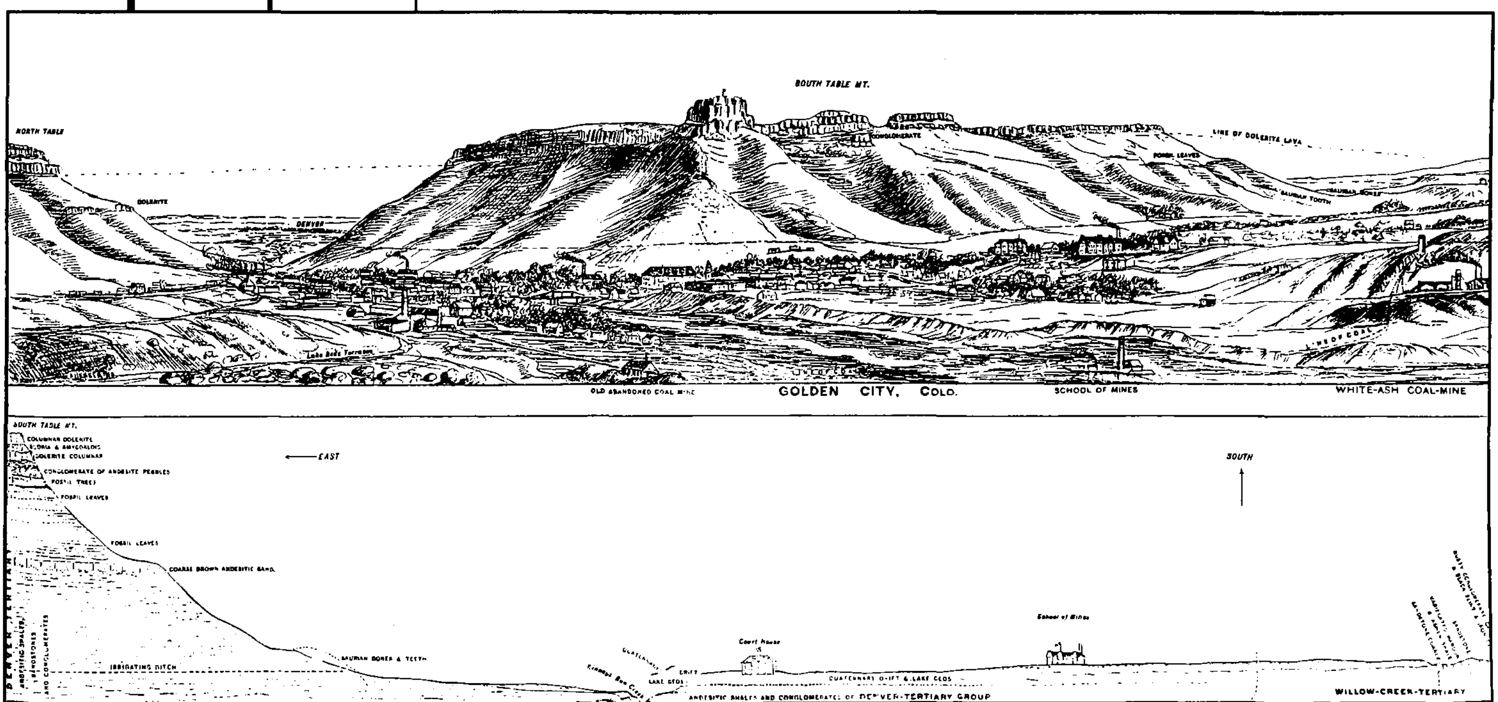
Bulletin 51

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

By Robert J. Weimer



Lakes, 1889

Colorado Geological Survey
Department of Natural Resources
Denver, Colorado
1996

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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
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ISBN-13: 9781884216565
DOI: https://doi.org/10.58783/cgs.b51.bsvl1261
Colorado Geological Survey
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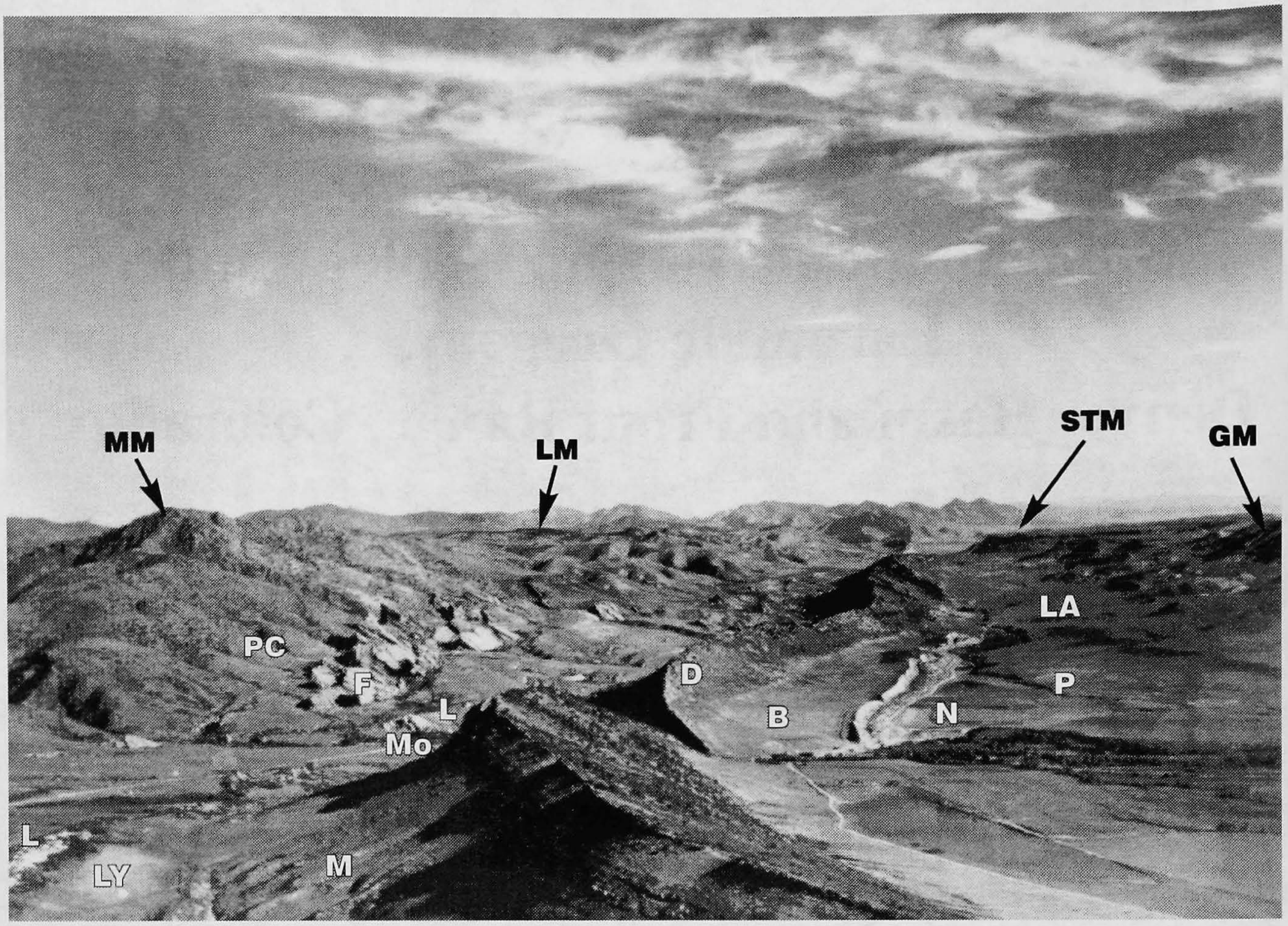

View of the eastern edge of the Front Range looking north-northwest from south of Morrison, Colorado. Town of Morrison (Mo) is west of prominent water gap in Dakota Group Sandstones in foreground: Photo by T.S. Lovering, U.S. Geological Survey.

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

Preface

The classic outcrops in the foothills of the Front Range have been the site of geology field trips for more than a century. In this volume two field guides and a number of essays contain new and revised observations and interpretations about these outcrops and related subsurface. The guides are a compilation and integration of work by many authors. The popularity of this part of Colorado for geoscience research to interpret past history is reflected by the voluminous included reference lists.

The field guides are topical in nature and have been prepared for trips sponsored by three international geoscience meetings held in Denver in the fall of 1996; Geological Society of America; Society of Exploration Geophysicists; and, Society of Petroleum Engineers. Regional scientific and professional societies have also scheduled field trips, and portions of the guides will be of interest to residents of the Denver Metropolitan Area. The major themes are structure (with new emphasis on the role of wrench faulting), stratigraphy, petroleum system and geologic history of the eastern Front Range and western Denver Basin.

The two guides are published in one volume because a person using one guide for trip stops will find useful reference material in nearby stops described in the second guide. Inasmuch as the geologic description at each stop stands by itself and the trips are planned as one-day excursions, longer or shorter trips can be organized with a different ordering or combination of stops.

The geologic concepts describing the origin of the mountains and the larger petroleum fields in the Denver Basin have a wide application. Therefore, this volume should be of special interest to people conducting petroleum exploration and production programs in all of the Rocky Mountain intermountane basins, and similar foreland basin settings in the world.

Gratitude is expressed to the Colorado Geological Survey and the Geological Society of America for planning, editing, and publishing these guides.

Bob Weimer

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Part 1

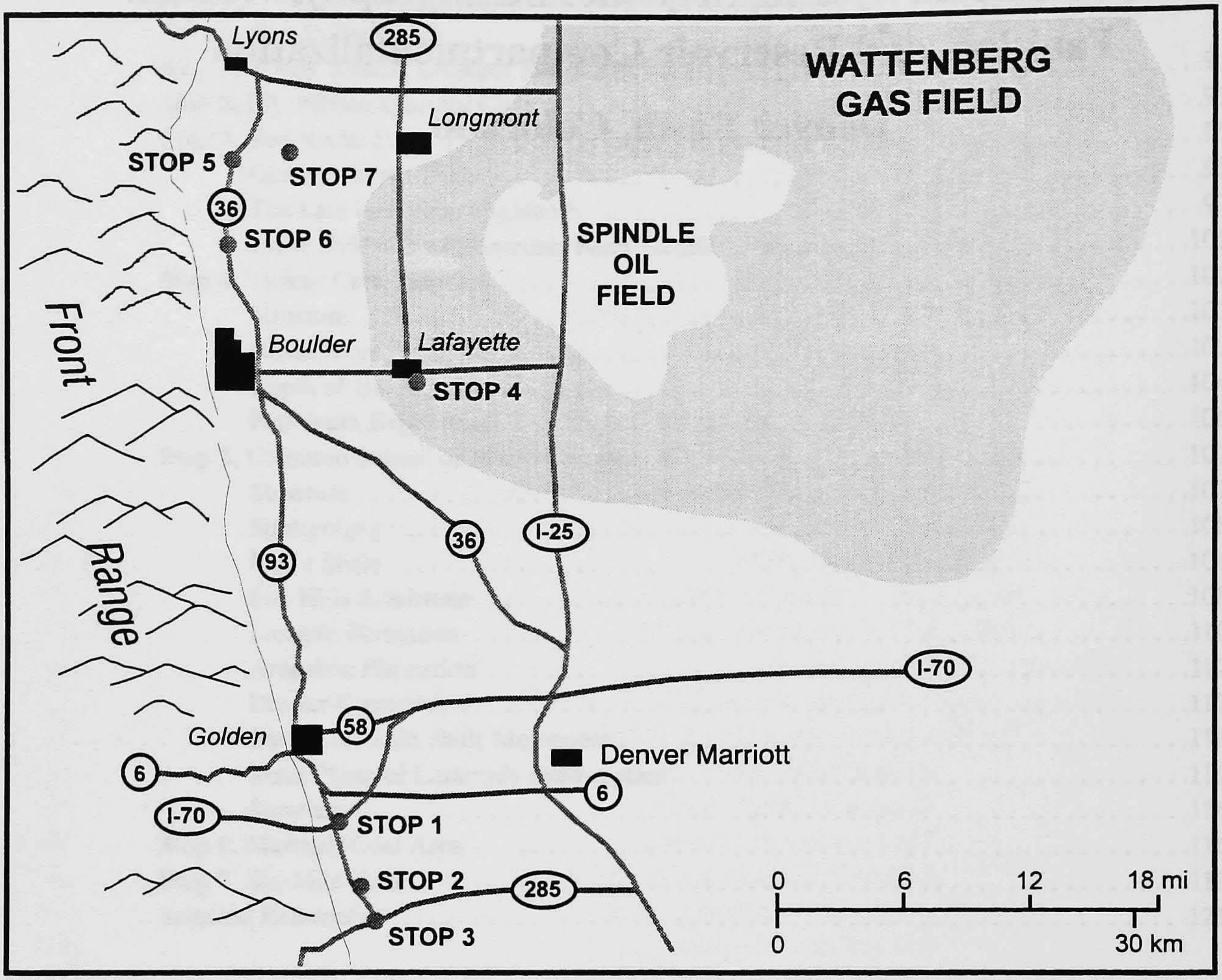
The Petroleum System, Sequence Stratigraphy, Wrench Faulting, and Reservoir Compartmentalization

Denver Basin, Colorado

Acknowledgements

The following individuals and companies contributed well data and base maps to implement this project. Their assistance is gratefully acknowledged: Michael Decker, Prima Energy Corp.; John Cantwell, NARCO; James Crafton, Snyder Oil and Gas; Gary Minke and Wayne Peterson, Amoco Production Co.; Union Pacific Resources; Fred Rothange, Quality Drilling Fluids; Peter Loeffler, Durango Petroleum; R. C. Surdam, IER, University of Wyoming; GRI Grant to IER #5089-260-1894; J. E. Warme and T. L. Davis, Constance Dodge, Colorado School of Mines; T. D. Sheldon, Consultant; S. A. Sonnenberg, Consultant. Barbara Brockman and Barry D. Perow assisted in manuscript preparation.

1. A Field Guide to the Central Denver Basin



Stop 1: I-70 Road Cut. Overview Denver Basin and Lower Cretaceous Stratigraphy.

Stop 2: Rooney Road - Graneros Source Rock.

Stop 3: Turkey Creek - Lower Cretaceous reservoirs, oil seeps, and Sequence Stratigraphy

Stop 4: Lafayette area: discussion of Basin Center fields and pools.

Stop 5: Muddy (J) Sandstone (Lower Cretaceous), (Fort Collins and Horsetooth members); fault zone.

Stop 6: Codell Sandstone Member of Carlile Shale and Fort Hays Member of Niobrara Formation (Upper Cretaceous); physical evidence for unconformity and fracturing.

Stop 7: Hygiene Sandstone Member of Pierre Shale (Upper Cretaceous-Campanian); cycle of shelf sedimentation.

Figure 1. Index map of field trip route with stops.

INTRODUCTION TO FIELD TRIP

This field trip relates the stratigraphy and structure, observed in the Cretaceous strata along the Front Range, to the petroleum fields of the central Denver Basin. Data are presented which describe the petroleum system, sequence stratigraphy of Lower Cretaceous reservoirs, and new data on the wrench faulting that extends across the basin.

Stops are scheduled to observe key outcrops along a 40-mile (64 km) stretch from Turkey Creek south of Morrison to north of Boulder (Figure 1). The field trip starts at the I-70 Road Cut where the geology is regarded as typical of the mountain flank area (Figures 2, 3).

The most spectacular geologic feature of the mountain foothills is the "Dakota Hogback" (locally known as Dinosaur Ridge) through which I-70 was cut. The layering in these rocks dips to the east toward and under Denver (Figures 4 and 5). These beds were originally flat-lying and once extended over the area of the mountains at the time they were deposited within and along an ancient seaway that covered the western interior of the United States. The Dakota Group and associated formations were inclined to their present position when the mountains were uplifted during the Laramide orogeny, (71-50 Ma). A block of the earth's crust pushed up to form the mountains and a second crustal block remained low, now forming the basin underlying Denver and the Great Plains. In the intervening zone between these major blocks, rocks were tilted at high angles and broken by the Golden and other fault zones. As a result of this crustal movement, Precambrian rocks similar to those that form the mountains to the west (elevation 7,200 ft, 2200 m) are overlain by more than 13,000 ft (4000 m) of stratigraphic section under Green Mountain. Of this stratigraphic section, approximately 8,000 ft (2450 m) is marine Cretaceous. Regressive shoreline deposits (Fox Hills) and coal-bearing strata (Laramie) crop out along Rooney Road at the base of Green Mountain, visible from the east end of I-70 (Figure 3). Most of the Benton, Niobrara and Pierre Shale is cut out by the Golden fault. The latest Cretaceous and Tertiary conglomerates and volcanic rocks (Arapahoe and Denver formations) record the early structural uplift of the Front Range prior to the main phase of Laramide deformation (Figure 5).

The Dakota Group sandstones, present in the eastern portion of the I-70 Road Cut, are highly productive of oil and gas in the Great Plains region of eastern Colorado, western Nebraska, and eastern Wyoming. The main reservoir is the Muddy (J) Sandstone. The Dakota serves also as an important source of artesian ground water at shallow depths under the eastern Great Plains. Several high quality shale layers (kaolinite) have been mined by surface and underground methods from the upper Dakota in the vicinity of the road cut, and mine portals are visible near the eastern base of the hogback.

The construction of I-70 has exposed the internal features of the hogback formations for travelers to view, study and enjoy, and provides a "Gateway to the Colorado Rockies," as well as a "gateway to the past".

STOP 1
I-70 ROAD CUT

Dakota Group sandstones (Lower Cretaceous) form a prominent ridge because of more rapid erosion of the non-resistant strata on each side: the Morrison, Ralston Creek, and upper Lykins formations to the west; and, the marine shales of the Benton, Niobrara, and Pierre formations to the east (Figures 4 and 5). Thicknesses and lithologies of these units are shown by the stratigraphic section (Figure 3). The I-70 Road Cut is designated as a Point of Geologic Interest along the U.S. Interstate Highway System. Parking areas and walkways have been provided for ease in viewing the stratigraphic sections on both the north and south sides of the cut. Signs with illustrations and descriptions have been placed along the exposures to guide visitors through 650 ft (200 m) of the exposed Jurassic and Lower Cretaceous section. Descriptions and interpretations of this classic section are provided by LeRoy and Weimer (1971) and Weimer and Land (1972). In addition, guides to the textures, structures and paleontology of the Dakota Group at the Alameda Parkway Road Cut (1 mi-1.6 km to the south) have been published by MacKenzie (1968) and Chamberlain (1976), and by more recent work by workers of Dinosaur Ridge park (e.g. Lockley, 1994).

Dips of strata are different on each side of the Road Cut. In the north side dip is 65°E. whereas in the south side the dip is 45°E. The change is because of differential movement on the northeast-trending Cherry Gulch fault zone during the deformation (Figure 5).

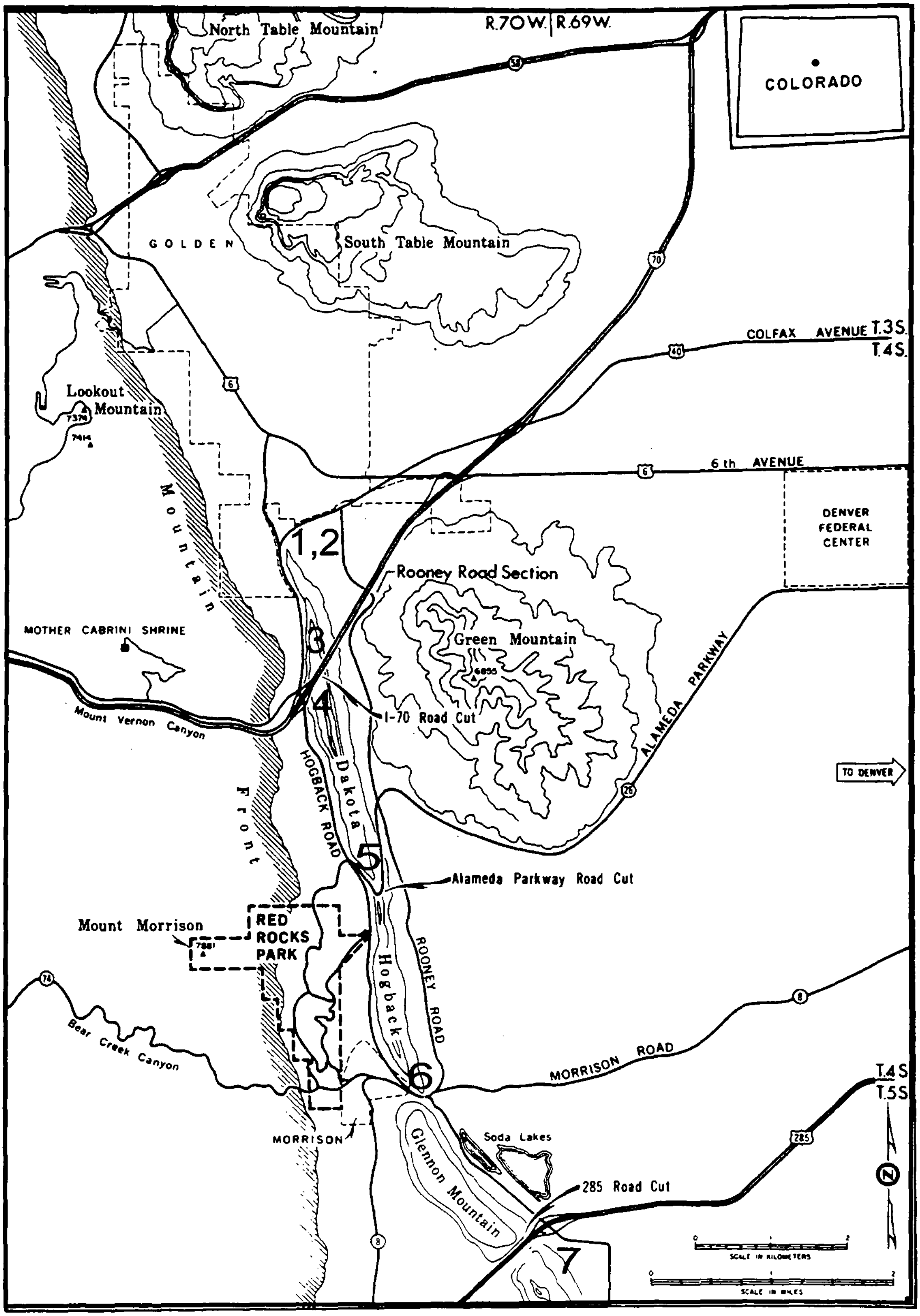


Figure 2. Location map of geographic features in the Golden-Morrison area with 7 measured sections. Stops are at 3, 4 and 7 (after LeRoy and LeRoy, 1978).

GENERALIZED STRATIGRAPHIC SECTION
Golden-Morrison Area
Jefferson County, Colorado

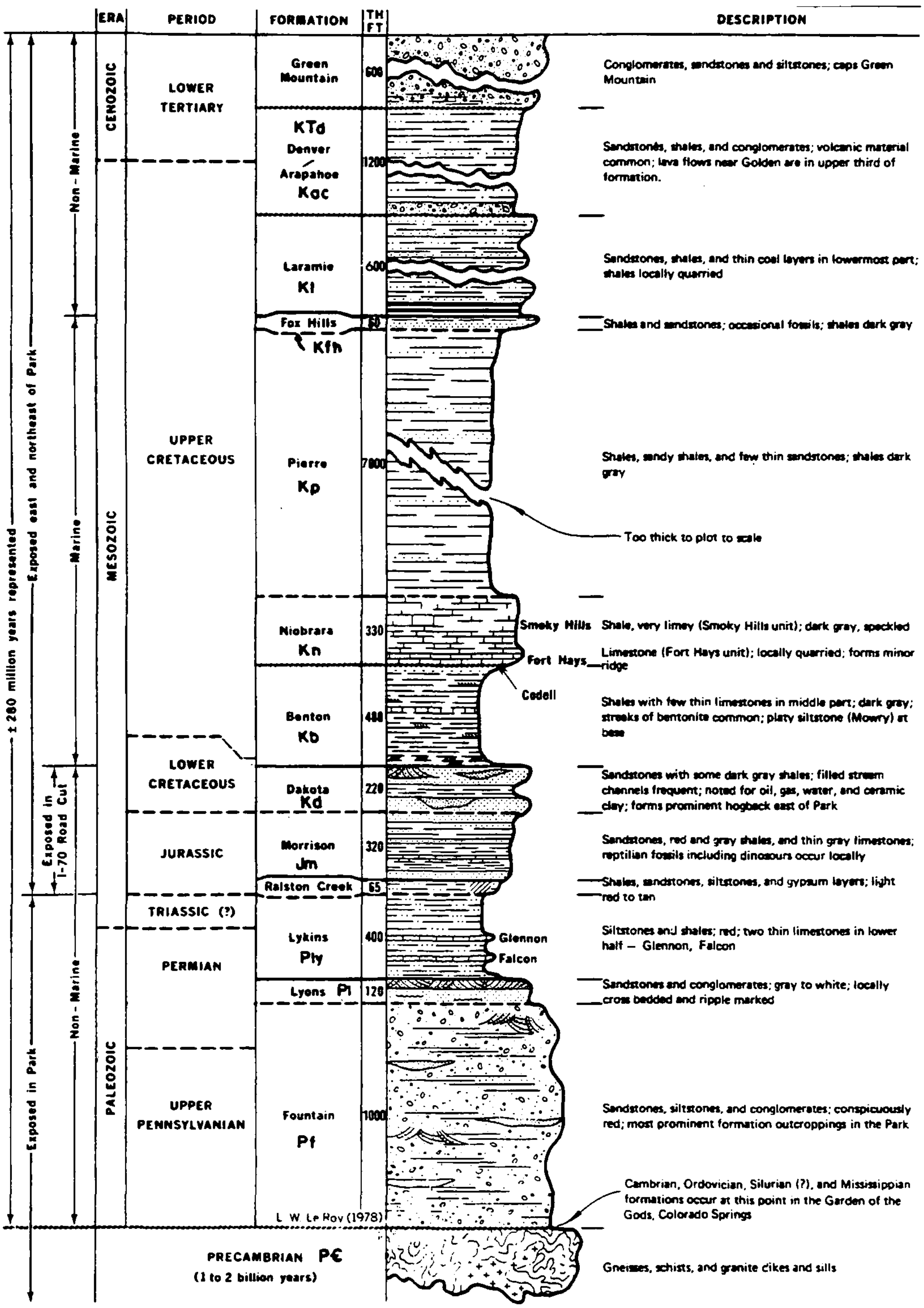


Figure 3. Stratigraphic section, Golden-Morrison area (from Weimer and LeRoy, 1987).

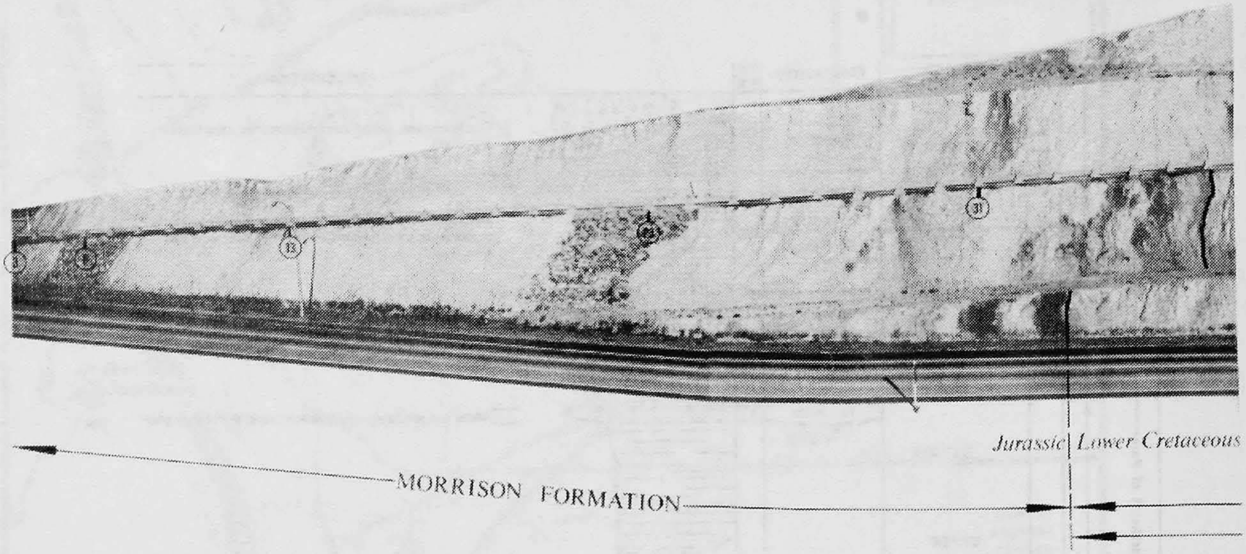


Figure 4A. North slope of I-70 Road Cut (LeRoy and Weimer, 1971).

For surface mapping purposes, the Dakota Group has been divided into 2 formations, the South Platte and Lytle (Figure 4). Regionally, the South Platte can be subdivided into 3 units, the Plainview Sandstone, Skull Creek Shale and Muddy (J) Sandstone, overlain by a thin distinctive gray shale and siltstone unit in the lower Benton called the Mowry (Figure 6). Two types of sandstone bodies comprising the Muddy (J) Sandstone in the Denver Basin were described by MacKenzie (1965, 1971) from outcrops along the west margin of the basin near Fort Colllins which he formally named the Fort Collins and Horsetooth Members. The members are separated by a subaerially exposed erosional surface interpreted by MacKenzie as recording a major drop in sea level.

The older Fort Collins Member is a very fine- to fine-grained sandstone containing numerous marine trace fossils and is interpreted to be a widespread delta-front sandstone deposited during regression of the shoreline of the Skull Creek sea. This member is absent in the Golden-Morrison area. Sandstones of the younger Horsetooth Member are fine- to medium-grained, well sorted, cross-stratified, and contain carbonized wood fragments. Lenticular sandstones, intercalated with siltstone and mudstone, are interpreted to be channels of fresh and brackish water origin deposited as valley fills. Field trip stops 1, 3, and 5 deal with the Horsetooth Member of the Muddy. Of the measured sections of the Dakota Group along 6 mi (9.6 km) of outcrop (Figure 2), the best exposed and easiest to access sections are I-70, Alameda Road (noted for dinosaur trackways) and Turkey Creek. Lithologies, thicknesses and interpretations are plotted and correlated for each of 6 localities (Figure 6).

Sediments of the Dakota Group were deposited as part of the fill of the Western Interior Cretaceous foreland basin. An epeiric seaway extended from the Arctic to the Gulf of Mexico, and occupied a 500 to 1000 mi (805 to 1640 km) wide basin (Weimer, 1984). This foreland basin formed on thick continental crust, and was bordered on the west by a fold and thrust belt, and on the east by the Canadian shield. The early Cretaceous Dakota Group sediments were derived from a dominantly western source. The Skull Creek, Muddy (J) and Mowry record basinwide transgressive, regressive and transgressive deposits in the shallow seaway.

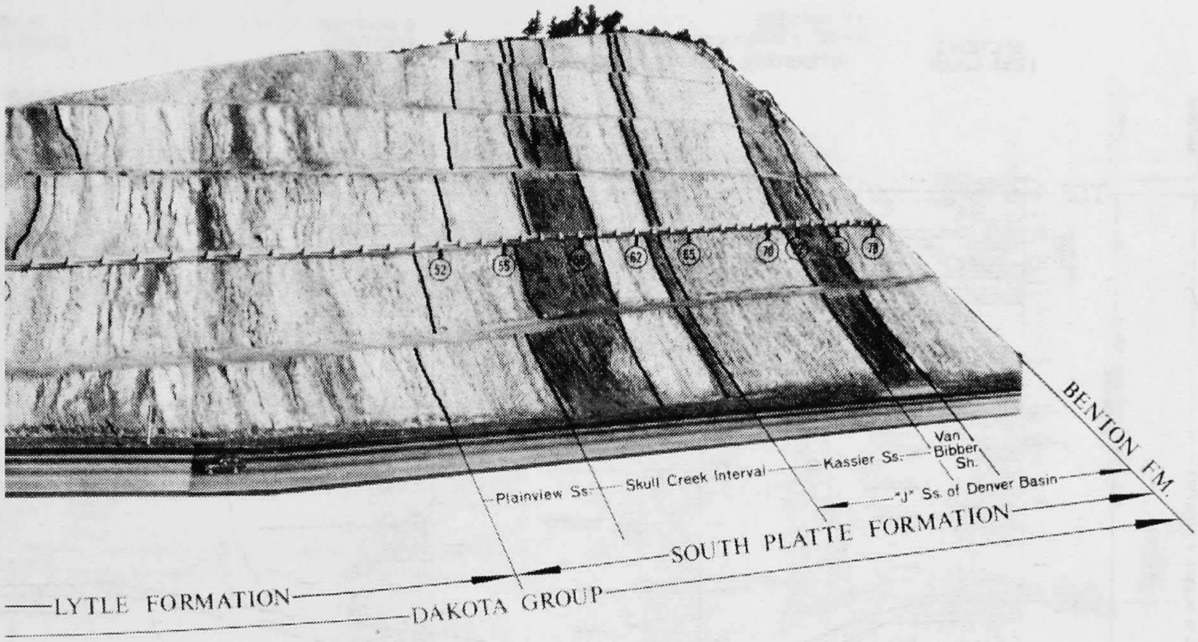


Figure 4B. North slope of I-70 Road Cut (LeRoy and Weimer, 1971).

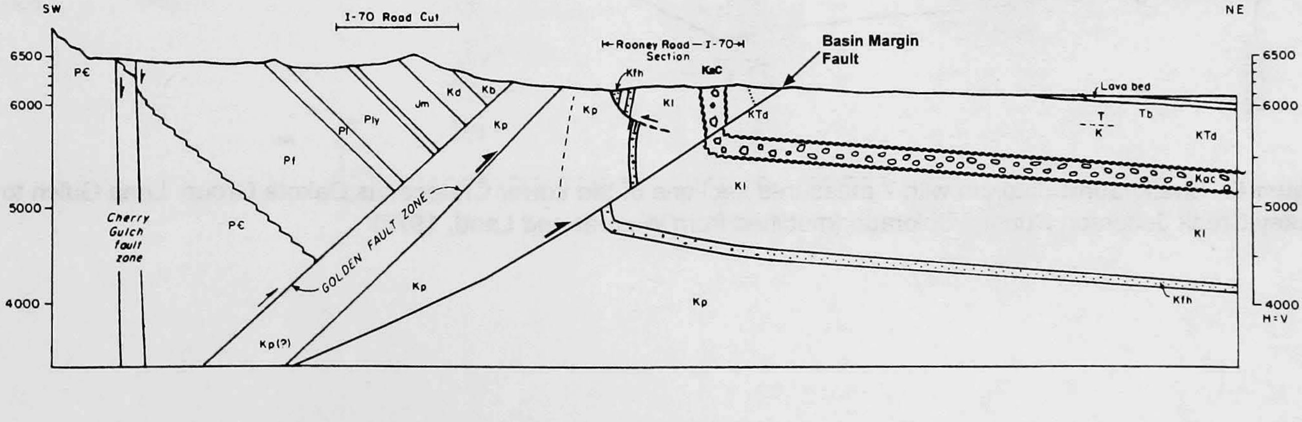


Figure 5. Structure cross-section of east flank, Front Range uplift along south side of I-70. Horizontal scale same as vertical; formation symbols same as Figure 3 (modified after Weimer, 1973).

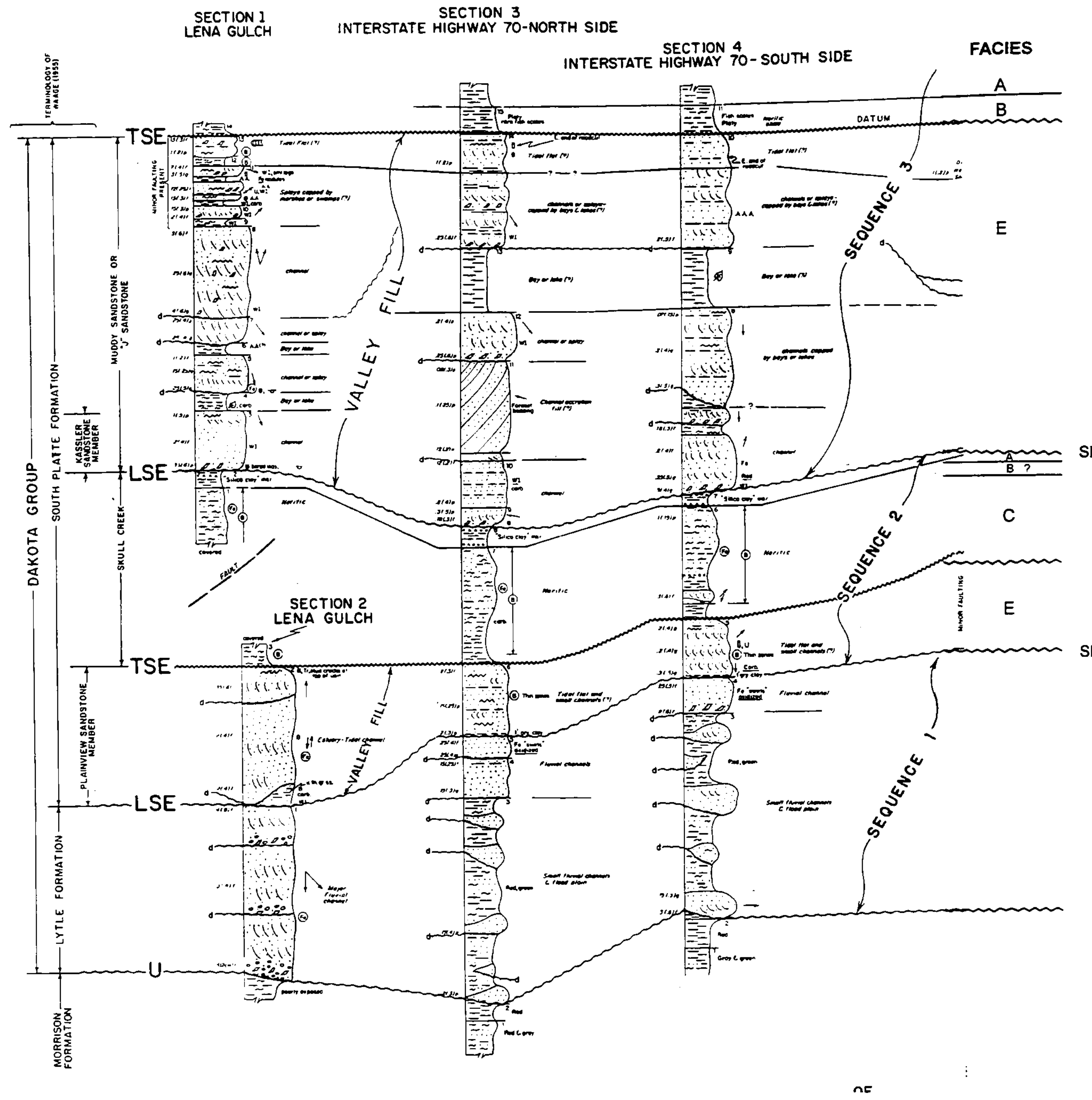
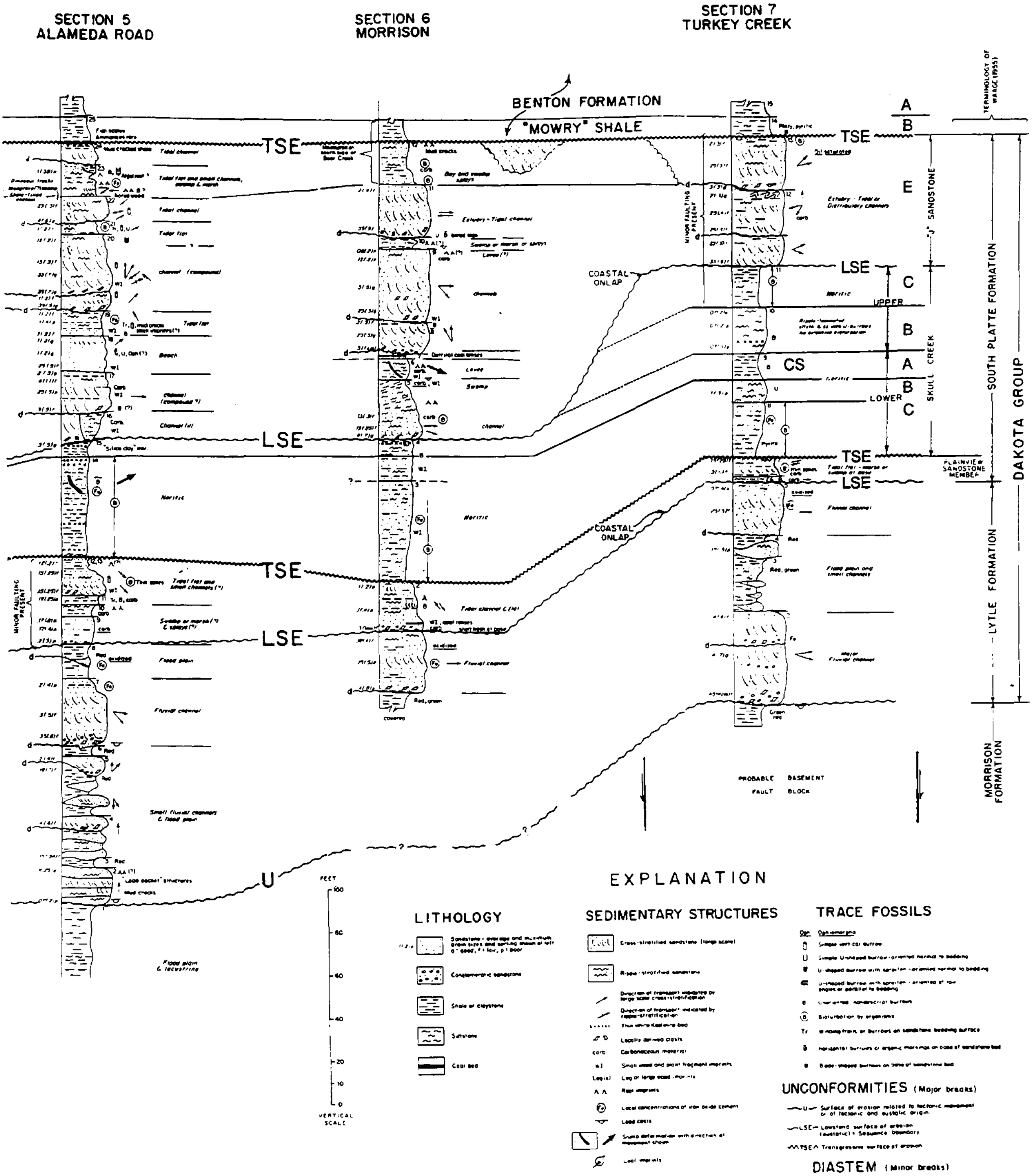


Figure 6. Stratigraphic diagram with 7 measured sections of the Lower Cretaceous Dakota Group, Lena Gulch to Turkey Creek Jefferson County, Colorado (modified from Weimer and Land, 1972).


SECTION 5
ALAMEDA ROAD
SECTION 6
MORRISON
SECTION 7
TURKEY CREEK
BENTON FORMATION
"MOWRY" SHALE
TSE
LSE
TSE
LSE
TSE
LSE
TSE
LSE
U
COASTAL ONLAP
COASTAL ONLAP
CS
UPPER
LOWER
A
B
E
C
B
A
B
C
"J" SANDSTONE
SKULL CREEK
PLAINVIEW SANDSTONE MEMBER
SOUTH PLATTE FORMATION
LYTLE FORMATION
DAKOTA GROUP
MORRISON FORMATION
TERMINOLOGY OF WAAGE (1955)
MINOR FAULTING PRESENT
PROBABLE BASEMENT FAULT BLOCK
Neritic
Channel
Fluvial channel
Flood plain
Small fluvial channels & flood plain
Flood plain & lacustrine
Beach
Tidal flat
Tidal channel
Swamp
Levee
Estuary - Tidal channel
Fluvial channel
Major fluvial channel
Flood plain and small channels
EXPLANATION
LITHOLOGY
Sandstone
Conglomeratic sandstone
Shale or claystone
Siltstone
Coal bed
SEDIMENTARY STRUCTURES
Cross-stratified sandstone (large scale)
Ripple-stratified sandstone
TRACE FOSSILS
UNCONFORMITIES (Major breaks)
DIASTEM (Minor breaks)
FEET
100
80
60
40
20
10
0
VERTICAL SCALE

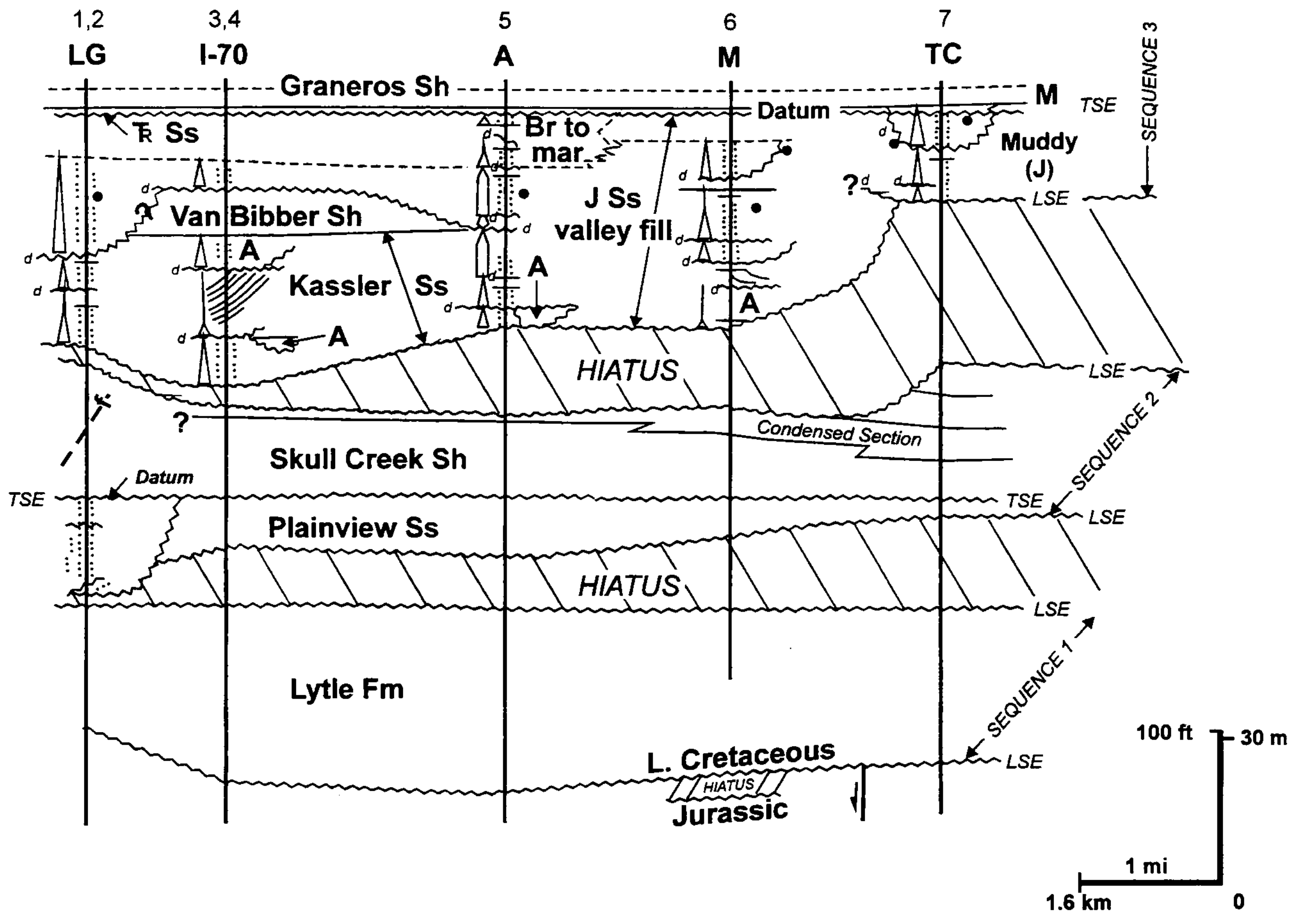


Figure 7. Simplified chronostratigraphic diagram from Figure 6 separating sequences on unconformity boundaries (LSE). Datum horizon is flattened on TSE. Genetic units of channel sandstone indicated with incised valley fill (IVF). A = channel abandonment fill; Br to mar = more brackish to marine; TrSs. - transgressive sandstone.

In the I-70 outcrops, the formations are composed of a diverse association of depositional facies ranging from alluvial valley, fluvial, deltaic, coastal plain and tidal flat, to neritic. These facies can be grouped into depositional systems, that define the stratigraphic architecture of the strata. Delineation of the systems is based on the recognition of genetically significant stratigraphic surfaces that define sequence boundaries, transgressive surfaces; and condensed sections.

Three unconformity-bound depositional sequences labeled 1, 2 and 3 have been established for the Dakota Group (Figure 6). Collectively, they comprise a 270-395 ft (82-120 m) thick clastic section. Sequence 1 is the nonmarine Lytle Formation, Sequence 2 is the Plainview Sandstone and Skull Creek Shale; and, Sequence 3 is the Muddy (J) Sandstone and overlying marine shales of the Benton Group.

The sequence boundaries, resulting from lowstand surfaces of erosion (LSE's), provide the basis for separating the 3 sequences as genetically related packages and for then studying their depositional history (Figure 7). The transgressive surfaces of erosion (TSE's) over a small study area were formed as essentially flat scour surfaces and, therefore, are the best features for use as datum horizons. More detailed discussion of the sequence stratigraphy of the Dakota Group in the Denver basin is given in another section of this guidebook.

Hydrocarbon production from the Dakota Group clastics on the west flank of the Denver basin has been in excess of 20 million bbl of oil, mainly from the Muddy (J) Sandstone interval in three old anticlinal fields; Wellington, Fort Collins and Horse Creek (MacKenzie, 1971). As reported by Higley et al. (1992), about 800 million bbl of oil and 1.2 TCF of gas was produced from the entire Denver basin with 90 percent from the Muddy (J) Sandstone. During the past 25 years, the most important petroleum discoveries in the Denver basin have been in the area of the basin center Wattenberg gas field. Wattenberg is estimated to have an ultimate production of 1.3 trillion cubic feet (tcf), and produces mainly from tight, upper delta front sandstones of the Fort Collins Member. Channel sandstones (valley fill) of the Horsetooth Member, similar to those observed at I-70, are the principal petroleum reservoirs on the east flank of the Denver basin. Significant reserve potential probably still exists in subtle stratigraphic traps in the Upper Cretaceous section in other parts of the Denver basin.

STOP 2
ROONEY ROAD - GRANEROS SHALE
(Stream-Cut Section, 0.5 Mi [0.8 Km] South of Rooney Ranch)

Important source beds for oil and gas in the Denver Basin occur in the lower part of the Upper Cretaceous. These source beds are found in the Mowry, Graneros, Greenhorn, Carlile, Niobrara and lower Pierre formations (Clayton and Swetland, 1980; Gautier et al., 1984; Barlow, 1986; Kauffman and Coates, 1994; and Rodriguez, 1985). The purpose of this stop is to examine source beds in the Graneros shale (the lower formation of Benton Group) at the Rooney Road section, especially a high gamma ray interval recognized throughout the Denver basin.

The Rooney section has been described, sampled for physical and organic geochemical analyses, and gamma-ray logged by Pietraszek-Mattner, 1995 (Figure 8) (Slatt, et al., 1995, p. 86). The lithologies and outcrop log are easily correlated with a cored well from the Second Creek field (Bass Box Elder Farms #6-32) located approximately 30 mi (48 km) east of the outcrop section (Figure 9).

The outcrop of the Graneros consists of clay-rich and silty shales. The section fines upward (more clay rich) followed by a coarsening upward interval (more silty).

The gamma-ray log mimics this trend. The clay-rich rocks have higher gamma radiation than the silt-rich rocks. The clay-rich rocks are massively bedded and black. The silt-rich rocks are finely laminated and generally lighter colored. Pietraszek-Mattner (1995) interprets the silty zones to be deposited in proximal marine settings and the clayey intervals to be deposited in distal marine settings.

Samples from the outcrop and Bass well cores were collected by Pietraszek-Mattner and analyzed by Core Laboratories. The organic geochemistry data for the Rooney Road Graneros section is summarized in Table 1. TOC content ranges from 0. 95 to 5.26 wt %. In general, TOC increases with increasing clay content. The highest TOC values of 5.26 wt % correspond to a high gamma-ray interval at 68 ft (21 m).

The Graneros section at Rooney Road is thermally immature as indicated by low T MAX values and low transformation ratios (S1/[S1+S2]). The low thermal maturity is probably due to shallow maximum burial depth. The present day outcrops were never buried as deeply as the Denver basin section prior to uplift and exposure during the Laramide orogeny. The largest transformation ratio is 0.17 with a T MAX of 429°C.

The geochemical analyses of the Graneros section in the Bass well, Second Creek field, are listed in Table 2. The highest TOC's in the well, 4.42 wt %, also corresponds to high gamma-ray readings. The relationship between high gamma ray values and high TOC content was also demonstrated for marine source beds in the Niobrara Formation by Sonnenberg and Weimer (1993), source beds similar to the Graneros.

The Graneros section in the Box Elder Farms well 6-32 is regarded as thermally mature and in the oil generating window. Transformation ratios range from 0.14 to 0.26 and T MAX ranges from 441 to 451°C. Transformation ratios and T MAX values increase with thermal maturity of the source rock.

STOP 3
TURKEY CREEK
(US 285 and Dakota Hogback)

The three depositional sequences described at the I-70 Road Cut can be delineated in the excellent outcrops of the Dakota Group at Turkey Creek, 5 mi (8 km) south of I-70. However, significant changes in thickness and lithology occur between the sections. The overall thickness of the Dakota Group is 260 ft (80 m) compared to 370 ft (114 m) at I-70 because of penecontemporaneous movement on the Turkey Creek paleostructure. Thinning occurs throughout the Dakota Group but mainly in the combined Skull Creek-Muddy (J) interval. But within this interval, the Skull Creek is thicker and more complete because of less erosion at the top by the LSE; and, the Muddy (J) is thinner because the lower valley-fill sandstones to the north are absent (Figure 6), and possibly because of minor truncation at the top of the interval by the TSE at the

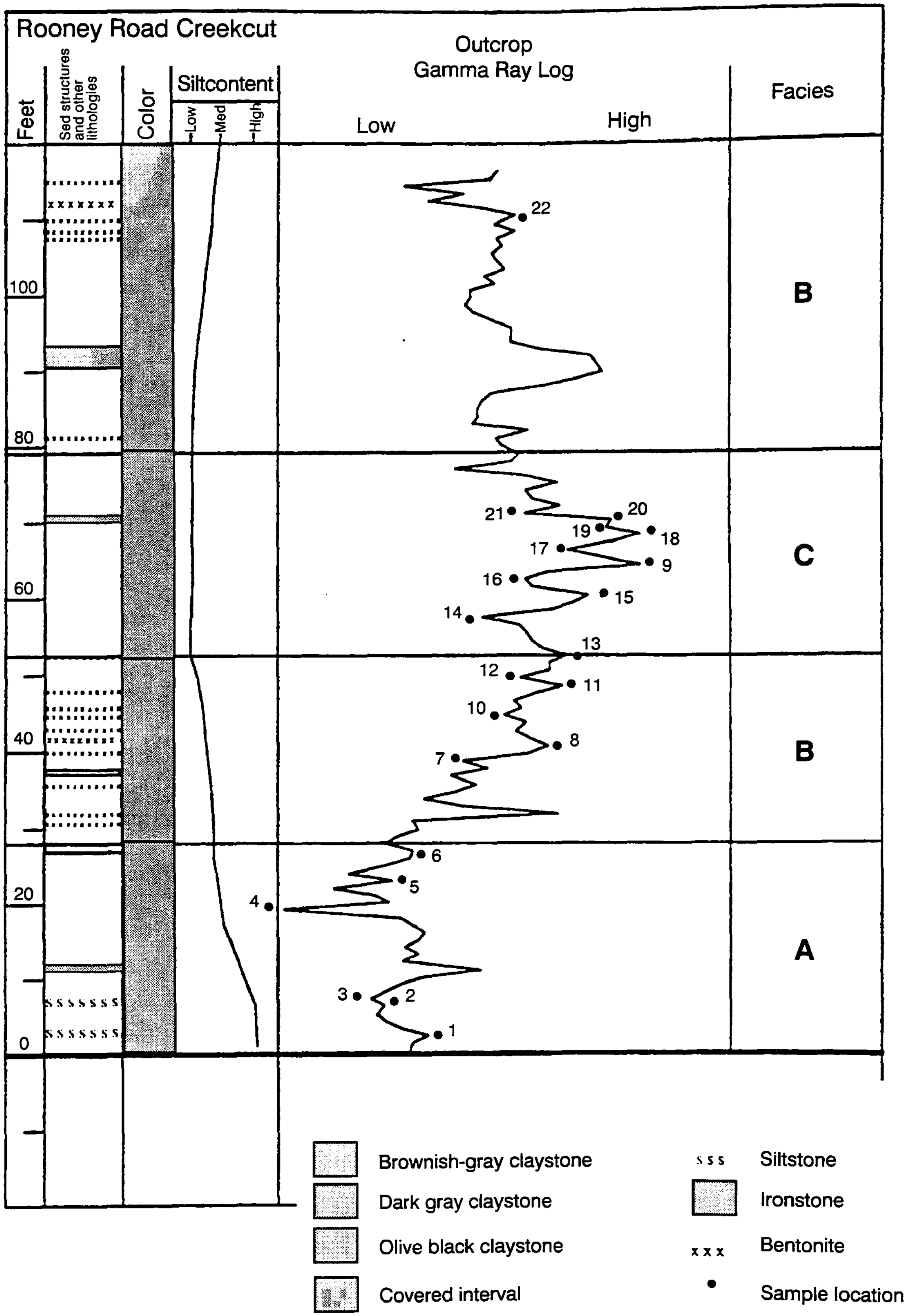


Figure 8. Measured section of Graneros Shale southwest of Rooney Ranch with surface gamma ray log (from Pietraszek-Mattner, 1995).

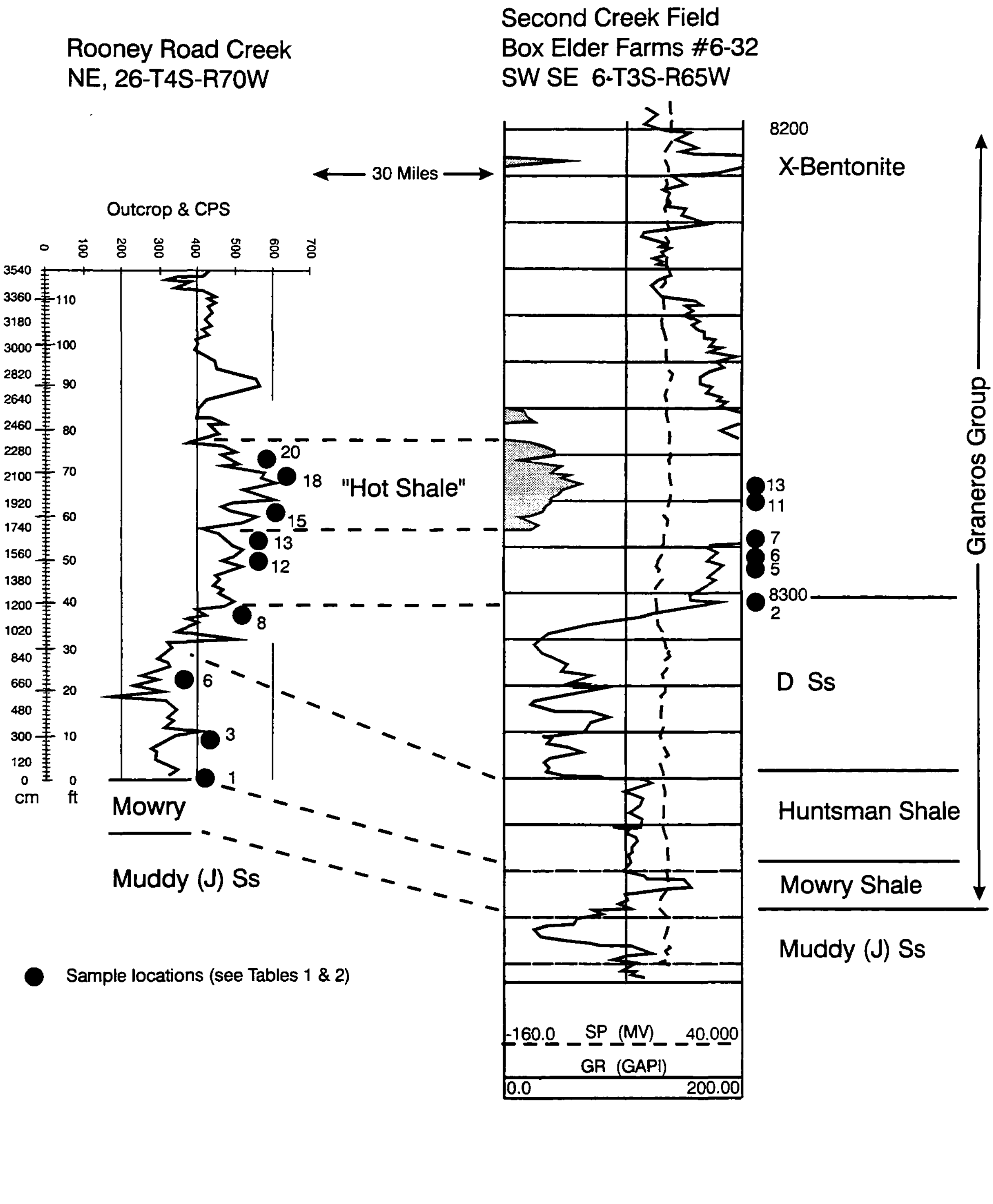


Figure 9. Correlation of surface gamma ray log from Rooney Road to subsurface of Denver basin (modified after Pietraszek-Mattner, 1995).

Table 1. Rooney Road, Graneros Shale Section; organic geochemistry analyses (from Pietraszek-Mattner, 1995).

Sample	Location (ft.)	Tmax Deg C	TOC wt%	S1 mg/g	S2 mg/g	S3 mg/g	HI	OI	Reactive Carbon	Transformation Ratio	Facies
AMC 20	70	426	4.61	0.3	24.13	0.5	523	11	53	0.01	
AMC 18	68	428	5.26	0.41	28.92	0.14	550	3	55.8	0.01	C
AMC 15	61	419	4.62	0.2	11.75	1.13	254	24	25.9	0.02	
AMC 13	53	429	3.36	0.12	8.46	1.82	252	54	25.5	0.01	
AMC 12	50	428	2.81	0.08	6.29	1.02	22	36	22.7	0.01	B
AMC 8	39	423	2.84	0.11	4.82	0.61	170	21	17.4	0.02	
AMC 6	24	429	1.53	0.05	0.35	1.1	23	72	2.6	0.13	
AMC 3	9	424	0.95	0.05	0.25	0.92	26	97	3.2	0.17	A
AMC 1	0	428	2.13	0.08	1.44	1.07	68	50	7.1	0.05	

From Pietraszek-Mattner, 1995.

TOC = Total Organic (wt%); S1 = Free Hydrocarbons (mg/g); S2 = Pyrolyzable Hydrocarbons (mg/g);
S3 = CO2 released during pyrolysis (mg/g); HI = Hydrogen index = [(S2/%TOC) x 100]; OI = Oxygen Index = [(S3/%TOC) x 100];
Reactive Carbon = [10 x (S1+S2)/%TOC]; Transformation Ratio = S1/(S1+S2)

Table 2. Bass Box Elder Farm 6-32 Graneros core (SW SE Sec. 6, T. 3 S., R. 65 W.; organic geochemistry analyses (from Pietraszek-Mattner, 1995).

Sample	Core Depth	Log Depth	Tmax Deg. C	TOC wt%	S1 mg/g	S2 mg/g	S3 mg/g	HI	OI	Reactive Carbon	Transformation Ratio	Facies
BEF 13	8285	8277	445	4.42	2.7	10.46	0.15	237	3	29.8	0.21	C
BEF 11	8288	8280	441	3.77	2.44	8.99	0.15	238	4	30.3	0.21	
BEF 7	8296	8288	447	2.93	1.74	5.61	0.19	191	6	25.1	0.24	
BEF 6	8299.5	8291.5	447	3.13	1.94	6.68	0.15	213	5	27.5	0.23	B
BEF 5	8302	8294	448	2.05	1.06	3.08	0.06	150	3	20.2	0.26	
BEF 2	8309.5	8301.5	451	1.28	0.3	1.82	0.09	64	7	8.8	0.14	A

From Pietraszek-Mattner, 1995.

TOC = Total Organic (wt%); S1 = Free Hydrocarbons (mg/g); S2 = Pyrolyzable Hydrocarbons (mg/g);
S3 = CO2 released during pyrolysis (mg/g); HI = Hydrogen index = [(S2/%TOC) x 100]; OI = Oxygen Index = [(S3/%TOC) x 100];
Reactive Carbon = [10 x (S1+S2)/%TOC]; Transformation Ratio = S1/(S1+S2)

base of the Mowry Shale. The outcrop of the Muddy (J) Sandstone is oil-saturated.

Sequence Stratigraphy and Facies

To demonstrate correlations to the Denver basin where thousands of wells have been drilled, the Turkey Creek section (Figure 6) is compared with a typical well log section from the subsurface (Figure 10).

Sequence 1 is the nonmarine Lytle Formation (105 ft, 30.7 m) and unconformably overlies the Morrison Formation. The lower Lytle is medium to coarse grained, with transported clay grains and clasts of kaolinite. Chert-pebble conglomerate lenses are present throughout the unit but are concentrated in the lower part. Most of the unit is trough cross-stratified in sets 1 to 3 ft (0.3 to 1 m) thick which show SSE transport. This thick channel, exposed on the north side of the highway at Turkey Creek (unit 2; Figure 10), pinches out about 500 yards (460 m) north. The channel is not present on the south side of the highway. The lower Lytle is interpreted to be deposited as part of a major fluvial braided channel. The upper Lytle contains interbedded sandstone and varicolored mudstone units. The sandstones are fine- to medium-grained and interpreted to be deposited in fluvial and flood plain environments. On the north side of the road, convergence of the red claystones and buff sandstones in the upper Lytle is related to channel margin sedimentation and thinning away from a major channel located south of the highway.

No indigenous fossils have been found in the Lytle of the Golden-Morrison area but regional correlations indicate a late Aptian or early Albian age (McGookey et al., 1972). The dinosaur bones in the Morrison Formation date the formation as Late Jurassic so the unconformity has a large time gap, perhaps as much as 20 million years.

Sequence 2 includes the Plainview Sandstone and the overlying marine Skull Creek Shale. The Plainview consists of sandstones and interbedded carbonaceous shale. The sandstones are fine- to medium-grained, ripple to tabular cross stratified, sub-parallel laminated with thin interbeds of claystone. Bimodal transport directions are observed along with zones of burrowing.

An unconformity at the base of the Plainview Sandstone forms the upper boundary of the Lytle fluvial deposits. This unconformity has been interpreted by previous workers as a regionally extensive "transgressive disconformity" (Waage, 1959; MacKenzie, 1971). The Lytle/Plainview contact is underlain by yellow to brown sandy claystones that exhibit evidence of leaching and oxidation. Channeling at the contact and the development of an incised valley fill (IVF) about 65 ft (20 m) thick occurs at the Lena Gulch section (Section 1, Figure 6). The Plainview thins to the Turkey Creek section (12 ft, 3.7 m) by coastal onlap to the Turkey Creek paleostructure. All lithologies in the Lytle are characterized by a total lack of carbonaceous material, indicating a high degree of oxidation in the fluvial environments. By contrast, the Plainview had gray carbonaceous layers, and burrowed sandstones typical of coastal plain swamp/marsh (with root zones), tidal flats and channels.

The contact between the Plainview Sandstone and Skull Creek marine shale and siltstone is sharp and interpreted as a transgressive surface of erosion (TSE). Regionally, thin layers of conglomeratic sandstone are observed on the TSE at the base of the marine Skull Creek Shale (or equivalents) which represents lag deposits associated with a water deepening event because of a relative rise in sea level.

The Skull Creek section consists of 90 ft (28 m) of gray siltstone, shale and clayey sandstone. The dominant lithology of this interval is mottled-gray mixtures of sand, silt, clay, and carbonaceous material. In two intervals much of the primary stratification has been largely destroyed by marine bioturbation. A 10 ft (3 m) condensed section (CS) of dark-gray laminated shale and bentonite separates the Skull Creek into a lower and upper member. This unit, occurring approximately 40 ft (9 m) above the transgressive surface at the base of the Skull Creek (measured section - unit 9), is the deepest water deposit and may represent a time of maximum flooding on the margins of the depositional basin. The unit contains mixed illite and kaolinite clays, and has the highest TOC content (total organic carbon) in the Skull Creek. Inoceramus casts have been found in the condensed section at the Turkey Creek, Morrison and I-70 sections (Figure 7). These fossils are believed to be from either the I. comancheanus or I. bellvuensis faunizone.

The bioturbated sandy shale in the lower Skull Creek (Unit 8, Figure 10) is correlated with the Eldorado Springs Sandstone to the north (MacKenzie, 1971, DuBois, 1996, Zahar, 1989). The lithologies of the Skull Creek may be arranged in a vertical sequence of facies (Figures 6 and 10). The lower member is transgressive (water deepening); the upper member is regressive (water shallowing). In a complete regressive cycle, five facies may be ordered laterally and stacked vertically as described in Table 3. However, because of unconformities, the rate of water depth changes and the available accommodation space, the cycles are seldom complete. The facies in the Turkey Creek Section in relation to formations and members for Plainview, Skull Creek, Muddy (J) and Benton are designated on Figures 6 and 10. The incomplete order is caused principally by erosion. The LSE (sequence boundary) at the contact between the Skull Creek and Muddy (J) has removed the upper C and D facies. The TSE at the base of the Skull Creek has removed facies D from the Plainview. Therefore, the shallow marine and shoreline sandstones, an important reservoir facies, are absent from the transgressive and regressive cycles.

Sequence 3 consists of incised valley-fill (IVF) deposits of the Muddy (J) Sandstone, and the overlying marine Mowry Shale and Benton Group. The contact between the sandstone and the underlying Skull Creek at Turkey Creek is a sharp, scoured surface that represents a regional erosional unconformity that

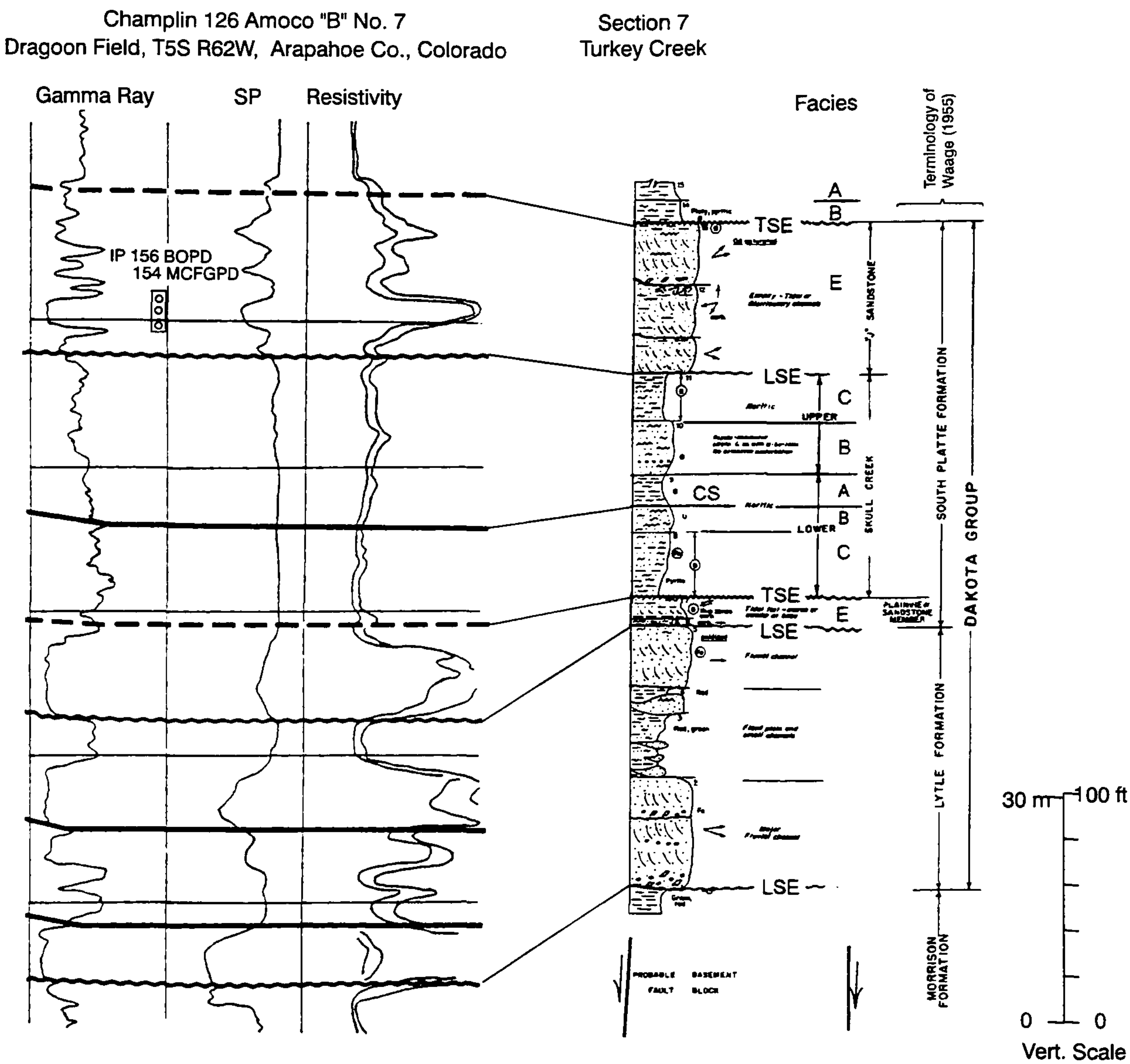


Figure 10. Correlation of Turkey Creek Section to subsurface well log at Dragoon Field, Arapahoe County, Colorado (refer to Figure 6 for legend).

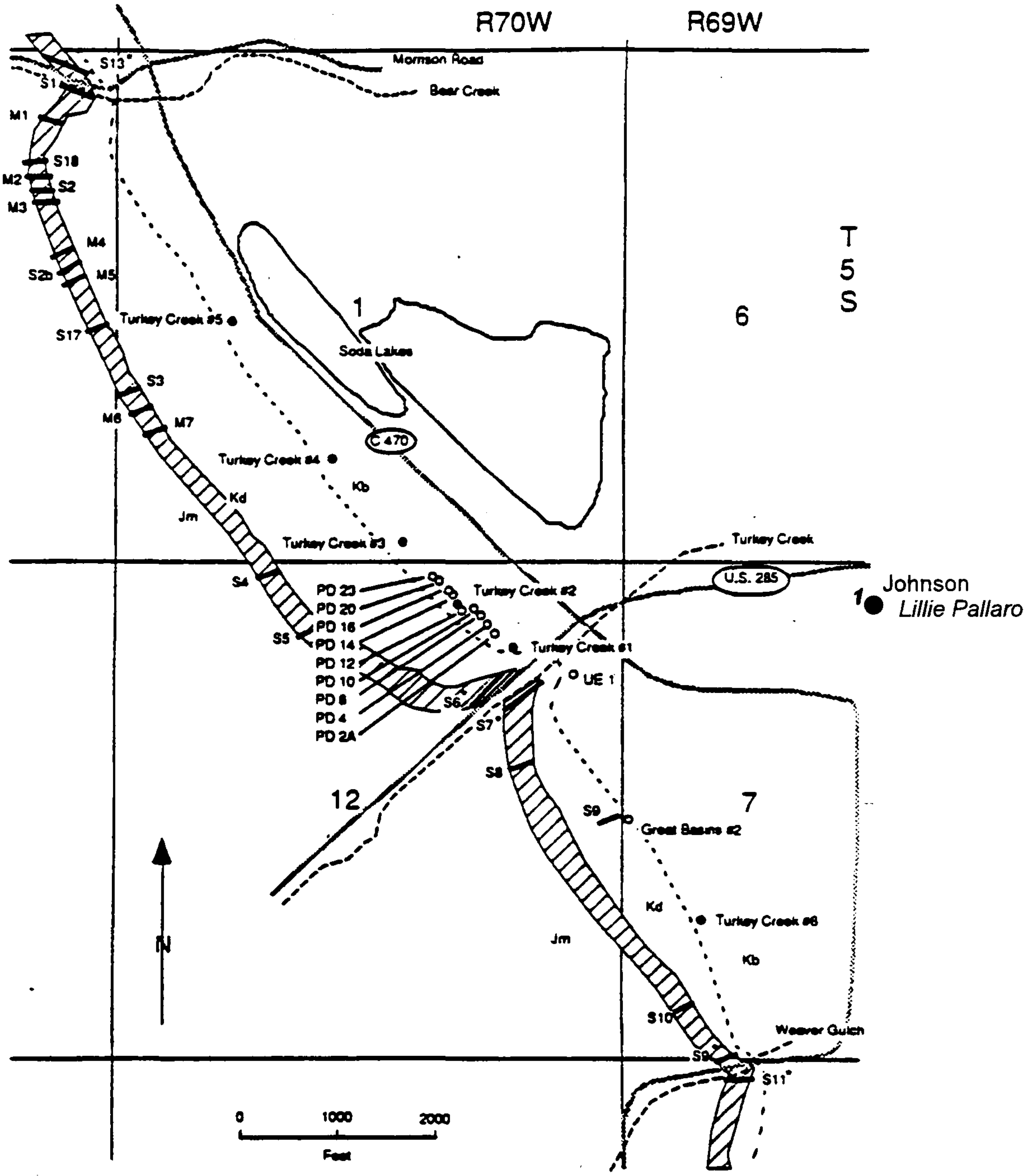


Figure 11. Base map of J Sandstone outcrops near Morrison, Colorado (modified from Bedwell, 1974). PD and UE locations mark uranium core holes for which lithology logs were available. S number indicates a measured section from MacMillan (1974); * indicates where these were measured. M number indicates new measured sections (from Chapin, 1989).

Table 3. Facies lithologies in a complete regressive cycle of the Skull Creek and Muddy (J) (from Weimer, 1992).

Formation	Facies	Lithology	Environment of Deposition
Muddy (J) Horsetooth Member	E	Gray fine-grained to medium-grained cross-stratified sandstone, shale; coaly	Fluvial-valley fill; coastal plain
Fort Collins Member	D	Gray burrowed, cross-stratified sandstone. delta front or shoreface	Shoreline and upper
Skull Creek	C	Gray bioturbated sandstone and shale lower shoreface	Aerobic lower delta front, or
	B	Black shale; siltstone, very fine-grained sandstone; ripple lamination; graded beds. Infrequent Arenicolites burrows and shell hash;	Anaerobic, neritic intermediate water depth
	A	Black laminated shale with bentonite and shell layers; highest total carbon content; contains Inoceramid fossils. Condensed section	Anaerobic, neritic deepest water depth

occurs at the base or within the Muddy (J) throughout eastern Colorado. The Muddy (J) consists of 60 ft (18 m) of sandstone with some interbeds of dark gray, carbonaceous shale. The sandstones are fine- to medium-grained and cross stratified in sets 1 to 3 ft (0.3 to 1 m) thick. Transport directions range from SSE to NNE in lower part; SW in the middle part; N to NE in the upper part. The overall interval is a compound unit consisting of two or three channel sandstones which occur as genetic units 10-30 ft (3-10 m) thick with sharp bases and slightly fining-upward textures. Each sandstone was deposited as channel active-fill and the middle unit is capped by abandonment fill consisting of laminated siltstone and claystone that contains slump structures. The uppermost channel sandstone is capped by burrowed siltstone. This channel sandstone exhibits features suggestive of brackish water and/or tidal currents. Evidence of periodic slack water, suspension deposition (such as during periods of high or low tide) is found in the preservation of concentrations of fine carbonaceous detritus on cross-strata foresets, or clay drapes at the tops of cross-strata sets.

The IVF deposits of the Muddy (J) Sandstone are capped by a well-developed transgressive surface (TSE). This surface is best exposed on the south side of the road at Turkey Creek, and is defined by an irregular, burrowed surface locally overlain by a pebble lag. A thin (6-8 in - 4-4.5 cm), lenticular, coarse- to medium-grained highly burrowed sandstone overlies the TSE and is abruptly overlain by the succeeding transgressive shales and then graded siltstones and sandstones of the Mowry. At Turkey Creek, Diplocraterion burrows commonly pipe down from the TSE into the upper Muddy (J) Sandstones, and Rhizocorallium burrows occur above the TSE, suggesting a rapid upward deepening character to the transgressive deposits. If shoreline and shoreface deposits were ever present (facies D and C, Table 3), they were removed by erosion during the transgression (TSE).

The "Mowry" above the TSE is 10 ft (3 m) thick and is composed of shale, gray siltstone and bentonite. The thin beds of rippled siltstone have sharp bases and grade upward into organic-rich black shale. The lithologies are facies B (Table 3) and represent abrupt water deepening believed to be related to a combination of sea level rise and tectonic subsidence.

The water depth is estimated to be 100 to 150 ft (31 to 47 m). The rather uniform regional distribution of lithology and thickness were described by Serrano de Rojas (1981). Impressions of the ammonite genus Metengonoceras were collected from the Mowry Shale at Alameda Parkway section (Cobban, 1994). According to Cobban, the specimens probably represent the M. aspenanum zone, the 4th of 5 faunizones (in ascending order) in the Mowry of central Wyoming where the formation is 200 to 300 ft (62 to 92 m) thick.

The LSE at the base of Muddy (J) was a time of subaerial exposure during which valley incisement occurred. The valley was cut as much as 70 ft (21 m) more deeply to both the north and south of Turkey Creek probably reflecting the influence of the Turkey Creek paleostructure along which minor movement occurred to give a topographic high. The maximum erosion was on the margins of the high. Moreover, where the incised valleys are deepest, the lower channel fill sandstones south of Turkey Creek are conglomeratic with chert pebbles up to 0.4 in (1 cm) (Figure 14). No conglomerate has been observed in the valley fill north of Turkey Creek. Only the upper half of the incised valley fill (IVF) is present at Turkey Creek (Figures 6 and 14).

Reservoir Characteristics

Reservoir continuity can be reconstructed in the Muddy (J) Sandstone in the Turkey Creek area because of the large number of core holes drilled for uranium exploration and for petroleum development in the oil-saturated channel sandstones (Figure 11; from Chapin, 1989). Data from these cores were combined with measured surface sections along a 2.5 mi (4 km) stretch of the hogback to reconstruct a facies restored section showing discontinuities within the IVF (Figure 12, Chapin, 1989; MacMillan, 1974). In the facies reconstruction, facies 1 is a fine- to medium-grained cross-stratified sandstone, and facies 2 is a rippled laminated sandstone. They are both a part of active channel fill. Non-reservoir rocks are: facies 3, siltstones and claystones deposited as channel abandonment fill; and, facies 4, claystones, siltstones, and very fine-grained sandstone deposited in overbank channel margin areas. The channel sandstones have sharp scour bases and average 25 ft (8 m) thick, except where eroded into by a younger channel, and are 0.5 to 1.5 mi (0.8 - 2.4 km) in width.

Porosity values, measured from outcrops, average 20 to 21% in facies 1 and 17-18% in facies 2 (Figure 13, Chapin, 1989). Core data have similar in values. These porosities are more than twice as high as those measured in the Muddy (J) Sandstone reservoir in the Wattenberg field (8-10%) in the basin center. These comparisons, together with low vitrinite reflective values from outcrops (Higley et al., 1992) indicate that the burial history of Muddy (J) Sandstone in the outcrop area was not greater than 6000 ft (1840 m).

Structure

The Turkey Creek anticline is an east-plunging structural nose reflected by a bulge in the Dakota Group outcrop in the hanging wall of the Golden Fault. The axis trends N.50°E. and is also observed in the outcrop of the upper Pierre, Fox Hills, Laramie and Arapahoe Formations to the east of the Golden Fault. This folding is believed related to a basement fault zone along which recurrent movement has occurred, as shown by the thinning of formations and facies changes in Dakota Group outcrops from Golden to Sedalia (Figures 6 and 14).

Turkey Creek is the only locality along the mountain front where deep wells give control for depicting the subsurface structure associated with the Golden fault.

The Johnson Lillie Pallaoro well was drilled in 1954 about 0.5 mi (0.8 km) east of the oil-saturated sandstone outcrop in an attempt to establish production. The well, drilled to a total depth of 9649 ft (2950 m) found the Dakota Group to be tight and non-productive, and was plugged back for completion as a producing well from a fractured Fort Hays interval at 8956-80 ft (2730-40 m). After several years of production, the well was abandoned. A second well, drilled by Great Basins 2000 ft (600 m) to the northeast, was plugged and abandoned after finding the Muddy (J) Sandstone to be tight.

The outcrop and well data were integrated in a structural cross-section by Berg (1962) to illustrate the fold-thrust nature of the mountain flank deformation. A newly revised structural section is presented and discussed in another guidebook article by Weimer (1996).

Small faults and numerous fractures cut the Muddy (J) Sandstone in the Turkey Creek outcrop. The main trend of horst-graben faults is N.60°W., with offsets from a few ins. (cms) to 6 ft (2 m). Pyrite

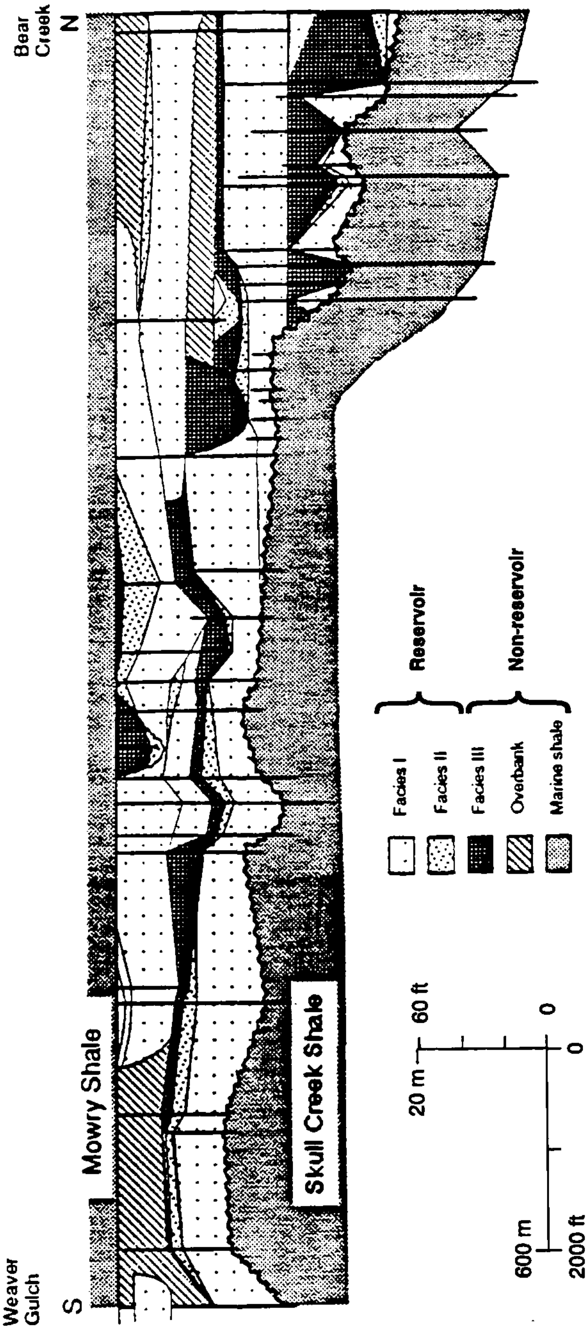


Figure 12. Muddy (J) Sandstone outcrop restored section from Bear Creek to Weaver Gulch (modified from MacMillan, 1974). Location of sections shown on Figure 11 (Chapin, 1989).

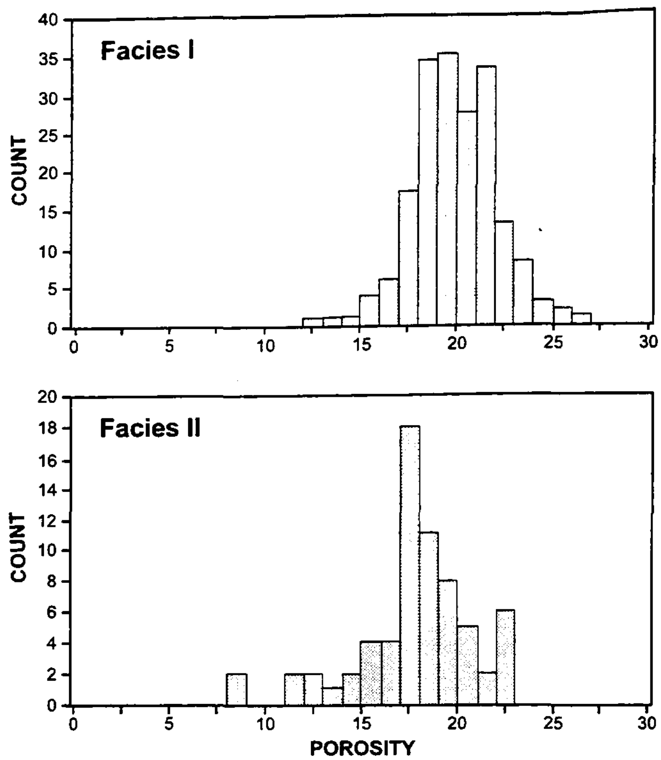


Figure 13. Muddy (J) Sandstone outcrop porosity distribution by facies (Chapin, 1989).

occurs along some of the these fractures where the mineral replaces the quartz grains. Open fractures were migration paths for oil to migrate from Graneros and overlying source beds to the Muddy (J) Sandstone. In addition, if the reservoir were buried at depth and productive, fracture porosity and permeability would contribute significantly to production. The oil occurs in a location where lenticular channel sandstones cross the Turkey Creek nose.

Comparison with Other Outcrop Areas of Dakota Group

The Muddy (J) Sandstone, measured in sections along a 110 mi (188 km) outcrop, can be grouped into a south, central and north area. Turkey Creek is typical of the south area, Hygiene Road of the central area, and Spring Canyon of the north area (Figure 15). The following descriptions compare these 2 other reference sections with the Turkey Creek section, and provide data for correlation to the subsurface of the Denver Basin.

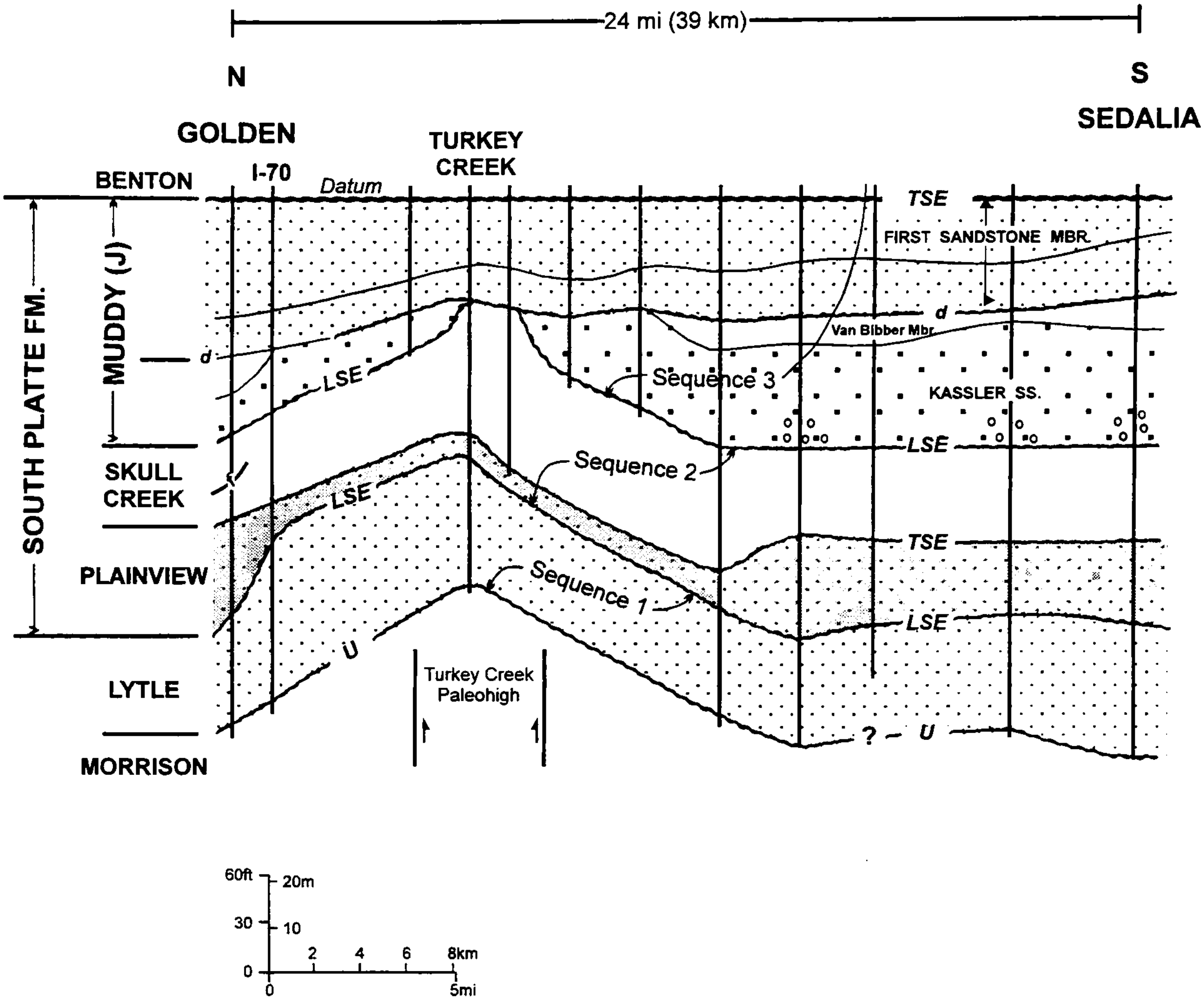


Figure 14. Stratigraphic section from outcrops Golden to Sedalia. Thickness of formations and members from Waage (1961), Weimer and Land (1972), MacMillan (1974) and Poleschook (1978).

Spring Canyon Dam (Southwest of Fort Collins)

The Spring Canyon Dam area (Sec. 32, T. 7 N., R. 69 W.) is a reference section for Lower Cretaceous stratigraphy in the Front Range foothills and the Denver basin (Figure 16). The formations, members, lithofacies, ichnofacies, sequences with key surfaces, and depositional environments show many of the same characteristics as observed at Turkey Creek. The main differences are the occurrence of the Fort Collins Member and a thinner section of the Horsetooth Member.

The classic work of MacKenzie (1965, 1971) laid the foundation for the geologic model observed in the outcrops (Figure 16) and in the subsurface. The ichnofacies are illustrated on Figure 17 (MacKenzie, 1971 and Chamberlain, 1976). The microfaunas and lithologies for the marine Skull Creek Shale and the marine Mowry and Graneros Shale are reported by Eicher (1965). Detailed stratigraphy of the Skull Creek Shale at Spring Canyon Dam, Dixon Dam and Soldier Canyon Dam is reported by Graham and Ethridge (1995). Inoceramus comancheanus and I. bellvuensis occur in the middle Skull Creek Shale as well as the ammonite E. marcianus (Graham and Ethridge, 1995).

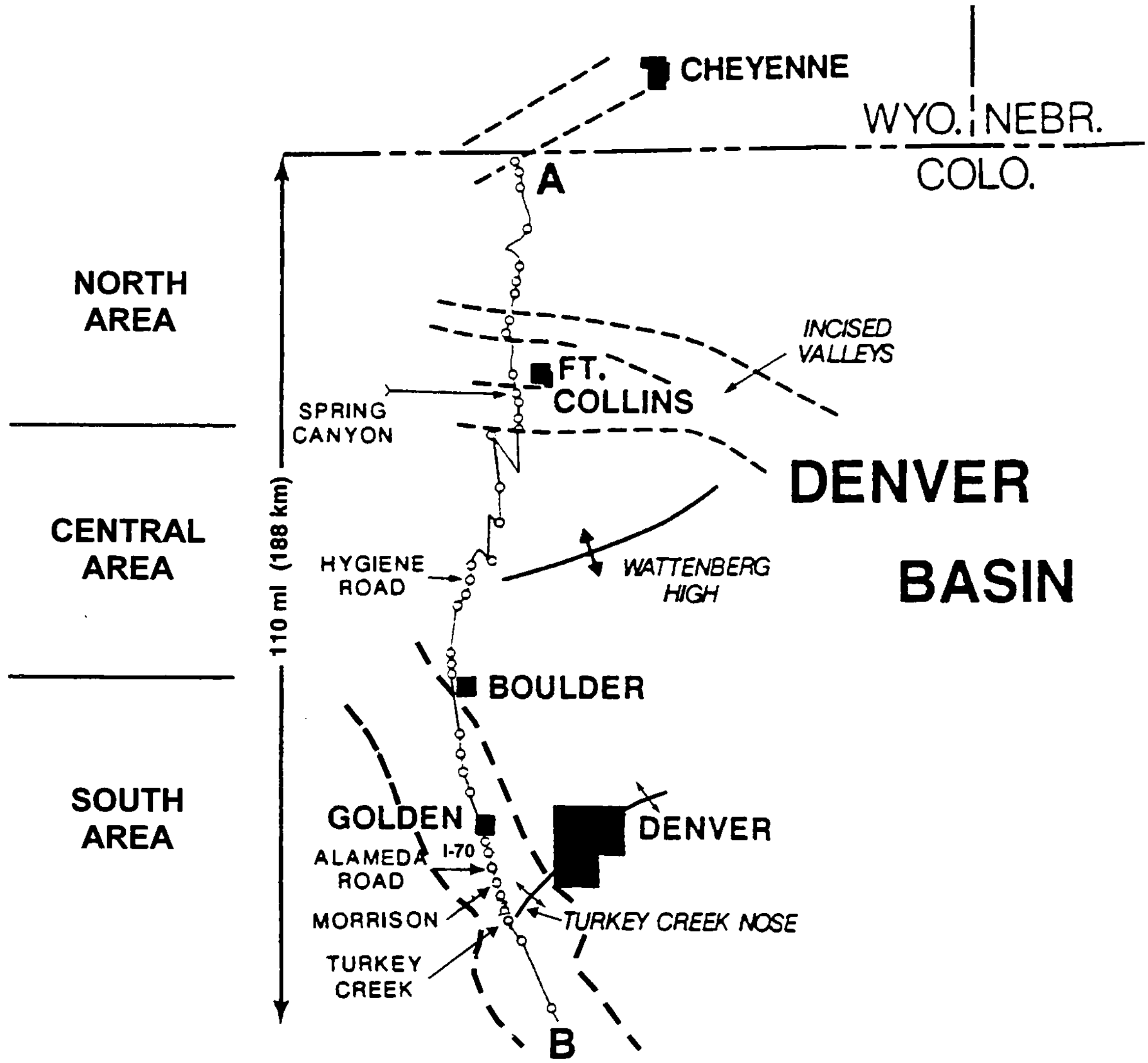


Figure 15. Index map for reference sections and incised valleys in outcrop.

The Dakota Group section exposed at Spring Canyon dam extends upward from the Lytle Sequence, through the Plainview/Skull Creek Sequence into the Muddy/Mowry Sequence for a total thickness of 280 ft (85 m). This discussion begins with the condensed section (CS) of the Plainview/Skull Creek Sequence and progresses through the Skull Creek regressive deposits and the Fort Collins Member, across the sequence boundary at the base of the Muddy (J) Horsetooth Member (IVF) and up to the transgressive surface of erosion (TSE) just below the Muddy/Mowry Formation contact.

Only the middle and upper parts of the Skull Creek interval are exposed at this locality. They consist of a shallowing upward, gradational succession of facies from neritic shale to middle delta front sandstone. This sedimentary pattern is interpreted to represent a regressive depositional system. At the base of the Skull Creek outcrop, the section consists of dark-gray, marine silty shale which contains three thin bentonites, numerous thin ripple-stratified calcareous siltstones, and several thin, lenticular bioclastic limestones, composed of fragments of Inoceramids (facies A). The accumulation of bentonite often occurs during times of slow sedimentation or relative

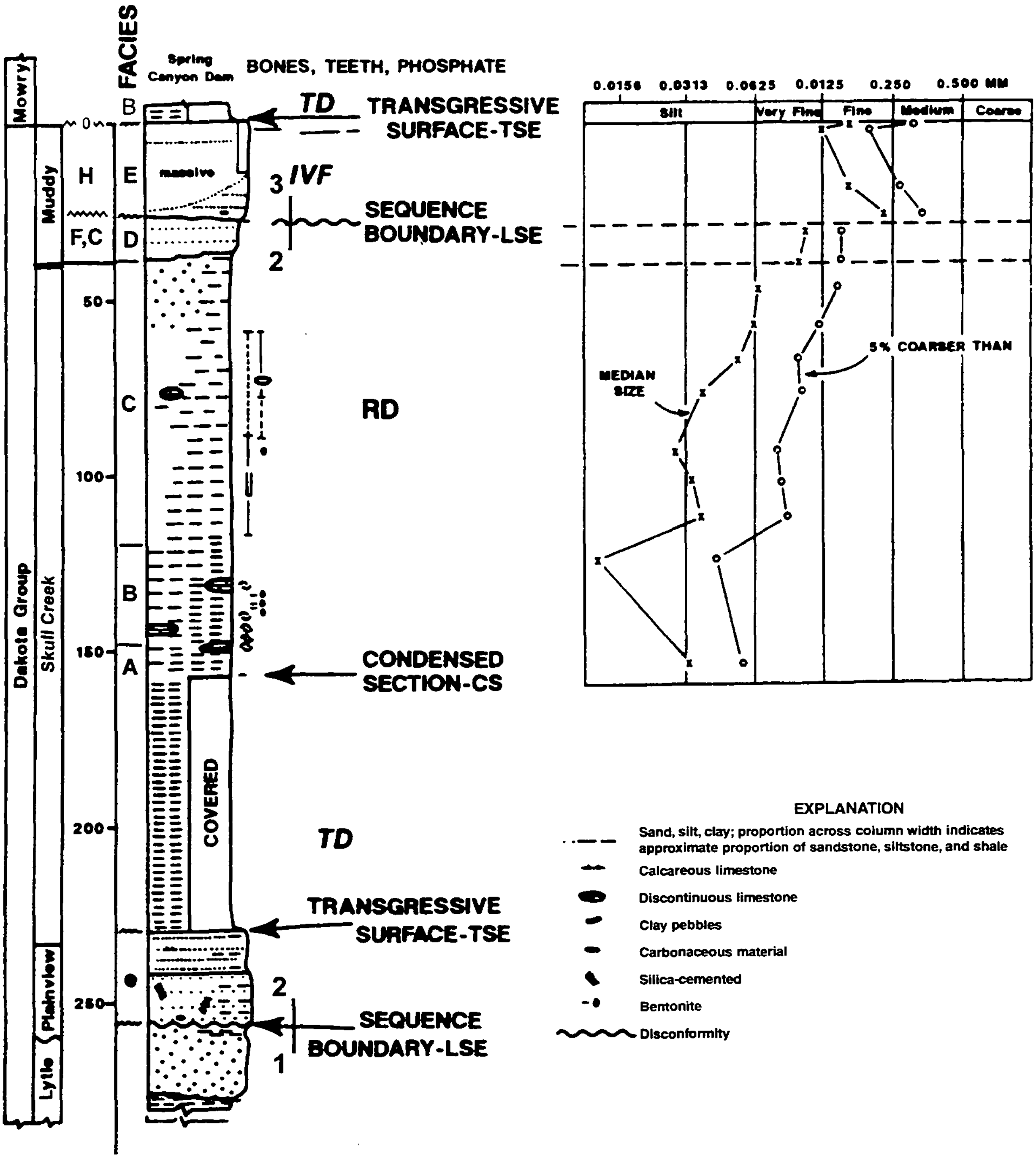


Figure 16. Stratigraphic section of Dakota Group, Spring Canyon Dam southwest of Fort Collins. Modified after MacKenzie (1963), and Baum, et al., (1988).

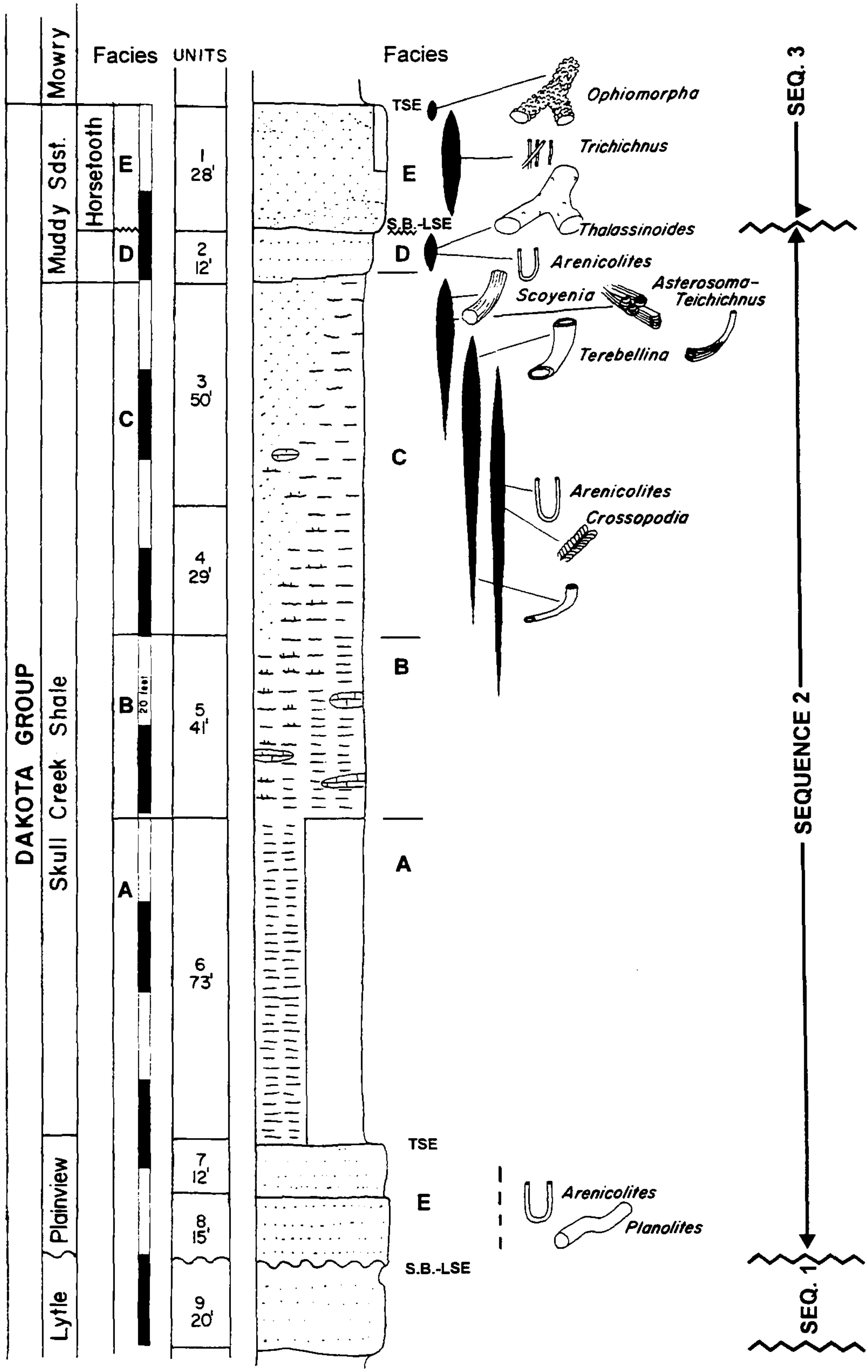


Figure 17. Trace fossils in the Dakota Group, Spring Canyon Section (from Chamberlain, 1976).

starvation, such as during formation of the condensed section. Samples of shales from this part of the section also exhibit the highest values of total organic carbon (TOC), also observed in the Skull Creek nearby at Spring Canyon. These observations suggest that the CS probably occurs near the base of the middle Skull Creek.

The Skull Creek shales become progressively more silty and sandy upward, showing well developed ripple-stratification (lenticular bedding) and thin, very fine-grained sandy storm deposits (facies B). Commonly, thin beds of sandstone, with a sharp base grade to shales. Small U-shaped Arenicolites are the first identifiable trace fossils to appear during the gradual environmental transition. As the silty shales become increasingly more sandy a transition in bedding is observed from lenticular bedding to an absence because of destruction by bioturbation. These deposits are interpreted to record a prograding deltaic system comprised of sandstones (facies C) which coarsen upward into somewhat cleaner lower and middle delta-front sandstone (facies D).

Overlying the Skull Creek Shale is a white, very fine-grained clayey sandstone with large-diameter burrows and indistinct stratification. This sandstone is the Fort Collins Member of the Muddy Sandstone (facies D). The lower contact is gradational with the sandy Skull Creek below (typically placed at the most pronounced color change), and records continuous deposition. The only stratification observed in the Fort Collins Member consists of undulating, irregular surfaces parallel to bedding. The Fort Collins Member is interpreted as a delta front of the Plainview/Skull Creek Sequence.

The upper contact of the Fort Collins Member with the overlying Horsetooth Member of the Muddy Sandstone is a sharp, scoured surface, identified as a sequence boundary, the same as a lowstand surface of erosion (LSE). A pronounced increase in grain size is observed across this unconformity, as well as a distinct change in sandstone character. The lowermost sandstones of the Horsetooth Member are medium-grained, and fine upward into well-sorted, fine-grained sandstones. The sandstone in the lower 2-13 ft (0.6-4 m) are tabular to trough cross stratified in sets ranging up to 2 ft (0.6 m) thick (MacKenzie, 1965). Transport direction is southeast to east. Overlying this is a massive, structureless sandstone on the order of 13 ft (4 m) thick, filling a scour on the south side of the road. These sandstones are interpreted as fluvial, active channel-fill deposits filling an incised valley (IVF) at the base of the Muddy/Mowry Sequence. The amalgamated or compound channeling observed here is an important characteristic of IVF deposits. The channel sandstones have excellent porosity and permeability and similar sandstones produce petroleum at the nearby Fort Collins and Wellington fields.

A surface at the top of the Horsetooth Member is sharp, irregular, and burrowed. A conspicuous lag deposit overlies the surface and consists of rounded chert pebbles (several mm in diameter), light-brown weathering clay and phosphate pebbles, and locally, shark's teeth. This surface is interpreted as the transgressive surface (TSE) at the top of the Muddy/Mowry Sequence IVF deposits. Above the lag is a thin, medium-grained, burrowed, transgressive sandstone which is directly overlain by dark-gray siliceous, transgressive mudstones. In many instances the very sharp, unconformable nature of the TSE will lead geologists to interpret this surface as the sequence boundary (SB=LSE), and in fact, the TSE does merge with the SB (LSE) on the interfluves between incised valleys. However, it is important to keep in mind that the transgressive surface formed as a result of a rise in relative sea level, and in sequence stratigraphy sequence boundaries are defined as unconformities cut by relative drops in relative sea level.

Hygiene Road Section (North of Boulder)

At Hygiene Road only 60 ft (19 m) of Skull Creek and Muddy (J) Formations are exposed (Figure 18). When compared to the Spring Canyon Dam outcrop, several important differences are apparent. Clear evidence of subaerial exposure of the unconformity (LSE) within the Muddy (J) is present, and channelized IVF deposits of the Horsetooth Member as occurs at Turkey Creek and Spring Canyon dam are not developed here (Figure 15). These observations indicate that the thin Horsetooth deposits are located marginal to incised valleys and are related to onlap onto depositional topography probably caused by recurrent movement on the large Wattenberg high (Figure 15). In addition, the type Fort Collins Member of the Muddy Sandstone (facies D) is absent, as at Turkey Creek, because of truncation by the LSE. A similar truncation occurs (Figure 19) between the outcrop and the Wattenberg field where the Fort Collins Member is the main gas reservoir over thousands of square miles.

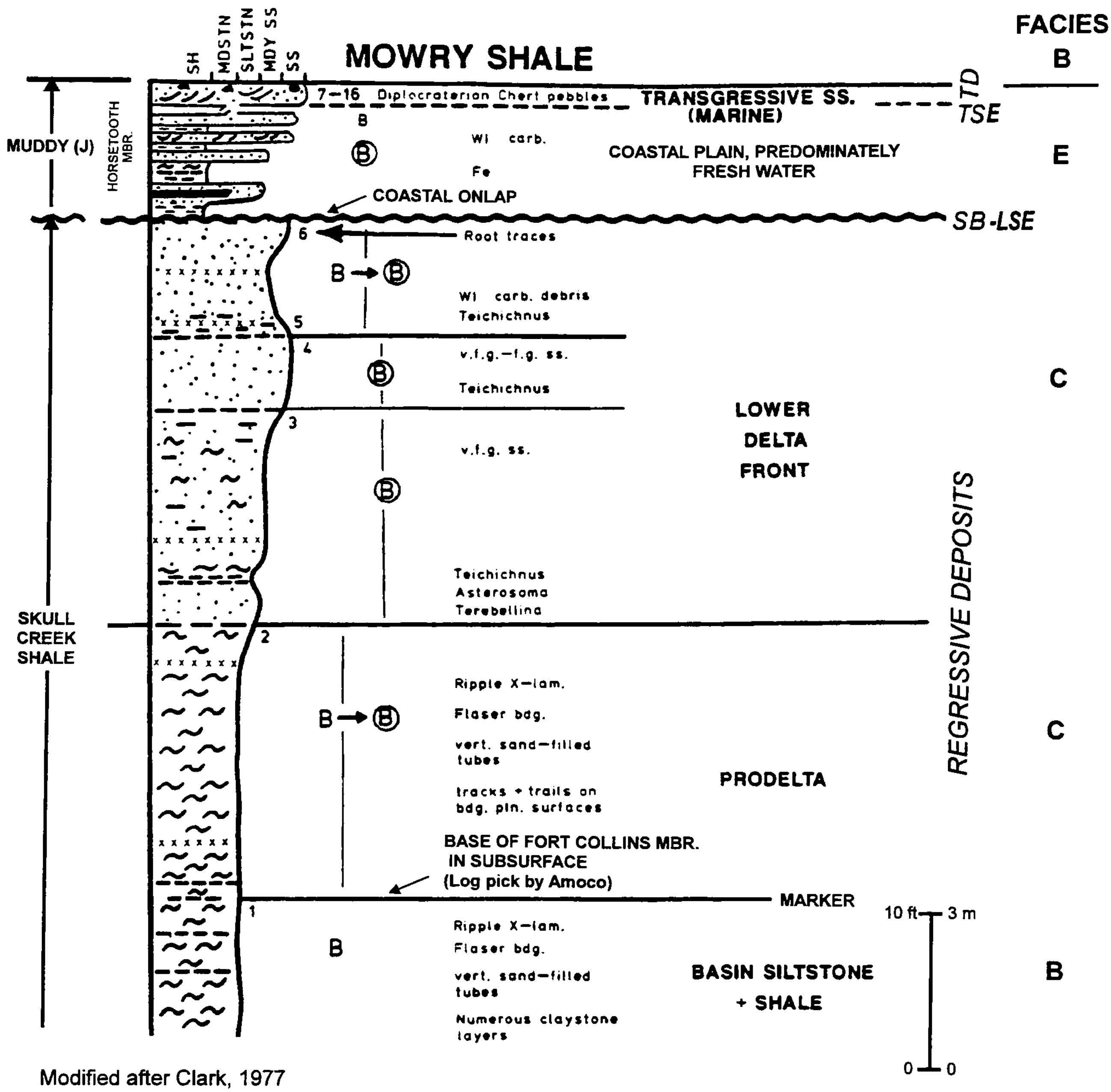


Figure 18. Stratigraphic section of Dakota Group near intersection of Hygiene Road and U.S. Hwy. 36, Sec. 32, T3N-R70W.

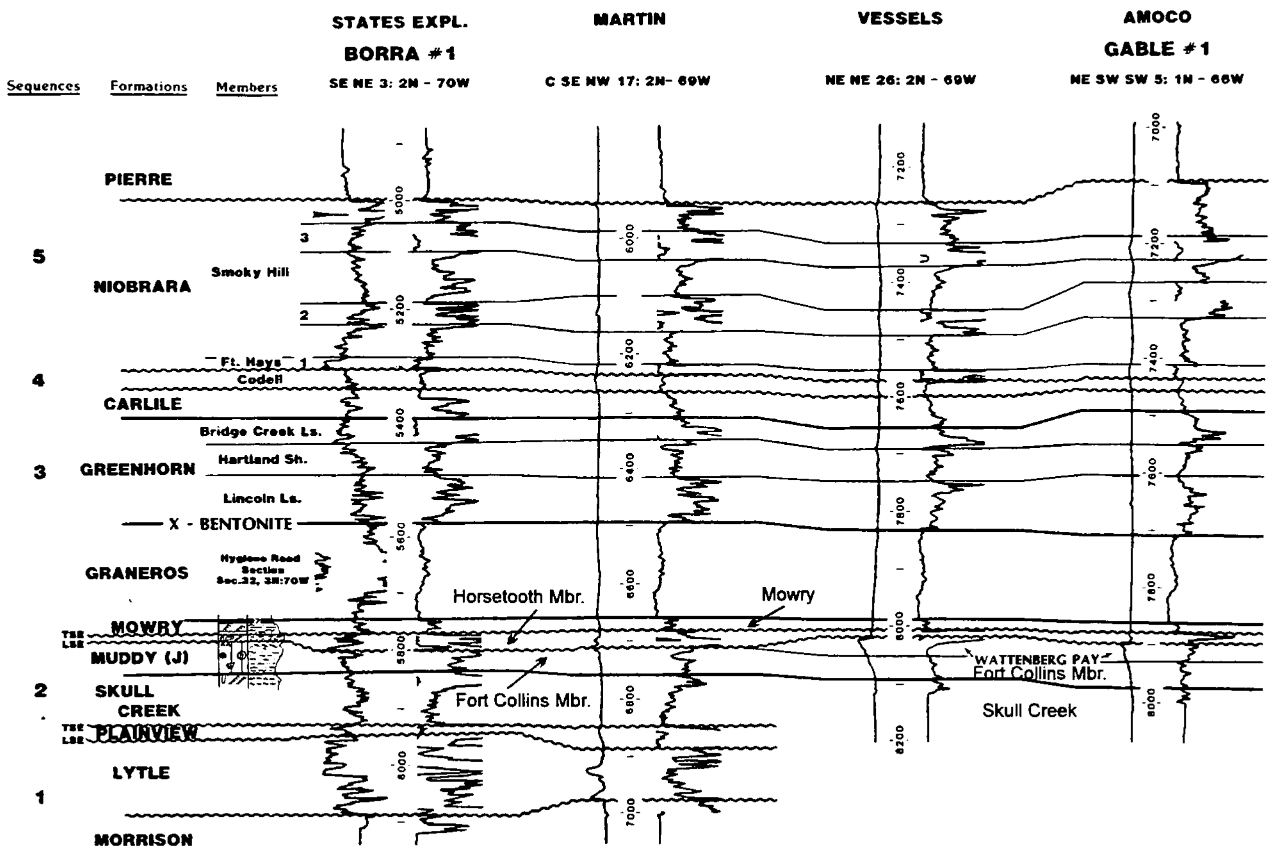


Figure 19. East-west electric log section from Hygiene Road outcrop to east side of Wattenberg Field.

The Skull Creek section preserved here at Hygiene Road is interpreted to consist of regressive deposits, with the condensed section (CS - facies A) probably occurring just beneath the base of the exposure. The succession of facies in the Skull Creek is quite similar to that at Spring Canyon, grading from lenticular-bedded, "basin" shales (facies B) to burrowed, well-stratified, prodelta silty shales with increasing bioturbation in indistinctly bedded lower delta-front sandstones (facies C) just below the unconformity. The upper delta-front and nearshore sandstone facies D of the Fort Collins Member seen at Spring Canyon Dam are absent. Trace fossils preserved in the marine deltaic deposits are an assemblage containing Teichichnus, Asterosoma and Terebellina. The upward gradation into more sand in the upper Skull Creek reflects an increase in depositional energy. The upper contact of the Skull Creek bioturbated shaly sandstone is a sharp, erosion surface (LSE), marked by well-preserved rooting, indicating subaerial exposure. Root casts are commonly vertical and up to several inches (cm) in length. This unconformity (sequence boundary) is overlain by interbedded carbonaceous shales and fine-grained sandstones interpreted as aggradational coastal plain deposits of the Muddy (J) Mowry Sequence. These are dominantly fresh- to brackish-water deposits which probably accumulated during the last stages of valley-fill deposition at the tops and on the flanks of the incised valleys with thinning onto the interfluves.

At the top of the coastal plain deposits is a thin, cross-bedded, marine sandstone with a chert pebble lag at its base, and Diplocraterion burrows. This sandstone sits on the TSE and constitutes the lowermost part of the marine transgressive deposits.

One of the most important reservoirs in the

Denver basin is the delta front sandstone of the Fort Collins Member, the widespread reservoir in the giant Wattenberg Field. The "pay zone" at the top of Fort Collins Member varies from 10-30 ft (3-9 m) and is truncated by the LSE along the west side of the field. Thus, the trap is an unconformity seal which prevents the gas accumulation from leaking to the surface. Mountain flank faulting may also contribute as seals.

The Muddy (J) contact with the Skull Creek is placed stratigraphically lower in the subsurface than in surface outcrops (Figures 18 and 19). This correlation explains why subsurface mapping shows the Fort Collins Member to occur in surface section (Weimer and Sonnenberg, 1989), whereas the correlation to the type Fort Collins Member locality near Spring Canyon Dam shows this member to be absent at Hygiene Road (Figure 18).

STOP 4
1.5 Mi (2.4 Km) EAST OF LAFAYETTE (Near Nov. 1992 Well Blowout in NW Sec.1, T.1S., R.69W.)

This stop is in the southwest portion of the aerially extensive oil and gas fields that straddle the axis of the Denver basin (Figure 20). Collectively, these are referred to as the basin center fields of the greater Wattenberg area The purpose of the stop is to discuss the petroleum geology and history of these fields, that are still under active development. From the accepted date of discovery of Wattenberg as 1970, more than 10,000 wells have been drilled in the basin center area. Ultimate production might be in excess of 1.5 TCF of gas and 100 million bbls of oil and condensate.

The basin center fields are, for the most part, positioned over the Wattenberg thermal anomaly ("hot spot") where temperature gradients are 2 to 3 times a normal gradient for the Denver basin (Meyer and McKee, 1985). Vitrinite reflectance data show high values in the area of present high temperature (Higley et al., 1992).

Oil and gas has migrated from mature source rocks to 3 main Cretaceous reservoirs, each of which forms separate pools. The Muddy (J) Sandstone is the main reservoir at an average depth of 7600 ft (2320 m). This reservoir, producing mainly from a widespread delta front sandstone, is underpressured by .600 to 800 psi (compared to a normal gradient of .43 psi/ft). The Muddy (J) gas reservoir is developed largely on 160 acre pattern.

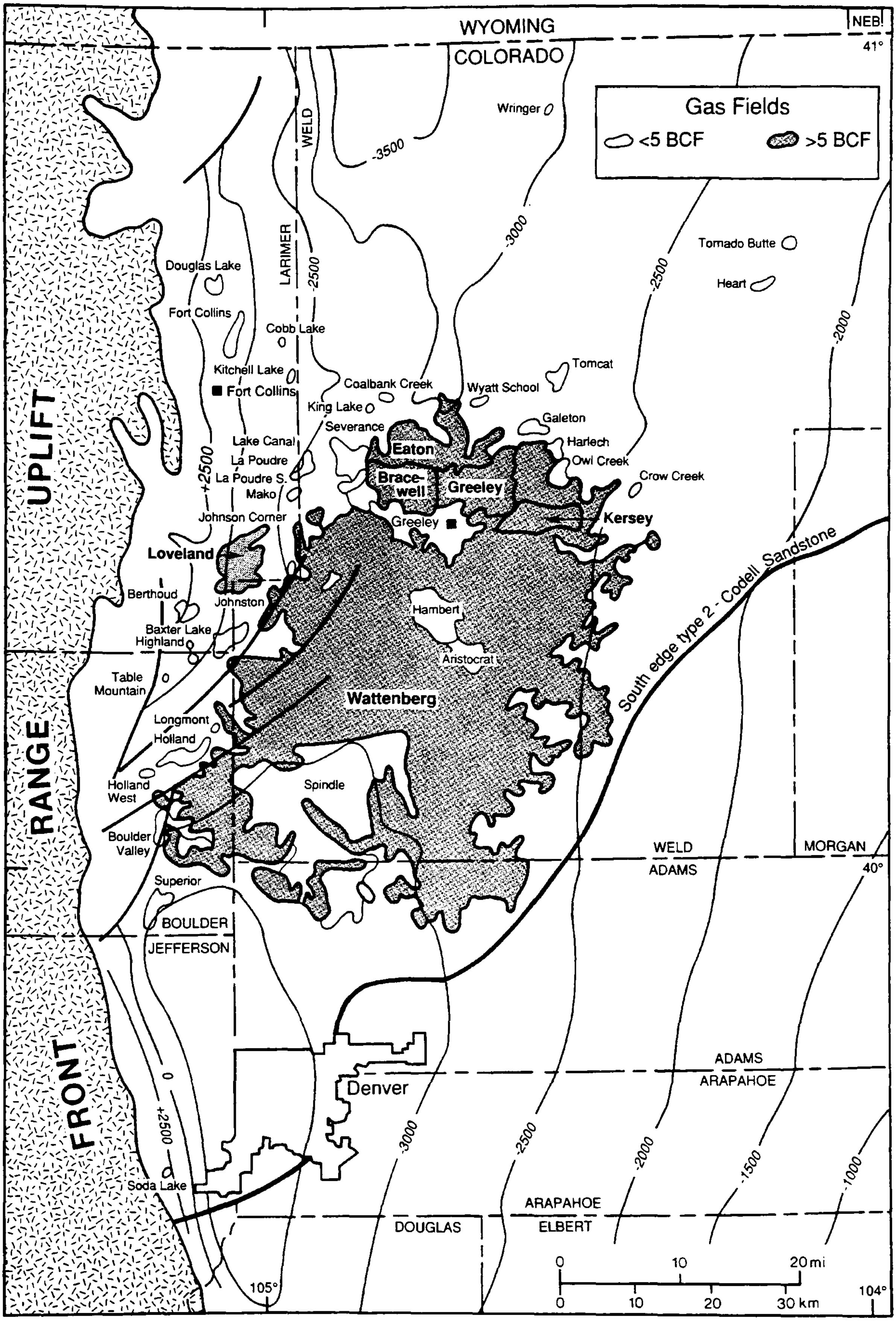
The Codell - Fort Hays reservoir, stratigraphically 450 ft (140 m) higher, is also productive over a large area but this interval, within the mature source bed package, is overpressured by as much as 1000 psi. The Codell is a sheet-like marine tight sandstone, whereas the Fort Hays Member of the Niobrara is fractured marine limestone with very low matrix porosity and permeability. Spacing is variable depending upon whether the area is classed as gas or oil. Many areas within the Wattenberg field are not presently developed because wells are completed in the Muddy (J).

Production from Terry and Hygiene Sandstones members that occur in the middle portion of the Pierre Shale occurs at depths of 4300 to 5000 ft (1370-1550 m). Although more areally restricted, important oil and gas production occurs at the Spindle (Moredock and Williams, 1976), Hambert and Aristocrat fields (Al-Raisi et al. 1994) (Figure 20). Accurate pressure data from the fields are limited, but these reservoirs are believed to be slightly underpressured (Hemborg, 1993). They occur 1600 ft (488 m) above the mature source rock package. The origin of the reservoirs is marine shelf bars that have a northwest-southeast orientation in the Terry Sandstone but with variable trends in the Hygiene Sandstone (Moredock and Williams, 1976; Porter and Weimer, 1982).

All of the sandstones producing within the basin center fields are classified as "tight sand reservoirs". Natural fracturing, related to recurrent movement on basement wrench fault systems, and hydraulic fracture treatment to stimulate wells enhance production and contribute to favorable economics for development.

Seals that contribute to entrapment of petroleum across the basin axis, in the broad south-plunging syncline, are facies changes, unconformities, faulting and diagenesis. Although generally classed as an underpressured basin because of the hydrodynamics of the Muddy (J) and D sandstones, newly compiled data indicate widespread overpressures in the Benton, Niobrara and lower Pierre formations. Over the years, when a drilling well encountered an extensive fault and fracture system in the overpressured cell, blow outs occurred, and occasionally wells caught on fire.

Figure 20. All fields in the Codell-Niobrara associated gas play. Major reservoirs are shaded. Structure contoured (in ft) on top of the Muddy (J) Sandstone (from Hemborg, 1993).


WYOMING
COLORADO
NEB
41°
Gas Fields
<5 BCF
>5 BCF
Wringer
-3500
WELD
LARIMER
-2500
-3000
-2500
-2000
Tornado Butte
Heart
Douglas Lake
Fort Collins
Cobb Lake
Kitchell Lake
Fort Collins
Tomcat
Coalbank Creek
Wyatt School
King Lake
Severance
Galeton
Lake Canal
La Poudre
La Poudre S.
Mako
Eaton
Brace-well
Greeley
Harlech
Owl Creek
Crow Creek
+2500
UPLIFT
Johnson Corner
Greeley
Kersey
Loveland
Berthoud
Johnston
Hambert
Baxter Lake
Highland
Aristocrat
Table Mountain
Wattenberg
South edge type 2 - Codell Sandstone
Longmont
Holland
RANGE
Holland West
Spindle
Boulder Valley
WELD
ADAMS
MORGAN
40°
Superior
BOULDER
JEFFERSON
ADAMS
ARAPAHOE
FRONT
Denver
0
+2500
-3000
-2500
-2000
-1500
-1000
Soda Lake
ARAPAHOE
ELBERT
DOUGLAS
105°
104°
0 10 20 mi
0 10 20 30 km

A case history of a blow out from the Fort Hays interval 1.5 mi (2.4 km) in Boulder County east of Lafayette will be discussed. The fractured reservoir at 8200 ft (2500 m) depth is part of the Lafayette wrench fault zone, an eastward extension of the Idaho Springs-Ralston shear zone mapped in the Precambrian of the Colorado Mineral Belt (Weimer, 1996).

Recurrent movement on northeast-trending wrench fault zones, mapped as continuations of the basement shear zones of the Colorado Mineral Belt, control the fracturing, and therefore economic production, within the Wattenberg field. In addition, wrench faulting controls oil and gas migration, styles of deformation (vertical vs. listric), reservoir compartmentalization and trapping. This new geologic model should assist in developing "sweet spots" in the Denver and other faulted basins which have tight sands and basin center accumulations.

STOP 5
HYGIENE ROAD SECTION

South of intersection of US 36 and Hygiene Road)

This stop is to examine the outcrop of the Muddy (J) Sandstone on the east side of U.S. Highway 36, 10 mi (16 km) north of Boulder. A stratigraphic section is described (Figure 18), and correlated to the subsurface of the Wattenberg field (Figure 19). The Hygiene Road section, in a regional context, is described with the correlation discussion of the Dakota Group (Stop 3).

Of additional interest in regard to understanding attributes of the Muddy (J) reservoirs is faulting and fracturing. A fault zone, trending east-northeast, cuts the north portion of the outcrop. Several closely spaced faults and fractures occur within the 20 ft (6 m)-wide fault zone. Slickenslides, horizontal to bedding, indicate that rock breakage was related to a right lateral strike slip fault. This type of small-scale faulting is important to production in the tight-gas sandstone reservoirs of the Wattenberg field. Massive hydraulic fracing of rocks in a bore hole could connect with natural fracturing to significantly enhance production. The interconnection would make 1 well a much better producer than another well without such a connection.

This outcrop is about 1 mi (1.6 km) south of a major northeast-trending wrench fault zone named the Windsor fault by Stone (1985). The small fault zone at Hygiene Road is synthetic to the major zone. Mapping of faults and fractures within the Wattenberg field is a project in progress by Weimer (1996).

STOP 6
EAST FLANK SIX-MILE FOLD
(4 Mi [6.4 Km] North of Intersection of US 36 and CO 7, North of Boulder)

This stop is to observe the stratigraphic and structural features of the Codell Sandstone Member of the Carlile Shale and the Fort Hays Limestone Member of the Niobrara Formation (Figure 21). These marine units are widespread in the Denver basin, and together they form an important, but low yield, oil and gas reservoir that is under active development (Figure 20). The reservoir is a combination of fractures, principally in the Fort Hays, and tight sandstone of the Codell. In the basin-center producing area over the Wattenberg "hot spot", the reservoir is sandwiched between mature source rocks and is overpressured. Pressure and migration seals between the basin-producing area and the outcrop are believed related to faulting.

The Codell Sandstone is fine-grained highly burrowed (bioturbated) sandstone with low porosity and permeability (details in Figure 21). The unit varies from a wedge edge to 50 ft (15 m) in thickness but only 35 ft (11 m) is exposed at this locality. The member is bounded above and below by unconformities (Weimer and Sonnenberg, 1983). Locally, thin (less than 0.5 ft (15 cm) and irregular bodies of coarse-grained sandstone with chert pebbles overlie the bioturbated clayey sandstone facies. Exposed in the outcrop, this coarse material is interpreted as a lag representing relict or palimpsest marine shelf deposits. The low permeability results from bioturbation of interbedded clay and sand deposits and the filling of pores by authigenic smectite, chlorite and calcite (Weimer and Sonnenberg, 1983). The lower sharp contact of the bioturbated clayey silty sandstones of the Codell and the dark gray laminated shales of the Carlile is not exposed. This contact is a surface of erosion, which shows regional truncation, and, locally in cores, has a lag of thin coarse-grained sandstones.

The dominant lithologies of the Niobrara are limestones (chalks) and interbedded calcareous, organic-rich shales and bentonites. Niobrara thickness ranges from 280 to 300 ft (85 to 92 m). Four limestone intervals, averaging 30 ft (9 m), and three intervening shale intervals (averaging 47 ft (14 m) occur regionally and are easily recognized on geophysical logs (Figure 19). The lower limestone is named the Fort Hays Member and the overlying units are grouped together as the Smoky Hill Member.

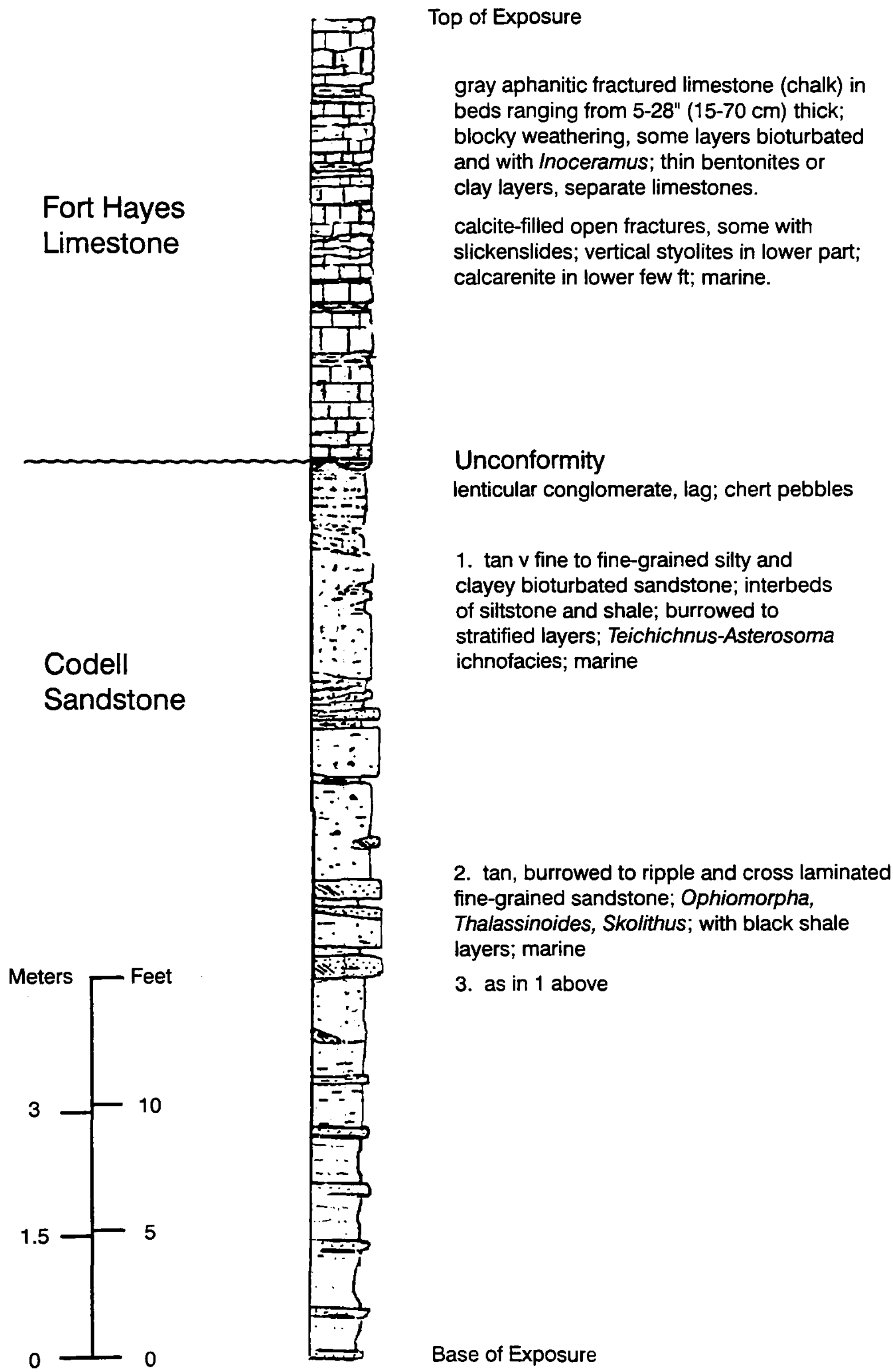


Figure 21. Stratigraphic column for Fort Hays Limestone Member of the Niobrara Formation and the Codell Sandstone Member of the Carlile Shale.

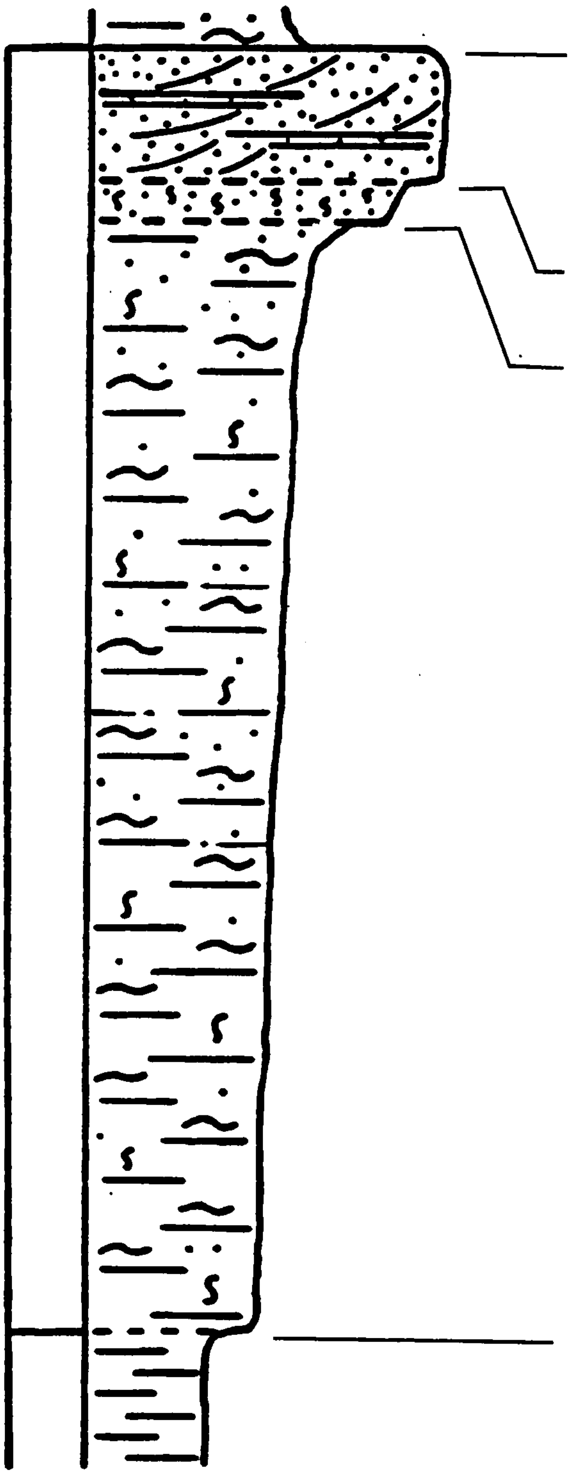


Figure 22. Composite stratigraphic section for Davis Reservoir SE Sec. 4, T. 2 N., R. 70 W. and Foothills Reservoir (NE Sec. 34, T. 3N., R. 70 W.) sections of Hygiene Member of Pierre Shale (modified from Porter, 1976).

The Fort Hays Member is 20 ft (6 m) thick, but only the lower 14 ft (4 m) is exposed. Individual limestone beds vary from 6 to 24 in (15-60 cm) in thickness and are separated by 2 to 6 in (5-20 cm) layers of shale or bentonite. Vertical intersecting fractures give the outcrop a blocky appearance. Calcite lines the east and northeast-trending fractures, whereas the north-northwest trends are void of calcite. Styolites vertical to bedding have a N.15°W. trend indicating an east orientation of the principal horizontal stress (PHS) at the time of styolite formation.

The fractures are concentrated in the more brittle limestones with some breaks crossing several chalk and shale layers and other confined to 1 or 2 layers. Most fractures do not extend into the Codell Sandstone. Terminated calcite crystals in open fractures indicate as much as .4 in (1 cm) of open space at the time of calcite infilling. This type of open fractures is oriented mainly N.80°E., parallel to the direction of the PHS.

The distribution of the Codell and Fort Hays is related to widespread marine environments of deposition and fluctuations of relative sea level in relation to movements on regional tectonic elements. The following is summarized from papers by Weimer (1984) and Weimer and Sonnenberg (1983). A broad structural doming of central Wyoming and northern Colorado during a sea-level drop about 90 m.a. caused erosion of marine lower Carlile strata. Chert and phosphate pebbles and thin lenticular coarse-grained sand formed as a lag on the erosional surface. Codell sand was deposited as marine shelf and shoreline sand during the lowstand of sea level, and reworked during a subsequent sea level rise. A second drop in sea level between 89 and 89.5 m.a., concurrent with regional doming in northern Colorado along the Trans-Continental arch, caused erosion with another lag with pods of conglomeratic sandstone. During the subsequent rise of sea level, the Fort Hays limestone onlapped the structural arch, first with thin deposits of calcarenite, and as the water deepened, with pelagic chalk and clays.

The sedimentation and erosion associated with the above events are believed to have been by marine processes. No evidence has been reported for subaerial exposure of the strata.

Details of the lithologies, biostratigraphy, fracturing and regional correlations of the Niobrara-Codell outcrop sections are summarized by Kauffman and Coates (1994) for the Lyons-Boulder area.

STOP 7
EAST OF FOOTHILLS RESERVOIR
(2.2 Mi [3.5 Km] East of Intersection of US 36 and Hygiene Road)

This stop is to observe the reservoir characteristics of the Hygiene Sandstone, one of 2 sandstones in the Pierre Shale productive at the Spindle oil field 10 mi (16 km) downdip to the southeast. The Terry Sandstone, 400 ft (122 m) stratigraphically higher than the Hygiene, does not extend to the outcrop.

The outcrop is on private property south of Hygiene Road and 1.7 mi (2.7 km) west of the town of Hygiene for which the sandstone was named. Lithology of the 60 ft (18 m) exposed section is tan fine- to medium-grained porous and permeable sandstone. Details of grain size, composition, and physical and biogenic structures are given on Figure 22. From Hygiene cores of the Spindle field, the lithologies of the producing sandstone are similar to the outcrop, but the pay zone averages only 25 ft (8 m) in thickness (Porter and Weimer, 1982).

The Hygiene Sandstone Member is blanket-like with a distribution in outcrop from Boulder to Fort Collins of 50 mi (80 km) and with a width eastward into the subsurface of 20 mi (32 km). The updip seal on the Spindle field, to prevent migration to the outcrop, is the northeast-trending Longmont wrench fault zone.

2. Summary of Petroleum Geology

THE PETROLEUM SYSTEM, DENVER BASIN

The genetic relationship between a layer of active source rock and the resulting oil and gas fields is called a petroleum system (Magoon and Dow, 1994, p. 3). The emphasis in the search for and development of oil and gas has shifted to consider first the overall petroleum system within a basin, and then to define specific plays and drillable prospects.

The nearly 100 years of exploration and development in the Denver basin has followed the historical nation-wide pattern: drilling near oil seeps; locating anticlinal traps, first by surface mapping and then by use of geophysics; searching for stratigraphic and source-rock fractured traps; and, developing the large synclinal basin center accumulations. This paper summarizes current thought about the petroleum system of the Denver basin with emphasis on the continuous hydrocarbon accumulation in the greater Wattenberg field area (Figure 23). This basin center area is in a mature stage of development with closely spaced subsurface control. By analyzing and interpreting the well data, geologic models are formulated which may assist in the exploration and development in less well known basins.

Two types of geologic basins are discussed in this report. One is the structural basin, called the Denver basin, in which, after deposition and burial, the formations were downwarped into a structural low (Figure 24). This deformation was during basin and mountain building movements in the crust between 71 and 50 Ma, the period of the Laramide orogeny. The second type of basin, covering the western interior of the continent, was the Cretaceous basin of deposition, in which the source rocks and reservoir rocks of the Denver basin were deposited. The Cretaceous time interval for this basin before fragmentation by the Laramide was 110 to 71 Ma.

Basin Features and Traps

The essential data in basin analysis that must be collected to define the petroleum system is: basin type and deformational history; thickness and types of sedimentary layers; types of traps; source, reservoir and seal rock evaluations; and, fluid distributions and pressures through time.

The Denver basin is an asymmetric foreland basin with a gentle east flank with 0.5° west dip and a folded and faulted west flank with steep dips (Figures 23 and 24). The basement is of Precambrian age, older than 1.6 Ga, and is composed of igneous and metamorphic rocks. Of the approximately 13,000 ft (4000 m) of stratigraphic section in the basin, 9500 ft (2200 m) is Cretaceous and lower Tertiary, of which 80 percent is marine Upper Cretaceous. Late Paleozoic and Mesozoic rocks make up the lower 3500 ft (1080 m) of the section.

Several types of traps, known to occur within the overall Denver basin, are also found within the greater Wattenberg area (Figure 25) (Weimer, 1992). Seals that trap oil and gas in sandstone reservoirs are caused by facies (or capillarity) changes, faults, clay plugs within channel sandstones, diagenesis, unconformities, anticlines, or combinations of these features.

Cretaceous Source Rocks

Over the past decade organic geochemistry research has identified source rocks for oil and gas in the Denver basin and described the timing of generation and migration to traps. Several organic-rich layers in the Graneros, Greenhorn, Niobrara and Pierre formations are recognized (Figure 26) that are believed to have generated large volumes of oil and gas (Clayton and Swetland, 1980). The source rocks consisting of type II oil-prone organic matter occur in the lower 900 ft (275 m) of the Upper Cretaceous, largely in condensed sections deposited in the Western Interior basin. Approximately 500 ft (150 m) of this interval consists of shale with total organic carbon (TOC) estimated to range from 1 to 6 percent (Gautier et al., 1984; Barlow, 1986; Pietrasek-Mattner, 1995, Kauffman and Coates, 1994). Shales with the highest TOC values (4 to 6 percent) also have high gamma ray values (Sonnenberg and Weimer, 1993, Smagala, et al. 1984). These "hot shales" occur in the Sharon Springs Member of the Pierre Shale, within the Niobrara Formation, and in the middle part of the Graneros Shale (Figure 26). The Muddy (J) Sandstone reservoir occurs beneath the Graneros Shale source rock, and the Codell Sandstone and Fort Hays Limestone reservoir is within the overall source rock interval.

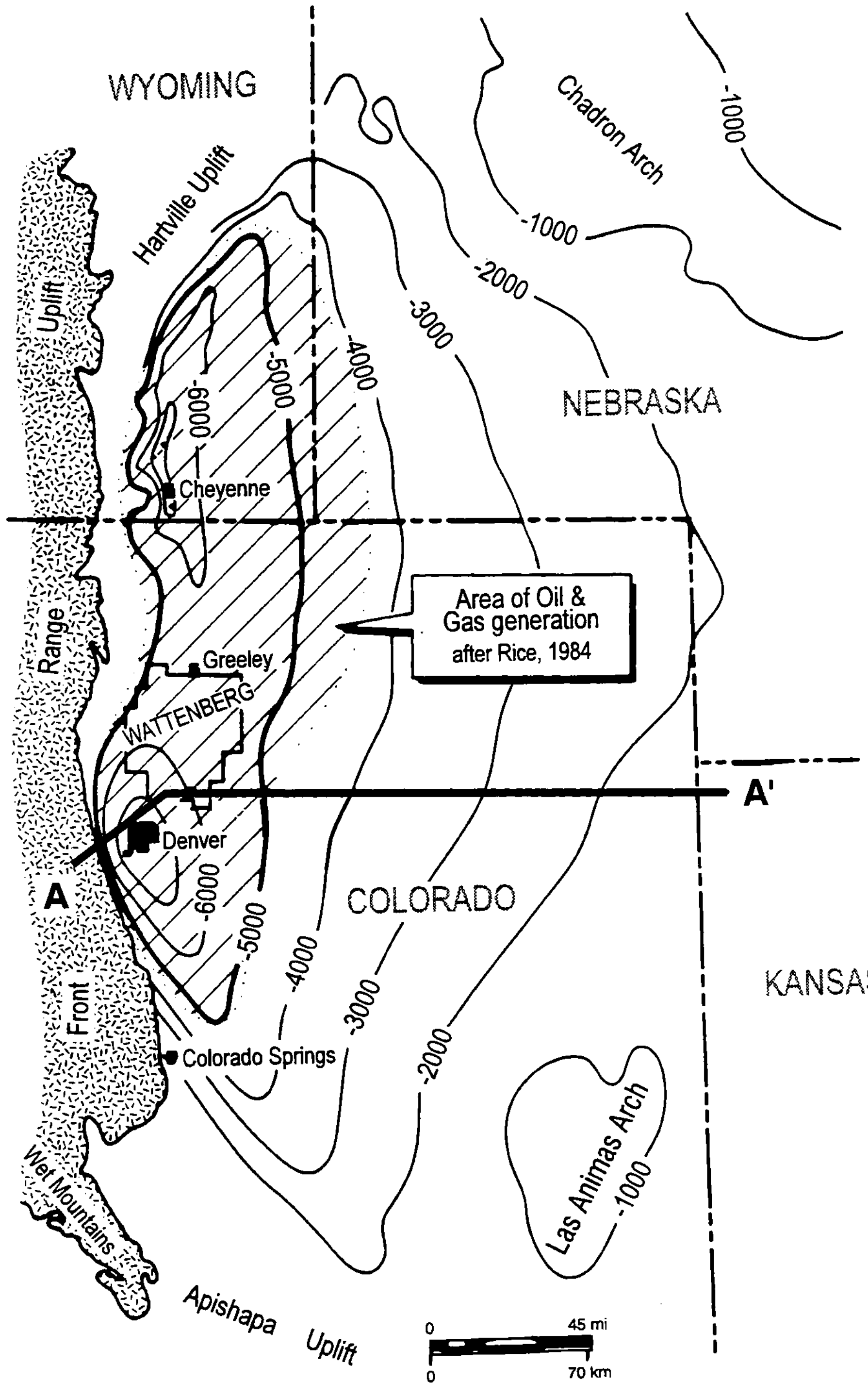


Figure 23. Area of oil and gas generation in Denver basin (Rice, 1984) superimposed on structure contour map. Contour interval = 1000 ft (305 m).

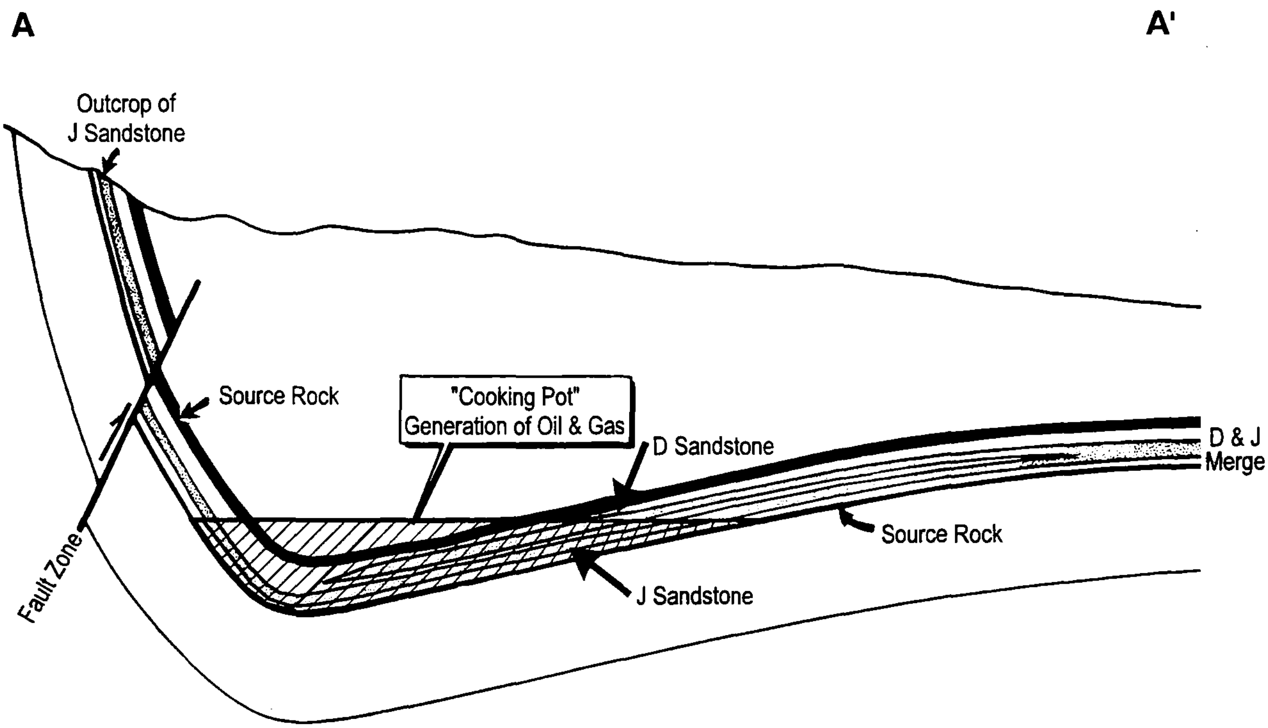


Figure 24. Diagrammatic cross section, Denver basin with distribution of D and Muddy (J) Sandstone. Upper and lower source rocks are in the Graneros Shale and Skull Creek Shale, respectively.

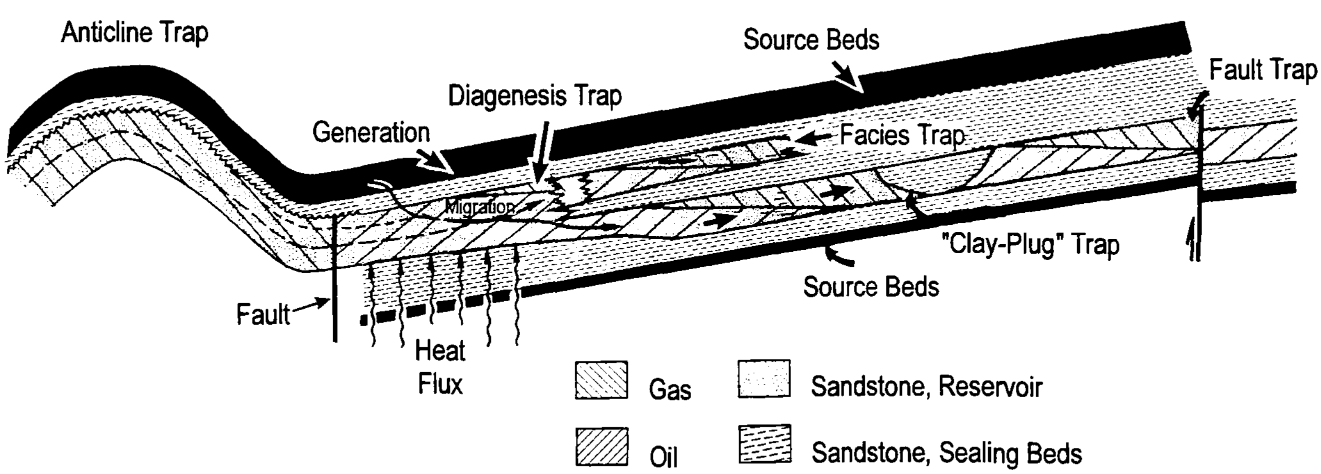


Figure 25. Types of oil and gas traps, Muddy (J) Sandstone, within basin center accumulations, not to scale.

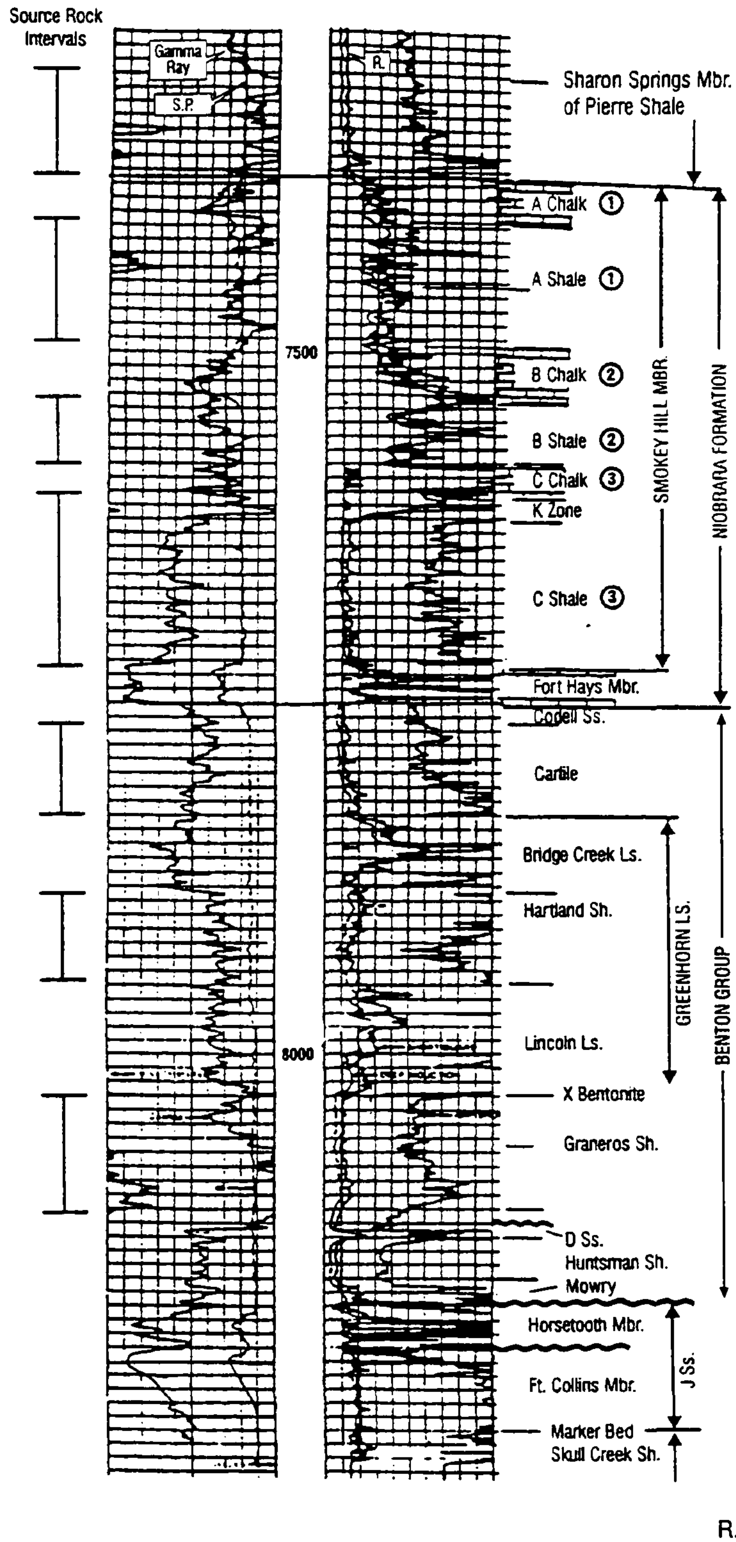


Figure 26. Well log stratigraphic section from Skull Creek Shale to lower Pierre Shale with intervals of source rocks and stratigraphic units.

The high TOC shales are widespread marine units in the Denver basin. During the early phase of oil generation, the original water in the reservoir sandstones was displaced. Therefore, oil and gas may be produced in the greater Wattenberg area wherever porosity and permeability can be predicted in reservoir rocks. Reservoirs that yield only water are not present in the deeper portion of the Denver basin, but are found at shallower depths on both the east and west flanks.

The generation of oil from source rocks is related to the original composition of the organic material and to temperature. Temperatures increase with depth because of the thermal gradient in the earth's crust. A source rock is regarded as mature, i.e. generating crude oil or gas, when the temperature is high enough to change a solid (organic matter in rock) to a liquid (crude oil) or gas. With increasing temperature the liquid may be later changed to gas, referred to as "thermogenic gas". The time interval that a rock is subjected to a certain temperature field is also important to generation. MacMillan (1980) prepared a burial history curve for the Denver basin and used a time-temperature index to determine the time when the Cretaceous source rocks started generating hydrocarbons. He concluded first initial oil generation started when the depth of burial reached 7800 ft (2380 m) about 65 Ma (end of Cretaceous). That the oil generation may have began as early as 70 Ma is suggested by Crysdale and Barker (1990) and Tainter (1982).

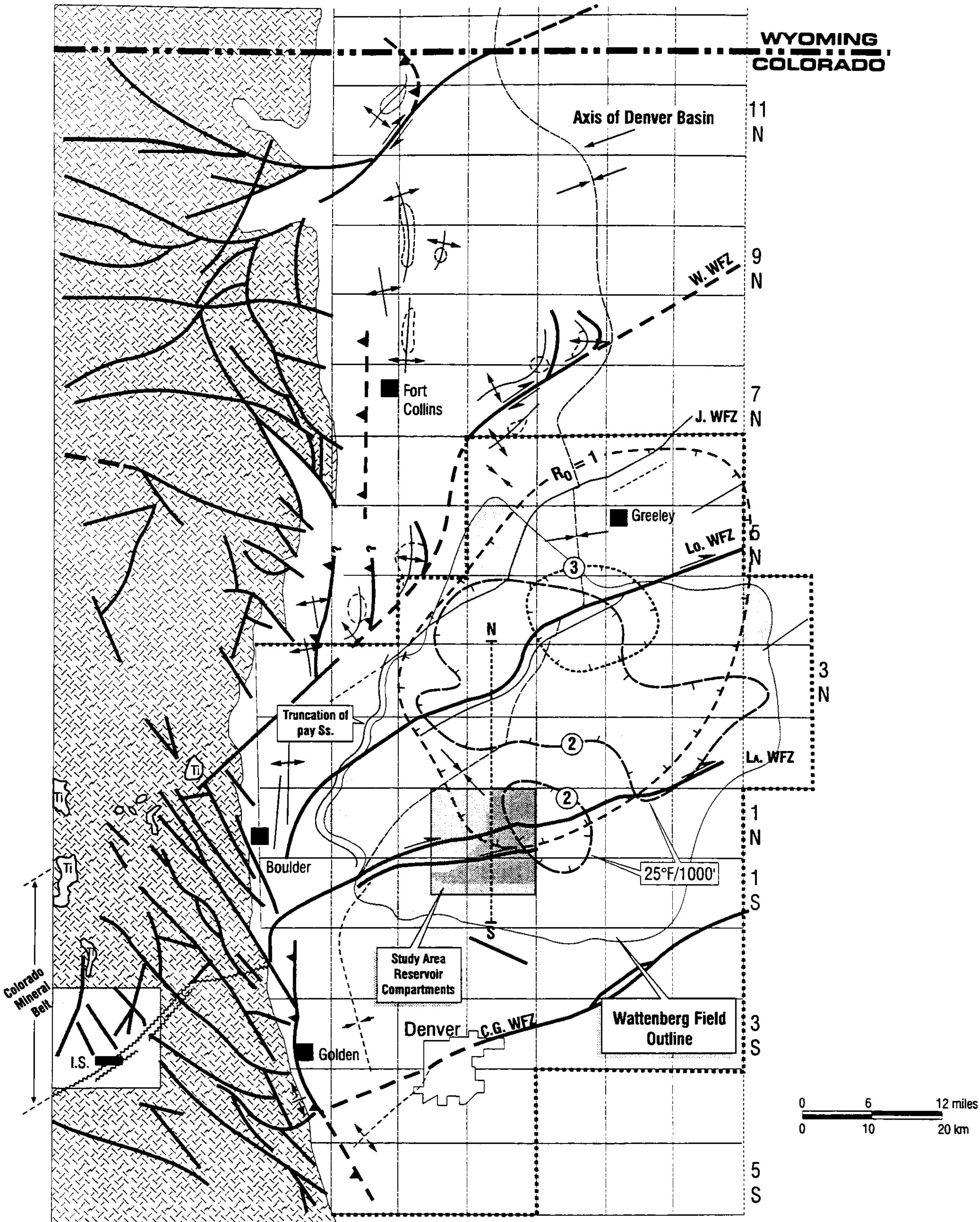
Temperatures and Pressures

An unusually high temperature gradient is present in the Wattenberg field (Myer and McGee, 1985; Higley and Gautier, 1988; Higley et al., 1992) (Figure 27). This thermal anomaly ("hot spot") is superimposed on the overall temperature field related to the burial history of the basin (Figures 23 and 24). Myer and McGee (1985) and others have related the high heat flow to igneous intrusive masses in the basement rocks that occur along the projected fault trends of the Colorado mineral belt. Collectively, the wrench faults mapped across the basin (Figures 27 and 33). are a major zone of weaknesses in the crust that controlled emplacement of intrusives and later heat flow into the overlying sedimentary rocks. The most likely age of the intrusives is late Cretaceous—early Paleocene although intrusives of Oligocene age are also possible (Mutschler, et al. 1987). Based on the amount of erosion of Precambrian rocks to expose Tertiary intrusions in the Colorado Mineral Belt, the depth of the "hot spot" intrusives is estimated to be 2000 to 3000 ft (600-920 m) below the top of the Precambrian.

Because of thermal maturation, the source rock interval and lower portion of the Pierre shale are presently overpressured over the "hot spot" (Figures 27 and 28). The overpressures occur as a cell which is sealed from the underlying Muddy (J) and D sandstones, which are underpressured (Pruit, 1978; Belitz and Bredehoeft, 1988), and from the overlying Hygiene and Terry sandstone members of the Pierre Shale also regarded as underpressured. An extensive study was conducted by Zhao (1996) of anomalous pressures, hydrogeochemistry, and thermal maturation of Cretaceous sandstones throughout the Denver basin. He interpreted the formation of pressure compartments in the basin center to be caused by hydrocarbon generation and the evolution of permeability seals in tight sandstones. The pressure variations are relative to a gradient of 0.43 psi.

Pressure information in fields reported by Hemborg (1993) have been supplemented by data released by operators or consultants in the Wattenberg and Spindle field areas. The pressure points for 28 wells in Ts. 3 and 5 N., R. 65 W. and T. 3 N., R. 66 W. are plotted (Figure 28) for which mud weights were significantly increased during drilling by addition of barite to prevent blow-outs. The dot for each well is placed at the depth at which the high pressure, believed to be related to fracture systems, was encountered. Similar pressure data points, as well as recorded blow-outs, some with fires, have been observed throughout the Wattenberg field.

Figure 27. Map showing relationship of Wattenberg field thermal anomaly to wrench fault zones that are an extension of the Colorado Mineral Belt. Three criteria for recognizing the "hot spot" are shown: 1. a contour of Ro values of 1 for the Muddy (J) Sandstone (from Higley, Gautier and Pawlewicz, 1992; 2. contours for 25° F./1000 ft (14°C/300 m) gradient from Myer and McKee, 1985, as mapped on Muddy (J) Sandstone; and 3. Gas-oil ratio of 15,000 for Codell Sandstone as mapped by Wright and Fields, 1988 indicating area of thermogenic gas wells. Hatchures point in direction of higher values.


WYOMING
COLORADO
Axis of Denver Basin
11 N
9 N
7 N
5 N
3 N
1 N
1 S
3 S
5 S
W. WFZ
J. WFZ
Lo. WFZ
La. WFZ
C.G. WFZ
Fort Collins
Greeley
Boulder
Golden
Denver
$R_0 = 1$
3
2
2
N
S
Truncation of pay Ss.
25°F/1000'
Study Area Reservoir Compartments
Wattenberg Field Outline
Ti
Ti
Ti
I.S.
Colorado Mineral Belt
69W
68W
67W
66W
65W
64W
0
6
12 miles
0
10
20 km
R.J. WEIMER, 10/95

Oil and gas is generated in the high pressure cell associated with the source rock interval and have migrated to the low pressure reservoir intervals (Figure 28). The exact nature of the seals at the base and top of the pressure cell is uncertain, but may be related to diagenesis in the organic-rich source rocks, or bentonites within the shale formations. Lateral seals may be caused by regional faulting and/or related diagenesis.

The geographic distribution of the Wattenberg "hot spot" is based on several criteria. Direct temperature measurements of fluids in the fields show an unusually high gradient plotted as a 25° F/1000 ft (14°C/300 m) isotherm (Figure 28) (Myer and McKee, 1985). Moreover, regional levels for temperature of source rocks can be defined by vitrinite isoreflectance (R°) contours (Higley et al., 1992). For the Muddy (J) Sandstone a R° contour value of 1 is plotted for comparison with the present temperature gradient (Figure 27). There is a close correspondence for the overall thermal anomaly.

In addition, Smagala et al. (1984) and Rice (1984) and others report that this basin center gas in the Muddy (J) Sandstone is of thermogenic origin. In the areas surrounding the Wattenberg gas field, where temperatures are lower, both oil and gas are produced (e.g. Ts. 2 and 3 S., Rs. 64 and 66 W). A similar relationship, but in a smaller area centered in T. 4 N., R.66 W., is observed in gas-oil ratios (GOR) in the Codell Sandstone pool, which is stratigraphically 450 ft (138 m) higher. A 15,000 GOR contour [(Figure 27) (from Wright and Fields, 1988)], is used to classify gas wells (higher values) from oil wells (lower values). This GOR anomaly is also interpreted to be related to maximum generation of thermogenic gas.

Reservoir Characterization and Burial History

Reservoirs in the Wattenberg field are found in the Muddy (J), Codell, Hygiene and Terry sandstones, and in dense fractured limestones of the Niobrara Formation (Figure 26). Because of low porosity and permeability the sandstone reservoirs are classed as "tight", and production is enhanced either by natural fractures or by hydraulic fracturing. With the exception of the Horsetooth Member of the Muddy (J) Formation, all of the sandstones are of shallow marine origin. The Horsetooth was deposited in valley-fill or coastal-plain environments.

Many detailed studies have been published about the reservoirs of the Denver basin. For descriptions of the petrology and thickness variations of the Wattenberg and Spindle fields reservoirs, the reader is referred to summary papers by Weimer et al., (1986, 1989); Higley and Smoker, (1989); Porter and Weimer, (1982), and Pittman, (1989).

The principal reservoir for the Denver basin is the Muddy (J) Sandstone, and regional diagenetic changes affecting reservoir quality are described by Higley and Gautier (1986, 1987, 1988). Porosity and permeability in all members of the Muddy (J) Sandstone in the Denver basin decrease because of depth of burial and associated higher temperature (Figures 29 and 30). The decrease results primarily from diagenetic processes that caused mineral growth, generally silica overgrowths and clay minerals, within the pore space of the original reservoir sandstone. An east-west cross section for the Denver basin illustrates the relationship among depth, porosity, permeability and thermal maturity (R°) for the Muddy (J) Sandstone (Figure 29). The Turkey Creek section (T.C.) has been added to the original by Higley and Gautier (1987). The line of section passes south of the Wattenberg "hot spot" and, therefore, is believed to reflect normal changes in the burial history of the basin (Figure 31). The median porosity decrease with depth shows some local variations, but generally reservoir quality is uniformly low in the basin center. Diagenesis, destroying porosity and permeability, appears to have been more intense over the high heat flow area of the Wattenberg "hot spot" (Higley and Smoker, 1989).

Unusual concentrations of silica in the Muddy (J) Sandstone have been noted in the greater Wattenberg area. Early in the drilling history, Matuszczak (1973) mapped a high "siliceous" area along the north margin of the Wattenberg field (Greeley area), and Higley and Smoker (1989) report up to 15 percent silica cement in two wells in the Wattenberg field. Reinert and Davies (1976) reported up to 10 percent quartz cement in the Third Creek field area, and Weimer (1992) reports that quartz cement, occurring along a linear trend on the west side of the oil field, may provide a seal from downdip gas wells. The quartz cement occurs as irregular zones (tongues) within productive sandstone and also as linear vertical zones within the sandstone, suggesting fault control on fluid movement.

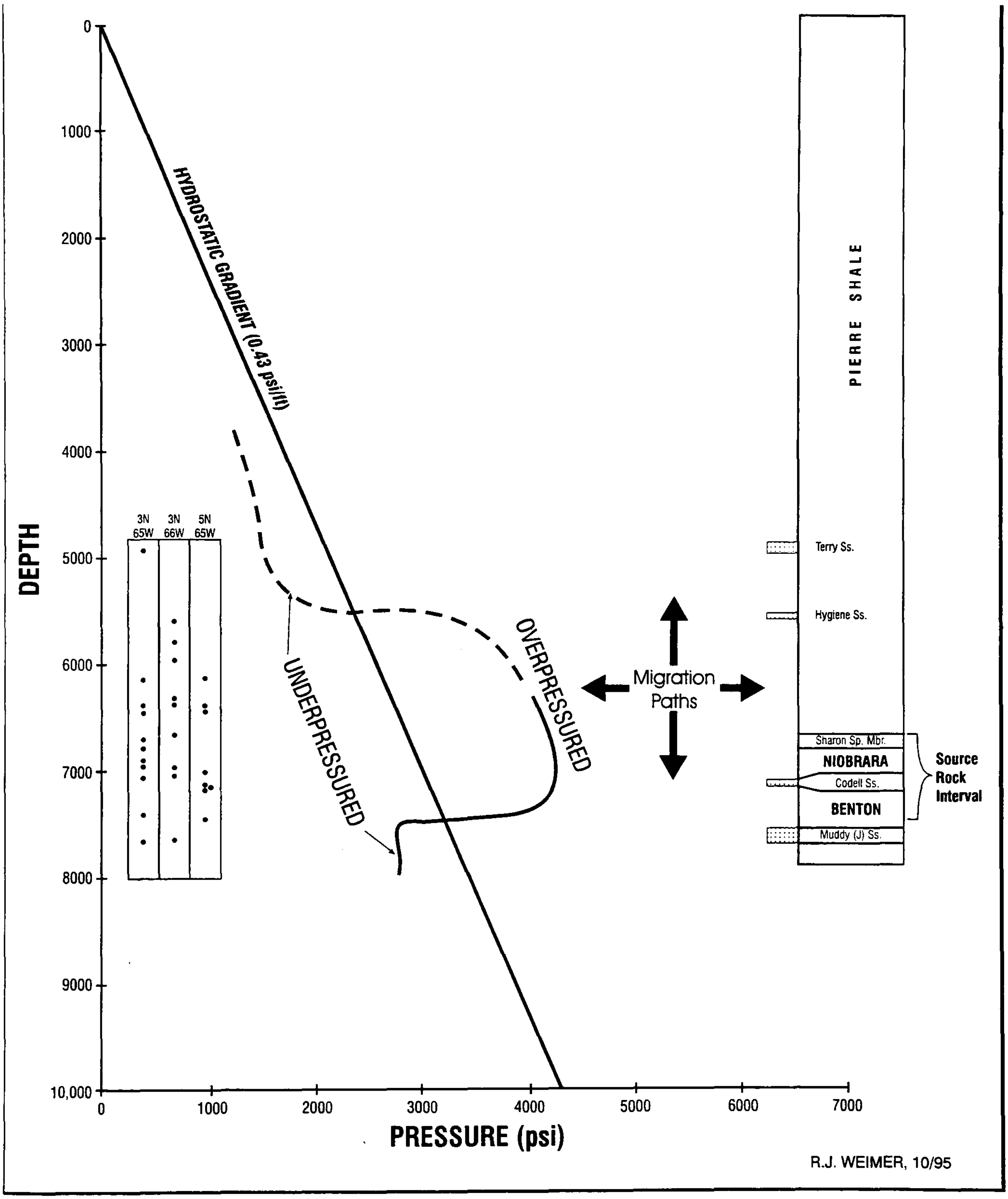


Figure 28. Pressure plot for Ts. 3 N., Rs. 65 and 66 W., and 5 N., R. 65 W. Dots indicate the stratigraphic level in wells for which pressure data are available.

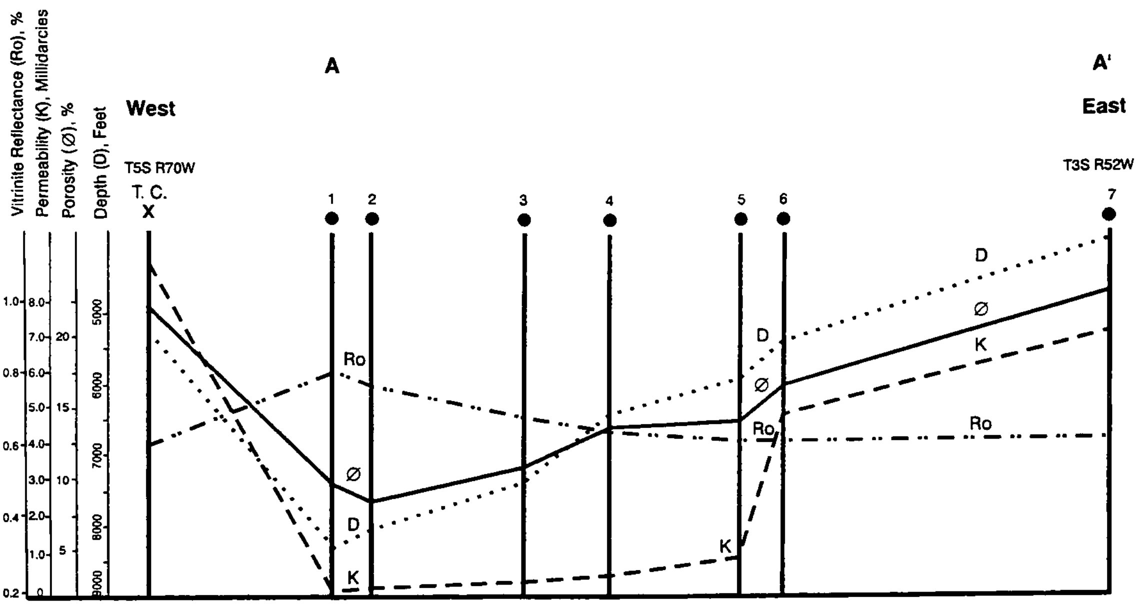


Figure 29. East-west section across Denver basin from T. 3 S., R. 52 W. to Turkey Creek outcrop sec. 12, T. 5 S., R. 70 W. (location on Figure 30). Relationships are illustrated for the Muddy (J) Sandstone among depth (D, in feet), porosity (Ø in percent), permeability (K, in millidarcies) and thermal maturity (Ro, in percent) of the Muddy (J) Sandstone in the Denver basin (modified after Higley and Gautier, 1987). Turkey Creek (T.C.) section added by Weimer.

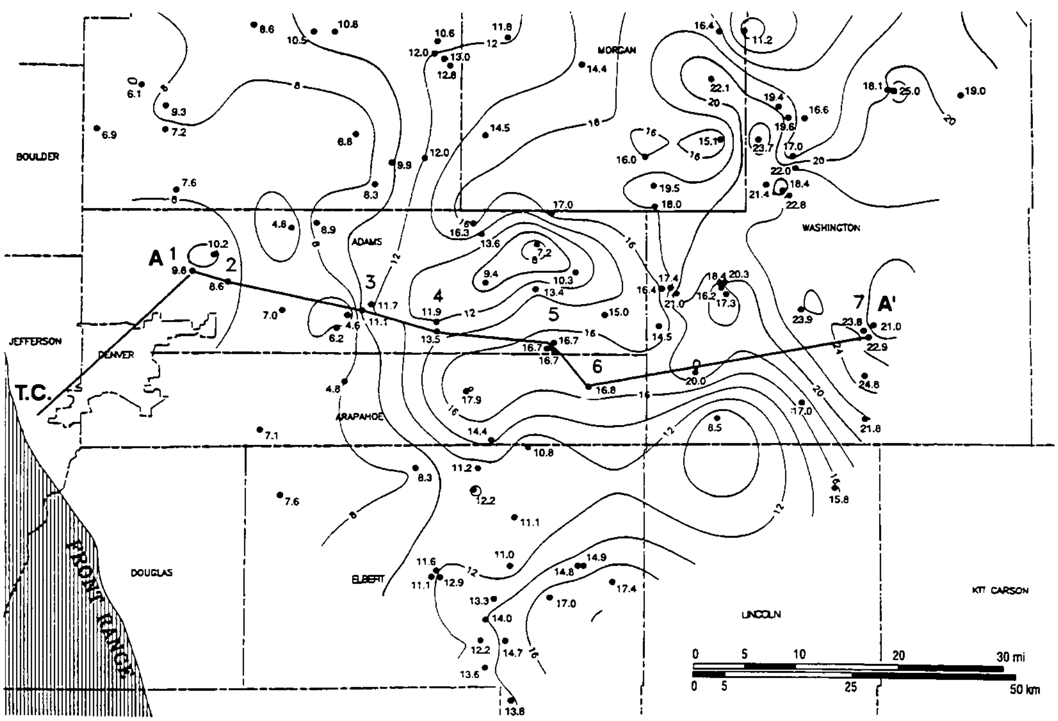


Figure 30. Median porosity contour map of the Muddy (J) Sandstone, central Denver basin (from Higley and Gautier, 1987). Contour interval = 2 percent.

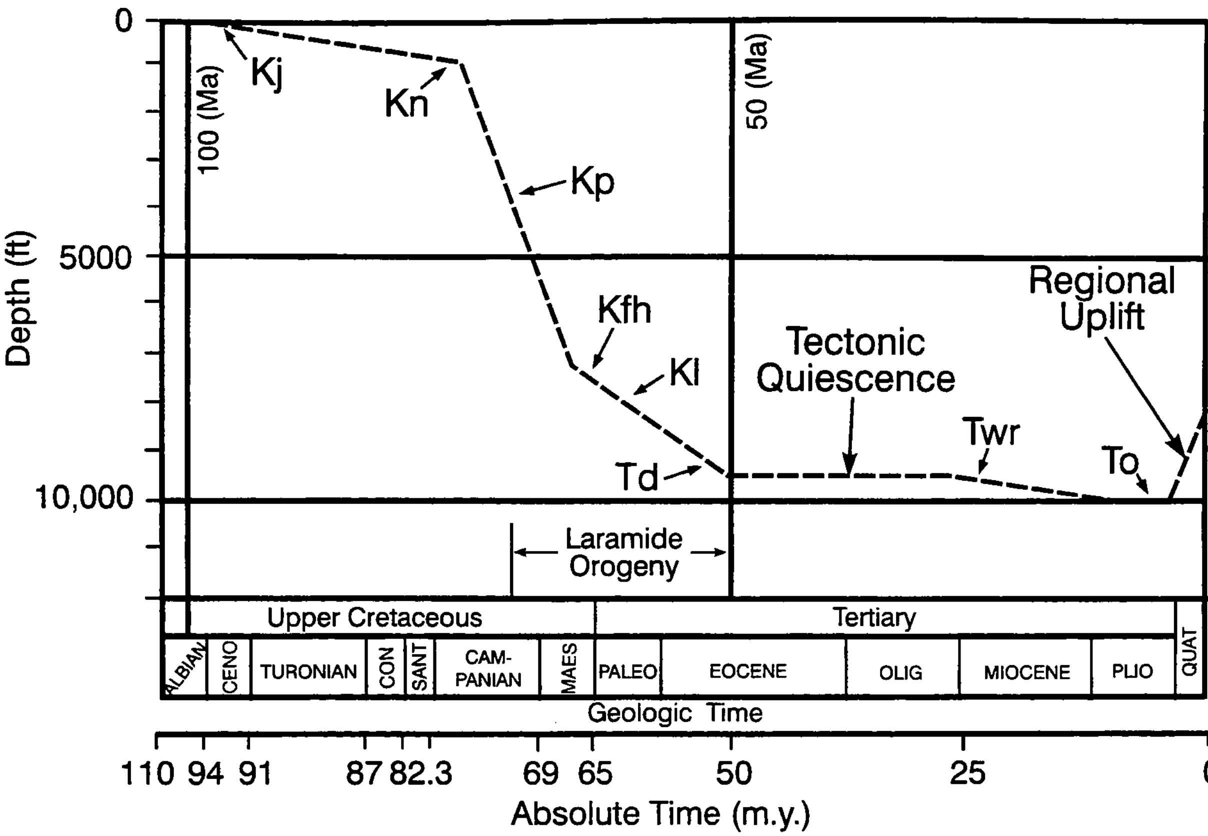


Figure 31. Generalized profile of subsidence of Muddy (J) Sandstone in axial portion of Denver basin. Kj = deposition of top of top Muddy (J) Sandstone, Kn = deposition of top Niobrara Formation, Kp = deposition of Pierre Shale, Kfh = deposition of Fox Hills Sandstone, Kl = deposition of Laramie Formation, TKd = deposition of Dawson Arkose and Denver Formation, Twr = deposition of White River Group, To = deposition of Ogallala Formation.

The origin of the silica is uncertain but is postulated to be derived from within the sandstone reservoirs by pressure solution, or precipitation of dissolved silica from solutions derived from outside sources (Reinert and Davies, 1976). The outside source may be compaction fluids from sedimentary layers rich in biogenic silica (e.g. the Mowry Shale), or from hydrothermal solutions related to intrusives causing the Wattenberg "hot spot", or other sources. In either case, faults and fractures may have been pathways by which silica was introduced into the sandstones.

The large areal size of the Wattenberg field reservoir is the result of the widespread Fort Collins Sandstone Member of the Muddy (J) Formation, which was deposited in a prograding delta front environment. However, faulting and fracturing associated with the major wrench fault zones that cross the Wattenberg field (Figure 27) are an additional important factor in making the "tight gas sands" economical. The faulting and fracturing is equally important to production from the other reservoirs in the greater Wattenberg area.

STRUCTURE OF GREATER WATTENBERG AREA

The gentle east flank of the Denver basin has been regarded, historically, as a stable tectonic element with only minor warping, or structural nosing during subsidence, and block rotation to a 0.5° west structural dip. Folding and faulting of the basin strata were visualized as largely confined to the narrow west flank. Exceptions to this viewpoint were authors who projected the well-known Precambrian wrench fault systems of the Front Range, along which Laramide movement occurred, into or across the Denver basin (e.g. Spencer, 1961; Anderman and Ackman, 1963; Haun, 1968; Stone, 1969; Warner, 1978; Curtis, 1988, and Weimer, 1978, 1980). Faults mapped at the surface in latest Cretaceous rocks were believed to extend to the basement. However, seismic data reported by Davis (1974, 1985) indicated a disharmonic relationship among shallow depth fault zones (e.g. Boulder-Weld fault zone) and the basement structure. The wealth of new closely spaced well data provides the basis for defining the structural styles at different stratigraphic levels.

This paper presents new maps and cross sections and describes the importance of wrench faulting and related fracturing in petroleum exploration and development in the greater Wattenberg area. The concepts and deformational styles formulated from this area of dense subsurface control may have application in other less developed Rocky Mountain basins which have "tight" gas reservoirs as targets.

Old and New Mapping

Early in the development of Wattenberg field, when wells were spaced on 320 or 640 acres and large areas were undrilled, structure contour maps were drawn which showed no faulting at the Muddy (J) Sandstone level (Figure 32, Weimer, 1980; Myer and McKee, 1985). With contouring spaced at 100 ft (31 m) intervals the structure was depicted as a regional broad south-plunging syncline with local strike or dip changes of low magnitude. Computer-generated structure contour maps show similar structure. Although it straddles the basin axis, most of the field is on the east flank of the basin.

Over the past decade, the infill drilling on 160 acre spacing, with now more than 3000 control points, allows for mapping details of structure not previously possible (Figure 33). The following factors were used in a structure contour mapping program:

- Structural datum elevations on the top of the Muddy (J) Sandstone were posted from a computer data base; the datum points were not generally verified from direct observation of logs, but spot checks indicate an accuracy of elevations within a range of 6 to 15 ft (2 to 5 m).

- By using a 10 ft (3 m) contour interval in areas of closely spaced wells, strike and dip anomalies in relation to regional patterns were hand contoured to identify faulting and/or related folding. Moreover, some of the fault trends on contour maps were confirmed by recognition of normal faults cutting the Muddy (J) to Fort Hays interval within the Spindle field study area (Figures 34 and 35). In the mapping program the following assumptions were made:

- Offset of strata and abrupt changes in strike or dip are primarily the result of rigid basement block rotation along fault planes because the Muddy (J) Sandstone deformed primarily by brittle deformation.
- minor drape folding may also be present, especially associated with movement along and close to fault planes.
- the tectonic fault block model is controlled by recurrent movement on basement faults; some, if not all, of the major fault block movement during the Cretaceous was by wrench faulting (until about 60 to 64 Ma).
- Faults and fractures are nearly vertical because of origin associated with wrench faulting and strike-slip movement.
- The synclinal axis of Denver basin is offset and the trend modified because of wrench faulting (Figure 33).

Wrench Fault Model

The wrench fault style of deformation follows the earlier work by Stone (1969) and is part of the Colorado lineament of Warner (1978), although these authors did not show fault patterns in the Cretaceous section.

In the greater Wattenberg area five major east-northeast-trending fault zones are recognized with numerous synthetic and antithetic faults (Figure 33). From north to south, the wrench fault zones are named Windsor (Stone, 1969), Johnstown and Longmont (from field usage), Lafayette (named here) as a continuation of the Idaho Springs-Ralston shear zone, and Cherry Gulch, a northeast-trending shear zone, 6 mi (9.6 km) south of Golden. The order of importance in deformation is uncertain and may have changed through time, although the Idaho Springs-Ralston seems the most dominant. The five main zones are spaced 10 to 20 mi (16 to 32 km) apart and each shows significant variation in trend especially north indentations in the northeast trends, probably formed at intersections of fault trends. More northwest and north-south faults are probably present but are difficult to map where they parallel structural strike and evidence for faulting is only a change in regional dip.

Evidence for wrench faulting is summarized as follows:

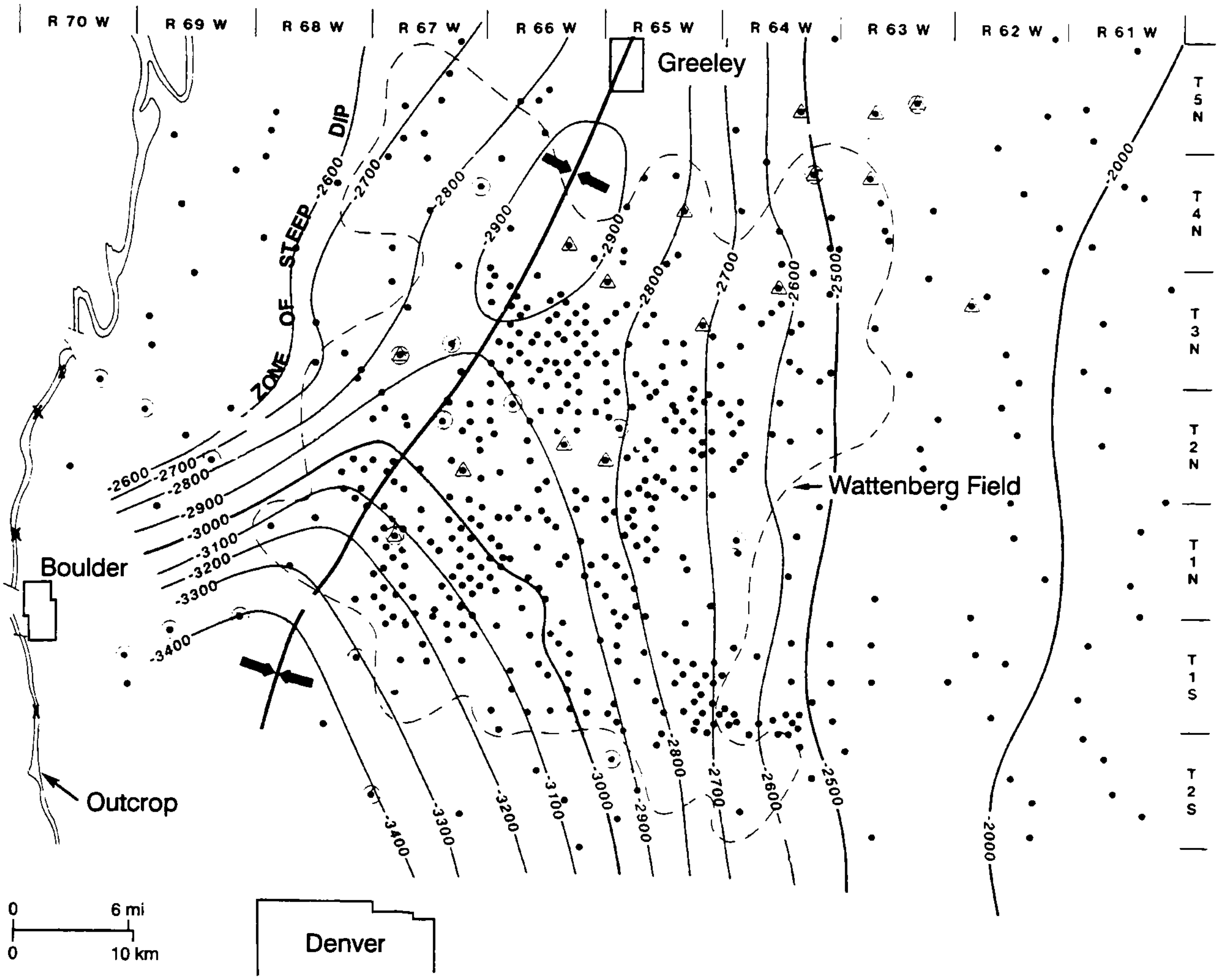


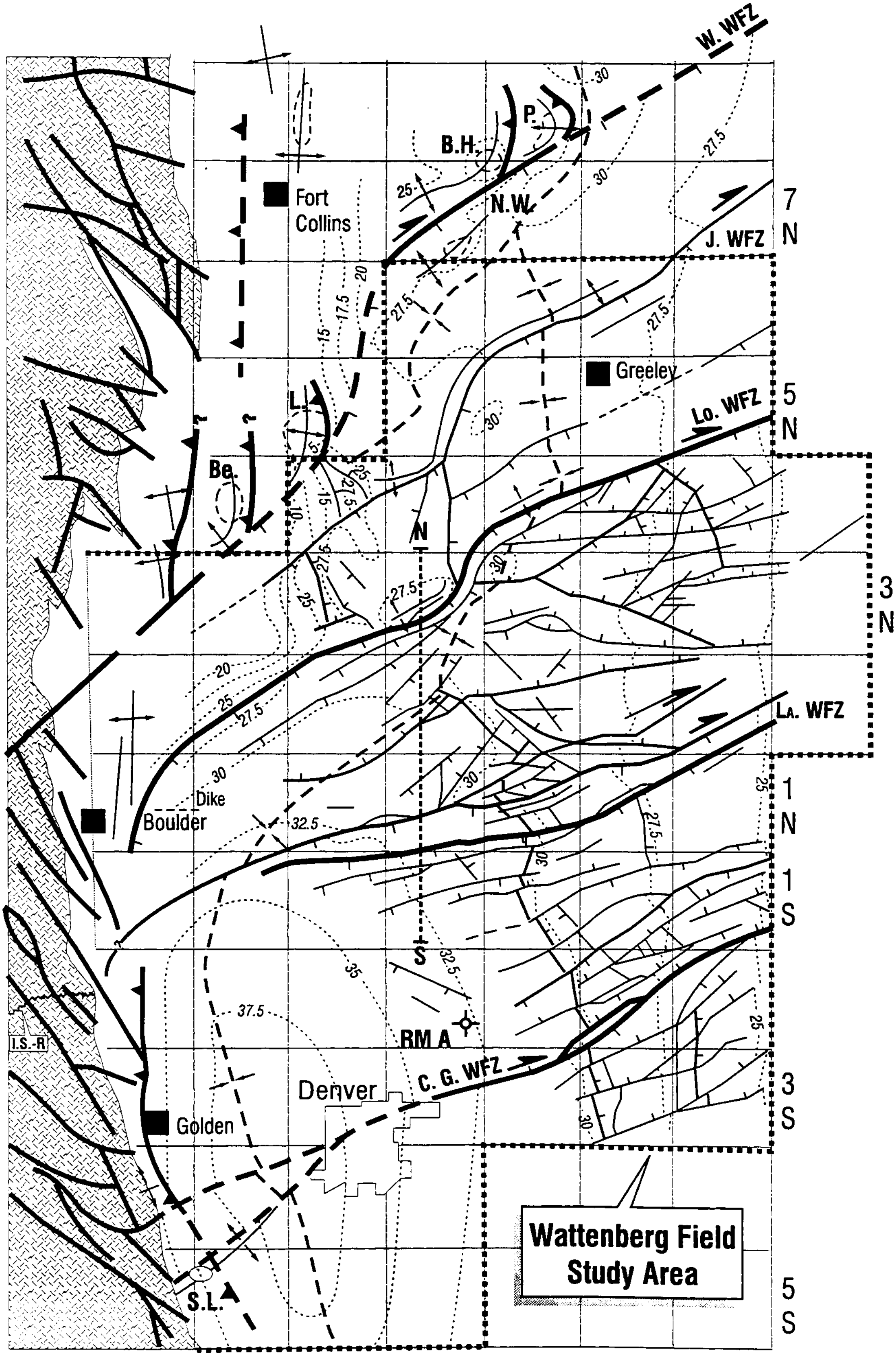
Figure 32. Structure contour map of Wattenberg Field area. Contoured on top of Muddy (J) Sandstone. Contour interval is 100 ft (30.5 m). Solid dots are control wells; those with triangles have cores from Muddy (J) Sandstone.

• In the Muddy (J) to Fort Hays interval, vertical to near vertical faults and fractures occur with only a small percentage (6% or less) cut by wells. Based on limited seismic data, the faults are believed to extend to the basement.

• Stylolites vertical to bedding and slickenslides parallel to bedding are observed in the Niobrara limestone outcrops between Boulder and Lyons. Horizontal slickenslides are also present in minor fault zones in Muddy (J) Sandstone outcrops with right lateral movement. These features are diagnostic of wrench faulting.

• The subsurface mapped faults fit a regional pattern of faults, folds and thrusts related to east-directed horizontal stress, confirmed by the stylolites. This style explains the amount of deformation in the basin at least 50 mi (80 km) distance from the mountain front (Figure 33).

• An east-west tension fracture parallel to the principal horizon stress was filled by the Valmont dike at approximately 64 Ma (Larson and Drexler, 1988). This dike parallels small open fractures in the Niobrara outcrops that are filled with calcite.



W. WFZ
P.
B.H.
N.W.
Fort Collins
J. WFZ
7 N
Greeley
Lo. WFZ
5 N
L.
Be.
N
3 N
La. WFZ
Dike
Boulder
1 N
1 S
S
RM A
C. G. WFZ
Denver
Golden
I.S.-R
3 S
S.L.
Wattenberg Field Study Area
5 S
69W
68W
67W
66W
65W
64W

Figure 33

EXPLANATION

Structural Features

(WFZ) Wrench Fault Zone
W. Windsor
J. Johnstown
Lo. Longmont
La. Lafayette
C.G. Cherry Creek
I.S. - R.SZ Idaho Springs - Ralston Shear Zone

Oil Fields and Wells

S.L. Soda Lake
Be. Berthoud
L. Loveland
B.H. Black Hollow
P. Pierce
N.W. New Windsor
RMA Rocky Mountain Arsenal Well

2° Strike and dip of strata (from wells)

Precambrian outcrop

Axis of anticline

Axis of syncline

Inferred direction of wrench movement

S N Line of cross section

Figure 33. Structure contour map and wrench fault zones in central Denver basin with synthetic and antithetic faults and/or associated drape folds in the Wattenberg gas field and adjacent area. Fault patterns in Denver Basin areas are mapped by structure contouring on top of Muddy (J) Sandstone, and by identifying faults cutting the Fort Hays, Benton and Muddy (J) intervals. Fault patterns in Front Range from Tweto, 1979. Faults are near vertical to vertical and basement related. Arrows indicate direction of wrench movement. Contours x 100 represent subsea depths to top of Muddy (J) Sandstone

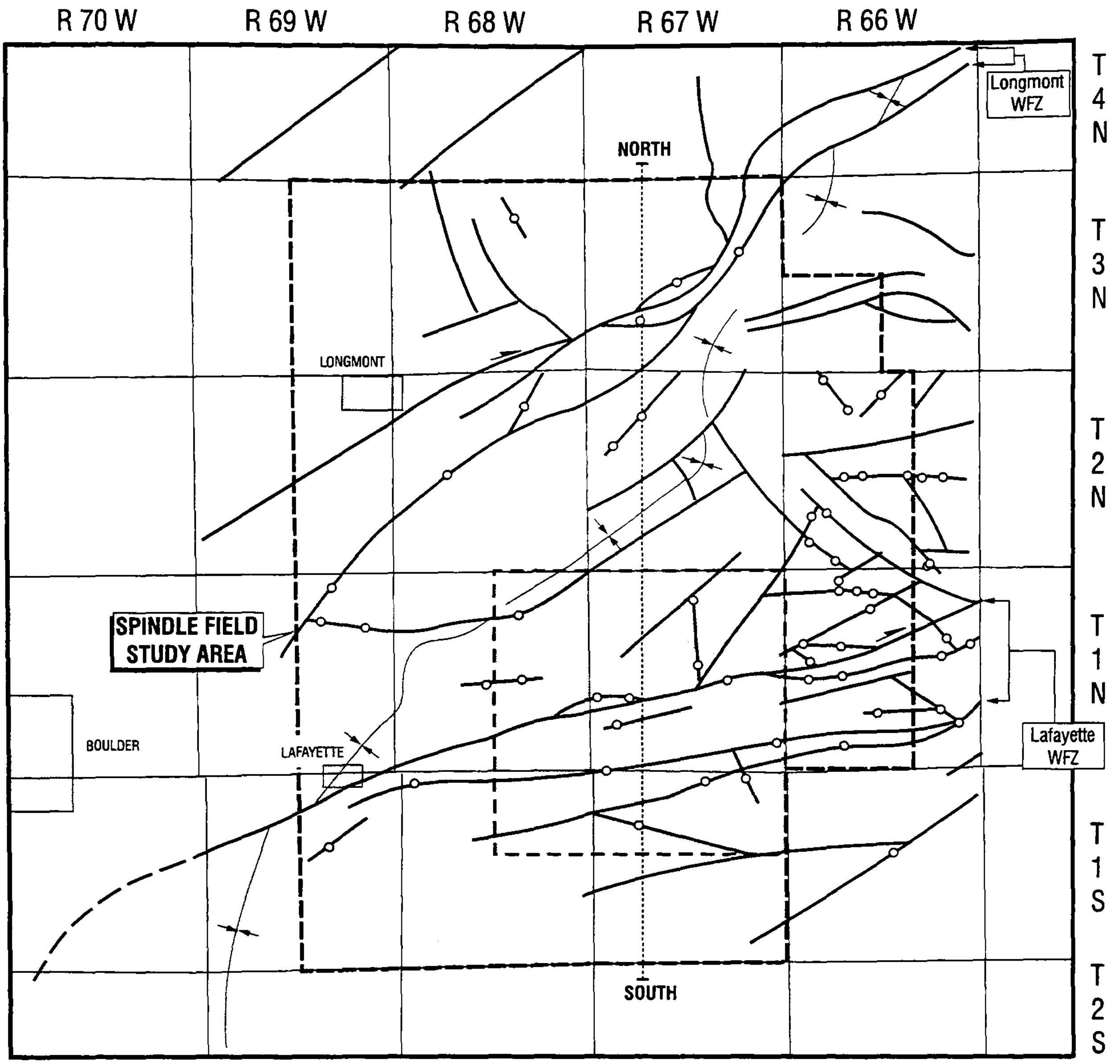


Figure 34. Fault pattern at Muddy (J) Sandstone level from Figure 33 for Spindle field study area. Circles indicate wells in which normal faults cut either the Fort Hays Limestone, Benton Group or the Muddy (J) Sandstone (Figure 26). Synclinal axis of Denver Basin is offset and/or deflected by faulting as shown. These fault patterns may have minor variations from patterns determined by structure contouring on Figure 33.

- The basin axis is offset from south to north by the fault zones by right lateral movements (Figure 33).

- The faults, where cut in wells, are normal and have a vertical throw from 20 to 100 ft (6 to 31 m). Only the vertical component of fault movement can be measured by well data, or by single seismic lines, but compartmentalization of reservoirs suggest an important lateral component of movement.

- Different styles of faulting are present at different stratigraphic levels (Figure 35), but the faults appear to be genetically related to recurrent movements on the near vertical basement faults.

Some of the above listed features may also be explained by other structural styles of deformation, but collectively the data favor wrench faulting.

Spindle Field Study Area

The Spindle field study area covers 12 townships within the greater Wattenberg area (Figures 34 and 36). The purpose of the smaller study area is to relate the basement faulting of the Lafayette and Longmont WFZ to listric-type faulting that occurs in the upper Niobrara and Pierre formations. The important Spindle oil and gas field, producing from the Terry and Hygiene sandstones, lies immediately south of the Longmont WFZ and north of, and within, the Lafayette WFZ. Gas and condensate is also produced from the deeper Muddy (J) Sandstone developed on a 160 acre spacing. The Spindle field, originally drilled on 80 acres, now has been infilled on 40 acre spacing.

Approximately 840 well logs were analyzed for faulting in the 1000 ft (305 m) interval from the Skull Creek Shale to the top of the Sharon Springs Member of the Pierre Shale (Table 4). The faults located by structural contour mapping (Figure 33) on top of the Muddy (J) Sandstone were observed in the Muddy (J), Benton and Fort Hays interval in about seven percent of the well logs (Figure 34). By contrast 16 percent of the logs showed faults in the Smoky Hill Member of the Niobrara and the lower Pierre. This higher percentage reflects the listric nature of the faulting so that more wells cut the lower angle normal fault planes.

The largest concentration of faults is in T. 1 N., R. 66 W. along the Lafayette WFZ, where 48 percent of 73 wells are faulted. Observed faults are along both synthetic and antithetic trends, but some townships, away from the main WFZ, have very few faults. The faults are all normal faults and missing section averages 40 ft (12 m).

The genetic relationship between the listric and vertical faults are illustrated by a structural cross-section (Figure 35). Wells are spaced about 1 mi (1.6 km) apart along a 26 mi (42 km) long (Table 5). The cross section was originally prepared using 1 in. (0.25 cm) = 100 ft (31 m) electric logs which were taped together to simulate a seismic section. In general, wells were drilled to the Skull Creek Shale but some are deeper. Procedures and observations were as follows:

- Twenty-five time-stratigraphic intervals from the Skull Creek Shale to above the Terry Sandstone were searched for faults (total interval = 4000 ft [1210 m]).

- Vertical to near-vertical faults were taken from faults mapped at the Muddy (J) level (Figure 33).

- Clustering of listric faults were identified at 2 main stratigraphic levels, upper Niobrara (Smoky Hill Member) and lower Pierre, and upper Hygiene and Terry sandstones.

- The disappearance of the small listric faults at depth may be because of passage into bedding planes (Davis, 1985), or by merging with the basement faults as a type of negative flower structure. The latter is favored because this relationship would develop stress during recurrent wrench fault movement, to initiate the faulting.

- All faults are normal, and no repeated or thickened section was observed, a condition expected if the listric faults passed into bedding planes.

- In general basement faults step down to the south, except in the area of well numbers 3 through 6 where an anticlinal closure is present in the Muddy (J) Sandstone. This is at a northward bend in the Longmont WFZ (Figures 33 and 35).

- Oil generated in the source rock interval has migrated 1500 ft (460 m) vertically along faults to be trapped in the Hygiene and Terry sandstones (Figure 28).

The structure of the Spindle field area was mapped by Moredock and Williams (1976) and drawn without faults (Figure 37). Using a bentonite bed near the base of the Terry Sandstone as a structural datum, strata strike N. 50 to 60° E. and dip 0.5° to the southeast. The field is entirely on the northwest flank of the Denver basin at the Terry level. At the time of map preparation control points were spaced at 80 acres with large undrilled areas. The contouring shows many structural anomalies drawn as plunging folds. When infill drilling for pilot water flooding was initiated, virgin pressures were found in fault blocks, so Amoco Production Company decided to infill the entire field

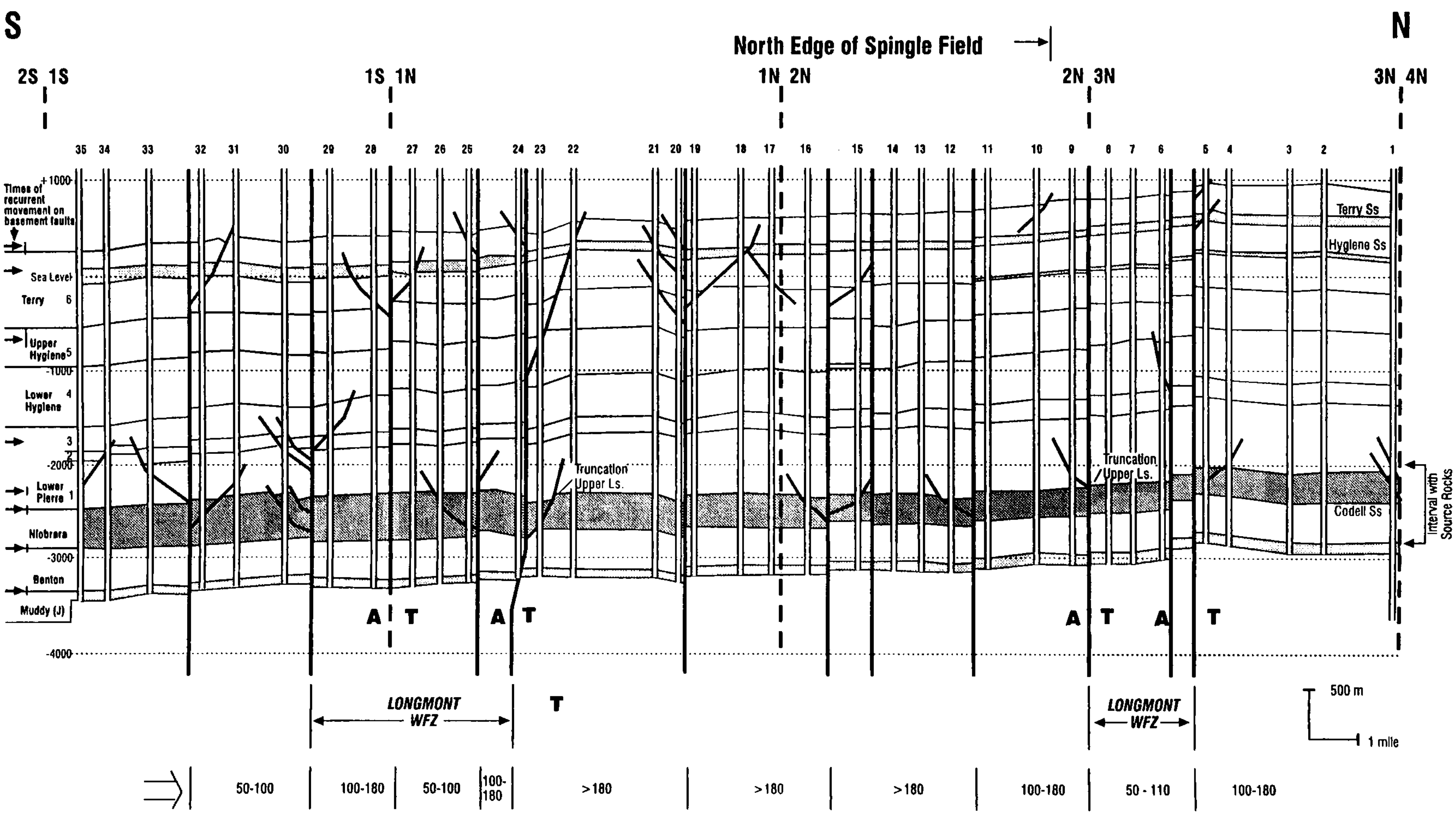

S
N
North Edge of Spingle Field
2S 1S
1S 1N
1N 2N
2N 3N
3N 4N
35 34 33 32 31 30 29 28 27 26 25 24 23 22 21 20 19 18 17 16 15 14 13 12 11 10 9 8 7 6 5 4 3 2 1
Times of recurrent movement on basement faults
+1000
Sea Level
Terry 6
Upper Hygiene 5
-1000
Lower Hygiene 4
3
2
-2000
Lower Pierre 1
Niobrara
-3000
Benton
Muddy (J)
-4000
Truncation Upper Ls.
Truncation Upper Ls.
Terry Ss
Hygiene Ss
Codell Ss
Interval with Source Rocks
A T
A T
A T
A T
LONGMONT WFZ
T
LONGMONT WFZ
500 m
1 mile
50-100
100-180
50-100
100-180
>180
>180
>180
100-180
50 - 110
100-180

Table 4. wells in north (N) - south (S) structural section through R 67 W from T 3 N to T 1 S.

Well Name	Sec	Location Spot T.	R.W.
1. General Oil Magnason	4	3N	67
2. Amoco Smith	8	3N NESWSW	67
3. Amoco Houston	17	3N SWNENE	67
4. Amoco Means	15	3N NESWSW	67
5. Martin Strong	21	3N NE	67
6. Amoco Kurtz	28	3N SENESW	67
7. Amoco 1-8 Hazel	32	3N NESWNE	67
8. Amoco Dodeno Unit	33	3N NESWSW	67
9. Amoco Baldwin	4	2N NESWN	67
10. Western O&M Sprague	9	2N NWSESW	67
11. Energy Minerals	16	2N -----------	67
12. Amoco Greeley Nat. Bank	15	2N SWNESW	67
13. Amoco Prem-Turkey	22	2N NESWNE	67
14. Amoco Deepe	22	2N SWNESW	67
15. Amoco C-Hunt	28	2N NESWNE	67
16. Macchi-Ross Gumeson	32	2N SWNENE	67
17. Amoco 1-D Miller	5	1N NESWNE	67
18. Amoco 1-C Miller	4	1N NESWSW	67
19. Vessels Hingley	8	1N SWNENE	67
20. Amoco-RMFuel C-6	8	1N NESWNE	67
21. Amoco -RMF 1	8	1N SWNWSW	67
22. Amoco uprr 42 PanAm 1	17	1N NESWSW	67
23. Vessels Herbers	20	1N NWSENE	67
24. Amoco Marguerite	20	1N NESWSW	67
25. Amoco 1-B Foxtail Frms	28	1N NWSESW	67
26. Amoco 1-C Howard	32	1N NWSESW	67
27. Rocky Mtn O&G Jacobucci	32	1N SW1/4	67
28. Rocky Mountain O&G Degenhart	5	1S NENE	67
29. Rocky Mountain O&G Zarlengo	4	1S NESW	67
30. Amoco Elder	9	1S SWNE	67
31. Rocky Mountain O&G McElwain #1	17	1S NENW	67
32. Rocky Mountain O&G McElwain #2	17	1S SE1/4	67
33. Marlis Gupfer	20	1S SWSW	67
34. Vessels Davidson	29	1S NENE	67
35. Vessels Bramming	31	1S	67

Figure 35. North-south structural cross section (N-S) in R. 67 W. from T. 4 N. through T. 1 S., across the Spindle field. Five producing intervals are indicated: Muddy (J) Sandstone; Codell Sandstone and Niobrara, Hygiene and Terry Sandstones. Two styles of faulting are shown: near-vertical to vertical faults (believed to be basement-related), extending from Muddy (J) Sandstone to above the Terry Sandstone, and 2 major intervals of listric faulting: the Niobrara and lowermost Pierre, and the Hygiene-Terry. Offset of strata is indicated only by faulting, although drape folding may be present as well. Times of recurrent movement on basement faults, believed to cause the listric faulting, is shown on left side of figure. The location of numbered wells is shown in Table 4. GOR = Gas/Oil Ratio.

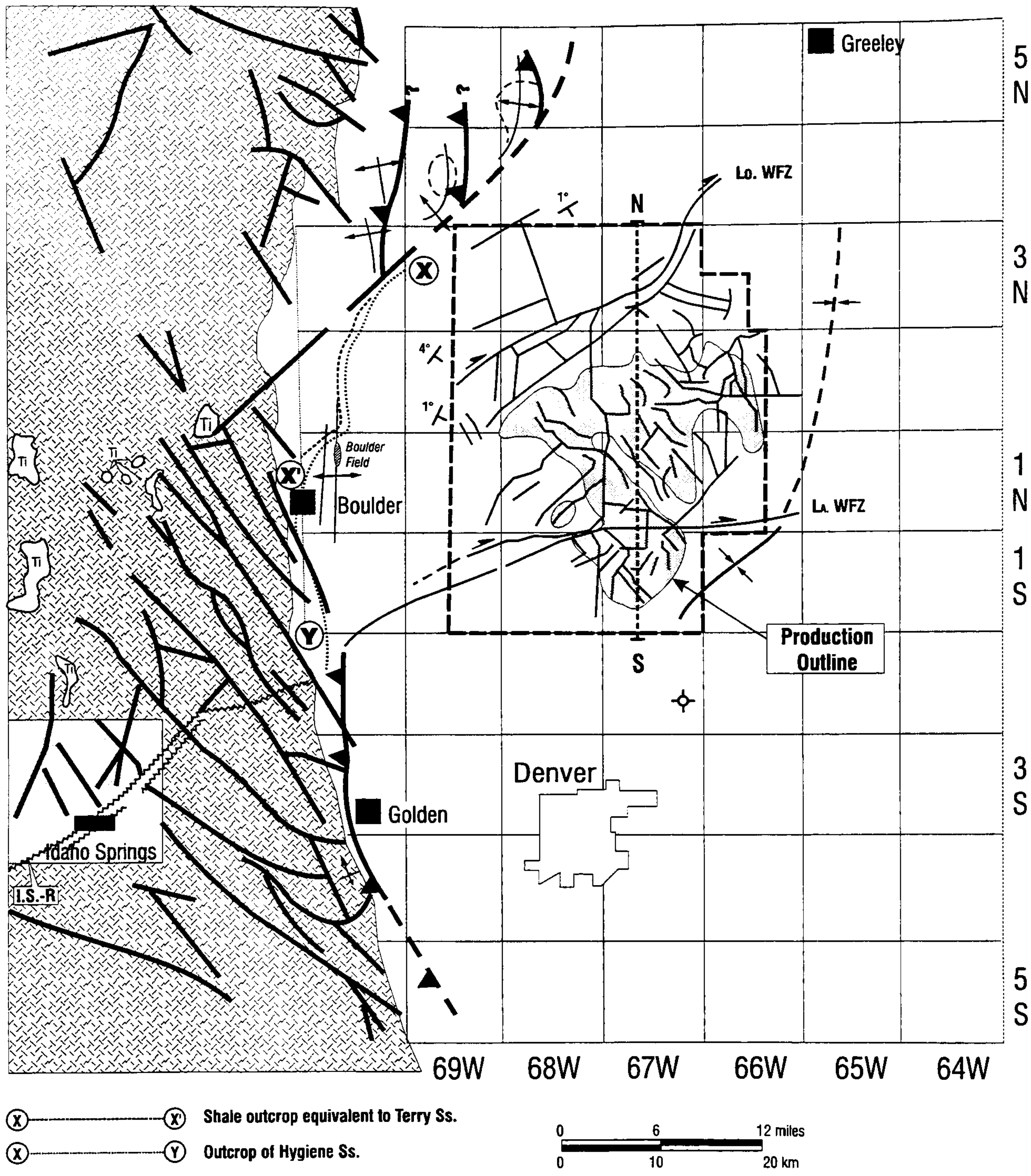


Figure 36. Lines are faults and/or associated drape folds within Spindle field and adjacent area as mapped by structure contouring on top of Terry Sandstone. Faults may be either listric, cutting the Terry and related strata, or near vertical to vertical and basement related (refer to N-S section, Figure 35). Refer to Figure 33 for explanation of abbreviations.

Table 5. Faults observed in wells in Spindle Study area T 2 S through T 3 N, R 66-69 W.

Township-Range	No. of wells	No. of faults cutting Niobrara and lower Pierre	No. of faults cutting Fort Hays, Benton and Muddy (J) Ss.	% faulted
1 S., 67 W.	38	13	4	45
1 S., 68 W.	29	2	1	10
E1/2, 1 S., 69 W.	5	2	1	60
1 N., 66 W.	73	23	11	48
1 N., 67 W.	120	12	12	20
1 N., 68 W.	60	19	3	37
E1/2, 1 N., 69 W.	41	13	3	63
2 N., 66 W.	117	21	10	26
2 N., 67 W.	108	18	6	22
2 N., 68 W.	98	3	1	4
E1/2, 2 N., 69 W.	0	0	0	0
3 N., 67 W.	104	9	3	12
3 N., 68 W.	41	1	1	5
E1/2, 3 N., 69 W.	6	–	–	0
	840	136 (16%)	56 (7%)	

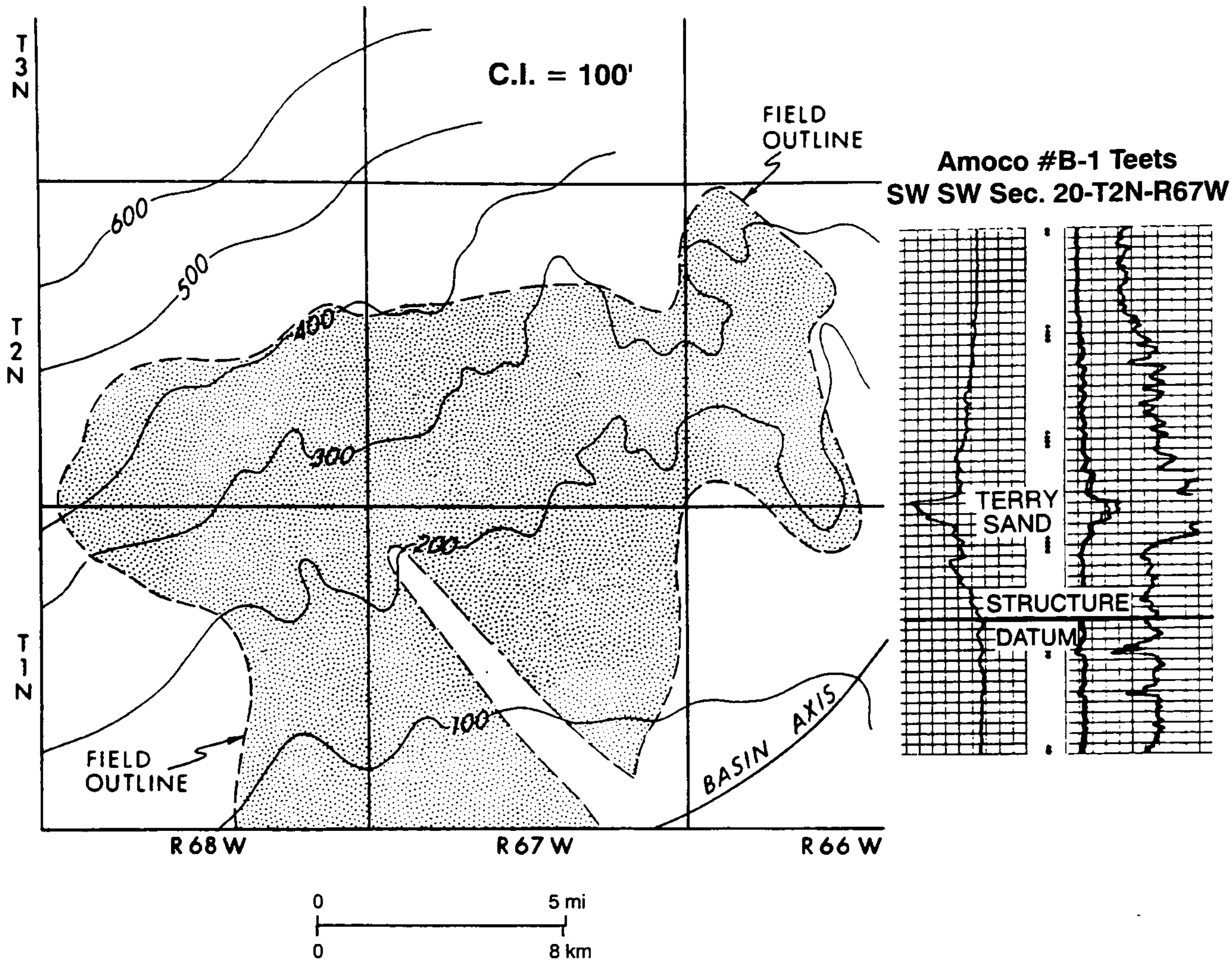


Figure 37. Structure contour map on structure datum near base of Terry Sandstone (from Pittman, 1989; after Moredock and Williams, 1976) with no faulting. Contour interval 100 ft (30.5 m).

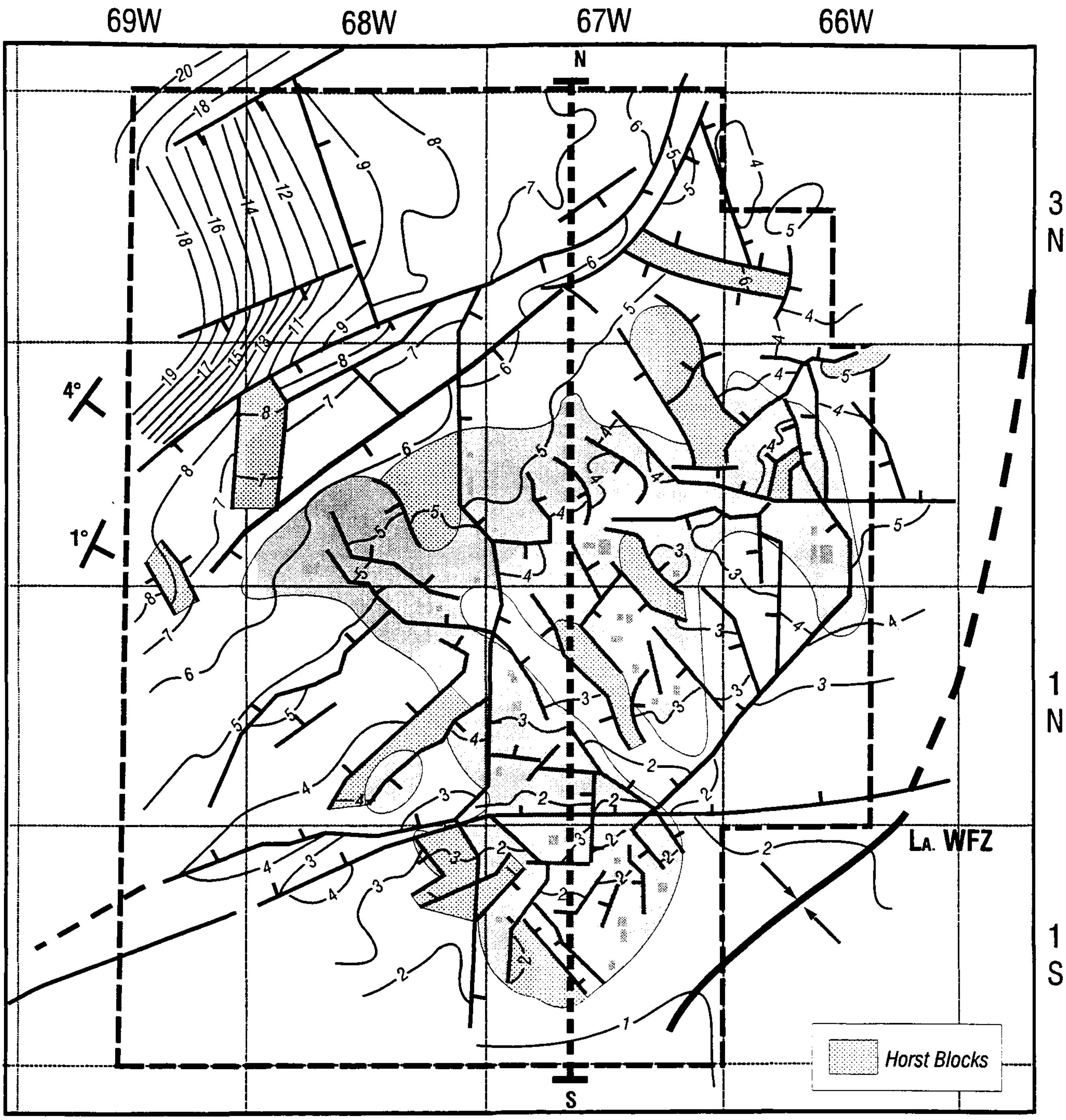


Figure 38. Structure contour map on top of Terry Sandstone with horst-graben fault interpretations. Contours x 100 represent above sea level elevations on top of Terry Sandstone. Contour interval is 100 ft (30.5 m). Stippled pattern = horst blocks. Hatchures on downthrown side of faults.

and produce on 40 acre spacing (Duane Moredock, personal communication).

By use of a computer-posted map incorporating structural data in the Spindle field study area a new contour program was completed with a 10 ft (3 m) contour interval. The datum horizon is the top of the Terry Sandstone, and field-wide this boundary, as picked on electric logs, may vary from 10 to 30 ft (3 - 9 m), but locally identification by a single operator is more accurate. The contour interval on Figure 38 is 100 ft (31 m).

The new interpretation shows a horst-graben style and many normal faults between the Longmont and Lafayette WFZ. Increased dips occur in a fault block structure between the Longmont and Windsor WFZ.

Two sandstone reservoirs produce in the Spindle field (Figure 35). The lower Hygiene Sandstone extends as a blanket to the outcrop 9 mi (14.4 km) to the northwest, whereas the upper Terry Sandstone pinches out into shale before reaching the outcrop (Figure 36). The northwestern updip seal on the Hygiene Sandstone may be caused by diagenesis related to the Longmont WFZ (Figure 38).

A comparison of the structure contour map and fault map of the Muddy (J) Sandstone (Figures 33 and 34) with the Terry Sandstone map (Figure 38) clearly shows the disharmonic relationship between the deep and shallower structure as depicted on the cross section (Figure 34).

Recurrent Movement on Wrench Faults

One of the important concepts to the fault styles shown by the cross section is recurrent movement on the basement WFZ. Although Paleozoic movement has been described on some of the major faults, this discussion is confined to Cretaceous history.

Times of recurrent movement on faults in the greater Wattenberg area are identified by arrows and by numbers on Figures 35 and 39. Data in support of large scale fault block movement are summarized as follows:

• Thinning, truncation and onlap of strata have been observed across the Wattenberg area within the interval from the Muddy (J) Sandstone to the base of the Pierre Shale (Figures 40 and 41) (Weimer, 1980, Weimer et al., 1986). Episodic movement occurred individually, or collectively, on the Lafayette, Longmont and Windsor WFZ. Evidence for a vertical component of movement is identified for the times indicated by numbers on Figure 2.17:

1. Thinning of upper Dakota Group (base Skull Creek to base Benton Group) (Haun, 1963; Sonnenberg and Weimer, 1981) with truncation of the upper part of the Muddy (J) Sandstone (Figure 40).
2. Unconformities at base and top of Codell Sandstone as part of regional structural doming (Weimer, 1978, 1984; Sonnenberg and Weimer, 1981; Weimer and Sonnenberg, 1983); onlap of Fort Hays on upper unconformity (Weimer, 1978).
3. Beveling of the upper 100 ft (31 m) of Niobrara Formation on an east-west trending fault block uplift between Lafayette and Longmont WFZ (Figures 35 and 40; Weimer, 1980) and regional thinning of Niobrara (Sonnenberg and Weimer, 1981).
4. Interval of listric faulting in Niobrara and lowermost Pierre Shale from wells and seismic (Figure 35) (Davis, 1985).

• Depositional patterns changed for the Pierre Shale and younger formations with a north-south strike and eastward thinning. Evidence for fault movement is less well developed.

5. Formation of Tepee Buttes (organic carbonate mounds) in lower Pierre (Baculites scotti zone, Scott and Cobban, 1965) and older intervals of Pierre in subsurface (T. Sheldon, personal communication).
6. Thinning and isopach reversal in Terry and Hygiene time-stratigraphic intervals (Porter, 1989);
7. Terry interval of listric faulting (Figure 2.13).
8. Seismic evidence of interval of listric faulting in Upper Pierre (Davis, 1974, 1985).
9. Thickening of coals in the lower Laramie and of sandstones in the Fox Hills within graben structures of the Boulder-Weld fault zone (Weimer, 1976).
10. Main phase of deformation giving horst-graben structures of Boulder-Weld fault zone associated with Lafayette WFZ (an extension of the Idaho Springs-Ralston shear zone) (Weimer, 1996).
11. Southward and eastward tilting of

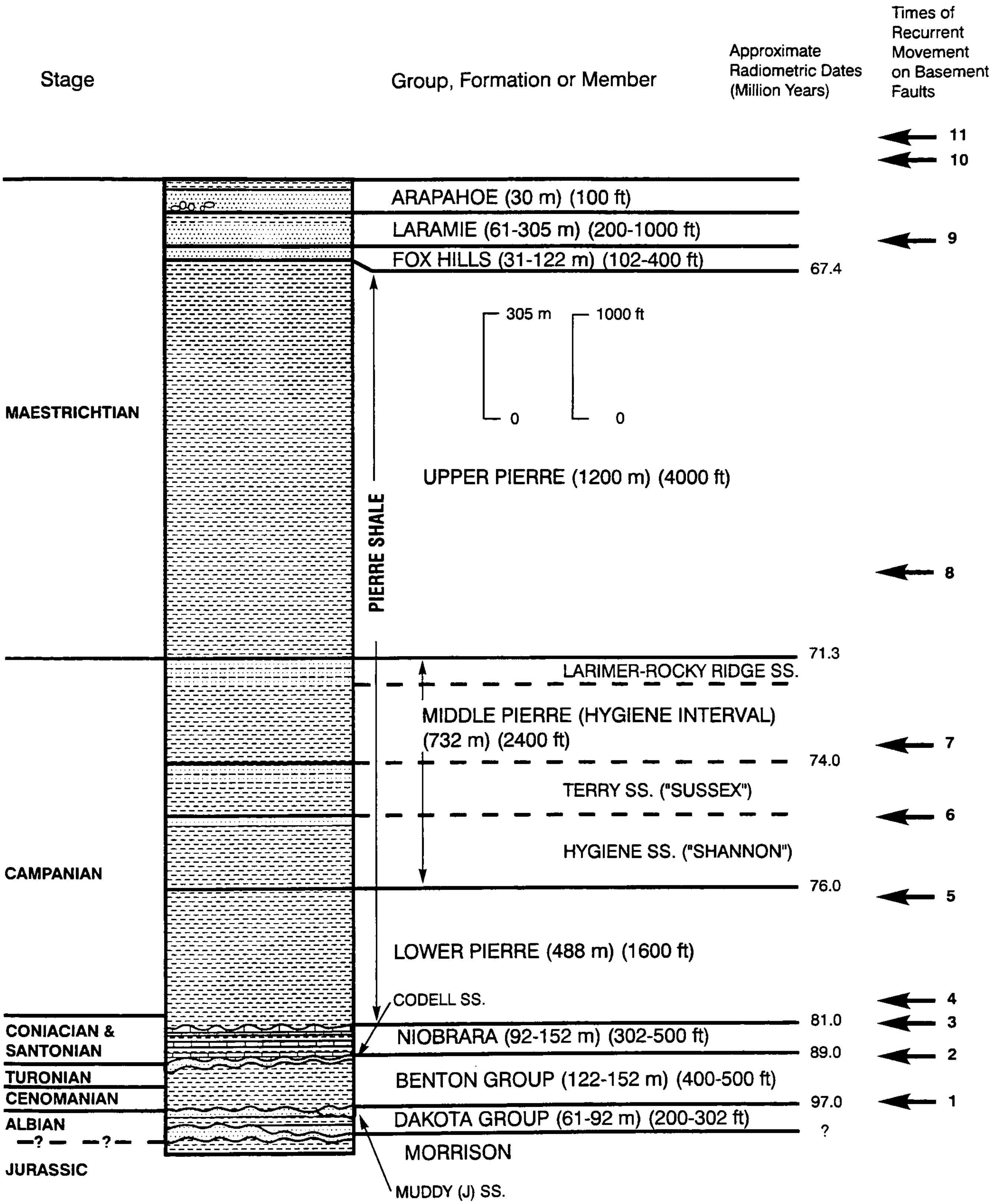


Figure 39. Stratigraphic column for Cretaceous strata, Spindle field area. Times of recurrent fault movement indicated by arrows.

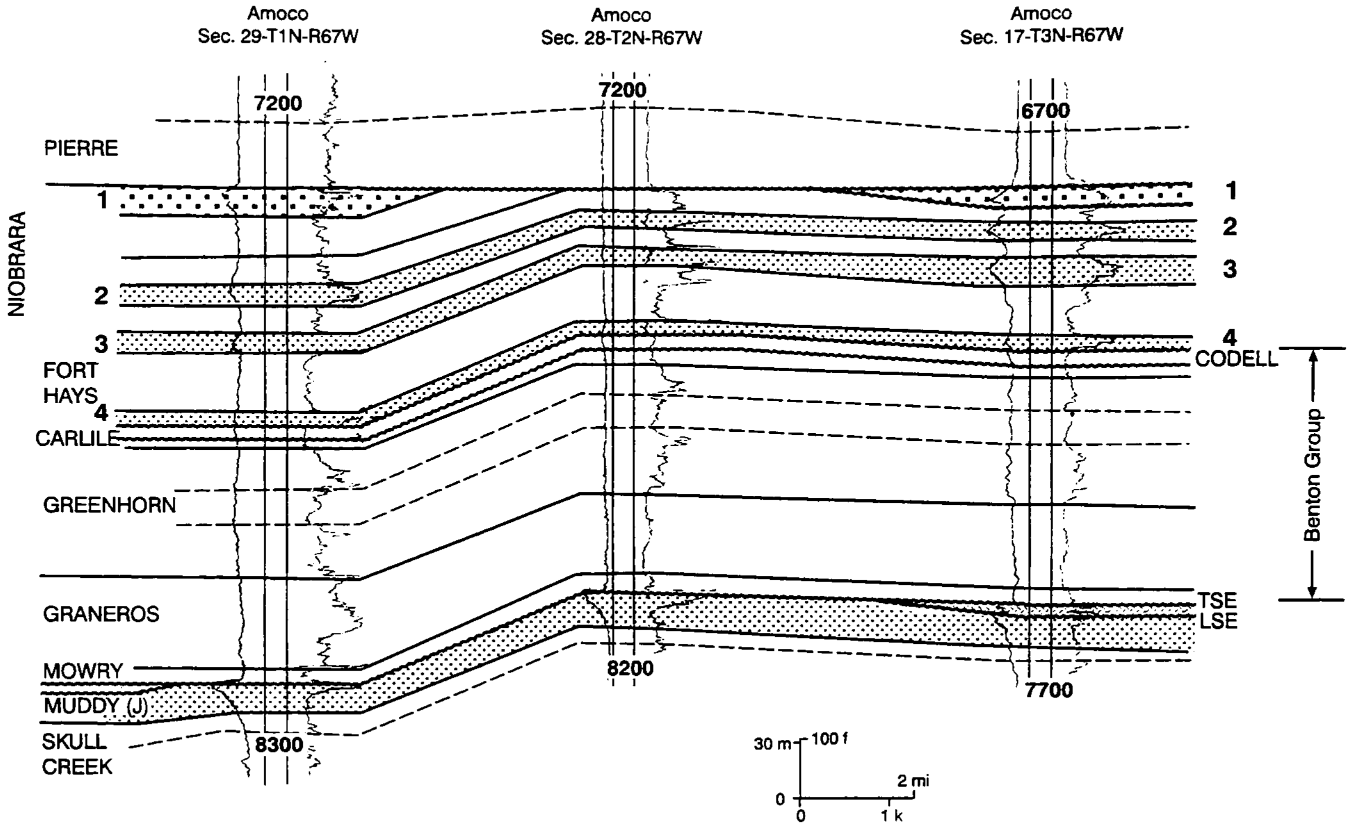


Figure 40. Electric log cross section showing major unconformities in upper Muddy (J) Sandstone, at base and top of Codell Sandstone and at top of Niobrara.

the entire stratigraphic section by uplift along the Windsor WFZ and adjacent area.

In summary, the Cretaceous section, spanning a time interval of 110 to 65 Ma, has evidence of episodic fault movement influencing stratigraphic patterns every few million years. Faulting occurred on the sea floor and coastal plain during deposition, but also offset layers after deposition.

Reservoir Compartmentalization

In two pilot study areas, the widespread wrench faulting, identified by structure contour mapping, fragments the Muddy (J) Sandstone into reservoir compartments. These pilot areas, if representative of the greater Wattenberg area, suggest that compartmentalization may be more prevalent than previously thought, not only for oil and gas in the Muddy (J) but in younger reservoirs as well.

In a nine-township area surrounding the Denver International Airport (Figures 33 and 42) reservoir compartmentalization is related to facies distribution, faults and diagenesis. Muddy (J) reservoirs are 10-90 ft (3-28 m) thick and produce at an average depth of 8000 ft (2450 m). Based on integration of geology, geophysics and petroleum engineering, individual fields are within basin center, continuous type accumulations. Superimposed on a regional 0.5° west dip, the edges of reservoir compartments follow both northeast and north-northwest fault trends. Evidence for segregation into compartments are gas opposite oil at the same structural elevations and gas downdip from oil. Because few wells cut the faults in the productive intervals, the dip of fault planes is regarded as near vertical with offsets from 10 to 100 ft (3-31 m). Faulting and associated fracturing may enhance production (e.g. T. 2 S., R. 65 W., Figure 42), or provide seals by silica diagenesis, gouge, or offsetting reservoirs against impermeable shale. The conditions are unknown as to why some faults seal, and others,

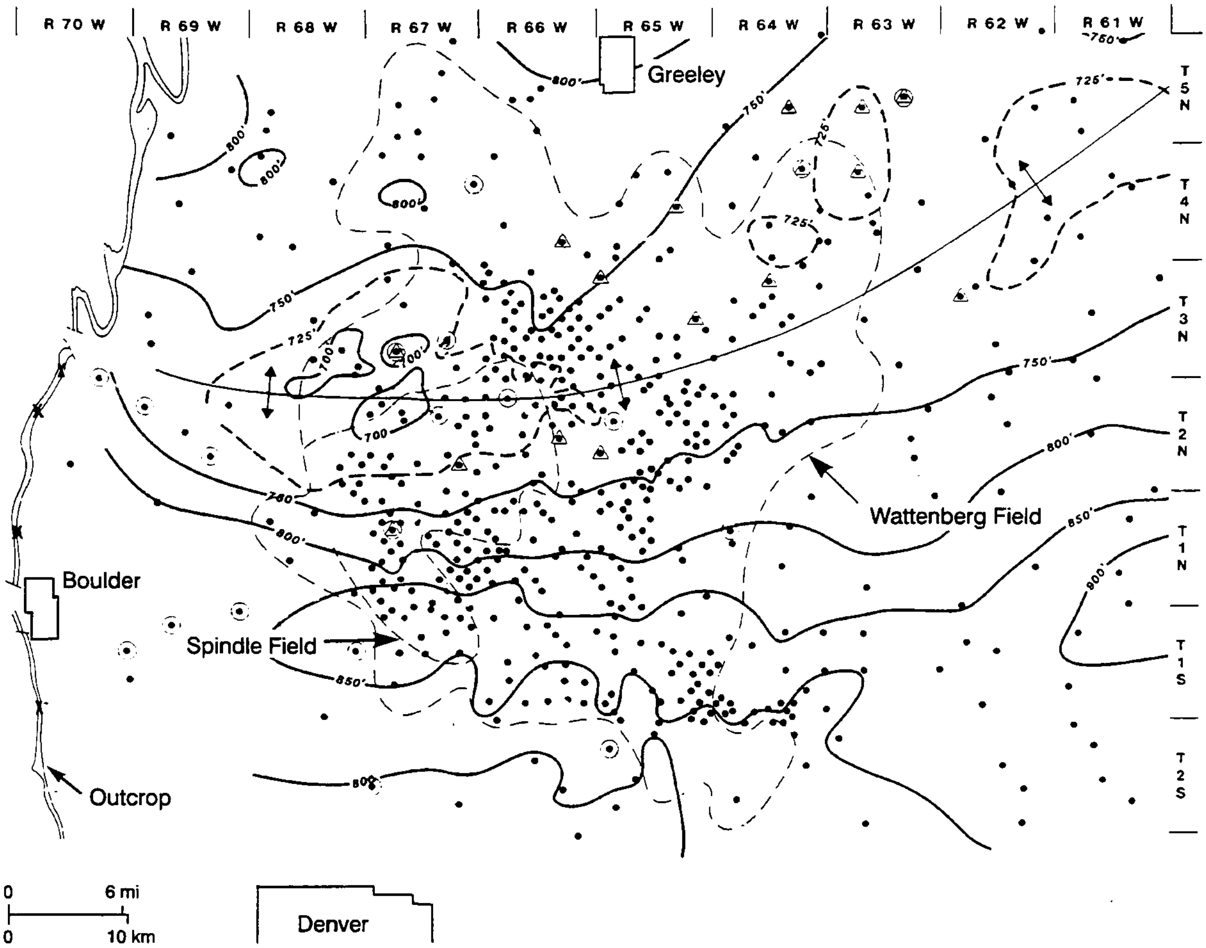


Figure 41. Paleostructure indicated by isopach map from top Niobrara Formation to top of Muddy (J) Sandstone. Contour interval is 50 ft (15.2 m).

with associated fracturing, enhance production within a reservoir compartment. A better understanding of the diagenesis and the timing of fluid movement in relation to the faulting may provide an answer to the question.

The second area of detailed analysis was selected to determine if faulting associated with the Lafayette WFZ, an extension of the Precambrian Idaho Springs-Ralston shear zone, compartmentalized the Muddy (J) Sandstone reservoir (Figures 34 and 43). Within the Wattenberg gas field, the area is nine mi (14.4 km) on a side and produces gas from the relatively uniform delta front Fort Collins Sandstone. The pay interval varies from 15 to 25 ft (3 to 5 m) at an average depth of 8300 ft (2500 m). Except where broken by faults, the structural strike is west-northwest and the dip is less than 0.5° south (Figures 33 and 35). The area is near but east of the Denver basin axis.

From cumulative production of wells drilled on 160 acre spacing, gas-oil ratios (GORs) were computed and related to mapped fault patterns. The GOR is the quantity of gas in cubic feet produced with one barrel of oil (or condensate). GORs in the Muddy (J) reservoirs vary from 15,000 to 300,000 with step-like changes across faults. Because some production data were reported by lease, instead of individual wells, extrapolation was necessary in a few areas. To explain the observed anomalies several additional faults were added (Figure 43). A few mapped faults do not show discernible GOR changes from one side to the other. Adequate pressure data and other well test information are lacking to confirm the fault seals.

Overall, the GOR patterns indicate reservoir compartments with considerable variation in gas and oil (liquid) production. An example of cumulative production for one township (T. 1 N., R. 67 W.) shows

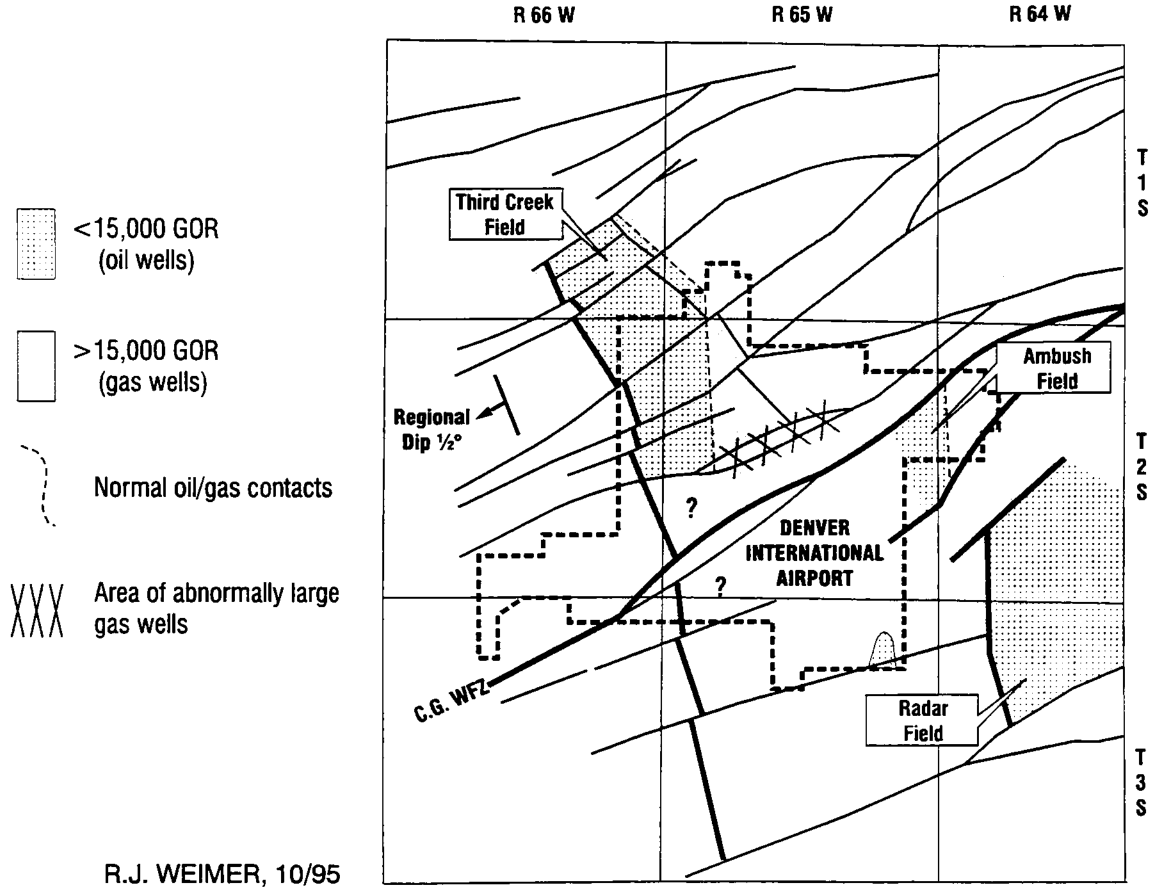


Figure 42. Area of T. 1 S. to T. 3 S. and Rs. 64-66 W. enlarged from Figure 33. Faults along which seals compartmentalize the Muddy (J) Sandstone reservoir are indicated by heavy lines. Other faults, and associated fracturing, generally enhance production in Muddy (J) and D Sandstones (from Weimer, 1992). Structure contours for area are shown on Figure 33.

a range from 0.4 to 6.1 bcf per section (Table 6) and a total production is recorded of 97.1 bcf and 1.04 million barrels of oil. If the production variation is related to natural processes, and not to engineering production problems, the cause is probably related to diagenesis, thickness changes and fracture density and distribution.

Variation in GORs are known areally to be related to production procedures and flow rate through time, relative permeabilities differences to gas and oil, perforated intervals in relation to oil and gas contacts, and temperature variations in areas of thermogenic gas. All of the causes need to be investigated more fully in the study area, but the large and coincident GOR variations across faults may be temperature related caused by heat flow variations in individual fault blocks within the Wattenberg "hot spot".

Although compartmentalization of the Terry and Hygiene reservoirs in the overlying Spindle field have not been analyzed in detail, the listric faulting of the Terry Sandstone and the development history indicates compartments (Figures 35 and 38). Moreover, similar faulting to the east, possibly associated with the Longmont WFZ, in the Latham, Hambert and Aristocrat fields (T. 3-4 N., R. 64-65 W.) has compartmentalized the Terry bar sandstones (Al-Raisi, 1994; Al-Raisi et al., 1994, and Edington et al., 1994).

The faults, fragmenting the Muddy (J) Sandstone reservoirs, are thought to project to the basement, based on limited seismic and deeper well data across the major wrench fault zones. But how fragmented is the basement of igneous and metamorphic rocks where broken by Precambrian shear zones? The answer to the question comes from a comparison of the study area

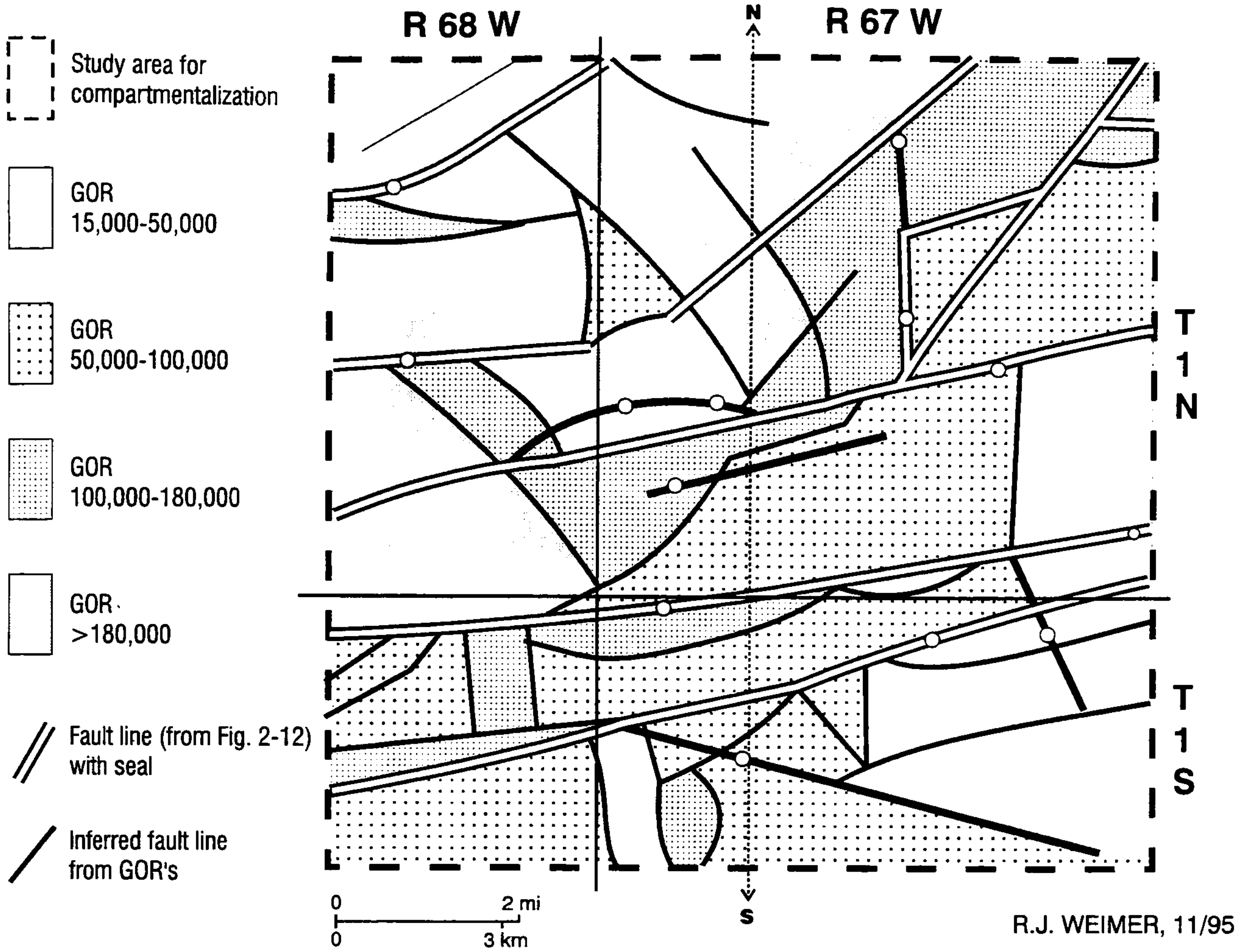


Figure 43. Compartmentalization of Muddy (J) Sandstone reservoirs by faults based on gas/oil ratios (GOR). Base map from Figure 34.

fault map (Figures 34 and 36) with a compilation map of the exposed basement faults within and adjacent to the Idaho Springs-Ralston shear zone (Figure 44) (Tweto and Sims, 1963). Located along the same shear zone and similar in size, the maps show amazing similarity of trends and density of faults. Inasmuch as the main rock breakage in the basement is of Precambrian age, then recurrent movement on the faults initiated by right lateral shear would impart a similar pattern to overlying sedimentary rocks as observed in the Denver basin. Moreover, the distribution of metaliferous veins (largely of Oligocene age) filling open faults and fracture systems gives a measure of the widespread nature of fluid movement. Mineralization occurs along all fault and fracture trends, with a possible preference to the northeast direction. Recurrent movement on the Idaho Springs-Ralston shear zone, which averages 1.5 mi (2.4 km) in width, would also initiate movement on synthetic and antithetic faults in the overlying sedimentary rock, perhaps for several miles (km) on each side. In summary, the exposed basement structure supports the interpretation of basement-related wrench fault patterns in the Muddy (J) Sandstone of the greater Wattenberg area.

Collectively, the research in these two smaller study areas has developed a "fault block compartment model" related to complex interactive processes. The model may be applicable throughout much of the Wattenberg field of the Denver basin, and perhaps to other Rocky Mountain basins where wrench faulting is known to occur.

Table 6. Cumulative production for Muddy (J) Sandstone from T 1 N, R 67 W as of July 1, 1995.

Section	BCF	Bbls	Section	BCF	Bbls
1	2.4	16,450.	19	2.6	8,030.
2	4.2	25,170.	20	3.7	17,880.
3	4.9	22,600.	21	4.4	41,900.
4	4.5	16,270.	22	2.9	46,100.
5	2.3	3,250.	23	3.3	71,700.
6	1.6	3,605.	24	2.5	72,400.
7	2.0	21,050.	25	.9	38,900.
8	2.5	17,420.	26	2.1	57,600.
9	6.1	27,750.	27	1.1	46,400.
10	4.3	33,500.	28	1.1	44,100.
11	5.1	52,280.	29	1.7	15,800.
12	4.2	44,090.	30	2.3	12,050.
13	2.3	42,720.	31	1.0	8,420.
14	2.7	42,520.	32	1.6	17,660.
15	3.4	44,290.	33	1.6	10,700.
16	4.5	34,080.	34	2.7	35,570.
17	2.1	4,150.	35	1.4	31,780.
18	.7	4,230.	36	.4	25,410.
Sub-total	59.8	455,420.	Sub-total	37.3 bcf	584,500. bbls
	37.3	584,500.			
Total	97.1 bcf	1,039,920 bbls			

Average for 135 wells = .72 bcf and 7,700 bbls oil

Styles of Wrench Faulting

The styles of deformation in sedimentary strata caused by wrench faults are summarized by du Rouchet (1981); Zolnai (1988); Sylvester (1988) and Harding (1990, 1991). Because of a lack of data on the dip and vertical projection of fault planes, a final version of a structural model has not been formulated for the greater Wattenberg area. However, the ubiquitous occurrence of normal listric faulting in the Niobrara and lower and middle Pierre formations (Figure 35) indicates a modification of the divergent wrench fault style of Harding (1991) (negative flower structures of other authors). The revised model must incorporate the concept of episodic recurrent movement along the wrench fault zones. Analogue model experiments by Schreurs (1994), using a small box apparatus, show disharmonic patterns of synthetic and antithetic faults above a rigid base plate broken by a single wrench fault. Except for the dip of the fault planes this work may simulate fault patterns in the study areas.

In addition, reverse faulting has been mapped by Spencer (1961) and Kittleson (1992) in the uppermost Pierre, Fox Hills, Laramie and Arapahoe formations (Figure 39) exposed at the surface in the Boulder-Weld fault zone. This vertical change from normal style to reverse style faulting may be related to a new stress field causing positive palm tree (flower) structures (Sylvester, 1988). The change would be from the divergent to convergent wrench fault styles as diagrammed by Harding (1991).

Changes in styles may also occur along the same wrench fault zone, or among the series of more or less parallel wrench faults. For example, the style of deformation on the north side of the Windsor WFZ is quite different from the styles of deformation at different stratigraphic levels of the Lafayette WFZ (Figures 33 and 35). Moreover, the time of movement shifted from one WFZ to another. Because each fault zone has its own characteristics, and yet is interrelated to others, a final model must resolve these complexities. High resolution, seismic data, not presently available, are needed to resolve uncertainties in style changes with depth and time.

The presence of the Wattenberg thermal anomaly with the divergent wrench fault style has similarities, but on a smaller scale, to the Salton Sea geothermal anomaly in southern California which is associated with divergent wrench faulting (a transtensional overstep area) along the San Andreas fault system (Corona, 1996).

Summary

The dynamic interrelationship between tectonics and sedimentation and recurrent movement on basement faults emphasizes the importance of analyzing the role of structure on the basin center petroleum occurrences. The structural axis of the Denver basin shifts eastward in successively younger strata because of movement on the wrench fault systems and a progressive shift of depocenters in the Pierre Shale (Figure 45). Superimposed on this overall pattern is deformation on synthetic and antithetic faults related to right lateral movement along five major northeast-trending WFZ. North and northwest wrench faults although present are more subtle and difficult to map.

How have the wrench fault zones impacted the petroleum system? The following points are impressions, some of which are substantiated and some are not:

- Control of emplacement of igneous intrusives in the basement as a heat source for Wattenberg thermal anomaly;

- Fluid movement in fault zones transfer heat to overlying sedimentary layers which influence maturation and generation of petroleum in source rocks and may cause diagenesis preferentially in sandstones within and adjacent to faults;

- Fracturing of rock enhances production from tight reservoirs by enlarging reservoir capacity and permeability;

- Faulting and fracturing controls migration from source rock to reservoirs; fractures may be open or closed; for example, faults provided conduits for vertical migration from source rock to Terry and Hygiene reservoirs, and seals between basin center accumulations and the outcrop sections;

- Recurrent movement on faults controlled unconformities, thicknesses, and facies changes, and initiated clusters of listric fault systems at three main stratigraphic levels (Niobrara-lower Pierre interval, Hygiene and Terry intervals, and Fox Hills-Laramie-Arapahoe interval).

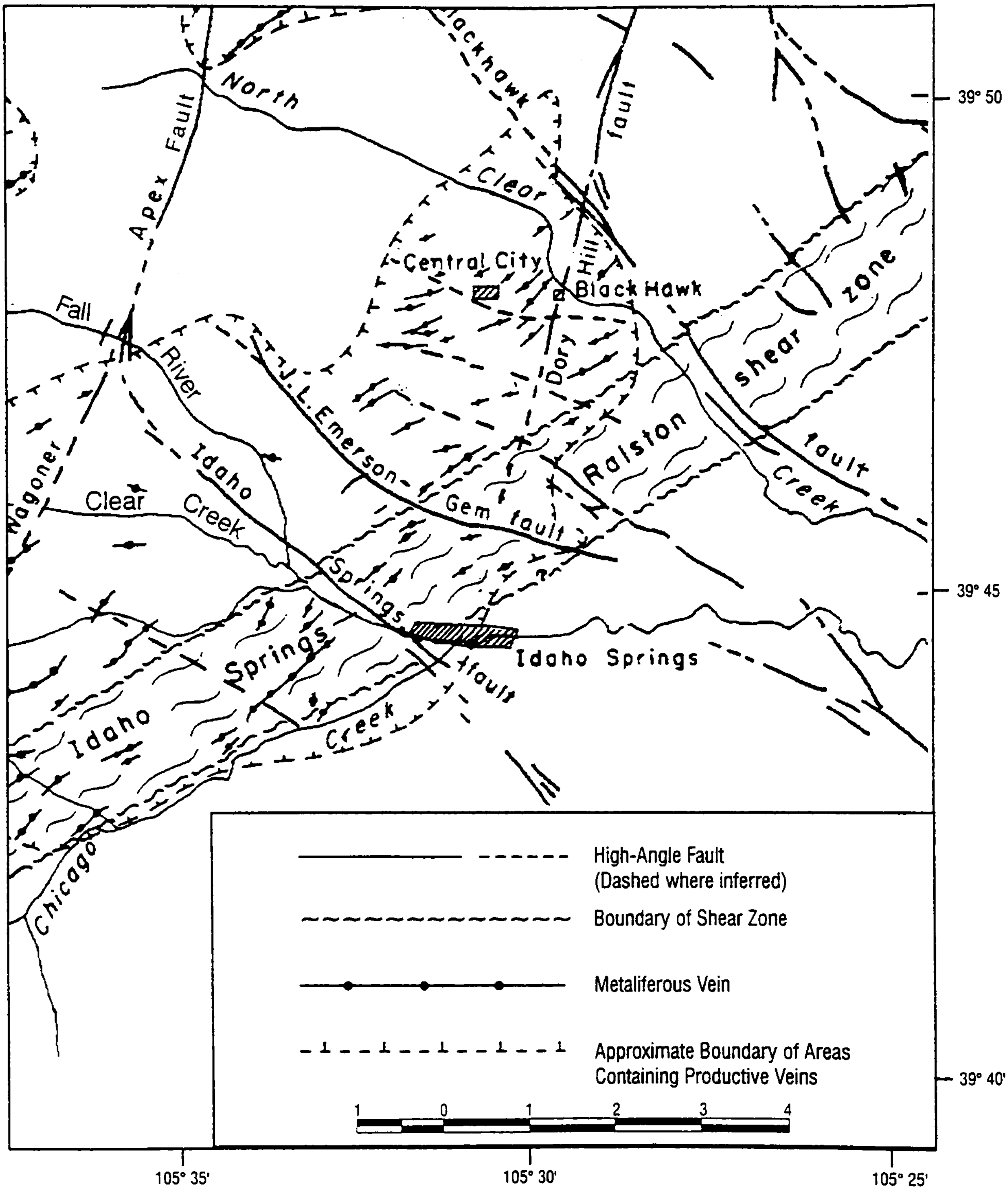


Figure 44. Map of Idaho Springs--Central City area showing Precambrian tectonic features associated with Idaho Springs--Ralston shear zone. Area is approximately 8 x 10 mi (13-16 km) (refer to Figure 36 for location). (from Tweto and Sims, 1963).

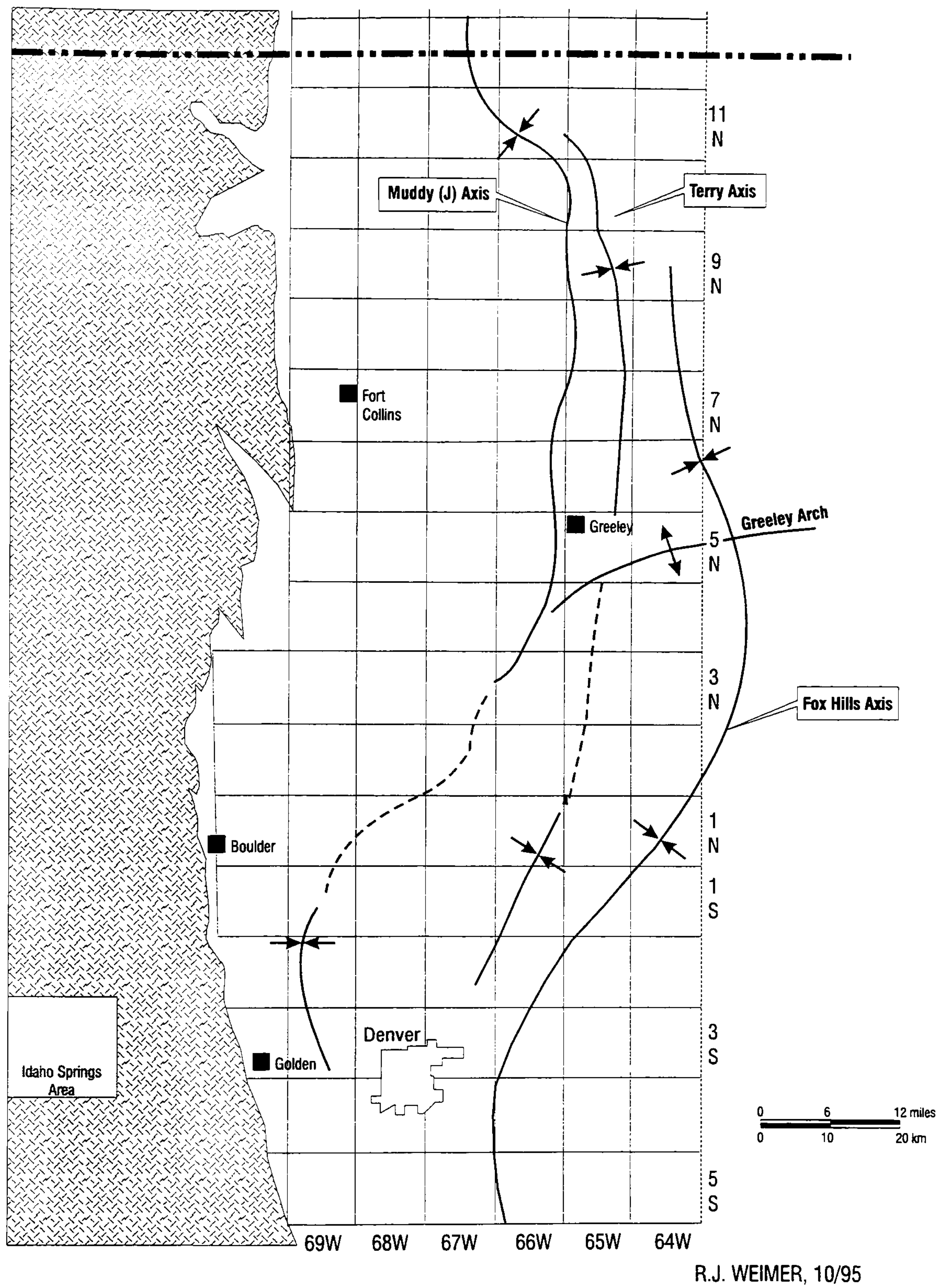


Figure 45. Present structural axes of central Denver Basin at three different stratigraphic levels: Muddy (J) Ss., Terry Ss. and Fox Hills Ss.

SEQUENCE STRATIGRAPHY, DAKOTA GROUP

The origin, distribution and modification of productive reservoirs are perhaps the most important subjects in exploration and development of basin center petroleum occurrences. Sequence stratigraphy is a new approach, using unconformities and other key surfaces, to understanding reservoirs. The purposes of this paper are to summarize the concepts and interpretations developed from a sequence stratigraphic analysis of the Dakota Group (Lower Cretaceous), Denver basin and to describe the integration of surface and subsurface data.

In the Rocky Mountain region, the Muddy (J) Sandstone has produced more than 1.5 billion bbls of oil-equivalent hydrocarbon (BOE), largely from stratigraphic traps (Dolson et al., 1991). According to Higley et al., (1992), "about 90 percent of the 800 million bbls of oil and 1.2 trillion cubic feet of gas produced from the Denver basin has been from the "J" Sandstone". Because of the large production and reserves, this formation remains the principal target for exploration and development.

Outcrop, core and log data from the Denver basin record a geologic history typical of the Muddy (J) Sandstone over much of the eastern portion of the Western Interior depositional basin of the U.S.A. and Canada. Thus, the geologic models developed for the Denver basin, to understand the reservoirs within the petroleum system, have widespread application to other Laramide basins.

A 42-minute videotape illustrating sequence stratigraphic concepts and interpretations for the Dakota Group has been produced by the Rocky Mountain Association of Geologists (Weimer, 1989).

Concepts and Definitions

Sequence stratigraphy is the study of genetically related strata which are bounded by unconformities or their correlative conformities (Vail et al., 1977). In the Denver basin analysis, the concept of correlative conformities is not applicable for the Muddy (J) Sandstone because sequence boundaries do not pass into conformable section. Facies models are used to interpret the genetically related strata and must be developed in order to interpret accurately the unconformities. A facies is defined as the local lithologic or biologic aspect of a chronostratigraphic unit. An unconformity is defined as a sedimentary structure of regional occurrence in which two groups of rocks are separated by an erosional surface; the erosion may be by subaerial or submarine processes. A formation is an assemblage of rock masses grouped together for convenience in mapping and description.

Two types of major erosional surfaces are observed either within or at the formation contacts of the Muddy (J) Formation. Each is associated with major changes of relative sea level but the magnitude of erosion may be influenced by local tectonic features. One type, a sequence boundary, is called a lowstand surface of erosion (LSE) related to a lowering of base level which causes subaerial exposure and incisement of drainages into older deposits. The second type is a transgressive surface of erosion (TSE) related to shoreline and shoreface (marine) erosion that is related to a rising sea level and water deepening. The unconformity associated with the TSE normally occurs within a depositional sequence; however, locally the two surfaces may merge.

A third-type of surface is more subtle than the LSE and TSE but can sometimes be identified in relation to nondeposition with possible minor erosion. If present, it occurs within a marine condensed section that generally has a high total organic content, e.g. the middle Skull Creek Shale. Minor scour may concentrate lags of shells, or glauconite and phosphate grains. Bentonite may occur in shale layers above or below the surface. In sequence stratigraphy such a surface has been called: the surface of maximum transgression; surface of maximum flooding; or surface of maximum starvation. Where this surface merges with the TSE, it cannot be recognized as a separate entity.

Minor erosional surfaces associated with depositional processes within environments of deposition are called diastems (e.g. scour at the base of a channel). These surfaces may merge with and modify the regional erosional surfaces (e.g. the LSE at the base of the Muddy (J) Sandstone).

Change of Concepts Through Time

The marine Skull Creek Shale, the overlying Muddy Sandstone, and marine Benton Shale record the oldest transgressive-regressive-transgressive cycle in the United States Western Interior basin. In a relatively stable tectonic setting, these three formations record slow rates of deposition on the thick continental crust of the craton. A north-south regional cross section, along the west flank of the Denver basin, shows general lithologies, formation names, and the

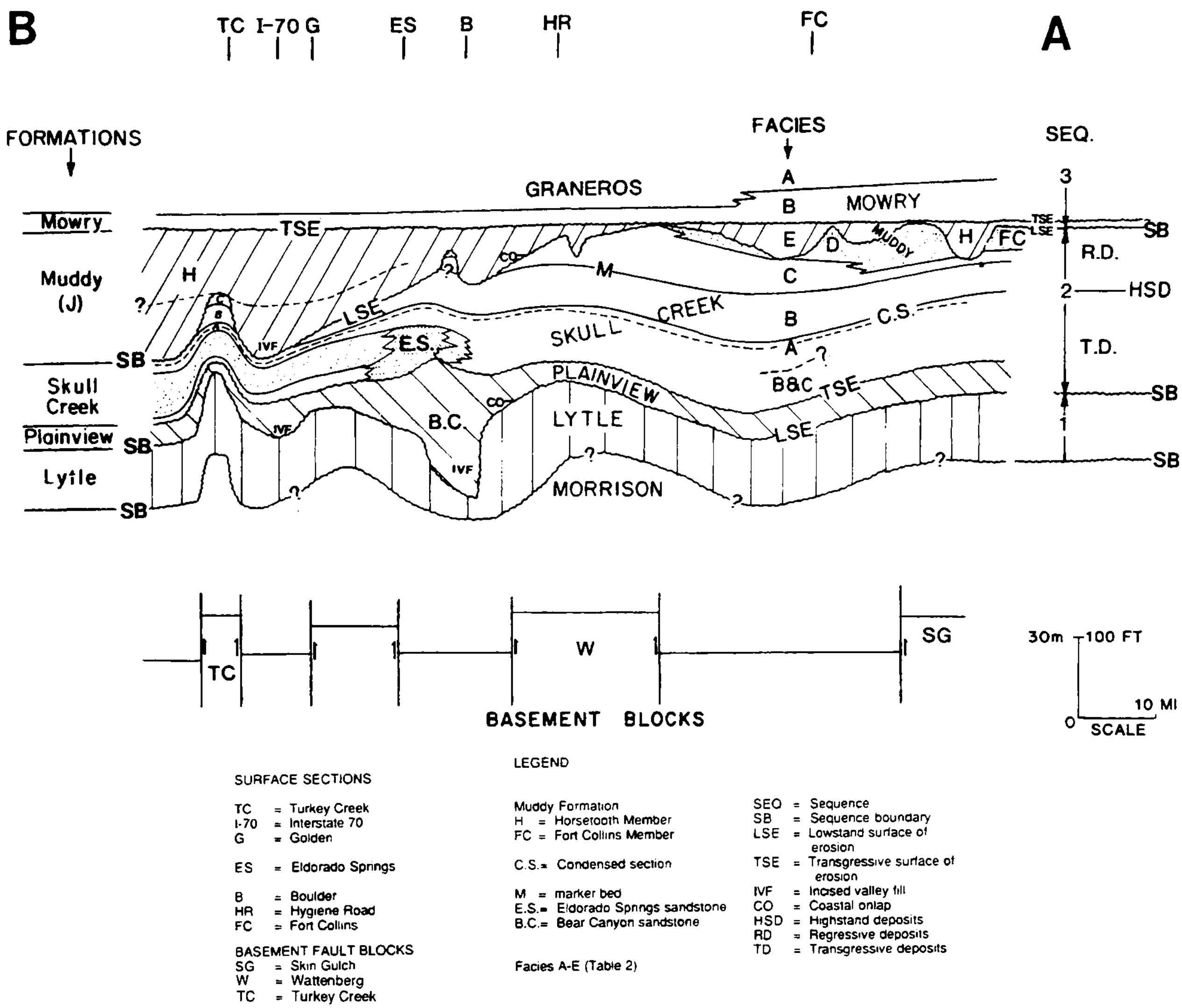


Figure 46. Restored stratigraphic section of Dakota Group (Albian) along the Front Range uplift from Colorado-Wyoming state line to south of Morrison, Colorado. Section was compiled from outcrop sections and nearby subsurface. Modified after MacKenzie (1971) and Weimer (1984). Facies boundaries are diachronous.

stratigraphic position of three widely recognized Lower Cretaceous unconformities (sequence boundaries) (Figure 46). In addition, thickness and lithologic changes relative to the unconformities and basement fault blocks are indicated. Lithologies of facies A through E are described in Table 7 and incorporated into the formations on the sequence stratigraphic diagram.

Early workers did not recognize unconformities within the widespread shallow-water Muddy (J) Sandstone that intertongues with neritic marine shale. Interpretations of the same outcrop data can be compared by three restored cross-sections based on measured sections where exposed along the 110 mi (188 km) distance. Lateral changes in lithologies and thicknesses at the same stratigraphic level were interpreted as caused by facies changes from fluvial-deltaic sandstones to marine shales, and by varying rates of sedimentation (Figure 47, Waage and Eicher, 1960). The South Platte Formation in the Morrison area changed northward to a section of marine shale (Skull Creek Shale) and Muddy Sandstone, the lateral equivalent of the First Sandstone Member of the South Platte (Figure 47).

Table 7. Facies lithologies.

Facies	Lithology	Average Thickness	
E	Gray fine-grained to medium-grained, cross-stratified sandstone, shale; coaly	10-100 ft	3 - 31 m
D	Gray burrowed, cross-stratified sandstone	50 ft	15 m
C	Gray bioturbated sandstone and shale	65 ft	20 m
B	Black shale; siltstone, very fine-grained sandstone; ripple lamination; graded beds	30 ft	9.2 m
A	Black laminated shale with bentonite and shell layers; highest total carbon content	15 ft	4.6 m

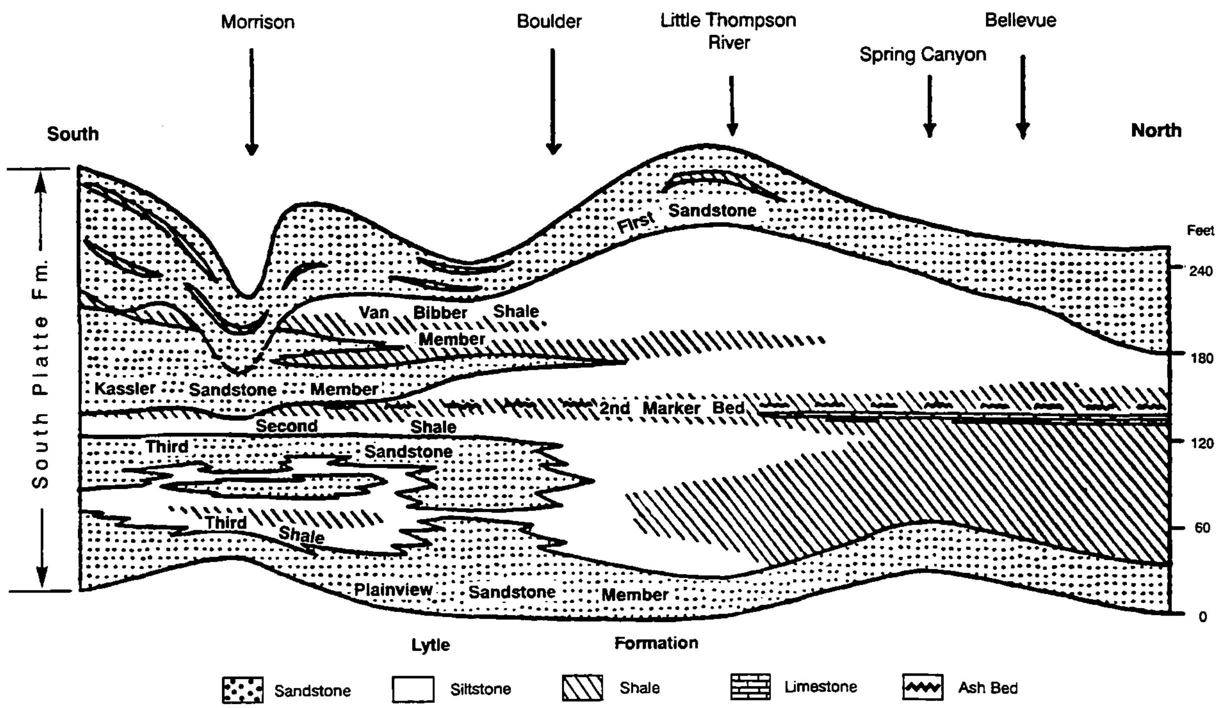


Figure 47. North-south restored section along Front Range with changes in South Platte Formation (from Waage and Eicher, 1960).

Table 8. Criteria for recognition of unconformities in Outcrops and Cores

Lowstand surface of erosion (LSE) (sequence boundary):

- Evidence of subaerial exposure: root zones, paleosol, or chemical changes with early cementation by kaolinite, silica, siderite, and calcite (may be removed by diastem at base of younger channels);
- Missing facies because of erosional scour; most commonly the D facies - delta front or shoreface;
- Coarse-grained lag with charcoal or coaly fragments at base of channel sandstone resting on marine shale or marine very fine-grained bioturbated sandstone.

Transgressive surface of erosion (TSE):

- Missing facies: facies B or C sharply overlies E with facies D missing;
- Thin relict deposit (<30 cm): lag of coarse-grained or conglomeratic sandstone and clay clasts, intensively burrowed sandstone, or concentration of phosphate grains, shark's teeth, fish bones, glauconite;
- Reworked sandstone above surface as marine bars.

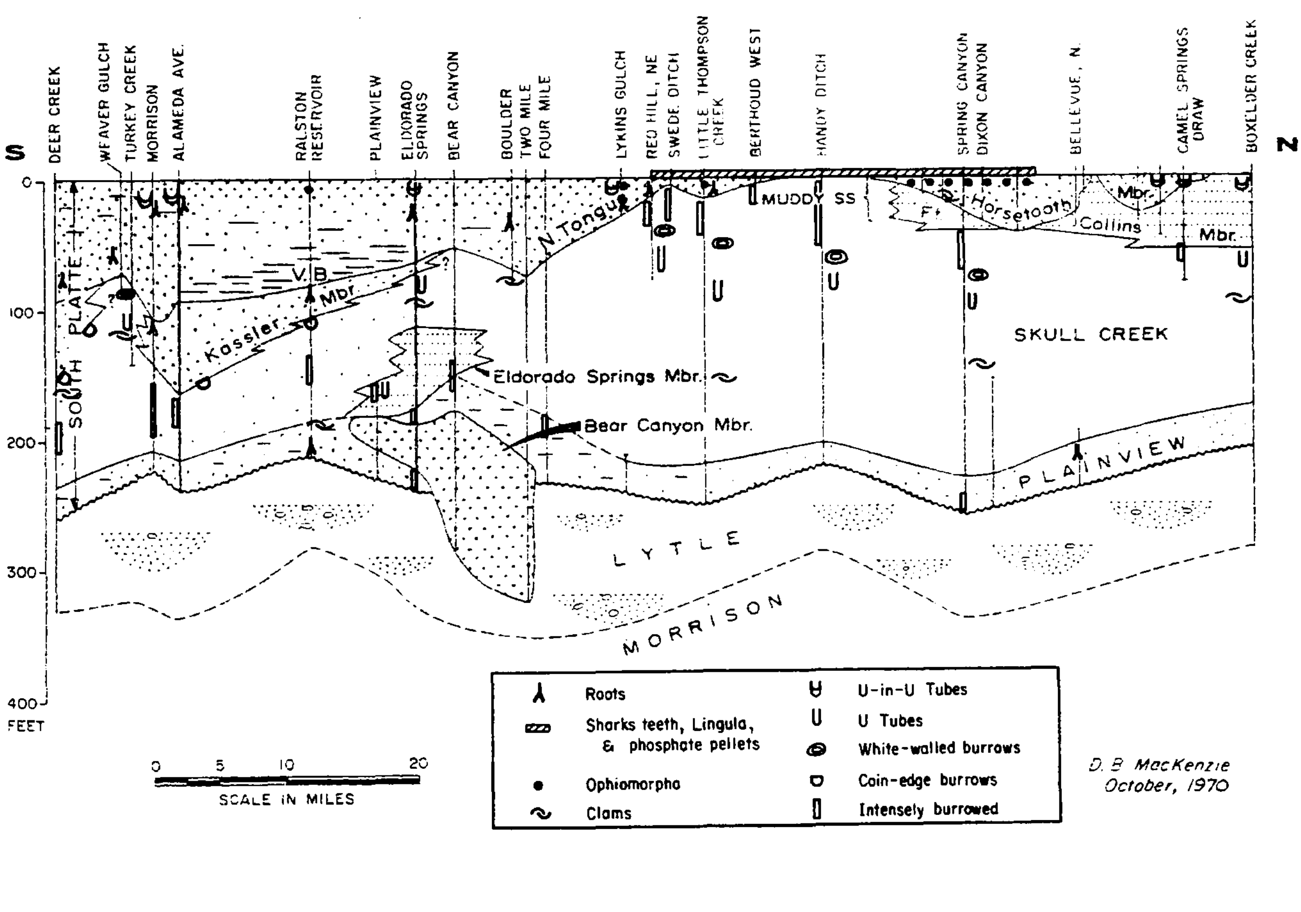


Figure 48. North-south restored section of Dakota Group, northern Front Range foothills, Colorado (after MacKenzie, 1971). Datum is top of Dakota Group.

In a monumental work, MacKenzie (1963, 1971) named the Fort Collins and Horsetooth members of the Muddy (J) Sandstone and recognized that the members were separated by a regional unconformity caused by a lowering of relative sea level (Figure 48). However, the unconformity was not placed at the base of the Muddy (J) Sandstone in the southern half of the diagram, and the facies change model of Waage and Eicher (1960) in the lower South Platte Formation was retained. Incorporating the excellent work presented in these two cross-sections in a sequence stratigraphic analysis of tracing regional erosional surfaces, the third cross section was prepared (Figure 46, Weimer, 1984, 1992). The diagram illustrates valley-fill deposition above a regional unconformity (sequence boundary), and that valley fills are younger than deposits at the same stratigraphic level outside the valleys. The criteria used in recognizing unconformities in outcrops and cores are described in Table 8 (Weimer, 1992).

This compilation of data from many workers over the past 25 years now clearly indicates the role of regional unconformities in controlling reservoir distribution and petroleum seals. No Muddy (J) exploration prospect is now complete without an evaluation of reservoir facies in relation to the widespread unconformities.

Correlation of Surface to Subsurface

In the Denver basin, the Muddy (J) Sandstone ranges in thickness from 30 to 140 ft (9 to 46 m) (Figures 49 and 50). Thickest sections are in areas where fluvial deposits rest on marine Skull Creek shale. Regional thickness variations of the Muddy were mapped by Haun (1963) and related to patterns of fluvial-deltaic sedimentation, similar to ideas by Waage and Eicher (Figure 47). The thickness and distribution of units within the Skull Creek Shale are critical to interpreting the origin of the Muddy (J) Sandstone. The Skull Creek is dominantly marine shale and varies in thickness from 50 to 200 ft (18 to 61 m). The greatest thickness is where the upper contact is transitional with the overlying Muddy (J) Sandstone. The thinnest sections are where only the lower Skull Creek is present because erosion, prior to deposition of the Muddy (J) Sandstone, cut out the upper part of the Skull Creek (Figures 46 and 50).

The two members of the Muddy (J) can be easily recognized in the subsurface, especially where cores are available (Figure 50). The older Fort Collins

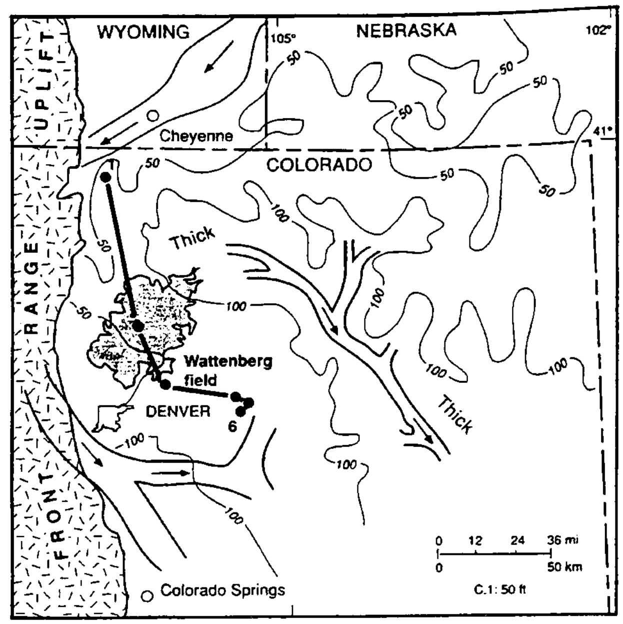


Figure 49. Isopach map of Muddy (J) Sandstone with main incised drainages and arrows indicating flow directions. Modified from Weimer, et al., 1986.

Member is a very fine- to fine-grained sandstone containing numerous marine trace fossils and is interpreted to be delta-front sandstones deposited during regression of the shoreline of the Skull Creek sea. Because of the transitional nature of the contact with the Skull Creek Shale, electric logs are "funnel-shaped" over the interval. Sandstones of the younger Horsetooth Member are fine- to medium-grained, well sorted, cross-stratified, and contain carbonized wood fragments. Productive sandstones are interpreted to be channels of fresh and brackish water origin deposited as part of valley-fill deposits. Because of the sharp scoured contact with the Fort Collins Member of the Muddy Formation, or the Skull Creek Shale, the electric logs are commonly "bell shaped". The upper contact with the Benton (Mowry) Shale is sharp.

The first use of the term "valley-fill deposits" in association with productive sandstones in the Denver basin (Nebraska part) was by Harms (1966). He described two sandstone units in the Muddy (J) Sandstone that have lithologies similar to the Fort Collins and Horsetooth members of the Muddy Sandstone. Production is from valley-fill channel sandstones in the Horsetooth Member.

On the east flank of the Denver basin, subsurface geologists have subdivided the Muddy (J) in 3 members (Figure 50). Correlating to the surface

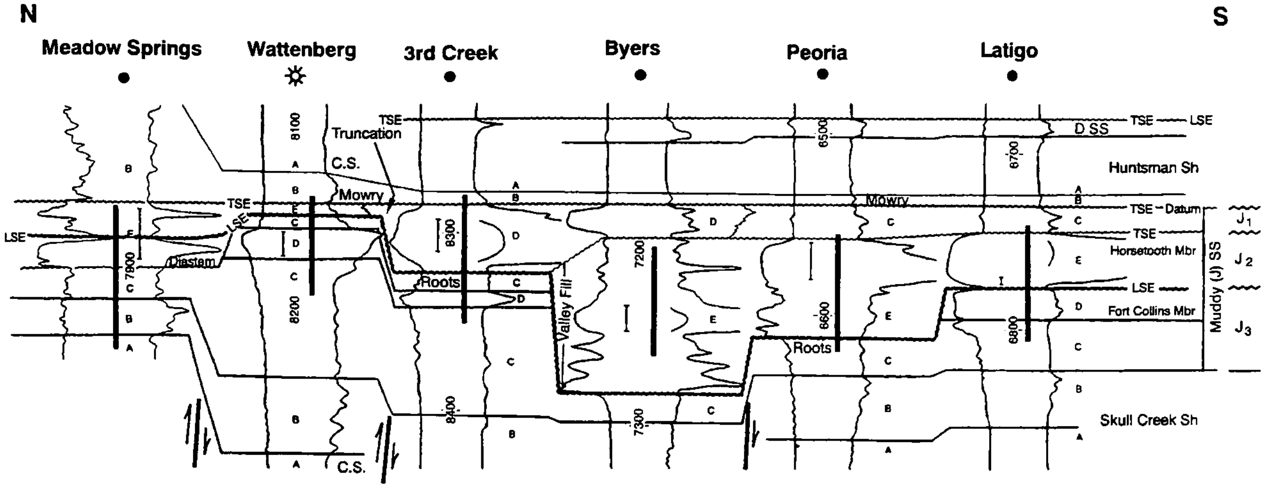


Figure 50. Electric log section from Meadow Springs to Latigo fields. Heavy bar shows cored intervals; light bar shows perforated intervals. Facies boundaries are diachronous. Location of section is indicated on Figure 49.

outcrops, J3 is marine sandstone and equivalent to the Fort Colllins Member; J2 is valley fill and equivalent to the Horsetooth Member; and, J1 is marine shale and sandstone. J1 is thin or absent in outcrop and Wattenberg field sections because of non-deposition and/or truncation (Figure 50). The thick sections over 100 ft (31 m) of the Muddy (J) in the east-central Denver basin is because of greater valley incision and fill (J2) and the presence of the J1 transgressive and regressive cycle (facies C and D, Figure 50).

In summary, three types of reservoirs, separated by erosional surfaces, are identified by field names on the electric log section (Figure 50). The most widespread is the Fort Collins Member (J3) in the Wattenberg field. Although the oldest, this reservoir generally occupies a high stratigraphic level. Second-type reservoirs of the Horsetooth Member (J2), between the lowstand surface of erosion (LSE = sequence boundary) and the transgressive surface of erosion (TSE), are younger but may be at a lower stratigraphic level than the Fort Collins Member. Examples of this relationship are indicated by the channel sandstone reservoirs in the Byers, Peoria, and Latigo fields. Sandstones should not be correlated based only on stratigraphic level. A third type of reservoir occurs as marine sandstone bars and deltaic shoreline sandstones above the transgressive surface of erosion (TSE) on top of the Horsetooth (J2 Member). The sandstones are narrow, elongated, and have trends different from the valley-fill channel systems. These sandstones are marine and related genetically to a younger transgressive-regressive cycle than the Fort Collins-Horsetooth cycle. An example of production from these youngest sandstones is reported in Poncho Field (Ethridge and Dolson, 1989 and in other fields (Dolson et al., 1991).

The sequence boundary (LSE) may be within, at the base, or at the top of the Muddy (J) Formation. Regardless of stratigraphic position, the sandstone reservoirs above the LSE, primarily in the incised valley fill, are younger than the Fort Collins Member below the unconformity.

Geologic Model

Following the highstand transgressive deposits of the Skull Creek Shale, a regressive event deposited deltaic shoreline and shallow marine sandstones that have a transitional contact with the underlying Skull Creek Shale (Figure 51). Depositional patterns over basement fault blocks, where slight fault block movement influenced topography and sedimentation, depended on the rates of submergence and sediment supply. Rivers and associated deltas positioned themselves in structural and topographically low areas

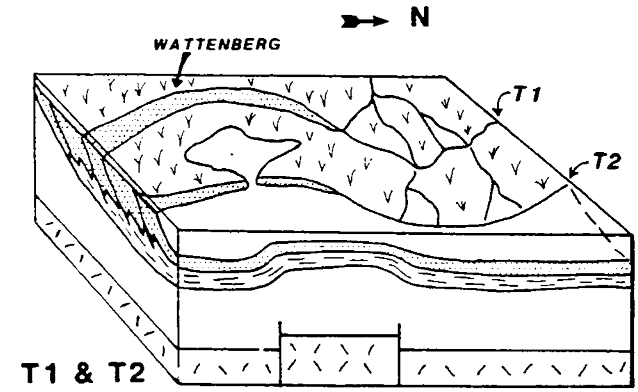


Figure 51. Depositional and tectonic model for highstand regression over basement fault blocks with penecontemporaneous fault movement. T1 = Time 1; T2 = Time 2. Rate of sediment supply exceeds rate of subsidence or submergence. Not to scale (from Weimer, 1984).

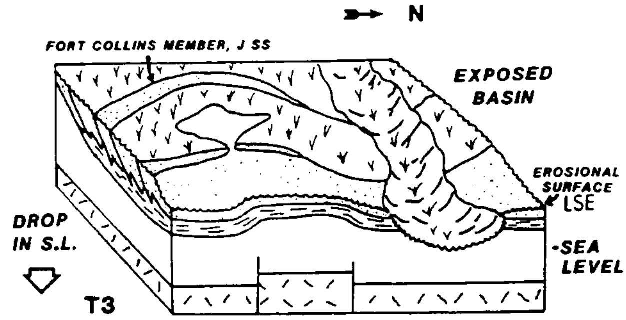


Figure 52. Lowstand sea level (T3 = Time 3) recorded as basin-wide erosional surface (LSE) resulting from subaerial exposure (major sequence boundary). Root zones form on exposed marine shales and sandstones. Not to scale (from Weimer, 1984).

(i.e., grabens), whereas delta margin or interdeltaic sedimentation occurred along an embayed coast over structural horst blocks. Delta front and shoreface sands extended seaward from the shoreline a distance controlled by effective wave base. The shoreline prograded seaward to position T2 and a sheet-like sand body was deposited over a large area (Fort Collins Member pay sandstone of Wattenberg field, Weimer et al., 1986). These depositional patterns are highstand regressive deposits that developed during a stillstand or slightly lowered sea level.

A drop in sea level occurred (T3) during which a large portion of the depositional basin (Skull Creek seaway) was drained. River drainages were incised into older strata, especially in topographic lows which correspond with the graben fault block areas (Figure 52). Over much of the Denver basin the base of the incisement is on the T1 or T2 sand complex (Fort Collins Member). Locally, the erosional surface cut into the Skull Creek Shale. The depth of valley incisement in the Denver basin varies from 20 ft (6 m) to more than 100 ft (31 m). This drop in sea level is related to the worldwide low sea level reported by Vail et al. (1977) as occurring approximately 97 to 98 Ma, although the dating is uncertain because of limited radiometric information. The geographic distribution of the major incised valleys during the lowstand is shown on paleodrainage maps for the Muddy (J) Sandstone and in the outcrop restored section (Weimer, 1984, 1992, and Dolson et al., 1989). The paleovalleys represent areas where the Muddy (J) Sandstone is dominantly fresh and brackish water deposits which generally have a thickness up to 100 ft (31 m).

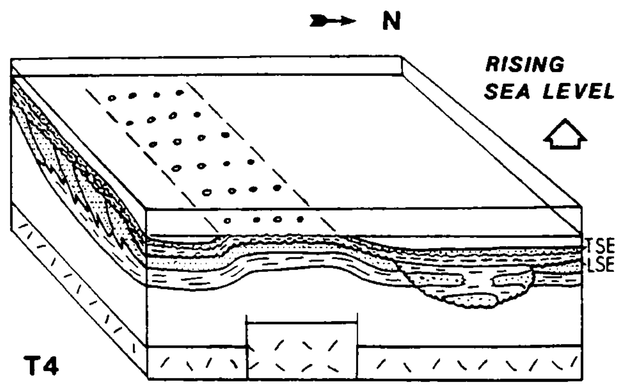


Figure 53. Rising sea level during Time 4 (T4) with fill of incised valley and deposition of marine shale and sandstones. A thin transgressive lag (generally <1 ft [.3 m] thick), sometimes with coarse-grained material, occurs on a surface of erosion (transgressive surface) at top of valley fill. Lowstand surface of erosion (LSE) and the transgressive surface of erosion (TSE) are labeled. Not to scale (from Weimer, 1984).

A rise in sea level occurred (T4, Figure 53) during which the incised valleys were modified and filled with fluvial and estuarine sandstone, siltstone, and shales. The incised valley-fill deposits may be zoned as more fresh water deposits in the lower part and brackish to marine in the upper part. The zoning reflects aggradational fill and landward movement of the shoreline (transgression) associated with coastal onlap on the lowstand surface of erosion (LSE).

With a continued rise in sea level, the coastal plain deposits were transgressed by shoreline and shoreface environments and an associated erosional surface formed over a large area (TSE). In some outcrop sections, a thin lenticular bed (1 ft; 0.3 m) of fine- to coarse-grained conglomeratic sandstone is observed at the top of the Muddy (J) Sandstone (MacKenzie, 1963). Although included in the Muddy (J), the layer is a relict or palimpsest sandstone genetically related to the Mowry transgression. The conglomeratic sandstone occurs in minor scour depressions associated with the transgressive surface of erosion (TSE). Where the coarse materials are absent, the transgressive deposit is a thin fine-grained sandstone, intensively burrowed by marine organisms.

This record of sediment reworking during the transgression of the sea over shoreline and coastal plain deposits, and the widespread thin nature of the Mowry, indicate rapid and uniform water deepening in the area of the west-central Denver basin during the transgression. No significant structural movement occurred although locally 20% thinning might suggest minor movement of fault blocks. The convergence of the lowstand and transgressive surfaces over interstream divides (structural highs) suggest that more erosion occurred in those areas by the shoreline and shoreface erosion than in the valley areas.

Following T4 the entire region received marine laminated siltstone and shale deposition (Mowry and Graneros shales, facies B and A, Figure 50). The organic rich black shales were deposited under anoxic bottom conditions during which time detrital input was slower so concentration of organic matter increased. The resultant condensed section has a high total organic carbon content in shale layers.

Facies and Environments of Deposition

A facies model (Figure 54A) has been reconstructed from the outcrop and the subsurface of the Wattenberg field area to explain the highstand regressive deposits of the upper Skull Creek and the genetically related Fort Collins Member of the Muddy (J) Formation. Progradation places the lateral facies changes in a vertical section, the relationship in which facies are usually observed (e.g., in cores and logs). But when considered in a vertical stacking pattern, facies may correspond to either a member or a formation. The facies model indicates the diachronous nature of the boundaries of lithologic units.

Five facies from A through E, in ascending order of water shallowing, are recognized in Skull Creek and Muddy formations. The lithologies and thicknesses of the facies are listed on Table 7 and related to processes within the environments of deposition and water depths. The facies thicknesses are determined by outcrop measurements and from cores. Because the lithologies can be recognized by mechanical log patterns (Figure 54A), the facies also can be easily identified and mapped regionally.

Processes in depositional environments responsible for the facies (Figure 54B) are reconstructed using the following: presence or absence of burrowing, indicating aerobic or anaerobic bottom conditions; percent of organic carbon present; energy as reflected by grain size and sedimentary structures; presence or absence of graded beds; nature of contacts; and paleosols or chemical changes beneath the lowstand surface of erosion (LSE) separating facies E from whatever underlying facies.

Assuming that tectonics and eustasy did not vary significantly during the rapid regression, and by decompacting the sedimentary column, an average water depth for the Skull Creek seaway is estimated to be approximately 200 ft (60 m) (from the top of facies D to middle of facies A). Depth variations may occur because of structurally induced topography by fault block movement, causing local thinning of facies.

Following deposition of facies D, and possibly the thin overlying coastal plain deposits, a relative sea level drop occurred and paleodrainages were incised into facies D, C or B. The magnitude of incisement varies from a few ft. (m) to as much as 100 ft (31 m). Facies E may be coastal plain deposits and distributary channels of a prograding deltaic shoreline beneath the LSE, but more commonly, it is a fluvial and/or estuarine valley-fill deposit and associated interfluve deposits above the LSE.

Of particular significance in stratigraphic trap exploration are the seals formed by paleosols (early diagenesis) under the subaerially exposed surface of erosion (LSE-sequence boundary) (Weimer and Sonnenberg, 1989).

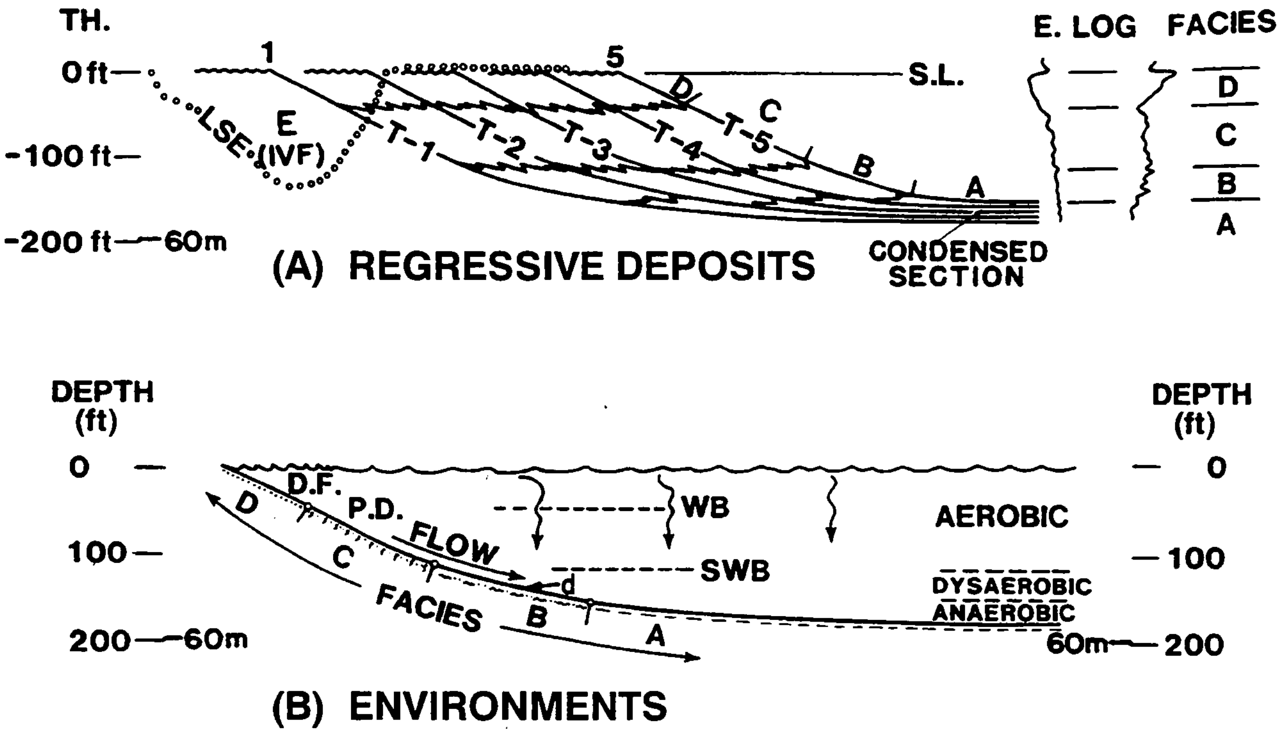


Figure 54 (A). Facies model for regressive deposits of Skull Creek and Fort Collins Member of Muddy Formation. T-1 through T-5 represent time surfaces (paleoslopes) during progradation of shoreline. LSE = lowstand surface of erosion (sequence boundary). Note that facies (lithologic) boundaries are diachronous.
(B) Depositional environments and water depths for facies A-D. WB = wave base, SWB = storm wave base, D.F. = delta front, P.D. = prodelta, d = deformed layers by slumping. Modified after Davis et al. (1989).

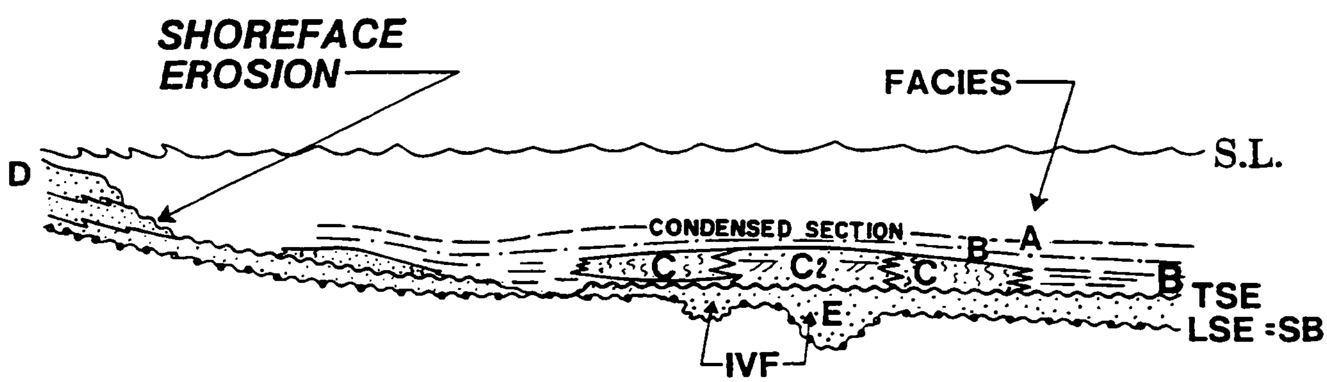


Figure 55. Facies development in relation to the transgressive surface of erosion (TSE) during relative sea level rise (water deepening). Refer to Table 8 for lithologies of facies A-E. C2 is an offshore central marine-bar facies with cross-stratified sandstone. Thin relict residual deposits may or may not form on TSE. LSE = lowstand surface of erosion, SB = sequence boundary, IVF = incised valley fill.

During the Mowry transgression and water deepening, the lithologies deposited above the TSE are quite variable (Figure 55). Because of shoreface erosion causing the TSE, facies D generally is absent except in areas of minor stillstands of the shoreline (e.g. J1, Figure 50). Reworked sands occur as thin burrowed sandstone lags, or as marine bars (sand ridges) above the TSE. In the outcrop area of the Denver basin, facies B deposited in water depths of more than 100 ft (31 m) overlies the TSE (illustrated in the right side of Figure 55). This abrupt water deepening appears related to both tectonic subsidence and eustatic rise. In a part of the outcrop area over the Wattenberg paleohigh, the TSE and LSE merge (center of Figure 46). Continued water deepening resulted in the entire Western Interior basin being inundated with maximum transgression during the time of Greenhorn Limestone deposition (Cenomanian).

Summary

Sequence stratigraphic concepts have been used to analyze the origin, age, geometry and diagenesis of reservoirs in the Muddy (J) Sandstone of the Denver basin. Every well drilled in the basin has at least two regional unconformities and in some parts of the basin three or more. By tracing the erosional surfaces of lowstands and transgressions caused by relative sea level changes, sandstone trends can be mapped for each member and related to pools and production data. From the field studies new ideas are generated for application in exploration and production programs in undeveloped areas.

FIELDS, POOLS AND RESERVOIRS

The basin center petroleum accumulations have several stratigraphic levels of production that could be classified as pools within one large field. But geographically, as fields developed as discrete entities,

Table 9. Summary of data about Wattenberg field (from Higley and Smoker, 1989). References for reservoir characterization: Matuszczak, R. A., 1973; Peterson, W. L. and S. D. Janes, 1978; Myer, H. J. and H. W. McGee, 1985; Weimer, R. J., S. A. Sonnenberg and G. B. C. Young, 1986; Young, G. B. C., 1987; Higley, D. K. and J. W. Smoker, 1989; Weimer, R. J. and S. A. Sonnenberg, 1989; Hemborg, H. T., 1993.

Field Data:	**Wattenberg Field**
Discovered:	1970
Geographic Location:	T1N R67W, Weld County, Colorado
Reservoir:	Fort Collins & Horsetooth Members, J Sandstone
Nature of Trap:	Stratigraphic, unconformity, faulting
Lithology of Reservoirs:	Fort Collins- very fine grained, moderately sorted, quartz arenite and sublitharenite
Depositional Environments:	Mainly delta front and nearshore marine (Fort Collins), with valley-fill (Horsetooth)
Diagenesis:	Compaction, chlorite rims, quartz overgrowths, calcite cementation and contemporaneous dissolution of feldspar and lithic fragments, calcite dissolution, illite-smectite, late fracturing (Weimer, et al, 1986)
Porosity Types:	Intergranular with minor matrix microporosity and secondary dissolution
porosity (Weimer, et al, 1986)	
Porosity:	8 - 12%
Permeability:	0.05 - 0.005 md
Water Saturation:	Average 44%
Temperature:	Average 260°F (112°C)
Drive Type:	Gas expansion
Reservoir Depth:	Average 7600 ft (2316 m)
Reservoir Thickness:	Average 20 ft (6 m)
Areal Extent:	627,000 acres (253,700 ha)
IP:	100 - 3600 MCFGPD
Cumulative Production (1/89):	15,500,000 BO, 566.2 BCFG
Approximate Ultimate Recovery:	0.9 - 1.2 TCFG

Table 10. Summary of data about Codell-Fort Hays fields (basin center area), Denver basin. References for reservoir characterization: Weimer, R. J. and S. A. Sonnenberg, 1983; Wright, J. D. and R. A. Fields, Jr., 1988; Panigoro, H., 1988; Hemborg, H. T., 1993.

Field Data:	Basin Center Fields
Producing Interval:	Codell Sandstone and Fort Hays Limestone
Geographic Location:	Adams, Boulder, and Weld Counties, Colorado
Present Tectonic Setting:	Denver Basin
Depositional Setting:	Shallow water shelf (Late Cretaceous seaway)
Age of Reservoir:	Upper Cretaceous
Lithology of Reservoirs:	Bioturbated fine-grained sandstone
Depositional Environments:	Marine neritic
Diagenesis:	Codell: compaction, chlorite, illite-smectite, quartz and calcite cements
Porosity Types:	Primary and secondary intergranular; fracture
Porosity:	10%
Permeability:	.1 md
Water Saturation in Pay:	60%
Fractures:	Extensive in Fort Hayes Limestone
Nature of Trap:	Stratigraphic; faulting
Entrapping Facies:	Shales
Source Rock:	Benton and Niobrara groups
Hydrocarbon Migration:	Paleocene
Discovered:	1981
Reservoir Depth:	6,800 - 7,200 ft
Reservoir Thickness:	10 - 25 ft Codell; 20 - 30 ft fractured Fort Hayes
Areal Extent:	>627,000 acres (253,700 ha)
Average IP:	Highly variable
Original Reservoir Pressure:	4,000 psi
Drive Type:	Solution gas
Cumulative Production (1/93):	193 BCF; Oil (?)
Estimated Oil in Place:	400,000,000 BO
Oil Gravity	60° API

and named and spaced by the Colorado Oil and Gas Commission, large numbers of field names were given for different parts of the same accumulation (Hemborg, 1993, Part 1, Figure 20). Moreover, separate field names are used in the same geographic area for different pools. An example is the Spindle oil field area occurring above the Wattenberg gas field, and an additional complication is production from the Codell-Fort Hays reservoir in the same area. These terminology complications add additional work and some uncertainty to field studies, and must be resolved in order to analyze accurately production data to interpret reservoir performance.

Field data have been compiled for the three most important fields (pools) of the greater Wattenberg area and presented as Tables 9, 10 and 11. Along with the field information, major references are listed that describe the reservoir characteristics of the producing intervals. Production from other stratigraphic horizons and fields is summarized by Hemborg (1993).

Table 11. Summary of data about Spindle Field (from Porter, 1989). References for reservoir characterization: Treckman, 1960; Moredock, D. E. and S. J. Williams, 1976; Porter, K. W. and R. J. Weimer, 1982; Pittman, E. D., 1989; Porter, K. W., 1989; Hemborg, H. T., 1993.

Field Data:	**Spindle Field**
Producing Interval:	Hygiene & Terry Sandstone Members, Pierre Shale (AKA Shannon and Sussex)
Geographic Location:	Adams, Boulder, and Weld Counties, Colorado
Present Tectonic Setting:	Denver Basin
Depositional Setting:	Marine shelf (Late Cretaceous seaway) with fluctuating sea levels
Age of Reservoir:	Upper Cretaceous
Lithology of Reservoirs:	Glauconitic feldspathic litharenite
Depositional Environments:	Offshore marine sand
Diagenesis:	Chlorite, quartz, and calcite cements; dissolution of feldspars, lithic fragments, and calcite; kaolinite
Porosity Types:	Primary intergranular, secondary intergranular, and microporosity
Porosity:	Maximum 19%; average 14%
Permeability:	Maximum 17 md; average 2 md
Water Saturation in Pay:	Range 25 - 80%; 60% average
Fractures:	Significant
Nature of Trap:	Stratigraphic and diagenetic; faulting
Entrapping Facies:	Shaly sandstones and marine shales of Pierre
Source Rock:	Benton Group shales, Niobrara and Sharon Springs
Hydrocarbon Migration:	Paleocene
Discovered:	June 10, 1971
Reservoir Depth:	4,300 ft (Terry) - 5,000 ft (Hygiene) (1,370 - 1,550 m)
Reservoir Thickness:	25 ft (Terry) - 20 ft (Hygiene) (6.2 - 7.7 m)
Areal Extent:	63,400 acres (25,658 ha)
Average IP:	125 BOPD
Original Reservoir Pressure:	1,450 psi
Drive Type:	Solution gas
Cumulative Production (1/93):	49,200,000 BO, 236 BCFG
Estimated Oil in Place:	500,000,000 BO
Oil Gravity:	42° API
Minimum Water Saturation:	30%

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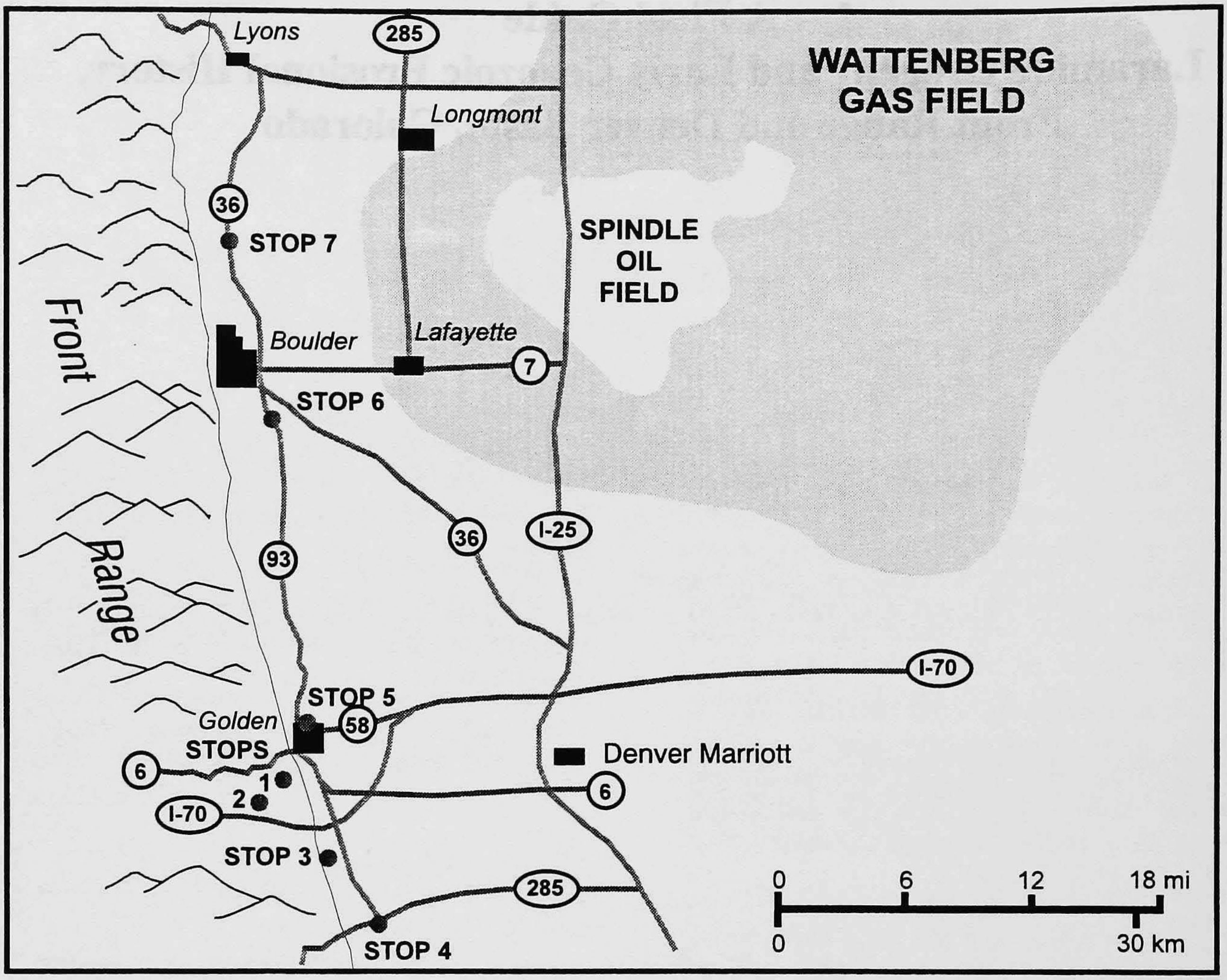
Part II

A Field Guide
Laramide Orogeny and Early Cenozoic Erosional History, Front Range and Denver Basin, Colorado



Stop 1.	Precambrian shear zone; Windy Saddle, Lookout Mountain.
Stop 2.	Eocene erosional surface; Mount Vernon Country Club
Stop 3.	Paleozoic tectonics and sedimentation; Red Rocks Park
Stop 4.	Laramide mountain flank deformation; restored tectonics, Paleozoic tectonics and sedimentation; Turkey Creek
Stop 5.	Laramide tectonics and sedimentation and volcanic events; Colorado School of Mines
Stop 6.	Laramide shallow depth fault zone associated with wrench faulting; Laramie Formation coal mines; Marshall
Stop 7.	Cretaceous early Laramide deformation; wrench faulting; 6 mi (9.6 km) north of Boulder

Figure 1. Index map showing field trip stops.

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.

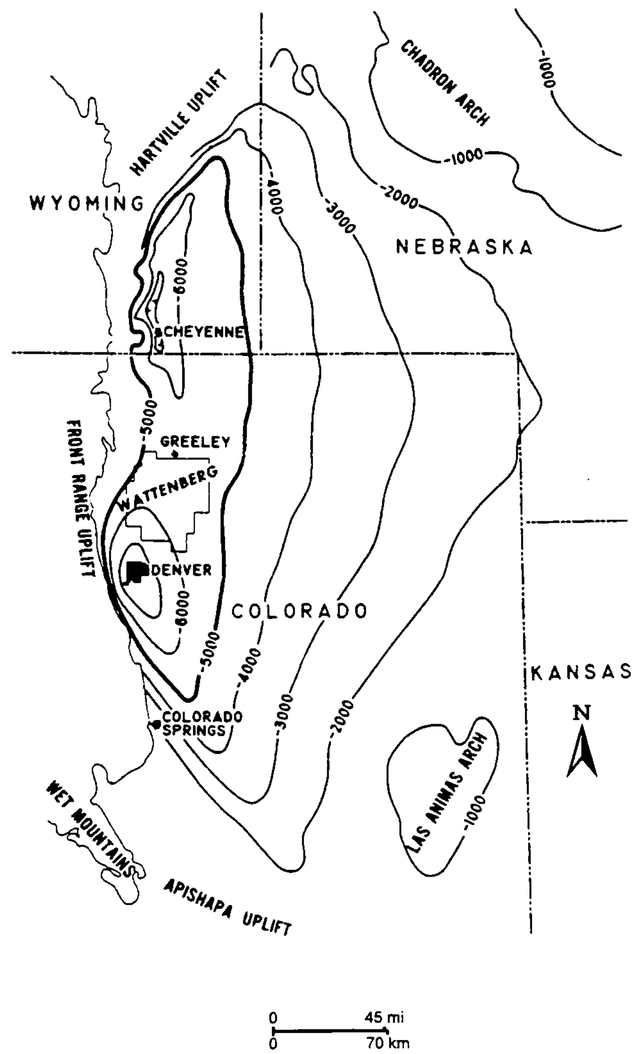


Figure 2. Structure contour map on top of Precambrian for Denver Basin and related structural features (from Matuszczak, 1973). Contours are in feet.

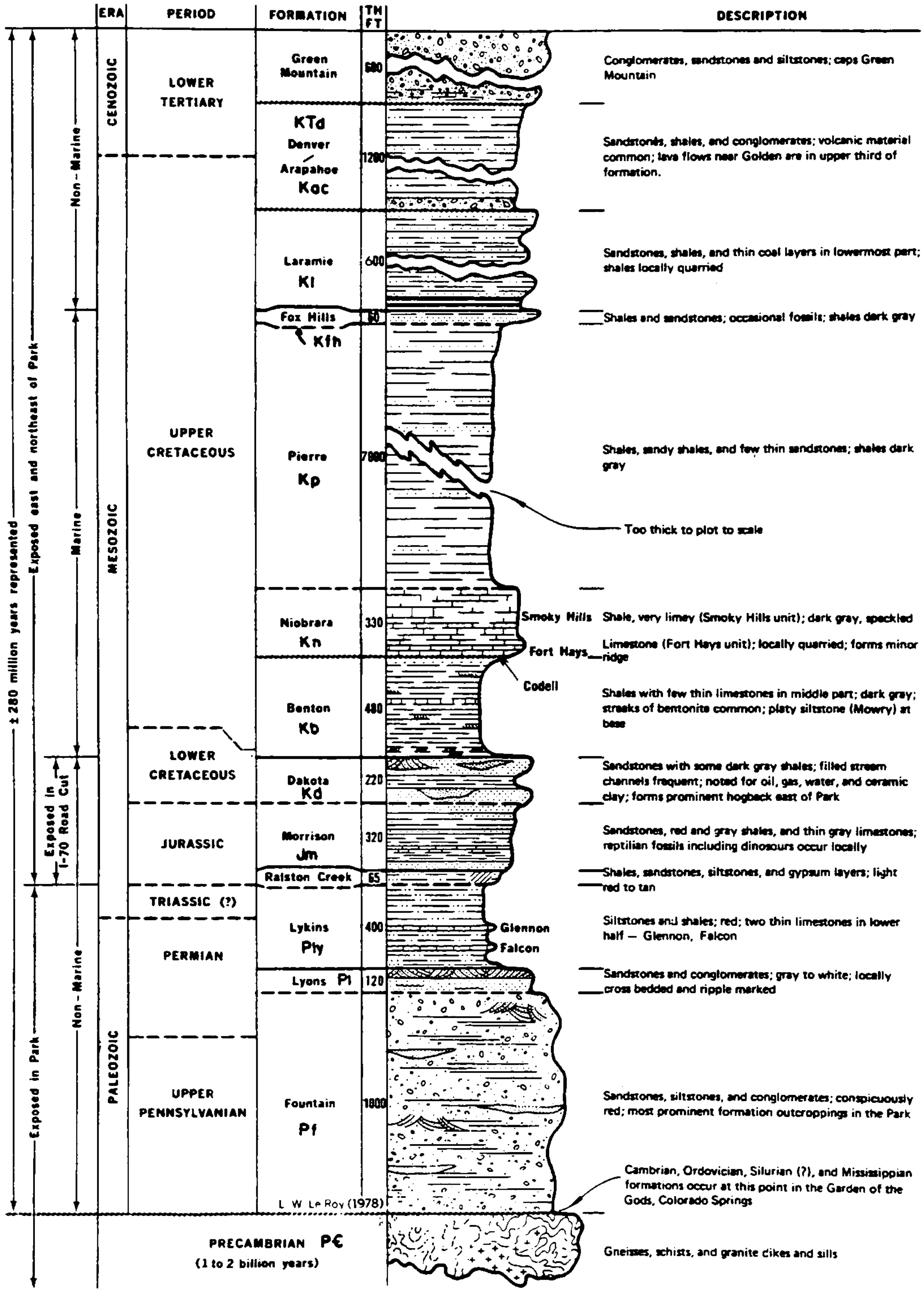


Figure 3. Generalized stratigraphic section in Golden-Morrison-Evergreen area, Jefferson County, Colorado (from Weimer and LeRoy, 1987).

Structural relief on the top Precambrian is approximately 14,000 ft (4270 m) from the eastern margin of the Front Range (7200 ft - 2200 m) to the bottom of the Denver basin (Figure 2). Rocks in the stratigraphic section of the basin and mountain flank ranges in age from Pennsylvanian to lower Tertiary (Figure 3) with approximately 10,000 ft (3100 m) of Cretaceous age.

The field trip will visit key outcrop localities to interpret the Laramide events to include the following: Precambrian and Paleozoic ancestry; mountain uplift and flank deformation; orogenic sedimentation; Laramie coals; volcanic record; and the Eocene erosional surface marking the end of the orogenic phase.

By compiling this trip, I wish to acknowledge the many students of the Laramide and geologic history of the Front Range and Denver basin. Much has been done—much remains. I also wish to thank Steve Sonnenberg, Barry Perow and Barbara Brockman for assistance in preparation of this guide.

STOP 1
WINDY SADDLE, LOOKOUT MOUNTAIN
(On Lariat Loop Road, West of Golden)

Windy Saddle separates Mount Zion and Lookout Mountain, and is located on a Precambrian shear zone within the Idaho Springs Formation (Figures 3 and 4). The broken, crushed and altered gneiss and schist, exposed at Windy Saddle, is typical of fault zones that bound a mosaic of fault blocks in the Front Range and elsewhere in Colorado. The rocks in the shear zones erode more easily so stream drainages, in general, follow shear zones, e.g. Clear Creek to the west. Moreover, the shear zones are poorly exposed and, therefore, are best known where excavations or mining have occurred.

The location and names of fault zones mapped in the Precambrian and Phanerozoic rocks in the Golden-Morrison-Evergreen area (Figure 4) are known from quadrangle mapping by geologists of the U.S. Geological Survey (Bryant et al., 1973, Sheridan et al., 1972, Smith, 1964, Van Horn, 1957 and Sheridan et al., 1967). This area is a microcosm of the geology of the Front Range and the major events and concepts relating to the tectonics are summarized as follows:

- Igneous and metamorphic rocks comprising the Precambrian basement of Colorado yielded by brittle deformation to form a mosaic of fault blocks bounded by shear zones. This deformation occurred during one or more orogenic periods in the late Precambrian (Tweto and Sims, 1963; Tweto, 1980b; Warner, 1978, 1980). Locally, fault trends may have any orientation, but regional trends are northeast and northwest. Dip of the fault planes at time of origin was nearly vertical (Figure 5a).
- The fault blocks may be tens of miles in width and length, or may be much smaller (a few miles in width and length).
- The rock strength remains high for the unbroken portion of the fault blocks but is low for shear zones bounding the blocks.
- At times during the Phanerozoic when the crust was highly stressed, the stress was relieved primarily by movement along pre-existing zones of weakness, that is, along faults or shear zones. New, but minor, zones of breakage may have developed (Weimer, 1980).
- Because of the above factors, movement recurred along many of the same basement faults throughout the Phanerozoic. Direction of recurrent movement along a given basement fault is normally consistent, but examples of a reversal in direction are common, especially along wrench fault zones.
- Following the above reasoning the faulting in both the late Paleozoic orogeny, and the Laramide orogeny, for the most part, followed the older Precambrian fault zones in the basement.

Strata overlying basement fault blocks mimic the mosaic pattern by faulting or by drape folding (Figure 5b). The east end of the Windy Saddle shear zone passes into a drape fold in the Paleozoic and Mesozoic strata because of recurrent movement during the Laramide (Figure 4). However, many faults and fractures in the basement do not cut the overlying sedimentary cover indicating that Phanerozoic movement did not occur and the faulting is thus dated as Precambrian in age (e.g. Stop 3, in Red Rocks Park).

The history of the uplift of the Range will be discussed at Stop 4. However, the Precambrian in the Lookout Mountain area has been analyzed for apatite fission track ages and yielded data indicating ages greater than 100 Ma (Kelley and Chapin, 1995).

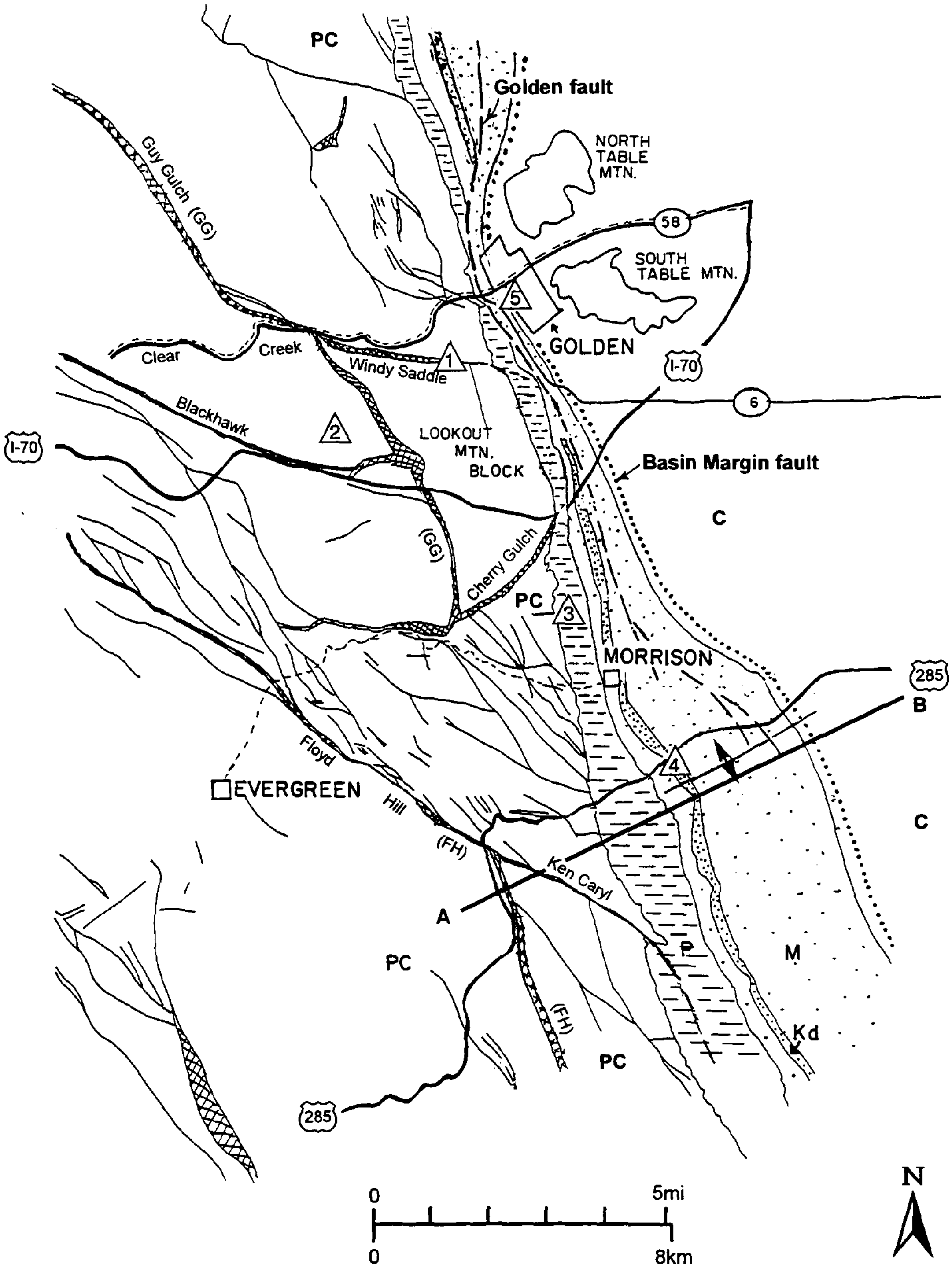


Figure 4. Simplified geologic map with field trip stops and compilation of faults in Golden-Morrison-Evergreen area. From Tweto (1979 and 1980), Trimble and Machette (1979), and geologic quadrangle maps. Symbols are on Figure 3.

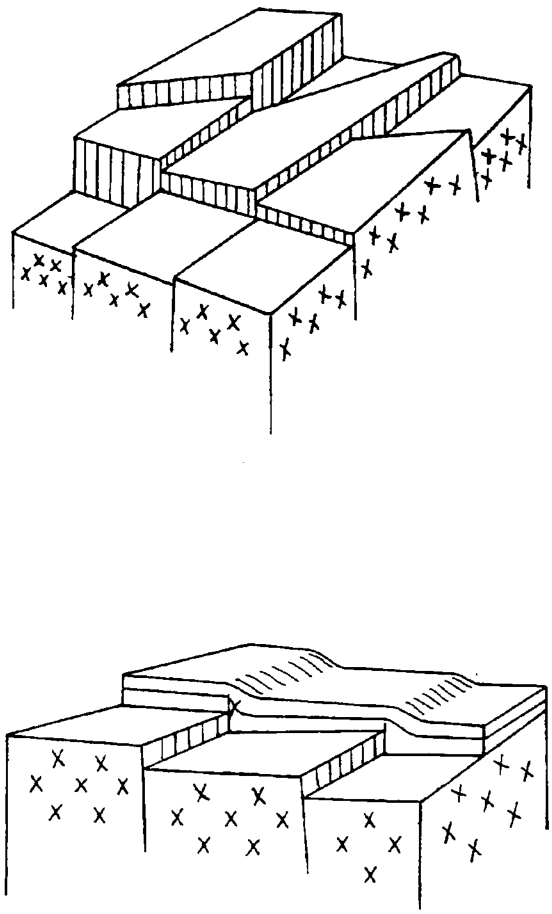


Figure 5. A. Diagram of a mosaic of fault blocks produced by three directions of faulting; B. drape folding of overlying sedimentary strata (after Clement, 1977).

STOP 2
MT. VERNON COUNTRY CLUB
(Clubhouse, 1.5 Mi [2.4 Km] NE of Exit 254, I-70)

Two Cenozoic erosional features are spectacularly displayed at Stop 2. One is the Eocene erosional surface (EES) that beveled the top of Lookout Mountain and has a slope from west to east, varying from 65 ft to 100 ft per mi (12-20 m per km) (Figure 6). The second feature is Clear Creek Canyon which has about 2000 ft (600 m) of relief from the canyon rims to the Clear Creek.

The EES is a regional feature on the Front Range that formed after the cessation of Laramide orogenic movements (Tweto, 1975; Scott, 1975; Epis and Chapin, 1975; Scott and Taylor, 1986; Trimble, 1980). Locally, it has also been referred to as the Bergen Park surface, for a small village 6 mi (9.7 km) to the west (Figure 6). The surface projects eastward over the top of Green Mountain (elevation 6863 ft - 2100 m) and into the Eocene sedimentary section (Soister and Tschudy, 1978, and Soister, 1978b). The unconformity represented by the widespread paleosol (late Paleocene or Early Eocene) (Soister and Tschudy, 1978) and the unconformity at the base of the Castle Rock Conglomerate (or the Wall Mountain Tuff) (Oligocene) (Soister, 1978) may converge into the EES on Lookout Mountain.

The surface represents an important break between the orogenic deformational style of the Laramide and the epeirogenic style of the post-Eocene. Recent studies by Leonard and Langford (1994), of the Rampart Range to the south, indicate that little or no post-Laramide movement occurred on the range-bounding faults. The conclusion indicates that the topographic relief presently observed is the result of denudation below the EES in the mid- to late Cenozoic. However, the change in gradients of the EES in the lower 3 miles (4.9 km) of Clear Creek Canyon (Figure 6), may be the result of minor post-Eocene fault block rotation on the Guy Gulch fault zone (upthrown on west side).

A profile across the lower portion of the Clear Creek Canyon (Figures 6 and 7) shows different erosional levels in the Canyon. The post-Eocene erosional history is recorded by the cutting of Clear Creek Canyon and similar features along the length of the Front Range (Figure 8, Scott and Taylor, 1986). The EES forms the upper benches and rim of the canyon; the middle benches represent the remnants of the base of a Miocene canyon at elevations of 7000 to 7200 ft (2140 to 2200 m); and, the narrow lower benches, where developed, are at or near the level of Clear Creek.

The canyon events resulting from late Cenozoic geomorphic processes are illustrated in a diagram by Scott (1975) (Figure 8). Renewed uplift of the Front Range in the Pliocene imparted a higher stream gradient to Clear Creek (now 140 ft - 43 m per mi) and the narrow V-shaped inner gorge was eroded. Steep walls rise abruptly 500 to 700 ft (152 - 214 m) above present stream level.

Successful efforts are now underway by the Jefferson County Open Space program to acquire lands to preserve Clear Creek Canyon as a nature park. The

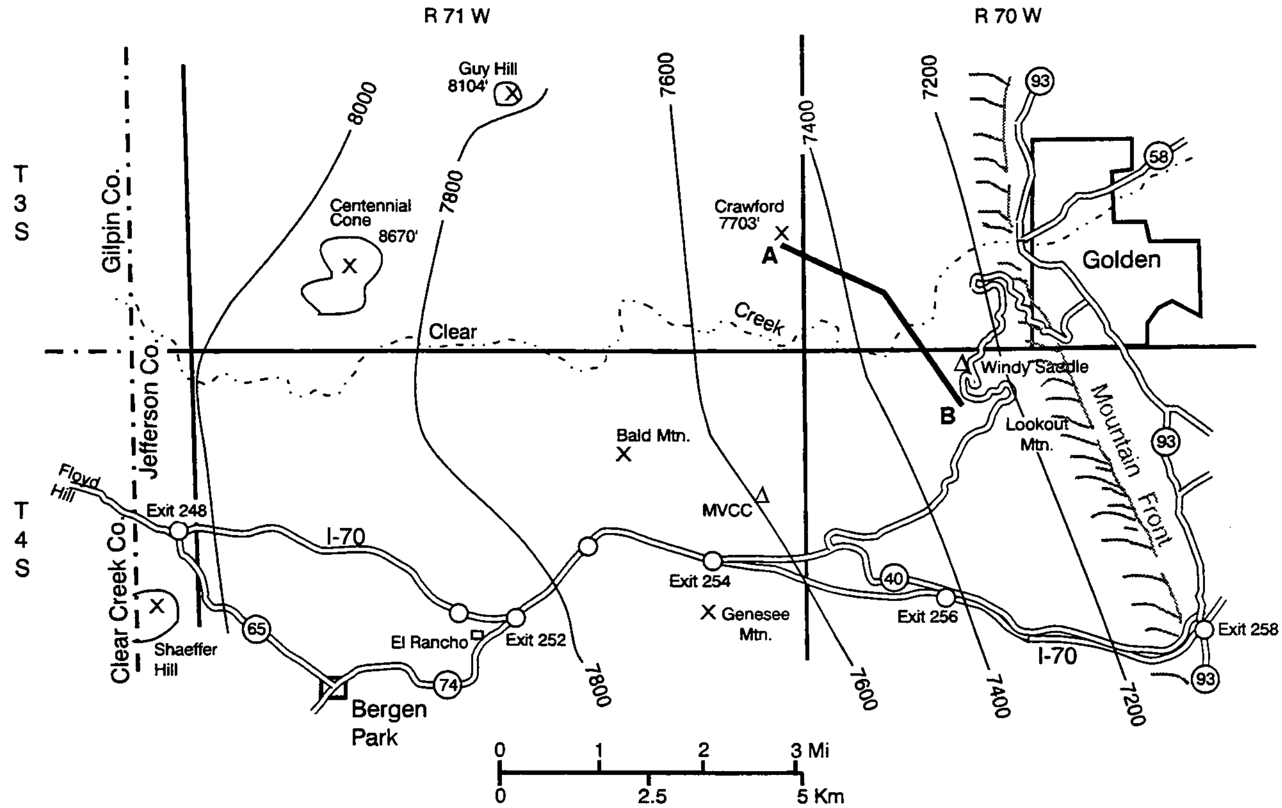


Figure 6. Contour map of present elevations (in ft) of the Eocene erosional surface as interpreted from the divides marginal to Clear Creek Canyon.

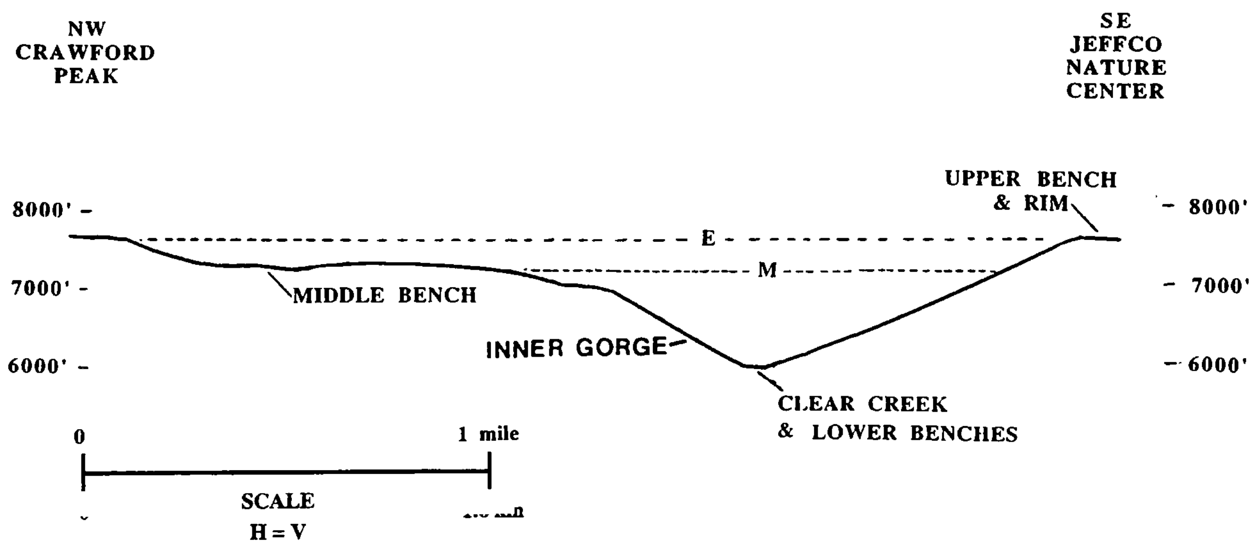


Figure 7. Topographic profile of Clear Creek Canyon. E = restored Eocene erosional surface; M = Miocene erosional surface.

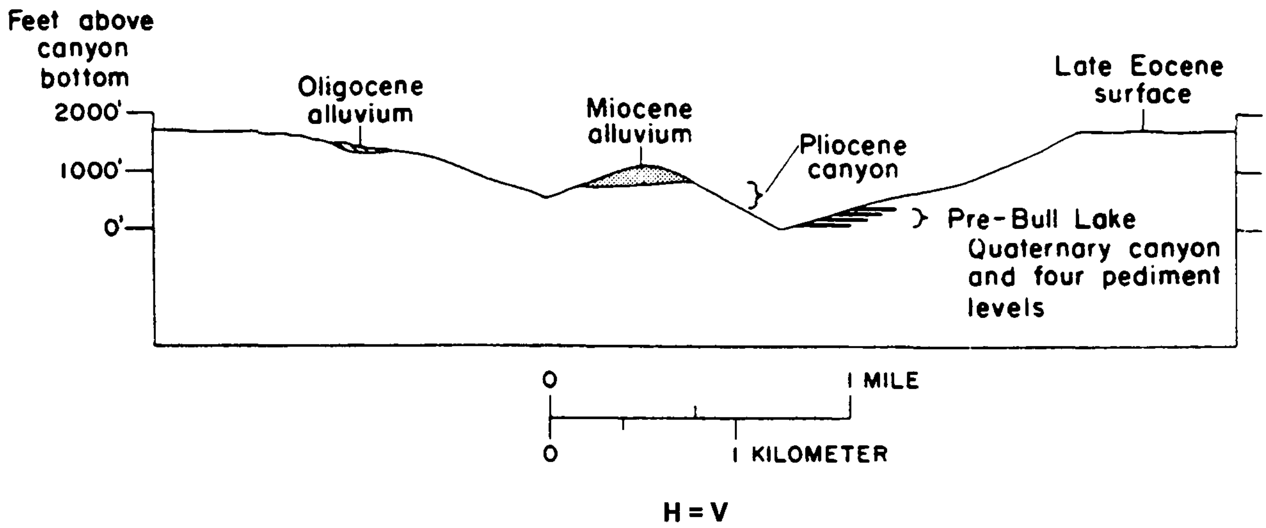


Figure 8. Typical Front Range canyon showing the form resulting from Cenozoic geomorphic processes. The four marks in the lower part of the canyon represent the levels of the four pre-Bull Lake pediments (from Scott, 1975).

geological uniqueness of the Canyon, the lack of development and the closeness to a major metropolitan population have been major reasons for the preservation program.

STOP 3
RED ROCKS PARK
(Upper Parking Lot near Amphitheater)

The purpose of this stop is to discuss the geology of the Park and to present new data pertaining to the late Paleozoic highlands, an ancestry to the Laramide orogeny. The following description is modified from Weimer and LeRoy, 1987).

Geology of the Park

Red Rocks Park takes its name from the spectacular red monuments of the Fountain Formation of Pennsylvanian and Early Permian age. The formation is composed of red arkoses, sandy mudstones, and conglomerates, and is the most conspicuous and oldest sedimentary unit in the Park (Figure 3). It forms the beautiful and unique setting for a 10,000-seat amphitheater. The 975-ft (300-m) formation has an outcrop width of approximately 0.6 mi (1 km) and a length of 1.25 mi (2 km). The lower half of the section is resistant to erosion and forms the scenic landscape that was the basis for establishment of the Park by the City and County of Denver.

The Fountain is an excellent example of a vast complex of shallow braided channels deposited on alluvial fans, or in small fault-controlled valleys marginal to and east of the nearby ancestral Front Range Highland. The angular nature of mineral and rock grains and clasts, the immature nature of the sediment, the trough cross-stratification (showing a dominant east transport) and occasional mud-cracked layers and root zones all support this interpretation of depositional setting.

The oldest Fountain strata were deposited on an irregular weathered surface on top of the Precambrian Idaho Springs Formation (Figure 9), which can be observed along the access road northwest of the upper parking area at the amphitheater. The Idaho Springs Formation represents the crystalline basement, and is the oldest group of rocks within the Park; estimated age is older than 1,700 Ma. The formation is composed of amphibolite and granite gneisses with minor schist layers and is resistant to erosion. The top of the Idaho Springs forms an east-dipping surface from which much of the Fountain Formation was stripped by erosion.

The upper 3 to 5 ft (1 to 2 m) of the Idaho Springs (observed at road level) is a weathered zone in which iron-rich silicate minerals have been oxidized to hematite. Upward along the exposed contract, this

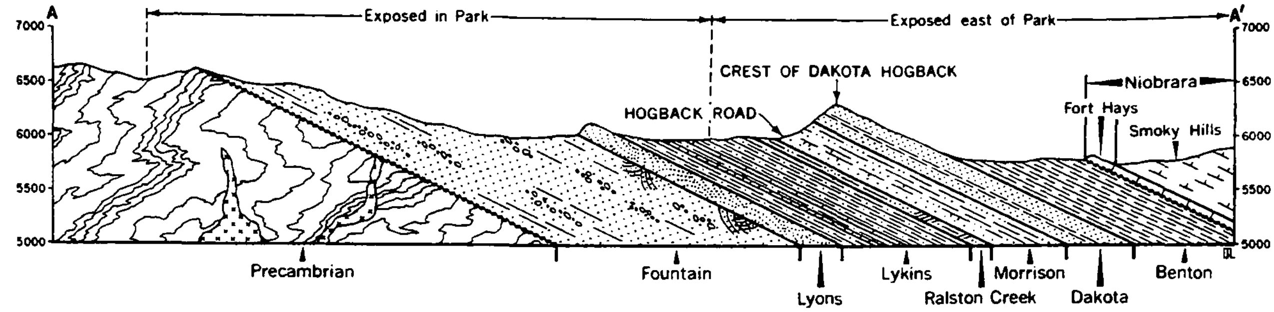


Figure 9. Southwest-northeast geologic cross section, Red Rocks Park (from LeRoy and LeRoy, 1978).

weathered zone is removed by scour at the base of a channel in the lowermost Fountain. A concentration of cobbles marks the base of this channel.

The contrast in fabric and lithology above and below the unconformity (nonconformity) is the most striking geologic change in the Park. Foliation in the gneiss generally trends east-west and dips 70° to 80°S. Several sets of closely spaced joints are obvious features; in addition, a shear zone 100 ft (30 m) north of the contact controls the position of a small east-west drainage observed on the slope west of the curve in the road. Strata of the overlying Fountain Formation strike N10°W and dip 26°E. Few joints are observed in the sedimentary strata overlying the basement. Because the age of the lowermost Fountain is estimated to be approximately 300 Ma, the missing record of the unconformity represents a hiatus (time gap) of 1.4 b.y.

Two Permian formations, the Lyons and Lykins, are intermittently exposed in the eastern half of the park (Figure 9). However, the best locality from which to view these formations is the southeast corner of the park, along the north side of Colorado 74, in the town of Morrison. The overall thickness of the Lyons is 230 ft (70 m) and of the Lykins is 390 ft (120 m). The upper portion of the Lykins may be Triassic in age.

The Lyons can be subdivided into three units in the Park, all well developed at the Morrison outcrop. The lower unit is light gray conglomerate arkose composed of genetic units 3 to 10 ft (1 to 3 m) thick. A complete genetic unit begins with a scour surface overlain by cross-stratified conglomerate that grades upward into fine- to medium-grained feldspathic sandstone, occasionally capped by thin green shale beds at the top. The shale beds may contain simple sand-filled

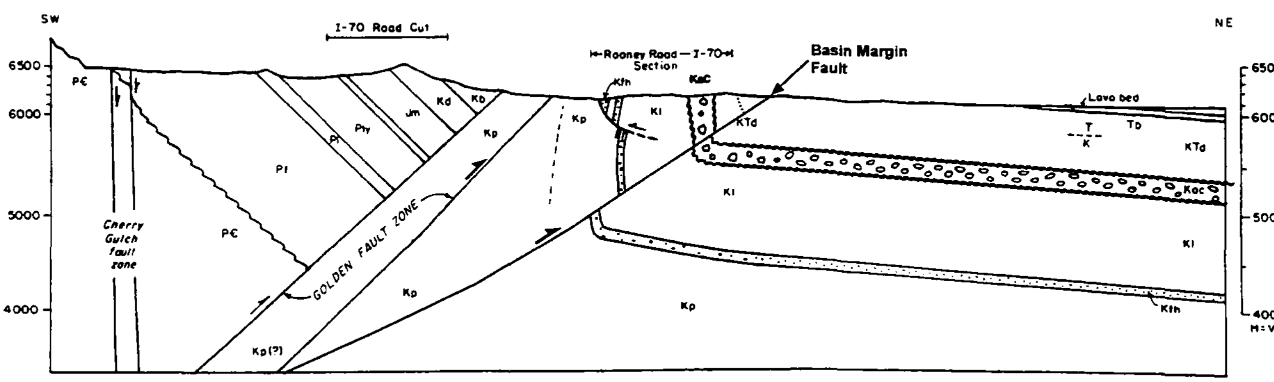


Figure 10. Structure cross section of east flank, Front Range uplift along south side of I-70; 1.5 mi (2.4 km) north of Red Rocks Park.

burrows, possibly made by insects. These stacked genetic units are interpreted as narrow channels of a braided stream deposit. The middle unit is fine-grained parallel- to cross-laminated feldspathic sandstone. Several green mudcracked shales (illite), 0.5 to 2 in. (1 to 5 cm) thick, are locally developed in the Morrison section. The upper unit is a mixture of the lithologies of the lower and middle units.

The lower unit of the Lyons is interpreted as consisting of deposits of an eastward-flowing braided stream complex on the east side of the ancestral Front Range Highland; overall setting is similar to that of the Fountain. The fine-grained, well-sorted middle Lyons, and an interval that shows the same lithology in the upper unit, are interpreted as eolian deposits blown from the wadis (arroyos) by northerly winds. The middle unit has both dune and interdune deposits: the deposits viewed at the Morrison section are largely interdune, but 0.6 mi (1 km) to the north, cross-stratified fine-grained sandstone characteristic of eolian dunes is dominant in the middle Lyons Formation. The Morrison section is a well known locality for illustrating the intertonguing of deposits of coarse-grained fluvial and fine-grained eolian environments.

The Lykins Formation consists of brick-red, thinly bedded siltstones and shales. Two crinkly laminated carbonate layers, the Glennon and Falcon members (Figure 3), are present in the lower 100 ft (30 m) of the Lykins. At Morrison, the Falcon Member is 60 ft (18 m) above the base of the Lykins; the Glennon Member is 110 ft (33 m) above the base. Three thin (1.5 in.; 4 cm thick) carbonates are locally present in the lower 10 ft (3 m) of the Lykins at Morrison. The Lykins is interpreted as a nonmarine aqueous deposit, either related to widespread supersaline restricted marine, or to saline freshwater lake conditions. The absence of fossils prevents accurate reconstruction of the environments.

The formations of the Park are part of an east-dipping rotated block in the hanging wall of the Golden fault zone (Figure 10). The trace of the Golden fault is east of the Dakota hogback within the Cretaceous section. An eastern splay of the Golden fault, the Basin Margin fault, marks the change from the vertical to overturned dips of the latest Cretaceous formations to the low dips of the Cretaceous-Tertiary strata.

The Late Paleozoic Highlands

Pennsylvanian and Permian highlands formed the ancestral rocky mountains in Colorado and adjacent states (Figure 11). As a continuation of the extensive Oklahoma-North Texas wrench fault system, these uplifted highlands shed coarse arkoses into adjacent depositional basins (Curtis, 1958; Mallory, 1960; DeVoto, 1980a). Red Rocks Park is located between the Front Range highland and the west side of the ancestral marine Denver basin.

The limited preserved record in outcrops of the late Paleozoic deformation and the Laramide overprint of folding and faulting have made the unraveling of the overall tectonic history a difficult task. However, the Paleozoic deformation in southeastern Colorado, known from well and seismic data, gives a model for reconstructing the paleohistory of the Front Range.

The thickness variation for an isopach interval, from the Precambrian to the top of the Dakota Group (Lower Cretaceous) in eastern Colorado, reflects patterns related to deposition of the Pennsylvanian and Permian strata and movement on basement faults (Figure 12).

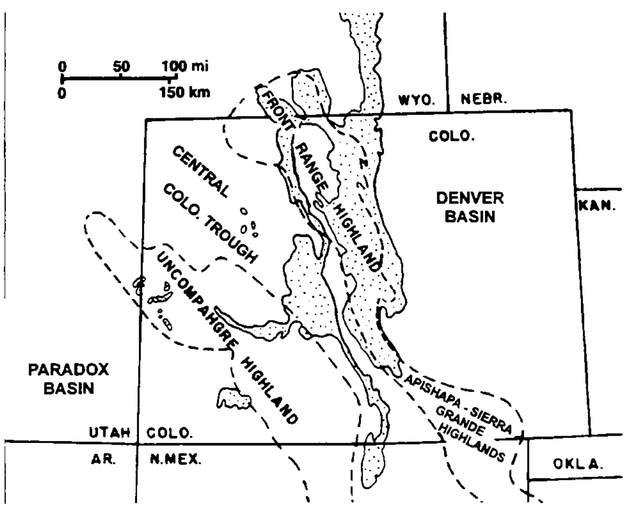


Figure 11. Paleogeographic map for the late Paleozoic. Dashed line outlines ancestral highlands (modified from Mallory, 1960). Present Precambrian outcrop areas shown by stippled pattern.

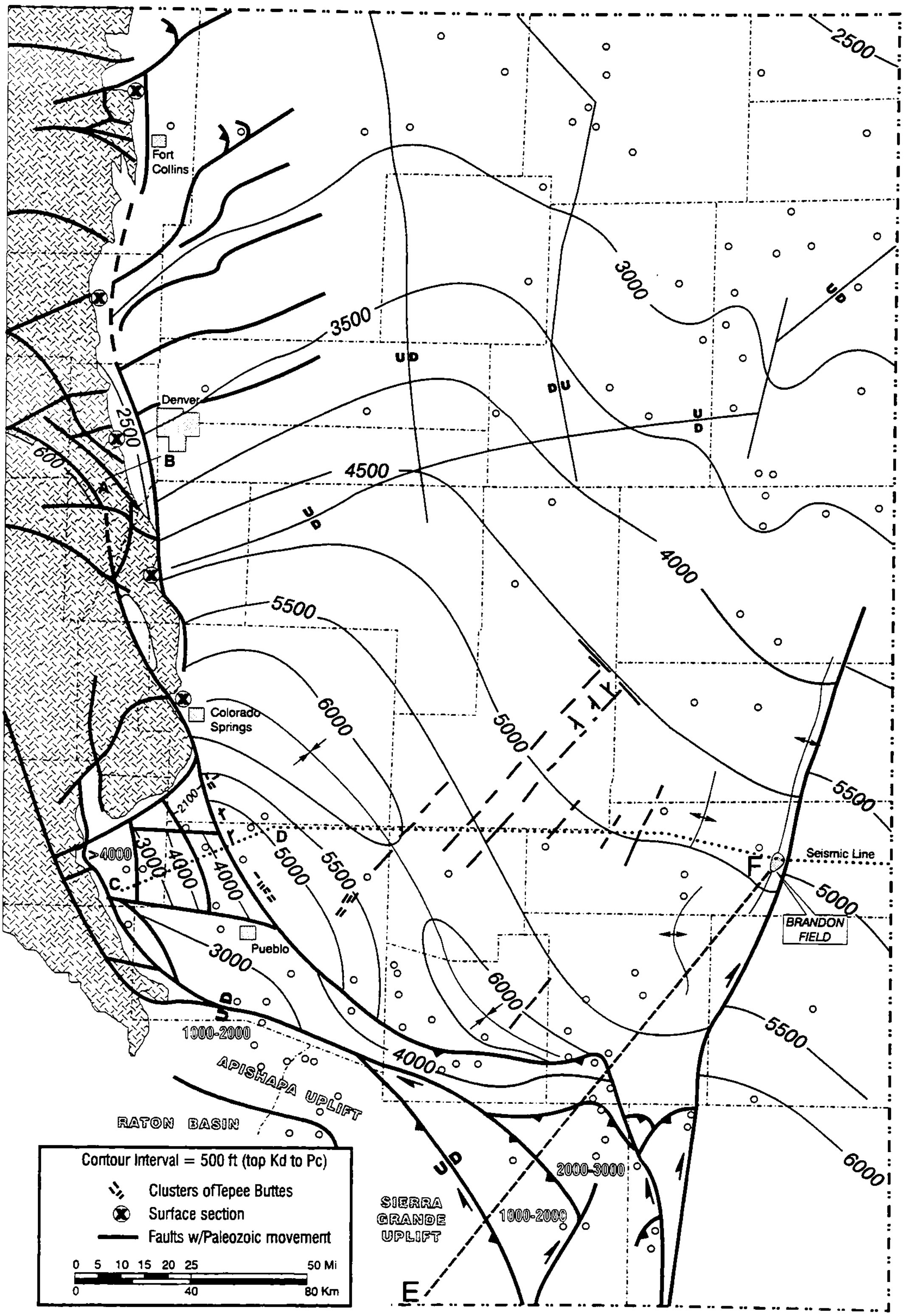


Figure 12. Isopach map from top of Dakota Group (lower Cretaceous) to the top of Precambrian. North half of map modified from Haun, 1968. Basement patterns in Precambrian from Tweto (1979, 1980).

The axis of the depositional trough, which contains over 6000 ft (1840 m) of strata, extends southeast from Colorado Springs to the Las Animas arch and parallels the Apishapa and Sierra Grande Highland. The thick Colorado Springs-Garden of the Gods section is an exposed part of the trough (Grose, 1960). Thinning occurs onto the highland which was a source of arkose to the Denver basin. During the Atoka time the north margin of the highland was broken into a series of blocks by wrench faulting, along which recurrent movement occurred into the Permian (Figures 12 and 13). Where north- and northwest-trending wrench faults bifurcated and changed to westerly trends, high angle reverse faults were initiated. Thinning to the south across the fault blocks was progressive with Permian lying on Precambrian on the top of the highland. Collectively the fault blocks show over 4000 ft (1220 m) of structural movement during the Pennsylvanian and Permian.

In the area of the Sierra Grande-Apishapa Highland, Laramide deformation was minor. The Dakota Group, an excellent regional marker formation, still covers most of the uplift. A structure contour map on top of the Dakota Group (Figure 14) and cross-section (Figure 13) shows only moderate doming and arching believed caused by crustal movement related to the Laramide. Occasionally regional monoclines occur over older fault trends (Scott, 1968) indicating recurrent movement. Both the Apishapa and the Sierra Grande uplifts, named for the structures shown on the map (Figure 14), show Laramide arching over the old late Paleozoic highland with the magnitude shown by the contours. The Las Animas arch is a northeast extension of the Sierra Grande anticline, named for a locality in New Mexico.

A similar tectonic pattern of sedimentation associated with fault block movement is observed on the southern plunge of the Front Range in the Pueblo, Cañon City and Red Creek arch area (Figures 12 and 14). Data from outcrop, well data and a regional east-west seismic line (from the Cañon City graben to the Colorado-Kansas state line) confirm the northwest trend and style of late Paleozoic deformation from the highlands of southeast Colorado into the Front Range highland. Weimer (1980) described thinning across fault blocks in the Cañon City—Red Creek area with recurrent movements during both the late Paleozoic and Laramide along the same basement fault zones.

Significant changes occur in thickness trends of Pennsylvanian and Permian strata between the outcrop and subsurface of the central Front Range (Haun, 1968). These changes are caused by major fault block movement described as the basin, central and highland blocks (Figures 12 and 15). In the Red Rocks Park, the thickness of the interval top Dakota to top Precambrian is 2400 ft (730 m) (central block) in contrast to 3500 ft (1080 m) (basin block) in the U. S. Army Rocky Mountain Arsenal well drilled to the Precambrian, [T.D. 12,045 ft (3670 m) 6 mi (9.7 km)] northeast of Denver (Figures 12 and 15) (Scopel, 1964). Based on

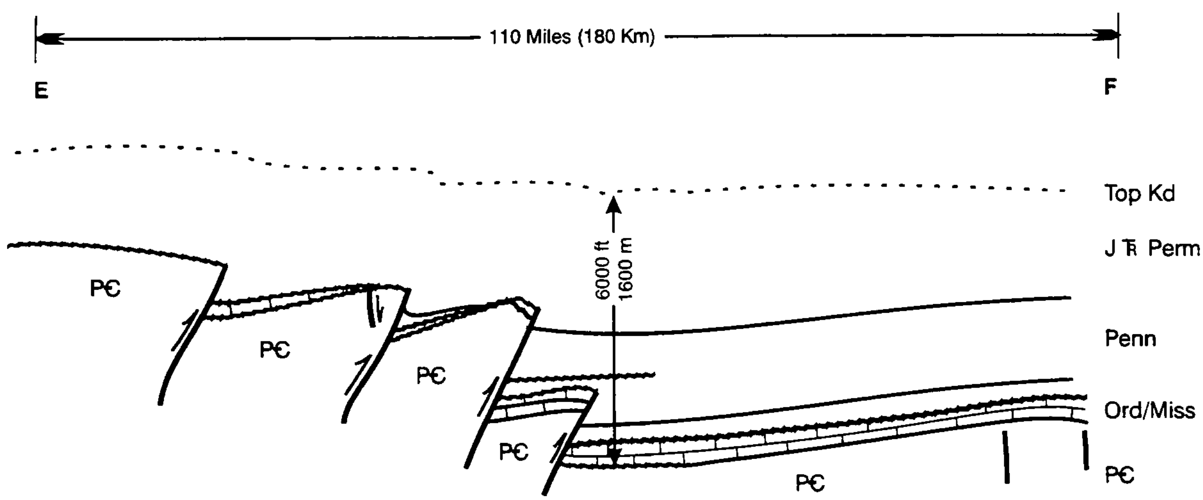


Figure 13. Diagrammatic structural cross section from Brandon oil field to near New Mexico state line.

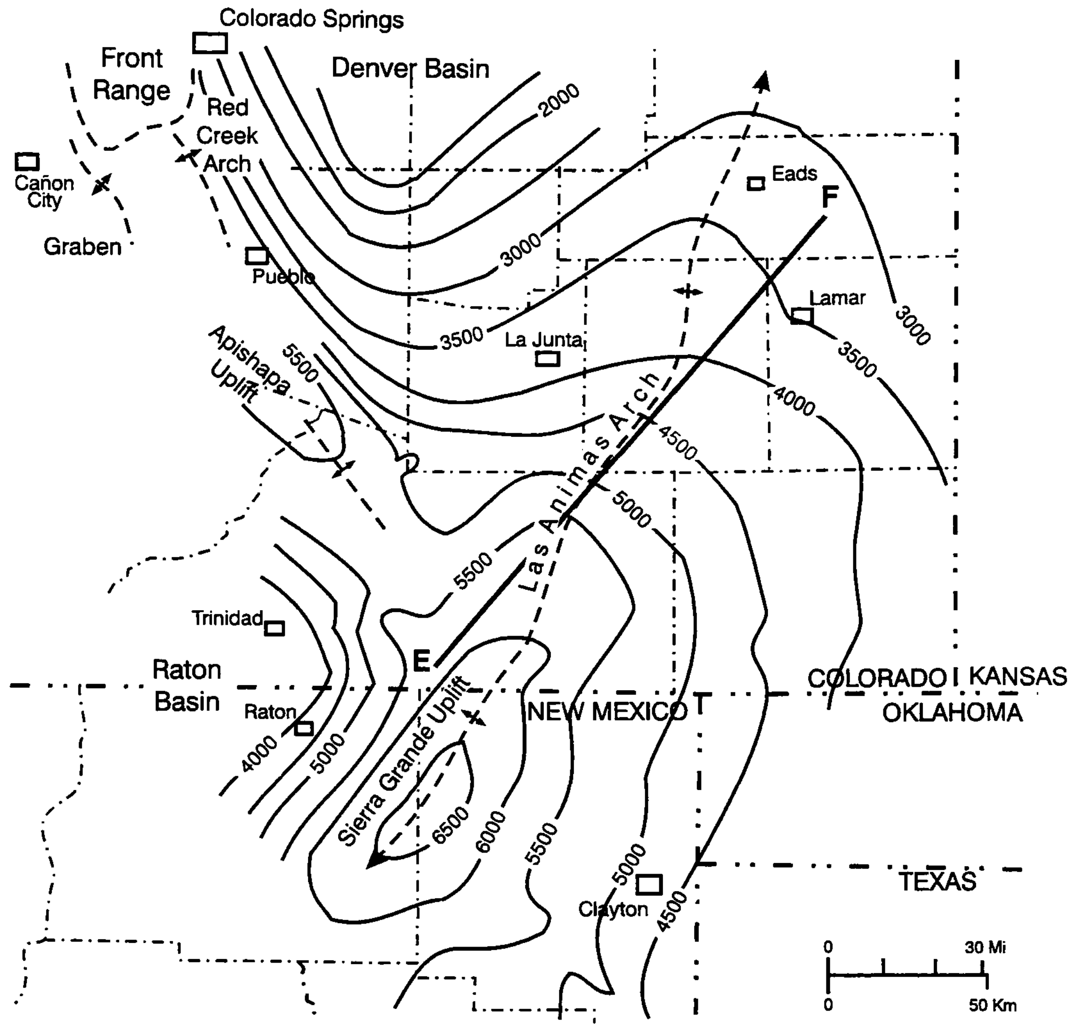


Figure 14. Structure contour map on top Dakota Group. Contour interval is 500 ft.

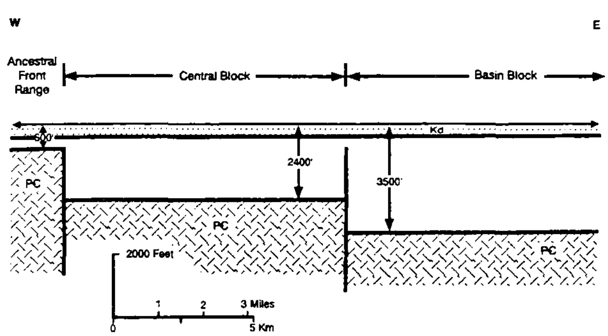


Figure 15. East-west section restored to top Dakota Group (Kd) showing thickness variations in interval to top Precambrian (PC) across postulated fault blocks.

seismic data the thinning is caused by fault movement along or near an ancestral Golden fault zone. Additional westward thinning is projected because the source of sediment to the Fountain Formation is the Front Range highland block (F.R.H., Figure 15). A reconstruction places only 600 ft (194 m) of strata of the Morrison Formation and Dakota Group on the highland block. Following the model of southeast Colorado, the faults bounding these basement blocks

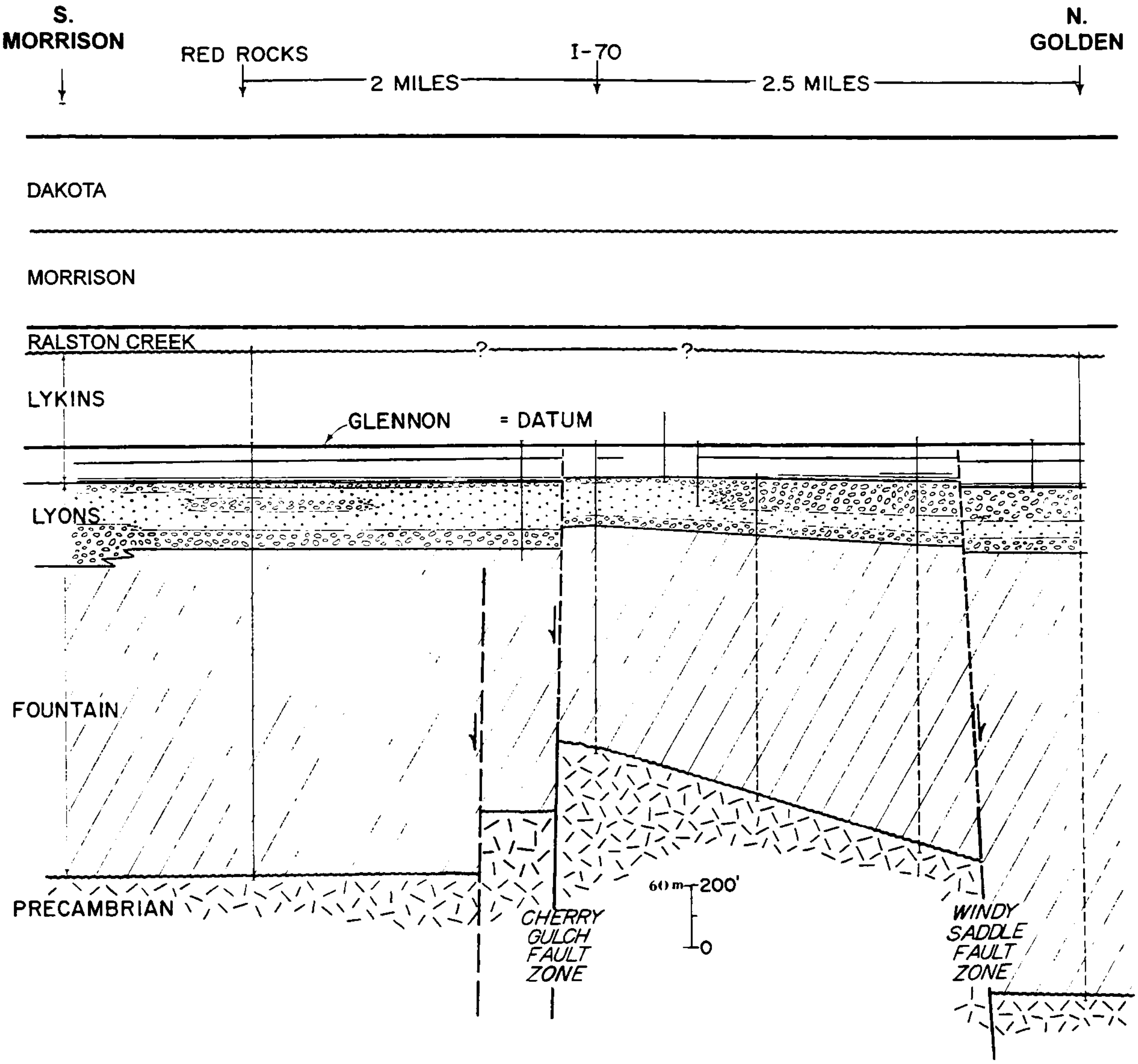


Figure 16. North-south section from Golden to Morrison in the central block (Figure 15) shows depositional thinning across fault zones. Vertical lines are control sections (dashed where not exposed). Heavy lines in Lykins Formation are thin carbonates. (modified after Weimer, 1973). Refer to Figure 4 for geographic localities and fault traces.

are believed to be regional in extent. Although not clearly defined, limited data suggest fault zones similar to the ancestral Golden fault, are probably present elsewhere along the eastern margin of the Front Range highland (Figure 11).

Recurrent movement on basement faults has been mapped within the central fault block (Figure 16). The stratigraphic data between the towns of Golden and Morrison show thinning and facies changes associated with a horst block bounded by the Cherry Gulch and Windy Saddle fault zones (Figures 4 and 16) (modified from Weimer and Land, 1972). A 30 percent depositional thinning occurs in the Fountain, Lyons and Lykins formations across the horst. The Cherry Gulch fault is believed to be a major northeast-trending wrench fault zone projecting across the Denver basin.

Other Evidence for Basement Fault Trends

The distribution of Cambrian, Ordovician and Mississippian strata, in the subsurface of the Denver basin, is interpreted to be controlled by recurrent movement on basement fault blocks (DeVoto, 1980b; Ross and Tweto, 1980 and Sonnenberg and Weimer, 1981). Fault block movement caused paleotopography and during highstands of the sea, marine strata onlapped fault blocks and covered the entire region. During lowstands, subaerial erosion removed some, or all, of the strata from the positive fault blocks with preservation in the graben areas. The fault pattern in northeastern Colorado (Figure 12) is based on these concepts with Ordovician and/or Mississippian carbonates preserved in the downthrown blocks and absent over the upthrown blocks. Thus, Pennsylvanian rests on Precambrian over the positive blocks such as observed at Red Rocks Park. The northward wedgeout of the Ordovician and Mississippian strata was the basis for first use of the term Transcontinental arch, meaning a broad northeast-trending positive area during the lower and middle Paleozoic across northern Colorado. This structural feature was overprinted by the Pennsylvanian tectonics of the Front Range as illustrated by Figure 12.

Additional evidence for recurrent basement fault movement is the occurrence of Tepee Buttes in the Pierre Shale. Tepee Buttes are small carbonate mounds that formed by accumulation of shells of organisms in the area of hot water emanations along fault zones cutting the Cretaceous sea floor. The geology and age of the Tepee Buttes are summarized by Howe (1983). Clusters and trends of the Tepee Buttes from Howe (1983), and from the geologic map of Colorado (Burbank et al., 1935) are plotted on Figure 12. The trends are established by combining seismic data showing faults cutting the basement, and surface mapping (e.g. the Pueblo anticline by Scott and Cobban, 1986).

These concepts are important to petroleum exploration in the Denver basin because Tepee Buttes have been recognized in wells in the giant Wattenberg field (Sheldon, T., personal communication). The occurrences can be used as evidence for basement faulting and in determining fracture trends important to production.

Six northeast-trending wrench fault zones occur in the area between Denver and the Wyoming state line (Figure 12). These fault zones have been determined by subsurface mapping and integration of these data with outcrop observations. The wrench fault zones are extensions of known shear zones in the Precambrian (Weimer, 1996, in press).

STOP 4
TURKEY CREEK SECTION

This stop is where U.S. Highway 285 crosses the Dakota Group outcrops (Figure 17). The purpose of the stop is to describe mountain deformation, restorations, and tectonics and sedimentation related to the Laramide. The exposed section is the upper Morrison Formation, Dakota Group and lower Benton Formation (Figure 18). The Dakota Group consists of 320 ft (100 m) of sandstone, siltstone and shale interpreted as fluvial, coastal plain and marine deposits. At the west end of the road cut, red, green and tan mudstones and siltstones of the upper Morrison Formation are exposed beneath the conglomeratic sandstone of the Lytle Formation.

Oil-saturated sandstones are present in the upper part of the Dakota Group (Muddy or J Sandstone). The oil occurrence is in a stratigraphic trap, now breached by erosion, where lenticular fluvial channel sandstones cross an east-plunging anticline named the Turkey Creek nose.

Structure

Because of the oil occurrence, shallow and deep drilling was conducted east of the outcrop (Figure 17) which gives subsurface control for the Golden Fault zone. The well and outcrop data were incorporated into a structural cross-section by Berg (1962, the central part of Figure 18) and used as one example for the fold-thrust concept of mountain flank deformation in the Rocky Mountains. Berg's section has been modified and expanded to both the east and west to illustrate more clearly the overall framework of the deformation.

The revised structure section incorporates all of the major features of the Laramide orogeny: uplift and rotation of a basement block giving the form of a monocline; overturning of the lip of the block by folding; faulting and thrusting over a undeformed Denver basin block; and, the Eocene erosional surface. The base of the rotated block is marked by the Basin Margin fault believed to be an eastward branch of the Golden Fault zone. The abrupt change from undeformed basin strata to the steeply dipping strata of the deformed zone is illustrated by a new east-west seismic section 6 mi (9.7 km) to the south at Deer Creek (Hu, 1993). A similar relationship is shown by seismic sections in the Rocky Flats area north of Golden (Domoracki, 1986; Ebasco team, 1993). A few

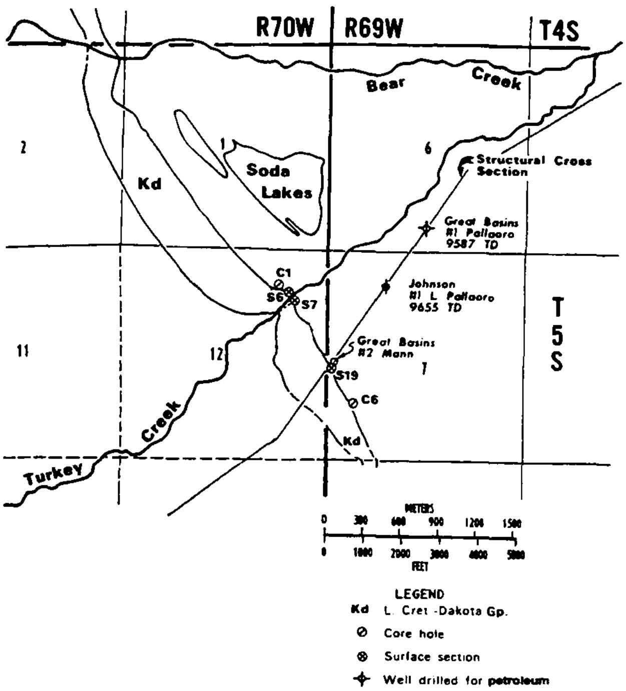


Figure 17. Index map for Turkey Creek area (from MacMillan and Weimer, 1976).

hundred feet of section is cut out by movement on the Basin Margin fault. The surface trace of the fault is placed at the change from steep to shallow dips within the Denver Formation, a relationship observed all along the central Front Range.

The projection of the eroded Dakota Group and older strata over the Front Range block (Figure 19) follows the model developed from the southeast Colorado studies (Figures 13, 14 and 15). The Floyd Hill shear zone is arbitrarily picked as the fault margin of the Paleozoic Front Range Highland. The Laramide Golden fault zone, overprinting the Paleozoic structure, may merge into a vertical fault at the ancestral Golden Fault, or the Floyd Hill shear zone, or both (Figure 19).

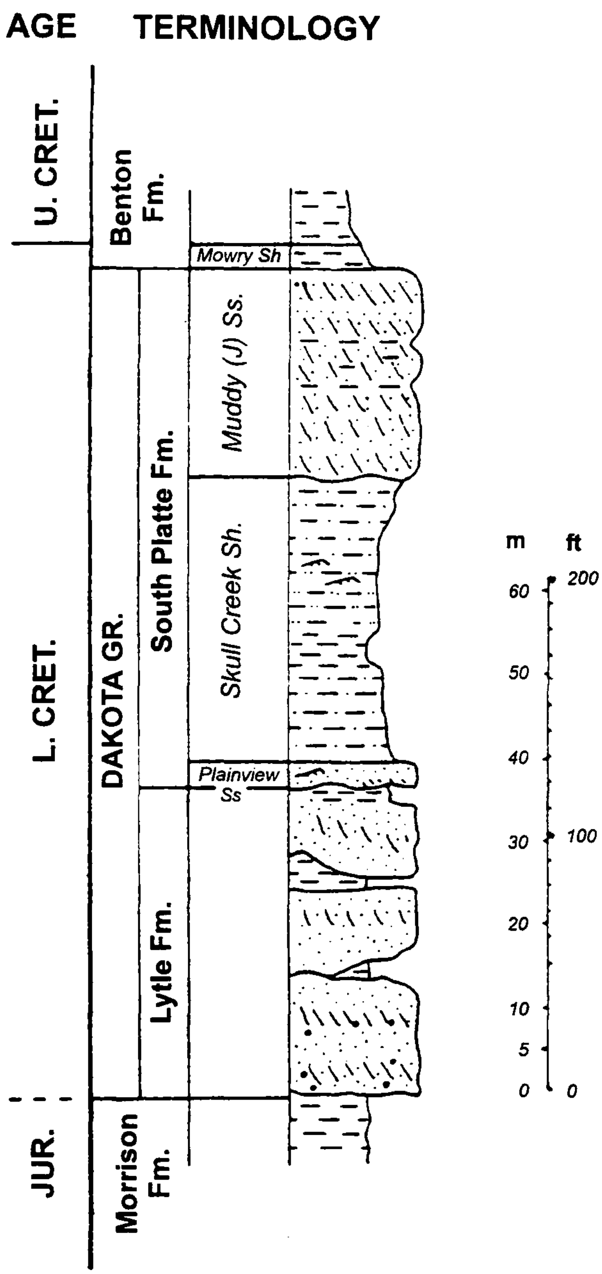


Figure 18. Stratigraphic section of Dakota Group (Kd), Turkey Creek area.

Restoration

In a palinspastic reconstruction, the mountain block is restored to a datum at the base of the Arapahoe Conglomerate (Figure 20). The lithology and stratigraphic history of the formations recording the Laramide orogeny will be discussed in detail at Stop 5 on the CSM campus. However, important points related to this restoration are summarized as follows:

- The Arapahoe conglomerate contains clasts of igneous rocks indicating that the Front Range was eroded to the basement during deposition. These clasts could not have come from the Central Block (Figure 20) because the Fountain Formation (IP, Figure 19) still covers most of the Block. Therefore, the source was farther to the west, probably the Front Range Highland block (Figure 15).

- Conglomerates at the base of the Cretaceous portion of the Denver Formation contain andesite porphyry clasts and volcanic material indicating an initiation of igneous activity in the source area.
- After the major mountain flank deformation, the Eocene erosional surface developed during a period of tectonic quiescence.

Not shown in the restoration and structural section is the possibility of angular unconformities between the Arapahoe and the basal conglomerate of the Denver Formation and within the Denver as reported by Reichert (1954).

Depth of Burial

Many features from outcrop sections indicate that there was much less burial depth for the central and mountain blocks than for the Denver basin block. Collectively, the evidence suggests a rotation and beveling of the central block by the unconformity at the base of the Arapahoe before the intense deformational phase. The position of the present edge of the Dakota Group is restored on Figure 19 with an estimated burial depth of 6000 ft (1840 m). This is based on a comparison of vitrinite reflective (Ro) values and porosity and permeability in outcrop sandstones with those in the Denver basin (Figure 21, Higley and Gautier, 1987). From outcrop studies, the Ro values are 3 to 4 (Higley and Gautier, 1992), the average porosity values 21 to 23 percent, and the average permeability values exceed 80 md (Chapin, 1989; MacMillan and Weimer, 1976). The cross section illustrating the relationship among depth, porosity,

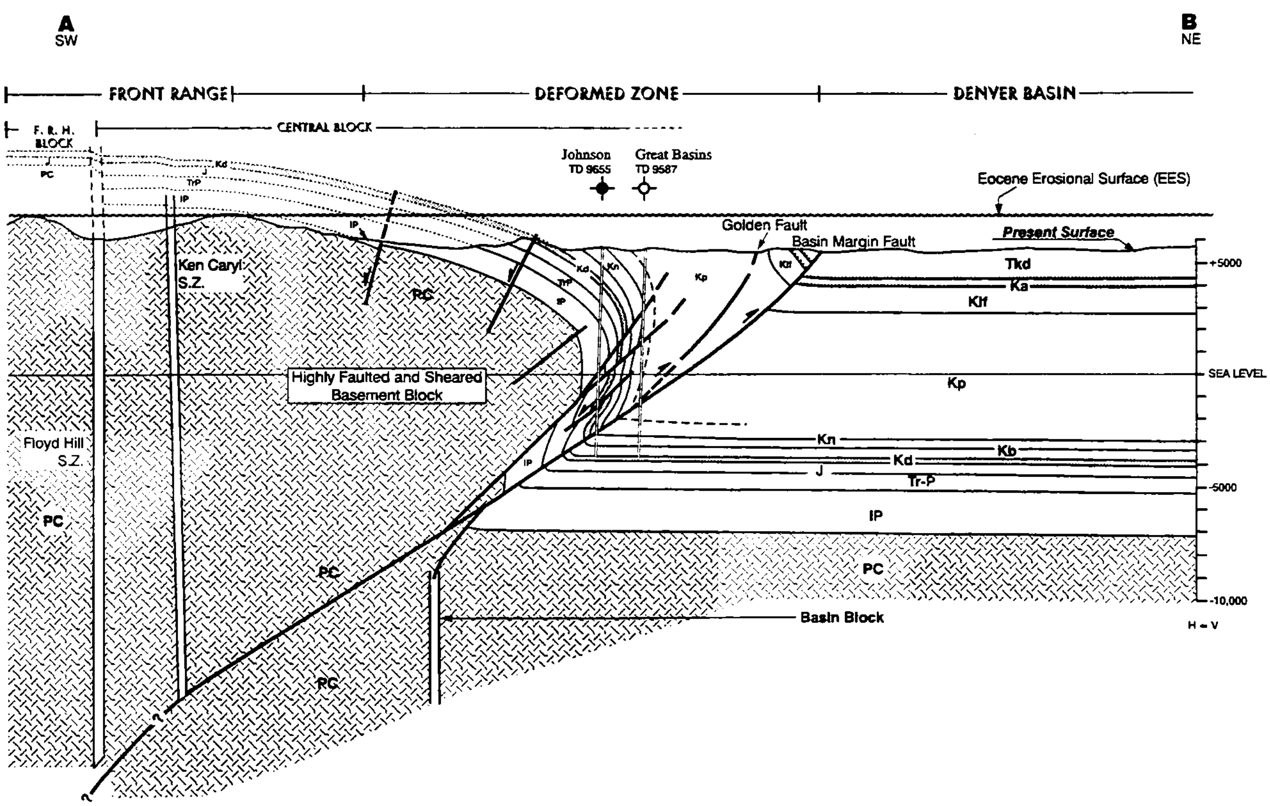


Figure 19. Structural cross section through Turkey Creek area. Central portion with deep wells modified after Berg (1962).

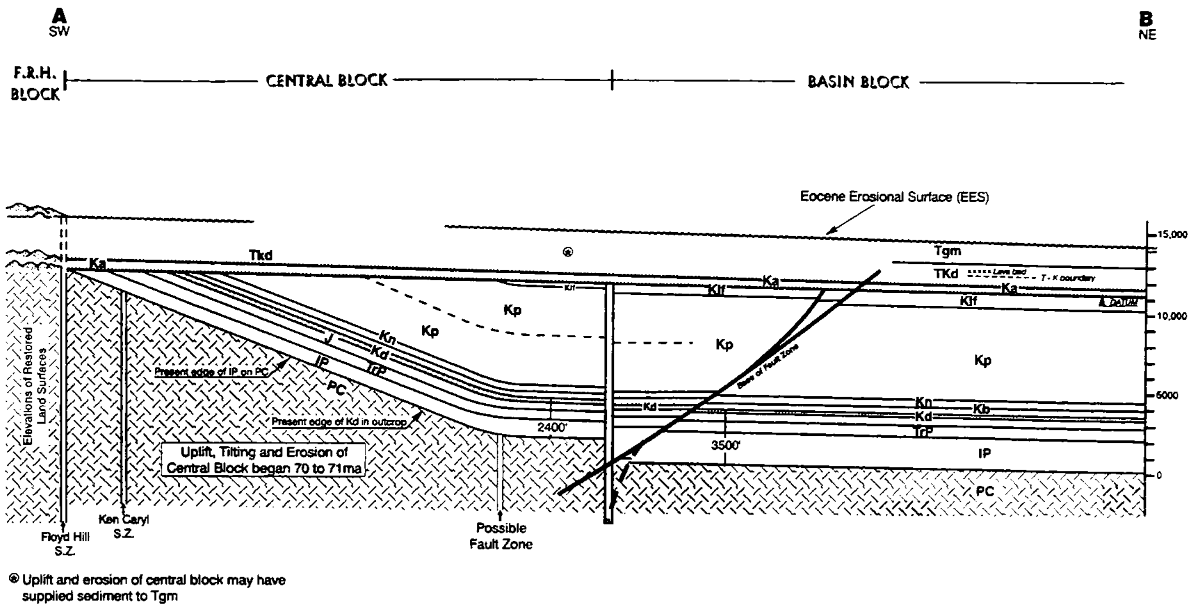


Figure 20. Palinspastic restoration of structural cross section (Figure 19) interpreting tectonic and sedimentation patterns for late Cretaceous and early Tertiary formations. Probable angular unconformity between Arapahoe and Denver formations not shown.

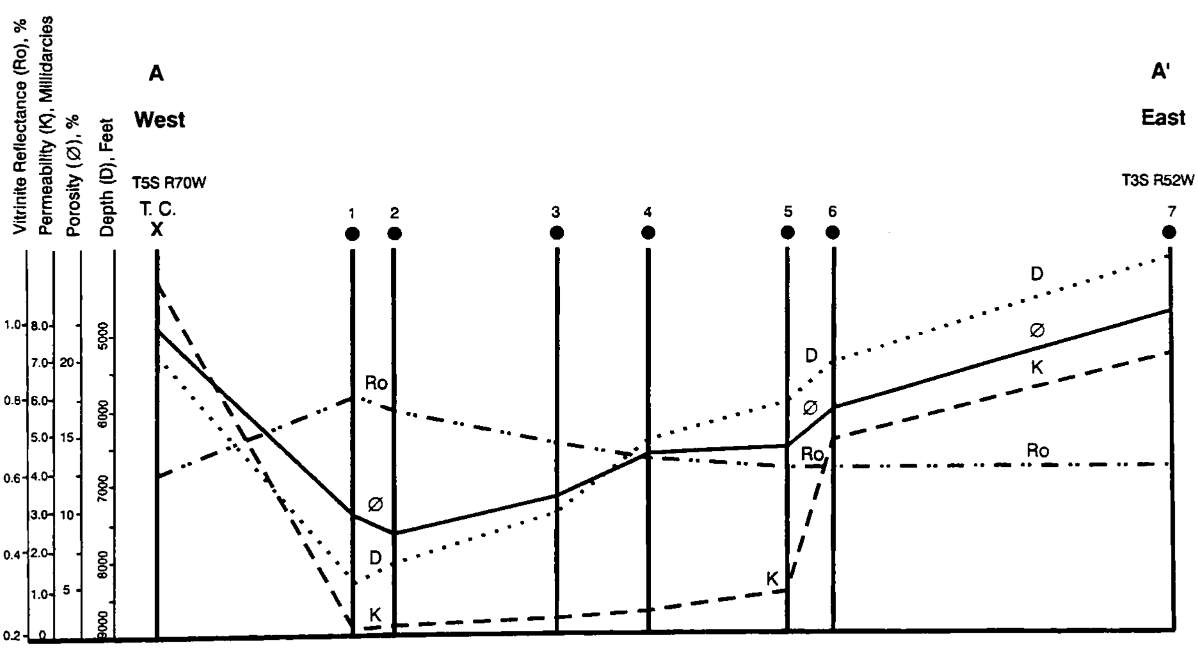


Figure 21. East-west section across Denver basin from T. 3 S., R. 52 W. to Turkey Creek outcrop Sec. 12, T. 5 S., R. 70 W. Relationships are illustrated for the Muddy (J) Sandstone among depth (D, in feet), porosity (Æ in percent), permeability (K, in millidarcies) and thermal maturity (Ro, in percent) of the Muddy (J) Sandstone in the Denver basin (modified after Higley and Gautier, 1987). Turkey Creek (T.C.) section added by Weimer.

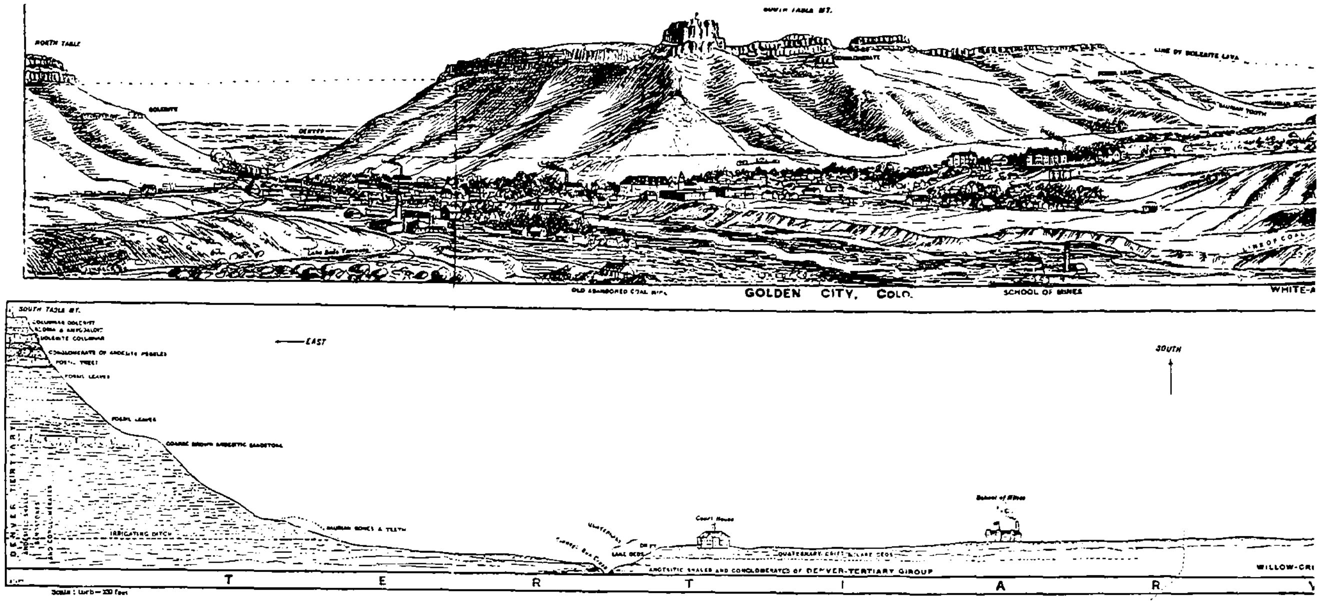


Figure 22. Sketch of geologic and geographic features of the greater Golden area (Lakes, 1889).

permeability and thermal maturity for the Muddy (J) Sandstone in the Denver basin suggests an outcrop area burial history similar to the shallow east flank of the basin, i.e. in the range of 6000 ft (1840 m).

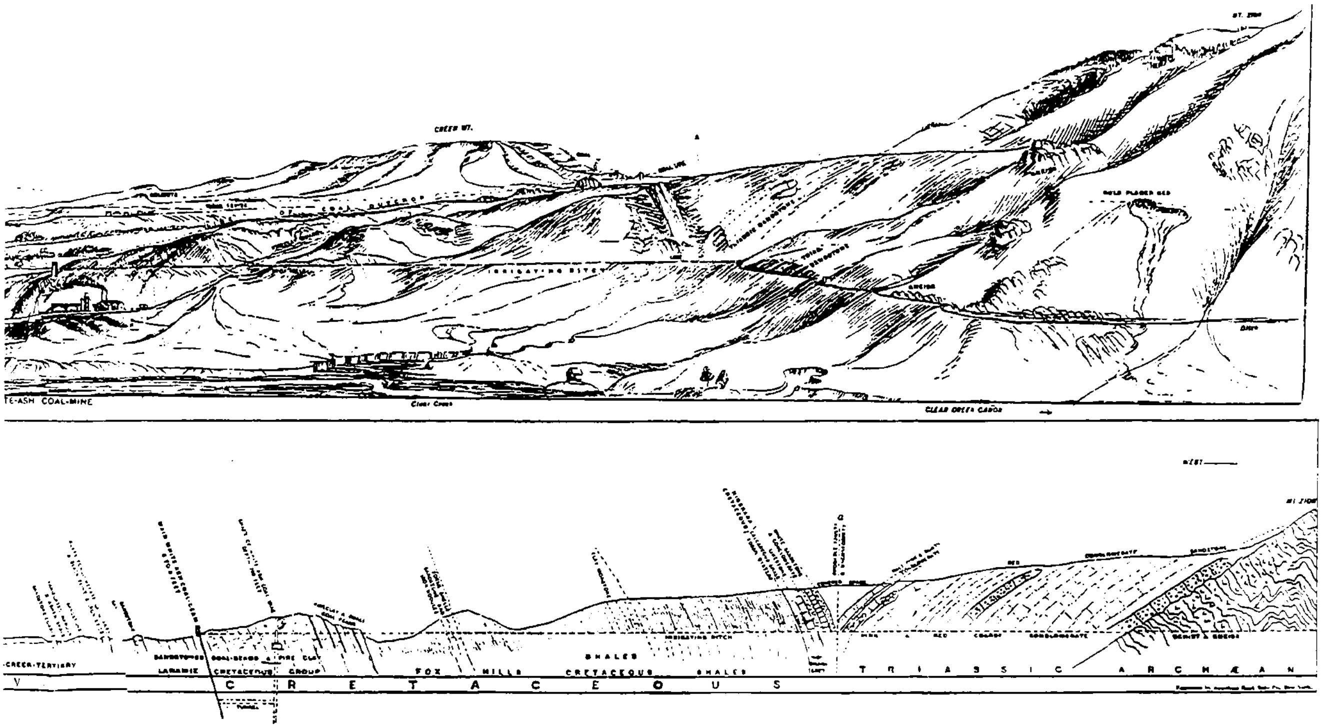
In addition, apatite fission-track cooling ages obtained from Precambrian rocks of Lookout Mountain indicate a total burial depth of less than 6500 - 8300 ft (2 - 2.5 km) (Kelly and Chapin, 1995).

Finally, the sedimentation patterns in the Upper Pierre, Fox Hills and Laramie formations, summarized by Weimer (1976) and Weimer and Tillman (1980) record the final regression of the Cretaceous sea from eastern Colorado and the early structural movements of the Front Range. They cite evidence that erosion of the lower Pierre and older strata was concurrent with deposition of the above units on the eastern margin of the central block and the Denver basin (Figure 19).

Petroleum Exploration

The concepts of different burial history for the Basin and Central Blocks have a direct bearing on petroleum exploration. The Johnson and Great Basin wells, drilled east of the outcrop, cut the Golden Fault zone and found the Muddy (J) Sandstone in the foot wall to have low non-commercial porosity and permeability, although oil shows were reported in cuttings and cores. The structural cross section (Figure 18) and the Denver basin stratigraphic cross section (Figure 21) explains the discrepancy between good quality reservoir rocks in outcrop and poor quality in the two wells at depths of 9500 ft (2900 m).

The Johnson L. Pallaoro well, although drilled in 1954 to the Dakota Group, was plugged back and completed in a 35-foot zone of fractured Fort Hays Limestone, the lower member of the Niobrara Formation. The well discovered the Soda Lake field and produced 15,275 bbls of oil before abandonment. This was the first well completed in the deeper portion of the Denver basin from the Fort Hays-Codell interval. The interval is a widespread reservoir and the target for development in the greater Wattenberg field in the basin center north of Denver. The Johnson well may be



evidence that the basin center accumulation may extend to the Soda Lake field.

STOP 5
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.

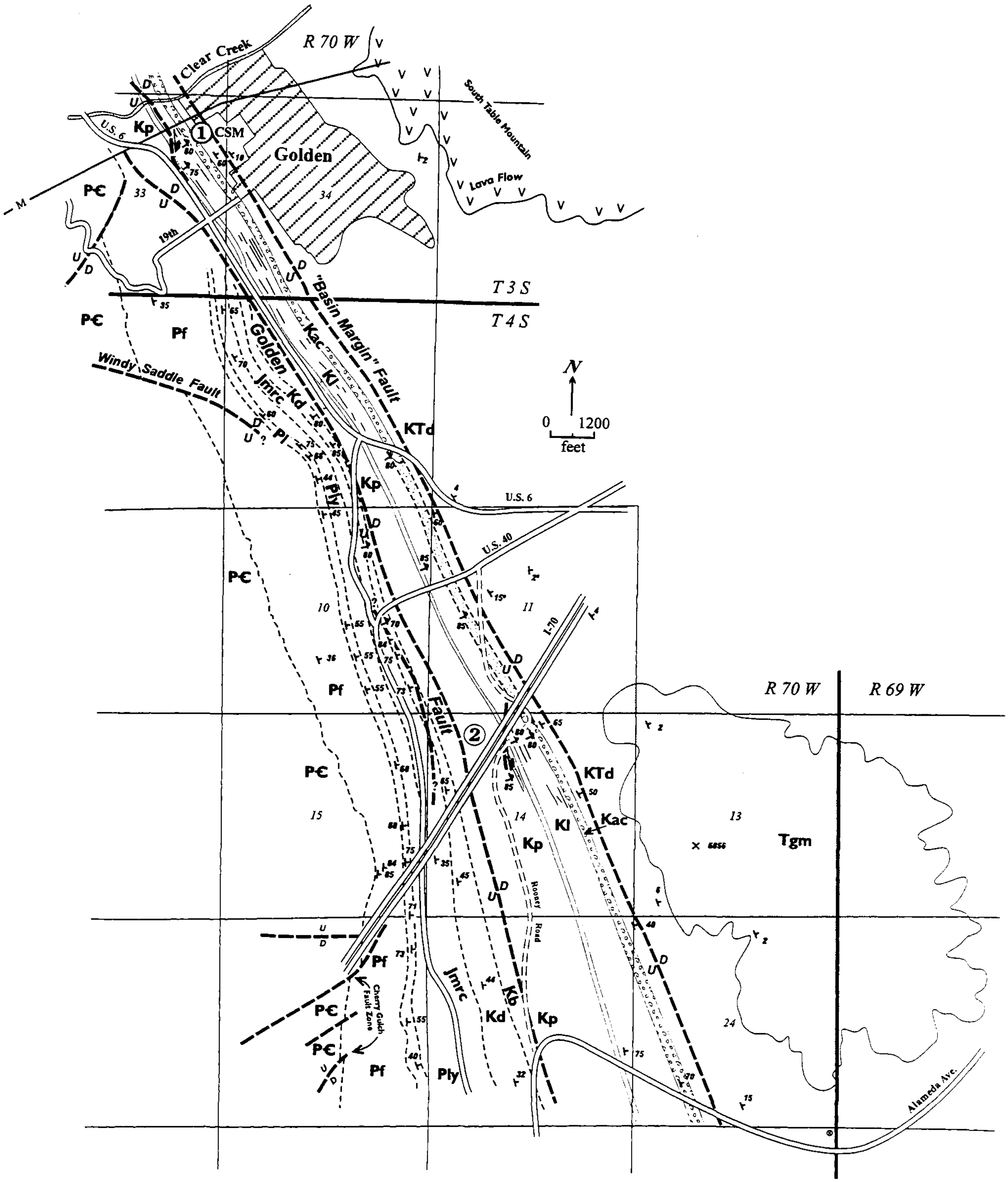


Figure 23. Bedrock geologic map from Golden to I-70 with reference sections 1 and 2.

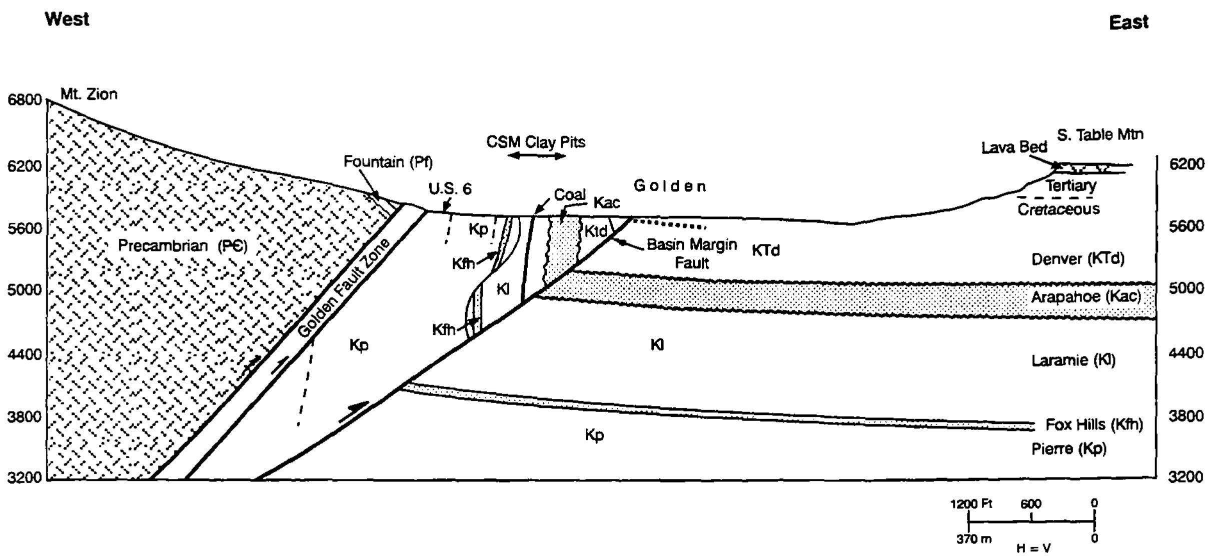


Figure 24. East-west structure cross section with CSM clay pits and campus area.

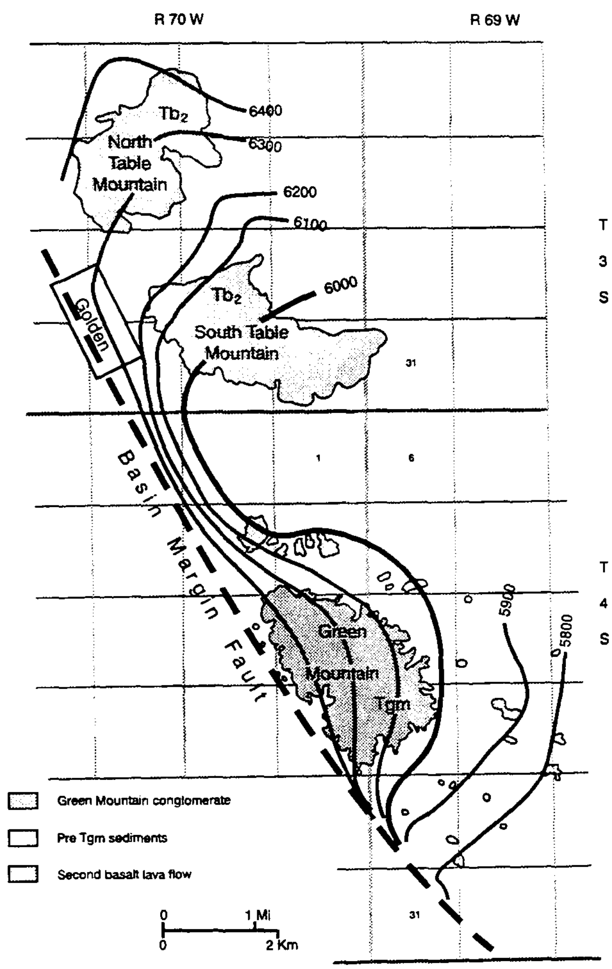


Figure 25. Structure contour map (in ft) on the base of Tertiary basalt flow 2, Golden-Green Mountain area (modified from Reichert, 1954).

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

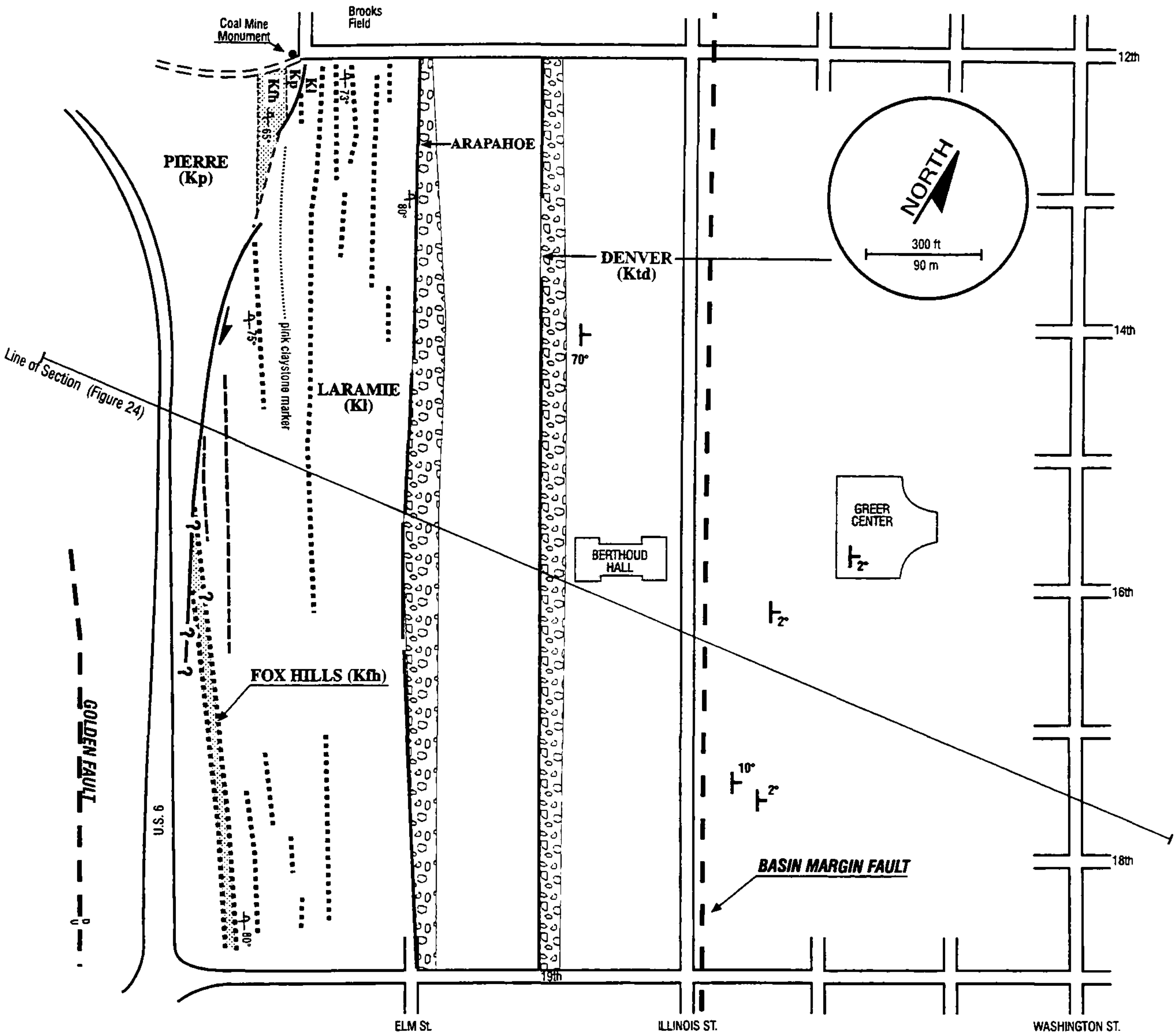


Figure 26. Bedrock geologic map of CSM clay pits and campus area. Sandstones within the Laramie Formation are dotted lines; intervening intervals are claystone.

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 trhe 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

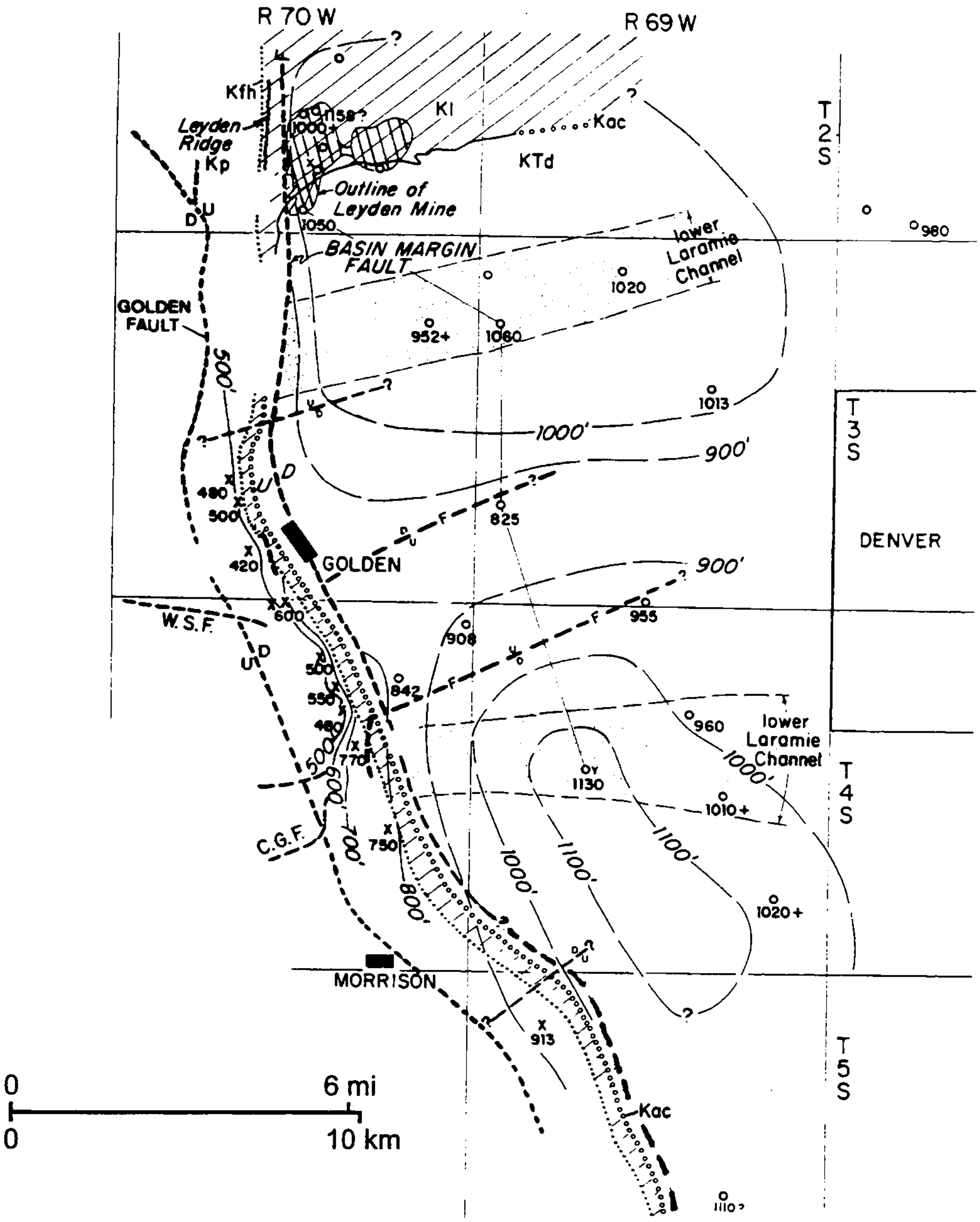


Figure 27. Geologic map and isopach map with combined thicknesses (in ft) of Laramie and Fox Hills formations. Fault patterns are indicated with trace of Golden fault restored to estimated original position before uplift of Front Range (from Weimer, 1976).

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

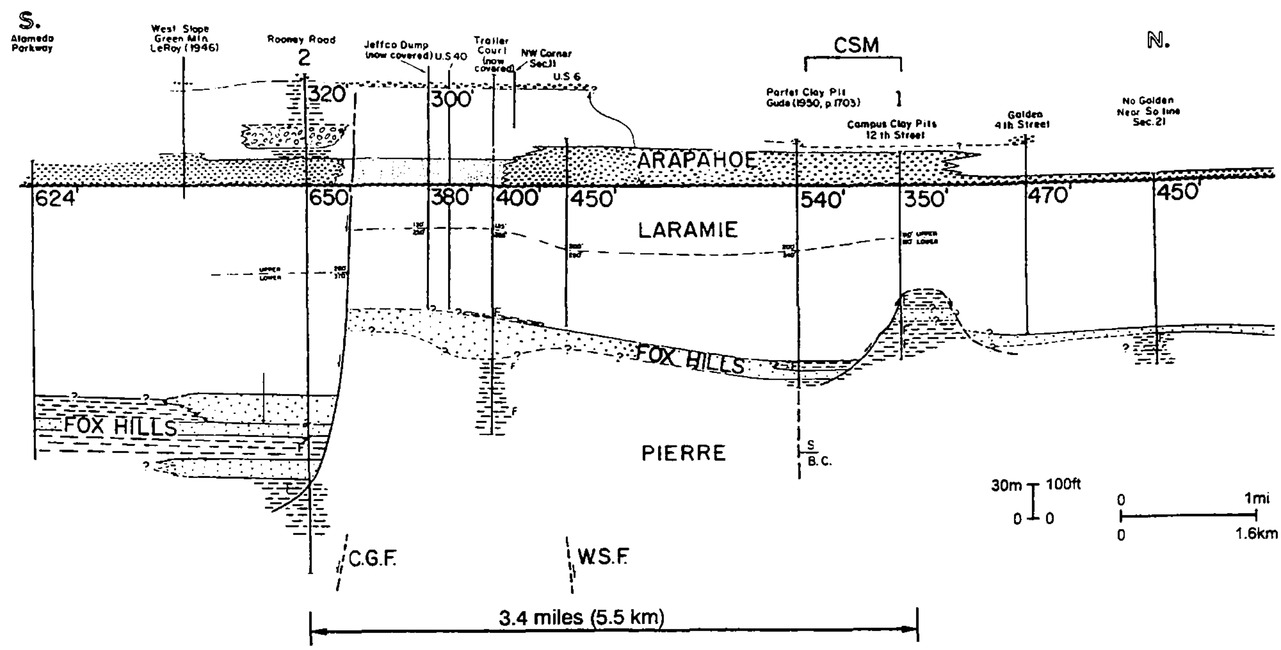


Figure 28. Stratigraphic restored section from north Golden to Alameda Parkway. Numbers are measured thicknesses for Laramie and Arapahoe formations from outcrops. Faunal zones in Pierre Shale--S = Sphenodiscus; B.C. = Baculites clinolobatus (from Weimer, 1976).

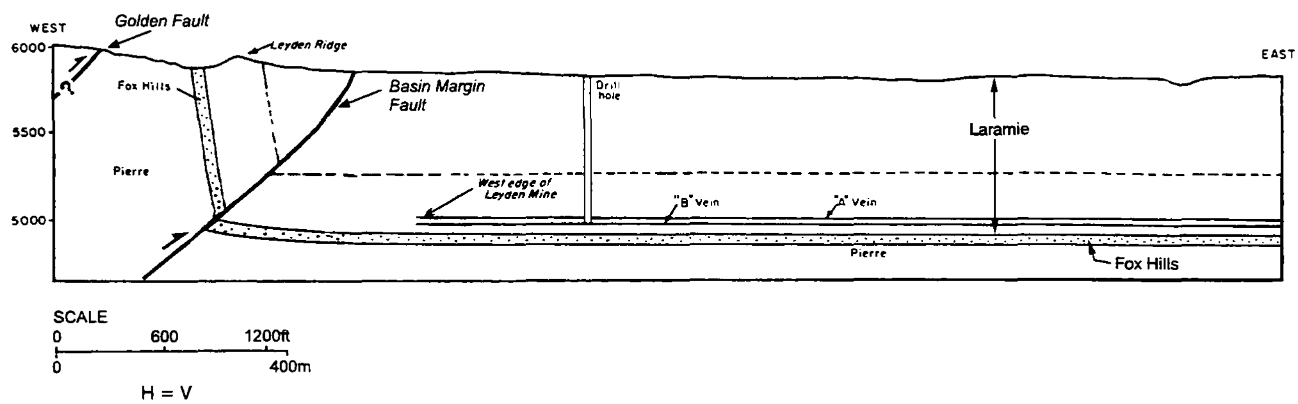


Figure 29. East-west structure cross section along Leyden Gulch relating outcrop and Basin Margin fault to Leyden Coal Mine (T. 2 S., R. 70 W.; refer to Figure 27). Golden fault location from Van Horn (1976).

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.

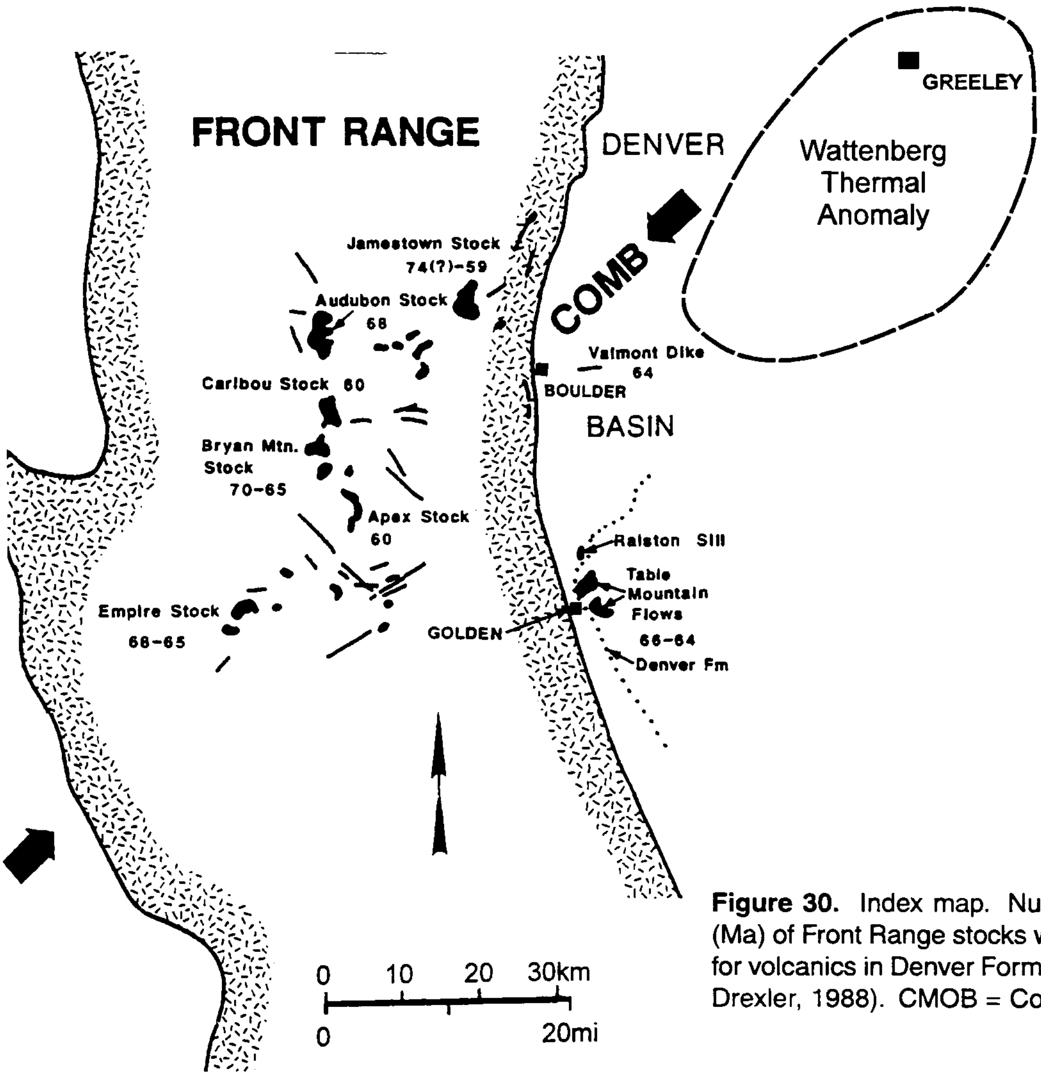


Figure 30. Index map. Numbers represent ages (Ma) of Front Range stocks which could be sources for volcanics in Denver Formation (from Larson and Drexler, 1988). CMOB = Colorado Mineral Belt.

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 6
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

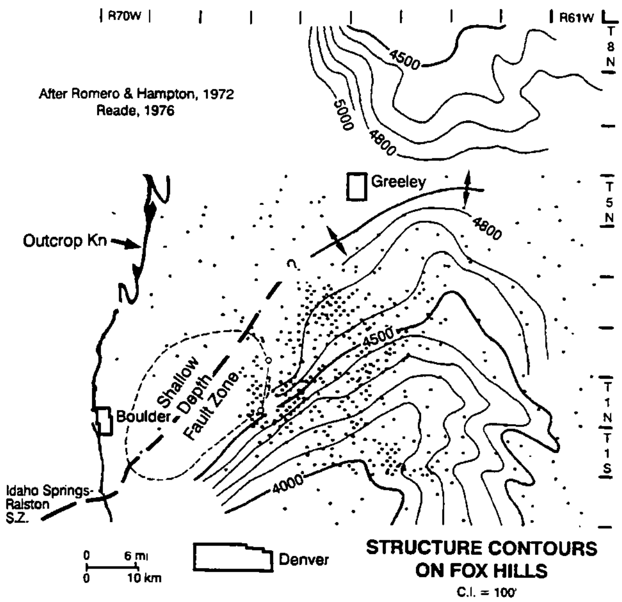


Figure 31. Structure contour map (in ft) on top of Fox Hills Sandstone. Shallow depth fault zone of Boulder-Weld coal field and axis for Greeley arch are indicated. Outcrop is for Niobrara Formation (Kn).

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,

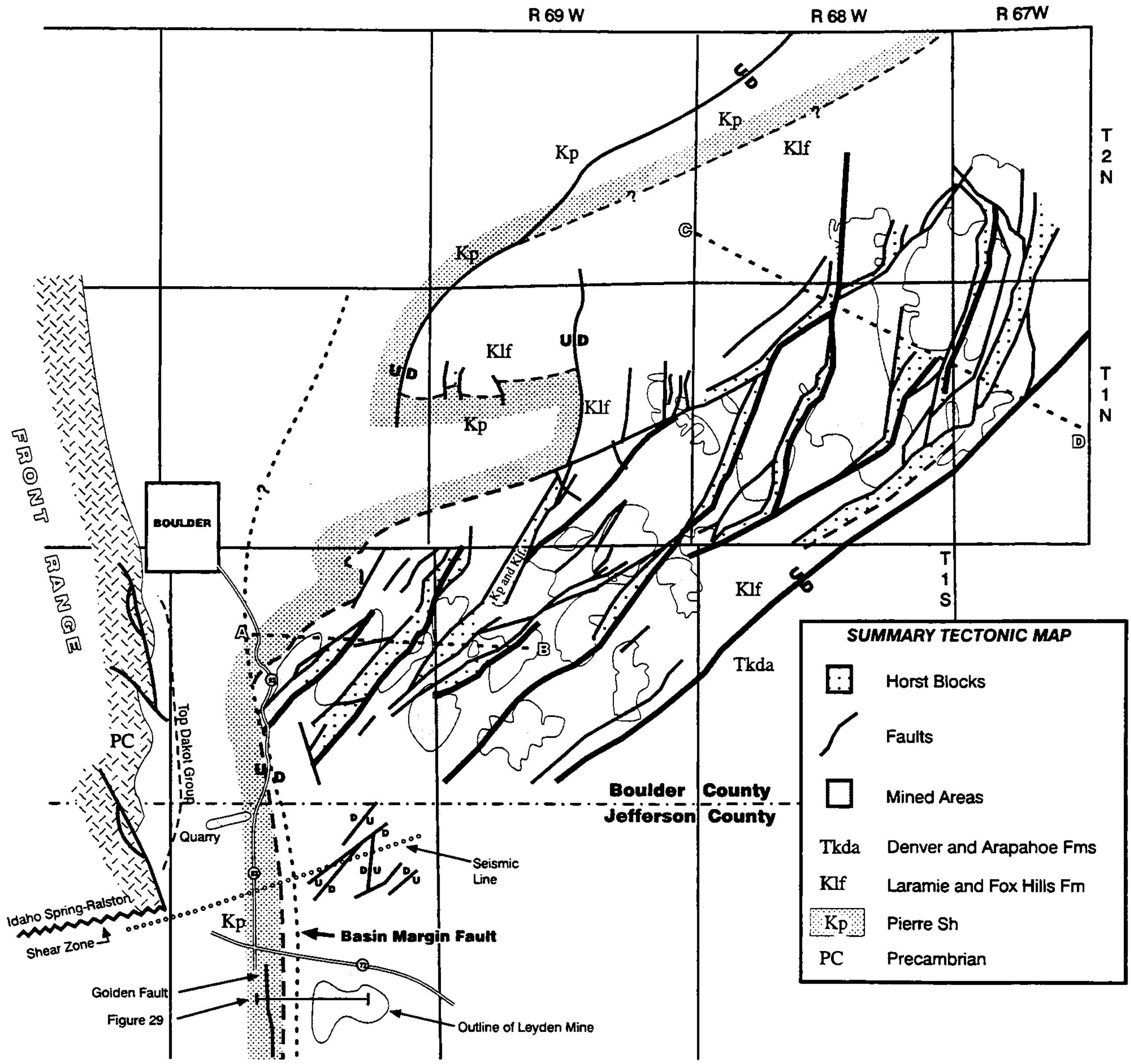


Figure 32. Fault map of Boulder-Weld coal field (modified after Colton and Lowrie, 1973; Spencer, 1961; Amuedo and Ivey, 1975; Kittleson, 1992 and Ebasco Team, 1993). Mountain front faults from Wells, 1967. North end of Golden fault from Van Horn (1976).

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).

STOP 7
SIX-MILE FOLD
(3 Mi [4.8 Km] North of Intersection of US 36 and CO 7, North of Boulder)

This stop is to examine small scale structural features in the Fort Hays Member of the Niobrara Formation which indicate wrench faulting. The Fort Hays and the underlying Codell Sandstone Member of the Carlile Shale (Figure 33) collectively make up a widespread but low-yield petroleum reservoir in the center of the Denver basin.

The dominant lithologies of the Niobrara are limestones (chalks) and interbedded calcareous and organic-rich shales and bentonites. Niobrara thickness ranges from 280 to 300 ft (85 to 92 m). Four limestone intervals, averaging 30 ft (9 m), and three intervening shale intervals (averaging 47 ft [14 m]) occur regionally and are easily recognized on geophysical logs. The lower limestone is named the Fort Hays Member and the overlying units are grouped together as the Smoky Hill Member. The intervening shales have high organic matter content and serve as source beds. The limestones and shales contain marine fossils.

Only 14 ft (6 m) of the 20-ft (6 m) Fort Hays is exposed at this stop. Individual limestone beds vary from 6 to 24 in (15-60 cm) and are separated by 2-6 in (5-20 cm) layers of shale or bentonite. Fractures are concentrated in the more brittle limestone which results in a blocky weathering pattern.

The Codell Sandstone is fine-grained highly burrowed (bioturbated) sandstone with low porosity and permeability. The unit varies in thickness from a wedge edge to 35 ft (11 m) and is bounded above and below by unconformities. Locally, thin (less than 0.5 ft [15 cm]) and irregular bodies of coarse-grained sandstone and limestone at the top of the formation overlie the bioturbated clayey sandstone facies. This coarse material is interpreted as a lag representing relict or palimpsest marine shelf deposits. The low permeability reflects bioturbation of interbedded clay and sand deposits, the filling of pores by authigenic smectite, chlorite and calcite (Weimer and Sonnenberg, 1983).

Studies of outcrop and quarry exposures and subsurface mapping have identified major right lateral wrench faults with dominant trends of N. 55° to 65° E. (Stone, 1969). Synthetic faults (and fractures) more or less parallel this trend; antithetic faults (and fractures) are N -S., to N.-35° W. Small scale features in the Fort Hays Limestone are horizontal slickenslides on calcite-filled fault planes, stylolites vertical to bedding, calcite-filled tension gashes, open fracture systems, and vertical tectonic breccias, all indicating horizontal movement. The principal horizontal stress (PHS) is oriented from the vertical styolites to have been N. 70° to 80° E. Open fracture systems with terminated calcite crystals parallel this trend. Individual gash openings with calcite linings are east-west, but a cluster of gashes, along with calcite-filled shear zones, align N.65° E. This is the main shear direction. A dominant set of fractures without calcite trend N.15° to 35° W. The stress field recorded in the Fort Hays is an easterly directed PHS. The slickenslides parallel to bedding, the stylolites vertical to bedding and the vertical fracture orientations all indicate the deformation occurred before the strata was rotated to the present structural dip by uplift of the range. The uplift of the Front Range was also by east-directed compression.

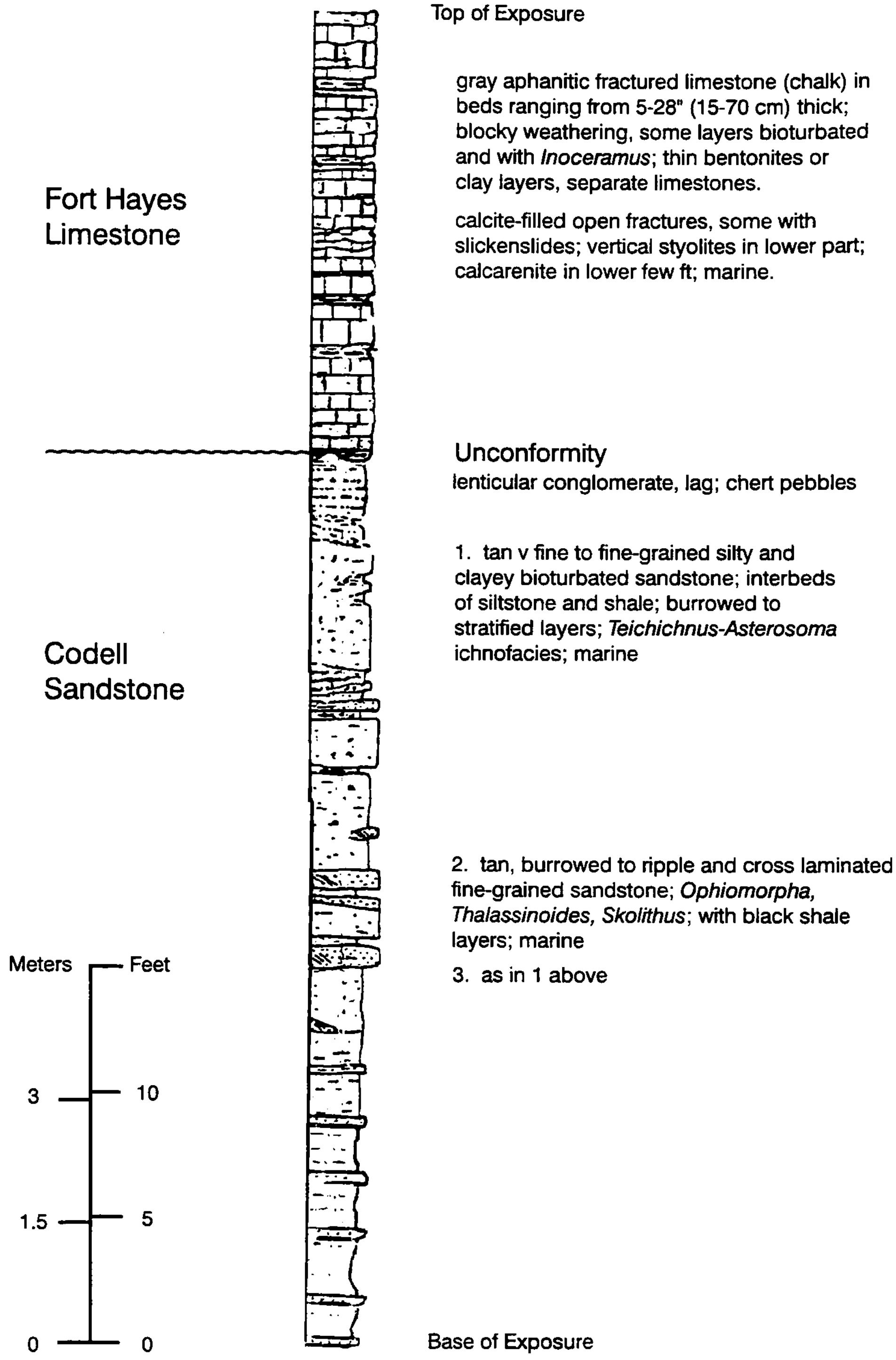


Figure 33. Stratigraphic column for Fort Hays Limestone Member of the Niobrara Formation and the Codell Sandstone Member of the Carlile Shale. Locality is east flank of 6-mile fold.

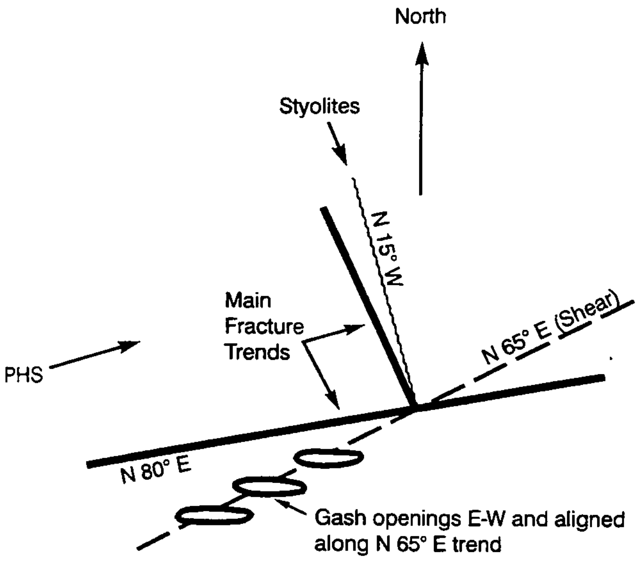


Figure 34. Map sketch of principal horizontal stress field orientation (PHS) from vertical stylolites and faults and fractures, Fort Hays Limestone, 6-mile fold locality.

The faults, fractures and styolites exposed in the Fort Hays Limestone in the Lyons cement quarry, 5 mi (8 km) to the north, show the same orientations and internal features as described above (Coates, J. M., 1995, personal communication). Additional features are brecciation and slickensides on multi-stage calcite-filled faults indicating recurrent movement.

In the giant Wattenberg field east of the outcrop, operators report (personal communication) that the PHS is oriented north-northwest, parallel to open fractures, based on massive hydraulic fracturing tests and production interference patterns. (also Smith et al., 1976) Moreover, geophysical data, and bore hole breakouts, indicate a similar PHS orientation (Zoback and Zoback, 1989). Over a large area, fractures enhancing production have both NE and NW orientations.

The outcrop and subsurface observations indicate that the PHS changed from an east direction early in the Laramide (late Cretaceous-early Tertiary), to north-northwest direction, possibly in the late Eocene or Oligocene.

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