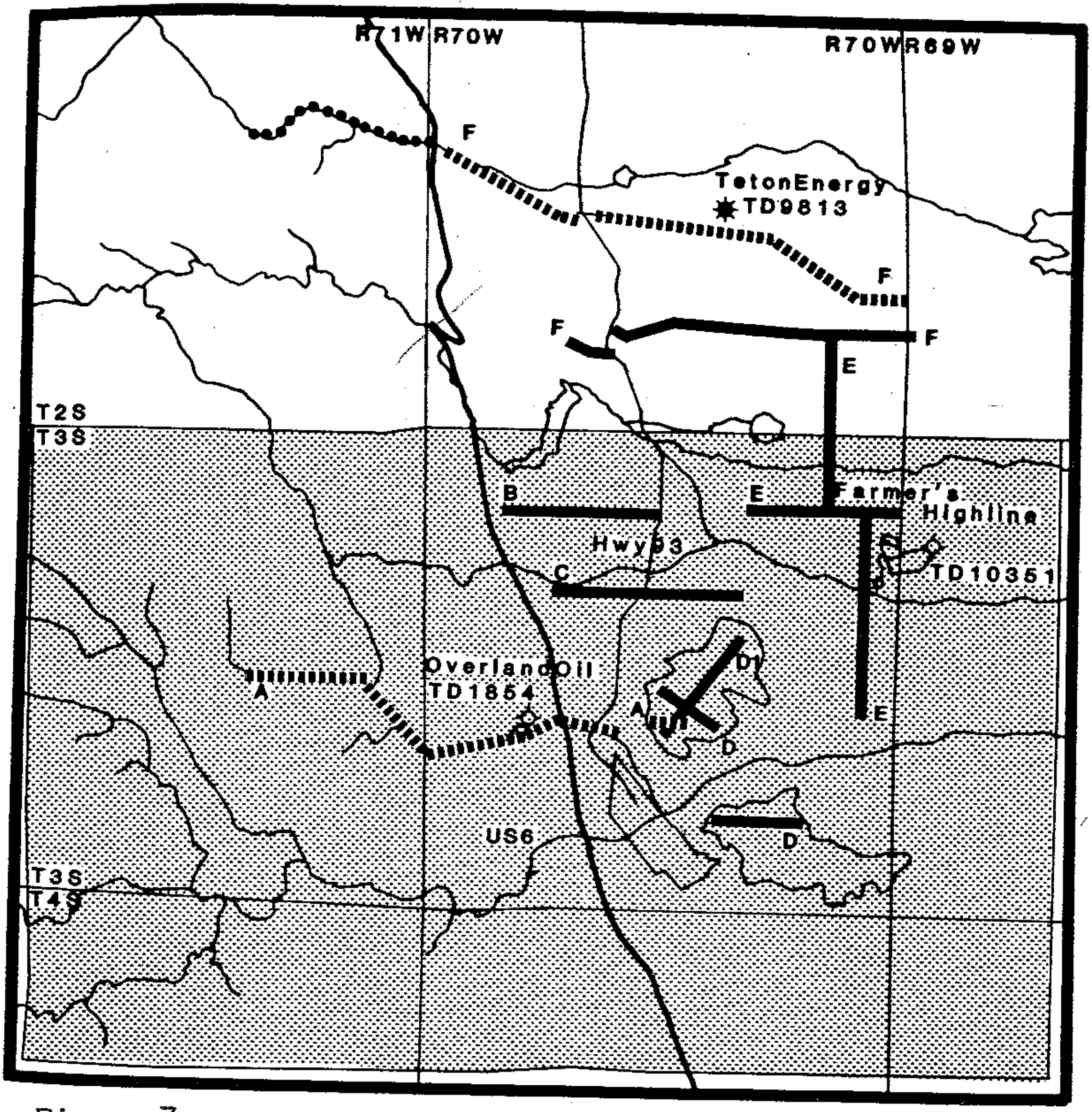


Figure 3. Geophysical survey location map. Stippled area denotes area of detailed gravity study. Dashed lines indicate seismic profiles collected or reprocessed in this study. Dots along Highway 72 show extent of gravity survey. Seismic profiles and original source of publication: A-Present study; B-Schuck (1976); C-Money (1977); D-Young (1977), D1=North Table Mountain line 1; E-Nelson (1977); F-Davis and Young (1977).

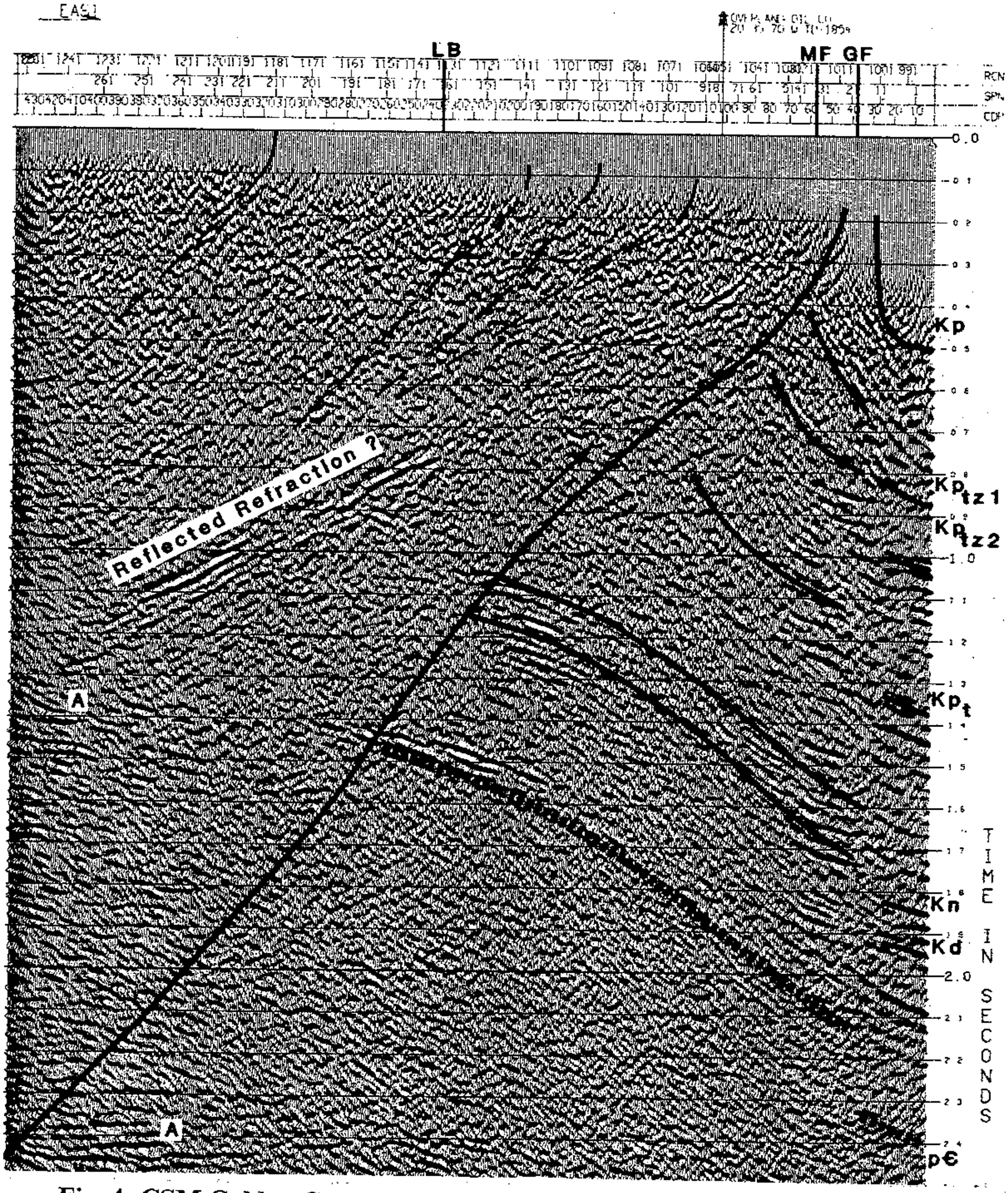


Fig. 4: CSM Golden Gate seismic line by Domoracki, 1986.

Interpreted migrated stack - Golden Gate Canyon

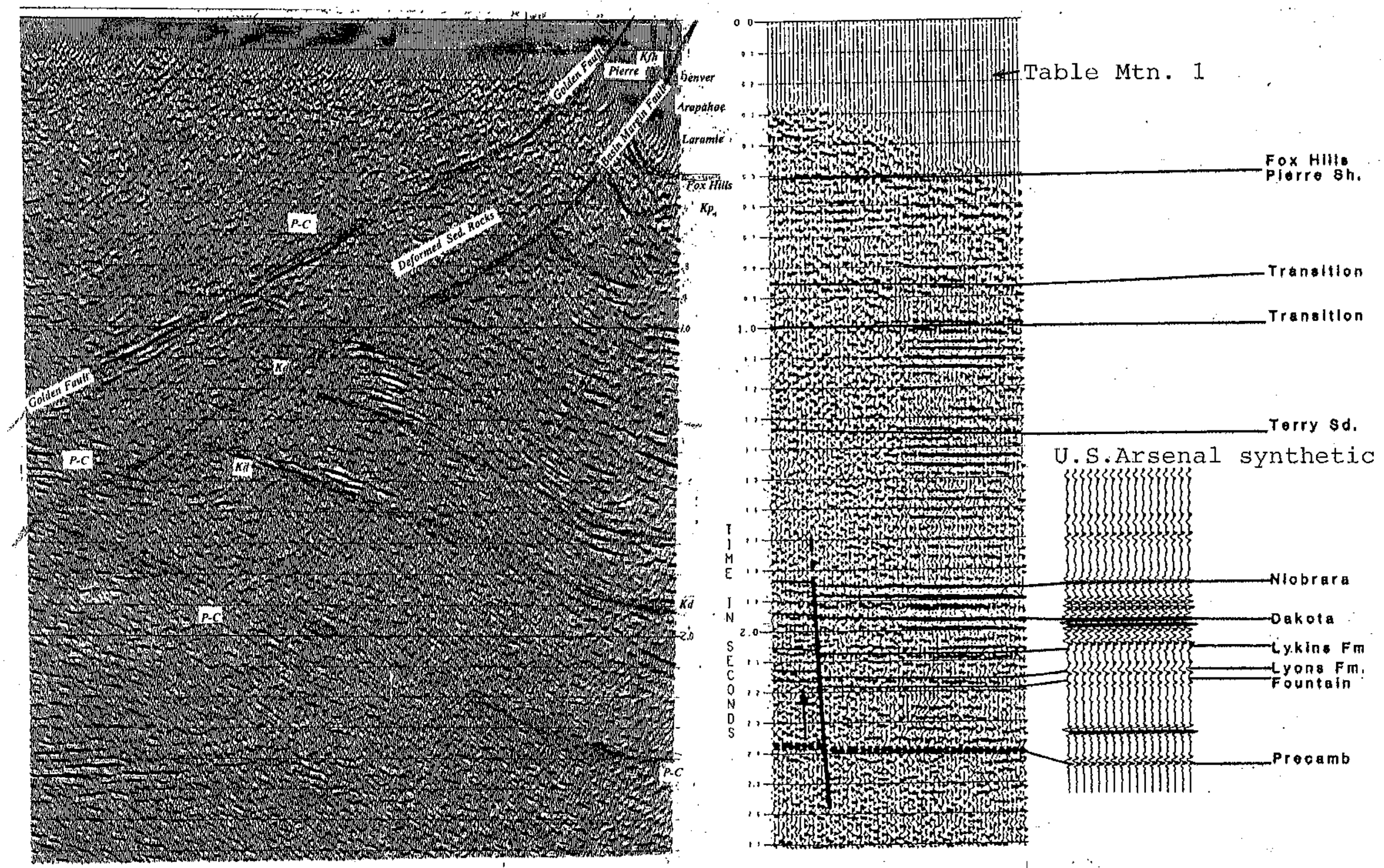


Fig. 5: New interpretation of Golden Gate line by Weimer and Davis, 2004.

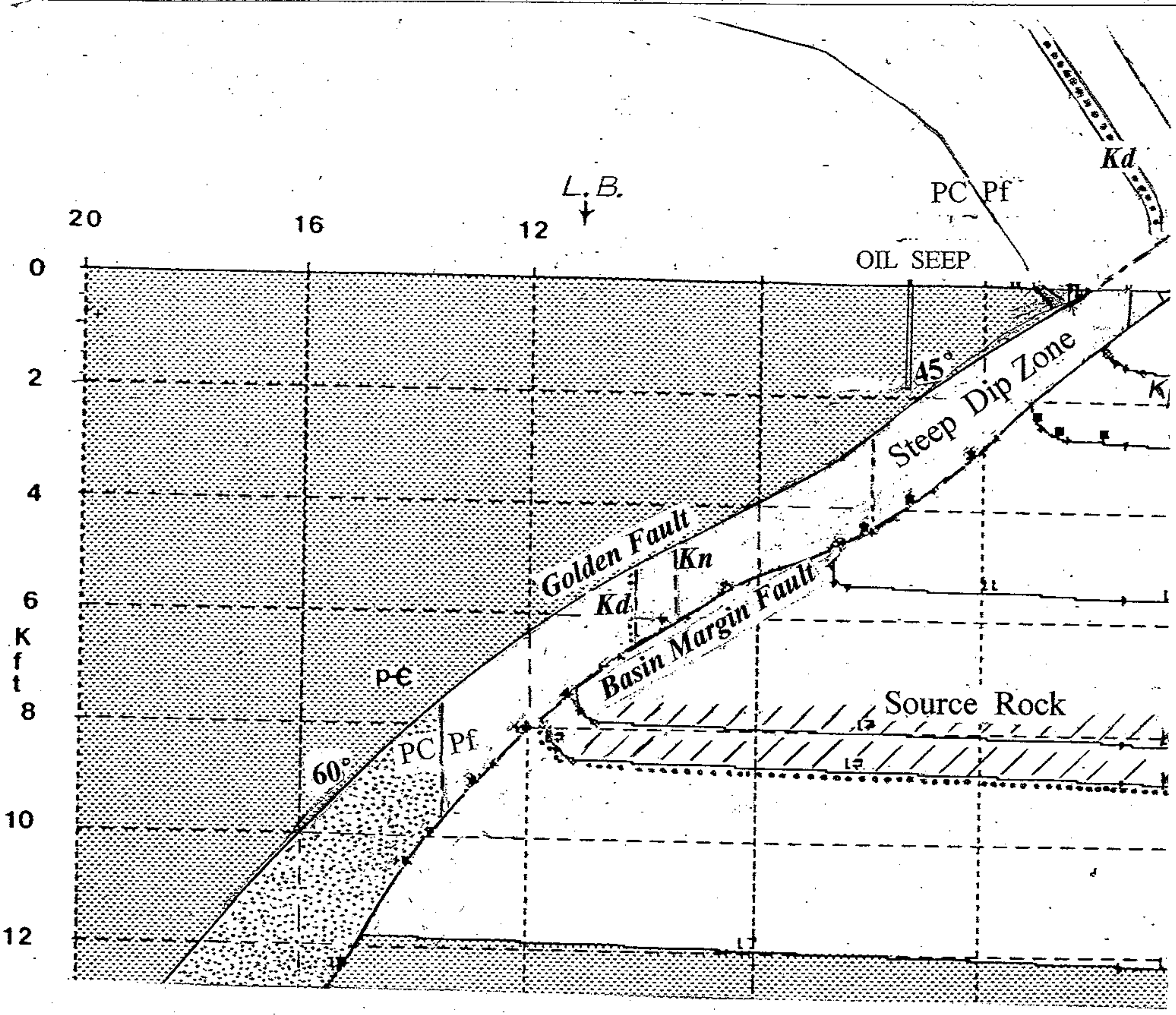
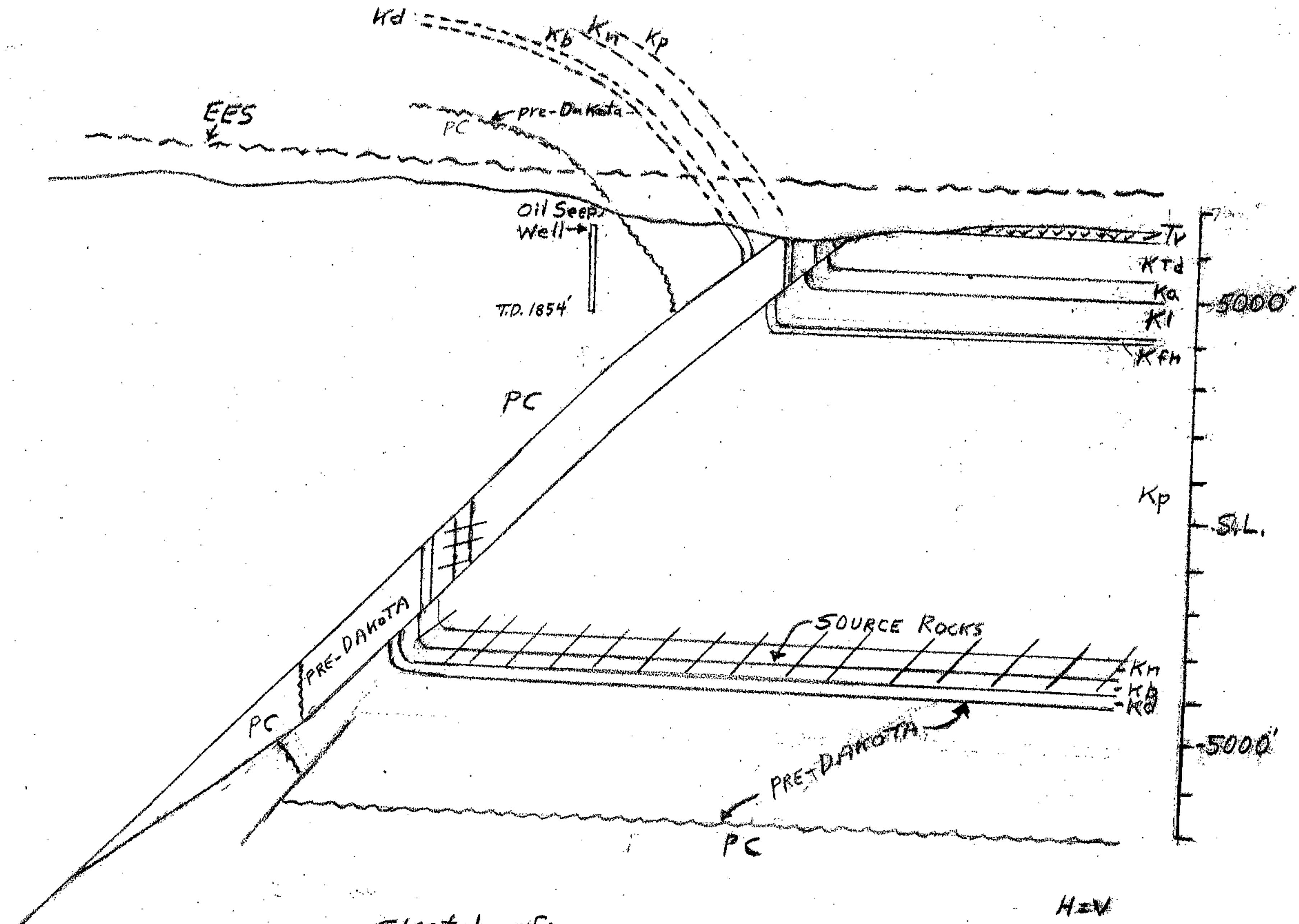


**Fig. 6: Advanced Interpretative Modeling System (AIMS) depth model; two fault plane model modified after Domoracki's one fault plane interpretation (1986, Fig. 27, p. 78).**



Sketch of:

Fig. 7: Geologic cross section one-half mile north of Golden Gate seismic line, modified after Van Horn, 1957.

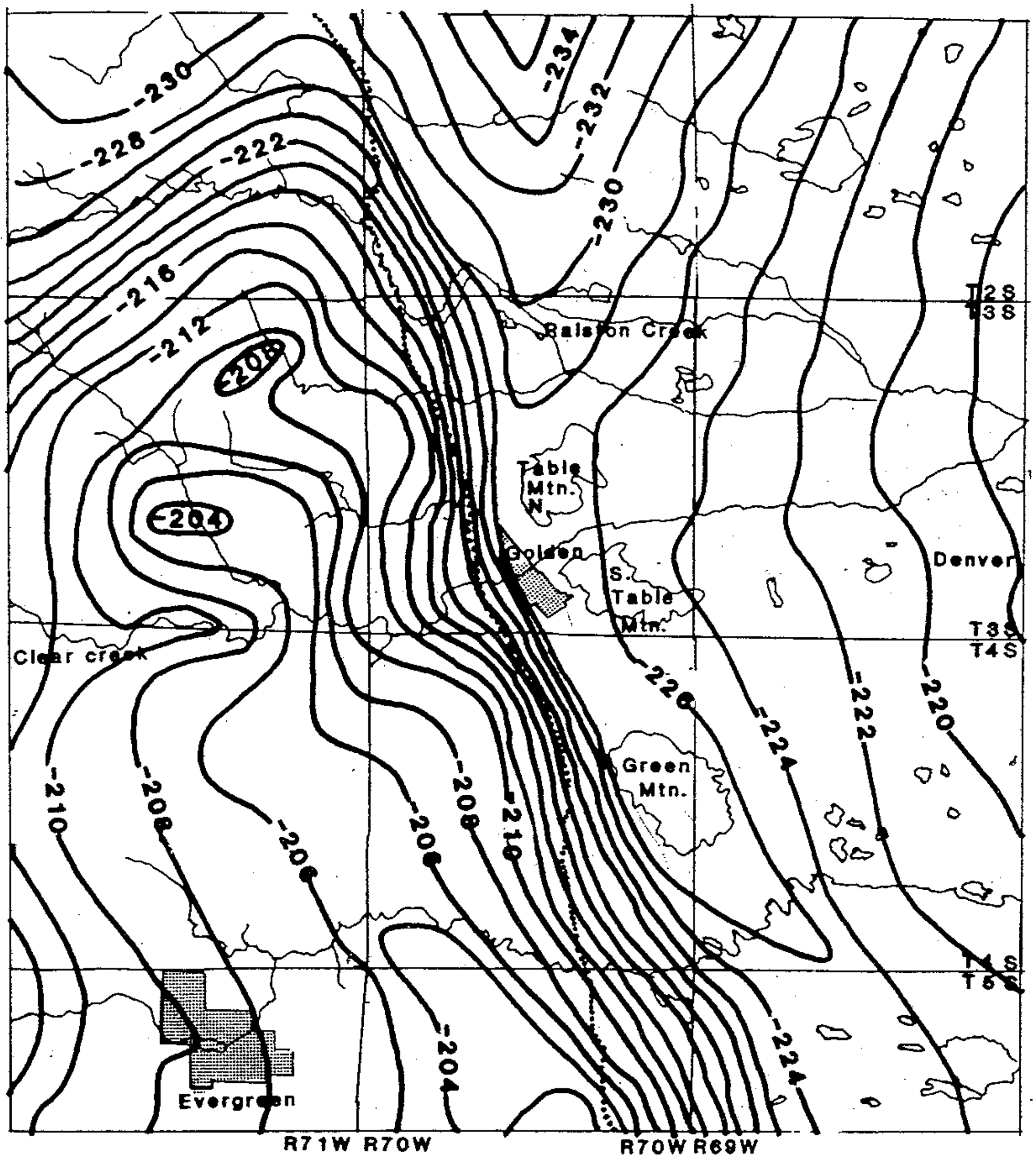


Fig. 8: *REGIONAL GRAVITY MAP (AFTER HAMZAWI, 1966)*

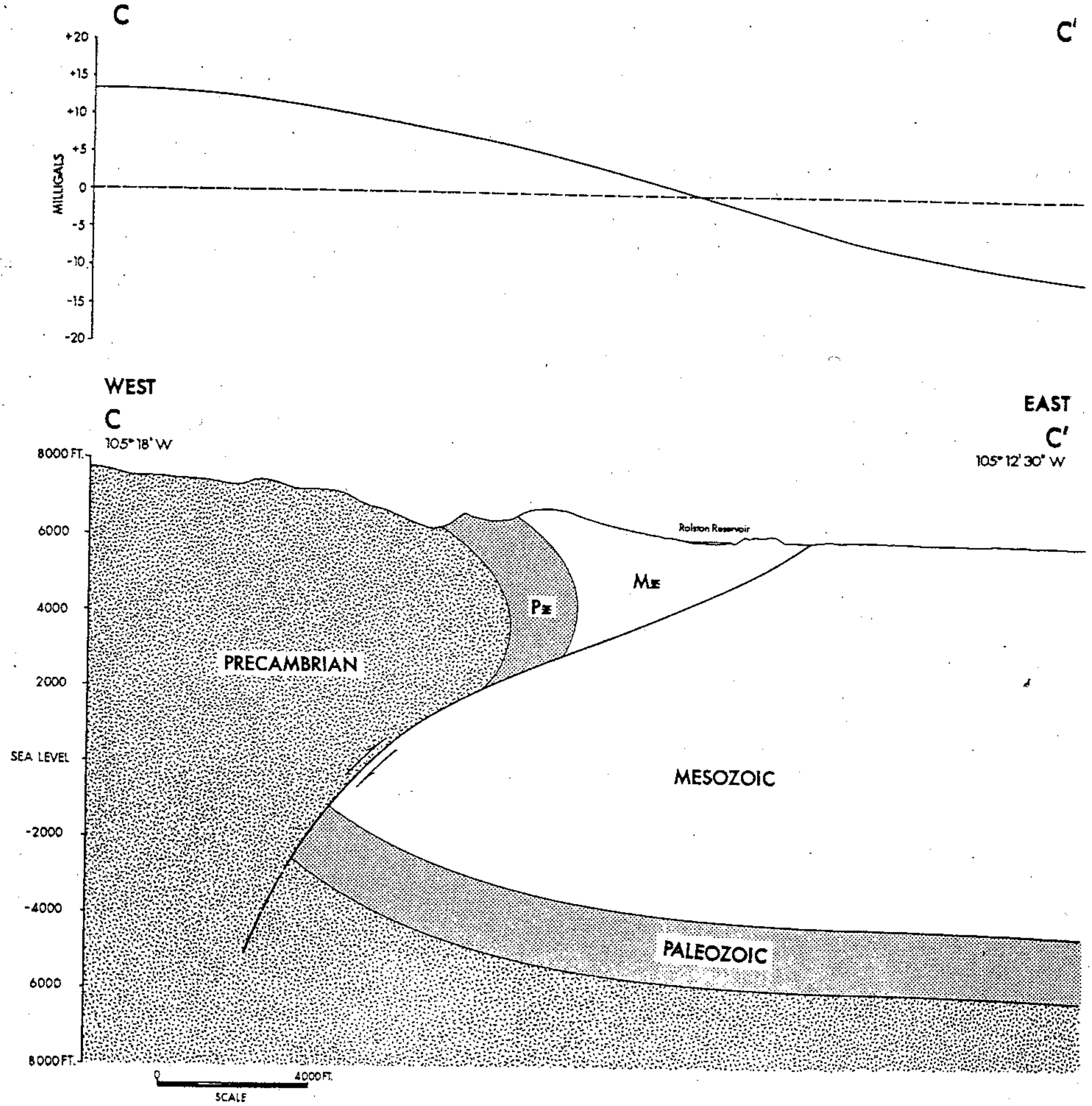


Fig. 9: ***BOUGUER GRAVITY PROFILE & CROSS SECTION***

***(after BIEBER, 1983)***

# Proterozoic of the Central Front Range –
# Central Colorado's Beginnings as an Island Arc Sequence

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*The Precambrian schists and gneisses of the Colorado Front Range have often been called the* ***"Idaho Springs Formation"****. This is not a valid formation name, but it remains in popular use as a way to refer to this sequence of lithological units.*

## Tectonics and Geology

Proterozoic rocks of Colorado represent addition of the Colorado Province to the Wyoming craton in a 1.8-1.7 Ga accretionary event (Condie, 1986). Current studies (e.g., CD-ROM Project) are endeavoring to determine details concerning how and when the individual components of the terrane were formed, location of boundaries of accreted arc sequences, and thus gain a better understanding of the tectonic processes involved. The metamorphosed volcanic and sedimentary arc sequence of the central Front Range is one component of the accreted terrane in the Colorado Province.

The boundaries of the central Front Range arc sequence are currently undefined. The eastern and western extents are terminated by Laramide-age faulting. To the south, a boundary separating the sequence from that of the Wet Mountains must exist, but has yet to be established. This boundary may be obscured by the Pikes Peak Batholith. The northern boundary is also difficult to determine as we have not yet recognized any clear lithological, geochemical, or structural breaks.

The arc sequence of the central Front Range has characteristics in common with others of the Colorado Province, but still differs in some respects. Metamorphic grade of the central Front Range is upper amphibolite. This is higher than many other Colorado sequences, such as the Gunnison Greenstone Belt at greenschist grade. The protolith of metasedimentary rocks in the central Front Range was pelitic shale, and quartzitic sandstones and conglomerates. Elsewhere in Colorado these may be greywackes, the more common sediment type found in similar sequences in the Gunnison area.

## Central Front Range Arc Sequence

The main units present in the central Front Range arc sequence are metamorphosed volcanic and sedimentary units, consisting of mica schists and gneisses, iron formations, calc-silicate gneisses, hornblende gneisses, amphibolite gneisses, felsic gneisses and quartzites (all part of a package unofficially called the "Idaho Springs Formation"), with plutons of Boulder Creek (~1700 Ma),

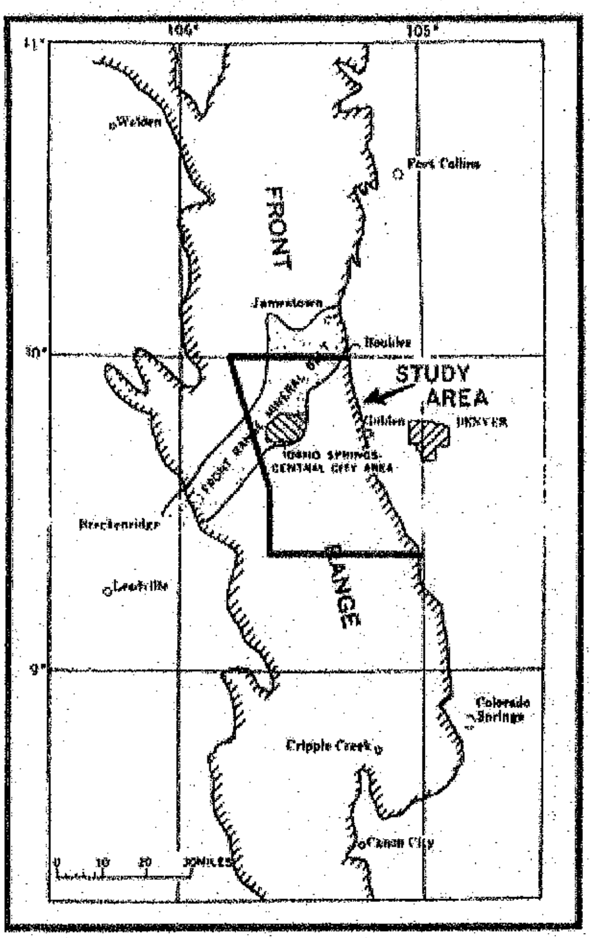

**Figure 1.** Location of study area.

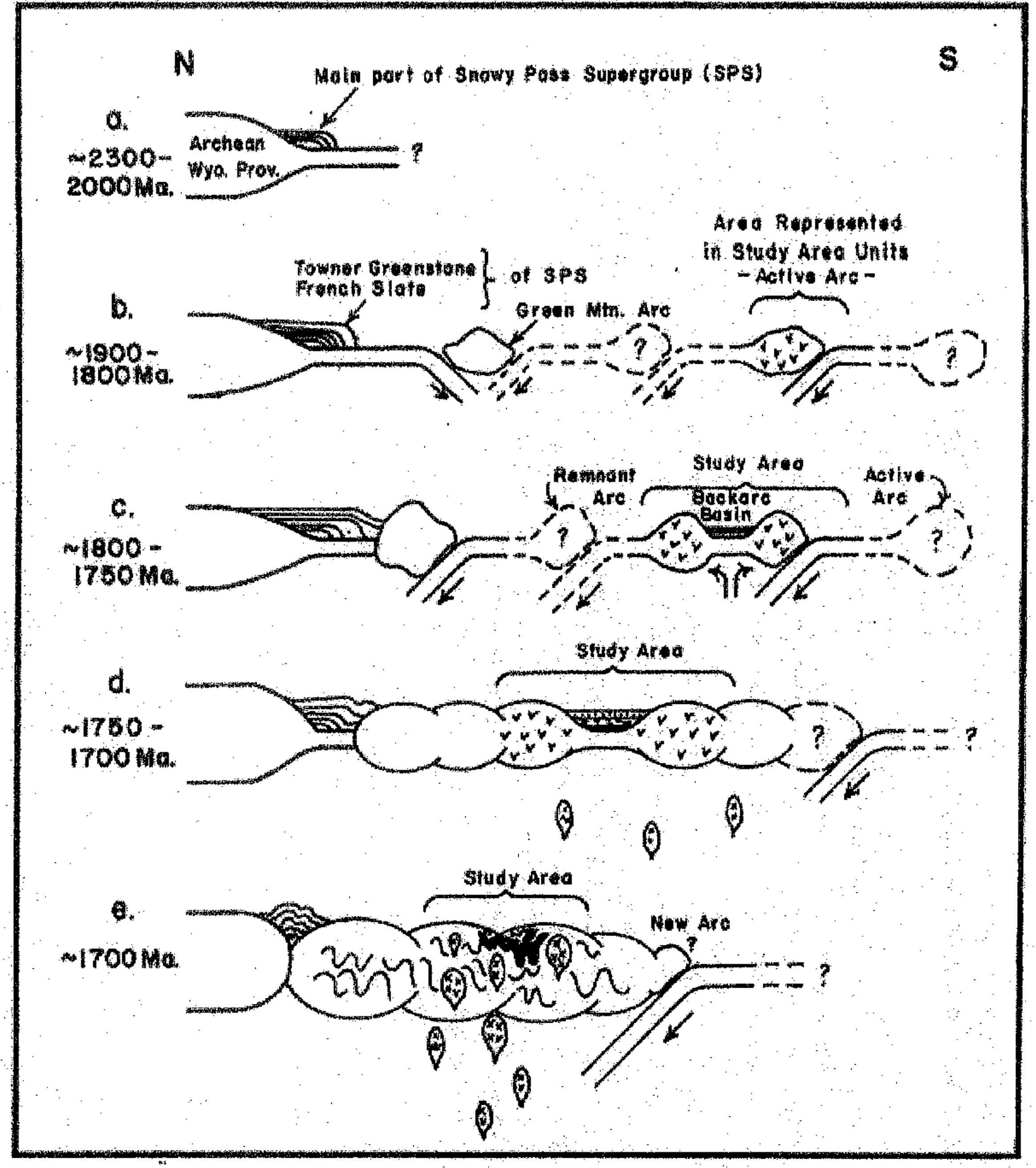

**Figure 2.** Generalized tectonic model for Front Range Proterozoic units.

Silver Plume (~1400 Ma), and Pikes Peak (~1000 Ma) ages. Isotopic data restrict the age of the gneisses to between 1700-1900 Ma. The units are interpreted as follows (Finiol, 1992):

> **Interlayered Gneiss**: Interlayered metamorphosed intermediate felsic and mafic volcanics, volcaniclastics, and related intrusives, representing a low-K tholeiitic immature bimodal volcanic arc assemblage related to subduction occurring south of the Wyoming craton.
>
> **Hornblende Gneiss**: Metamorphosed submarine volcanic sequence with related carbonates and cherts, representing backarc generation of submarine tholeiitic basalt flows, with interlayered carbonates, cherts, greywackes, and other minor sediments which accumulated during periods of volcanic quiescence.
>
> **Transition Zone**: Metamorphosed laterally variable package of chert, sediment, stratabound sulfides, and iron formations, representing exhalative-related deposits related to declining volcanic activity. The cherts and iron formations represent the more distal or lower temperature portions of hydrothermal vent deposits, and the sulfides nearer to the higher temperature vents.
>
> **Mica Schist**: Metamorphosed pelitic shales containing sandy channels and cherty carbonate pods, representing basin sedimentation in a continental margin arc.
>
> **Coal Creek Quartzite**: Metamorphosed sandstone with intercalated conglomerate and shale layers.

This arc sequence then collided with the growing Wyoming craton to the north, resulting in the deformation and metamorphism of the package. Syntectonic emplacement of the Boulder Creek plutons occurred as the area became part of the magmatic arc.

## Metamorphism

The metamorphic rocks of the central Front Range are of upper amphibolite grade: a high T – low P metamorphism, where anatectic melting reactions were reached. This indicates that heat added to the crust from intrusive bodies, rather than deep burial, was more important to the regional metamorphism.

One small area in the vicinity of White Ranch Park, Jefferson County, is of slightly lower metamorphic grade. P-T conditions for anatectic melting were not reached, and sillimanite-muscovite and/or andalusite-muscovite was stable. Indicated pressures and temperatures of metamorphism are 525° - 625° C at 3 - 3.75 kb (approximately 10-12 km depth). (Finiol, 1992)

Outside of the White Ranch Park area, anatectic migmatites are commonly developed and appear to be compositionally controlled. In the mafic and calc-silicate units, P-T conditions for anatectic melting were not reached, and the migmatites present are produced by injection, metasomatism, or subsolidus processes, not of anatectic origin. However, P-T conditions for anatectic melting are lower for rocks of pelitic and felsic compositions, and anatectic migmatites are common in the pelitic and felsic volcanic units. Degree of migmatization changes across the area. Though not a simple relationship, there is a general increase of metamorphic grade towards the Mt. Evans pluton.

## Future Work

We have learned much over the last 20 years about the how the Colorado Province was formed, but we still have much to discover. There is a need to define strategies for determination of arc

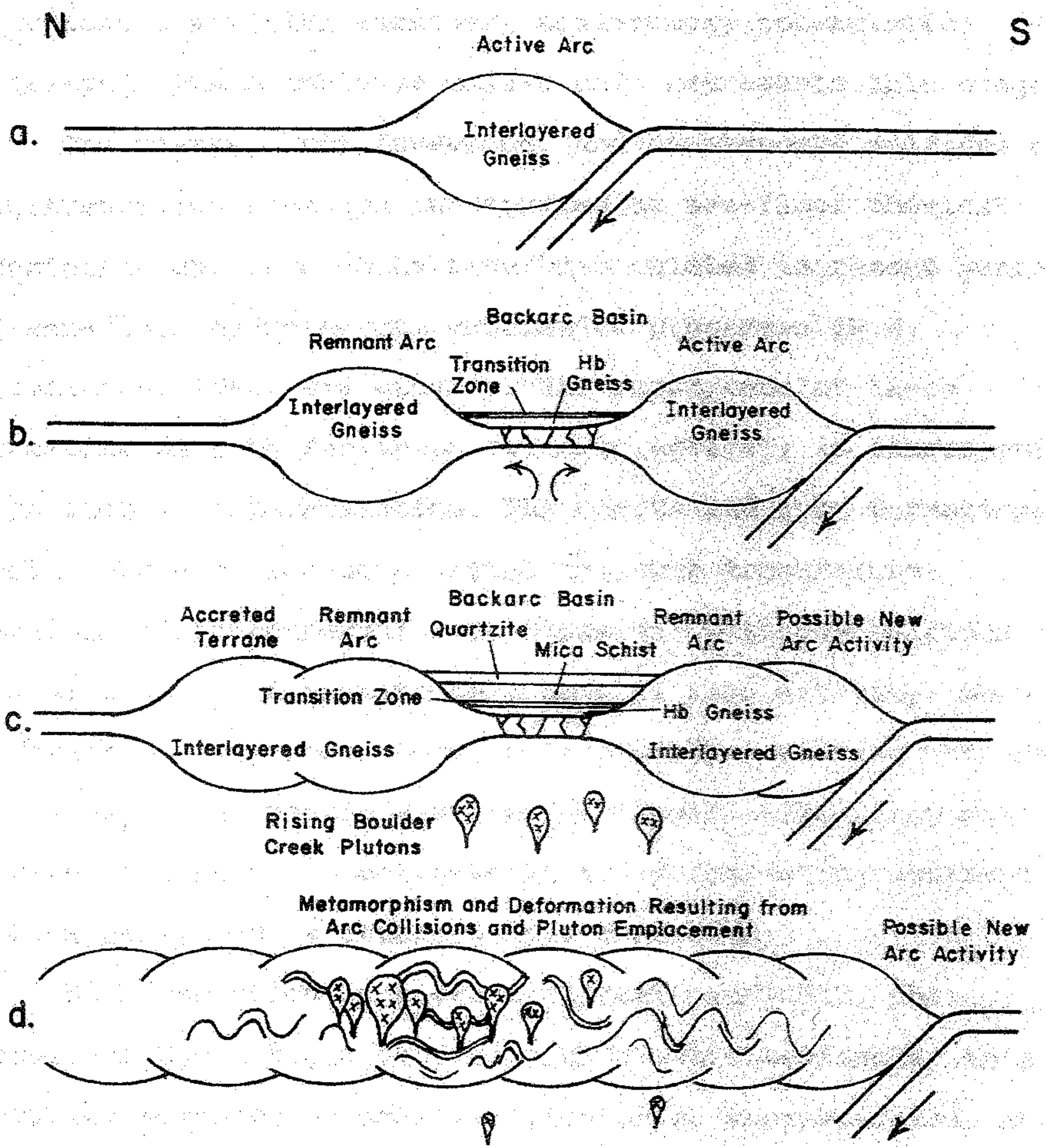

Figure 74. Tectonic model proposed for study area.
- a.) Interlayered gneiss unit produced as volcanic arc,
- b.) hornblene gneiss unit and transition zone deposited as volcanics, sediments, and exhalatives in BAB,
- c.) mica schist unit and quartzite of Coal Creek deposited as maturing sedimentary package in basin,
- d.) arc collisions produce metamorphism and deformation in the package and introduce plutons.

sequence boundaries, more accurately date the sequences, and determine more about the tectonic processes that formed the Colorado Province.

Through continued study of the central Front Range, we can work to define and understand the role this sequence plays in the larger picture. New work is underway to re-examine the Coal Creek Quartzite (Fisher & Lytle, 2004), looking past the metamorphic overprint with attention to sedimentalogic and stratigraphic detail. This may help to characterize basin extent, depositional environment, tectonic environment, etc., and may aid in defining arc sequence boundaries.

## Proterozoic Ore Deposits of the Central Front Range

Stratabound deposits of Pb, Zn, Cu, and W are found in the metamorphosed volcanic rocks and their interlayered sediments. Ores are synsedimentary and stratabound. Base metal sulfides of Pb and Zn range from disseminated to localized to true massive sulfide (>50% sulfide) in small pods to large bodies which were originally tabular or lenticular. Deposits contain up to $10^6$ tons of ore minerals. In places the sulfides occur with silicates. Common minerals include: sphalerite, chalcopyrite, galena, gahnite, pyrite, pyrrhotite, tetrahedrite, molybdenite, and other secondary and retrograde minerals. Average metal contents from 55 localities in this and similar Colorado Proterozoic terranes are: 5% Zn, 2.5% Cu, 0.5% Pb, 1-1.6 ounces Ag/ton, and 0.02-0.1 ounce Au/ton (Raymond et al, 1987). Minor amounts of Mo, W, Ni, Co, Cd, Ti, and Bi occur in some of the deposits (Sheridan and Raymond, 1982) along with occasional graphitic zones (Wallace, pers. comm., 1987). W - Cu deposits tend to be peripheral and spatially related to the Pb-Zn sulfides (Sheridan and Raymond, 1982). Scheelite and malachite are the predominant minerals. Average Cu content from nine samples is 1.8% (Sheridan and Raymond, 1984). Deposition of the metals in these sulfide deposits probably resulted from exhalation of hydrothermal fluids from sea-floor vents (Raymond et al, 1987). These deposits are most often hosted by more Mg-rich layers (indicating sea-floor metasomatic alteration) of calc-silicates, marbles, or anthophyllite-garnet-cordierite schists and gneisses that occur interlayered with submarine volcanics in the hornblende gneiss unit or transition zone.

Iron-rich metacherts and schists or small Algoman type iron formations occur scattered through the transition zone and occasionally within the hornblende gneiss near its contact with the transition zone. All of the iron-formation facies types can be found here: oxide facies, carbonate facies, sulfide facies, and silicate facies. The main iron bearing minerals present are magnetite, ilmenite, and hematite (secondary), which occur with various other phases (garnet, grunerite, biotite, muscovite, quartz). The iron is syngenetic and disseminated to massive (~65% FeO + $Fe_2O_3$) in the metasediments. These are also probable sea-floor exhalites related to backarc submarine volcanism, with differences from the base-metal sulfides due to such factors as fluid temperatures, duration and volume of fluid flow, and/or distance from vents.

Thin continuous stratiform layers rich in rutile ± corundum ± topaz (locally to 80% topaz) ± gahnite occur in the upper portion of the interlayered amphibolitic and felsic gneisses (originally bimodal arc volcanics). Their origin is problematic, but exhalative, weathering, and placer processes have been suggested. The weathering horizon origin is favored due to suggestions of a related minor unconformity (Sheridan, pers. comm., 1987; Marsh and Sheridan, 1976; and Sheridan and Marsh, 1976).

Laramide age U deposits occur in the transition zone associated with faults that cut the hornblende gneiss. U-Pb isotopic studies indicate that U was remobilized from the metavolcanics of the hornblende gneiss (disseminated in it, not originally U ore deposits) with an original age of 1730 ± 130 Ma. (Ludwig et al, 1985). The Schwartzwalder uranium mine has produced 17 million pounds of $U_3O_8$, with estimated reserves of at least 16 million pounds.

## Unit Descriptions (Brief)

from Finiol, 1992

### Interlayered Mafic and Felsic Gneiss Unit

The mafic gneiss and felsic gneisses are interlayered, with the mafic gneiss more prevalent in the lower layers and to the north, and the felsic gneiss more prevalent in the upper layers and to the south.

The mafic gneiss is a fine to medium grained, foliated amphibolite, composed of plagioclase and hornblende with possible minor biotite, sphene, clinopyroxene, and microcline.

The felsic gneiss is a very fine to fine grained, foliated metamorphosed quartz latite to dacite, composed of plagioclase, quartz, and microcline with possible minor biotite, hornblende, or muscovite. Some layers contain relict phenocrysts of microcline.

Both mafic and felsic gneisses contain thin layers of calc-silicates, which are composed of plagioclase, quartz, and epidote with possible calcite, hornblende, and other accessory minerals and indicate submarine deposition as impure carbonates.

Hornblendites are intrusive mafic to ultramafic bodies in the interlayered gneiss. They are medium grained, foliated amphibolites, composed of hornblende, some with relict phenocrysts which are now tremolite.

The transition to the next unit is a zone ~1-15 m thick of variable composition, gradational, often containing garnet and sillimanite. In places, this is represented by quartzites, marbles, metaconglomerates, or schists.

***On the field trip***, we will see this unit on the southern end of the area, near the mouth of Golden Gate Canyon. Here it is represented by predominantly felsic gneiss. It is a little coarser here than on the north. There are several calc-silicate layers (showing some boudinage), indicating that the felsic volcanics were submarine. There are some layers of garnet- and sillimanite- rich gneiss marking the gradational transition between the felsic gneiss and the overlying hornblende gneiss. The road up the canyon almost follows the contact between the felsic gneiss and the hornblende gneiss, and crosses the contact several times. Along the road, the generally pink outcrops are the felsic gneiss, and the dark grey-black outcrops are the hornblende gneiss. As we drive up

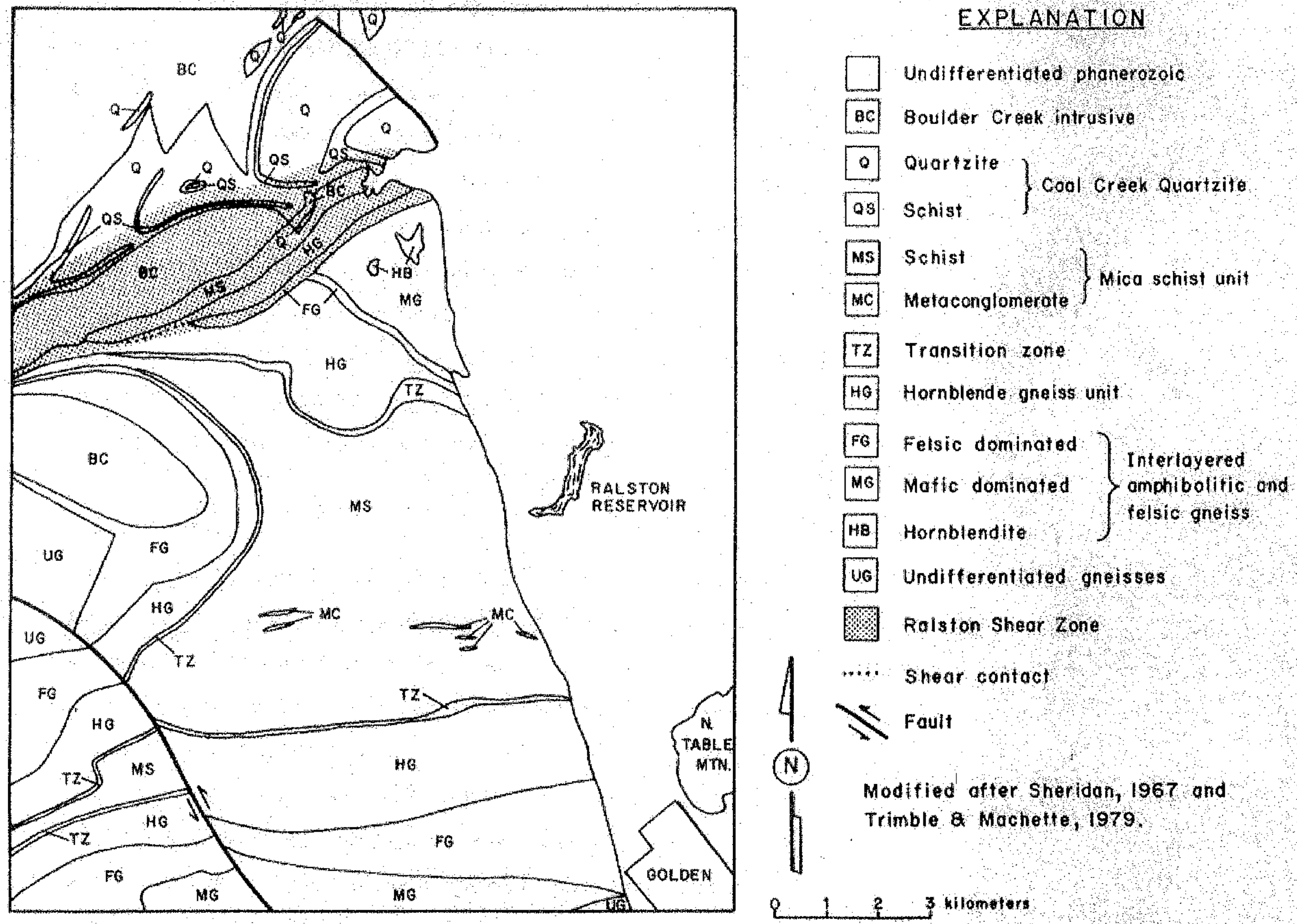

Figure 7. Major units of study area, modified after Sheridan et al (1967) and Trimble and Machette (1979).

Golden Gate Canyon, there are several outcrops of the felsic gneiss, showing a color variation in compositional layering. The pinker layers contain more microcline, the grayer layers more plagioclase. Most layers are .5 – 10 m thick.

## Hornblende Gneiss Unit

The hornblende gneiss unit is complexly interlayered amphibolite, calc-silicate, and schist. Amphibolite predominates in the lower part of the unit, and grades upwards into calc-silicates plus or minus schists. The calc-silicates are more prevalent to the north, and the more clastic schist layers to the south.

The hornblende gneiss is a moderate to strongly foliated, fine grained amphibolite, composed of hornblende and plagioclase with possible minor clinopyroxene. Layers can be massive or finely interlayered with calc-silicate. Some pillow and other volcanic textures are preserved.

Calc-silicate layers contain calcite, plagioclase, hornblende, clinopyroxene, quartz, and epidote, plus accessory minerals. They range from impure marbles to metacherts to true calc-silicate compositions. In some places and to the south, there is a more clastic contribution to the layer, which produces schists of variable compositions.

The transition to the next unit is gradational.

***On the field trip*** we will see this unit at the mouth of Golden Gate Canyon, at the contact with the felsic gneiss. There are several thick layers of amphibolite, with a large almost Y-shaped pegmatite just around the corner. As we drive up the canyon, the dark outcrops are the hornblende gneiss. We will pass an old, small log cabin next to an old Uranium prospect on the north side of the road. At this point, there is a thick, black, massive amphibolite layer next to a lighter grey unit of quartz-rich metasediment. We will also stop at the parking lot of the Golden Gate Grange, where we will see thick, dark layers of amphibolite, thin layers, and grey layers of quartz-rich metasediment. Also at this stop is a large Silver Plume pegmatite, with quartz, microcline, plagioclase, and muscovite. In several places in the area, the Silver Plume pegmatites also contain tourmaline. We will also be able to see an outcrop of the northern part of the hornblende gneiss near the gate of the Schwartzwalder Mine, where we will look at the iron formation. Here it is a thick amphibolite.

## Transition Zone

The transition zone is 3-100 m thick and is laterally variable composition. In most places, the unit is a thin, 3-20 m metachert. In other places, there is a clastic contribution to the unit, producing a quartz gneiss. In the area of the Schwartzwalder uranium mine, the unit thickens to 100 m and develops into an iron formation, with all 4 facies of iron formation present.

The oxide facies of the iron formation exhibits sedimentary structures, such as cross bedding and climbing ripples, etc. Garnet and magnetite grains define original bedding layers rich in iron.

The transition to the next unit is gradational.

***On the field trip***, we will see part of the iron formation portion of this unit in the canyon of Ralston Creek. At this point we are just outside the Schwartzwalder Uranium Mine property (Cotter Corp.), and are on the new addition to White Ranch Park of Jefferson County Open Space protected area. There are golden eagles and other raptors nesting in the cliffs above us, and mountain lion and black bear abundant in the area. Please be respectful of their need for relative quiet and solitude.
The iron formation here is oxide facies. There are magnetite-rich schists, iron-rich metacherts, and magnetite-quartz-garnet schists. There are a few thin calc-silicate layers within the iron formation layers, indicating submarine deposition.

### Mica Schist Unit

The mica schist is a highly pelitic schist, composed of quartz, muscovite, biotite, and sillimanite or andalusite, plus or minus garnet or cordierite. The schist varies from very quartz-rich to very andalusite-rich, with porphyroblasts of andalusite in White Ranch Park reaching 30+ cm. The schist exhibits sedimentary features such as cross bedding, and contains lenses and channels of coarser material, meta-conglomerate, or calc-silicate.

***On the field trip***, we will not see this unit. (There will be an opportunity to see it on later field trips.) We will be able to see some boulders of the schist at our lunch stop in the parking lot of the east entrance to White Ranch Park. These boulders are not quite representative of the schist in general, in that they exhibit more deformation than seen in most of the unit, and do not have the large andalusite porphyroblasts that can be seen elsewhere.

The transition to the Coal Creek Quartzite is obscured within the Idaho Springs – Ralston Shear Zone. The deformation within the shear zone is inconsistent, with areas that are relatively undeformed. Within these areas, the transition between the schist and the quartzite is gradational. The shear zone is interpreted as a sheared anticline.

### Coal Creek Quartzite – Thomas R. Fisher

The Coal Creek Quartzite is one of several clastic belts of similar age deposited in syntectonic basins during the accretion of Colorado onto the Wyoming Craton. At its type locality in Coal Creek Canyon, the Coal Creek Quartzite consists of at least four quartzite units (A, B, C, and D in ascending order) separated by three major schist units (Wells, 1967). The Units A and B are generally white to light gray and pink, fine-grained to conglomeratic, with layered hematite. Relict sedimentary structures are readily apparent in these units. Unit C is gray with only occasional pink and white layers. It is generally much more fine-grained and massive in appearance than Units A and B, and bedding is often inconspicous. Unit D, the upper most unit, is white to pink, generally fine-grained, with abundant lenses of conglomerate, some of which are very arkosic. The separating schist units are in gradational contact with the quartzites. Thickness of the Quartzite varies over the main exposure in the Coal Creek Syncline, however Wells (1967) suggests a total thickness upwards of 10000 feet (~3000 meters). The units thin both southward and northward from the axis of the syncline. The total extent of the Coal Creek is not clear. George and Crawford (1909) reported a Coal Creek-like quartzite present in the Araphoe Peaks area (Indian Peaks Wilderness) west of Boulder, that may be a time-equivalent unit.

The Coal Creek Quartzite occurs mainly within the Coal Creek Syncline, a northeast trending and plunging structure that extends into Eldorado Canyon to the north-northeast. This structure was interpreted by Wells (1967) and Wells, et al (1964) as being Precambrian in age and to be associated with implacement of the Boulder Creek quartz monzanites and granodiorites. The structure probably does not reflect the configuration of the original depositional basin, but may somewhat mark the original depo-center. Williams, et al, (2003) suggest that the Coal Creek and similar quartzites of Colorado and New Mexico were deposited in syntectonic basins developed on a stabilizing crust. They further suggest that the quartzites were deposited during continued thrust convergence in the late stages of the Yavapai orogeny. This interpretation remains somewhat problematic, and it is suggested here that the Coal Creek Quartzite may have been deposited in conditions more similar to those found during the accretion of the Mann (Leo) Shield onto the West African Craton. There, similar "bands" of (mineral bearing) quartzites and quartz-pebble conglomerates accumulated in a series of extensional half-grabbens associated with back-arc basins. Only further detailed structural, stratigraphic, and sedimentological field work will tell the whole story. It is hoped that this further field work will help reveal the true importance of the Coal Creek and similar units in understanding the crustal evolution of Colorado.

Recent investigations (Fisher and Fisher, 2004) of the Coal Creek suggest that the quartzites are fluvial in origin; most likely braided-stream deposits. Only the lowermost "A" unit has been studied to this point, however relict sedimentary structures preserved tell a story of the protolith. Generally, the lower unit consists of several stacked, fining-upward sequences of a few meters thickness each. Most of these units consist of a conglomeratic unit at the base, that transitions upward into small-scale trough cross bedding, then to more planar-laminar structures with accompanying decrease of grain-size. Some imbrication is apparent in the pebble conglomerates. Pebbles are generally equidimensional to ovoid to flat. Tectonic stretching of the pebbles is not apparent in this lower unit and individual grains are virtually undeformed (Wells, 1967). Little information has yet been gathered on paleocurrent directions. The intervening schist units are probably derived from pelitic shales. Thin partings of schist within the individual stacking units may suggest clay partings within the units. Well marked layers with hematite alteration may suggest subareal exposure during deposition, although it is apparent that some remobilization of hematite has occurred. The quartzite units exhibit generally blocky fracturing. Fracture planes tend to exploit depostional bedding planes.

The Coal Creek is in contact with the apparently younger Boulder Creek Granodiorite and quartz monzanites (Twin Spruce). These igneous units surround and broadly outline the Coal Creek Syncline, but the contacts are discordant in detail. Where the contact between the Quartzite and the igneous units can be observed, a micaceous selvage exists. This zone may range from absent to a few inches to a few tens of feet thick (Wells, 1967). Wells (1967) reported that where the selvage is well formed, the Quartzite typically grades into a muscovite-rich schistose quartzite nearest the contact.

***On the field trip,*** we will visit an outcrop of what is believed to be part of the basal most unit (Unit A of Wells, 1967, and Wells, et al, 1964) of the Coal Creek Quartzite, exposed in road cuts along the north side of Coal Creek. At this stop we will be able to observe relict sedimentary structures and a sequence of stacked, fining-upward units of a few meters thickness each. These units have been recently been interpreted as fluvial in origin; most likely braided-stream type deposits (Fisher and Fisher, 2004, in preparation). Most of the units are marked by a basal conglomeratic unit with possible scoured base. The conglomeratic units transition upward to small-scale trough-type cross bedding then to more planar-laminar like structures. Grain-size appears to decrease upward in relation to the change of sedimentary structures. Quartz pebbles are generally rounded and equidimensional to oval, although some are flat (Wells, 1967). Some indication of imbricate structures is present within the conglomerate beds. More distinct and well developed channels, up to several 10's of meters across and with deep scouring at their base occur in equivalent units further to the northeast at Eldorado Canyon. Large-scale trough-type cross beds also occur at the Eldorado locale.

Thin-section examinations by Wells (1967) show the grains are virtually undeformed at this outcrop. However, stretched-pebble conglomerates have been observed in equivalent units in the Golden Gate Canyon-White Ranch area and higher stratigraphically units near the mouth of Coal Creek Canyon. The exposures in Coal Creek Canyon lie in a northeast trending synclinal structure interpreted by Wells (1967) as Precambrian in age. We will also be able to observe the Boulder Creek quartz monzanite which apparently intrudes the Coal Creek Quartzite at this locale. Unfortunately, at the level of the road cut the contact between the two units is not exposed.

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***The Beartooth Ranch Homeowners Association** for their courtesy and permission to cross their properties.*

***"Take Only Photos, Leave Only Footprints!"***