Geologic Characterization Report

GEOLOGIC CHARACTERIZATION

Prepared For:

U.S. DEPARTMENT OF ENERGY
ROCKY FLATS AREA OFFICE
GOLDEN, CO

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1.0 INTRODUCTION

1.1 Purpose

The goal of the Rocky Flats Plant (RFP) Geologic Characterization effort is to develop a comprehensive geologic framework which can be used to define the direction, rate, and volume of ground water flow; delineate contaminant migration pathways; and characterize potential seismic risks. As a means of furthering these efforts, past geologic processes and events have been evaluated in light of current stratigraphic, structural, geophysical, and hydrogeologic data. This geologic characterization is intended to be used to formulate hydrogeologic models, design and implement ground water monitoring programs, and plan remedial activities.

1.2 Scope of Characterization

This multi-faceted investigation involved conducting a literature search and preparing an annotated bibliography; collecting and analyzing site-specific data; processing, describing, and interpreting core samples; analyzing selected core samples for grain size distribution; constructing stratigraphic maps using all subsurface data; reprocessing and interpreting seismic data; and delineating paleochannels by using high-resolution, shallow, seismic reflections. This written report is a synthesis of background information and recent geologic interpretations.

1.2.1 Literature Search

The following resources were used to prepare the annotated bibliography for the Geologic Characterization of the RFP and vicinity:

1. U.S. Geological Survey (USGS)
2. National Technical Information Service
3. Rocky Flats Plant Library
4. Colorado State Division of Water Resources
5. Colorado State Geological Survey
6. Colorado State Oil and Gas Commission
7. Colorado State Department of Natural Resources
8. Denver Earth Resources Library

9. Petroleum Information Corporation
10. W. W. Wheeler and Associates
11. Woodward-Clyde Consultants
12. Colorado School of Mines (CSM)
13. University of Colorado

1.2.2 Core Processing and Description

All the 1986, 1987, and 1989 cores were described and photographed. Cores of special interest were slabbed to allow detailed descriptions. Alluvium, colluvium, and valley fill were described using the Unified Soil Classification System (USACOE, 1953); whereas weathered and unweathered bedrock were described using techniques from the Manual of Field Geology (Compton, 1962). The soil and rock properties evaluated in the description process include: lithology, color using the Rock-Color Chart (GSA, 1984), grain size, cement type, grain sorting, grain rounding, bedding type and thickness, internal sedimentary structures, fracturing, faulting, and mineral composition. The amount of core recovered was routinely recorded. Standard geologic logging procedures are presented in Appendix G.

1.2.3 Reprocessing of Seismic Data

Approximately 13 miles of 600 to 1,200 percent Vibroseis™ (Trademark of Continental Oil Company) seismic data were reprocessed to augment the RFP Geologic Characterization. These seismic data were acquired in December of 1975 and in the spring of 1976 with the cooperation of the Department of Geophysics at CSM.

The CSM geophysical survey consisted of 8 seismic lines. Of the original 8 lines, only lines numbered 5 and 6 could be reprocessed. The remaining 6 lines were missing either field data tapes or acquisition information. "Seismic Data Reprocessing," compiled in 1989 by Ebasco Services, Inc., describes this task in detail and is included in Appendix E. A discussion of the seismic data is included in the "Structural Geology" section of this report.

1.2.4 Grain Size Analyses

A total of 335 samples collected from both alluvium and bedrock were selected from the 1986, 1987, and 1989 cores for grain size analyses. In addition, hydrometer tests were completed on 64 samples from key intervals in an effort to assess percentages of silt and clay. The numerical data are listed in Appendix A of this report; while graphs of the grain size distribution and hydrometer data are presented in Appendix D.

1.2.5 Geologic Report

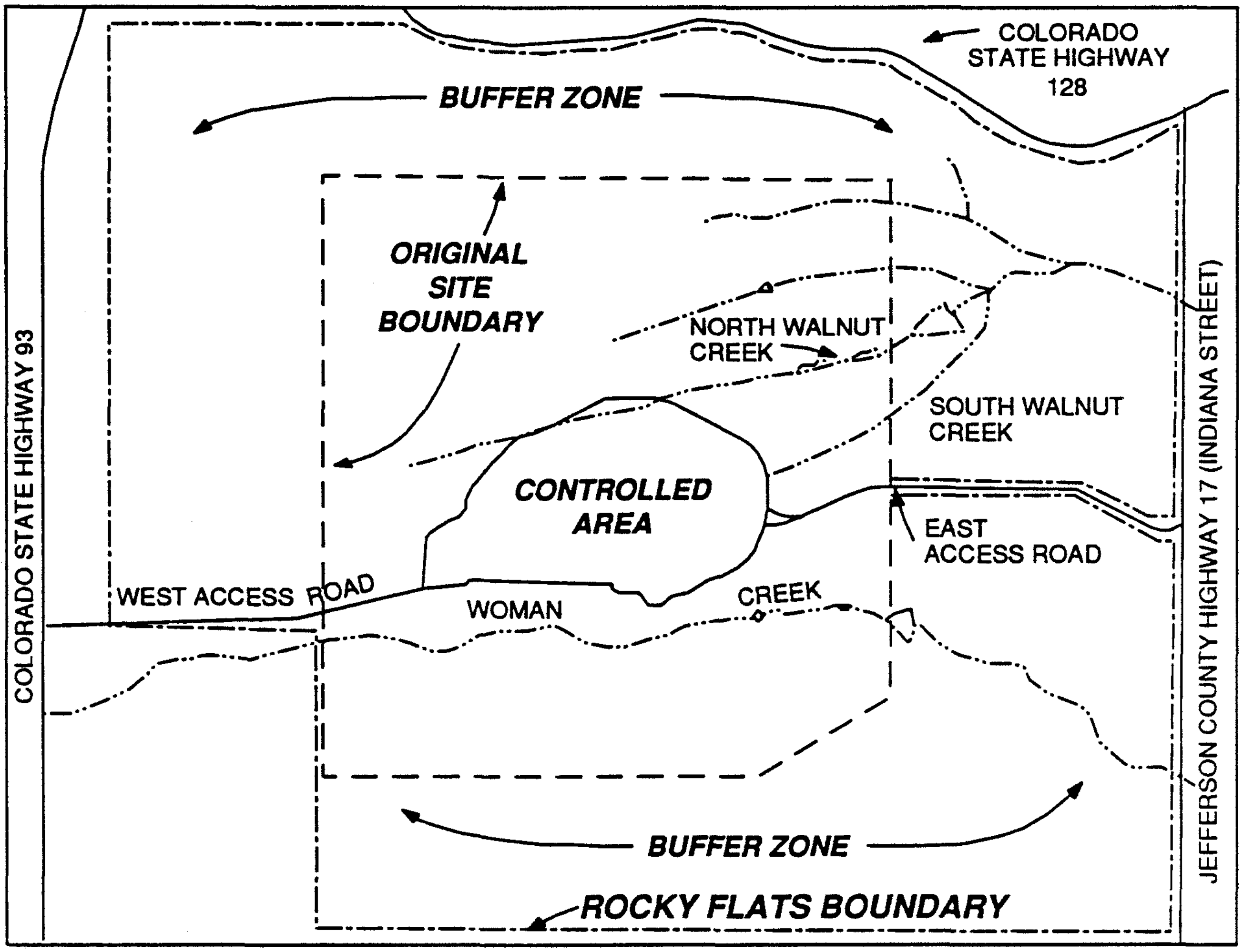
This geologic report summarizes previous geologic investigations, which are generally regional in nature, as well as recent interpretations pertaining to the Plant-specific stratigraphy and structural geology. The sedimentological model identifies the depositional processes that occurred in the past and the resulting lithologic spatial relationships which may affect ground water and contaminant transport, dispersion, and adsorption.

Included with this report are the following supporting documents:

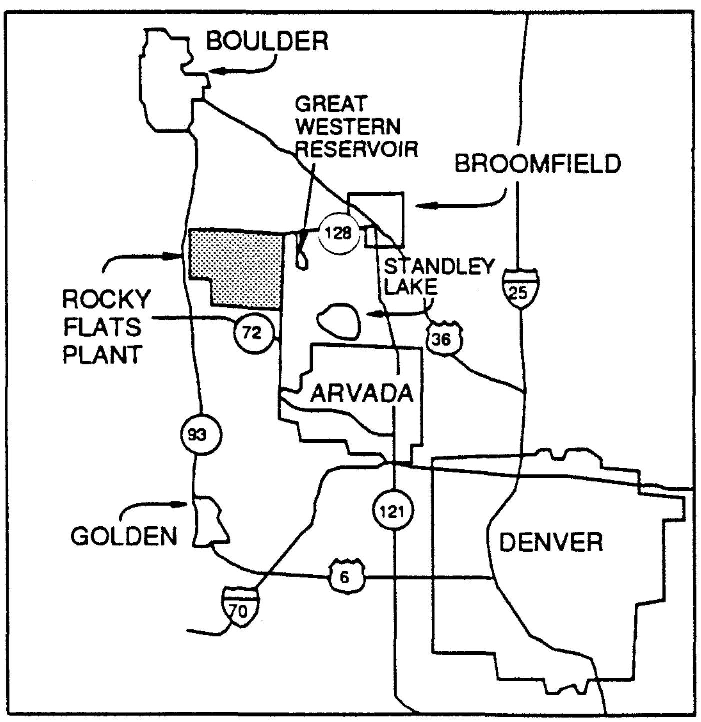
Appendix A	A list of all wells and their locations, sandstones, and grain size analyses;
Appendix B	Rolled maps and cross-sections at scales of 1' = 500' and 1' = 300';
Appendix C	An annotated bibliography of geologic reports relevant to the Front Range and the Rocky Flats Plant;
Appendix D	Graphs of all the grain size and existing hydrometer data;
Appendix E	"Seismic Data Reprocessing," a report describing the reprocessing of the CSM seismic data;
Appendix F	Color photographs of all 1986, 1987, and 1989 cores; and
Appendix G	The Visual Geologic Logging Protocol used for this investigation and the field copies of the core logs described by A.S.I. These include logs for 1986, 1987, and selected 1989 cores.

1.3 Location and General Setting

The Rocky Flats Plant is shown on the USGS Louisville Quadrangle (7-1/2 Minute Series) Map of 1965 in Sections 1-4, and 9-15 of Township (T) 2 South, Range (R) 70 West. It is approximately 16 miles northwest of Denver, Colorado, in northern Jefferson County (Figure 1). Access to the Plant is from State Highway 93 on the west and Indiana Street on the east.



Approx. scale 1"= 3,300'



Approx. scale 1"= 40,000'

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VICINITY MAP

GEOLOGIC CHARACTERIZATION

ROCKY FLATS PLANT

EG&G GOLDEN, COLORADO

FIGURE 1

VICMAPA.DRW

The RFP is situated approximately four miles east of the Front Range section of the Southern Rocky Mountain province on the western edge of the Colorado Piedmont section of the Great Plains Physiographic Province (Spencer, 1961). The Plant is located on a pediment alluvium that dips at approximately 1 degree to the east. The pediment and alluvial cover are dissected by several small eastward-flowing streams. South Walnut Creek has its headwaters one to two miles west of the RFP, while Woman Creek receives a portion of its water from Coal Creek.

1.4 Previous Studies

Briefly described below are 5 significant studies which have aided in evaluating the geology of the RFP.

The first study, entitled "Bedrock Geology of the Louisville Quadrangle, Colorado" (Spencer, 1961), includes maps of the stratigraphy and the principle structural features of the area. Spencer also described the economic geology of the Quadrangle, which includes sand and gravel, ground water, coal, oil, and natural gas. Notably, Spencer did not differentiate the Arapahoe Formation from the Laramie Formation; instead, he designated all of the strata immediately beneath the Rocky Flats Alluvium as the Laramie Formation.

The second study is entitled "Seismic and Geologic Investigation and Design Criteria for Rocky Flats Plutonium Recovery and Waste Water Treatment Facility" (Blume, 1972, Revised June 1974). This study was the first comprehensive subsurface investigation in the RFP area. It involved drilling boreholes, trenching, and conducting seismic refraction surveys. In general, the Blume report concluded that the facility was:

> ". . . underlain by approximately 25 feet of sandy, clayey gravel. Below the gravel is an average of 10 feet of weathered claystone of the Laramie Formation. Below the weathered claystone, unweathered claystone beds of the Laramie Formation containing occasional minor siltstone and sandstone beds extend to a depth in excess of 217 feet. The beds of the Laramie are relatively flat lying, dipping easterly between 5° and 15° . . . Visual surface inspection, continuous trench logging . . . and geophysical refraction survey . . . indicate that the site is free of faulting and has remained free of faulting for in excess of 1 million years."

The third and probably most accurate past investigation pertinent to the local geology is entitled "Hydrology of a Nuclear-Processing Plant Site, Rocky Flats, Jefferson County, Colorado" (Hurr, 1976). Hurr was the first to differentiate the Arapahoe Formation from the Laramie Formation. Of even more importance, he determined that the strata beneath the Plant dips at a rate of 1.25 degrees to 1.7 degrees to the east or southeast. Until 1976 this observation was overlooked by many geologists. Hurr also introduced some controversy as to whether or not the previously-mapped Eggleston Fault (Spencer, 1961) continued into the RFP area.

The fourth study, "Geologic and Seismologic Investigations for Rocky Flats Plant" (Dames and Moore, 1981), addressed the issue of the Eggleston Fault extension and discerned that the Fault does not extend into RFP.

Finally, high resolution seismic studies have revealed that the strata beneath the RFP are almost flat-lying with eastward dips of 1 to 2 degrees (Rockwell, 1989). Further investigations in the 903 Pad (Operable Unit 2) (see Map 1) area during 1989 (EG&G, 1991a) have confirmed that subcropping and buried paleochannels are present beneath the alluvium at the RFP and that the monoclinal fold, mapped originally from borehole information, is present in the western portion of the plant site (EG&G, 1991c).

2.0 STRATIGRAPHY

The stratigraphic section in the vicinity of the Plant extends from the Precambrian to the Quaternary. Figure 2 depicts a generalized stratigraphic section of the Golden-Morrison area; while Figure 3 illustrates a site-specific stratigraphic section of the geology beneath the RFP. West of the plant, rocks from Pennsylvanian/Permian to Late Cretaceous age are exposed along the western limb of a prominent monoclinal fold. The strata become progressively older from the east toward the west, with the Fountain Formation resting unconformably on Precambrian rocks of the Front Range.

2.1 Precambrian

Along the Front Range, the Precambrian rocks are made up of quartzites, schists, and gneisses, which have been intruded by younger Precambrian and Tertiary rocks. Most of the cobbles and pebbles contained in the Quaternary Rocky Flats Alluvium are composed of Precambrian quartzite and gneiss.

2.2 Paleozoic and Mesozoic Sedimentary Section

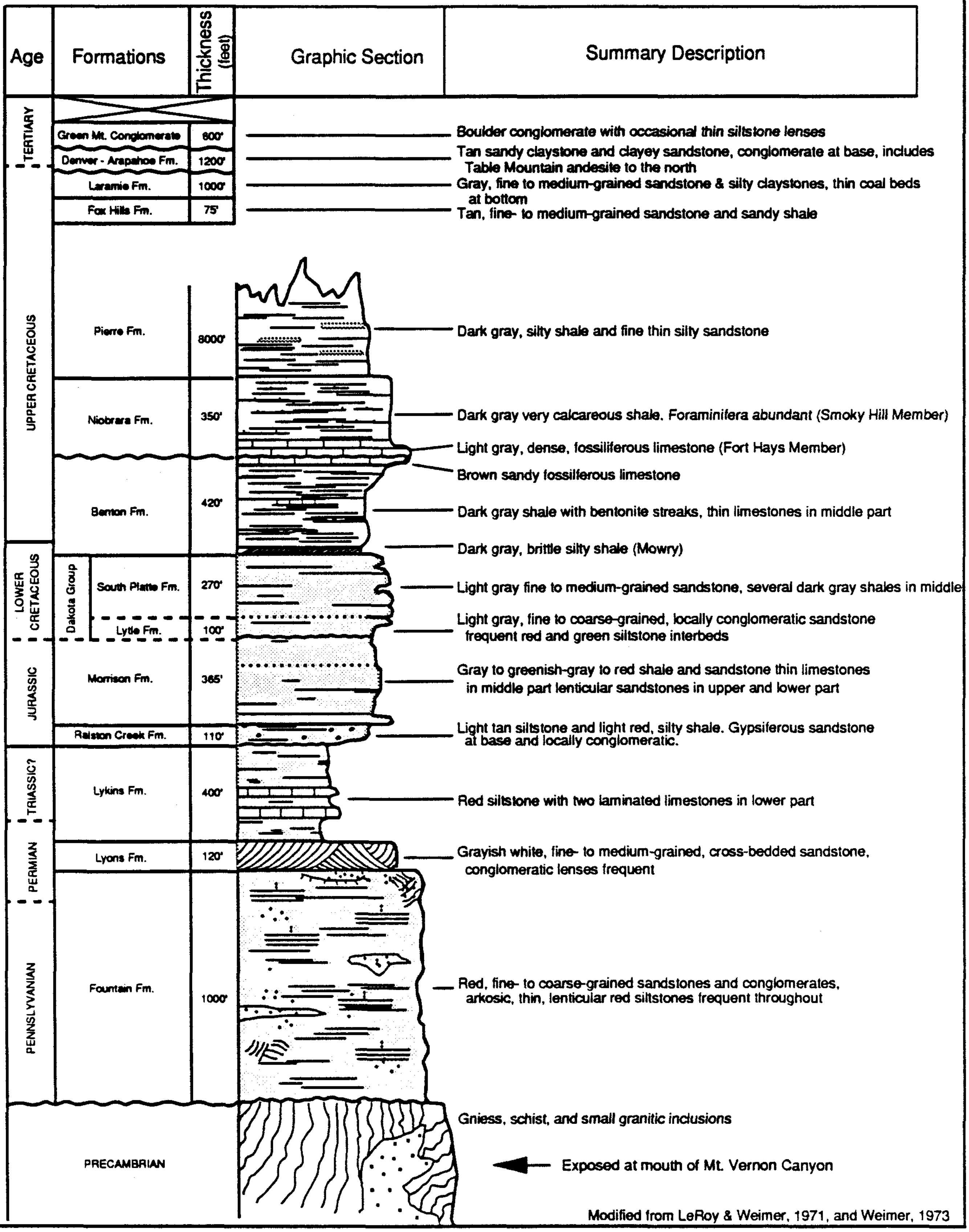
The total Paleozoic and Mesozoic stratigraphic section in the RFP area is estimated to be roughly 13,000 feet thick, assuming that each formation is approximately as thick in the subsurface as it is in the Front Range outcrop. In ascending age, the formations are described briefly below.

2.2.1 Fountain Formation (Pennsylvanian/Permian)

The Fountain Formation, which is approximately 800 to 1,000 feet thick, is composed of interbedded conglomerates, sandstones, and mudstones. The sandstones are reddish-orange, arkosic, and coarse grained to conglomeratic; the mudstones are dark reddish-brown, micaceous, and silty. The coarsest materials include cobbles up to 7 inches in diameter. The upper 30 feet of the Fountain Formation is composed of a fine-grained, crossbedded quartzitic sandstone, which is lithologically similar to the overlying Lyons Formation (Van Horn, 1957) (Weimer, 1971). The type areas for the Fountain Formation are located below Manitou Springs, along Fountain Creek, in the Colorado Springs Quadrangle, and at the head of Fountain Creek in the northeastern corner of the Pikes Peak Quadrangle (Wilmarth, 1938).

2.2.2 Lyons Sandstone (Permian)

The Lyons Sandstone is approximately 120 to 250 feet thick. It is of light gray, grayish-orange, and white color and composed dominantly of fine- to medium-grained sandstones;



Modified from LeRoy & Weimer, 1971, and Weimer, 1973

GENERALIZED STRATIGRAPHIC SECTION, GOLDEN-MORRISON AREA

GEOLOGIC CHARACTERIZATION
ROCKY FLATS PLANT
EG&G GOLDEN, COLORADO
FIGURE 2

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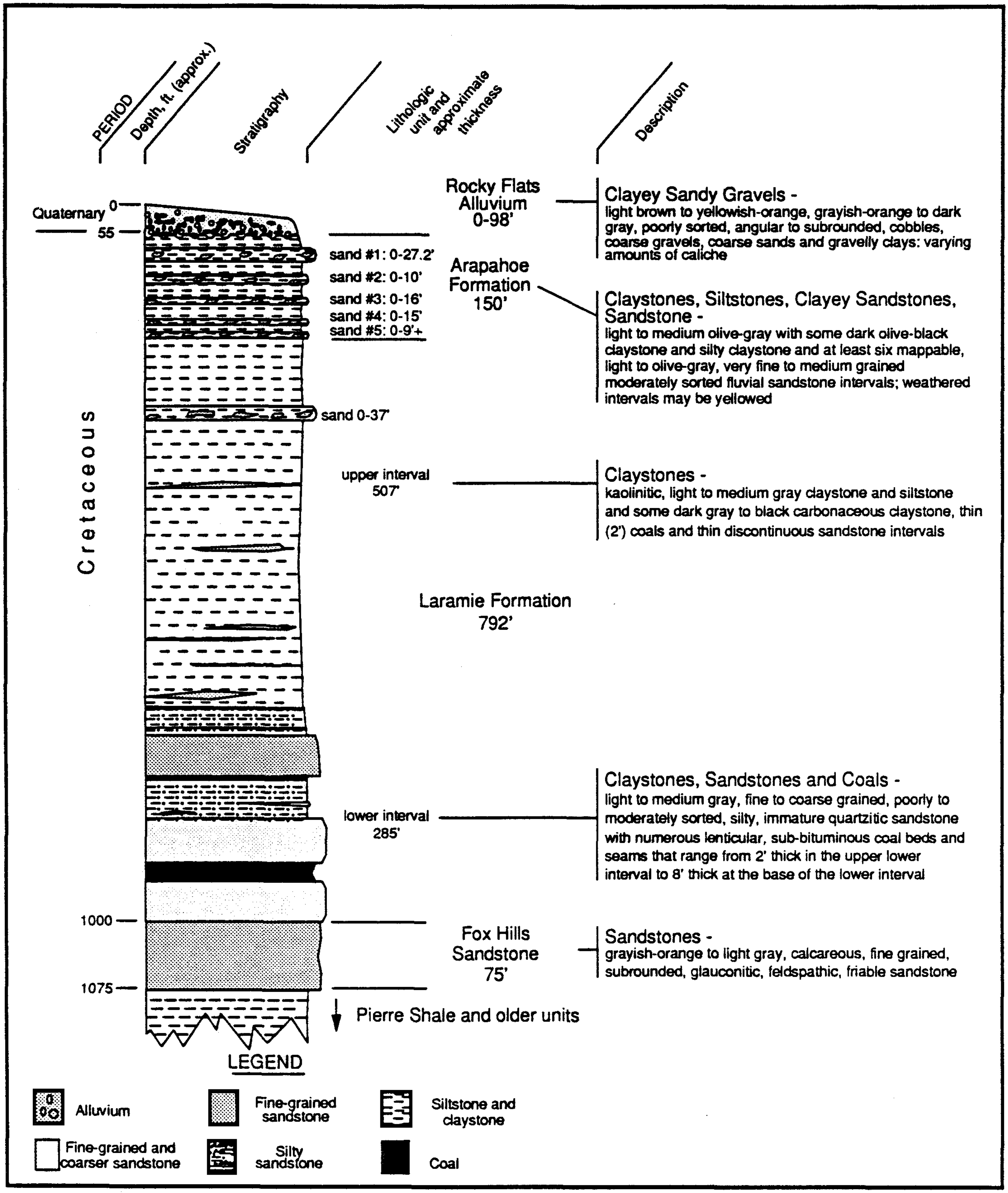


ROCKY FLATS PLANT SITE SPECIFIC STRATIGRAPHIC SECTION

GEOLOGIC CHARACTERIZATION

ROCKY FLATS PLANT
GOLDEN, COLORADO

EG&G

FIGURE 3

however, occasional interbeds of siltstones, mudstones, and conglomerates are present. South of Golden, Colorado, conglomeratic layers contain pebbles and cobbles are as large as 4 inches in diameter and are composed of quartz, chert, and sandstone (Van Horn, 1957). The type area for the Lyons Sandstone is at Lyons, Colorado (Wilmarth, 1938).

2.2.3 Lykins Formation (Permian/Triassic)

The Lykins Formation, which is approximately 390 to 450 feet thick, is composed of 5 members. In ascending order they are: the Herriman Shale, the Falcon Limestone, the Bergen Shale, the Glennon Limestone, and the Strain Shale. The shales are grayish-red, thinly-bedded, and slightly calcareous, containing thin beds of light gray, very fine-grained sandstone. The limestones are very light gray, hard, finely crystalline, and dolomitic, often exhibiting wavy bedding (Van Horn, 1957) (Spencer, 1961). The type area is in Lykins Gulch about 9 miles north of Boulder, Colorado (Wilmarth, 1938).

2.2.4 Ralston Creek Formation (Jurassic)

The Ralston Creek Formation is about 110 feet thick. It is composed principally of varicolored calcareous claystones, and to a lesser extent limestones (containing disseminated nodules of chalcedony), conglomerates, siltstones, and some gypsum. The Ralston Creek Formation was probably deposited in conditions similar to those of the overlying Morrison Formation (Van Horn, 1957) (Brady, 1969). The type area for the Ralston Creek Formation is on the south side of Ralston Creek approximately 3 miles north of Golden (Keroher and others, 1966).

2.2.5 Morrison Formation (Jurassic)

The Morrison Formation is 227 feet thick at its type section, but may be as thick as 350 feet in places. Locally, the Morrison Formation is dominantly composed of interbedded, multicolored claystones and siltstones also containing sandstones, thin dolomites, and fossiliferous limestones. The Morrison Formation was deposited as fluvial overbank and splay deposits, however sandstone channel deposits from small, meandering streams contribute as much as 20 percent to the total section (Brady, 1969). The Lexicon of Geologic Names states that the type section for the Morrison Formation is located about 2 miles north of Morrison in a roadcut exposure along the north side of West Alameda Parkway (Keroher and others, 1966).

2.2.6 Dakota Group (Lower Cretaceous)

The Dakota Group, which is approximately 290 to 370 feet thick, includes the Lytle Formation and the South Platte Formation. The Skull Creek Shale and the J Sandstone intervals, which are recognized in the subsurface to the east, belong to the South Platte Formation. In general, the Dakota Group is composed of sandstones, siltstones, and claystones; however, near its base the sandstone may be conglomeratic. The sandstones are light gray, fine- to medium-grained, non-calcareous, quartzitic, and resistant, containing abundant plant fragments (Weimer, 1976). Along the Front Range, the Formation has been mined for uranium. The Dakota Group type section is 2 miles north of Bellevue, Larimer County, Colorado (Keroher and others, 1966).

2.2.7 Benton Shale Formation (Lower/Upper Cretaceous)

The Benton Formation is generally 500 feet thick and is dominantly composed of shale, interbedded with siltstone, bentonite, and limestone. Based upon examination of an exposure at Ralston Reservoir, Van Horn subdivided the Benton Formation into three intervals. In ascending order, they are: Graneros, Greenhorn, and Carlile intervals. Overall, the Benton Formation is a dark gray to black shale, interbedded with very light gray to yellowish-orange bentonite, dark gray siltstone, and yellowish-gray limestone (Van Horn, 1957). The type area is at Fort Benton on the Missouri River about 40 miles below Great Falls, Montana (Wilmarth, 1938).

2.2.8 Niobrara Formation (Upper Cretaceous)

The Niobrara Formation unconformably overlies the Benton Shale and is composed of two members. In ascending order these are the Fort Hays Limestone Member and the Smoky Hill Shale Member. The entire section is at least 350 feet thick. The Fort Hays Limestone Member is made up of medium gray to yellowish-gray, hard, dense limestones interbedded with medium dark gray calcareous shales. The Smoky Hill Shale Member is a light gray to dusky-yellow calcareous shale and contains some beds of bentonite and gypsum (Van Horn, 1957). The Niobrara Formation is named for exposures along the Missouri River near the mouth of the Niobrara River in Knox County, Nebraska (Wilmarth, 1938).

2.2.9 Pierre Shale Formation (Upper Cretaceous)

The Pierre Shale Formation is over 8,000 feet thick and is predominantly a medium to dark gray non-calcareous montmorillonite shale. It contains foraminifera and Baculities clinolobatus, an ammonite, indicating that the Formation was deposited in a marine environment. The contact between the Pierre Shale and the Fox Hills Sandstone is complex because it represents a transition between marine and continental rocks. The type section for the Formation is in exposures at the old Fort Pierre in both Stanley and Hughes County, South Dakota (Wilmarth, 1938).

2.2.10 Fox Hills Sandstone Formation (Upper Cretaceous)

The Fox Hills Sandstone Formation is approximately 75 feet thick and is a grayish-orange to light gray color. The dominant lithology is a calcareous, fine-grained, subrounded, friable, glauconitic, feldspathic sandstone containing thin beds of siltstone and claystone. Weimer (1976) interpreted the Formation as a delta-front sandstone in facies relationship with the underlying Pierre Formation and the overlying Laramie Formation. The Fox Hills Sandstone is named for exposures in Fox Ridge in southwest Dewey County, South Dakota (Wilmarth, 1938).

2.2.11 Laramie Formation (Upper Cretaceous)

The Laramie Formation is about 800 feet thick and is composed of two intervals: a lower sandstone and coal interval and an upper claystone interval. The sandstones are light to medium gray, fine- to coarse-grained, poorly sorted, subangular, silty, and quartzitic, containing grains of black chert. Clay, mica, and carbonaceous material are also present (Van Horn, 1957) (Weimer, 1976). The claystones are dominantly light to medium gray and kaolinitic; however, dark gray to black carbonaceous claystones are also present (Van Horn, 1957) (Weimer, 1976). From 1852 - 1876, the Laramie Formation was originally called the Lignite Formation; however, the stratigraphic sequence above the Fox Hills Sandstone was renamed the Laramie Formation by later investigators (Wilmarth, 1938). This designation is now restricted to the Denver Basin of Colorado so that the type locality is considered to be east of the Front Range, along the western flank of the Denver Basin. (Keroher and others, 1966).

2.2.12 Arapahoe Formation (Upper Cretaceous)

The Arapahoe Formation is the uppermost bedrock unit underlying RFP and therefore more site-specific information is available for the Arapahoe Formation than any of the deeper formations. Unless otherwise noted, descriptions provided in this report are the result of the RFP's ongoing geologic characterization efforts. The Arapahoe Formation is 150 feet thick in the central portion of the RFP and is mainly composed of claystones, siltstones, and sandstones. Light to medium olive-gray and occasionally olive-black claystones and silty claystones are dominant. When weathered at the base of the alluvium, the claystones appear dark yellowish-orange. The color difference is the result of iron oxide staining occurring below the alluvial bedrock unconformity. The staining of claystones is common at depths from 1 to 20 feet below the base of the alluvium.

Most of the Arapahoe sandstones are very fine- to medium-grained; while some are coarse grained to conglomeratic, poorly to moderately sorted, subangular to subrounded, silty, clayey, and quartzitic. Trough and planar cross-stratification are common. The color of the unweathered sandstones is light gray to olive gray; whereas the colors of weathered sandstones present within 30 to 40 feet of the base of the alluvium show evidence of iron oxide staining. Weathered sandstones are commonly pale orange, yellowish-gray, and dark yellowish-orange.

The Arapahoe Formation is named for its thick development and exposures in Arapahoe County, Colorado (Keroher and others, 1966).

2.3 Mesozoic and Cenozoic Sedimentary Section - Latest Cretaceous/Tertiary

None of the Latest Cretaceous/Tertiary formations are present in the immediate RFP area. They are referenced herein because they are mentioned in the "Tectonic" section of this report.

2.3.1 Denver Formation (Latest Cretaceous/Paleocene)

The Denver Formation ranges from 900 to 1,200 feet thick and is composed of mudstones, lava flows, sandstones, conglomerates, and breccias which contain volcanic lithic fragments (Weimer, 1973) (Tweto, 1975). The lava flows of the Denver Formation are conspicuous cap rocks of the Table Mountains in the Golden area. Weimer (1973) placed the contact between the Arapahoe and Denver Formations "at the base of the abrupt influx of volcanic-derived material in the section." One of the type localities of the Denver Formation is along the southwest slope of Green Mountain (Wilmarth, 1938) (Keroher and others, 1966).

2.3.2 Dawson Formation (Arkose) (Latest Cretaceous/Eocene)

Tweto (1975) stated that the Dawson Formation is an arkose derived from the Pikes Peak Granite to the west. Both the Arapahoe and Denver Formations ". . . intertongue southward with the Dawson Formation."

Kluth and Nelson (1988) stated that the ". . . basal Dawson is concordant with the underlying Laramie . . ."; however, above an intraformational angular unconformity, younger units of the Dawson dip eastward at a different angle. The lower Dawson Arkose, therefore, may correlate with the lower Denver Formation, which is consistent in part with Tweto's observations. Deposition of the upper Dawson probably continued into the Eocene (Kluth and Nelson, 1988) (Chapin and Cather, 1983). The Dawson Formation is named for exposures at Dawson Butte about 6 miles southwest of Castle Rock, Colorado (Keroher and others, 1966).

2.3.3 Green Mountain Conglomerate (Paleocene)

Resting disconformably on the Denver Formation, Green Mountain Conglomerate is 600 feet thick and may be equivalent in part to the upper Dawson Arkose exposed at the Air Force Academy. The Green Mountain Conglomerate is a coarse conglomerate with lithic fragments of quartzite, sandstone, chert, Precambrian rocks, and andesite (Tweto, 1975). The type section for the Green Mountain Conglomerate is at Green Mountain southeast of Golden, Colorado (Keroher and others, 1966).

2.4 Quaternary Alluviums

The Quaternary alluviums have been divided into two main types depending on whether they cover pediments or are valley fills (Figure 3). All of the Quaternary alluviums have been correlated along the Front Range by their height above modern drainages and major streams. Each height represents a stable geomorphic level in the Quaternary (Scott, 1965).

2.4.1 Pediment Alluviums (Quaternary)

The Rocky Flats, Verdos, and Slocum Alluviums (Figure 4) are all gravelly pediment covers. The Rocky Flats Alluvium (Nebraskan or Aftonian in age) (Scott, 1975) ranges from 10 to 90 feet in thickness and occurs about 250 to 380 feet above modern streams (Scott, 1965). It is composed of poorly sorted, angular to rounded, coarse gravels, sands, and gravelly clays. Caliche amounts vary from trace to abundant. Colors of the Rocky Flats Alluvium include: light brown, dark yellowish-orange, grayish-orange, and dark gray.

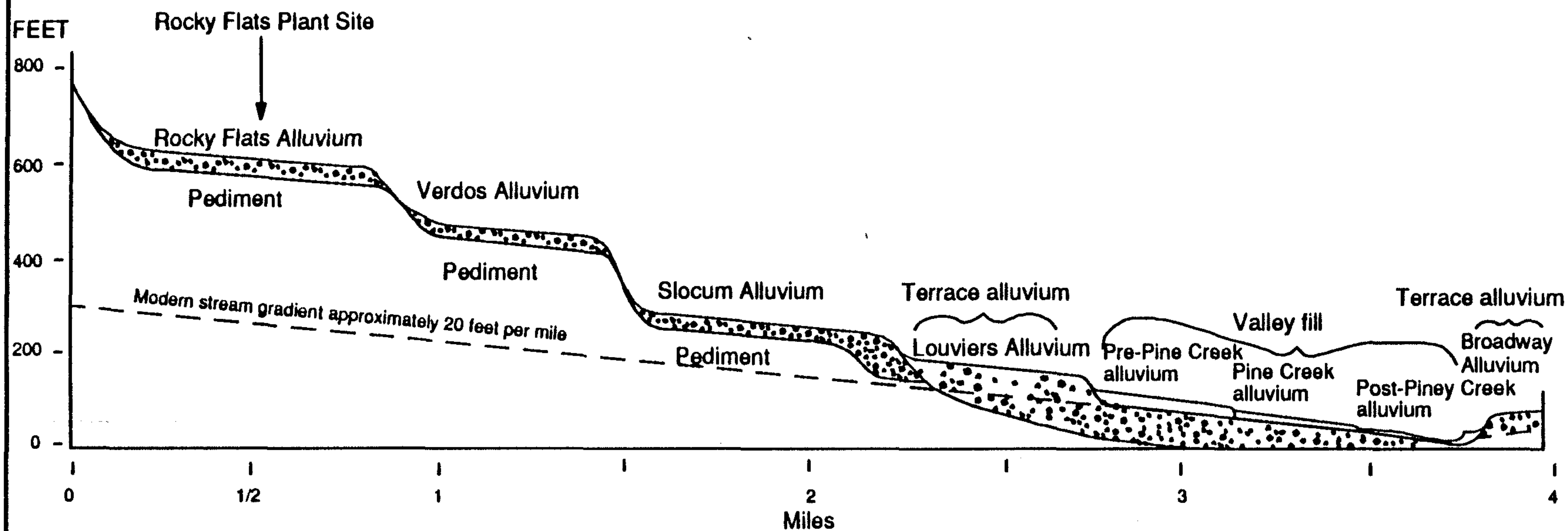
The Verdos Alluvium (Kansan or Yarmouth in age) is composed of brown, well-stratified, coarse gravel and coarse sand. This Alluvium ranges from 15 to 35 feet in thickness and occurs about 200 to 250 feet above modern streams (Scott, 1965).

The Slocum Alluvium (Illinoisan or Sangamonian in age) is composed of reddish-brown, well-stratified, clayey, coarse gravel and coarse sand. Ranging from 10 to 90 feet in thickness, the Slocum Alluvium occurs around 80 to 120 feet above modern streams (Scott, 1965).

2.4.2 Valley Alluviums (Quaternary)

Composed of reddish- or moderate-brown, well-stratified, coarse sand and gravel, the Louviers Alluvium (Early Wisconsin in age) ranges from 15 to 25 feet in thickness and forms well-developed terraces 40 to 80 feet above modern streams (Scott, 1965).

The Broadway Alluvium (Late Wisconsin in age) is composed of grayish-brown, coarse, pebbly sand and cobbley gravel. Ranging from 10 to 25 feet in thickness and forming



Taken from Final Environmental Impact Statement, Rocky Flats Plant Site

EROSIONAL SURFACES AND ALLUVIAL DEPOSITS EAST OF THE FRONT RANGE, COLORADO

GEOLOGIC CHARACTERIZATION
ROCKY FLATS PLANT
GOLDEN, COLORADO
FIGURE 4

EG&G

E-W-XSEC.DRW

widespread terraces 25 to 45 feet above modern streams, the Broadway Alluvium commonly occurs in channels cut into the Louviers Alluvium (Scott, 1965).

2.4.3 Recent Deposits

Among the most recent deposits in the Denver area are the Pre-Piney Creek, Piney Creek, and Post-Piney Creek Alluviums. The Pre-Piney Creek Alluvium (Early Recent in age) is composed dominantly of light brown silt and sand, but contains thin lenses of pebbles. It occurs 25 feet above modern ephemeral and smaller permanent streams in fill terraces up to 40 feet.

The Piney Creek Alluvium (Late Recent in age) is composed of gray or brownish-gray humic clay, silt, sand, and some pebble beds in layers ranging from 0.5 to 10 inches. It occurs 10 to 25 feet above modern streams in low fill terraces 4 to 25 feet thick (Scott, 1965).

The Post-Piney Creek Alluvium (Late Recent in age) is composed of two types of interbedded sandstones: one is grayish-brown, poorly consolidated, humic, and fine- to medium-grained; the other is black and magnetite rich. These deposits form the lowest terraces and floodplains of major streams. They are no more than 12 feet thick and are found from 0 to 12 feet above stream level (Scott, 1965).

3.0 STRUCTURAL GEOLOGY

Structurally, the RFP is located along the western margin of the Denver basin about four miles to the east of the Front Range uplift. The Front Range is the most easterly range of mountains in the Southern Rocky Mountain province. The Denver basin has a steep western flank and a broad, gentle eastern flank. Chapin and Cather (1983) described the basin as an asymmetric synclinal downwarp that is bounded on one side by a related uplift (Figure 5). The basin contains over 13,000 feet of Paleozoic, Mesozoic, and Cenozoic sedimentary rocks that rest on a Precambrian basement.

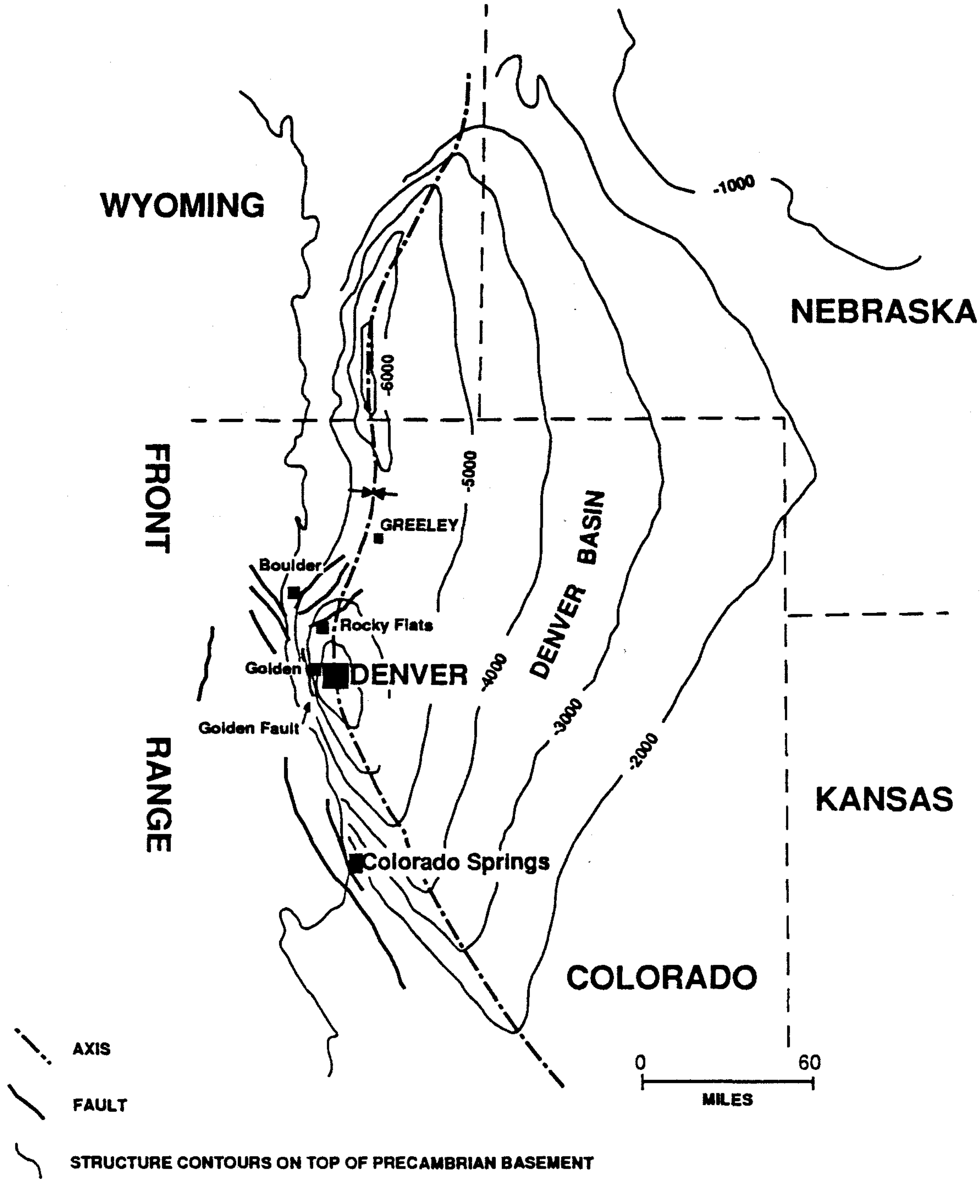
3.1 Tectonics

3.1.1 Pre-Laramide Tectonics

During the Pennsylvanian period, a major tectonic upheaval occurred in several places throughout the continental interior platform (western, central, and northern Colorado; north central New Mexico; and south central Wyoming). This uplift is generally referred to as the Ancestral Rockies (Tweto, 1975). By the beginning of the Triassic period, the Ancestral Rockies were almost totally eroded. During their destruction, volumes of sediment were supplied to the surrounding areas and became incorporated into the rock record. Along the eastern margin of the Ancestral Rockies, these sediments are represented by the Fountain Formation.

By the middle of the Mesozoic Era, plate tectonic movement caused dramatic evolutionary changes to North America. In the Jurassic Period, North America began to split away from Eurasia along the Mid-Atlantic ridge plate spreading center. As the infant Atlantic ocean began to form, the less dense crustal rocks of the North American plate were pushed westward and overrode the more dense oceanic Pacific plate. This created an arc-trench system in western North America. Incorporated in this system from west to east were a trench, subduction complex, fore-arc basin, magmatic arc, back-arc fold-thrust belt, and foreland basin (Dickinson, 1976).

The back-arc fold-thrust belt and the foreland basin began to form in the Late Jurassic and reached their maximum extent by Late Cretaceous (Dickinson, 1976). From Late Jurassic to Late Cretaceous, the foreland basin received sediments from the thrust belts to the west and the North American craton to the east. These sediments were later lithified and are represented by formations from the Morrison Formation to the Pierre Shale.



TAKEN FROM RCRA PART B-OPERATING PERMIT APPLICATION, 1986

STRUCTURE MAP OF THE DENVER BASIN

GEOLOGIC CHARACTERIZATION

EG&G

ROCKY FLATS PLANT
GOLDEN, COLORADO

FIGURE 5

DJSTRUCT.DRW

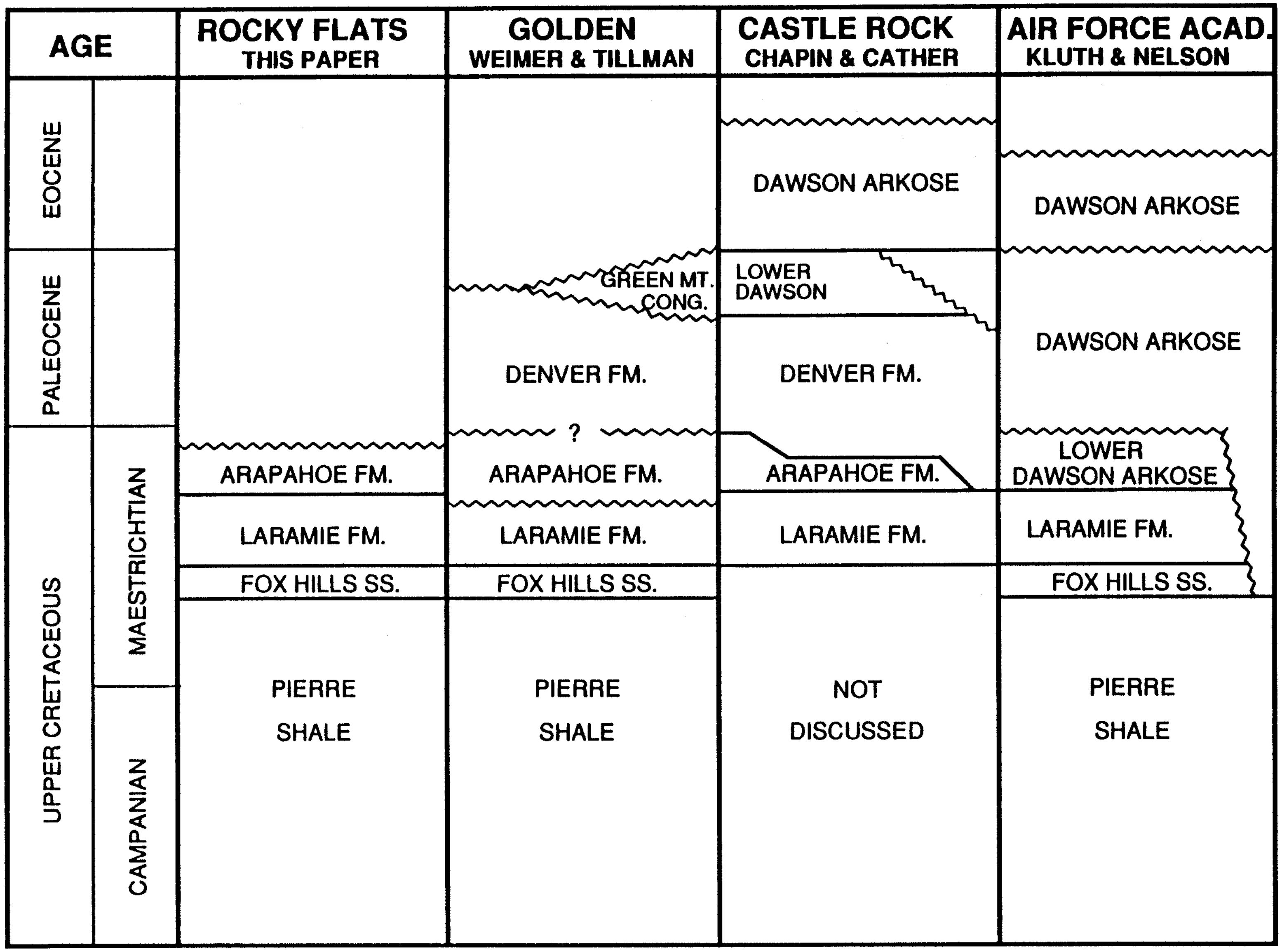
3.1.2 Laramide Tectonics

Tweto (1975) uses the term "Laramide" to describe the "orogenic events that occurred between Late Campanian Cretaceous and Late Eocene time." He further states that the Front Range uplift probably took place around 67.5 million years ago and that in a period of approximately 1.5 million years, erosion stripped off 3,000 feet of sedimentary cover exposing the Precambrian core.

The uplift probably began further to the west than the location of the present day Front Range and subsequently progressed to its present extent. This conclusion is based on the observation that the Laramie and Arapahoe Formations are significantly finer grained than the younger Denver and Dawson Formations. The conglomerates of the Arapahoe Formation and the pebbles that Tweto (1975) mentions from the upper part of the Laramie south of Denver possibly originated in a tectonic surge at the end of the Laramie deposition.

The Arapahoe Formation, the Denver Formation, and the Green Mountain Conglomerate appear to grade laterally into the Dawson Arkose in a complex sequence of depositional facies associated with very localized source areas. The correlation chart in Figure 6 contains a synthesis of all the published material presently available on local sedimentary rocks affected by Laramide tectonics.

Recent investigations of the Front Range and Wind River Range Laramide tectonic structures suggest that the Laramide uplifts are bounded by thrust faults which dip at rates of 30 to 35 degrees beneath the uplifts (Gries, 1983) (Smithson and others, 1978). Interpretations are based on gravimetric and deep-crustal seismic information obtained by the Consortium for Continental Reflection Profiling (COCORP). Another recent investigation was conducted by Bieber (1983) who constructed four west to east profiles of Bouguer gravity anomalies along the Front Range. The generalized cross-section at Ralston Creek depicts the Golden Fault which plunges beneath the Front Range uplift on an angle of between 22 and 30 degrees. Subthrusted Paleozoic rocks extend westward 2 miles under the Precambrian, Paleozoic, and Mesozoic rocks that were thrust to the east. Both Bieber (1983) and Gries (1983) conclude that horizontal compression was responsible for the development of the Front Range and its boundary thrust faults. However, Gries has also demonstrated that throughout the central and southern Rocky Mountain area, the direction of the compression has changed from east-west in the early and middle Laramide to north-south by the end of the Laramide. Because of this directional shift of the compressional forces, the Front Range was subjected to extensional forces at the end of the Laramide.



STRATIGRAPHIC CORRELATIONS DURING THE LARAMIDE ALONG THE FRONT RANGE AS REPRESENTED BY EACH GROUP OF AUTHORS

EG&G

GEOLOGIC CHARACTERIZATION
ROCKY FLATS PLANT
GOLDEN, COLORADO
FIGURE 6

STRATCOR.DRW

3.1.3 Post-Laramide Tectonics

Between the end of the Laramide Orogeny 45 million years ago and the end of the Eocene 37 million years ago, erosion reduced the Front Range uplift to a landscape that probably resembled the western part of the present Great Plains. During the Oligocene, the Eocene erosional surface was only slightly altered by channeling and in places was buried under alluvial and lucustrine deposits (Scott, 1975).

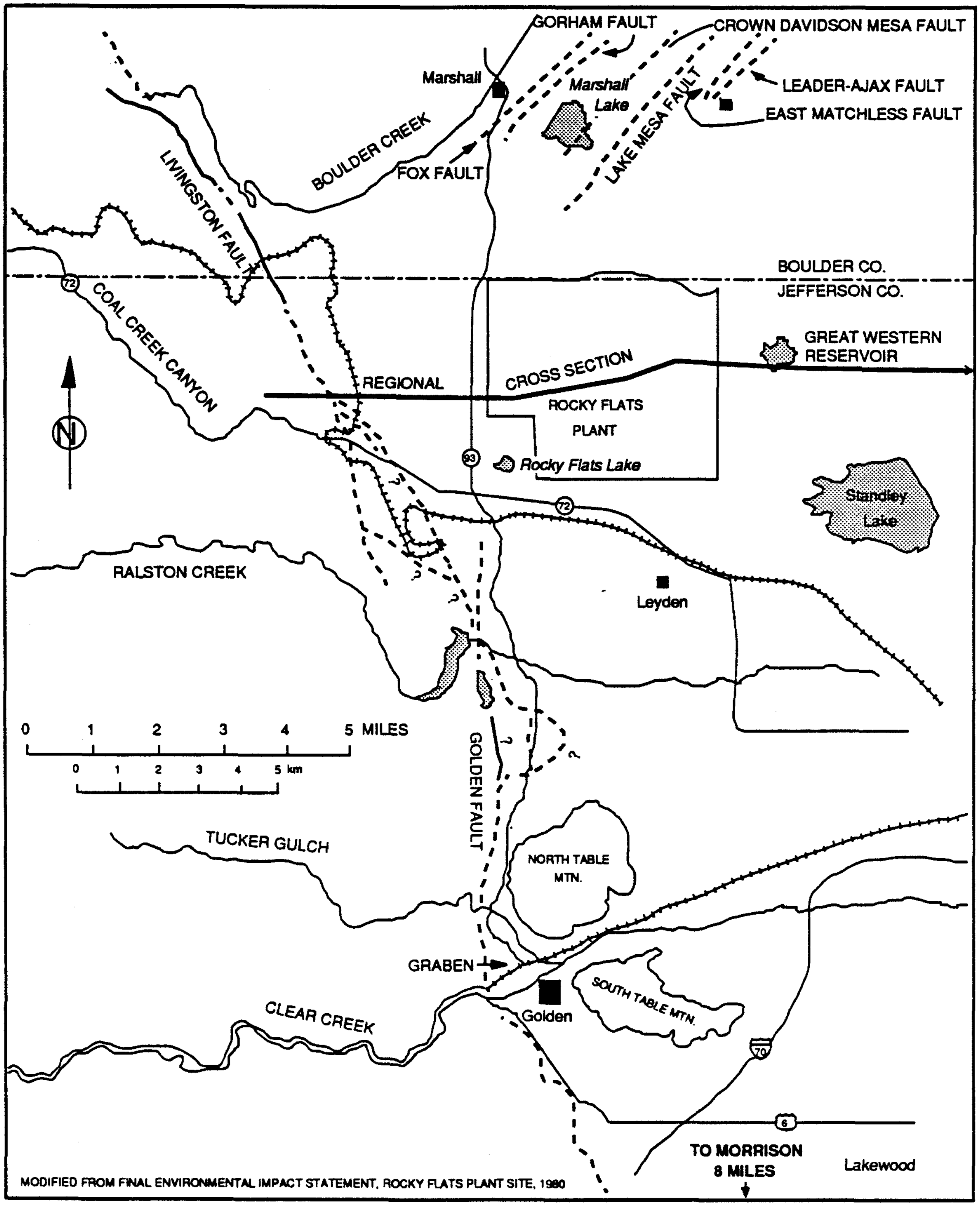
Eventually, another period of uplift began about 25 million years ago in the early Miocene and continued through the Pliocene. This event drastically changed the Eocene surface and uplifted the Front Range as much as 10,000 feet (RCRA Part B Operating Permit Application, 1988). The resulting tectonic style of horst and graben block faulting was caused by extensional forces.

3.2 Faulting

3.2.1 Golden Fault

In 1981 Dames and Moore was contracted to investigate the Golden Fault in terms of its lateral extent and timing of movement. At that time, it was hypothesized that a local graben structure located north of Golden and 800 feet east of the Golden Fault might be an extension of the Golden Fault (Figure 7). The Dames and Moore investigation was prompted by an earlier study conducted by the Colorado Geological Survey (C.G.S) in 1976. The C.G.S. workers had concluded that the graben had been formed during the Quaternary and was structurally related to the Golden Fault (RCRA Part B Operating Permit Application, 1988). Since an apparent structural relationship between the graben and the Golden Fault had been defined, it was thought that the Golden Fault had also been active during the Quaternary. Dames and Moore's work discredited this interpretation. Their conclusions regarding fault traces and movement are summarized below.

> There is ". . . no compelling evidence for tectonic activity of the Golden Fault."
>
> There is ". . . no evidence to suggest that the graben is tectonically or structurally related to the Golden Fault."
>
> There is no evidence to support a connection between the Golden Fault and the Livingston shear zone to the northwest of the Golden Fault; ". . . the faults are structurally separate."



LOCATION OF FAULTS BETWEEN GOLDEN AND MARSHALL, COLORADO

GEOLOGIC CHARACTERIZATION
ROCKY FLATS PLANT
EG&G GOLDEN, COLORADO
FIGURE 7

3.2.2 Eggleston Fault

The Eggleston Fault was defined by Spencer (1961) as a northwest-trending fault present at the Eggleston Reservoir. Even though Spencer did not see the actual fault plane, he interpreted it as a west-dipping high angle reverse fault with about 300 feet of throw. In 1976 when Hurr mapped the area, he projected the Eggleston Fault into the Rocky Flats Plant area on the basis of surface features.

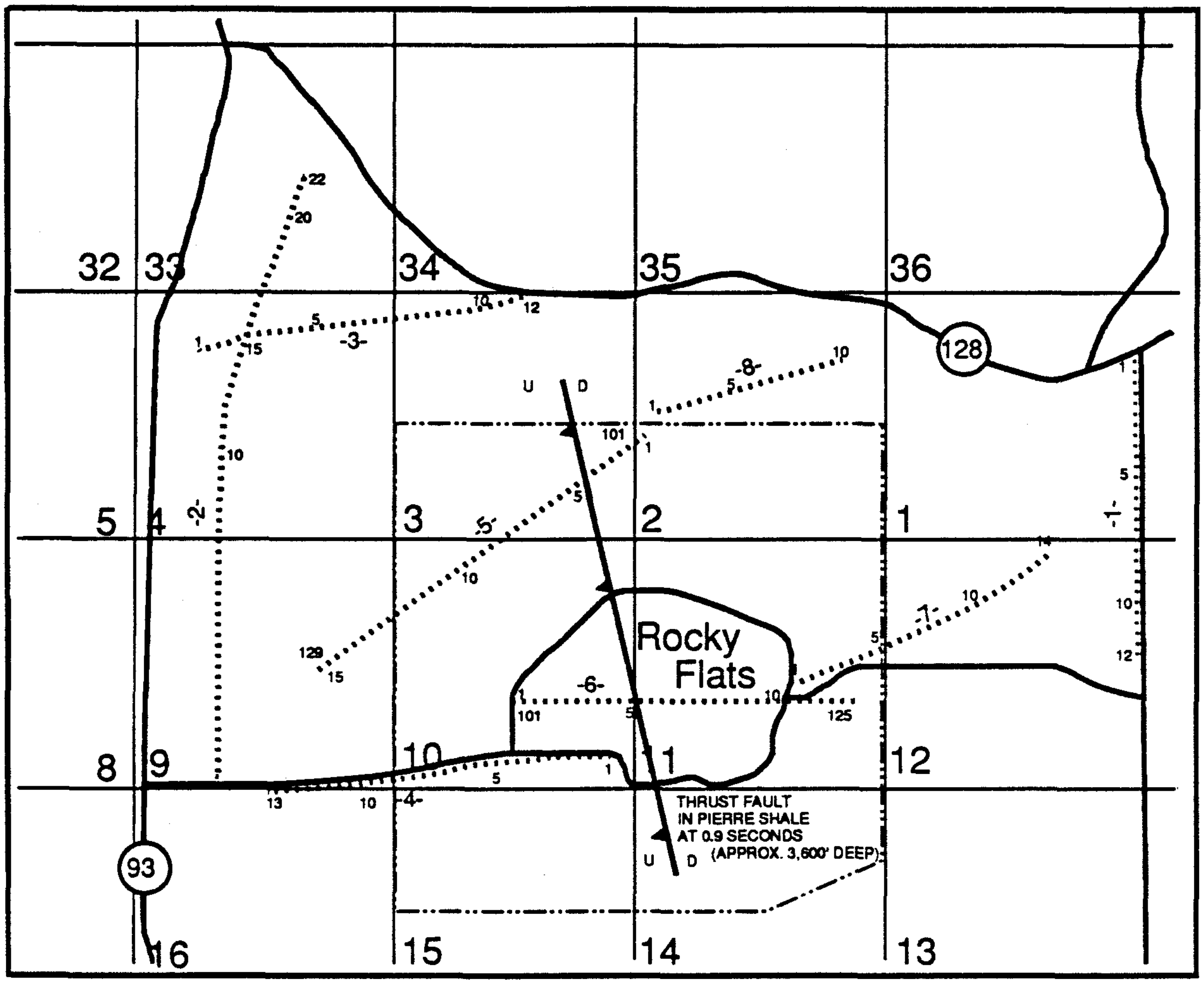
The Eggleston Fault was investigated by Dames and Moore in 1981 as part of the "Geologic and Seismologic Investigations for Rocky Flats Plant." After an extensive trenching program at the Eggleston Reservoir, Dames and Moore concluded that ". . . the Eggleston Reservoir Fault does not exist and that the bedrock units exposed on the surface near the reservoir are all conformable deposits of the Laramie Formation." Furthermore, an on-site inspection of the surficial features in the area surrounding the RFP (conducted by Dames and Moore) did not reveal any faulting in the Plant area. The questionable features that were investigated turned out to be either false leads or ". . . gravity slumps and growth faults [which developed] during deposition in the prograding delta environment in Late Cretaceous time."

3.2.3 Reprocessed Colorado School of Mines Seismic Data

During December of 1975 and the spring of 1976, 13 miles of seismic data were acquired in the RFP area under the direction of Tom Davis, Department of Geophysics, Colorado School of Mines. The records were 600 to 1,200 percent Vibroseis™ (Trademark of Continental Oil Company) and are included in the Environmental Impact Statement, Rocky Flats Plant, 1980.

Of the original 8 lines, only lines 5 and 6 could be reprocessed. The remaining 6 lines were either missing field data tapes or acquisition information. The report entitled "Seismic Data Reprocessing" is included in Appendix E.

Both lines 5 and 6 show a west to east thrust fault in the Pierre Shale Formation below RFP. The fault becomes detached from the bedding plane below 1.1 seconds, and at 0.7 seconds it either dies out in the Pierre Shale or enters a new bedding plane. In addition, line 6 shows a small east to west back-thrust that becomes detached from the bedding plane at 1.2 seconds. At the toe of the dominant west to east thrust (1.1 seconds), the back-thrust dies out or enters a new bedding plane. The maximum throw on the main west to east thrust is about 80 feet at 1.1 seconds. Figure 8 shows the location of the west



MODIFIED FROM DAVIS, 1976

1975-76 CSM SEISMIC PROJECT LINE LOCATION

GEOLOGIC CHARACTERIZATION
ROCKY FLATS PLANT
EG&G GOLDEN, COLORADO
FIGURE 8

to east thrust at 0.9 seconds, which is at a depth of about 3,600 feet. The explanation of why the thrusts were not recognized on the original CSM records is included in Appendix E.

The thrusts shown on seismic lines 5 and 6 were produced by compressional forces, and were probably formed during the Laramide Orogeny over 45 million years ago. A similar style of thrusting, also caused by compressional forces, is common along the eastern edge of the Wyoming Overthrust belt (Langman, Personal Communication). More recently, during a period which began in the Miocene approximately 25 million years ago and continued through the Pliocene, the area underwent block faulting (Scott, 1975). Because the Front Range is still undergoing extension, further movement along old thrusts is not expected.

4.0 GEOLOGIC MODEL

During the Late Cretaceous period, sedimentation east of the Front Range was altered by initial orogenic uplift (Figure 9). As the Cretaceous sea gradually regressed from the west to the east, the Fox Hills delta front sands, the Laramie delta plain deposits, and the Arapahoe fluvial deposits prograded eastward over the Pierre prodelta muds (Figure 10) (Weimer, 1973). This marine regression was occasionally interrupted by small-scale marine transgressions which were probably caused by variations in the rate of uplift along the Front Range. During transgressive pulses, thin intervals of Pierre prodelta mud were deposited above the Fox Hills Sandstone. As a result, the Fox Hills intertongues with the underlying Pierre Shale.

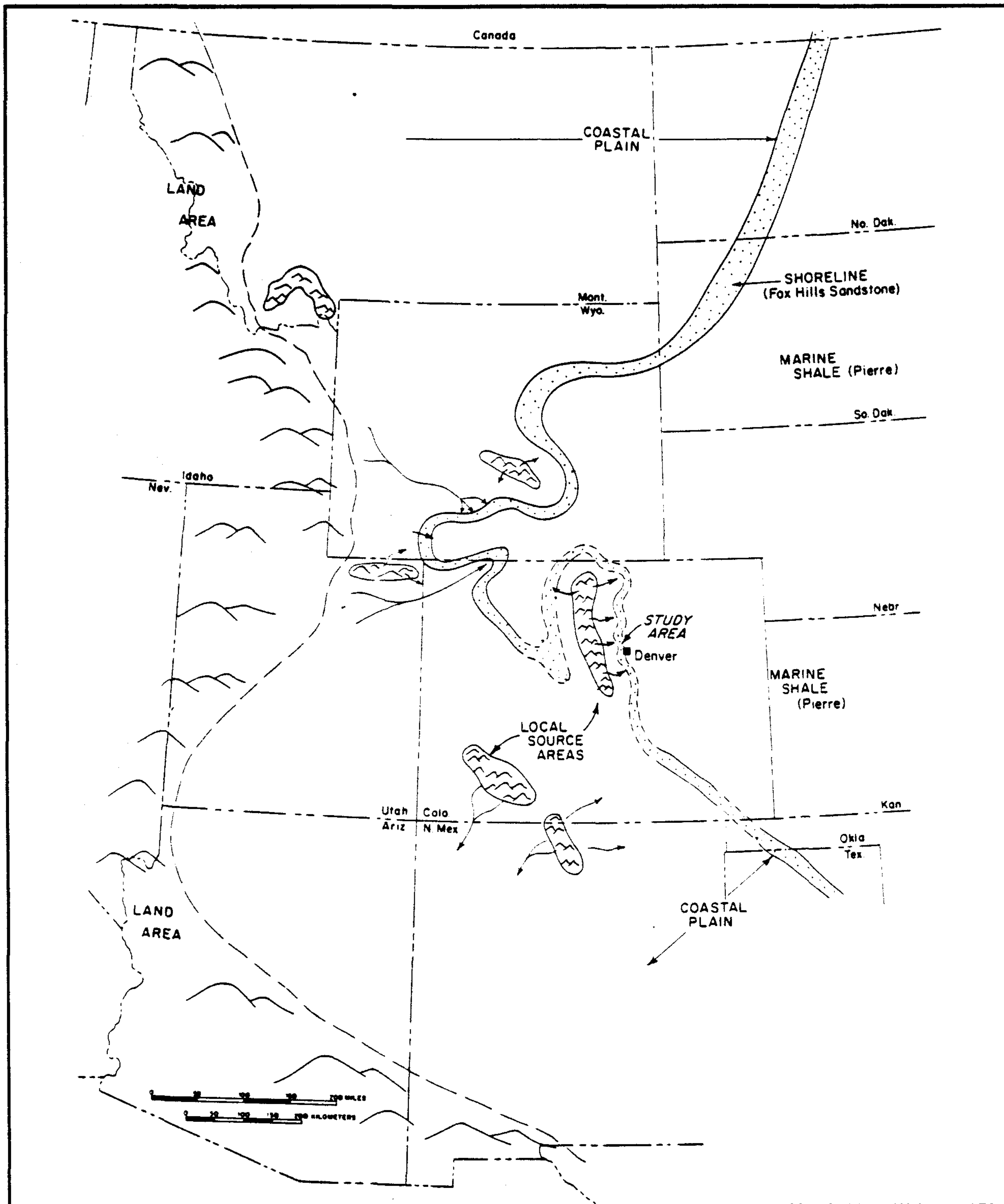
Figure 11 depicts an idealized drawing of a delta system modified from Weimer (1976). The Pierre Shale, the Fox Hills Sandstone, and the lower and upper intervals of the Laramie Formation are all shown as separate time-transgressive facies in the delta system. The younger Arapahoe Formation represents a fluvial system which eventually overrode the delta environments.

Data from all of the Rocky Flats subsurface cores, geophysical logs, and outcrops (Draft Surface Geologic Mapping, 1991) were used to make interpretations regarding the sedimentological history of the Arapahoe sandstones. In order to locate the proper stratigraphic position of the RFP subsurface section, the geophysical logs from two RFP boreholes were correlated with boreholes outside the plant area. The geophysical logs from borehole B304289 (37-89BR) (Plates 1A and 1B) were correlated to the Johnson F.H. and C.R. Co. No.1 well in Section 7, T.3 S., R. 69 W. (about 7 miles southeast of the Plant), and the Public Service No. 2 well in Section 27, T. 2 S., R. 70 W. (about 2 miles south of the Plant).

4.1 Stratigraphy

4.1.1 Laramie Formation

In the RFP area, the Laramie Formation is 792 feet thick and is divided into two intervals. Geophysical logs run in borehole B304289 (37-89BR) indicate that the borehole did not totally penetrate the lower Laramie interval. The logs stopped at a total depth of 640 feet at the base of an eight-foot coal bed within the Laramie Formation (Plate 1A and 1B). The top of the lower Laramie interval was defined on the basis of resistivity characteristics at a depth of 527 feet. At this depth, the resistivity drops from a baseline value of 18 ohm-m in the lower Laramie interval to 12.5 ohm-m in the upper Laramie interval. The

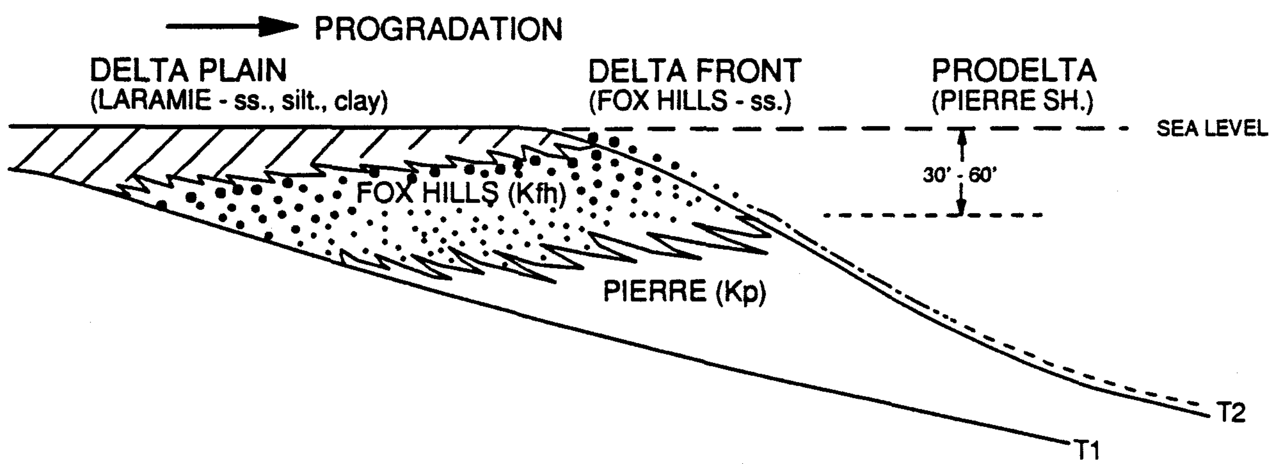


Modified from Weimer, 1976.

PALEOGEOGRAPHY OF WESTERN INTERIOR, U.S., DURING LATE FOX HILLS DEPOSITION

GEOLOGIC CHARACTERIZATION
ROCKY FLATS PLANT
EG&G GOLDEN, COLORADO
FIGURE 9

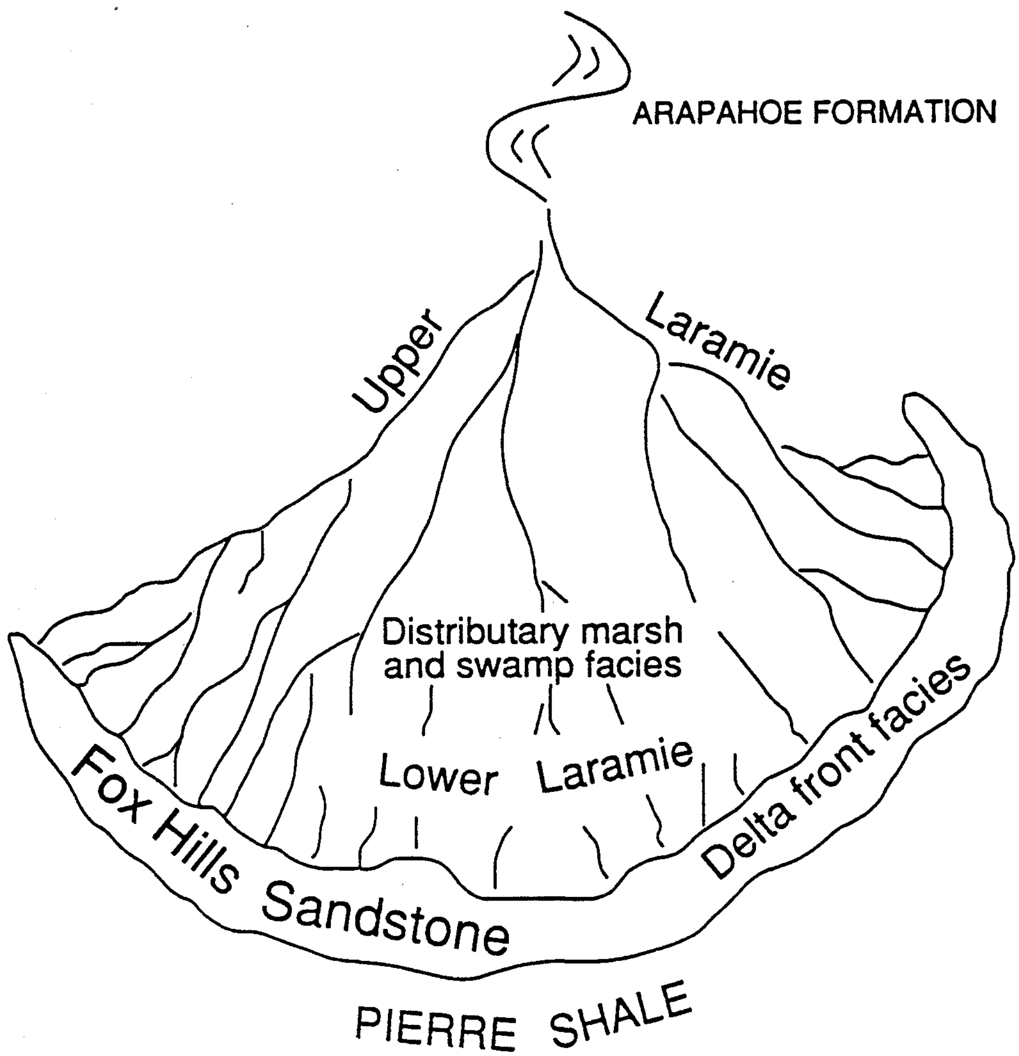
PALEOBOR.DRW



After Weimer, 1976

DELTA SEDIMENTATION MODEL RELATING FORMATIONS TO FACIES AND TO ENVIRONMENTS OF DEPOSITION

GEOLOGIC CHARACTERIZATION
ROCKY FLATS PLANT
GOLDEN, COLORADO
EG&G
FIGURE 10



MODIFIED FROM WEIMER, 1976

IDEALIZED DELTAIC MODEL FOR THE LARAMIE, FOX HILLS, AND PIERRE FORMATIONS

GEOLOGIC CHARACTERIZATION
ROCKY FLATS PLANT
GOLDEN, COLORADO
FIGURE 11

DELTASYS.DRW

minimum thickness of the lower Laramie is 113 feet; however, on the basis of correlation with previous regional work (Weimer, 1973), the lower Laramie is closer to 285 feet in thickness.

The contact between the upper Laramie interval and the overlying Arapahoe Formation also has been defined on the basis of textural and lithologic characteristics identified in the surface mapping program (Draft Surface Geologic Mapping, 1991). This contact correlates at depth 30 feet at B304289. This contact determination is shown on Plate 1A where the upper Laramie is 463 feet thick.

The upper Laramie interval is composed of mostly silty claystones, siltstones, and some fine-grained fluvial channel sandstones. The lower 150 feet of the upper Laramie interval contains numerous coals that range from 1 to 3 feet in thickness (Plates 1A and 1B). The silty claystones are light olive gray to olive black, massive, and occasionally sandy, containing some carbonaceous material. These are yellowish-gray to olive gray, once thinly laminated (1 mm to 10 mm). Siltstones contain abundant carbonaceous material, some iron oxide nodules, and slickensides along fracture surfaces.

Geophysical logs reveal that at borehole B304289, the lower Laramie is composed of several sandstones and numerous coal beds. One of the Lower Laramie sandstones, which are relatively laterally extensive, is 50 feet thick. The Lower Laramie sandstones are very fine- to medium-grained, moderately sorted, subangular to subrounded, and immature to submature. Coals beds range from 2 to 8 feet thick (Plates 1A and 1B).

4.1.2 Arapahoe Formation

The Arapahoe Formation is approximately 150 feet thick in the central portion of the RFP and consists mainly of claystones and silty claystones. It contains at least five mappable sandstone intervals. Due to the lenticular geometries of sandstones, they are not present in all of the boreholes or areas beneath the plant. (Maps 2, 2A, 3, 3A, and 4; All cross-sections). The sandstones and the distances between them are given in Table 1 (Page 31).

Most of the Arapahoe sandstones are poorly to moderately sorted, subangular to subrounded, silty, clayey, quartzitic, and very fine- to medium-grained; however, some are coarse grained to conglomeratic. Trough and planar cross-stratification are common sedimentary structures. The weight percentages of gravel, sand, silt, and clay determined from sieve analyses and hydrometer tests are presented in Appendix A. Hydrometer analyses were not performed on all samples, so in some cases the percentages of silt and clay have been determined from grain size curve extrapolations. When this has been the

Table 1

Arapahoe Sandstones: Thickness and Vertical Separation

Sandstone	Thickness	Vertical Separation between Sandstone Depending on Sandstone Thickness
Sandstone #1	0' - 27.2'	
		35' - 40'
Sandstone #2	0' - 10'	
		15'- 23'
Sandstone #3	0' - 16'	
		7' - 18'
Sandstone #4	0' - 15	
		2' - 8'
Sandstone #5	0' - 9'+	

case, the values are given in parentheses. Most of the sandstones have median grain size values (D50 values) of between 0.06 and 0.09 mm. Commonly, the Arapahoe sandstones occurring within 30 to 40 feet of the base of the alluvium are oxidized and are thus pale orange, yellowish-gray, and dark yellowish-orange. The sandstones that are not in the weathered zone are light gray and olive gray.

The claystones and silty claystones are light to medium olive gray. In the weathered intervals below the base of the alluvium, claystones are sometimes dark yellowish-orange and yellowish-brown as the result of iron oxide staining.

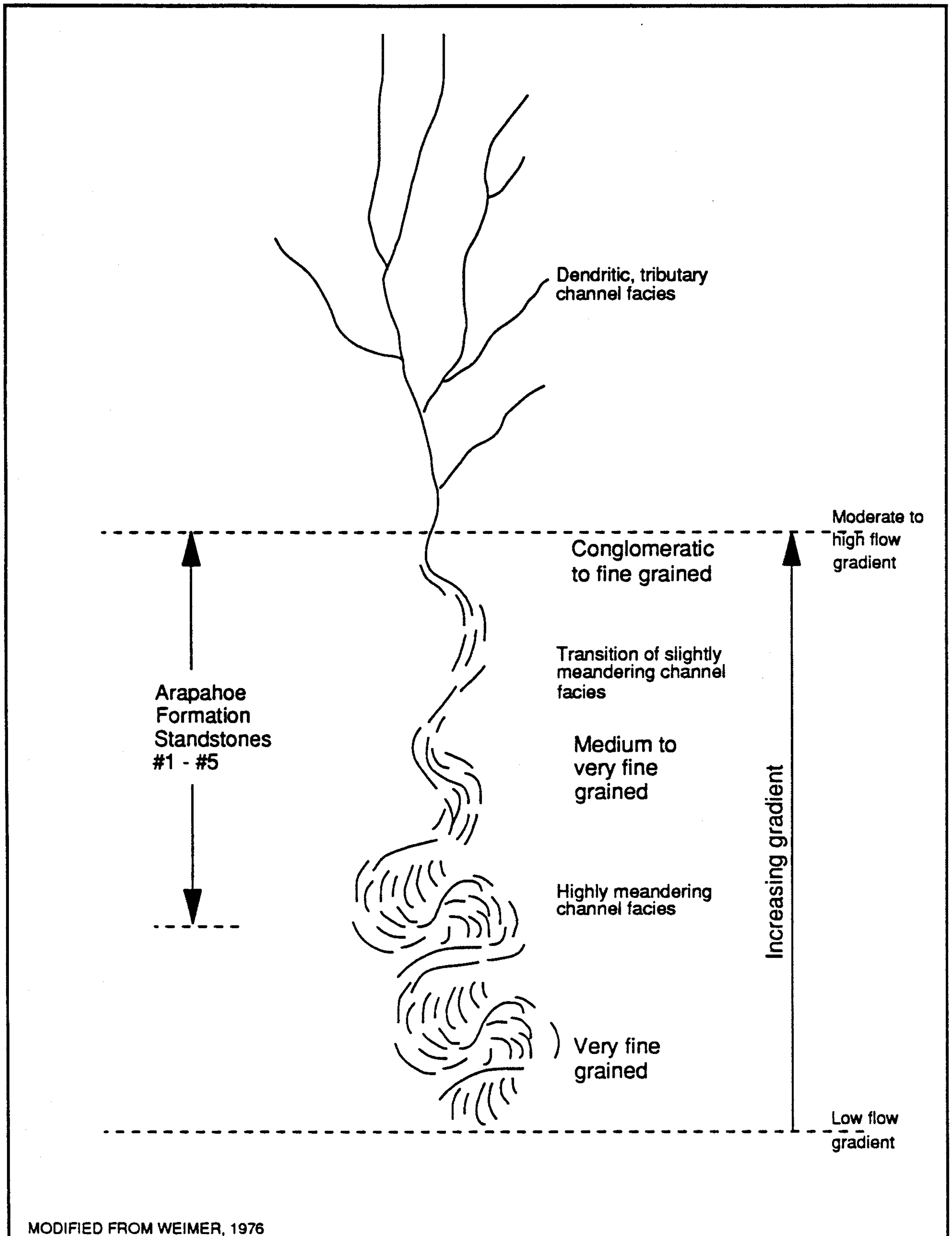
4.1.2.1 Depositional Model

The Arapahoe Formation is a fluvial deposit composed of channel, point bar, and overbank deposits. Figure 12 is an idealized fluvial system model for the Arapahoe Formation. Channel geometries vary from straight to highly meandering, depending on the gradient. Where gradient is high and the stream possesses excess energy (close to a mountain front), channel geometries are straight. Where the gradient is moderate, the stream is said to be graded and characterized by a meandering stream geometry. The discharge in a stream changes seasonally, but it is the flow during high water times that determines stream geometry. Figure 12 illustrates that gradient and channel type are related to the grain size of the resulting sediments. Conglomerates are deposited by high flow regimes in straight streams, whereas very fine-grained sandstones are deposited by moderate to low flow regimes in highly meandering streams.

The fluvial history of a formation can change laterally and vertically because of local changes in gradient and discharge. Figure 12 shows that the channel geometries for the Arapahoe sandstones beneath RFP were variable. However, most of the sandstones of the Arapahoe Formation at RFP are very fine- to medium-grained and represent deposition from meandering streams. Occasional conglomeratic sandstones have been documented and represent higher energy flow regime conditions.

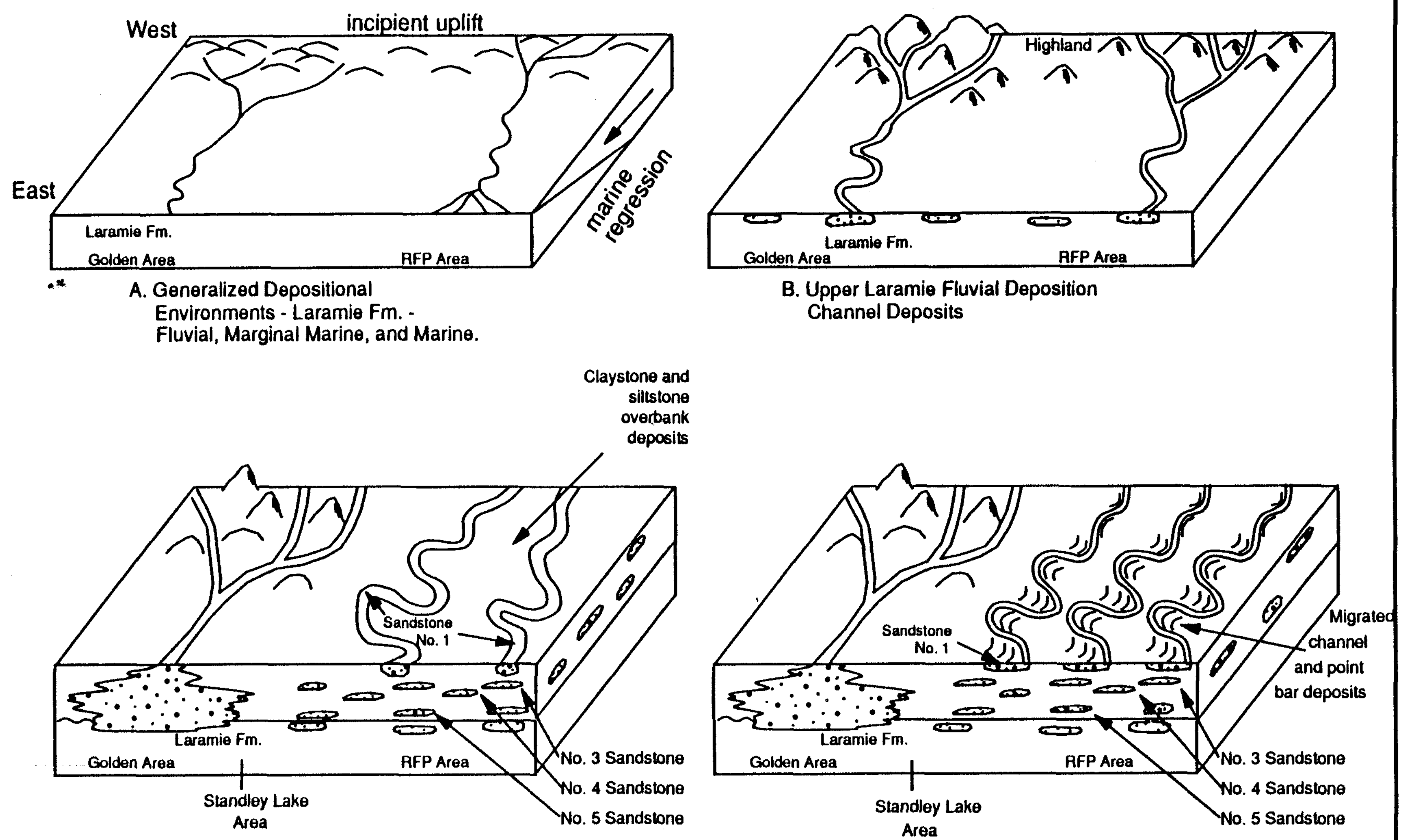
Figure 13 shows the sequence of events which occurred from the upper Laramie through the Arapahoe deposition. In places such as Golden, Colorado, the upper surface of the Laramie Formation appears to have been scoured by streams issuing from a highland created by a tectonic surge at the end of the Laramie deposition. This scoured area was rapidly filled with braided Arapahoe channel deposits.

These braided streams deposits cover a broad area, are poorly sorted, and have high sandstone and conglomerate to claystone ratios (greater than 8). The sediments were deposited from streams with steep gradients under high flow regime condition. (Figures 12 and 13).



IDEALIZED FLUVIAL SYSTEM: MODEL FOR ARAPAHOE FORMATION

GEOLOGIC CHARACTERIZATION
ROCKY FLATS PLANT
EG&G GOLDEN, COLORADO
FIGURE 12



A. Generalized Depositional Environments - Laramie Fm. - Fluvial, Marginal Marine, and Marine.

B. Upper Laramie Fluvial Deposition Channel Deposits

C. Arapahoe Fm. Fluvial Deposition

Interpretation 1.

Interpretation 2.

SEQUENCE OF EVENTS: END OF LARAMIE DEPOSITION THROUGH ARAPAHOE DEPOSITION

GEOLOGIC CHARACTERIZATION
ROCKY FLATS PLANT
GOLDEN, COLORADO
EG&G
FIGURE 13

BLOCKDIA.DRW

Because of its shallow subsurface depth, more data has been collected from Arapahoe Sandstone No. 1 than any of the other four sandstone intervals. It appears to have been deposited by meandering streams which had very low gradients. Sandstones in this interval are moderately to well sorted, very fine- to fine-grained, and have low sandstone to claystone ratios (approximately .25).

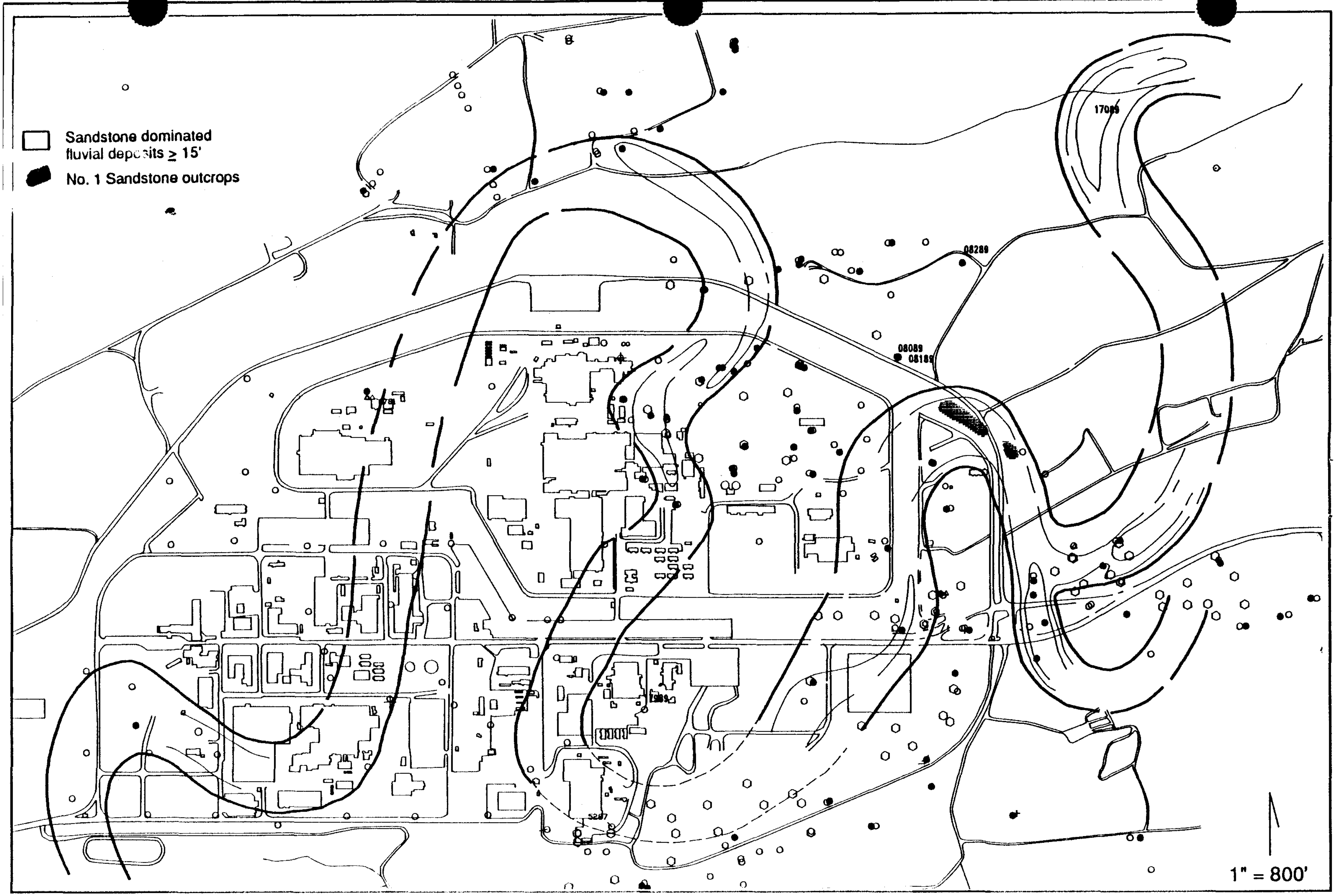
Figures 13, 14, 15 and Maps 2, 2A, 3, and 3A of Appendix B present two interpretations for the No. 1 Sandstone. Both interpretations support the idea that the No. 1 Sandstone was deposited by meandering streams. The first interpretation shows a continuous single channel system. Channel and point bar deposits are both recognized; however, channel fill deposits are dominant. The second interpretation depicts a multiple channel system containing migrated channel and point bar deposits. This interpretation is consistent with the observation that the Arapahoe No. 1 Sandstone is made up of more than one fining upward sequence. A minimum of three fining upward sequences can be recognized in boreholes where penetration of the No. 1 Sandstone is complete. In either interpretation, individual sandstones have lenticular geometries and may not be in hydraulic communication with one another. Overbank deposits of lower permeability are known to separate the sandstones in subsurface core drill log interpretation. Both interpretations should be evaluated through future drilling. Figures 13 and 14 are generalizations of Maps 2A and 3A.

Map 4 of Appendix B shows the channel trends interpreted for No. 3 and No. 4 Sandstones. These maps are highly interpretive since subsurface control for these sandstones is sparse. Future drilling will improve the stratigraphic correlations and the definition of these channel trends.

4.1.3 Pre-Wisconsin Pediment (Pleistocene)

Map 5 of Appendix B is a top of bedrock elevation contour map. This map shows the remnants of the pre-Wisconsin pediment as well as the effects of recent stream incitement. For purposes of discussion, three pediment remnants have been named - they are the North interfluve, the Plant interfluve, and the South interfluve (Map 5). The ancient pediment surface was covered by the Rocky Flats Alluvium during Nebraskan or Aftonian time and subsequently dissected by modern streams. Map 6 of Appendix B shows a thickness of the present alluvial cover. Most of the alluvial thickness can be attributed to the Rocky Flats Alluvium; however, the thicknesses of the colluvium and modern valley fill are also included.

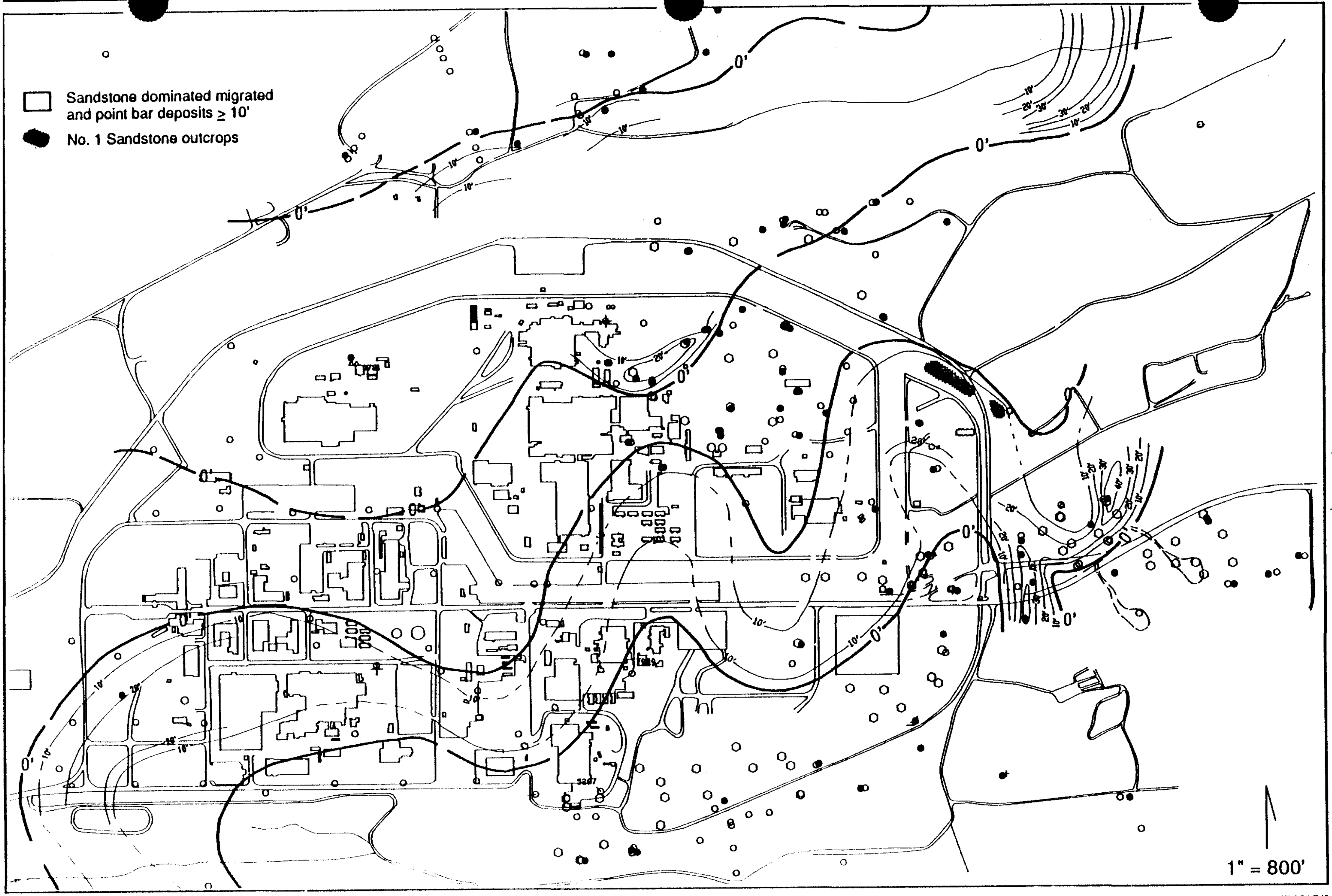
The Pre-Wisconsin pediment was not a featureless planar surface but rather an erosional surface that was cut by a well-developed network of west- to east-flowing stream drainages. These drainages appear to have had as much as 30 feet of cross-section relief



GENERALIZED ISOPACH OF ARAPAHOE SANDSTONE NO. 1
INTERPRETATION 1

GEOLOGIC CHARACTERIZATION
ROCKY FLATS PLANT
EG&G GOLDEN, COLORADO
FIGURE 14

FIG14BOR.DRW



GENERALIZED ISOPACH OF ARAPAHOE SANDSTONE NO. 1
INTERPRETATION 2

GEOLOGIC CHARACTERIZATION
ROCKY FLATS PLANT
EG&G GOLDEN, COLORADO
FIGURE 15

FIG15ROR.DRW

in their headwaters west of the Plant (Map 5). A borehole-controlled Pre-Wisconsin erosional high extends from the western to the central portion of the Plant interfluve. Similar erosional highs may also be present in the western portions of the North and South interfluves (Map 5).

Pre-Wisconsin stream drainages may have existed in the areas between the modern erosional highs. Though not proven, it is possible that the present stream drainages are controlled by the Pre-Wisconsin pediment topography. The following is a possible sequence of events for the development of the modern drainage system. Westward headward erosion occurred along the entire eastern margin of the Rocky Flats Alluvium. Eventually, enough Rocky Flats Alluvium was removed so that the Pre-Wisconsin pediment highs were exposed. Further erosion tended to proceed in the less resistant Rocky Flats Alluvium filling the Pre-Wisconsin drainages. As headward erosion progressed to the west, the current stream drainages became "locked in" to the Pre-Wisconsin drainages.

In the areas of the Pad 903, Mounds, and East Trenches at RFP, paleochannels of the Arapahoe Sandstone No.1 subcrop beneath the Rocky Flats Alluvium. It appears that these paleochannels formed resistant erosional ridges on the Pre-Wisconsin pediment (Map 5). For example, boreholes in the East Trenches area have revealed that the top of the bedrock is higher where Arapahoe paleochannels are present.

The specific data for these boreholes are given below.

Table 2

Presence or Absence of Arapahoe No. 1 Sandstone in Top of Bedrock

Borehole	Top of Bedrock Arapahoe No. 1 SS Present (feet)	Top of Bedrock Arapahoe No. 1 SS Absent (feet)
25-87BR	5942.4	
39-87BH	5942.4	
43-87BH		5929.3
46-87BH		5925.6

A similar paleochannel erosional high may exist in the area surrounding borehole 26-87, approximately 500 feet to the southeast. An erosional low is oriented from northeast to southwest and is present between the two resistant highs. Previous reports have described the low as an Arapahoe "paleochannel." However, this low is a paleovalley between two Pre-Wisconsin erosional highs (Map 5).

A prominent step in the bedrock surface is shown on all of the east-west cross-sections. The pediment surface drops 30 feet -- from a 5,933-foot elevation in borehole 51-87BH to a 5,903.7-foot elevation in borehole 28-87BR (Map 5). This step may delineate the eastern limit of Arapahoe No. 1 Sandstone or merely the eastern limit of one meander in the No. 1 Sandstone fluvial system. If the latter is true, other meander segments may underlie the Rocky Flats Alluvium further to the east along the Plant interfluve.

4.1.4 Rocky Flats Alluvium

The Rocky Flats Alluvium was deposited on a Pre-Wisconsin Pleistocene pediment during Nebraskan or Aftonian time (Scott 1965, 1975). The alluvium is composed of light brown to dark yellowish-orange, grayish-orange to dark gray, poorly sorted (well-graded), angular to subrounded cobbles, coarse gravel, coarse sand, and gravelly clay with varying amounts of caliche. Generally, it is coarser grained west of the Plant and becomes finer grained toward the east. Since the Rocky Flats Alluvium was deposited on a pediment that has as much as 30 feet of relief (Map 5), the alluvium ranges in thickness from a maximum of 70 to 98 feet in the area of the West Spray field to less than 10 feet in the central portion of the Plant and finally to around 45 feet in the East Trenches area (Map 6, Cross-Section A-A' and Site-Specific Cross-Section A-A'). Bedding is apparent in the alluvium only in the East Trenches area where a gravelly sand has been identified plunging eastward from an elevation of 5,932 feet in borehole 28-87BR to an elevation of 5,920 feet in borehole 31-87BR and finally to an elevation of 5,903 feet in borehole 40-86 (Site Specific Cross-Section A-A').

4.2 Structure

The most conspicuous structural feature of the Rocky Flats area is a monoclinal fold, which formed west of the plant during the Laramide Orogeny. According to Tweto (1975), the fold developed at the juncture where sedimentary rocks contact the Front Range border thrust. During the Miocene and Pliocene, the fold was probably modified by normal faults in the basement. The axial plane of the fold strikes roughly north-south and plunges at approximately 58 degrees to the west near borehole 52-86 in the West Spray field.

The Fox Hills Sandstone and the Laramie Formation, which comprise the west limb of the fold, dip to the east at roughly 50 degrees. The Arapahoe Formation, which forms the east limb of the fold, dips from 1 to 2 degrees to the east (Regional Cross-Section and Cross-Section A-A'). Along the west limb of the fold an angular discordance exists between the Late Cretaceous section and the base of the Quaternary Rocky Flats Alluvium.

4.3 Fractures

Even though a large number of "fractures" have been observed in the cores taken from boreholes at RFP, the fractures have not been described adequately. As a result, their characteristics are not well defined, and both open and healed fractures have been described as deep as 220 feet, for example in borehole B304289.

At present, it is believed that most of the fractures are induced during drilling and that they are not true open fractures because they commonly have slickensides on the fracture faces. The same sample produces similar fracture faces when it is broken by hand. Occasionally, an open fracture located in weathered bedrock below the base of the Rocky Flats Alluvium is filled with caliche ($CaCO3$) that has originated from the extensive evaporation of ground water and subsequent precipitation (See section 4.4).

Healed fractures with bedding offsets of less than one millimeter commonly occur in siltstones and very fine-grained sandstones, and are most easily observed in slabbed core. The fractures generally are less than 1 millimeter wide and are cemented with the same argillaceous cement and matrix material found in the host rock.

4.4 Geomorphologic Effects

The present land surface consists of a regional gravel-covered pediment dissected by east-west trending, small, intermittent streams which have dissected the Rocky Flats Alluvium and the bedrock.

The effects of the landform are:

1. The Rocky Flats Alluvium is breached wherever it is present along the length of the ravines.

2. The Arapahoe No. 1 Sandstone probably crops out in North and South Walnut Creeks at 5,905' - 5,920' (East Trenches area); in North Walnut Creek at 5,960' - 5,965' (Solar Pond area); and possibly in Woman Creek at 5,930 - 5,943' (East

Trenches area) (Maps 2, 2A, 3, 3A, Cross-Sections A-A' and G-G', and Site-Specific Cross-Sections A-A' and G-G').

3. The Arapahoe No. 2 Sandstone crops out in Woman Creek at 5,895' - 5,905' south of Pad 903 and possibly in North Walnut Creek at 5,925' - 5,930' in the Solar Pond area (Cross-Section G-G' and Site-Specific Cross-Section G-G').

4. The Arapahoe Nos. 3 through 5 Sandstones probably crop out in the RFP along stream drainages and in the ravines to the east of their subcrop locations at the west end of the Plant. Specifically:

   a. No. 3 Sandstone may crop out in North Walnut Creek at 5,815' east of well 6-86 and along Woman Creek at 5,850' - 5,900' (from the southern boundary of the Pad 903 to the 881 Hillside) (Map 3 and Cross-Sections B-B', D-D', and G-G', and Site-Specific Cross-Section B-B' and G-G').

   b. No. 4 Sandstone may subcrop beneath the entire series of "A" ponds. It may also crop out in North Walnut Creek at 5,800' east of well 6-86 and in Woman Creek at 5,840' - 5,857' from south of the East Trenches to south of Pad 903 (Map 3, Cross-Sections C-C', and B-B' and Site-Specific Cross-Section B-B').

   c. No. 5 Sandstone probably crops out in Woman Creek at 5,835' - 5,850' south of the Pad 903 area (Map 3, Cross- Sections B-B', and G-G', and Site Specific Cross-Section B-B' and G-G').

4.5 Caliche Mineralization

The amount of caliche mineralization in the interstices of the Rocky Flats Alluvium and the underlying weathered bedrock ranges from 0 to almost 100 percent. Map 7 shows the areas where caliche has been defined as "abundant." In these areas the amount of caliche in the interstices is greater than 25 percent over an interval of 1 to 2 feet. The distribution of caliche is primarily controlled by the alluvium's position east or west of the monoclinal fold axis, located near the West Spray field, and by the thickness of the Rocky Flats Alluvium (Map 6 and Cross-Section A-A').

It is quite possible that in the area west of the monoclinal fold axis water is able to percolate through the alluvium and move in to the subcropping sandstones. These sandstones form an angular discordance with the base of the alluvium that ranges from 49 degrees in borehole 52-86 to 9 degrees in borehole 48-86, 2,100 feet to the east (Regional Cross-Section and Cross-Section A-A'). Immediately below the alluvium in the

Plant area, the Arapahoe Formation dips at only 1 to 2 degrees to the east and is composed of approximately 80 percent claystone and silty claystone and about 20 percent sandstone (Maps 2 and 3). In this area, water is unable to penetrate the claystone and tends to remain in the Rocky Flats Alluvium and Arapahoe Sandstone No. 1. Because the alluvium is much thinner in the central portion of the Plant, the vadose zone ground water is subject to a great amount of surface evaporation and consequently deposits caliche ($CaCO_3$) in the pore spaces. Variations of this action may occur in the other alluvia and terraces found along the flanks of the stream drainages (Map 5).

5.0 HYDROGEOLOGY

5.1 Introduction

The RFP is situated in a regional ground water recharge area. Ground water recharge occurs as infiltration of precipitation, primarily where bedrock outcrops in the western portion of the RFP, along the west limb of the monoclinal fold (Cross-Section A-A'). Recharge also occurs as a result of seepage from streams, ditches, and ponds. At the local level, there are areas of discharge as well as recharge. Ground water discharges in streams and along slopes as seeps. Much of the ground water within the uppermost hydrostratigraphic unit becomes surface water or evaporates as it is discharged from the ground water system at seeps along slopes and in drainage valleys.

5.2 Aquifers

The water table aquifer at the RFP is primarily the unconsolidated alluvial material. It includes the Rocky Flats Alluvium which is present on broad topographic highs and the Valley Fill Alluvium, present in modern stream drainages. In the western portion of the RFP, where the thickness of the alluvial material is greatest, the depth to the water table is 50 to 70 feet below the surface. Although the water table depth is variable, it becomes shallower from west to east as the alluvial material thins (Map 6). In the stream drainages, seeps are common at the base of the Rocky Flats Alluvium at the contact with the claystones of the Arapahoe and Laramie Formations and where individual Arapahoe Formation sandstones crop out.

Generally, the ground water flows along the contact of the unconsolidated material and the Arapahoe Formation claystones in a downgradient direction to the east. The claystones have a low hydraulic conductivity, on the order of 1 x 10-7 centimeters per second (cm/s) (Table 3), effectively constraining much of the flow within the water table aquifer to the alluvial material above the alluvial/bedrock unconformity. Ground water in the sandstone units of the Arapahoe Formation occurs under confined conditions throughout most of the plant site. The exception to this is the occurrence of ground water in the subcropping units beneath the alluvial material. In this situation, the ground water exists under unconfined conditions. The No. 1 Sandstone subcrops frequently throughout the RFP area and therefore acts as an unconfined aquifer for a substantial portion of its occurrence. The lower sandstones of the Arapahoe Formation also subcrop at the unconformity, but in limited areas along valley slopes. The confining layers for the sandstones are the claystones and silty claystones of the Arapahoe Formation. The Arapahoe and the alluvial hydrostratigraphic units at RFP have relatively low hydraulic conductivities (Table 3) and, therefore, are not generally believed to be capable of

Table 3

Comparison of Hydraulic Properties

Source	Formation	Hydraulic Conductivity (cm/s)
Ground Water Assessment Plan Addendum - Draft EG&G, 1990	Valley Fill	9×10^{-5}
	Alluvium	5.3×10^{-4} - 2.1×10^{-5}
	Bedrock	5.4×10^{-7} - 4×10^{-8}
Hydrogeological Characterization of the Rocky Flats Plant, Hydro-Search, 1985.	Alluvium	1×10^{-3}
	Arapahoe Sandstone	4×10^{-5}
	Arapahoe Claystone	3×10^{-7}
Section E Groundwater Protection, Rockwell International, 1986.	Rocky Flats Alluvium	7×10^{-5}
	Walnut Creek Alluvium	3×10^{-5}
	Woman Creek Alluvium	3×10^{-3}
	Arapahoe Sandstone	2×10^{-6}
	Weathered Arapahoe Claystone	5×10^{-7}
	Unweathered Arapahoe Claystone	1×10^{-7}
	Qal (Valley Fill)	2×10^{-4}
.Draft Final Groundwater Protection and Monitoring Plan, EG&G, 1991.	Rocky Flats Alluvium Arapahoe Sandstone #1	6×10^{-5}
	Arapahoe Sandstones #3, 4, 5	10^{-6}
	Basal Arapahoe Sandstone	10^{-6}
	Arapahoe Claystone (Weathered & Unweathered)	10^{-7} - 10^{-8}
RCRA Part B Permit Application Rockwell International, 1988a.	Rocky Flats Alluvium	7×10^{-5}
	Valley Fill	3×10^{-3}
	Arapahoe Formation	2×10^{-6} - 1×10^{-7}
Hydrology Of A Nuclear-Processing Plant Site Hurr, 1976.	Rocky Flats Alluvium	1×10^{-2}
	Valley Fill	NA
	Arapahoe Formation	1×10^{-4}
RCRA Post Closure Care Permit Application Rockwell International, 1988b.	Rocky Flats Alluvium	9×10^{-6} - 4×10^{-8}
	Valley Fill	5×10^{-6}
	Arapahoe Formation	NA

Source: ASI, 1991.

producing economical amounts of water. The hydraulic conductivity of the Rocky Flats Alluvium and the Arapahoe No. 1 Sandstone is 6 x 10-5 cm/s, as set forth in the Draft Final Groundwater Protection and Monitoring Plan, June 13, 1991. The lower Arapahoe sandstones have a hydraulic conductivity of 10 -6 cm/s.

5.3 Uppermost Hydrostratigraphic Unit

A "Water Level Contour Map of the Uppermost Hydrostratigraphic Unit" is presented as Text Reference Maps Nos. 8 and 8A. This water level map was created from water levels measured in wells during the month of April, 1990. The wells do not uniformly penetrate either the alluvial material or the uppermost sandstone and therefore a true potentiometric surface of the water table cannot be generated. Instead, the measured water levels were used to represent the water table during the period of measurement for the uppermost hydrostratigraphic unit. The uppermost hydrostratigraphic unit consists of the alluvial material and the subcropping sandstone, as mentioned above. Where Arapahoe Formation sandstones subcrop beneath the alluvial material, there is a hydraulic connection between the units and the bedrock becomes a part of the water table aquifer. This is apparent in the water levels of adjacent wells. Well No. P207489, open only to the alluvial material, and Well No. P207389, open to both the alluvial material and the sandstone (Text Reference Maps 8 and 8A), both have water levels of 5,976 feet. Other wells, open to only the sandstone which is separated from the alluvial material by a few feet of silty claystone, display water levels consistent with confined conditions. An example of this situation is found in the adjacent wells: Well No. 4386, open only to the alluvial material, and 2387, open only to a sandstone confined by several feet of silty claystone. The water level in Well No. 2387 at 5,760.5 feet is 1-1/2 feet higher than that of the alluvial well, even though the sandstone well is open to a lower elevation.

The existence of a vertical gradient at the RFP is evidenced in the overall decrease in static water levels in monitoring wells with depth, particularly in the deeper sandstone units. This is apparent on the cross-sections of Appendix B depicting the deeper sandstone units.

A number of dry wells occur among the data used for this water level map resulting in anomalously dry areas. There are several conditions which may contribute to these anomalies. In some areas, a thin veneer of alluvial material is underlain by silty claystones of the Arapahoe Formation. Generally this occurs on valley slopes. The second case occurs on slopes as well, but involves a subcropping or outcropping sandstone. The first case may be due to the fact that the claystones have a very low hydraulic conductivity and do not allow infiltration of the ground water. In the second case, the lenticular sandstones act as pathways for ground water to seep to the surface, allowing rapid removal of ground water (See Cross-Section C-C').

The potential for mounding of head under ponds, such as the solar ponds, was not considered in the creation of the water level map resulting in higher apparent gradients. As such the map may be construed to represent a worst case scenario.

6.0 SUMMARY AND CONCLUSIONS

6.1 Reprocessed CSM Seismic Data

Of the 8 CSM seismic lines acquired in 1975 and 1976, only lines 5 and 6 could be reprocessed for this report. As a result of this reprocessing, a west to east thrust fault with a maximum throw of 80 feet was recognized on both lines. This thrust fault and a smaller back-thrust were produced by compressional forces during the Laramide orogeny over 45 million years ago. Additional movement is not expected because the area of the Front Range is presently undergoing extension not compression.

6.2 Geologic Model

6.2.1 Laramie Formation

Based on geophysical logs run in borehole B304289, the Laramie Formation in the RFP area is 792 feet thick and consists of two intervals. The lower Laramie interval is probably 285 feet thick and is comprised of several sandstones, (one of which is 50 feet thick) and numerous coals from 2 to 8 feet thick. The upper Laramie interval is 507 feet thick and is comprised of mostly deltaic silty claystones and siltstones with some distributary fluvial sandstones. The lower 150 feet of the upper Laramie interval contains numerous coals that range from 1 to 3 feet thick.

6.2.2 Arapahoe Formation

The Arapahoe Formation is 150 feet thick and contains mainly claystone and at least five mappable sandstone intervals. Due to their lenticular geometries, the sandstones are not present in all of the boreholes or areas beneath the Plant. No. 1 Sandstone was deposited by a meandering stream under a relatively low gradient. Two interpretations for the deposition of the No. 1 Sandstone are presented. The first interpretation (Maps 2 and 2A) shows No. 1 Sandstone as consisting dominantly of channel-fill deposits restricted, for the most part, to a single channel. The second interpretation (Map 3 and 3A) shows the No. 1 Sandstone as dominantly migrated channel and point bar deposits. In both cases, the individual sandstone geometries are lenticular, and individual sandstones may not be in lateral hydraulic communication. Figures 13, 14, and 15 contrast the two interpretations. Less is known about No. 2 through No. 5 Sandstones; however, it appears that they also were deposited by low gradient meandering streams. Although most of the sandstones of the Arapahoe Formation are relatively fine-grained, conglomerates have been documented in the area of the RFP. Most of the sandstones have median grain size values (D50 values) of between 0.06 and 0.09 mm.

6.2.3 Pre-Wisconsin Pediment

During the Pre-Wisconsin Pleistocene a pediment developed east of the Front Range and was later covered by the Rocky Flats Alluvium in Nebraskan or Aftonian time. For clarity in this report, the erosional remnants of this pediment in the Plant area have been named the North, Plant, and South interfluves.

The Pre-Wisconsin pediment appears to have been cut by a well-developed network of west to east stream drainages that had as much as 30 feet of relief in their headwaters to the west of the Plant. An erosional high extends from the western to the central portion of the Plant interfluve. Similar erosional highs may also be present in the western portions of the North and South interfluves.

It is possible that the positions of modern drainage locations were determined the by pediment paleodrainages.

Along the central portion of the Plant interfluve, paleochannels of Arapahoe No. 1 Sandstone form resistant ridges. In the East Trenches area, the pediment is as much as 10 to 12 feet higher in areas where the paleochannels are located at the pediment surface than in areas where they are absent.

The resistant high in the area surrounding borehole 26-87 may be a remnant of Arapahoe No. 1 Sandstone. The step down of the pediment (top of bedrock) to the east may indicate the eastern limit of the No. 1 Sandstone or merely the eastern limit of a meander located in the East Trenches area. If the latter is true, other No. 1 Sandstone meander segments may underlie the Rocky Flats Alluvium further to the east along the Plant interfluve.

The low between boreholes 25-87BR and 26-87 is not an Arapahoe "paleochannel." It appears to be an erosional valley which lies between two Arapahoe Sandstone No. 1 erosional remnants.

6.2.4 Rocky Flats Alluvium

The Rocky Flats Alluvium was deposited on a Pre-Wisconsin Pleistocene pediment during Nebraskan or Aftonian time. The Rocky Flats Alluvium is composed of varying colors of yellowish-orange, brown, and gray, and consists of poorly sorted, angular to subrounded cobblely gravel, gravelly sand, and gravelly clay with varying amounts of caliche. Generally, it is coarser grained west of the Plant and becomes finer grained toward the east. It ranges in thickness from 70 to 98 feet in the area west of the Plant to less than 10 feet in the center of the Plant, and finally to around 45 feet in the East Trenches area.

The East Trenches area was the only location in which bedding could be identified in the Alluvium.

6.3 Structure

A monoclinal fold is present in the western part of the RFP. The Fox Hills Sandstone and the Laramie Formation, which comprise the west limb of the fold, dip at roughly 50 degrees to the east; while the Arapahoe Formation, which comprises the east limb of the monocline, dips from 1 to 2 degrees to the east.

6.4 Fractures

Both open and healed "fractures" have been observed as deep as 220 feet. Fractures that have been described as open are believed to be induced during drilling. Similar fractures with slickensides on the fracture faces in claystones and siltstones are produced when core samples are broken by hand. Healed fractures commonly occur in siltstones and very fine-grained sandstones and have less than 1 millimeter of bedding offset. The fractures are generally less than 1 millimeter wide and are cemented with the same argillaceous cement and matrix material found in the host rock.

6.5 Geomorphologic Effects

The present land surface consists of a regional gravel-covered pediment dissected by east-west trending, small, intermittent streams, which have dissected the Rocky Flats Alluvium and the bedrock. The geomorphologic effects are:

1. The Rocky Flats Alluvium is breached wherever it is present along the ravines.

2. The Arapahoe No. 1 Sandstone probably crops out in North and South Walnut Creeks and possibly in Woman Creek.

3. The Arapahoe No. 2 Sandstone crops out in Woman Creek and possibly in North Walnut Creek.

4. The Arapahoe Nos. 3 through 5 Sandstones crop out in the ravines to the east of their subcrop locations at the west end of the Plant. Specifically:

    a. Nos. 3 and 4 Sandstones crop out in North and South Walnut Creek and Woman Creek. In addition, No. 4 Sandstone may also subcrop beneath the entire series of "A" Ponds.

b. No. 5 Sandstone crops out in Woman Creek and possibly in South Walnut Creek.

5. The Laramie Sandstones and the Fox Hills Sandstone appear to crop out only up-dip to the west of the Plant. A portion of the area underlies the West Spray field. East of this location these sandstones remain in the subsurface and pass under the RFP and into the Denver basin.

6.6 Caliche Mineralization

The distribution of caliche mineralization is primarily controlled by the alluvium's position east or west of the monoclinal fold axis. In the area west of the fold axis, water is able to percolate through the alluvium and move into the discordant subcropping sandstones. In the Plant area, the Arapahoe Formation dips at only 1 or 2 degrees to the east. In this area, water is unable to penetrate the claystone and tends to remain in the thin Rocky Flats Alluvium and Arapahoe No. 1 Sandstone. Because of this, the water is subject to a great amount of surface evaporation and as a result caliche (CaCO3) is deposited in the pore spaces. The presence of caliche mineralization may turn out to be a useful method to determine the general direction of ground water flow.

6.7 Hydrogeology

The RFP is located in a ground water recharge area. Ground water recharge occurs as infiltration of precipitation and as seepage from streams, ditches and ponds. The water table aquifer is primarily unconsolidated alluvial material. Where Arapahoe Formation sandstones subcrop beneath the alluvial material they are in hydraulic connection with the water table aquifer, and in these limited areas become a part of the uppermost hydrostratigraphic unit. Elsewhere, the sandstones exist as confined aquifers isolated by the relatively impermeable Arapahoe Formation claystones. These aquifers, including the water table aquifer, have relatively low hydraulic conductivities and are not capable of producing economic amounts of water.

Generally, ground water flow is toward the east. Much of the ground water within the uppermost hydrostratigraphic unit becomes surface water as it leaves the ground water system as seeps along slopes and in stream drainages.

7.0 RECOMMENDATIONS

Items 7.1 through 7.3 have been incorporated either totally or in part within the Phase II Geologic Characterization or the Operable Unit remedial investigations at RFP.

7.1 Drilling Recommendations

7.1.1 Drill two basal Arapahoe wells to an elevation of 5,800 feet above mean sea level (MSL), one to the north and one to the south of borehole 48-86 along the eastern edge of the West Spray field. These wells would be used to further characterize and monitor the Arapahoe and Upper Laramie Sandstones.

7.1.2 Drill a series of Arapahoe No. 1 Sandstone boreholes in order to define sandstone geometrics.

7.1.3 Drill at least three Arapahoe No. 2 Sandstone boreholes in order to define the aerial extent of No. 2 Sandstone in the 881 Hillside and Pad 903 areas.

7.1.4 Drill a series of Arapahoe No. 3 Sandstone boreholes in order to define the limits of the channel sands which are shown on Map No. 4.

7.1.5 Drill a series of Arapahoe No. 4 Sandstone boreholes in order to define the limits of the channel sands, which are shown on Map No. 4, and specifically to determine if No. 4 Sandstone is present under the "A" series of ponds.

7.1.6 Drill at least three Arapahoe No. 5 Sandstone boreholes in order to define the aerial extent of No. 5 Sandstone in the 62-86 and 14-87BR borehole areas. The above borehole locations should be determined with the input of the RFP staff.

7.2 Seismic Recommendations

7.2.1 A combined program of high-resolution shallow seismic (reflection) and boreholes should be made in the west buffer portion of the Plant in order to determine the geomorphologic character of the Pre-Wisconsin pediment and the variable thicknesses of the Rocky Flats Alluvium.

7.2.2 A west to east seismic (reflection) line should be acquired (shot) from west of the Livingston shear zone to east of the RFP. The line should be designed for deep information from below a depth of 600 feet to

Precambrian basement in order to determine if there are any unknown subsurface faults in the RFP area.

7.3 Surface Mapping Recommendation

7.3.1 Map the surface geology within two miles of the outer RFP boundary. This has never been done, but the effort should supply a great deal of regional structural information at an extremely low cost.

8.0 REFERENCES

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Note: All other references cited in this report may be found in the attached annotated Bibliography.

PLATE 1B

B304289
37-89BR 5/11/89

B304289

PLATE 1A

37-89BR 5/11/89

GUARD RESIS. 0 O-M 250

NAT. GAMMA 0 CPS 200

NEUTRON 1000 CPS 6000

NAT. GAMMA 0 CPS 200

NEUTRON 1000 CPS 6000

GUARD RESIS. 0 O-M 250

37-89BR 5/11/89