CLAY MINERALS OF THE FRONT RANGE: A FIELD GUIDE TO THE GEOLOGY, HISTORY, AND CLAY MINERALOGY OF THE CHIEFTAIN MINE, DINOSAUR RIDGE, PATCH MINE, AND OTHER LOCALITIES ALONG THE FRONT RANGE FROM DENVER TO BOULDER, COLORADO

Clay Minerals Society 39th Annual Meeting and Field Trip, June 13, 2002

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5. Visit to the Patch ("Glory Hole") open pit mine; geological and historical overview of gold mining operations with clay mineralogy sidelight.

6. Return to Boulder via Highway 119 through Nederland and Boulder Canyon.

INTRODUCTION

This field guide is intended to provide a historical, geological, and mineralogical overview of the route from Boulder to Golden along Colorado highway 93; emphasis is given to the Chieftain clay mine and the Dinosaur Ridge localities in or near the prominent hogback that parallels the foothills west of the plains, and to the historic mining districts of Idaho Springs and Central City. The return is via the Peak-to-Peak highway through Nederland.

Clays are ubiquitous along the Front Range of Colorado, and their mineralogy and economic importance along the field trip route will be highlighted where appropriate. Geologically, this diverse region varies from Tertiary sediments to Precambrian metamorphic rocks, and hosts a variety of clay minerals. Many of these find economic use for the manufacture of brick, pottery, fire brick (refractory fire clays), and ceramics. Clay minerals are also important associates in ore deposits, where they can occur as a substantial constituent in hydrothermal veins as well as an alteration product in wall rocks.

Beyond the positive economic significance of the state's clay mining operations, clays have had a negative impact as well, in the form of expansive soils that can adversely affect homebuilding by causing substantial structural damage. These expansive soils are popularly known as bentonite, which is largely composed of smectite clays (principally montmorillonite) that are diagenetically formed from airborne volcanic ash falls. Expansive soils are prevalent throughout populated suburban areas along the Colorado Front Range, including Douglas, Arapahoe, Jefferson, Boulder, and Larimer counties. They occur interstratified with Cretaceous shales and younger sedimentary rocks that are adjacent to the foothills (Eckel, 1997), e.g., the Pierre Shale, and the Laramie, Dawson, and Denver-Arapahoe formations (Hart, 1974). Significant damage to buildings and highways from Pueblo to Boulder has been documented by Hart (1974), although improvements in building methods, enforcement of building codes, and required monitoring for expansive soils over the past 20 years have attenuated this impact.

Geologic observations were made in this area as early as 1869 by members of the Hayden Survey (Hayden, 1869), but the earliest comprehensive survey of the region was made by Emmons and others (1896). More recent studies documenting the local stratigraphy and geology were made by Waldschmidt (1939), LeRoy (1946), Van Horn (1976), Reichert (1954), Waagé (1961), and Weimer (1996).

Field trip stops are shown in all upper-case letters in the "Field Trip Guide" section of this report, whereas points of interest and other noteworthy landmarks along the way are in lower-case letters. Mileages from Boulder are given in Appendix I for these stops and other areas of interest.

ACKNOWLEDGEMENTS

Mike Leidik and Jason McGraw (Robinson Brick Co.) provided information on the geology and mining operations of the Chieftain mine, and arranged for the site visit. Chip Parfet supplied information regarding the Rubey and Rockwell mines, and kindly gave a tour of his operations there.

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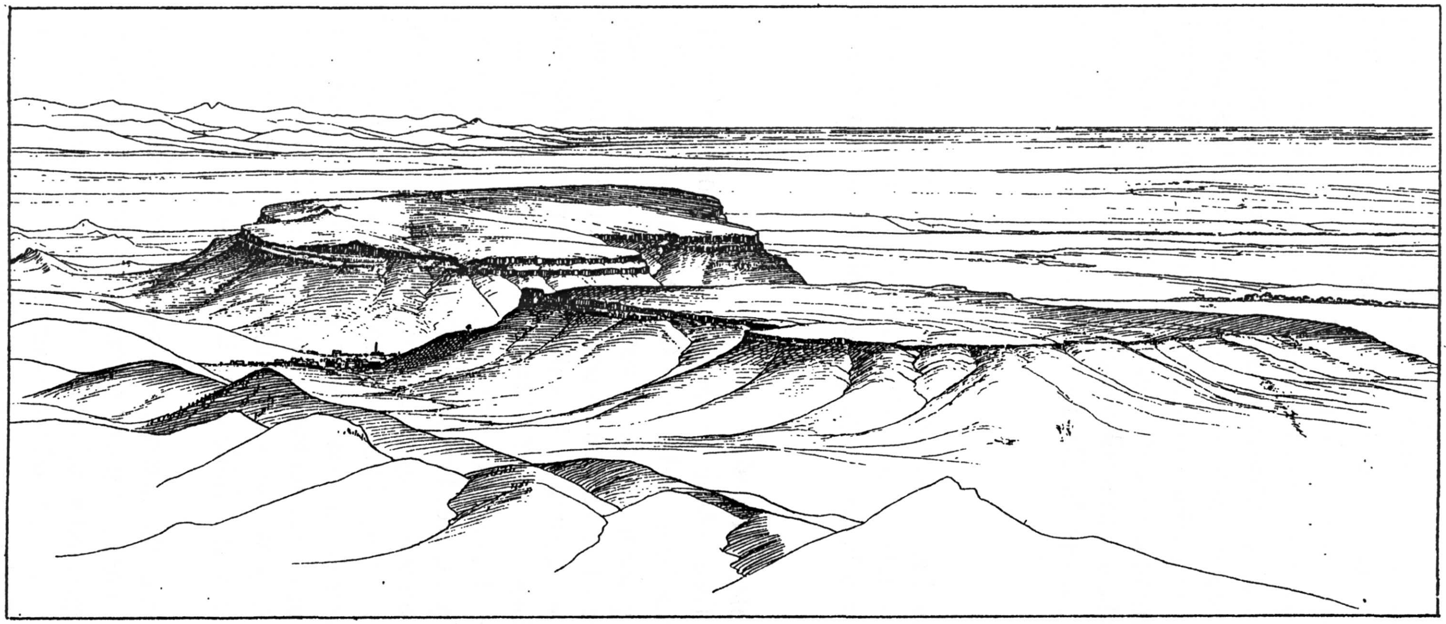
FIELD TRIP GUIDE

Boulder Flatirons
These upturned rocks are composed of the Pennsylvanian- to Permian Fountain Formation, and form the spectacular backdrop west of Boulder. The Fountain Formation sediments are nonmarine and were derived from erosion of the ancestral Rocky Mountains. The sediments consist of reddish-brown to yellowish-gray arkosic sandstones, shales, micaceous siltstones, and quartzose conglomerates whose distinctive hue is due to the presence of a pink microcline and iron oxides; the grains are cemented by iron oxides and silica (resulting in an erosion-resistant rock) or calcite (an easily eroded rock). This formation extends along the Front Range foothills, from Boulder to the Red Rocks Amphitheater (described below), and to Colorado Springs about 90 miles to the south of Denver, where the Garden of the Gods offers equally impressive scenery.

Ralston Dike
Ralston dike is presumed to be the source for the Table Mountain lava flows because of its similarity in age, given by Scott (1972) as 63 ± 2.7 million years (Ma), and petrography, with the shoshonite capping the Table Mountains (see below).

North and South Table Mountain
The North and South Table Mountains are flat-topped mesas (fig. 1) that lie conspicuously to the northeast and east of Golden; they are a result of a lava cap that protects the underlying sediments from erosion. The mesas are bisected by Clear Creek; the world-famous Coors Brewery and a porcelain manufacturing plant (formerly owned by the Coors family) are located in the valley between the Table Mountains. Two Tertiary lava flows, dated at about 63 Ma (Scott, 1972), form the cap of the Table Mountains, while a third, less extensive flow, crops out in sediments of the late Cretaceous- to Tertiary Denver Formation about 150 feet below the cap. The flows, associated with the Laramide orogeny, are composed of a potassic basalt known as shoshonite (Van Horn, 1976). The Cretaceous-Tertiary (K-T) boundary is located within sediments of the Denver Formation, approximately 197 feet below an outcrop of the first (earliest) lava flow that is seen on the south side of North Table Mountain, above Colorado Highway 58. R.W. Brown identified the K-T boundary in 1939 based on fossil-bearing strata on South Table Mountain (Brown, 1943).

The Denver Formation is characterized by poorly consolidated sandstones, claystones and conglomerates that are composed primarily of altered andesitic debris. The clastic Denver sediments, deposited as alluvial fans, were derived from eastward-flowing streams carrying volcanic material that originated west and northwest of Golden. Dinosaur remains of *Triceratops* have been found in Denver sediments on the slopes of South Table Mountain, and poorly silicified petrified wood is locally abundant on the slopes of North Table Mountain. Fossilized plant leaves and twigs, representing about



Golden City and the Table Mountains, viewed from a point six miles south. WM. H. HOLMES.

Figure 1. The Table Mountains and Golden (from Marvine, 1874)

225 species, have been recorded from localities on the south side of South Table Mountain (Knowlton, 1930).

Several rock quarries are located within the lava flows; stone mined from these quarries was used for paving blocks for street surfacing in early downtown Denver, for crushed rock for concrete aggregate and railroad ballast, and also for ornamental, monument, and building stone. The riprap for the Cherry Creek Dam near southeast Denver was provided in 1948 and 1949 by the Wunderlich quarry located on South Table Mountain. A quarry on the southern end of North Table Mountain has been a source of mineral specimens.

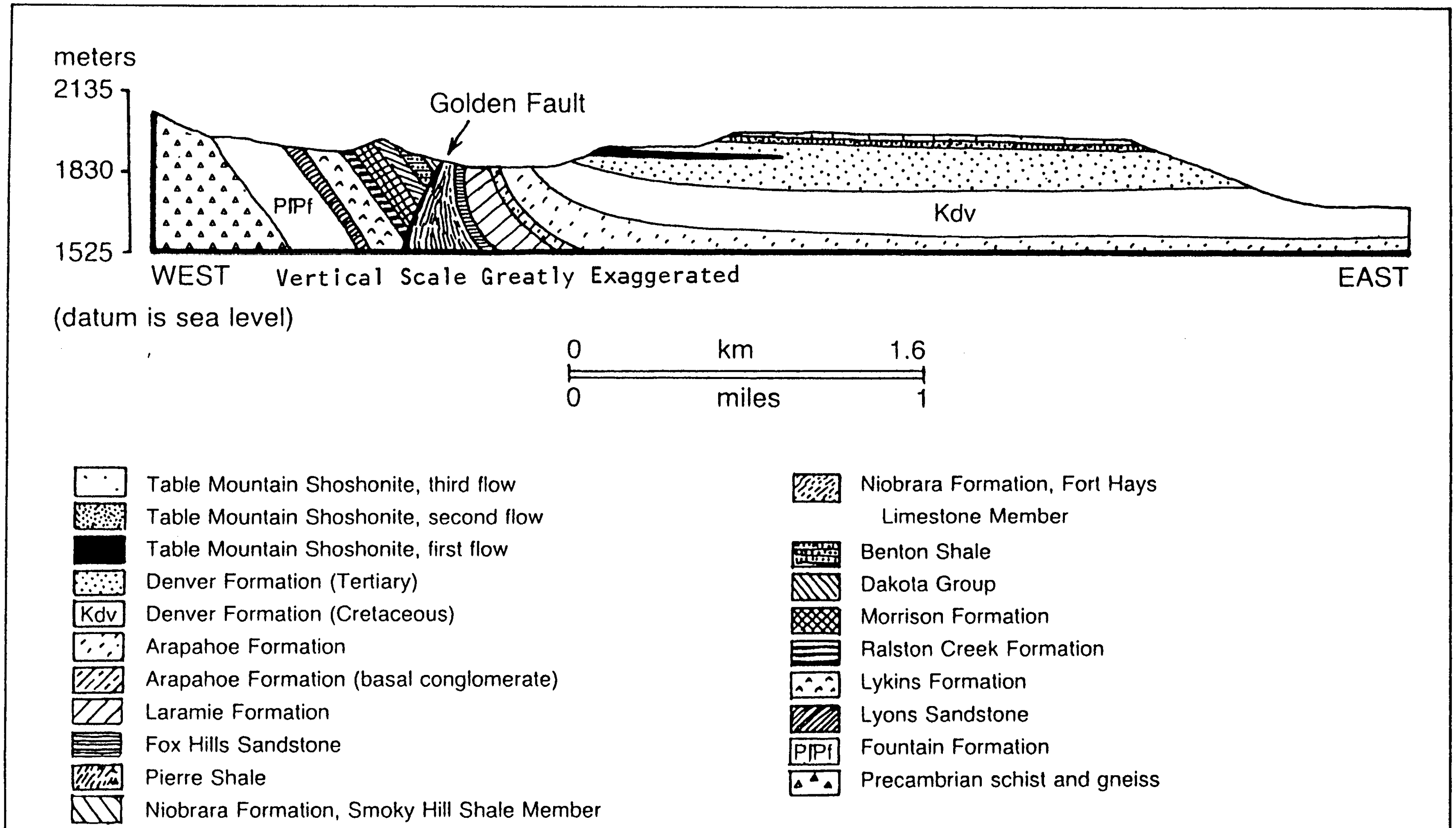
The Table Mountains are mineralogically an important locality, being noted as early as 1882 (Cross and Hillebrand, 1882, 1885) for zeolite and related minerals that occur in vesicular cavities localized in the upper one-third of the second capping flow (fig. 2). Perhaps most noteworthy of the minerals are the various habits of thomsonite of a quality seldom found elsewhere in the world. Analcime, calcite, chabazite, fluorapophyllite, mesolite, natrolite, and stilbite are among the more conspicuous species here, while cowlesite, garronite, gonnardite, laumontite, levyne, and offretite are some of the rare and less easily discernable minerals. Vesicles are commonly partly filled with a smectite-group clay mineral (Kile and Modreski, 1988a), and nontronite was reported as an alteration of phenocrysts in the lava (shoshonite) on South Table Mountain (Schlocker, 1947).

Further information on the mineralogy of the Table Mountains and the area geology is given by Patton (1900), Van Tuyl and others (1938), Waldschmidt (1939), Van Horn (1976), and Kile and Modreski (1988a). A geologic section for North Table Mountain and stratigraphy in the Golden area are shown in figures 3 and 4, respectively. Parts of North Table Mountain have recently been incorporated into the Jefferson County Open Space system, and most activities, including mineral collecting, are now prohibited or limited. Minerals from this locality can be seen at the Colorado School of Mines Geology Museum in Golden.

The Clay Industry in Colorado

The Laramie Formation near Golden has yielded enormous quantities of a variety of clays (Butler, 1914). The Laramie clayrocks, however, provide largely non-refractory (i.e., low melting temperature) clays. Refractory clays (i.e., high-melting point clays as used for high-temperature fire brick, ceramics, etc.) are mostly found in the Dakota Group, also known as the Dakota Formation or Dakota Sandstone. The Dakota Group is composed of the Lytle Formation, a light-gray to white sandstone interbedded with claystone, and the overlying South Platte Formation, composed of brown-weathering sandstone and dark-gray clay shale and siltstone. The highly refractory clays are found principally in the uppermost South Platte Formation (Waagé, 1961), where they occur in beds of carbonaceous fire clays in compact sandstones.

Figure 2. Zeolite-bearing cavity in shoshonite at North Table Mountain.
Cavity contains calcite, thomsonite, mesolite, chabazite, and analcime.



Geologic section of the North Table Mountain area (adapted from Van Horn, 1957).

Figure 3. Geologic section of the North Table Mountain area (Kile & Modreski, 1988a)

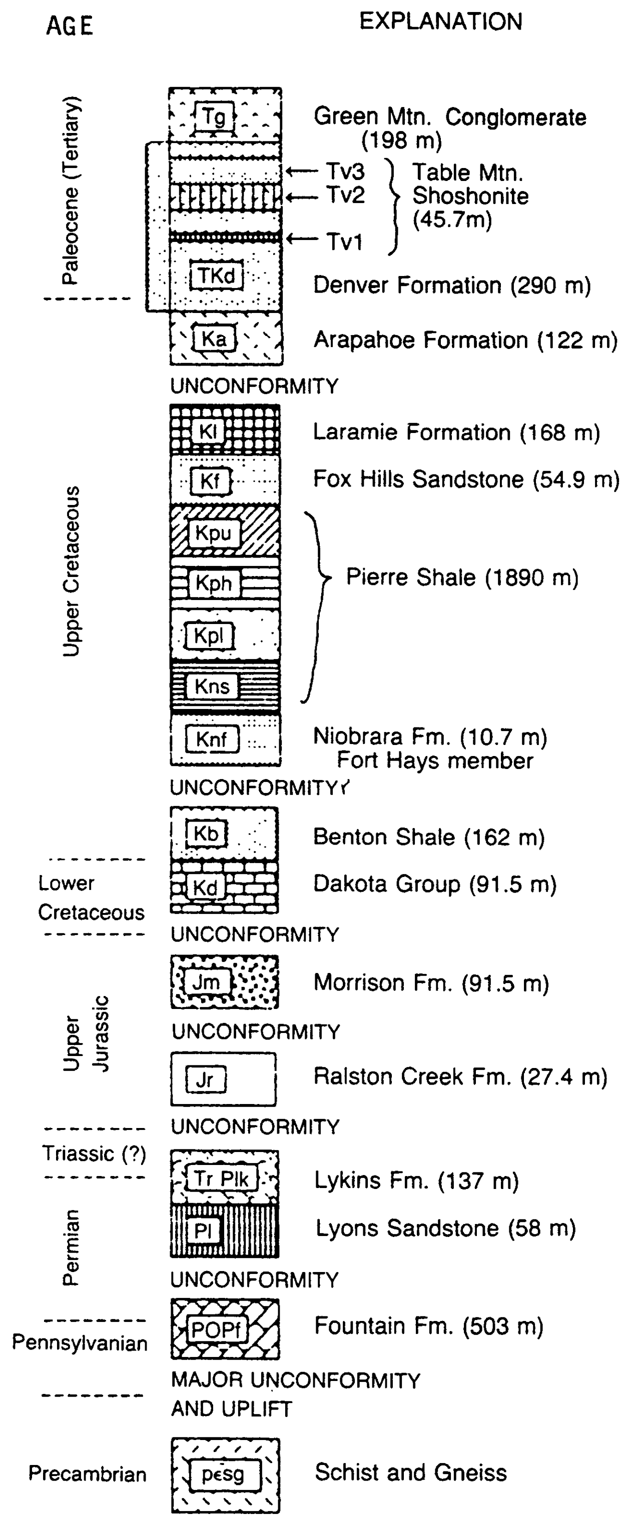


Figure 4. **Stratigraphy in the Golden area. Formation thickness given in meters (adapted from Scott, 1972, and Van Horn, 1976).**

Waagé (1961) gives a concise history of the production of refractory clays in Colorado. Early mining history of clays is not well documented, which is likely due to a relative lack of glamour as compared to precious metals mining and to a much smaller economic impact as compared to coal and iron. The first production in Colorado of refractory clayrock was in Golden during the late 1880's, although Ries and Leighton (1909) note that "Dakota fire clays were mined here [the Golden area] as early as 1864 or 1865". The use of fire clay by a brick works in Golden was mentioned by Hollister (1867), and Berthoud (1880) records a brewery and fire-brick works being erected at Golden in 1867. By the 1870's an extensive industry of fire brick and pottery manufacture had developed in the Golden area. By 1895 notable Denver area brick manufacturers such as the Golden Fire Brick Co. and the Denver Fire Clay Co. were established, utilizing clays mined from the Dakota Group from hogbacks north and south of Golden.

Sources of refractory clayrock other than those at Golden were not exploited until the mid-1880's. Near the turn of the century clays were being mined in Douglas County and near Cañon City, and by the early 1900's clays were being mined in the Dawson Arkose near Calhan in El Paso County, and in the Dakota Group at Turkey Creek in Pueblo County. Since 1910 the dominance of refractory clay production in the Golden area has been overshadowed by clay mining activity in the Arkansas River valley area. As of 1961 the easily mined refractory clays had been exhausted in the Golden area.

The usual source for clay is shale, which is essentially indurated clay. Ordinary shale requires weathering to render it to a usable plastic clay, whereas clay-shales that have not undergone substantive hardening are readily usable. The clay industry in eastern Colorado has largely been for the brick-making industry, which is among the oldest enterprises in Colorado. Hard, dense building brick requires high furnace temperatures, whereas common, soft, porous brick requires only moderate furnace temperatures. Soft bricks can be made with ordinary clays that are available almost anywhere, but most such clay in eastern Colorado has little or no economic value. To be of use in the brick-making industry or as pottery, the clay must be plastic when wet in order to permit molding, and it must not shrink when hardened in a furnace or kiln. Deposits must be easily accessible, as low values for the raw product do not permit excessive mining and transportation costs. Only the better grades of refractory clays and china clays realize sufficient value to warrant shipping to distant markets. In 1941, Colorado producers of fire clay reported a value of $143,000 for 85,000 short tons (Vanderwilt and others, 1947), which translates to about 8 ¢ per pound.

Refractory clays (also known as fire clays) have been defined, by a "viscosity" test, as withstanding temperatures of 1670 °C, measured in the early 1900's by using a Seger cone # 27; these are pyramidal objects composed of varying proportions of quartz, kaolin, feldspar, etc., and which melt at specific temperatures in a kiln or furnace (Butler, 1914). Fire clays are usually predominantly a kaolinitic material (i.e., a clayrock containing a high percent of Al_2O_3) and are much less widely distributed than are clays suitable for ordinary brick making. The most important deposits are found in a black shale zone in the Dakota Group near Golden, Colorado Springs, and Cañon City, among other localities where the formation is exposed. Fire clays of intermediate grades are found locally in the Laramie Formation.

Uses of clay products from eastern Colorado (abstracted from Butler, 1914):

- Soft, stiff, dry-pressed, semi-dry pressed, and flashed-bricks
- Earthenware clay
- Yellow and Rockingham ware clay
- Stoneware, white-ware, porcelain (China) clay
- Ball, drain-tile, and sewer-pipe clay;
- Roofing tile clay
- Refractory-goods clay (fire clay) for crucibles, scorifiers, muffles, fire brick, furnace and stove linings, retorts, insulators, etc.
- Terra-Cotta clay
- Paving-brick clay
- Floor- and wall-tile clay
- Enameled-brick clays
- Slip or glaze clay
- Ballast clay
- Portland-cement clay

"Non-burned" clays also find uses, such as:

- Paper fillers
- Fuller's earth absorbent
- Polishing powders and abrasive materials
- Ultramarine clay (a very fine-grained, white clay)
- Adobe (a mixture of clay and straw)
- Food additives (!)
- Medical plasters
- Assorted manufacturing processes, such as for alum

Rubey and Rockwell mines, Golden, Colorado

The brick manufacturing industry is among the oldest in Colorado, and the Rubey and Rockwell mines are the oldest clay mines in the state, having been operated since 1877 (oral commun., Chip Parfet, 2001). Clay from these mines has been used in the brick- and pipe-making industries. The mines are located essentially within the city limits of Golden, and lie mostly within the Upper Cretaceous Laramie Formation. The Laramie Formation is composed of a series of interbedded gray to buff or white quartzose and massive sandstones, in addition to clays, sandy shales, carbonaceous claystones, and lenticular coal seams, some of which are economically minable. A complete section of the Laramie Formation was noted in this mine by LeRoy (1946), who called it the Parfet mine and described the formation as 582 feet thick. These mines were active through August 2001, and are now being converted to a golf course by the city of Golden.

Cretaceous dinosaur footprints (hadrosaur, theropod, and ceratopsian tracks) are found in the Golden area in the Laramie Formation (Lockley, 1988), as well as tracks of

Triceratops. Numerous fossil leaves and plant fragments have been also noted in this formation; exceptional palm fronds are exposed on the walls of the Rubey and Rockwell mines, and are being preserved as part of the golf course.

A sample analyzed by X-ray diffraction (XRD) from the Rubey mine [< 2-micron (μ) fraction, fig. 5] shows illite, kaolinite and smectite; quantitative XRD analysis (whole-rock sample) shows 38 percent illite, 13 percent disordered kaolinite, and 11 percent ferruginous smectite, in addition to 39 percent quartz.

CHIEFTAIN MINE

The Chieftain mine, owned by the Robinson Brick Company, is an operating clay mine located in Upper Cretaceous bedded sediments. Figure 6 shows the location of this mine, Dinosaur Ridge, and Red Rocks Park, discussed below. Clays are mined here for use in the brick-making industry, the Robinson Brick Company having started operations in Denver in 1880 (fig. 7). In the southernmost part of the mine (south of Alameda Parkway), the Fox Hills Formation, a light buff to yellowish or yellowish brown, sandy, medium-grained sandstone, and light gray to gray interstratified clay shales and silty, arenaceous shales, and the Laramie Formation, a gray to white sandstone interbedded with clay lenses and thin coal seams, are exposed. The northern part of the Chieftain mine shows only sediments of the Laramie Formation. The Fox Hills Formation shows intermittent clay veins; the lower Laramie Formation in the southern Chieftain mine is about 100 feet wide, and the mined layer of the upper Laramie is about 100-125 feet wide. The upper and lower Laramie strata are separated by 20-30 feet of sandstone with clay lenses and stringers; downdip the Laramie shows a trend toward higher amounts of coal and sandstone. These beds show a dip of about 75-80° (Jason McGraw, Robinson Brick Co., oral Commun., 2002).

The lower Laramie Formation provides "buff-firing" clays, whereas the upper part of the formation provides a "red-firing" clay. The "firing" (or "burning") color of the clay is not necessarily related to the color of a particular sediment sample; consequently, it is the results of fired test samples that determine which zone within a bed is mined. Sediments of the Laramie Formation fire at temperatures of about 2000-2200 °F. (i.e., a Seger cone # 7), whereas clays mined from formations to the east (e.g., the Arapahoe Formation) or west (e.g., the Pierre Shale) of the Laramie are of a lower quality for brick making. The Arapahoe sediments fire at temperatures of 1700-1800 °F., whereas the Pierre Shale fires at only 800 °F. (Jason McGraw, Robinson Brick Co., oral Commun., 2002). Elsewhere along the Front range, clayrocks of the Dakota Group (sandstones, claystone and shales of the Cretaceous Lytle and South Platte formations) serve as the most important commercial source of refractory clays (Waagé, 1961). Clays from the Dakota Group, containing as much as 80-90 percent kaolinite, fire at temperatures as high as 4000-5000 °F., and are used as a "white-burning" clay that lightens brick color. Robinson Brick Company also mines clays from shales of the Dakota Group near Pueblo and Fort Carson (both located south of Colorado Springs), and the Dawson Arkose near the town of

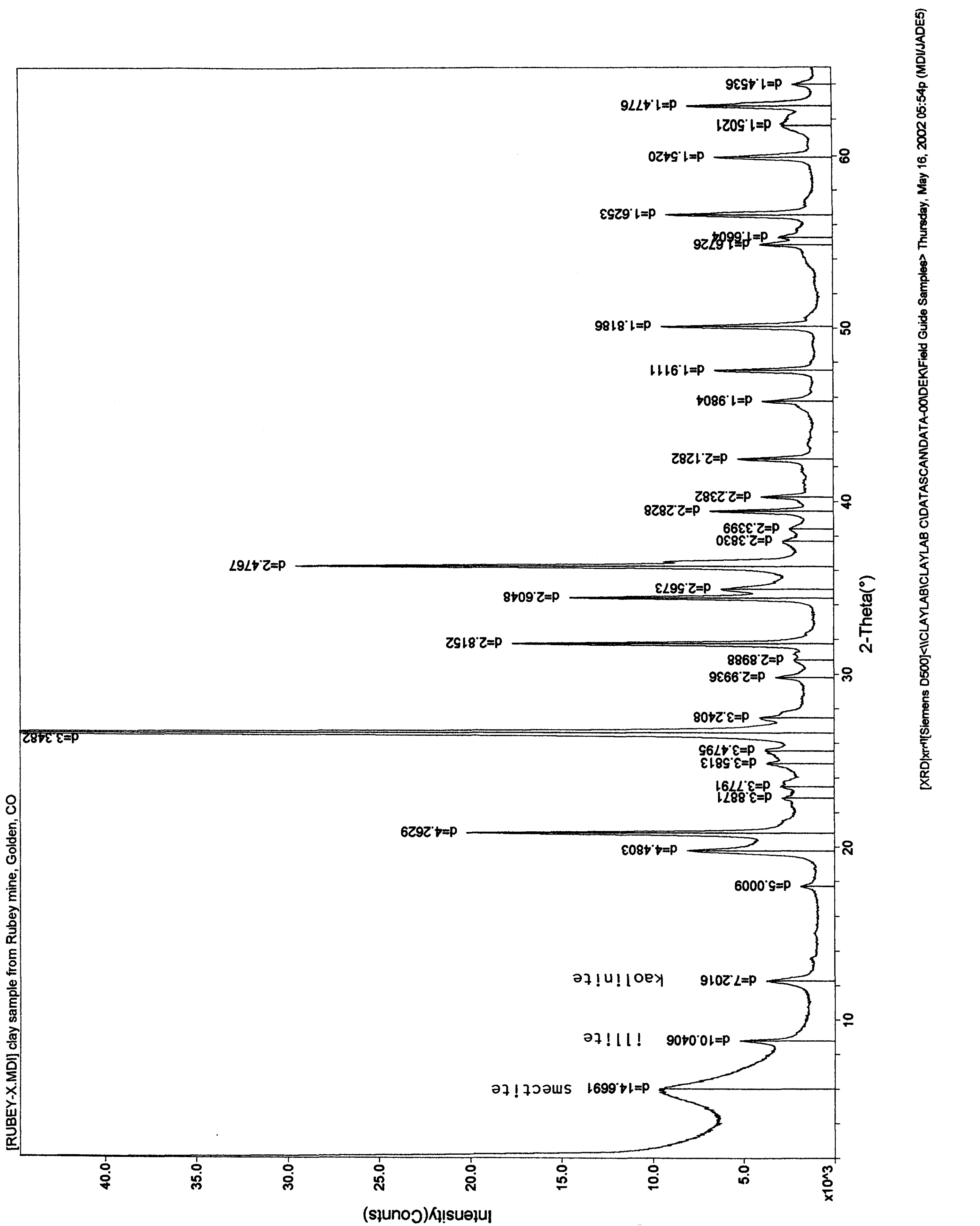


Figure 5. X-ray diffraction pattern of clay sample from the Rubey mine, Golden; first-order peaks are identified.

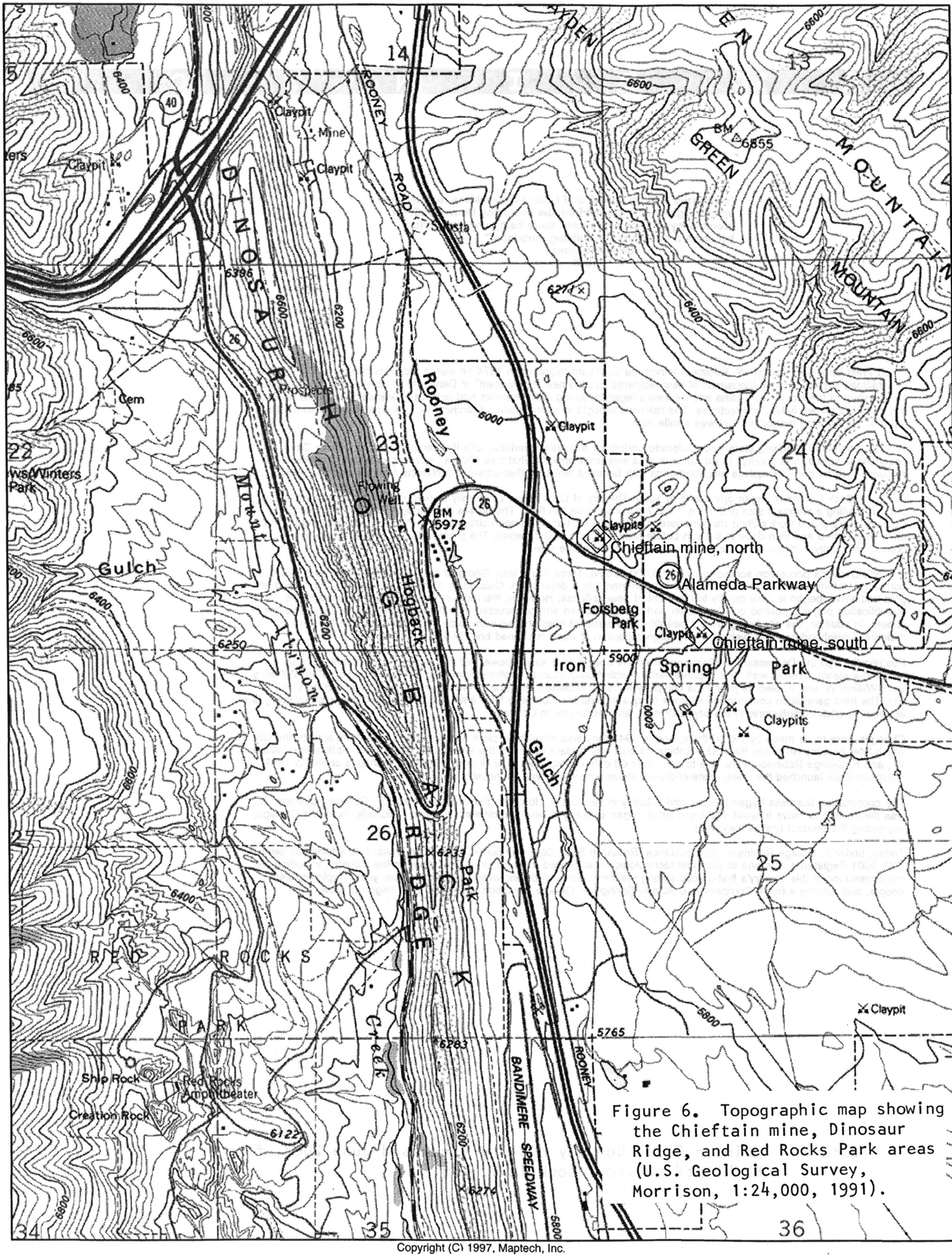


Figure 6. Topographic map showing the Chieftain mine, Dinosaur Ridge, and Red Rocks Park areas (U.S. Geological Survey, Morrison, 1:24,000, 1991).

R O B I N S O N

"Gold gave birth to Denver and funded the reckless rush to grow up into a great city. Almost from the beginning Denver built for prominency in brick and stone...there being no wood, brick becomes a necessity for building purposes."
Demas Barnes
1865

When West Virginian, George W. Robinson joined the westward migration in 1874 he wasn't alone. Between 1870-1920 the new railroad system brought thousands of new residents into the new "boom-town" of Denver City. Attracted by the majesty and mystery of the Rocky Mountains and westward legends, young entrepreneurs and politicians wished to reap the rewards of Colorado's mines, fields, and factories. The railroads brought in many families searching for new opportunities, which they found in the budding metropolis that was a mile high.

In 1876, soon after reaching statehood, Colorado undertook a cultural overhaul, with the beautification of Denver City becoming a number one priority. The downtown area was transformed! What was once a city ravaged by fire and filled with saloons, became one of exquisite neighborhoods with beautiful buildings that attracted architects from all over the world.

Robinson Brick Company began operations in 1880. The city of Denver had previously passed ordinances outlawing adobe brick, instituting a standard size of 8 ? x 4 ? x 2 ? that had to be kiln fired. The horses that brought the Robinson Family to Colorado were put to work pulling clay scrapers, and George W. turned an open circular mill that mixed clay with water. The brick was formed and then dried in the sun before fired in kilns fueled by wood. The process took 27-30 days, limiting production to only 2 million brick during the six warm months of the year.

In 1890, Denver's population soared to over 106,000 people. Three years later George's son, William B. Robinson, joined the company. Unfortunately that same year Colorado entered into a depression. Colorado's number one industry, the mining of gold and silver, began to slow rapidly to the point of near collapse. However, the morale was not to be shaken and the beautification projects pushed on. Downtown parks were planned and constructed and Denverites began to enjoy tree-lined streets. In addition, the city had gained a beautifully constructed opera house with golden pressed brick, the finest of residential neighborhoods, as well as a very large collection of world renowned brick buildings downtown.

Pushing through the Depression, William converted the operation to steam power, added pressed brick machines, and installed a steam dryer as well. The improvements enabled production to continue through the winter months. When William's sons William W. and F. George joined the company in 1927, Robinson was one of more than 20 brick manufacturers in the city. The third generation continued to improve on quality, and the Company later emerged from those highly competitive years as the only brick manufacturer in the city of Denver, and the largest in Colorado.

Changes were to be made by the brothers, and in 1941 they shut down their plant and donated much of the land to the city, which later became Robinson Park. The Robinsons built a new plant w/ one of the West's first tunnel kilns. At this time William W., and F. George Robinson were able to offer over 60 different varieties of brick and 117 different shapes of tile. In 1959 Robinson Brick launched their new, state-of-the-art showroom, which was an industry first.

The construction business began to slow down rapidly in the 1970's. However, the Chairman's son, F. George Robinson, Jr. was determined to move forward. Robinson Brick began shipping to new and different markets nationally, including Chicago; expanding the product line as they went.

Today, under F. George Robinson, Jr.'s guidance, Robinson Brick Company continues to drive forward. In addition to being ISO: 9001 Registered, it is one of the most technologically advanced manufacturing operations in the industry, including the implementation of this country's first robotic setting machine. While producing over 100 MM brick per year, employing 245 people, and running a Block Company in Colorado Springs, F. George Robinson, Jr. hasn't even begun to slow down.

Figure 7. Robinson Brick Company history (accessed June 2002, from URL http://www.robinsonbrick.com/).

Parker, southeast of the Denver-Metro area; the firing characteristics of these materials are similar to those of the Laramie.

The Robinson brickworks is located in Denver, near Santa Fe and Dartmouth Avenues, where clays are formed, dried and kiln-fired. The Laramie "ores" contain a relatively high percentage of smectite along with kaolinite, with small amounts of illite and a considerable amount of quartz. The presence of smectite gives a desirable "longer firing range" (i.e., its firing characteristics are consistent over a wide temperature range), but it also gives an undesirable drying property, whereby the products are more liable to cracking.

Accordingly, kaolinitic clays from the Dawson Arkose are added to Laramie sediments to give better drying characteristics to this material. As many as 25-30 different clay types are mined and blended to give the desired color and properties of the final product. Activity at this mine is intermittent, with about 100,000 tons being mined mostly in the months of March-April every other year.

XRD patterns (glycolated samples, < 2-μ fraction) for samples 7 (a white sandstone, east side of mine), 8 (a buff sandstone, west side of mine) and 9 (a yellowish-brown siltstone, west side of mine), designated as DR-7, DR-8 and DR-9 on the diffraction patterns, are shown in figs. 8, 9 and 10, respectively. Quartz and K-feldspar are relatively uniform among these samples, ranging from 50-65 percent quartz and 10-24 percent K-feldspar. A sample taken from an "ore" pile from this mine shows mostly smectite (fig. 11). Quantitative XRD data corresponding to samples 7, 8 and 9 (whole-rock samples, designated as FG-7, FG-8, and FG-9) are shown in table 1. These data show that sample 7 (white sandstone) is predominantly smectite, sample 8 (buff sandstone) is principally smectite with 11 percent kaolinite, and sample 9 (yellowish-brown siltstone) is predominantly kaolinite. Quantitative analysis of a pink clay lens (whole-rock sample, results not shown) from the west side of the northernmost mine shows 22 percent illite and 5 percent disordered kaolinite, in addition to 11 percent K-feldspar, 2 percent plagioclase, and 63 percent quartz.

DINOSAUR RIDGE

Dinosaur Ridge lies just north of the town of Morrison (after which the famous dinosaur-bone-bearing beds were named) along upturned Cretaceous and Jurassic sedimentary rocks (fig. 12). The Dakota Hogback is named for the erosion-resistant sandstones of the Dakota Group that comprise a part of the hogback. This site contains a series of stops along Alameda Parkway, the first of which is the Visitor Center where guidebooks, maps, and other information pertaining to the area can be purchased. Dinosaur footprints, ripple marks, trace fossils, and *in situ* fossilized dinosaur bone are among the many attractions here. The area is currently being maintained by the Friends of Dinosaur Ridge, a non-profit organization dedicated to the preservation and educational use of this unique resource. Smith (1964), MacKenzie (1968), and LeRoy and Weimer (1971) provide details of the stratigraphy and geology of the sedimentary rocks in this vicinity;

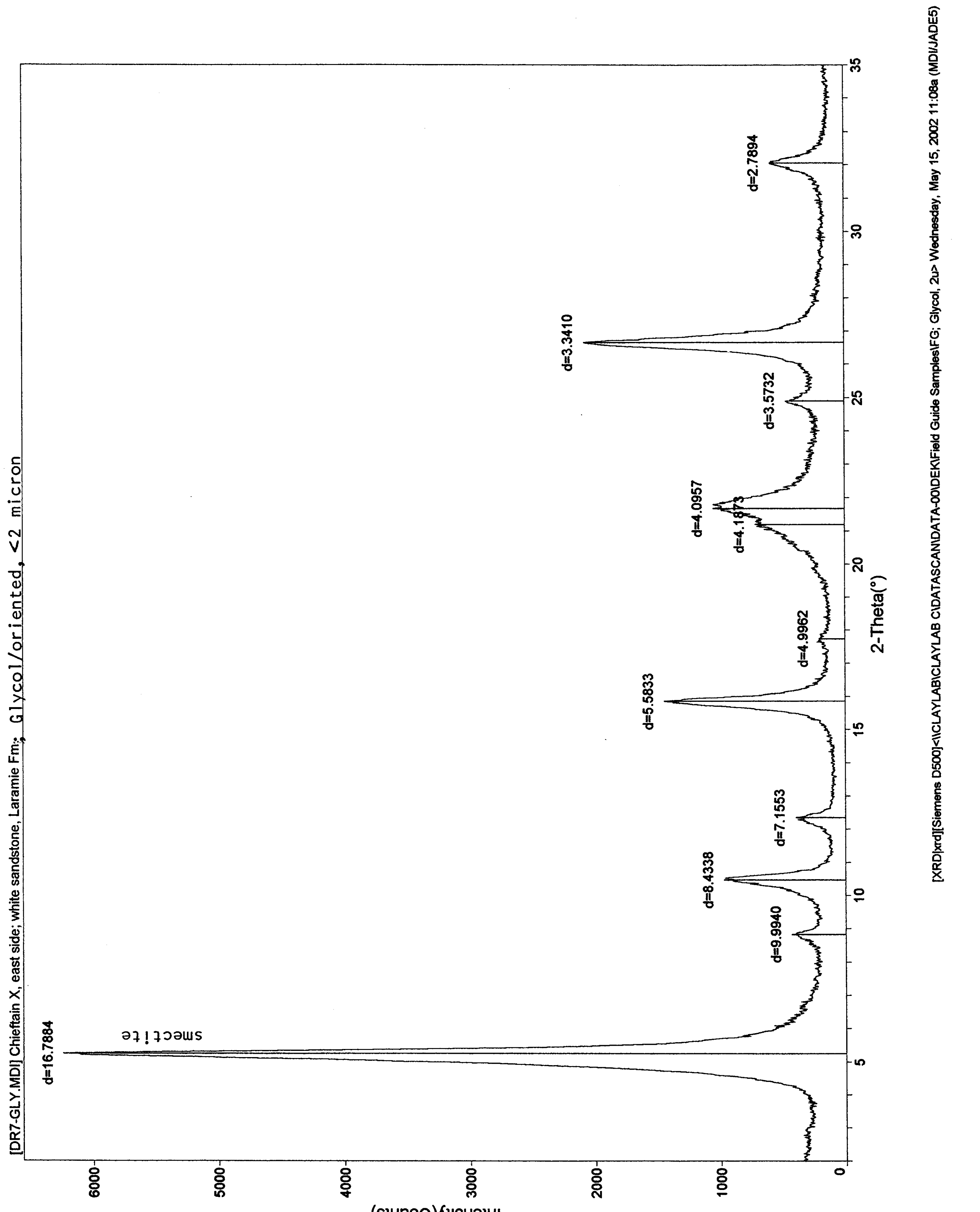


Figure 8. X-ray diffraction pattern of white sandstone from the Chieftain mine (sample DR-7).

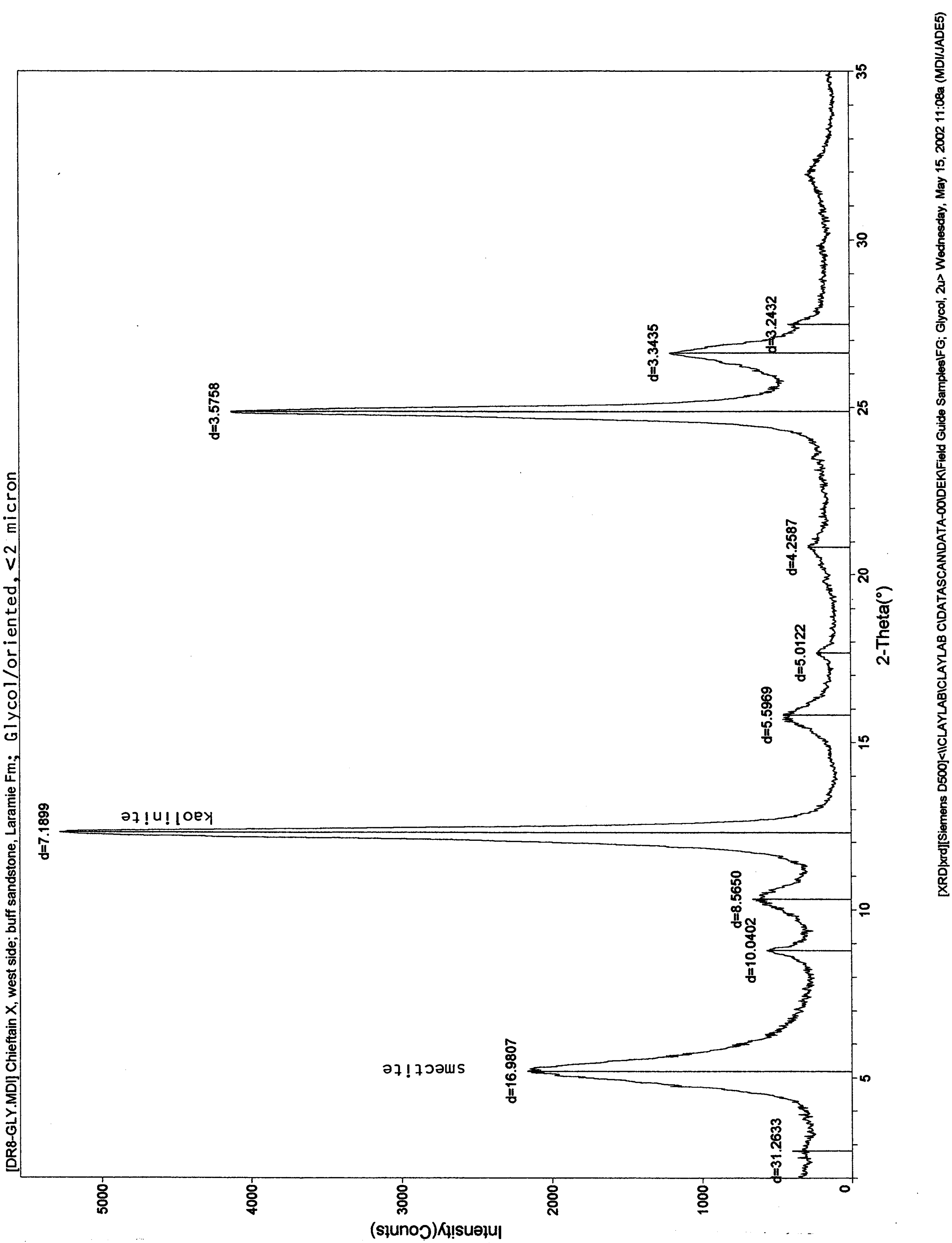


Figure 9. X-ray diffraction pattern of buff sandstone from the Chieftain mine (sample DR-8).

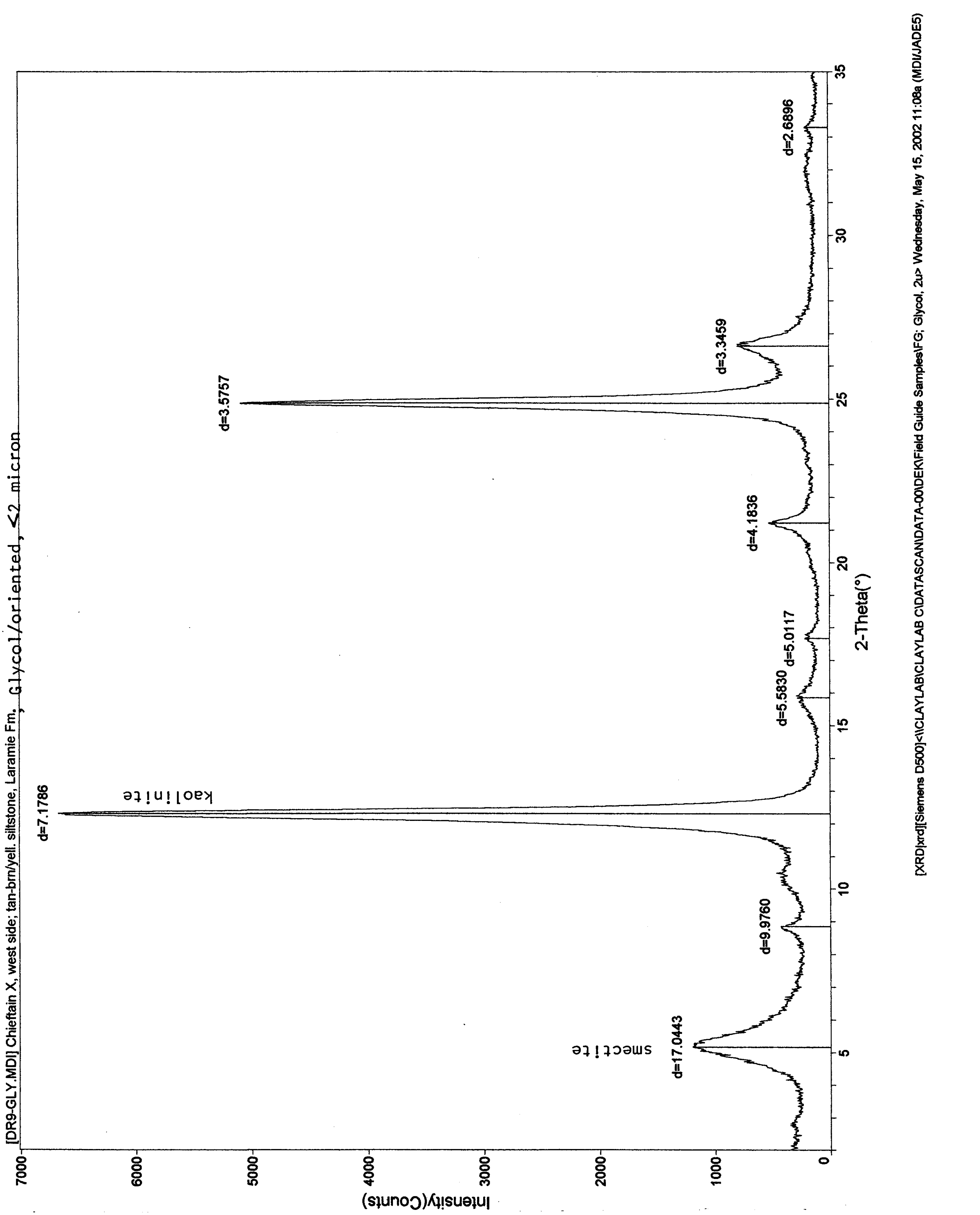


Figure 10. X-ray diffraction pattern of brown-tan siltstone from the Chieftain mine (sample DR-9).

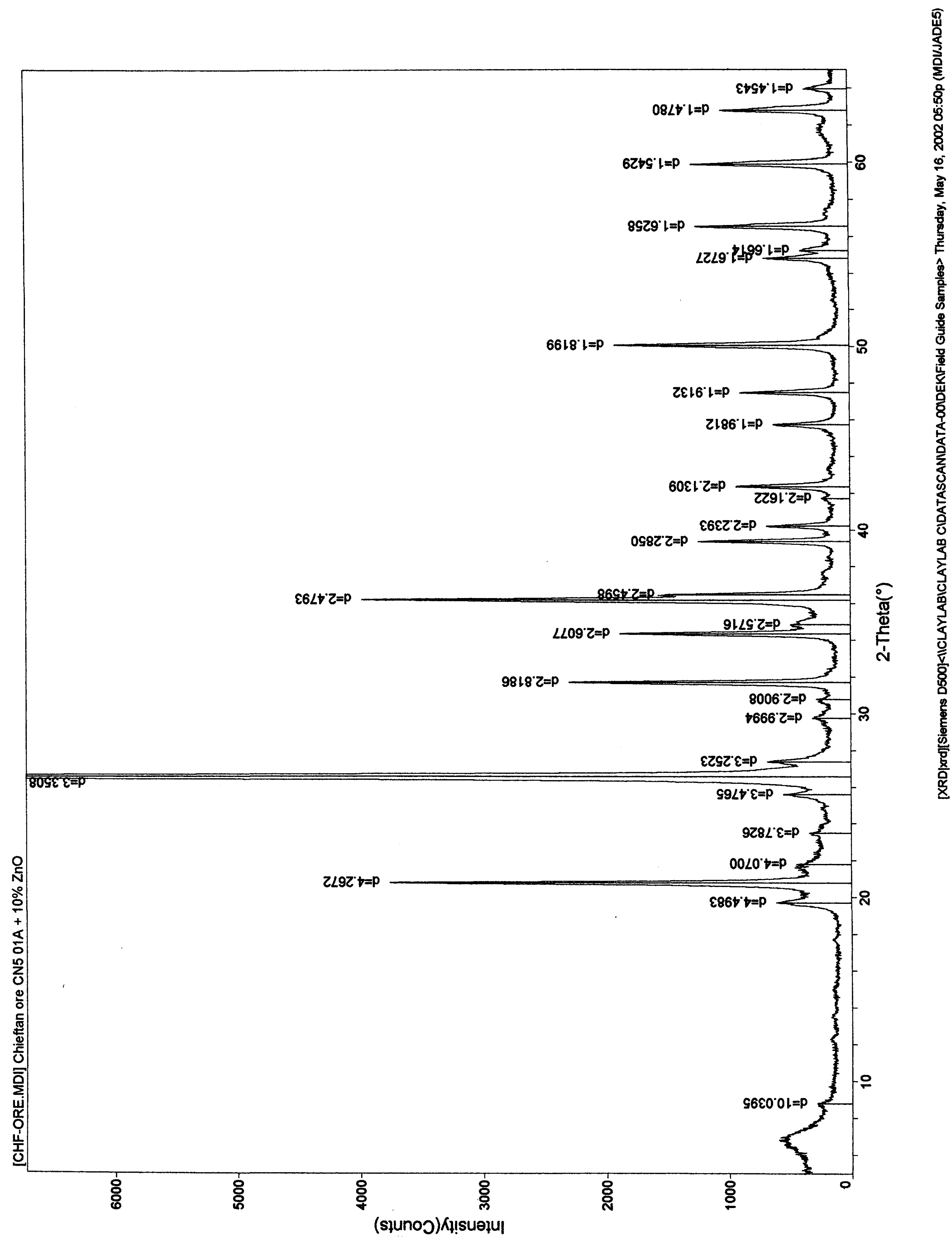


Figure 11. X-ray diffraction pattern of an "ore" sample from the Chieftain mine.

Table 1. Quantitative mineralogy results for clay samples from the Chieftain mine (samples FG-7, 8 & 9).

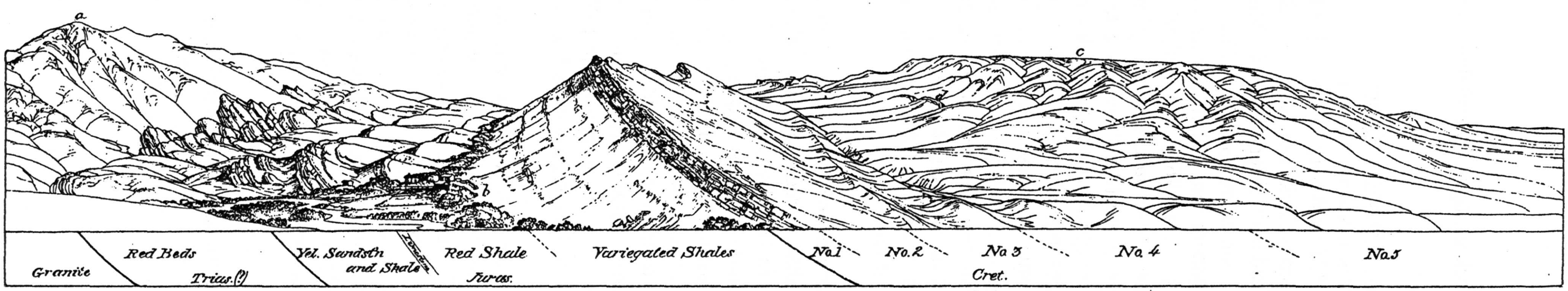
	FG-7
Mineral	Weight %
NON-CLAYS:	
intermed. Microcline feldspar	10
Mg-calcite	0
Dolomite	0
Quartz	65
Total non-clays:	76
CLAYS:	
1Md illite	12
Chlorite Tusc	12
Total Clays:	24
Total:	100
Not constrained	
Fspar region degree of fit:	0.276
Clay region degree of fit:	0.106
ZnO correction factor:	1.000

	FG-8
Mineral	Weight %
NON-CLAYS:	
intermed. Microcline feldspar	24
Quartz	59
Total non-clays:	83
CLAYS:	
disordered kaolinite	11
1Md illite	11
Total Clays:	22
Total:	104
Not constrained	
Fspar region degree of fit:	0.120
Clay region degree of fit:	0.107
ZnO correction factor:	1.000

	FG-9
Mineral	Weight %
NON-CLAYS:	
intermed. Microcline feldspar	19
Quartz	61
Total non-clays:	80
CLAYS:	
disordered kaolinite	11
1Md illite	11
Total Clays:	21
Total:	101
Not constrained	
Fspar region degree of fit:	0.157
Clay region degree of fit:	0.121
ZnO correction factor:	1.000

WEST

EAST



a, Bear Station b, Morrison d, Line of Coal outcrop-vertical c, Green Mt. Lignitic-horizontal.

Section at Bear Cr.

Figure 12. The Dakota Hogback and Red Rocks formations north of Morrison (from Hayden, 1876).

figures 13 and 14 show the bedrock stratigraphy and diagrammatic sections in the Denver-Golden area.

Historical Development of Colorado Dinosaur Quarries.

Dinosaurs were discovered in Jurassic sediments on the west side of what is now known as Dinosaur Ridge in March of 1877 by Arthur Lakes and H.C. Beckwith, who described giant vertebrae and a femur 14 inches thick (Lewis, 1960). By June of 1877, three-quarters of a ton of fossil bones had been shipped to O.C. Marsh at Yale University in New Haven, Connecticut, whereupon he assigned B.F. Mudge to oversee the operation. By July 1877 another one and a quarter tons of bones were shipped to Marsh; work continued in this area until 1879 (Lewis, 1960). Altogether Marsh opened 10 quarries on Dinosaur Ridge, with examples of *Apatosaurus* (popularly known as *Brontosaurus*), *Diplodocus*, *Allosaurus*, and *Stegosaurus* (the Colorado state fossil), being recovered from the Morrison quarries. Marsh quickly published a description of a creature excavated from this site that was estimated to be 50-60 feet long (Marsh, 1877). One of the more prominent original dinosaur quarries in this area is located on the west side of the hogback just north of the town of Morrison. Ten years later, in 1887, *Triceratops* was discovered nearby by G.L. Cannon, working with W. Cross and G.H. Eldridge, in the Upper Cretaceous Denver Formation on Green Mountain, a site two miles east of the original Morrison quarries. Hunt and others (2002) provide further information on the historical quarries in the vicinity of Dinosaur Ridge.

Other significant Colorado dinosaur quarries were almost immediately discovered in the Morrison Formation. A site was discovered about 100 miles south of Dinosaur Ridge, again in the Morrison Formation, in 1877 by O.C. Lucas. Located north of Cañon City and known as Garden Park, this find was excavated largely by E.D. Cope, who also recovered numerous important fossilized remains. Soon thereafter, in the late 1800's to early 1900's, excavations by E. Riggs in the "Redlands" near Grand Junction (at a site now known as Riggs Hill) on the western slope yielded significant fossils which were sent to the Chicago Field Museum of Natural History. In northwestern Colorado, at the Colorado-Utah border, reptilian remains were reported in 1871 by J.W. Powell at a locality that was later developed into Dinosaur National Monument.

The focus of dinosaur excavations soon moved, however, from the various Colorado quarries to Como Bluff in Wyoming, which proved to be one of the most significant fossil beds in North America. Quarries from Colorado and other western localities yielded fossils that are now represented in many major museums in North America, including the Chicago Field Museum of Natural History, the Cleveland Museum of Natural History, the Carnegie Museum of Natural History, Yale-Peabody Museum, the Smithsonian Institution, and the Denver Museum of Nature and Science. The Denver Museum has on display a nearly complete *Stegosaurus*, found in 1937 at the Garden Park locality.

The two principal scientists of the era engaged in fossil recovery, O.C. Marsh, affiliated with the Yale-Peabody Museum, and E. D. Cope, who was associated with the Philadelphia Academy of Science, were in bitter competition to find and document the

ERA	PERIOD	FORMATION	THICKNESS FT	DESCRIPTION (Profile shows erosion form)	USE
CENOZOIC	Recent	Terrace Deposits	Thin	Gravel, sand, clay	Building material
	Tertiary (Early)	Green Mtn Conglomerate	600	Coarse conglomerate, sandstone, siltstone	
		Denver and Arapahoe Fms	1200	Lava flows, basaltic Sandstone, shale, conglomerate with volcanic pebbles	Building material
MESOZOIC	CRETACEOUS	Laramie Fm	1100		Coal Brick clay
		Fox Hills Ss	60	Sandstone, shale	
		Pierre Shale	8000	Dark gray shale (Marine)	
		Niobraras Ls (Fort Hayes Ls)	330	Limey shale, lower thin limestone (Marine)	Lime for cement whitewash
	Upper / Lower	Benton Shale	480	Dark gray shale (Marine)	
		Dakota Group (Ss)	220	Sandstone, shale	Oil, water ceramic clay Uranium
	JURASSIC	Morrison Fm	320	Red and green shale some sandstone	
	TRIASSIC	Ralston Cr. Fm	65	Sandstone and shale	
PALEOZOIC	PERMIAN	Lykins Fm (Glennon) (Falcon)	400	Shale, 1 or 2 limestone units, locally gypsiferous	Lime for cement, whitewash; gypsum
		Lyons Ss	120	Sandstone, locally near white	Flagstone
	PENNSYLVANIAN	Fountain Formation	1000 +	Red sandstone (Arkose, variety) conglomerate, and shale	Flagstone
PRECAMBRIAN		(Idaho Springs Fm)	Thick	Gneiss, some quartzite, cut by granite and other igneous rocks	Uranium, building stone

Figure 13. Bedrock stratigraphy in the Denver area (prepared by H. D. Drewes, USGS).

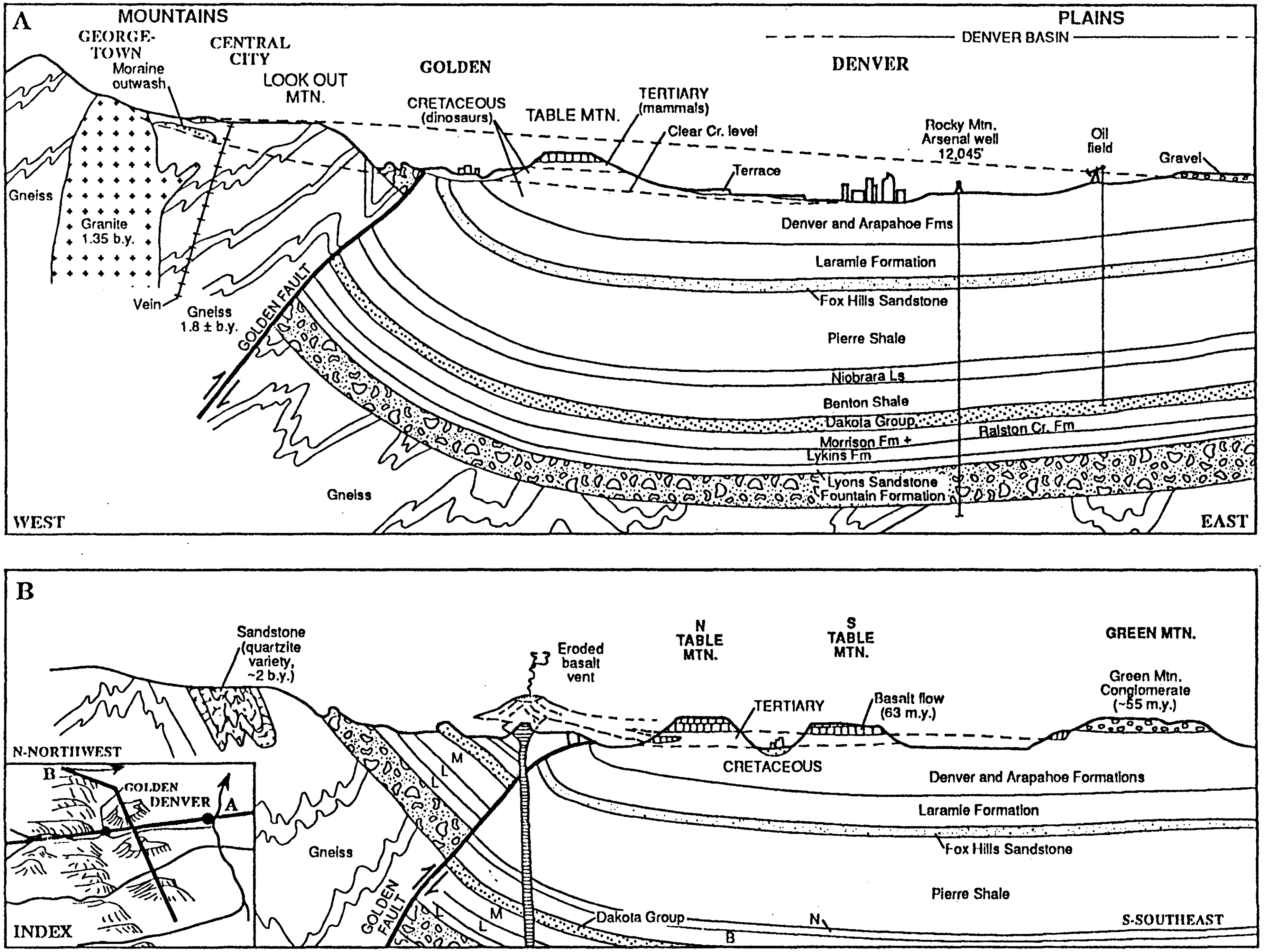


Figure 14. Diagrammatic sections, Red Rocks-Golden area (prepared by H.D. Drewes, USGS).

best and the most dinosaur skeletons; this rivalry is legendary in the paleontological world. One result of this hasty rush to publication is that many errors in description, speciation, and reconstruction were made, some of which are still perpetuated in museum collections. Ostrom and McIntosh (1966) give some insight into the bitter rivalry between Marsh and Cope.

Dinosaur tracks, described below, were discovered in abundance on the east side of the hogback during construction of Alameda Parkway in 1937. This site constitutes one of the most important and best-studied trackways in North America.

Dinosaur trackway.

Dinosaur Ridge features one of the better dinosaur footprint trackways in Colorado (fig. 15), with at least 37 different sets of tracks being recorded. This site shows numerous three-toed tracks of *Iguanodon* in lower Cretaceous sandstones of the Dakota Group; unlike skeletal remains, tracks provide direct evidence of the behavior of living animals. For example, *Iguanodon*, a large herbivore, is seen to be a quadrepedal animal, not bipedal as formerly supposed, and the parallel nature of sets of tracks gives evidence for travel in groups, much like a modern-day herd animal. Tracks also provide evidence of posture; for example, *Triceratops* impressions in the Laramie Formation infer an erect stance as opposed to a sprawled posture characteristic of amphibians. In addition, smaller tracks are those of a diminutive theropod carnivore, weighing perhaps 100-200 pounds with the approximate size and stature of a modern-day ostrich. These tracks were originally left along the shoreline or a tidal flat of the interior shallow Cretaceous marine sea that extended through the mid-section of North America. Accordingly, trackways are found intermittently along this entire stretch. Along the Front Range in Colorado they are found from Boulder to Golden, and in Roxborough Park. In southeastern Colorado, an exceptional trackway is found near Picketwire Canyonlands along the Purgatoire River. This is the longest set of dinosaur tracks in North America, and possibly the world (Lockley and Prince, 1988). These tracks occur in the Jurassic Morrison Formation, in contrast to those near Denver that are found in Lower Cretaceous sandstones of the Dakota Group. Dinosaur trackways also extend as far as Oklahoma and eastern New Mexico. The abundance of tracks along this Cretaceous shoreline is suggestive of a migration route (Lockley and Marquardt, 1995).

XRD analysis of a shale seam below the footprint-bearing sandstone (sample DR-3, $< 2\text{-}\mu$ fraction; fig. 16) shows primarily kaolinite. Quantitative results for the principal minerals in this sandstone (sample FG-3, whole-rock sample; table 2) show kaolinite (29 percent), illite/smectite (11 percent), and quartz (49 percent). Similarly, the dominant clay mineral in the overlying sandstone (sample DR-4, $< 2\text{-}\mu$ fraction; fig. 17) from a sample near the trackway is kaolinite.

Ripple marks.

These are readily discernible along the upturned sandstones of the Dakota Group. Both symmetric ripple marks, caused by oscillating wave motion, and asymmetric ripple marks, caused by directional current flow, have been observed in the sediments at Dinosaur Ridge.

Figure 15. Dinosaur trackway at the Dinosaur Ridge site; photo courtesy of Pete Modreski

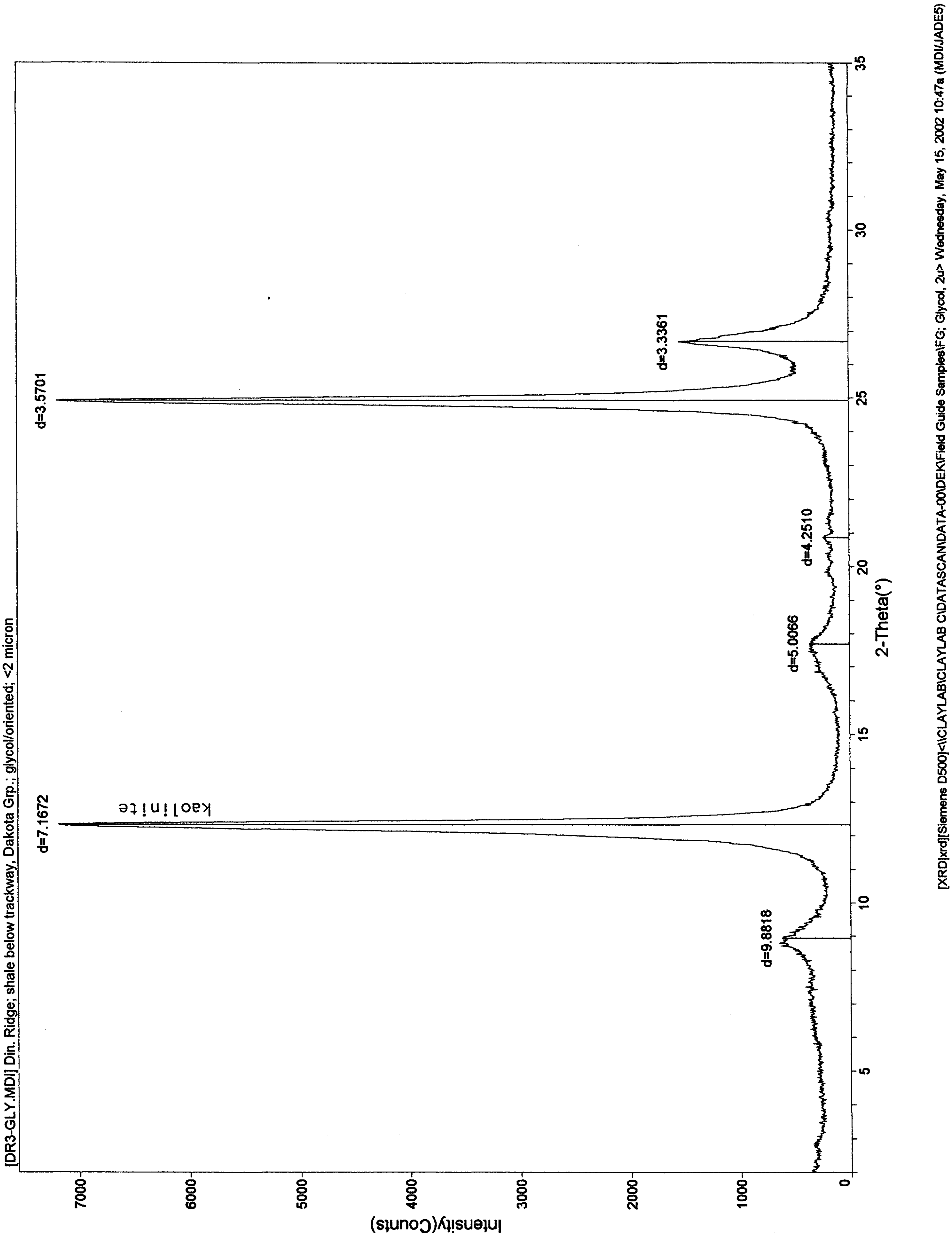


Figure 16. X-ray diffraction pattern of shale, Dakota Group at trackway (sample DR-3).

Table 2. Quantitative mineralogy results from clay samples from Dinosaur Ridge (samples FG-3, 5 & 10).

Sample Name:	FG-3
Mineral	Weight %
NON-CLAYS:	
K-spar	2
Quartz	49
Total non-clays:	51
CLAYS:	
1M illite	3
2M1 illite	8
kaolinite	29
Chlorite	8
Total Clays:	47
Total:	98
Not constrained	
Fspar region degree of fit:	0.068
Clay region degree of fit:	0.060
ZnO correction factor:	1.000

	FG-5
Mineral	Weight %
NON-CLAYS:	
Microcline feldspar	4
intermed. Microcline feldspar	0
Anorthoclase	2
Albite feldspar	0
Andesine	0
Alunite	1
Hematite (24.14; 62.44)	1
Quartz	23
Total non-clays:	30
CLAYS:	
Goethite	2
disordered kaolinite	9
1Md illite	55
Chlorite CCa-1	3
Chlorite CCa-3	1
Chlorite CCM	0
Chlorite Tusc	7
Total Clays:	76
Total:	106
Not constrained	
Fspar region degree of fit:	0.112
Clay region degree of fit:	0.081
ZnO correction factor:	1.000

	FG-10
Mineral	Weight %
NON-CLAYS:	
intermed. Microcline feldspar	7
Quartz	66
Total non-clays:	74
CLAYS:	
disordered kaolinite	12
1Md illite	13
Total Clays:	24
Total:	98
Not constrained	
Fspar region degree of fit:	0.100
Clay region degree of fit:	0.135
ZnO correction factor:	1.000

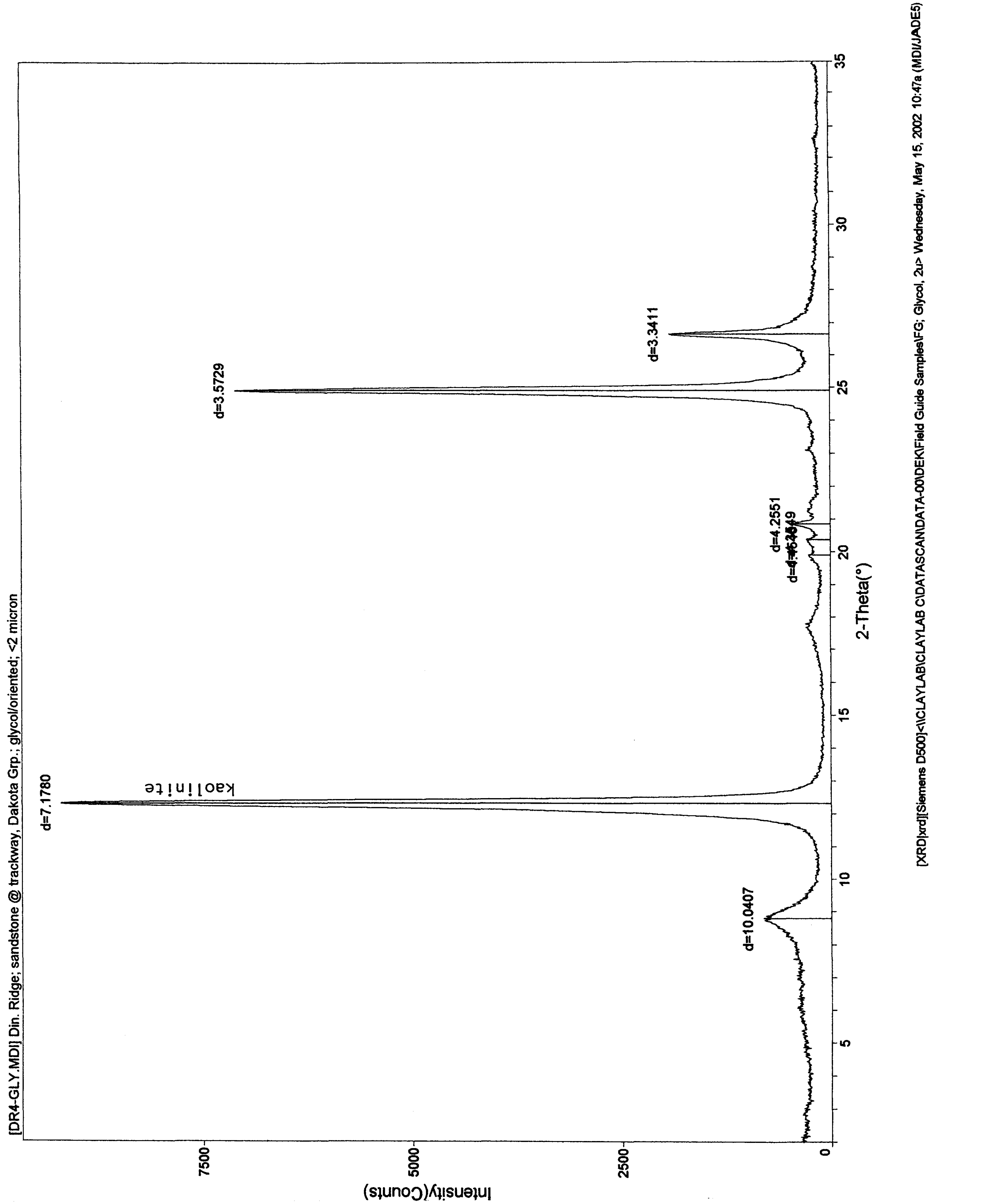


Figure 17. X-ray diffraction pattern of sandstone, Dakota Group at trackway (sample DR-4).

Concretion.
Although the exact nature of this unusual structure is still subject to some debate, it is likely a concretion that formed after nucleating around a fossil in the sedimentary rocks. It has occasionally provided a dramatic "canvas" that industrious artists have surreptitiously on at least one occasion transformed with paint into a bloodshot eyeball peering down at the oncoming traffic.

Volcanic ash layer.
A prominent 4- to 7-cm gray-white layer of a compact volcanic ash is exposed just west of the bend in Alameda Parkway; minute zircon crystals isolated from this ash have been radiometrically dated (U-Pb) to 105.6 ± 1.3 Ma, which correlates well with the 100-Ma age determined in samples collected from the Dakota sandstone in other studies (Lockley, 2001). A thin section of material (fig. 18) from this outcrop shows distinctive vermiform development of the kaolinite. XRD of a whole-rock sample (random mount, fig. 19) shows principally kaolinite, with minor quartz and possibly a trace of zircon (the presence of zircon has been confirmed in mineral separates). This deposit is equivalent to a tonstein, the formation of which is attributed to non-marine deposition and diagenesis of volcanic ash in a coal-forming environment (i.e., acidic, organic rich), which results in the formation of kaolinitic claystones, rather than smectitic clays (Bohor and Triplehorn, 1993).

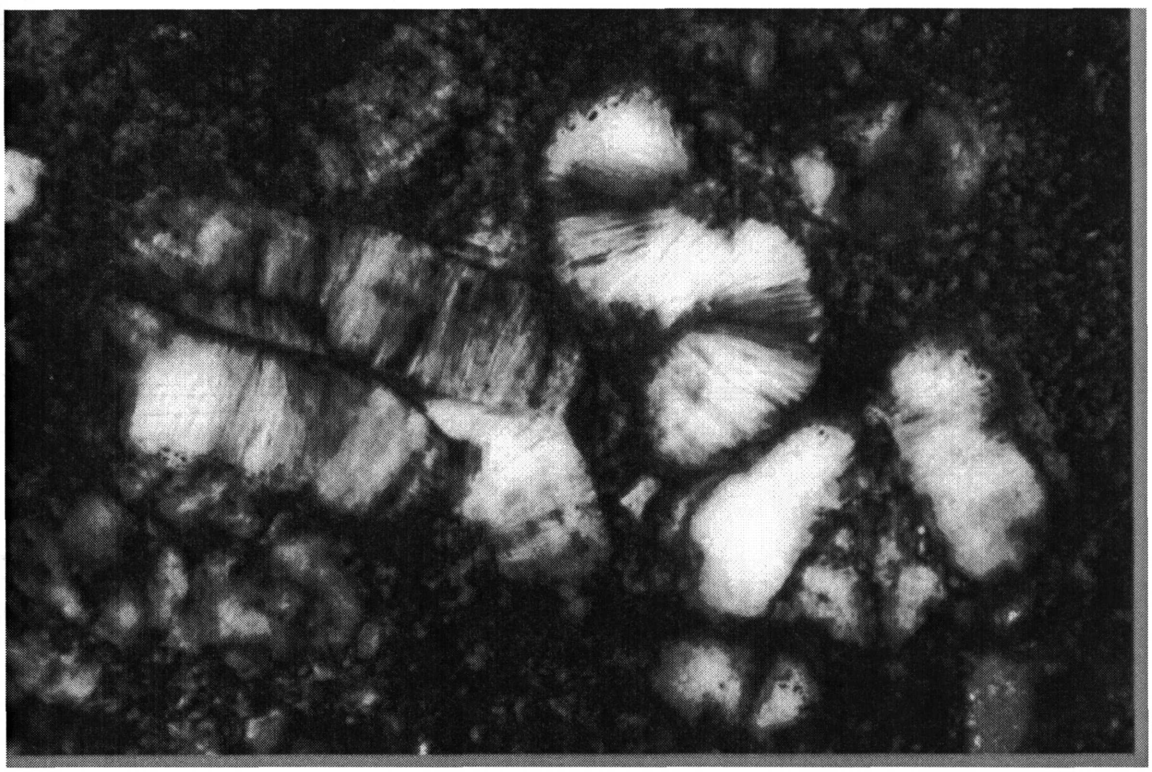


Figure 18. Photomicrograph of thin section from Dakota Group ash bed showing vermiform kaolinite. Field of view 0.35 mm across.

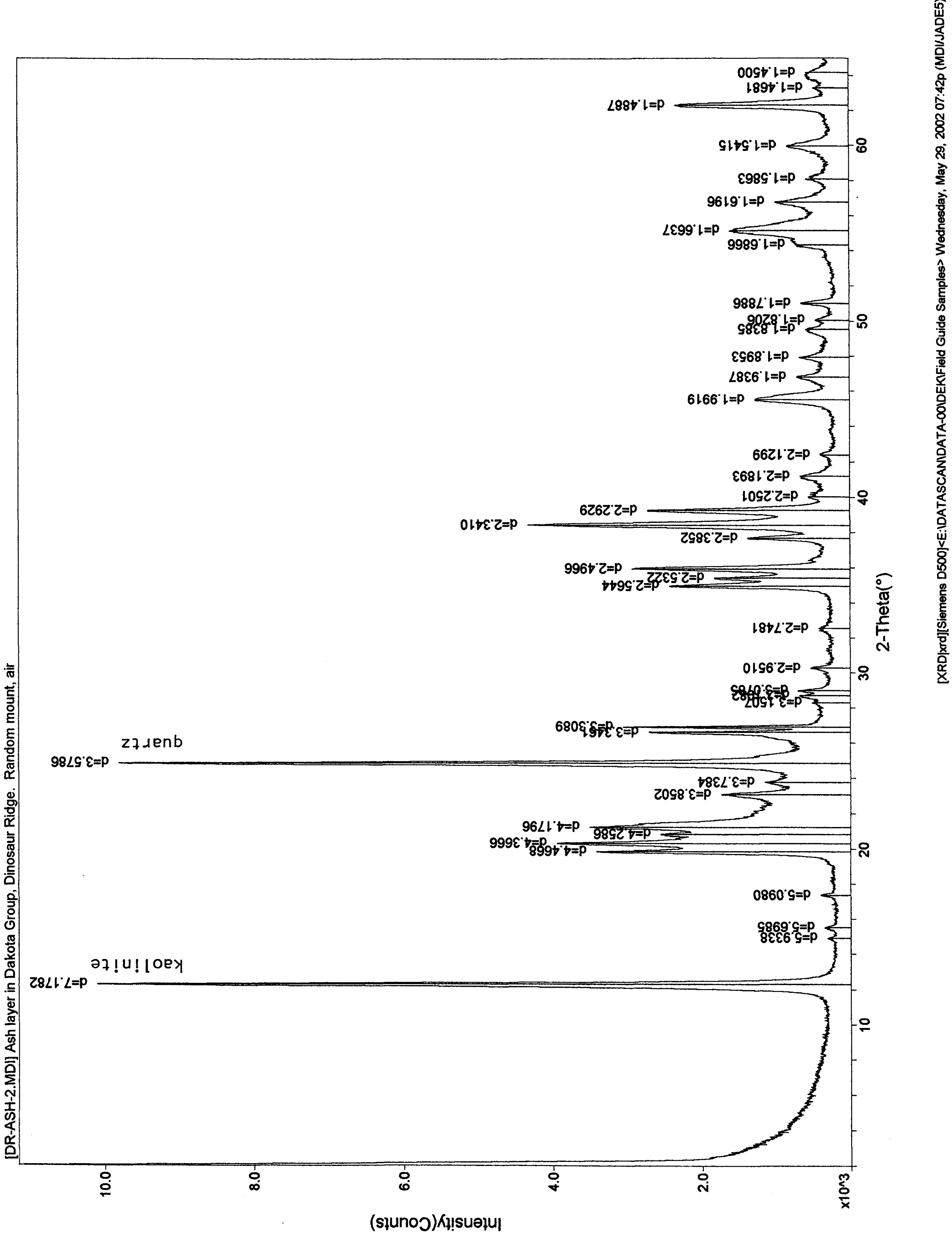


Figure 19. X-ray diffraction pattern of volcanic ash layer, Dakota Group.

Brontosaurus (Apatosaurus) footprints.
These are actually depressions in a Jurassic nonmarine sandstone. Their substantial size (one of which exceeds 1 meter in length) suggests that a large animal such as a *brontosaurus* (a sauropod) was the culprit; fortunately this 60-ton animal is nowhere to be found, as a nearby sign stipulates a 5-ton limit on Morrison streets. A shale from the Morrison Formation near the prints (sample DR-5, < 2-μ fraction; fig. 20) shows illite and kaolinite as the predominant clay minerals. Particle-size distribution analysis (using the MudMaster program) of a polyvinylpyrrolidone (PVP)-treated, < 2-μ fraction illite for this sample shows an asymptotic crystal size distribution with a mean size of 3.9 nanometers (nm) (fig. 21). Quantitative analysis of this shale (sample FG-5, whole-rock sample, table 2) gives 55 percent illite, 11 percent chlorite, and 9 percent kaolinite, with 23 percent quartz and 6 percent K-feldspar. An XRD pattern (glycolated, < 2-μ fraction, sample DR-10; fig. 22) and quantitative analysis (FG-10, whole-rock sample; table 2) of a sandstone from this same area again shows mostly illite (13 percent) and kaolinite (12 percent), with 66 percent quartz and 7 percent K-feldspar.

Fossilized dinosaur bone.
These bone fragments, recognizable as having a dark brown color and smooth texture, are found in the Morrison Formation, a 300-foot thick sequence of nonmarine sandstones, siltstones and mudstones. The upper one-third of this formation consists of buff, medium-grained sandstones interbedded with red to maroon shales, and the lower two-thirds consists of gray, thin-bedded sandy shales that were deposited in Jurassic river channels and floodplains. Excellent exposures of the Morrison Formation are seen at the large road cut (now designated as a Point of Geological Interest) along Interstate 70 (LeRoy and Weimer, 1971). The scattered nature of the bones at this locality suggests deposition and subsequent disarticulation in a river bed. Hubert and Panish (2000) further infer that the dinosaurs died during a period of severe drought, and that the bones were then transported to a deep pool by a subsequent flood event, where they were rapidly covered (and preserved) by sediment. Bones represented here are likely *Stegosaurus*, *Camarasaurus*, *Diplodocus*, *Allosaurus*, and *Apatosaurus* (i.e., *Brontosaurus*). Additional details of this site are provided by Jenkins and Jenkins (1993), Hubert and Panish (2000), and Modreski (2001).

A thin section of dinosaur bone (possibly *Triceratops*, fig. 23) is from a site in the Cretaceous Denver Formation near the Denver Federal Center a few miles east of Dinosaur Ridge. This section shows a distinct cell-like structure (called haversian canals) that is composed of an apatite framework (the walls of which are much thicker in this sample than seen in most fossilized bone) with a predominantly chalcedony interior and subordinate limonite. The apatite has been diagenetically altered from an original carbonate-hydroxyl apatite (i.e., dahllite) to a carbonate-fluorapatite (also known as francolite, Hubert and Panish, 2000). In contrast, thin sections of bone found at Dinosaur Ridge show the haversian canals to be partially filled with calcite, ankerite, and pyrite (altered to limonite), with subordinate amounts of kaolinite and chalcedony (Modreski, 2001). By comparison, dinosaur bone from the Como Bluff locality shows approximately equal amounts of chalcedony/α-quartz and calcite in the "cell" interiors, whereas bone found in western Colorado and Utah is predominantly composed of

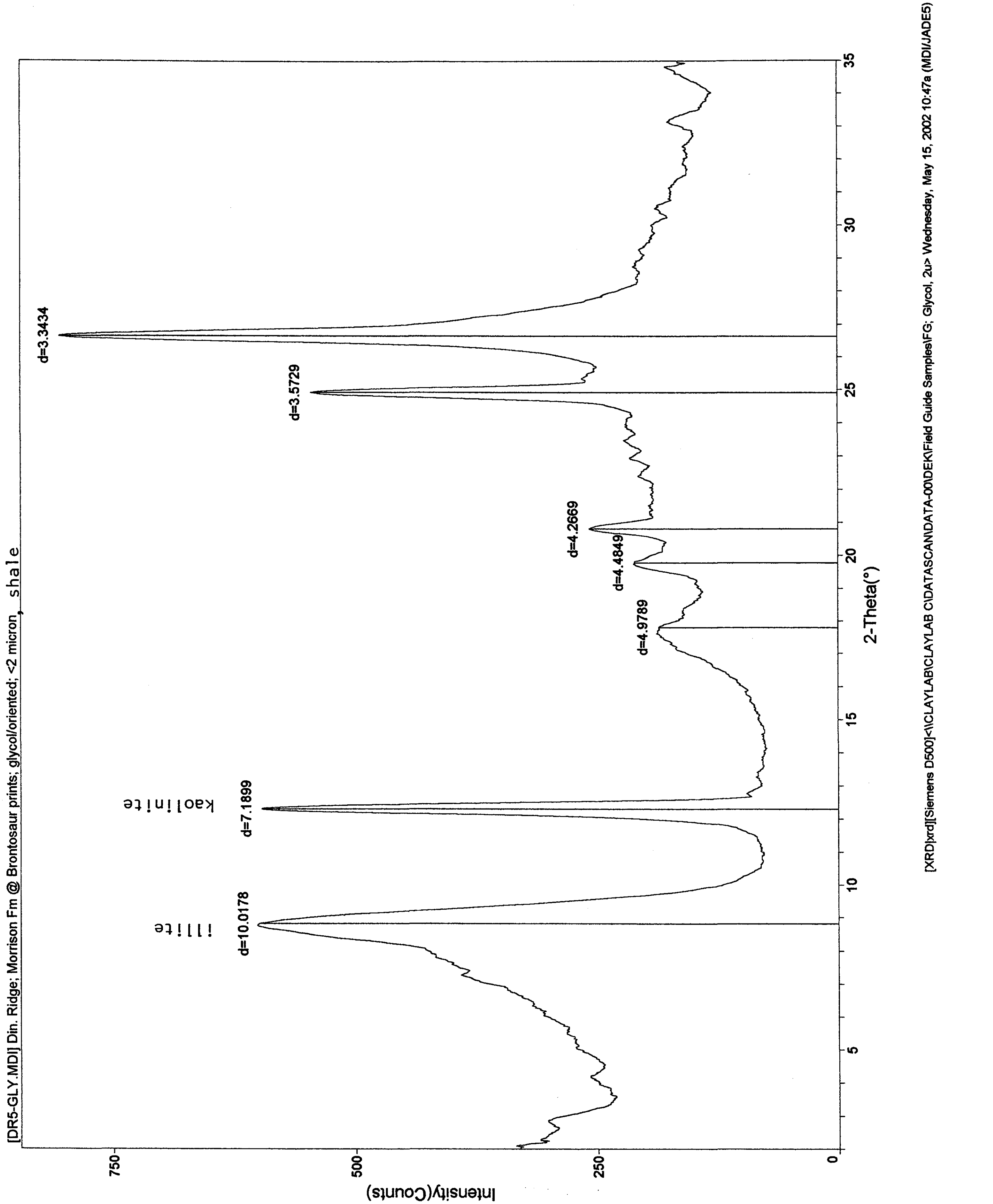
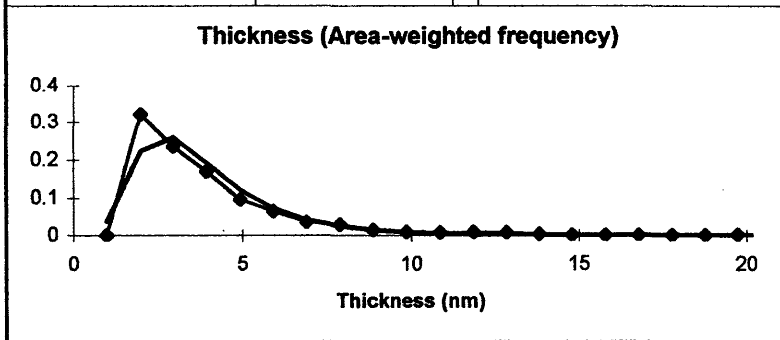
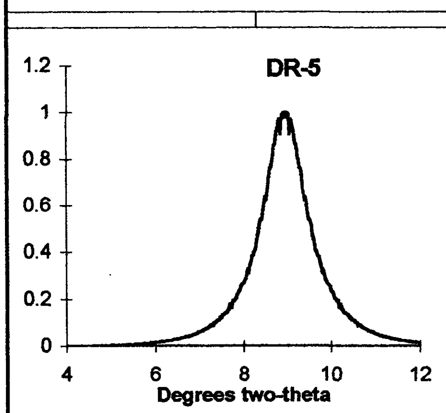
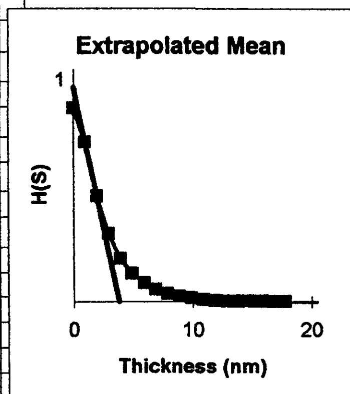


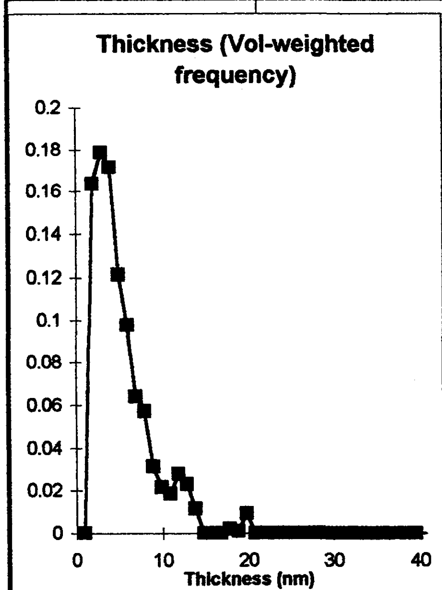
Figure 20. X-ray diffraction pattern of shale at Brontosaurus prints, Morrison Formation (sample DR-5).

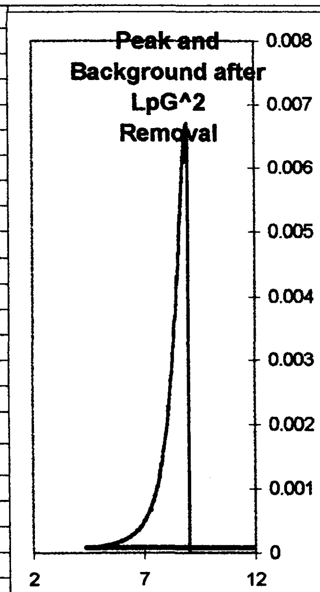
SAMPLE NAME	DIST. LIMIT? (nm)	SYM. STRAIN COR.? (1=YES)
DR-5	20	0
DATE OF MM ANALYSIS	SMOOTH POWER?	INST COR? (1 = YES; active if D2 ? 1)
5/29/02 15:28	0	0

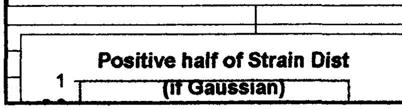


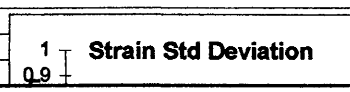












PVP-ILLITE
BEST MEAN (nm; EXTRAPOLATED; area-weighted)
3.9
MEAN (nm; DISTRIBUTION; area-weighted)
3.9
ALPHA (from nm)
1.22
BETA^2
0.25
VOL-WEIGHTED MEAN THICKNESS (nm)
5.3
POSITION INT. FN. (two-theta)
8.96
d-SPACING INT. FN. (Å)
9.870
ROOT MEAN SQUARE STRAIN (Å)
Not calculated
APPROX FUND PART THICK (nm; area-weighted)
3.9
ILLITE FIXED CATIONS/HALF-UNIT CELL (see L16)
0.66
SPEC a-b SUR AREA (M^2/g; density in cell L18)
191
HIDDEN KNOBS SET AT RECOMMENDATIONS?
YES
SYMM. STRAIN ANAL. NO. (0=NONE)
0
STARTING TWO-THETA
4.40
ENDING TWO THETA
9.00
STEP SIZE (TWO-THETA)
0.02
INCREMENT IN N USED FOR FOURIER ANALYSIS
1
REFLECTION ORDER
1
MAXIMUM SIZE CALCULATED
100
RADIATION WAVELENGTH? (Å)
1.54184
"n" IF ALPHA 1 ANALYSIS USED
K-ALPHA USED
FLIP?
L to R
EXPANDABILITY (%)
0
LpG^2's USED: INTERIOR/EDGES
illite, .89K, combo
PVP Kinney norm vs newmod illite,10-20 degree region
FRACTION OF INTERIOR LpG^2
0.74
LOWER LIMIT FOR DISTRIBUTION
0
OTHER INFORMATION
0

Figure 21. Particle-size distribution for illite from Morrison Formation shale (DR-5).

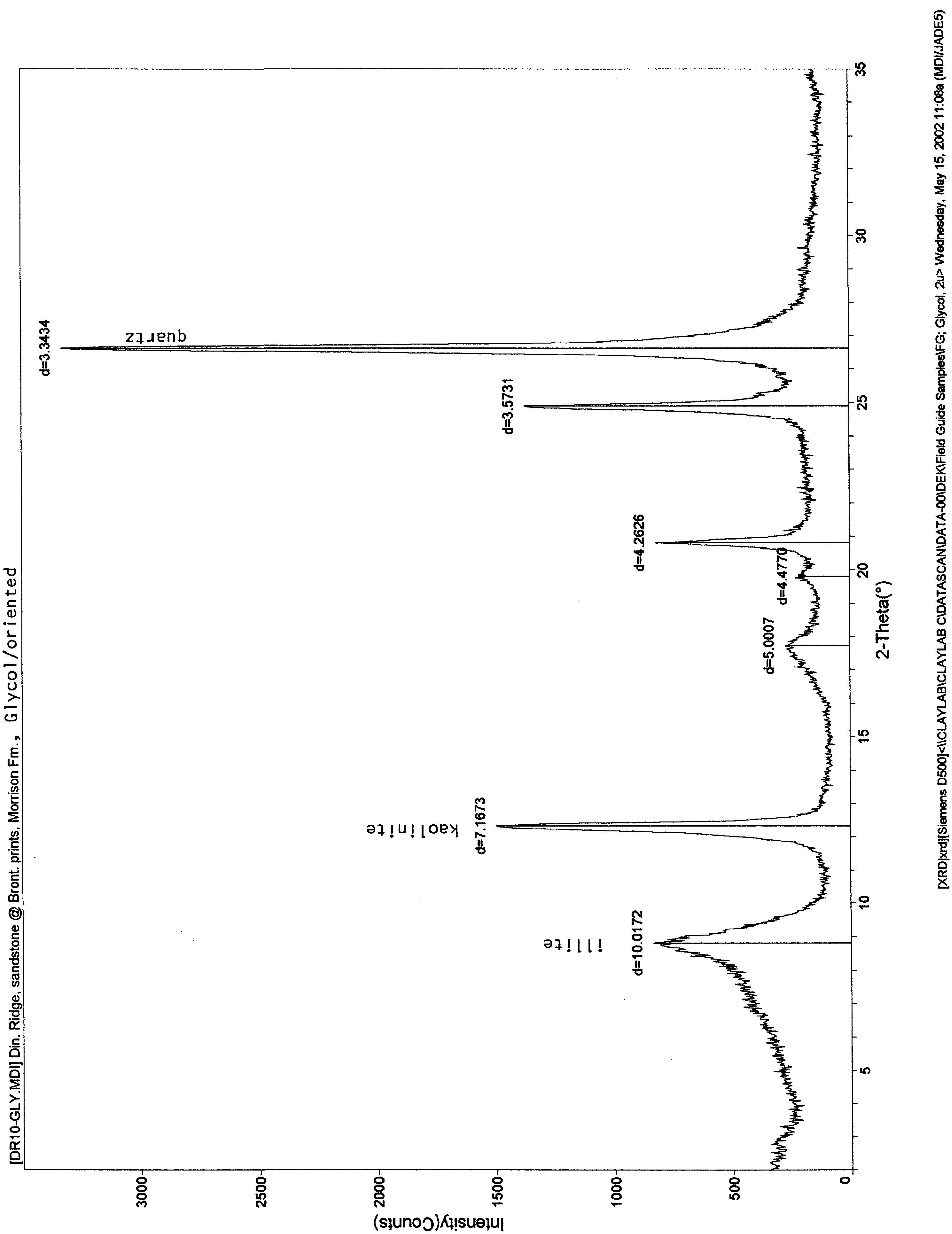


Figure 22. X-ray diffraction pattern of sandstone at Brontosaurus prints, Morrison Formation (sample DR-10).

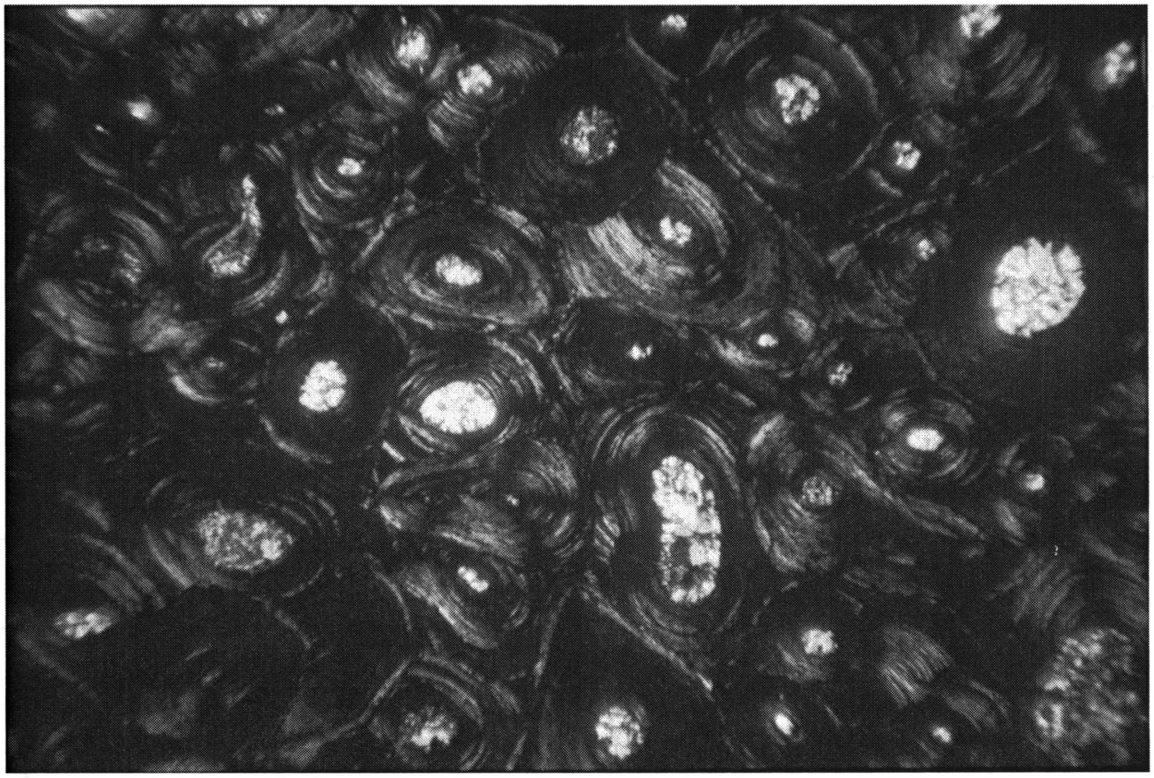


Figure 23. Photomicrograph of a thin section of dinosaur bone (possibly *Triceratops*) from the Upper Cretaceous Denver Formation east of the Denver Federal Center. Field of view 2.4 mm across.

chalcedony and a subordinate amount of carbonate; this latter fossilized material is consequently much harder, and frequently finds use in lapidary work. An XRD pattern (glycolated, < 2-μ fraction, sample DR-6; see fig. 24) of a sandstone near the bone outcrop shows the clay-mineral fraction to be composed mostly of kaolinite.

RED ROCKS AMPHITHEATER

Red Rocks Park is part of the Denver Mountain Parks system. These rocks are the same Fountain Formation that composes the Flatirons west of Boulder. As in Boulder County, they provide a spectacular view of upturned sedimentary "red rocks". Here the Fountain Formation forms a renowned outdoor amphitheater; with seating for 10,000, it provides a venue for concerts, Easter Sunday sunrise services, and other events. A panoramic view is also afforded the surrounding terrain and geological formations, including to the east the Dakota Hogback that comprises Dinosaur Ridge, and Green Mountain (the top of which is composed of coarse conglomerates, sandstones and siltstones) to the northeast; Precambrian metamorphic rocks (gneisses and schists) and granitic rocks form the backdrop to the west of the park. Additional information on the Pennsylvanian Fountain Formation can be found in Wahlstrom (1948), Runnels (1976), and LeRoy and LeRoy (1978).

XRD analysis of a shale sample (< 2-μ fraction; fig. 25) from the Fountain Formation shows the clay-size fraction to be composed mostly of kaolinite and small amounts of illite.

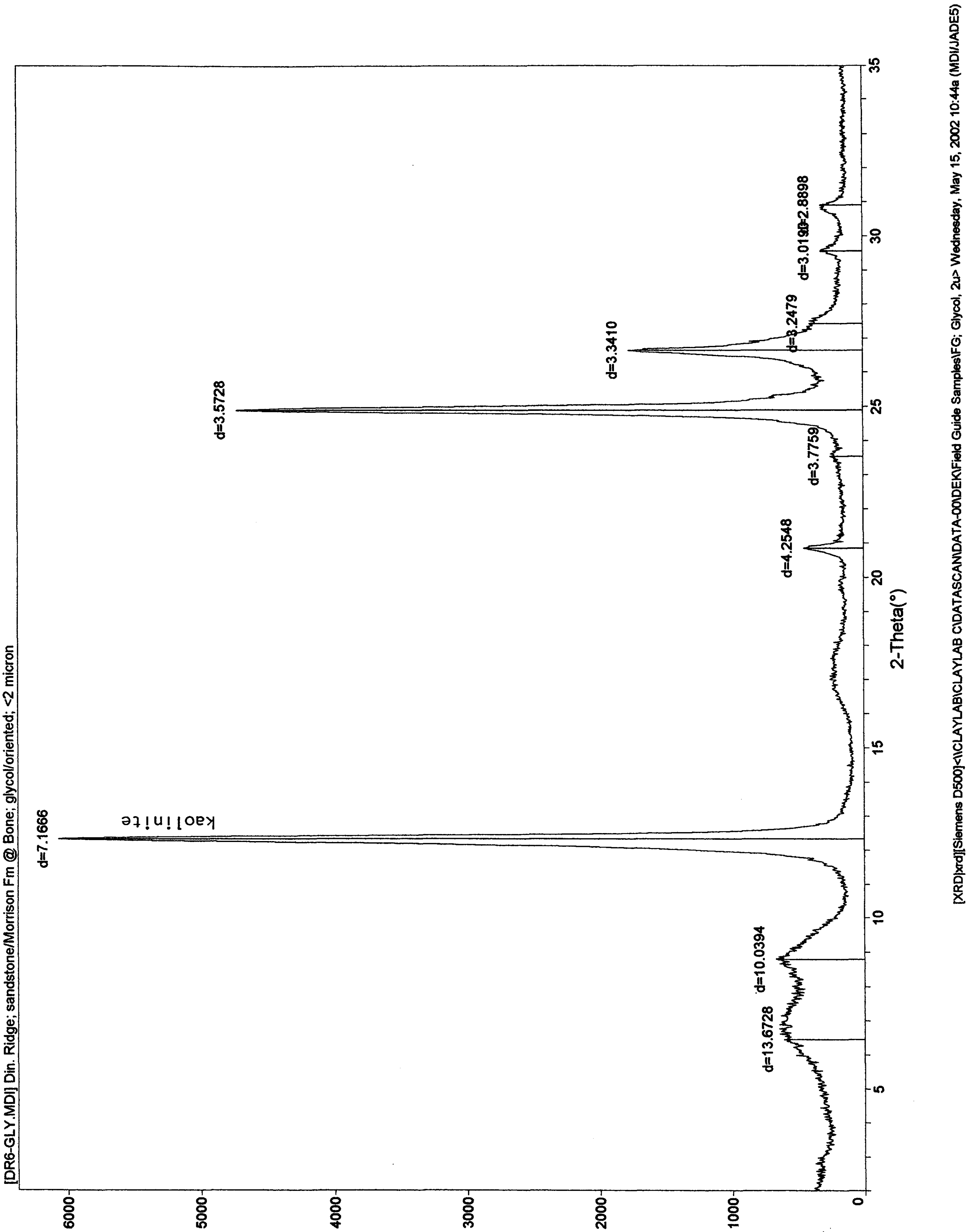


Figure 24. X-ray diffraction pattern of sandstone at bone outcrop, Morrison Formation (sample DR-6).

USGS

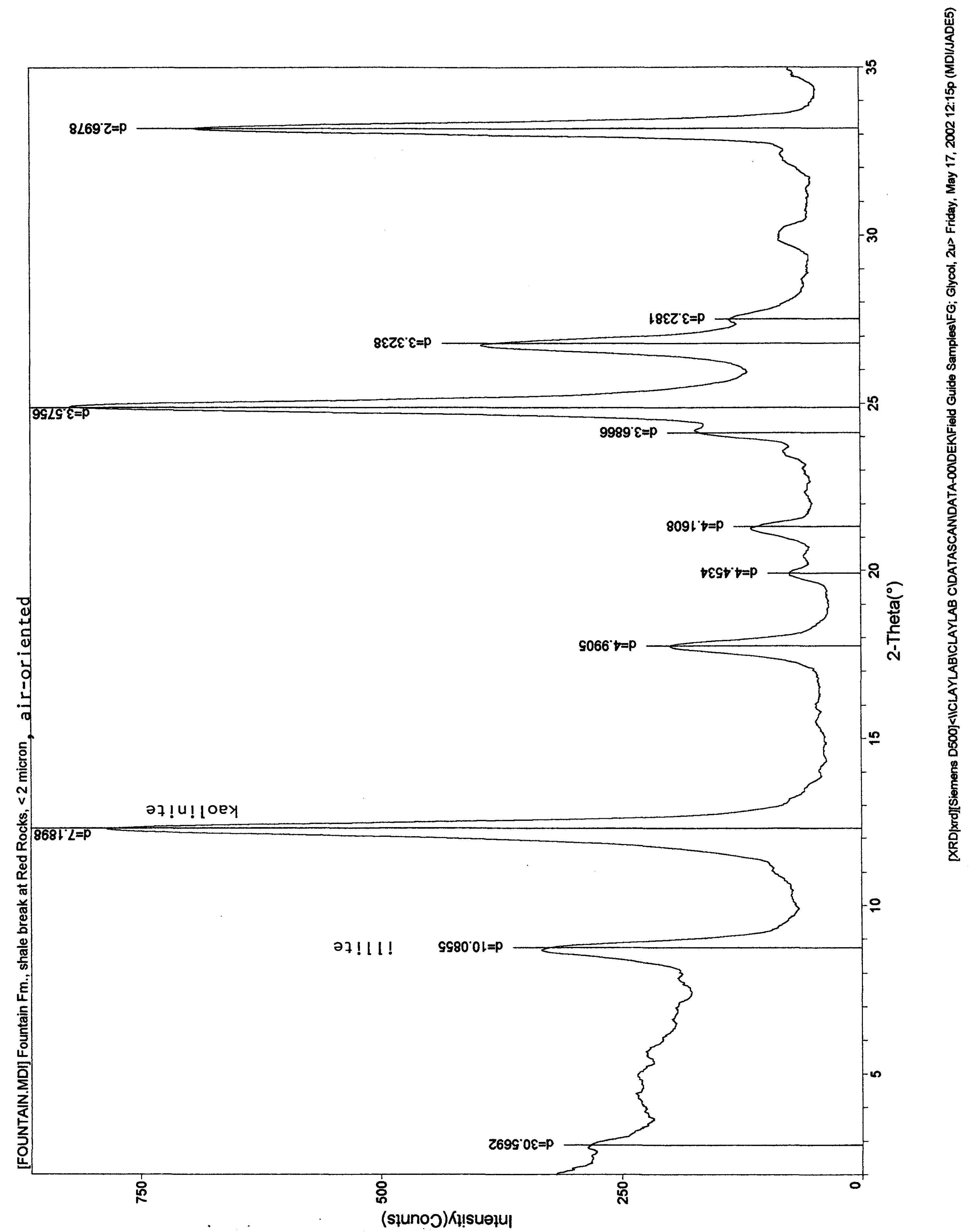


Figure 25. X-ray diffraction pattern of shale, Fountain Formation, Red Rocks Park.

Genesee Park Overlook

This overlook affords a spectacular view of the mountains comprising a part of the continental divide, as well as some of the gold mining areas near Central City in the Colorado Front Range mineral belt. Nearby is an interesting calc-silicate deposit accessible in a road cut that parallels Interstate 70; minerals occurring here include grossular, titanite, vesuvianite, epidote, allanite, hedenbergite, scheelite, and meionite (Kile and Modreski, 1994).

Idaho Springs and Central City mining districts

Idaho Springs was named after the hot, alkaline springs located within the town. It was here, at a site near the confluence of Chicago Creek and Clear Creek known as "Jackson's diggings", that George Jackson discovered placer gold in January 1859 (fig. 26). However, John Gregory's discovery of a lode gold deposit in the spring of 1859 at a site just east of Central City considerably accelerated the influx of prospectors. William Russell shortly thereafter found gold in a nearby gulch, located between Idaho Springs and Central City, that now bears his name. At the same time, mines were being developed in Nevada Gulch, the site of the now-deserted town of Nevadaville. Intense mining activity continued while the oxidized and easily milled ores were available, but as work progressed below the zone of supergene ore (which ranged from 50 to 175 feet in depth) the refractory primary ores encountered precluded the efficient recovery of gold. Mining thus stagnated after about 1866 while awaiting further development of more effective milling and smelting techniques. The first smelter in the area was built at Black Hawk, and the district began a period of increasing production from the lode ores. The financial panic and reduction in the price of silver in 1893 had a lesser impact on the mines of Idaho Springs and Central City as production in these districts could be shifted to gold-bearing ores, but by 1894 the continuing decline in the price of silver led to an overall reduction in mining activity. Activity in the mining districts slowly declined to a near standstill by 1918. In 1933 the increase in the price of gold led to a renewed flurry of mining, which again ceased with the beginning of World War II. The search for uranium ores (primarily pitchblende) led to some activity between 1950 and 1955. Since then there has only been a sporadic and minor amount of mining, with many of the mines being sealed by the Colorado Mined Land Reclamation program.

The Idaho Springs and Central City mining districts, together with smaller adjacent districts, shipped ores valued at about $200 million. The Central City district alone accounted for more than $100 million, while the Idaho Springs district shipped ores at about $65 million. Gold accounted for about 60 percent of the total value of the ore. All told, more than $400 million, as gold, lead, zinc, and copper, were mined from these and nearby Front Range mining districts (Chronic, 1980).

The predominant rock unit in the region is a Precambrian microcline-bearing gneiss interlayered with biotite gneiss, formerly referred to as the Idaho Springs Formation (Sims, 1960); pegmatite is also a conspicuous rock unit in the area. Early Tertiary intrusive porphyries are also abundant in the area, in some cases forming extensive irregular stocks characterized by a mineralized breccia that is cut by numerous small

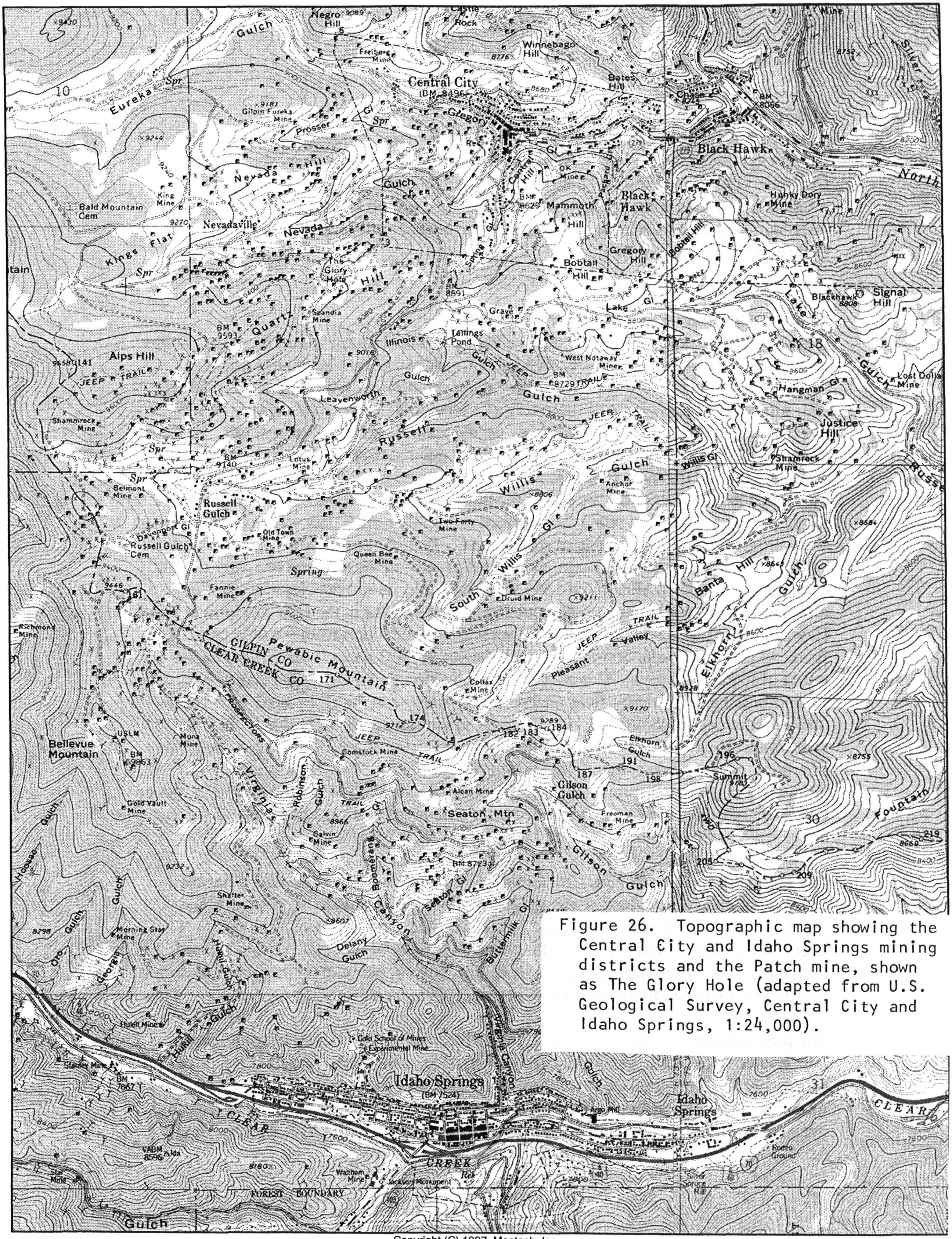


Figure 26. Topographic map showing the Central City and Idaho Springs mining districts and the Patch mine, shown as The Glory Hole (adapted from U.S. Geological Survey, Central City and Idaho Springs, 1:24,000).

branching veins (e.g., the Patch mine, see below). Most of the ore deposits in the district, however, are of the fissure-vein type, the most persistent being the California-Mammoth vein, which has been traced for approximately 2 miles and mined to a depth of 2,200 feet. Mineralization is mostly by fissure-filling rather than replacement, although exceptions are noted. The ores were probably derived from hydrothermal fluids related to Tertiary magmatic activity. Average gold content in the district ores varies between 1 to 3 ounces per ton, and silver content varies from 4 to 8 ounces per ton. Copper is generally less than 1.5 percent, but may range in some ores to 16 percent. The ore deposits are primarily pyritic gold, galena-sphalerite, and composite pyrite/galena sphalerite ores; these ore types are arranged in a concentrically zoned pattern noted by Sims and others (1963), with a central core of pyritic-type ores, and an outer peripheral zone of galena-sphalerite (Pb-Zn) veins (fig. 27). Stewart and Severson (1994) provide additional information on the geology, mining history and reclamation pertaining to the Idaho Springs area, and Lovering and Goddard (1953), Sims (1964), and Moench and Drake (1966a and b) give further details of the geology and mining industry of the Central City and Idaho Springs districts.

Argo Mill and Tunnel

The prominent tailings and buildings visible to the south (right) of Interstate-70 in the city limits of Idaho Springs are the Argo tunnel and mill. Originally named after Samuel Newhouse (an international mine promoter), the tunnel was started in 1893 and completed in 1910, with the intent of intersecting at depths of 1200 to 1600 feet many of the important veins in the Central City and Idaho Springs districts. Completion of this tunnel allowed water to be drained from the lower workings and a more economic means of ore haulage. The Argo tunnel extends 4.5 miles to a point 3/4 of a mile west of Central City and traverses the Patch orebody on Quartz Hill at a distance between 18,867 and 19,412 feet from the tunnel portal. Stories were told of the tunnel being used as a transportation route between these two towns during inclement winter weather. Other important mines connected to the tunnel by laterals were the Saratoga, Old Town, Calhoun, and Mammoth. Unfortunately, the high expectations for encountering valuable ore at depth were not realized. The tunnel was closed for all practical purposes in January of 1943 when miners inadvertently drilled into the bottom of the flooded Kansas mine shaft, resulting in a disastrous torrent of water that flushed the tunnel and killed four workers. The Argo Mill remains a conspicuous presence in Idaho Springs, and is now operated as a tourist stop.

Virginia Canyon ("Oh My God!") Road

This graded dirt road provides a spectacular overview of the town of Idaho Springs and surrounding mines (fig. 28). The route also gives an appreciation for the rugged terrain that early prospectors had to traverse without benefit of motorized vehicles. The near-ghost town of Russell, located in Russell Gulch, is en route to the Patch mine. The town and gulch were named after William Russell, one of the original gold prospectors in the area. Important mines were located in this area as early as 1859.

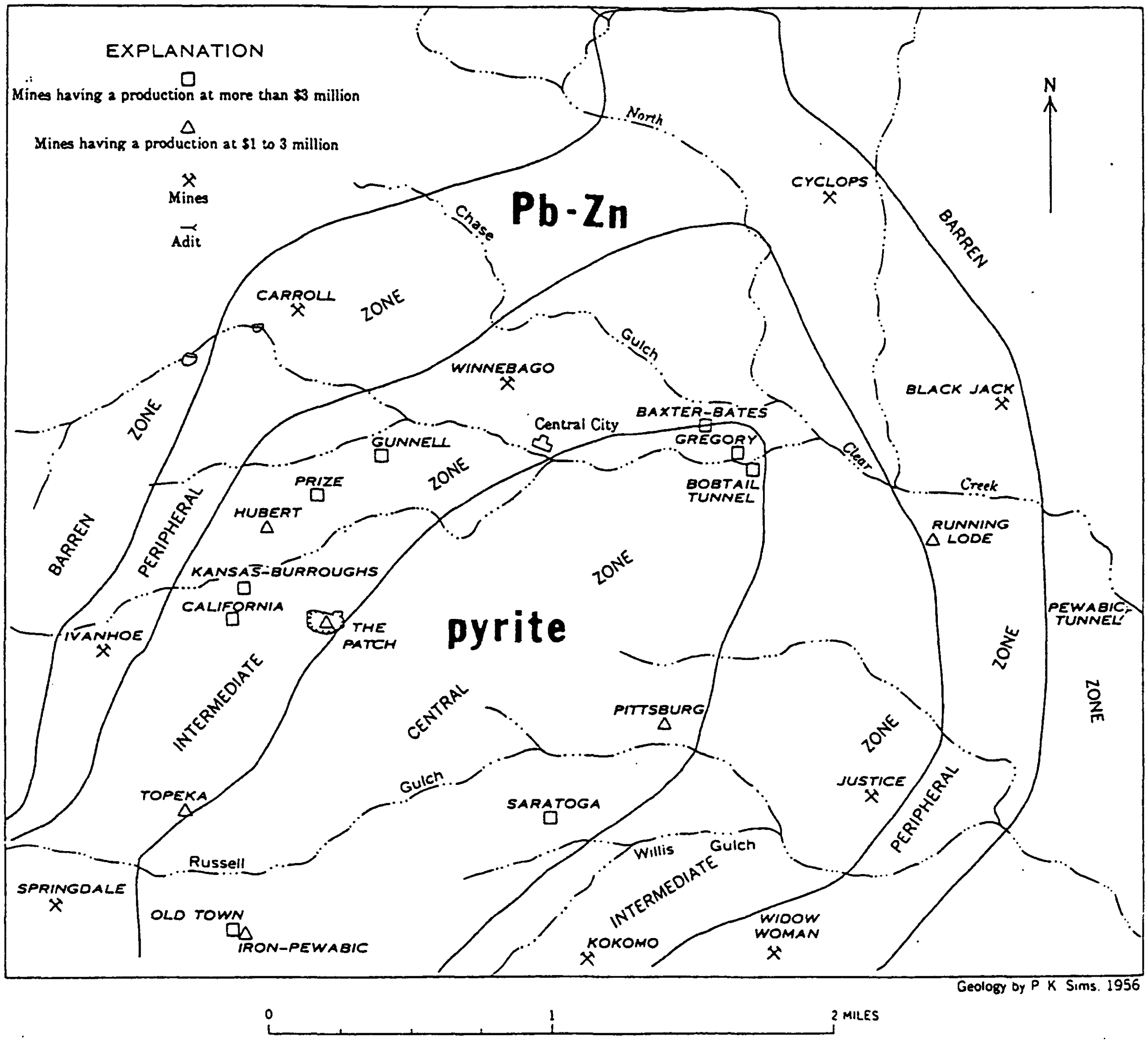


Figure 27. Mineral deposit zonation in Central City district (from Sims and others, 1963).

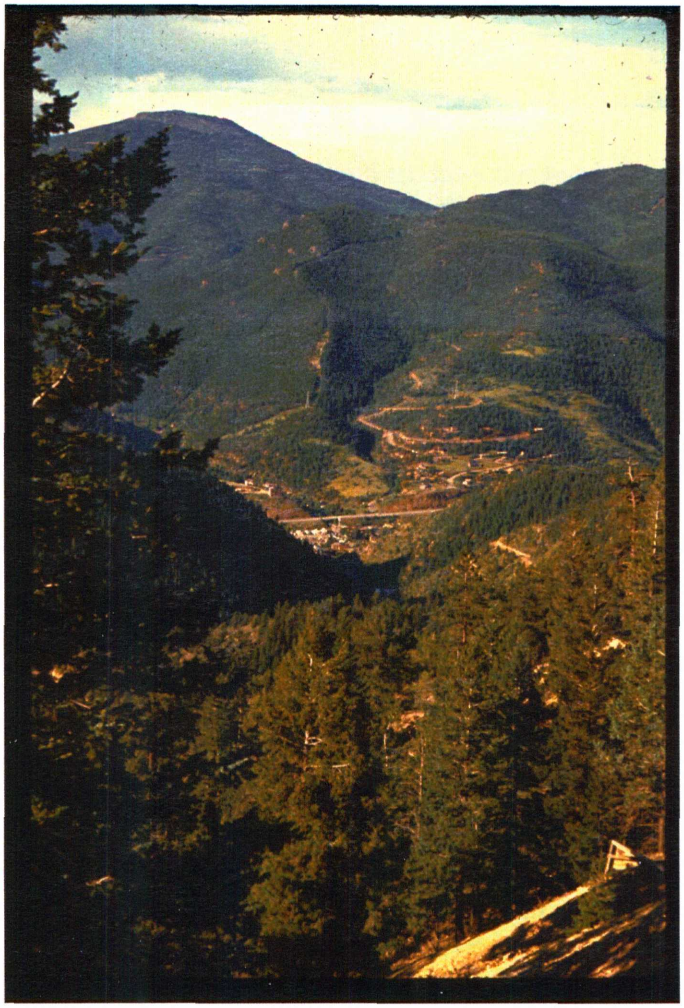


Figure 28. View of Idaho Springs from Virginia Canyon Road

Figure 29. View of the Patch mine, ca. 1972, looking west

PATCH MINE

CAUTION! *Deaths have been recorded at this locality when people wandered too close to open mine shafts, which are abundant in the area, and which are not always conspicuous. Moreover, rocks are constantly falling from the high walls of the open pit; prudence dictates that a respectful distance be kept from both hazards at all times during our visit.*

Mine workings and geology.

The Patch mine (fig. 29), located on Quartz Hill approximately one mile southwest of Central City, has had a colorful history including homicide and other assorted claims of fraudulent activities. This mine was located in 1929 by William Muchow, a Chicago dentist and mine promoter who consolidated numerous older mines on Quartz Hill and promoted the use of Patch mine ore for manufacture of dental gold (Muchow, 1952; fig. 30). Large-scale open-pit ("glory hole") mining by the Chicago-based Chain O' Mines Company thereafter progressed until 1937. Some of the prominent mines encompassed by the Patch mine are the San Juan, Rhoderick Dhu, Little Pittsburgh, Gardner, and Climax mines (figs. 31 and 32). In addition to the large open pit, the orebody was developed by three tunnels: the LaCrosse tunnel which enters from the north at the 300-foot level; the Quartz Hill tunnel entering from the east at the 700-foot level; and the Argo (formerly Newhouse) tunnel that enters from the south at the 1,600-foot level. The open pit mine is now about 750 feet long (east-west) and 400 feet wide (north-south). Activity at the Patch mine has been intermittent since the 1930's, with the last exploration and development work having been done in the early 1980's. A milling plant, located southeast of the mine alongside the main access road, has a capacity of more than 5,000 tons-per-day, and was reportedly operated on a limited basis during the early 1950's, and was last operated in the 1980's. It presently contains a ball mill, flotation cells, Wilfley tables, and an electroplating unit. Mine ownership has recently changed as a result of litigation.

The mine is a chimney-type or stockwork ore body of fractured and brecciated porphyry that is located within Precambrian granites, schists and gneisses, principally a microcline-bearing granite gneiss, but with Cretaceous/Tertiary Laramide bostonite porphyry occurring at several places. The breccia pipe, cut by a network of branching and interconnecting small veinlets, extends (dipping steeply to the north) 1,600 feet below the surface to the Argo tunnel level, where the ore assay values become substantially less than those in the upper workings. The nature of the interconnecting veinlets within the brecciated stockwork mandated that the entire deposit could be mined by open pit methods. Mineralization was mostly by fissure filling within the fractures. Substantial movement of breccia fragments is evidenced by considerable rounding and mixing of fragment types. Sims and others (1963) postulated that brecciation was a result of an upward thrust of magma that was accompanied by considerable gas, resulting in an explosion when lithostatic pressure was overcome. Alteration and mineralization followed the brecciation.

The Alice mine, located near Fall River Road about 5 miles east of the Patch mine, is a similar but smaller stockwork ore deposit of fractured quartz monzonite and alaskite

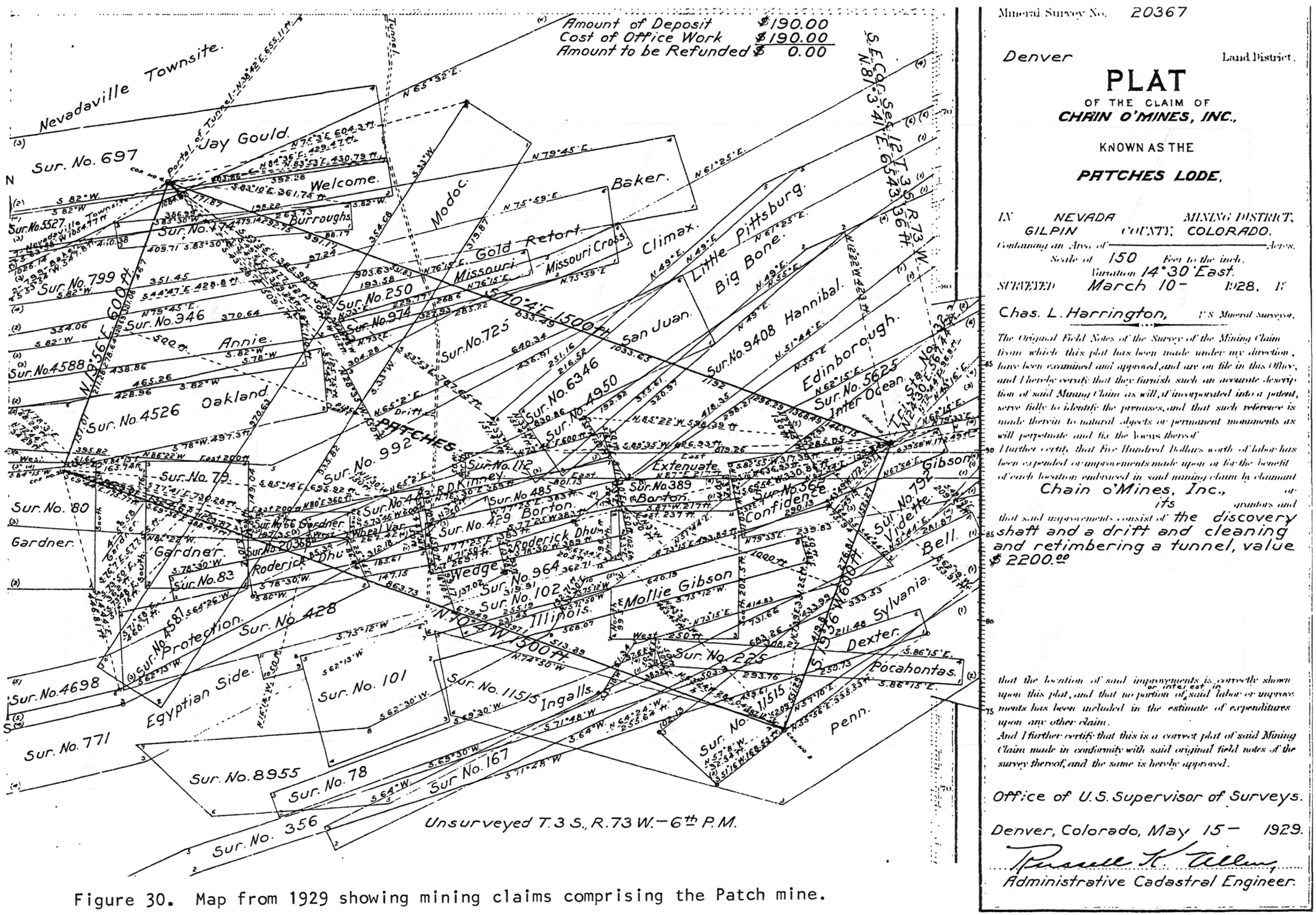


Figure 30. Map from 1929 showing mining claims comprising the Patch mine.

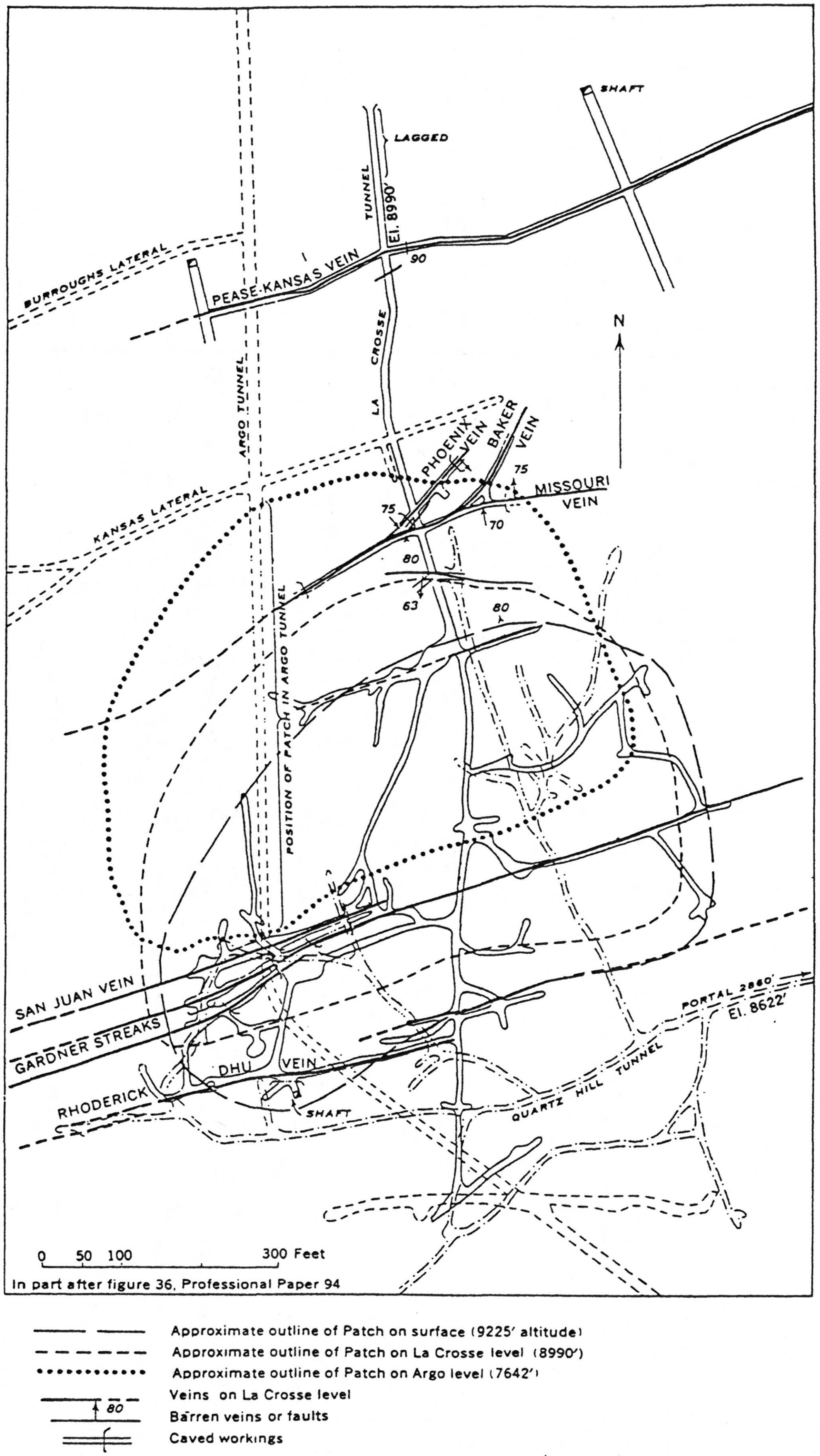


Figure 31. The Patch mine, Central City district (Lovering & Goddard, 1950).

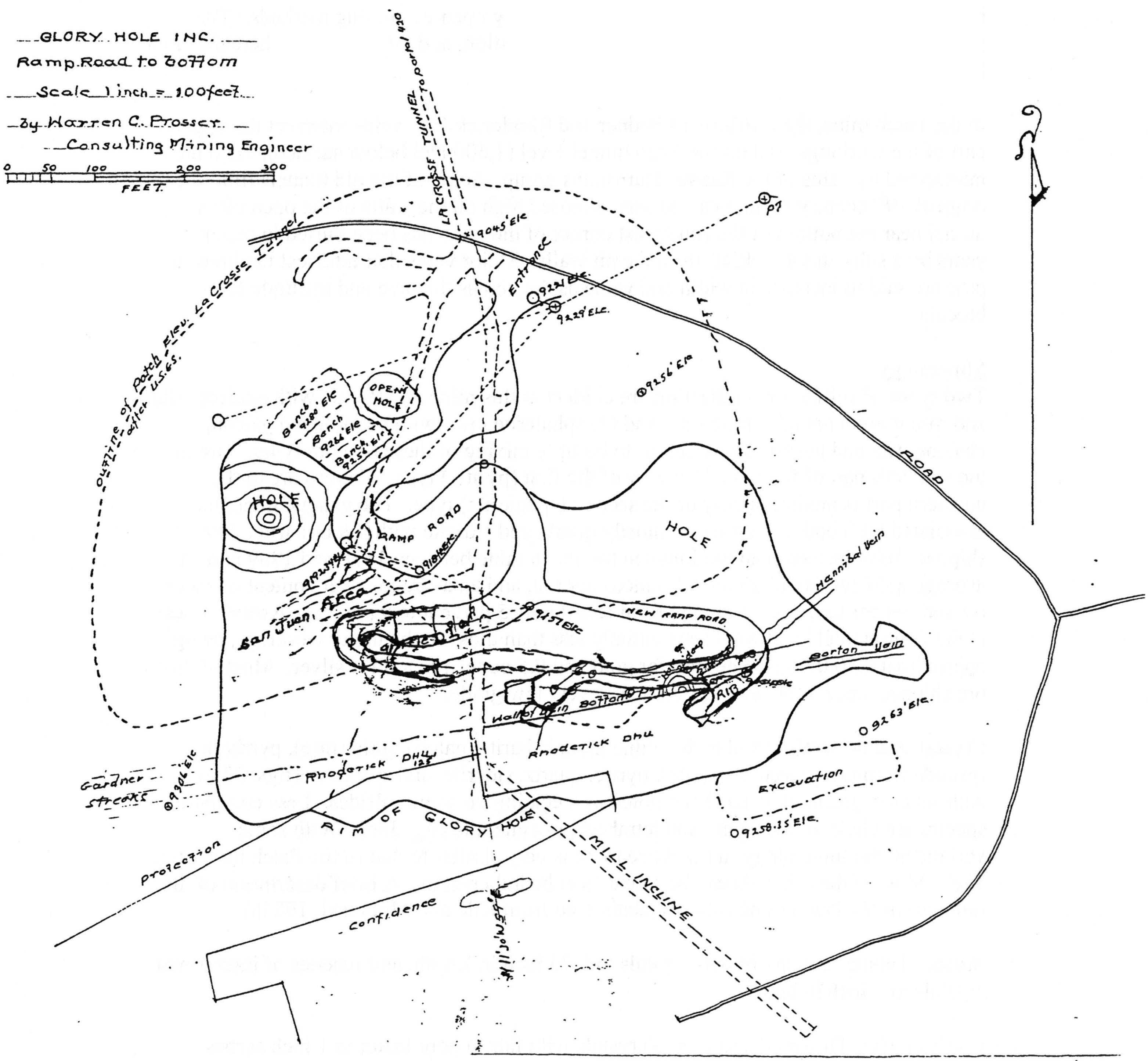


Figure 32. Sketch of the Glory Hole, by W. Prosser.

porphyries intruding Precambrian gneiss and schist. Mineralization here was mostly by metasomatic alteration and replacement along small interconnecting fractures, in contrast to that in the Patch mine, where mineralization occurred primarily by fissure filling. The Alice mine is much smaller in size than the Patch mine, but as with the Patch mine, the irregular nature of the veins allowed development by open-pit mining methods. The property was worked in the 1880's as a placer operation, and intermittently thereafter as a lode deposit.

In the Patch mine, the California-Gardner and Rhoderick Dhu veins intersect the upper part of the workings, and on the Argo tunnel level (1,600 feet below surface), the mine is intersected by veins of the Kansas-Burroughs group. Some of the old tunnels from the original 19th century mining can be seen exposed high on the walls of the open pit; a tunnel near the bottom of the southwest corner of the mine has been buried in recent years by a substantial rockfall from the pit walls. Major veins that intersect the breccia pipe are said to increase in width and value as they cross the pipe and infiltrate the breccia.

Mineralogy.

Two types of sulfide mineralization are evident at this mine: (1) Pyrite, with chalcopyrite and minor amounts of tetrahedrite; and (2) sphalerite ores, with subordinate galena, chalcopyrite and pyrite. There seems to be little mixing of these two ore types. Ore in the southern part of the mine is mostly of the first (pyritic) type, whereas ore in the northern part is predominantly of the second (sphalerite) type. The gangue minerals associated with both ore types are mostly quartz and siderite with minor barite. Ore shipped from the San Juan workings in the Patch mine between 1888 and 1909 had an average gold content of about 2.1 ounces per ton, and an average silver content of about 6.8 ounces per ton; copper ranged from less than 1.5 percent to 9 percent. Assay values at the Argo tunnel level were substantially less than those in the upper workings, being approximately 0.07 ounce per ton for gold and 0.5 ounce per ton for silver. Most of the ore shipped since 1900 was of a comparatively low grade.

Crystallized minerals found at this mine include barite, galena, gold (rare), pyrrhotite (pseudomorphs replaced by pyrite), pyrite, quartz, siderite, and sphalerite(figs. 33a-c); additionally, greenockite has been noted as a coating on some sulfides. Less common species are chalcopyrite, gold, and tetrahedrite-tennantite (fig. 33d). With some variations, the mineralogy in the Alice mine is very similar to that of the Patch mine (fig. 33e). Most of the minerals can be found as euhedral crystals. A brief description of the minerals at the Patch mine follows (abstracted from Kile and Modreski, 1988b):

Barite. Tabular cream-colored crystals to 0.75 inch in length, and rosettes of intergrown crystals to 1 inch in length.

Chalcopyrite. Distorted and etched crystals with fair to poor luster to 1 inch across; uncommon.

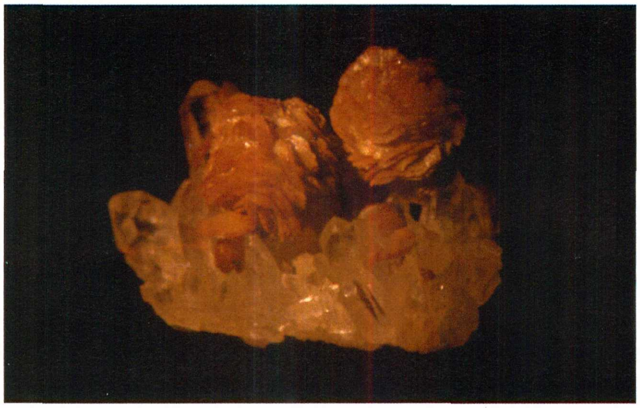


Fig. 33a. Siderite on quartz, Patch mine

Fig. 33b. Quartz, Patch mine

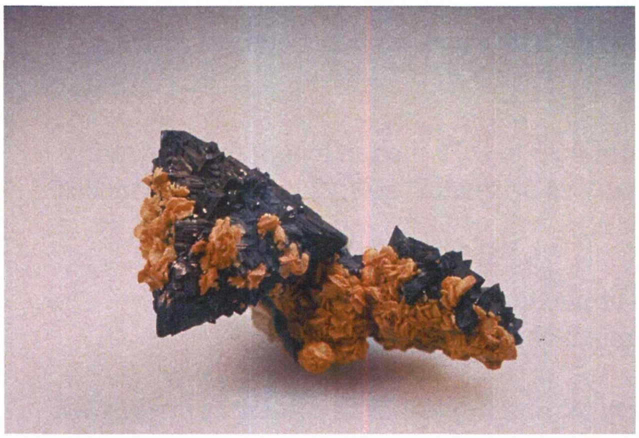


Fig. 33c. Sphalerite, siderite, Patch mine

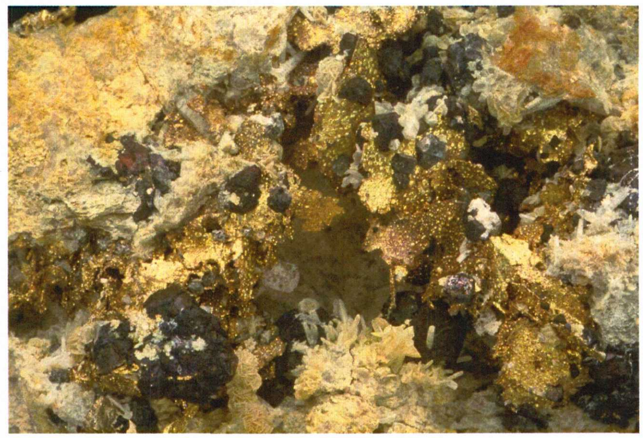


Fig. 33d. Native gold with sphalerite, quartz and siderite, Patch mine (field of view 6.2 cm. D. Bunk specimen, J. Scovil photograph)

Fig. 33e. Pyrite, siderite and quartz, Alice mine

Galena. Sharp cubes to 2 inches on edge, with corners sometimes modified by the octahedron; can also occur with a predominantly octahedral form.

Gold. Wire gold in aggregates exceeding 1 inch in length; also as a "leaf" habit (with individual leaves to about 0.5 inch) associated with sphalerite and siderite.

Greenockite. Greenish-yellow coating on earlier-formed minerals; predominantly an iron-free sphalerite, but with X-ray diffraction confirming the presence of intergrown CdS.

Pyrrhotite. Hexagonal pseudomorphs after pyrite to about 2 inches in length.

Pyrite. Cubic crystals (sometimes heavily striated) to 1 inch on edge; corners often modified by the octahedron.

Quartz. Typically as stout, clear crystals from 0.25 to 0.75 inch in length that can rarely show well-developed scepters, but occasionally as prismatic "milky" crystals to 3 inches in length.

Siderite. Cream-to-tan rosettes (sometimes brown due to an iron oxide coating) composed of single crystals that may be as much as 0.3 inch across.

Sphalerite. Black tetrahedral crystals (variety marmatite) to 1 inch across; as intergrown crystals comprising groups exceeding 2 inches across.

Tennantite-tetrahedrite. Reported from the Patch mine by Bastin and Hill (1917), but not observed as euhedral crystals.

<u>Clay minerals</u>.
The host breccia (originally a granite gneiss) shows locally extensive sericitic or argillic alteration that is conspicuous in thin section; feldspar minerals have been almost completely replaced by phyllosilicates, and only quartz remains along with secondary carbonate minerals and pyrite (fig. 34). An XRD pattern of this rock is shown in figure 35 (sample DR-1; glycolated pattern, < 2-μ fraction). Quantitative XRD analysis of this sample (whole-rock sample, designated FG-1; table 3) shows 50 percent illite/sericite with 39 percent quartz, 2 percent siderite, and 1 percent pyrite. Analysis of the fundamental particle size for the illite peak (using a PVP-treated, < 2-μ fraction sample and the MudMaster program) shows a lognormal size distribution with a mean size of 19.3 nm (fig. 36). Analysis of a clay-bearing lens from a sample in the north wall of the Patch mine (sample DR-2; glycolated, < 2-μ fraction; fig. 37) shows illite and kaolinite as the predominant clay minerals.

The mineralized cavities bearing crystallized sulfides and gangue minerals, which occur between breccia fragments and at intersections of ore-bearing veinlets, are often clay-filled. XRD analysis of one such sample (no. 83, fig. 38) shows the clay minerals to be predominantly illite with a small amount of kaolinite. Analysis of this illite (PVP-treated,

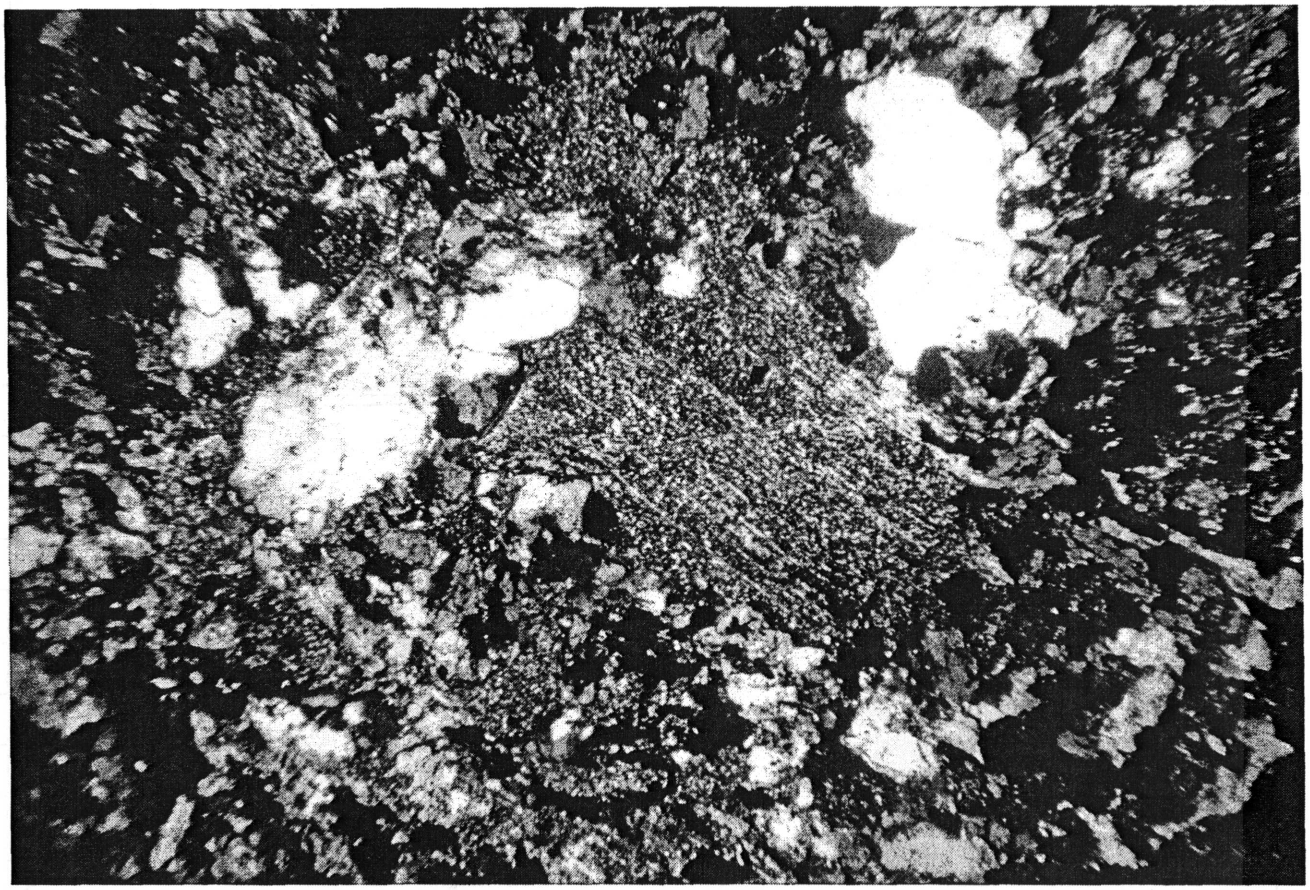


Figure 34. Photomicrograph of thin section of a sericitized ore-bearing granite gneiss from the Patch mine. Feldspars have been almost completely replaced by mica/illite, leaving only quartz with secondary carbonates (siderite) and pyrite. Sericitic/argillic areas appear here as fine-grained material in the center of the section.

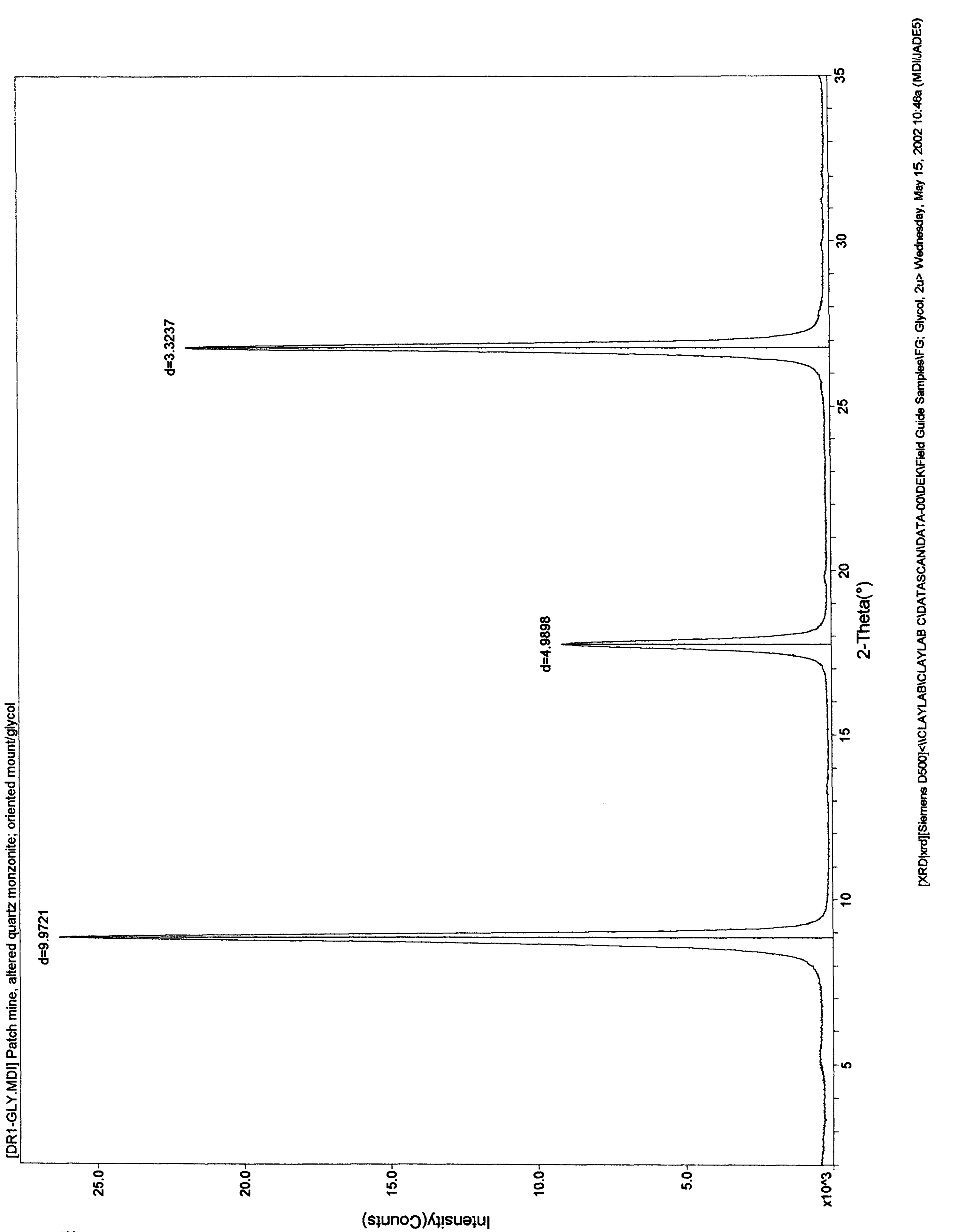
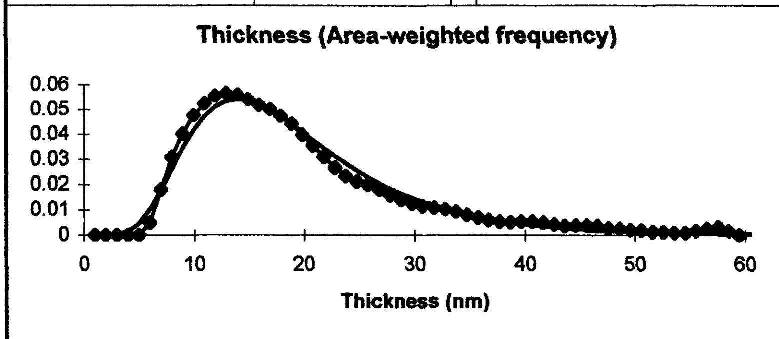


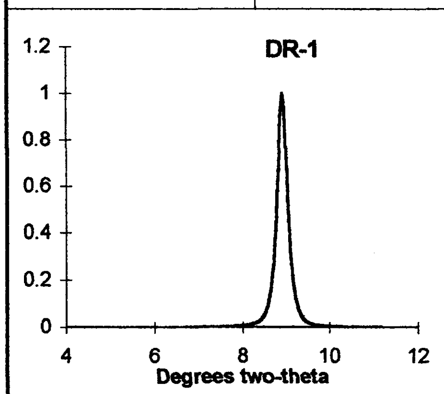
Figure 35. X-ray diffraction pattern of (DR-1) of altered granite gneiss, Patch mine.

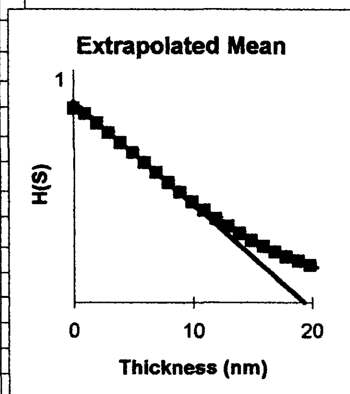
Table 3. Quantitative mineralogy results (FG-1), altered granite gneiss, Patch mine.

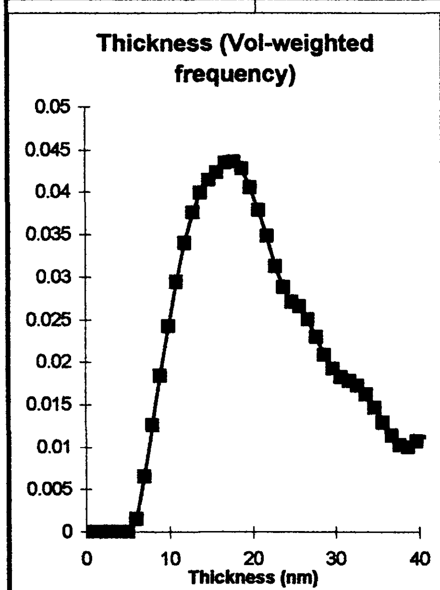
Sample Name:	FG-1
Mineral	**Weight %**
NON-CLAYS:	
intermed. Microcline feldspar	3
Albite feldspar	0
Pyrite	1
Siderite	2
Quartz	39
Total non-clays:	45
CLAYS:	
1M illite	14
2M1 illite	36
Chlorite Tusc	3
Total Clays:	53
Total:	98
Not constrained	
Fspar region degree of fit:	0.101
Clay region degree of fit:	0.059
ZnO correction factor:	1.000

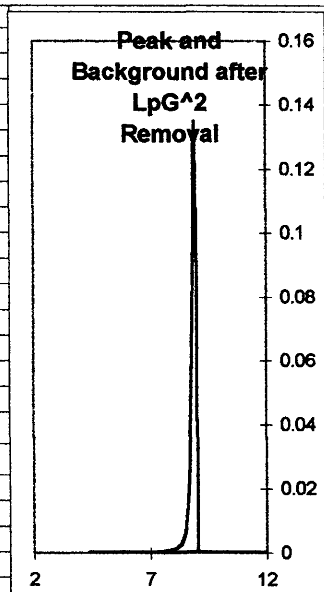
SAMPLE NAME	DIST. LIMIT? (nm)	SYM. STRAIN COR.? (1=YES)
DR-1	60	0
DATE OF MM ANALYSIS	SMOOTH POWER?	INST COR? (1 = YES; active if D2 ? 1)
5/29/02 15:14	1	0

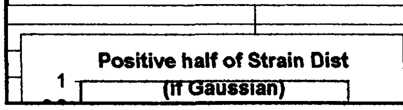


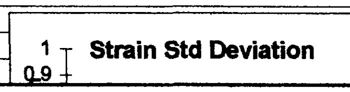












PVP-ILLITE
BEST MEAN (nm; EXTRAPOLATED; area-weighted)
19.3
MEAN (nm; DISTRIBUTION; area-weighted)
19.5
ALPHA (from nm)
2.85
BETA^2
0.22
VOL-WEIGHTED MEAN THICKNESS (nm)
24.5
POSITION INT. FN. (two-theta)
8.92
d-SPACING INT. FN. (Å)
9.914
ROOT MEAN SQUARE STRAIN (Å)
Not calculated
APPROX FUND PART THICK (nm; area-weighted)
19.4
ILLITE FIXED CATIONS/HALF-UNIT CELL (see L16)
0.84
SPEC a-b SUR AREA (M^2/g; density in cell L18)
38
HIDDEN KNOBS SET AT RECOMMENDATIONS?
YES
SYMM. STRAIN ANAL. NO. (0=NONE)
0
STARTING TWO-THETA
4.40
ENDING TWO THETA
9.00
STEP SIZE (TWO-THETA)
0.02
INCREMENT IN N USED FOR FOURIER ANALYSIS
1
REFLECTION ORDER
1
MAXIMUM SIZE CALCULATED
100
RADIATION WAVELENGTH? (Å)
1.54184
"n" IF ALPHA 1 ANALYSIS USED
K-ALPHA USED
FLIP?
L to R
EXPANDABILITY (%)
0
LpG^2's USED: INTERIOR/EDGES
illite, .89K, combo
PVP Kinney norm vs newmod illite,10-20 degree region
FRACTION OF INTERIOR LpG^2
0.95
LOWER LIMIT FOR DISTRIBUTION
0
OTHER INFORMATION
0

Figure 36. Particle-size distribution for illite from altered granite gneiss, Patch mine (sample DR-1).

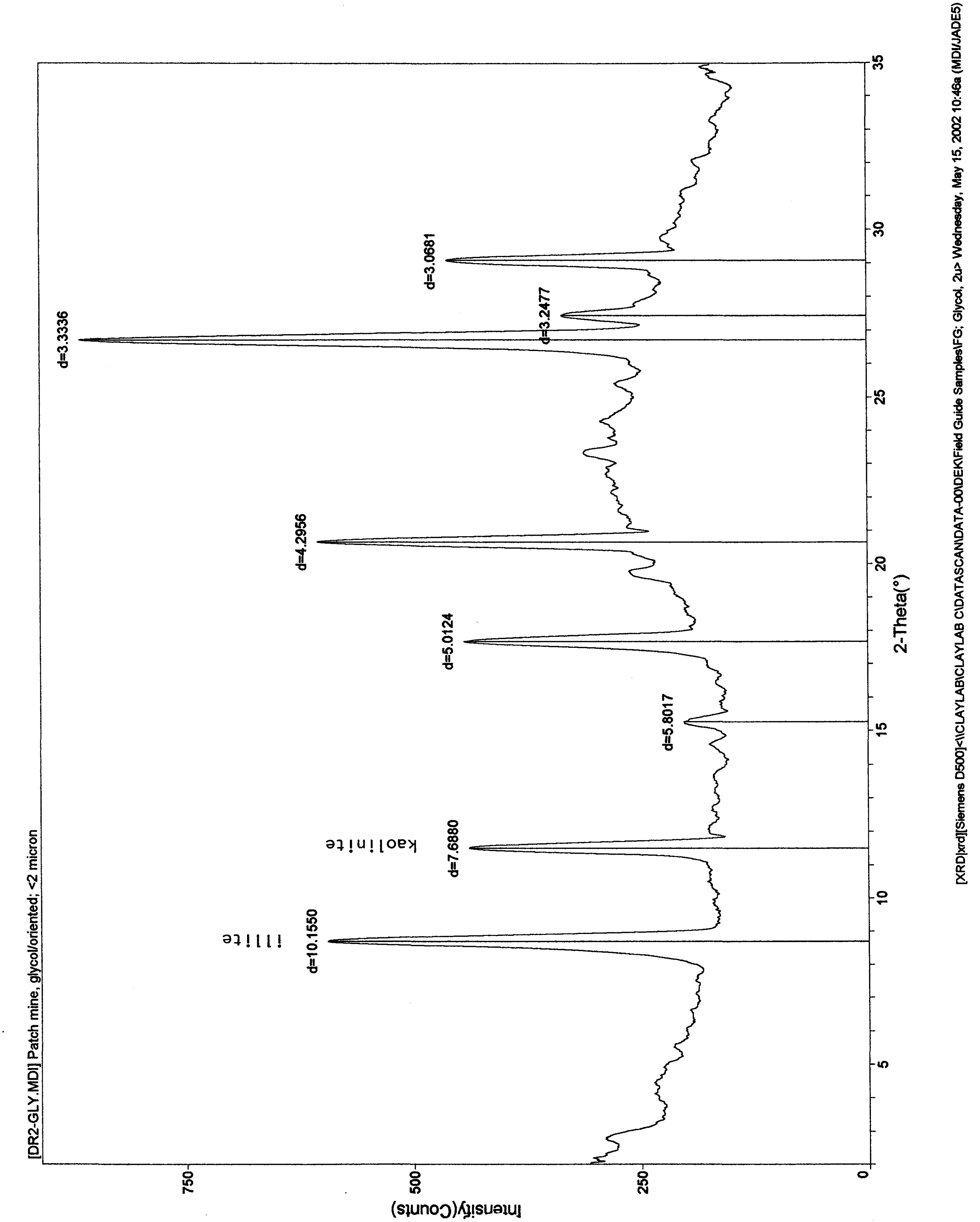


Figure 37. X-ray diffraction pattern of clay lens, Patch mine (sample DR-2).

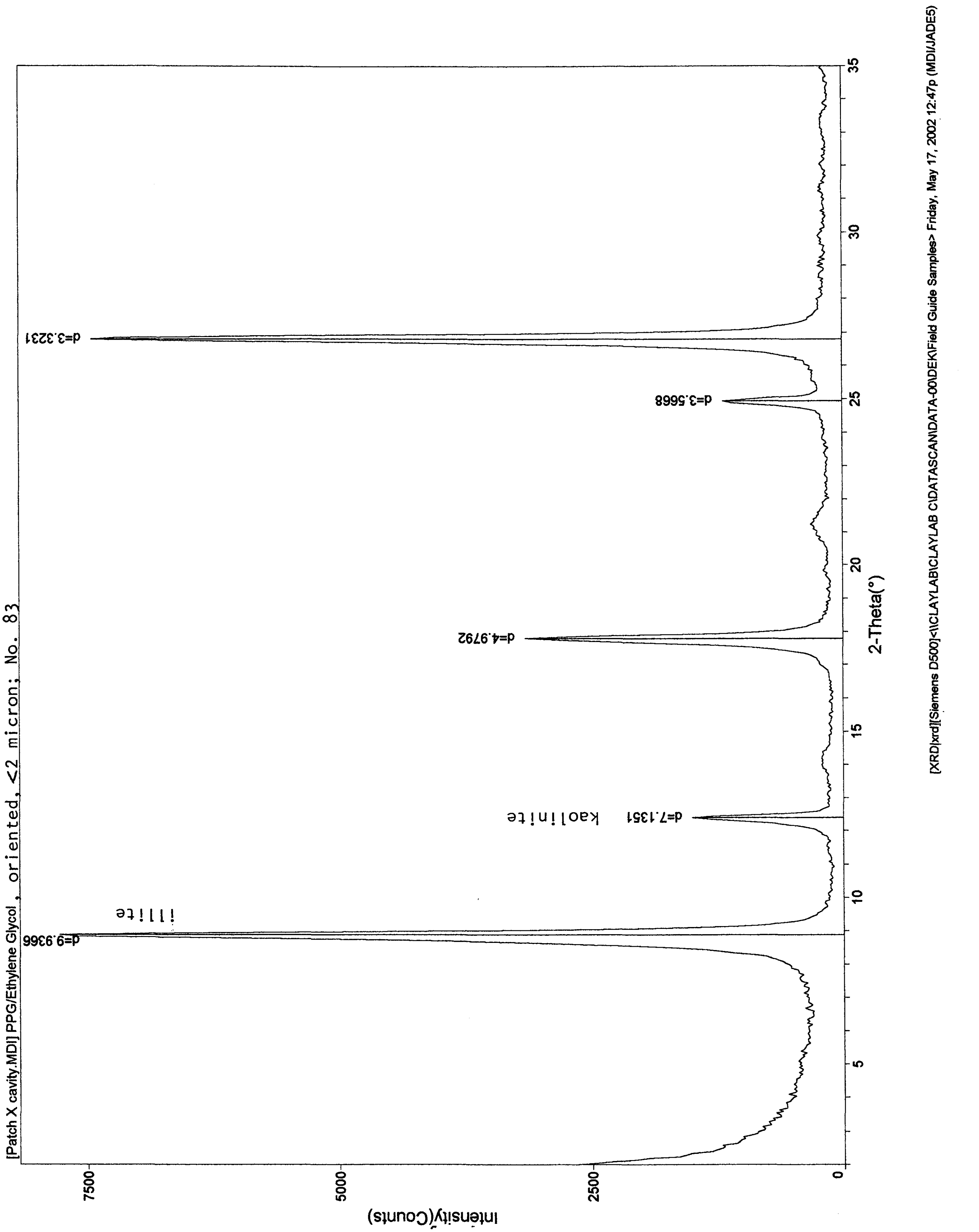
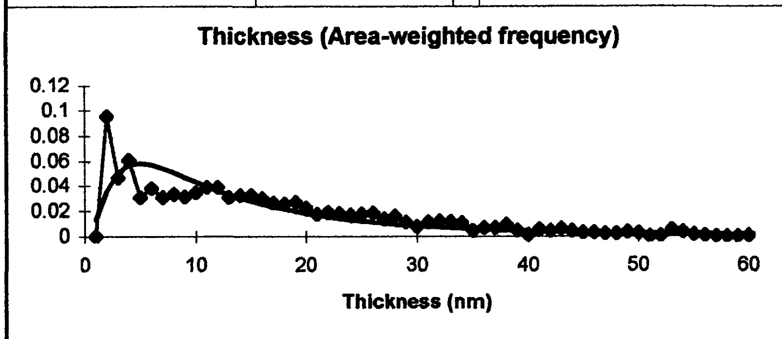
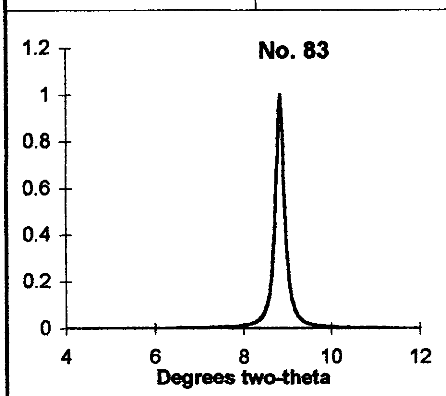
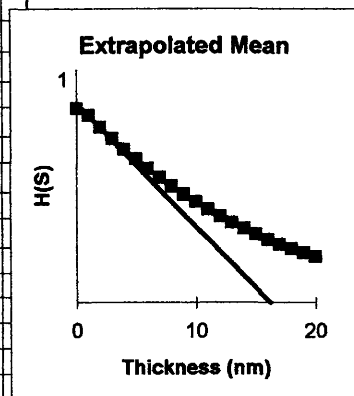


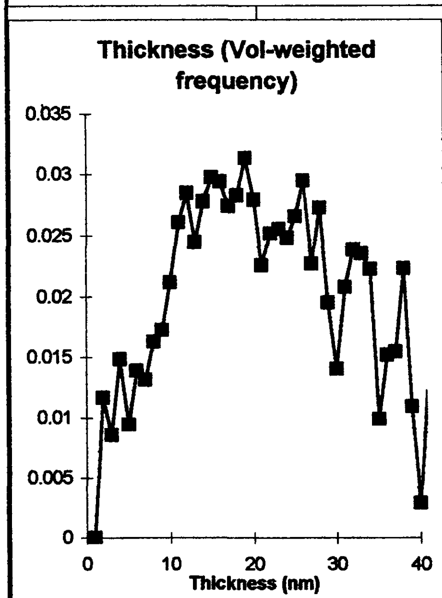
Figure 38. X-ray diffraction pattern of sulfide-cavity clay, Patch mine (sample no. 83).

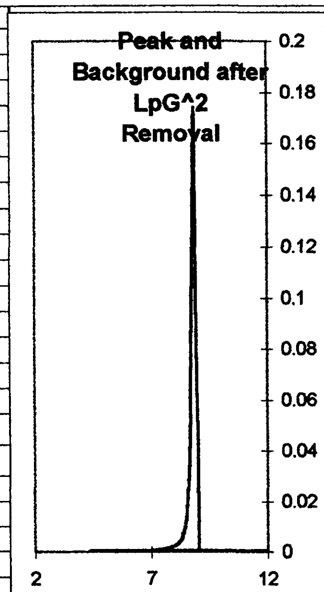
SAMPLE NAME	DIST. LIMIT? (nm)	SYM. STRAIN COR.? (1=YES)	PVP-ILLITE
No. 83	70	0	BEST MEAN (nm; EXTRAPOLATED; area-weighted)
DATE OF MM ANALYSIS	SMOOTH POWER?	INST COR? (1 = YES; active if D2 ? 1)	16.2
5/29/02 15:16	0	0	MEAN (nm; DISTRIBUTION; area-weighted)
			16.3

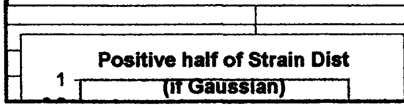


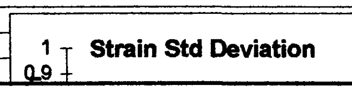












ALPHA (from nm)	2.43
BETA^2	0.85
VOL-WEIGHTED MEAN THICKNESS (nm)	26.8
POSITION INT. FN. (two-theta)	8.84
d-SPACING INT. FN. (Å)	10.003
ROOT MEAN SQUARE STRAIN (Å)	Not calculated
APPROX FUND PART THICK (nm; area-weighted)	16.1
ILLITE FIXED CATIONS/HALF-UNIT CELL (see L16)	0.84
SPEC a-b SUR AREA (M^2/g; density in cell L18)	45
HIDDEN KNOBS SET AT RECOMMENDATIONS?	YES
SYMM. STRAIN ANAL. NO. (0=NONE)	0
STARTING TWO-THETA	4.40
ENDING TWO THETA	9.00
STEP SIZE (TWO-THETA)	0.02
INCREMENT IN N USED FOR FOURIER ANALYSIS	1
REFLECTION ORDER	1
MAXIMUM SIZE CALCULATED	100
RADIATION WAVELENGTH? (Å)	1.54184
"n" IF ALPHA 1 ANALYSIS USED	K-ALPHA USED
FLIP?	L to R
EXPANDABILITY (%)	0
LpG^2's USED: INTERIOR/EDGES	illite, .89K, combo
	PVP Kinney norm vs newmod illite,10-20 degree region
FRACTION OF INTERIOR LpG^2	0.94
LOWER LIMIT FOR DISTRIBUTION	0
OTHER INFORMATION	0

Figure 39. Particle-size distribution for illite from sulfide cavity (sample no. 83), Patch mine.

Sheet1 Chart 3

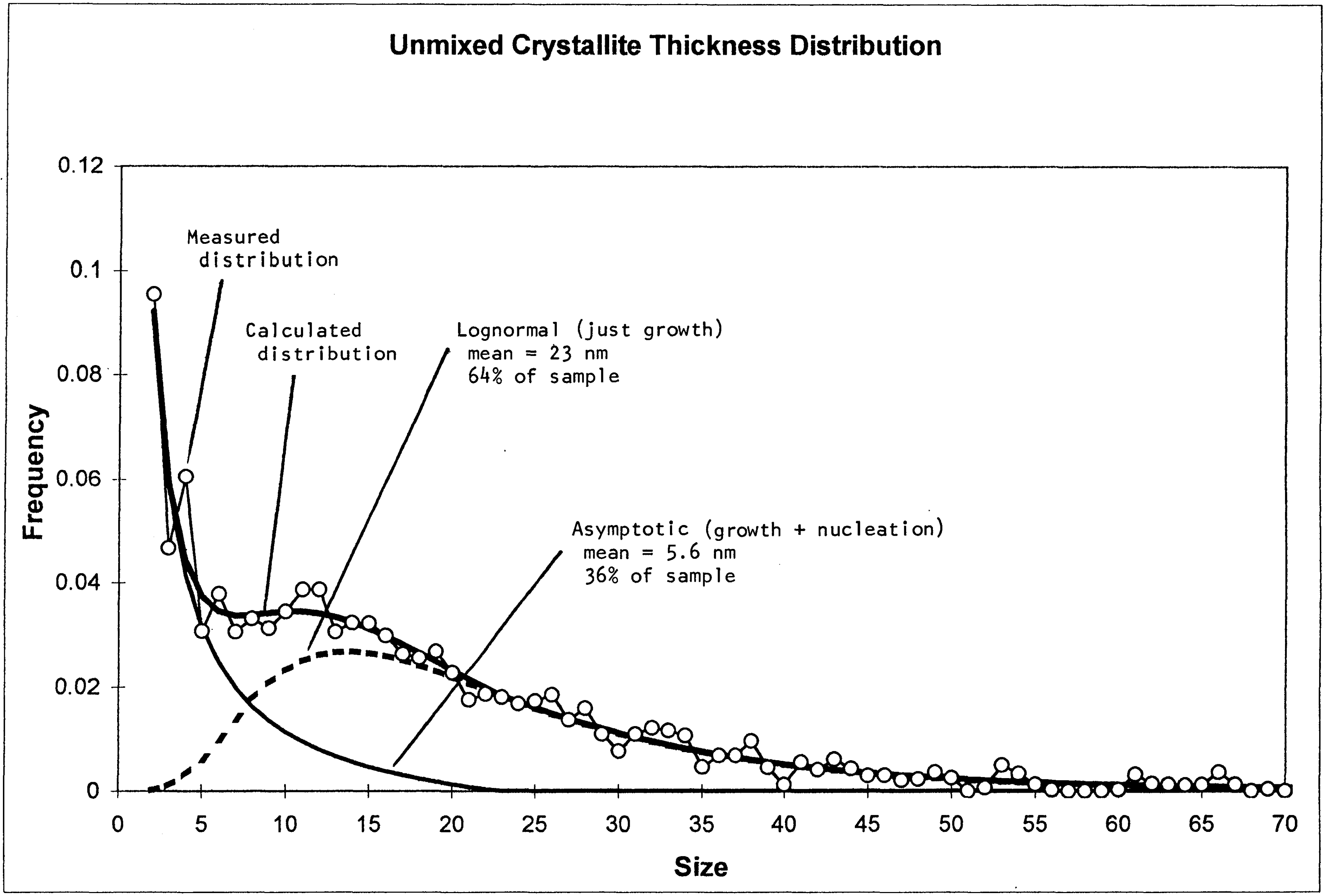


Figure 40. Crystal-size distribution modeling of the bimodal illite particle-size distribution (sample no. 83), Patch mine.

< 2-μ fraction) by MudMaster shows a mean particle size of 16.2 nm (fig. 39); this is in contrast to the larger mean particle size (19.3 nm) found in the sericitized host rock. Moreover, the crystal size distribution for this illite is bimodal, showing an asymptotic distribution for the curve on the left of the plot, and a lognormal distribution for the curve to the right. This suggests two discrete illite nucleation events in the sulfide cavity, with the earliest event producing the lognormal curve (mean size = 23 nm, which more closely approximates the illite particle size in the sericitic host rock), and the later event producing the asymptotic curve (mean size = 5.6 nm). A separate curve modeling these crystal size distributions is shown in fig. 40.

Central City Overlook

The overlook above Central City (fig. 41) gives a panoramic view of what was once one of the state's most prominent mining districts. This area was earlier called "the richest square mile on earth"; while probably not quite true, it was certainly one of the richer mining districts in the state of Colorado, and in the 1860's Central City rivaled Denver in importance. The Opera House with its famous "face on the bar room floor" was renowned for its cultural activities; Horace Tabor, of Leadville fame, was among the fortune-seekers who spent time prospecting the surrounding hills. Some of the important mines near Central City, such as the Couer d' Alene, National, and St. Louis, are also visible from this overlook. Central City is today a so-called "gaming" town, with legalized gambling.

Black Hawk

The Gregory lode, located between Central City and Black Hawk, is the site of the original lode gold discovery in Colorado. The town of Black Hawk is now a prominent gambling town. Note the effectiveness of historic preservation regulations that were intended to maintain the original appearance and ambiance of this mining town when gambling legislation was approved.

Peak-to-Peak Highway (Colorado 119)

Colorado highway 119 traverses areas of spectacular scenery between Black Hawk and Nederland, including a panorama of the Indian Peaks. The town of Rollinsville and the Eldora ski area are along the way.

Nederland; mining in Boulder County

Mining in Boulder County began in 1859 with the discovery of gold, and significant deposits of silver-bearing ores were located in the Caribou district in 1869. The towns of Ward, Gold Hill, and Jamestown were among the local centers of precious metals production. In addition to the ordinary gold- and silver-bearing ores found in Boulder County (e.g., galena, pyrite, chalcopyrite, tetrahedrite, arsenopyrite), perhaps the most noteworthy were the Au-Ag-Pb-bearing telluride minerals, such as altaite, calaverite, hessite, krennerite, petzite, and sylvanite, which were locally relatively common

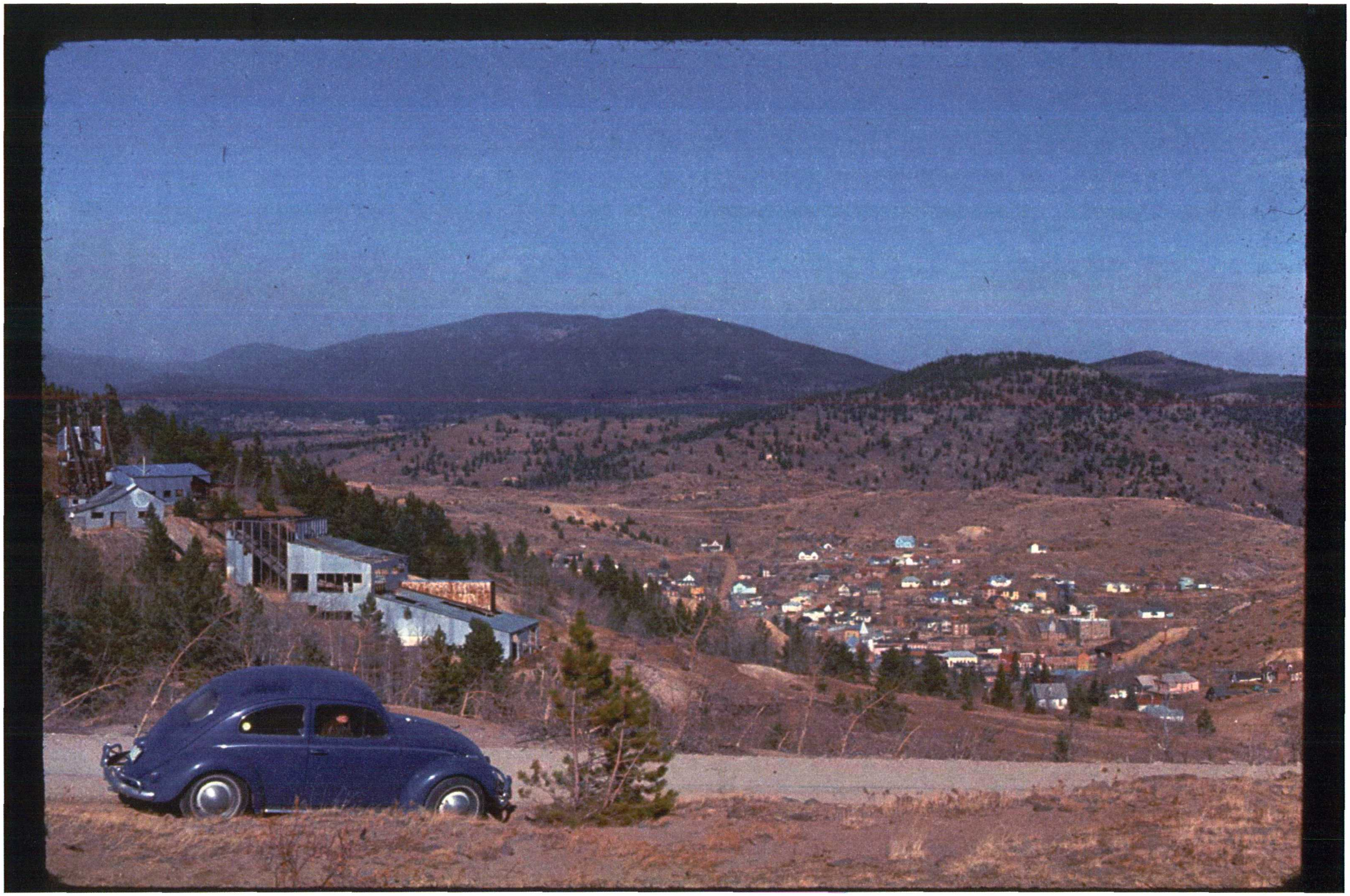


Figure 41. View of Central City in the early 1970's

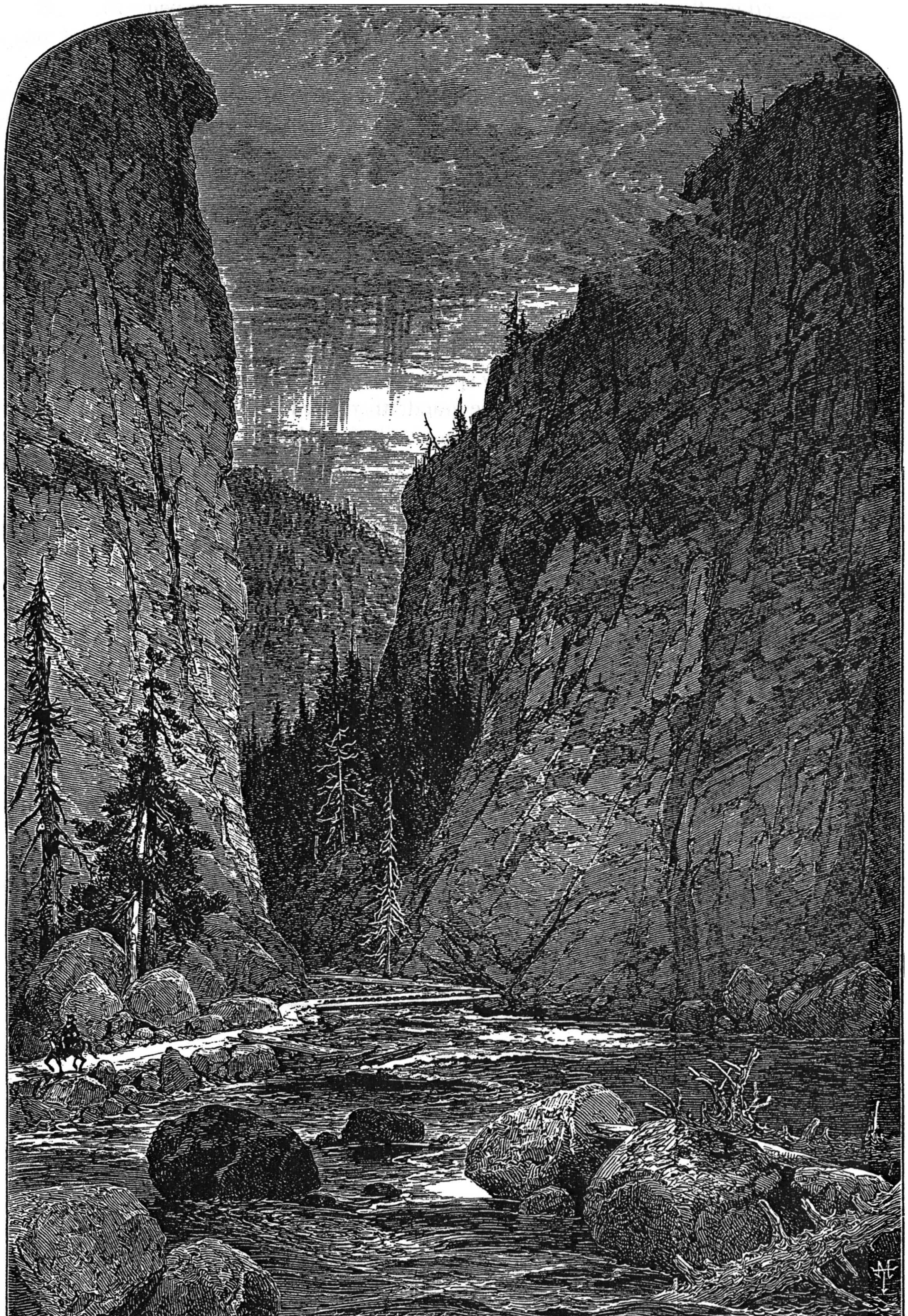
compared to other North American mining districts (Cripple Creek being the other notable locality for these rare tellurides). In contrast, Nederland was a center of tungsten mining; ores of this strategic metal, principally ferberite ($FeWO_4$), occurred in a northeast-trending belt through northern Gilpin and southern Boulder counties, and were mined in substantial quantity in the early 1900's. Economic deposits of fluorspar were mined near Jamestown through the mid-20th century. These mining districts lie predominantly in Boulder Creek Granodiorite, Silver Plume quartz monzonite, and in Precambrian gneisses, in addition to alkali feldspar syenite and quartz syenite of Eocene age (Colton, 1978; Gable, 1980). Additional information about Boulder County mining and tungsten deposits can be found in Henderson (1926), Lovering (1940), and Lovering and Tweto (1953).

Nederland has a colorful history that extends beyond its mining heritage. For example, the town of Nederland hosts, in early spring, the "Frozen Dead Guy Festival". This event was inspired by Trygve Bauge, whose grandfather, Bredo Morstoel, had passed away in 1989, whereupon Trygve dutifully cryogenically froze him with the idea of someday re-animating the preserved remains. Although Tyrgve was deported to Norway some years back, grandpa remains in a Nederland tool shed, frozen at –109° F with periodic maintenance by a dry-ice company for the past 7 years. The annual Frozen Dead Guy Festival features such unforgettable events as grandpa look-alike contests and coffin races. According to some accounts, Grandpa Bredo is technically not dead – he is only awaiting re-animation; his status with the U.S. Census Bureau is consequently uncertain, and there have been no substantiated reports of his contact by psychics.

Boulder Canyon

The last part of the return trip to Boulder encompasses a segment that passes through Boulder Canyon, an area of spectacular beauty that was recognized by the early 1870's by members of the Hayden Survey (fig. 42). Most of the rock comprising the canyon walls is the Precambrian Boulder Creek Granodiorite (Colton, 1978).

Boulder Falls enters the canyon near Boulder. This side-trip provides a short but scenic hiking trail to the falls located just north of the main highway.



Boulder Cañon, Colorado: Granite.

Figure 42. Lithograph showing Boulder Canyon (from Hayden, 1876).

REFERENCES

Bastin, E.S., and Hill, J.M., 1917, Economic Geology of Gilpin County and Adjacent Parts of Clear Creek and Boulder Counties, Colorado. U.S. Geological Survey Professional Paper 94, 379 p.

Berthoud, E.L., 1880, History of Jefferson County - - History of Clear Creek and Boulder Valleys, Colorado: Chicago, O.L. Baskin and Co., p. 353-377.

Bohor, B.F., and Triplehorn, D.M., 1993, Tonsteins: Altered volcanic-ash layers in coal-bearing sequences. Geological Society of America Special Paper 285, Boulder, Geological Society of America, 40 p.

Brown, R.W., 1943, Cretaceous-Tertiary boundary in the Denver Basin. Bulletin of the Geological Society of America, v. 54, p. 65-86.

Butler, G.M., 1914, Clays of Eastern Colorado: Colorado State Geological Survey, Bulletin 8, 353 p.

Chronic, H., 1980, Roadside Geology of Colorado: Missoula, Montana, Mountain Press Publishing Co., 322 p.

Colton, R.B., 1978, Geologic map of the Boulder-Fort Collins-Greeley area, Colorado: U.S. Geological Survey, Miscellaneous Investigations Series I-855G.

Cross, W., and Hillebrand, W.F., 1882, Communications from the U.S. Geological Survey, Rocky Mountain Division. I. On the minerals, mainly zeolites, occurring in the basalt of Table mountain, near Golden, Colorado: American Journal of Science, 3^{rd} series, v. 23, p. 453-459.

Cross, W., and Hillebrand, W.F., 1885, Minerals from the basalt of Table Mountain, Golden, Colorado: U.S. Geological Survey Bulletin 20, p. 13-29.

Eckel, E.B., 1997, Minerals of Colorado, updated and revised by Collins, D.S., Cobban, R.R., Foord, E.E., Kile, D.E., Modreski, P.J., and Murphy, J.A. Golden, Colorado, Fulcrum Press, 665 p.

Emmons, S.F., Cross, W., and Eldridge, G.H., 1896, Geology of the Denver Basin in Colorado. U.S. Geological Survey Monograph 27, 551 p.

Gable, D.J., 1980, Geologic map of the Gold Hill quadrangle, Boulder County, Colorado: U.S. Geological Survey, Geologic Quadrangle Map GQ-1525. Scale 1:24,000.

Hart, S.S., 1974, Potentially swelling soil and rock in the Front Range Urban Corridor, Colorado: Colorado Geological Survey Environmental Geology no. 7, 23 p.

Hayden, F.V., 1869, Preliminary Field Report [3rd Annual Report] of the U.S. Geological Survey of Colorado and New Mexico: Washington D.C., U.S. Government Printing Office, 155 p.

Hayden, F.V., 1876, Eruptive granites. Chapter V. *In* F.V. Hayden, Annual Report of the United States Geological and Geophysical Survey of the Territories, Embracing Colorado and Parts of Adjacent Territories: Report of Progress of the Exploration for the Year 1874: Washington D.C., U.S. Government Printing Office, 515 p.

Henderson, C.W., 1926, Mining in Colorado, a History of Discovery, Development and Production: U.S. Geological Survey Professional Paper 138, 263 p.

Hollister, O.J., 1867, Mines of Colorado: Springfield, Massachusetts, S. Bowles and Co., 450 p.

Hubert, J.F., and Panish, P.T., 2000, Sedimentology and diagenesis of the dinosaur bones exposed at Dinosaur Ridge along Alameda Parkway in the Morrison Formation (Upper Jurassic), Morrison, Colorado: The Mountain Geologist, v. 37, no. 2, p. 73-89.

Hunt, Adrian, Lockley, Martin, and White, Sally, 2002, Historic dinosaur quarries of the Dinosaur Ridge area: Morrison, Colorado, Friends of Dinosaur Ridge, 44 p.

Jenkins, J.T., and Jenkins, J.L., 1993, Colorado's Dinosaurs: Denver, Colorado, Colorado Geological Survey, 74 p.

Kile, D.E., and Modreski, P.J., 1988, Zeolites and related minerals from the Table Mountain lava flows near Golden, Colorado: Mineralogical Record, v. 19, p. 153-184.

Kile, D.E., and Modreski, P.J., 1988, Mineralogy of the Patch mine, Gilpin County, and the Alice mine, Clear Creek County, Colorado, *In* Mineralogy of Precious Metal Deposits: Denver, Colorado, p. 106-111.

Kile, D.E., and Modreski, P.J., 1994, Mineralogy of a calc-silicate locality near Genesee Park, Jefferson County, Colorado. Rocks and Minerals, v. 69, p. 298-308.

Knowlton, F.H., 1930, Flora of the Denver and associated formations of Colorado: U.S. Geological Survey Professional Paper 155, 142 p.

LeRoy, L.W., 1946, Stratigraphy of the Golden-Morrison area, Jefferson County, Colorado: Quarterly of the Colorado School of Mines, v. 41, 115 p.

LeRoy, L.W., and LeRoy, D.A., 1978, Red Rocks Park: Golden, Colorado School of Mines, 29 p.

LeRoy, L.W., and Weimer, R.J., 1971, Geology of the Interstate 70 Road Cut, Jefferson County, Colorado: Colorado School of Mines Professional Contribution 7.

Lewis, G.E., 1960, Fossil vertebrates and sedimentary rocks of the Front Range, Colorado, *In* Guide to the Geology of Colorado, R.J. Weimer and J.D. Haun, eds.: Geological Society of America, Rocky Mountain Association of Geologists and Colorado Scientific Society, p. 285-292.

Lockley, M.G., 1988, Dinosaurs near Denver, *In* Geological Society of America Field Trip Guidebook, 1988. Centennial Meeting, Denver, Colorado, G.S. Holden, ed. Professional Contributions, no. 12, Golden, Colorado, Colorado School of Mines, p. 288-299.

Lockley, M., and Hunt, A., 1994, Fossil Footprints of the Dinosaur Ridge Area: Morrison, Colorado, Friends of Dinosaur Ridge, 53 p.

Lockley, Martin, 2001, A field guide to Dinosaur Ridge, 3rd ed.: Morrison, Colorado, Friends of Dinosaur Ridge, 34 p.

Lockley, M., and Marquardt, L., 1995, A Field Guide to Dinosaur Ridge: Morrison, Colorado, Friends of Dinosaur Ridge, 32 p.

Lockley, M.G., and Prince, N.K., 1988, The Purgatoire Valley dinosaur tracksite region, southeast Colorado, *In* Geological Society of America Field Trip Guidebook, 1988. Centennial Meeting, Denver, Colorado, G.S. Holden, ed. Golden, Colorado, Colorado School of Mines, Professional Contributions, no. 12, p. 275-287.

Lovering, T.S., 1940, Tungsten deposits of Boulder County, Colorado: U.S. Geological Survey Bulletin 922-F, p. 135-156.

Lovering, T.S., and Goddard, E.N., 1950, Geology and ore deposits of the Front Range, Colorado: U.S. Geological Survey Professional Paper 223, 319 p.

Lovering, T.S., and Tweto, O., 1953, Geology and ore deposits of the Boulder County Tungsten District, Colorado: U.S. Geological Survey Professional Paper 245, 199 p.

MacKenzie, D.B., 1968, Studies for Students: Sedimentary features of Alameda Avenue cut, Denver, Colorado: The Mountain Geologist, v. 4, p. 1-13.

Marsh, O.C., 1877, Notice of a new and gigantic dinosaur: American Journal of Science, v. 14, p. 87-88

Marvine, A.R., 1874, The sedimentary rocks east of the Front Range. Chapter II. *In* F.V. Hayden, Annual Report of the United States Geological and Geophysical Survey of the Territories, Embracing Colorado - - The Exploration for the Year 1873: Washington D.C., U.S. Government Printing Office, 718 p.

Modreski, P.J., 2001, Geochemical and mineralogical studies of dinosaur bone from the Morrison Formation at Dinosaur Ridge: The Mountain Geologist, v. 38, p. 111-118.

Moench, R.H., and Drake, A.A., 1966a, Mines and Prospects, Idaho Springs District, Clear Creek and Gilpin Counties, Colorado: U.S. Geological Survey Open-File Report, 213 p.

Moench, R.H., and Drake, A.A., 1966b, Economic Geology of the Idaho Springs District, Clear Creek and Gilpin Counties, Colorado: U.S. Geological Survey Bulletin 1208, 91 p.

Muchow, W.M., 1952, How the Glory Hole was Made: Privately published, unpaginated.

Ostrom, J.H., and McIntosh, J.S., 1966, Marsh's Dinosaurs - - The Collections from Como Bluff: New Haven, Yale University Press, 388 p.

Patton, H.B., 1900, Thomsonite, mesolite, and chabazite from Golden, Colorado: Bulletin of the Geological Society of America, v. 11, p. 461-474.

Reichert, S.O., 1954, Geology of the Golden-Green Mountain area, Jefferson County, Colorado: Quarterly of the Colorado School of Mines, v. 49, 96 p.

Ries, H., and Leighton, H., 1909, History of the clay-working industry in the United States: New York, John Wiley and Sons,

Runnells, D.D., 1976, Boulder, a Sight to Behold: Boulder, Colorado, Privately published, 91 p.

Schlocker, J., 1947, Clays of the montmorillonite-nontronite group in basaltic rocks near Golden, Colorado [abs.]: Bulletin of the Geological Society of America, v. 58, no. 12, part 2, p. 1225.

Scott, G.R., 1972, Geologic map of the Morrison quadrangle, Jefferson County, Colorado: U.S. Geological Survey Map I-790-A.

Sims, P.K., 1960, Geology of the Central City-Idaho Springs area, Front Range, Colorado, *In* Guide to the Geology of Colorado, R.J. Weimer and J.D. Haun, eds.: Geological Society of America, Rocky Mountain Association of Geologists, and Colorado Scientific Society, p. 279-285.

Sims, P.K., 1964, Geology of the Central City Quadrangle: U.S. Geological Survey Quadrangle Map GQ-267.

Sims, P.K., Drake, A.A., and Tooker, E.W., 1963, Economic Geology of the Central City District, Gilpin County, Colorado: U.S. Geological Survey Professional Paper 359, 231 p.

Smith, J.H., 1964, Geology of the sedimentary rocks of the Morrison Quadrangle, Colorado: U.S. Geological Survey Geologic Miscellaneous Geologic Investigations Map I-428.

Stewart, K.C., and Severson, R.C., eds., 1994, Guidebook on the geology, history, and surface-water contamination and remediation in the area from Denver to Idaho Springs, Colorado: U.S. Geological Survey Circular 1097, 55 p.

Vanderwilt, J.W., Burbank, W.S., and Traver, W.M., 1947, Mineral Resources of Colorado: Denver, Colorado, State of Colorado Mineral Resources Board, 547 p.

Van Horn, R., 1957, Bedrock geology of the Golden Quadrangle: U.S. Geological Survey Geologic Quadrangle Map GQ 103.

Van Horn, R., 1976, Geology of the Golden Quadrangle: U.S. Geological Survey Professional Paper 872, 116 p.

Van Tuyl, F.M., Johnson, J.H., Waldschmidt, J.B., Boyd, J., and Parker, B.H., 1938, Guide to the geology of the Golden area: Quarterly of the Colorado School of Mines, v. 33, p. 5-29.

Waagé, K.M., 1961, Stratigraphy and refractory clayrocks of the Dakota Group along the northern Front Range, Colorado: U.S. Geological Survey Bulletin 1102, 154 p.

Wahlstrom, E.E., 1948, Pre-Fountain and recent weathering on Flagstaff Mountain near Boulder, Colorado: Bulletin of the Geological Society of America, v. 59, p. 1173-1190.

Waldschmidt, J.B., 1939, The Table Mountain lavas and associated igneous rocks near Golden, Colorado: Quarterly of the Colorado School of Mines, v. 34, 62 p.

Weimer, R.J., 1996, Guide to the petroleum geology and Laramide orogeny, Denver Basin and Front Range, Colorado: Colorado Geological Survey, Bulletin 51, 127 p.

APPENDIX I

Clay Minerals Society Field Trip Mileage Log

Abstract of Trip

1. Depart Boulder to Golden via Highway 93. Overview of local geology en-route: Ralston Dike, Table Mountains, clay mining activity in sediments of the Dakota Group and in the Laramie Formation.

2. Chieftain mine, Robinson Brick Co., Golden, Colorado; an active clay mining operation principally in the Laramie Formation, and also in the Fox Hills Formation.

3. Dinosaur Ridge (Alameda Parkway); exposures of dinosaur trackway (Dakota Group), ripple marks, dinosaur bone (Morrison Formation), concretion, etc. Overview of Cretaceous geology and clay mineralogy.

3. Red Rocks Park overlook (Fountain Formation); geological overview of area and lunch.

4. Drive to Idaho Springs via I-70, and then up Virginia Canyon Road (the dreaded "Oh My God!" road) toward Central City. Stop at scenic overlook.

5. Visit to the Patch ("Glory Hole") open pit mine. Geological and historical overview of gold mining operations with clay mineralogy sidelight.

6. Return to Boulder via Highway 119, through Nederland and Boulder Canyon.

Road Log (* denotes stops)

Mileage	Approx. time	Locality
0.0 *	8:00 a.m.	Table Mesa and Broadway. National Center for Atmospheric Research (NCAR), Flatirons, Green Mtn. (with kimberlite outcrop), Bear Peak, Devils Thumb, Bear Canyon.
1.4	-	Marshall Road; area coal mines in the Laramie Formation. Mines extend from the Marshall-Leyden area near here to Louisville and Hudson to the east.
2.6	-	Eldorado Canyon turnoff; Colorado State Park.
5.7	-	LaFarge TxI Boulder Plant on left; aggregate, crushed stone.

7.4	-	Rocky Flats; formerly a U.S. Department of Energy (DOE) plant manufacturing plutonium triggers for thermonuclear weapons, now an environmental remediation site.
8.2	-	North Table Mountain visible to southeast. Ralston Dike, the proposed source of lavas for the Table Mountains, visible to the southwest as a low, inconspicuous hill.
9.0	-	Downtown Denver (± brown cloud) visible to the southeast.
9.6	-	Ridge composed of upturned rocks of the Laramie Formation and a small clay mine are visible to left; a clay mine in the Dakota Group, evidenced by a substantial open cut, is visible at right.
11.9	-	Lake on left.
12.2	-	Turnoff to Ralston Reservoir
12.8	-	Turnoff to quarry operation on Ralston Dike
13.0	-	Three Tertiary lava flows visible on the northwest flank of North Table Mtn., two capping flows overlie Denver sediments; a lower flow (TV1) is above the KT boundary by ~150 feet.
14.5	-	Active clay mine on right, evidenced by cuts in sandstones and clayrocks of the Dakota Group. Ahead is Lookout Mountain, conspicuous with its radio antennae. Site of Buffalo Bill's grave.
15.2	-	Two capping flows on North Table Mountain now distinctly visible from the road.
16.1	-	City of Golden; intersection with Washington St. Castle Rock on South Table Mountain, and Clear Creek which bisects North and South Table mountains; Golden fault (a reverse fault) traverses the valley here, accounting for missing rock formations in the area.
17.1	-	Intersection of Hwy 6 and 58th Avenue; Colorado School of Mines (CSM) campus to left; Mines "M" on hillside above right.
17.4	-	Coors Brewery, in valley of Clear Creek, visible on left.
17.7	-	Clay mining activity/pits on left.
18.1	-	Intersection with 19th St., CSM campus to left. Green Mountain visible ahead.
18.7	-	Former clay mining operations; Rubey mine and others, operated since 1800's; numerous dinosaur footprints and fossil plants evident in the Cretaceous sandstones and clays. Now being reclaimed and converted to a golf course.
19.4	-	Turnoff (south) to Heritage Road. Jefferson County government office building to left.
20.4	-	Intersection with US Highway 40; Heritage Square ahead on right (this area reported to be an ancient Indian camp ground); Dakota Hogback on left.
20.9	-	Quarry on right.
21.3	-	I-70 road cut visible to left, exposing numerous upturned Jurassic to Cretaceous formations.
21.6	-	Intersection with I-70.
22.4	-	Red Rocks (Fountain Formation) visible to right. Dakota Hogbacks visible ahead and to the left.

23.0	-	Turn left on CO 26 to Dinosaur Ridge, right to Red Rocks City Park.
26.2	8:35 a.m.	Chieftain Clay mine, Robinson Brick Co., south pit entrance.
26.7 *	-	Chieftain Clay mine, Robinson Brick Co., north pit entrance.
27.0 *	10:00 a.m.	Dinosaur Ridge Visitor Center; restroom, books.
27.5 *	-	Dinosaur trackways; Dakota Group.
27.6	-	Trace fossils.
27.7	-	Ripple Marks.
27.8	-	Trailhead and more ripple marks.
27.9 *	-	Concretion; silicified ash bed.
28.1 *	-	*Apatosaurus* (*Brontosaurus*) footprints, Morrison Formation.
28.2 *	-	Dinosaur bones *in situ*.
28.3	-	Intersection Hwy 93; entrance to Red Rocks Park, part of Denver Mountain Parks.
29.5	-	Right turn to picnic area and overlook.
29.8 *	12:15 p.m.	Geological overlook/lunch stop, restrooms. Visible; Buckley radar, Denver plains (Pierre Shale, Laramie and Arapahoe formations), Dakota Hogback (Morrison Formation, west side, Dakota Group, east side), Red Rocks (Fountain Formation), Mt. Carbon (coal seams). [Optional side trip to amphitheater]
31.1	1:00 p.m.	Turn left onto CO 26.
32.5	-	I-70 intersection; I-70 road cut/Geological Point-of-Interest on right.
33.3	-	Precambrian rock exposures.
37.7	-	Genesse Park overlook and Buffalo herd; view (!) of Front Range mountains, Continental Divide and Central City district to west.
50.9	-	Argo (formerly Newhouse) mill and tunnel; town of Idaho Springs.
51.7	1:40 p.m.	Intersection with CO 113; left goes to Mt. Evans and the highest paved road in America (summit 14,264 feet). Turn right to Idaho Springs.
51.8	-	Right on Colorado Blvd.
52.0	-	Bear left at fork.
52.1	-	Turn left onto Virginia Canyon Road.
52.6	-	"Oh My God!" road; bear right toward Central City.
54.2	-	Ore loading platform.
54.5	-	Right turn to Central City.
54.8	-	Scenic overlook; 19th century mine dumps.
55.7 *	1:50 p.m.	Scenic overlook; Continental Divide.
56.6	-	Pavement starts; ore loading platform on right.
58.2	-	Town of Russell (ca. 1859) visible ahead; mostly a ghost town now, formerly with thousands of residents.
59.5	-	Chain O' Mines mill on right; entrance to Patch mine on left.
60.3 *	2:10 p.m.	Patch "Glory Hole" mine.
61.0	3:45 p.m.	Return to main road from mine.
61.4	-	Overlook of Central City and area mines.
61.9	-	Scenic overlook of Central City.

62.3	-	Downtown Central City.
62.5	-	Formerly Mountain City; original Gregory diggings on hillside above to right.
62.9	-	Town of Blackhawk.
63.3	-	Intersection with CO 119; turn left onto Peak to Peak Highway.
71.9	-	Panorama of Indian Peaks ahead.
72.1	-	Turnout for scenic view of Indian Peaks.
76.9	-	Town of Rollinsville.
80.1	-	Eldora Ski area on left; Arapahoe Peak visible in Indian Peaks range.
81.2	-	Road to Eldora.
81.7	4:15 p.m.	Town of Nederland.
82.3	5:00 p.m.	Barker Reservoir on right, Boulder water supply.
89.3	5:15 p.m.	Boulder Falls on left, a short hike up a side canyon. [Optional, ~ 30 min.]
96.9	~6:15 p.m.	Enter the city limits of Boulder.

<end>