The Kiowa Core, a Continuous Drill Core Through the Denver Basin Bedrock Aquifers at Kiowa, Elbert County, Colorado

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ABSTRACT

The Kiowa core was obtained as a component of the Denver Basin Project, a cooperative research effort to study the evolution of the Denver Basin, Colorado. The Kiowa core provides a virtually continuous stratigraphic record of the Upper Cretaceous and lower Tertiary strata of the Denver Basin. The upper portion of the core recovered strata conventionally referred to as the Arapahoe and Denver Formations and the Dawson Arkose. A prominent unconformity marked by a mature paleosol breaks these strata into two unconformity-bounded sequences; the lower sequence is termed D1 and the upper sequence, D2. Beneath these units and also penetrated by the core occur the Laramie Formation, Fox Hills Sandstone, and Pierre Shale.

The site for coring was selected in order to obtain fine-grained strata suitable for both palynological and paleomagnetic analyses. The coring effort recovered 93 percent of the 2,256 ft of rock penetrated, resulting in a nearly continuous record of the sedimentary rocks recording the retreat of the Cretaceous Interior Seaway and the subsequent uplift of the Front Range portion of the Rocky Mountains.

Palynological data constrain the Cretaceous-Tertiary boundary to a depth between 878 and 880 ft in the core. The palynological data also serve to bracket the age of the paleosol marking the unconformity between the D1 and D2 sequences to between middle Paleocene and earliest Eocene. The paleomagnetic data are interpreted to represent polarity intervals ranging from polarity subchrons 31r to 28n and polarity subchron 24r.

Hydrologic analyses indicate variable aquifer characteristics across the State-defined bedrock aquifers. Individual aquifer units exhibit generally lower water-yield potential than was identified to the west in a core drilled by the U.S. Geological Survey (USGS) in 1987 at Castle Pines, Colorado. Down-hole temperature measurements indicate a normal geothermal gradient of 30°C/ km. Perturbations of the gradient may represent active fluid flow through the aquifers penetrated by the core.

Petrographic examination of the cored sandstone and mudstone units document both the clay-rich character of the paleosol series marking the boundary between the D1 and D2 sequences, and variation in sandstone composition with depth. The lower sequence (D1) is characterized by litharenites with a significant volcaniclastic component, while the upper sequence (D2) is more arkosic. Extensive lignite beds occur in D1 in the cored interval and these appear as strong reflectors on the seismic line that passes near the core hole. A set of electric logs, core descriptions, and derived data sets accompany this report.

INTRODUCTION

The Denver Basin Project was established by the Denver Museum of Nature and Science (DMNS) (formerly the Denver Museum of Natural History) in 1998 as a multi-disciplinary, multiorganizational effort to study the geology, geohydrology, and paleobiology of the Upper Cretaceous and lower Tertiary sedimentary rocks that comprise the bulk of the bedrock aquifers of the Denver Basin. These rocks are of interest because they contain the depositional record of the retreat of the Cretaceous Interior Seaway and the uplift of the Front Range portion of the Rocky Mountains. These sedimentary rocks comprise the bedrock aquifers supplying groundwater to residents of the Denver Basin, and they also contain the record of the Cretaceous-Tertiary boundary event. As part of the Denver Basin Project, a core-drilling program was conducted in the town of Kiowa, Colorado (fig. 1), with the objective of obtaining a continuous drill core from the land surface to the top of the Pierre Shale. Coring was successful and drilling terminated in the upper Pierre Shale at a depth of 2,256 ft below the Kelly Bushing (KB) elevation of 6,363 ft. In this report all depth measurements dealing with the core are reported as feet below KB. This is conventional in the drilling industry. Selected measurements and analyses are reported in metric units, resulting in mixed units within the following text. A conversion table is provided at the front of the report. The core is stored at the USGS Core Research Center at the Federal Center in Lakewood, Colorado. The core hole currently serves as a water monitoring well in the Denver aquifer. Standing water levels have been measured at 319.4 ft and 322.1 ft below surface in May 1999 and March 2000, respectively.

The project team consisted of the DMNS (coordinating organization); the USGS Water Resources and Geologic Disciplines; the Colorado Department of Natural Resources; Office of the State Engineer; the Colorado Geological Survey; Elbert County; Colorado State University; University of Colorado at Boulder; New Mexico Institute of Mining and Technology; University of Alaska at Fairbanks; and the Scripps Institution of Oceanography. The DMNS acted as the umbrella organization under which the study was conducted. The DMNS also directed and conducted the geologic and paleontologic aspects of the study. The USGS Water Resources Discipline directed geohydrologic aspects of the study in cooperation with Colorado State University. The Layne-Western Division of Layne Geosciences, Inc. conducted the core-drilling operation. Geophysical logging was conducted by the Colog Division of Layne Geosciences, Inc. Temperature logging was conducted by the New Mexico Institute of Mining and Technology. The seismic line was acquired by R. J. Grundy and Associates.

Core samples were analyzed to determine the porosity, permeability, hydraulic conductivity, palynology, paleomagnetism, mineralogy, petrography, and fission track properties of the Denver Basin bedrock aquifers at the study site. Geohydrologic analyses of the core were conducted at the Department of Earth Resources at Colorado State University; palynological analyses of the core were conducted by the DMNS; the paleosol layer was analyzed at the Department of Geological Sciences at the University of Colorado, Boulder; paleomagnetic analyses of the core were conducted by the Geosciences Research Division of Scripps Institution of Oceanography; mineralogy and petrography of the core was analyzed by the DMNS; and fission track properties of the core were determined at the Department of Earth and Environmental Science at the New Mexico Institute of Mining and Technology. Descriptions of these analyses together with the observed data are presented below.

Purpose of the Denver Basin Project

The data presented in this report were collected to help develop an integrated geological and paleobiological framework for the Upper Cretaceous and lower Tertiary sedimentary rocks in the Denver Basin. These sedimentary rocks record the withdrawal of the Cretaceous Interior Seaway and the subsequent birth and evolution of the Front Range segment of the Rocky Mountains. Previous studies (for example, Dane and Pierce, 1936; Brown, 1943; Reichert, 1956; Soister, 1978a; Kirkham and

Ladwig, 1979) have developed a general framework for the age and environments of deposition represented by these rocks. Due to vegetation and soil cover in the area, there are no outcrop exposures of the continuous rock record. By obtaining a core through the entire succession, we permit examination of a continuous record of layered sedimentary rocks, obtaining a more detailed record of the depositional and paleobiological features associated with the evolution of the basin. A goal of the Denver Basin Project is to construct a chronostratigraphic and biostratigraphic reference for the Denver Basin based on magnetostratigraphy, lithostratigraphy, and palynostratigraphy of the Kiowa core. This reference section will serve as the basis for developing an integrated paleobiological and geological framework for Upper Cretaceous and lower Tertiary rocks in the Denver Basin. This framework will in turn serve as the basis for testing hypotheses related to the evolution of the Denver Basin and the Cretaceous-Tertiary boundary event. Extensive private and public construction in the 1990's has led to the creation of ephemeral outcrops that have yielded numerous fossils of relatively unconstrained stratigraphic position. The core will help to place these finds into a regional temporal context.

We also seek to obtain data on the hydrologic characteristics of the bedrock aquifers in an area of the Denver Basin where relatively little quantitative data are available. Beyond the present studies, we anticipate that the core from Kiowa will serve as a significant calibration point for future studies of the Denver Basin.

Scope of this Open-File Report

This report is designed to provide a summary of events associated with the coring of a 2,256-foot well in Kiowa, Colorado, and to present basic data collected during 1999 and 2000 from core analyses, aquifer testing, geophysical logging, and seismic profiling of the bedrock aquifers at the study site. It also contains sections provided by researchers who have studied individual aspects of the core samples. The report is a compilation of data obtained before December 2000. In keeping with the Open-File format, this report provides for the release of basic data and is considered preliminary.

Rationale for Coring and the Selection of the Kiowa Drill Site

Analyses of available outcrops and electric logs from the Denver Basin suggest that the history of the basin is recorded in the strata preserved in its central portion (Raynolds, 1997). Outcroppings of these rocks are poor and discontinuous in the basin. A cored well is the only suitable means to obtain a high-resolution continuous record of the strata. A previous drilling effort recovered a relatively coarse-grained, core near the Colorado Front Range at Castle Pines in 1987 (Robson and Banta, 1993). To obtain a record of fine-grained strata, which was anticipated to be more suitable for both palynological and paleomagnetic analyses, our drill site is far from the mountains, in an area where core from the full suite of rock units of interest can be collected with a minimum amount of drilling. The core hole location was also designed to obtain hydrologic information about the bedrock aquifers in an area of the Denver Basin where existing data are sparse. Published reports (for example, Robson and others, 1981a, 1981b) indicate that no deep groundwater data is available for hundreds of square miles surrounding Kiowa.

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DESCRIPTION OF THE DRILL SITE

Location and Facilities

The core hole was drilled in the northwest quarter of the southeast quarter of section 17, T. 8 S., R. 63 W., on the Elbert County Fairgrounds in the town of Kiowa, Colorado, at 39° 21' 08.7" N, 104° 27' 59.1" W (fig. 1). The site is at an altitude of 6,363 ft on the eastern flank of the Kiowa Creek drainage, and is near the geographic center of the accumulation of sediments that comprise the principal bedrock aquifers in the Denver Basin (fig. 2). The core site on the Elbert County Fairgrounds was selected in cooperation with Elbert County officials to optimize site logistics and minimize site disturbance. The site is about 100 meters NNW of the Agriculture Building on the Fairgrounds. The County made the Agriculture Building available for our on-site studies. A work area and display area were set up and manned by DMNS personnel from March 2, 1999 to April 19, 1999.

Geology and Geohydrology

The Denver Basin is a large structural depression that extends from the Front Range of Colorado into western Nebraska, Kansas, and eastern Wyoming (Robson, 1989) and reaches a maximum thickness of about 15,000 ft southwest of the drill site near the Elbert-El Paso County line (Robson and Banta, 1987, pl. 1). Beds dip steeply into the basin along its western margin and dip gently into the basin along its eastern, northern, and southern margins. The rock units and bedrock aquifers described in this report are Upper Cretaceous and lower Tertiary sedimentary layers that occupy the part of the Denver Basin above the Pierre Shale (fig. 3). Traditional geologic terminology in the basin has been modified in this report because the compositional criteria used to differentiate the Denver Formation (generally rich in andesitic material) and Dawson Arkose (generally rich in feldspathic material) are difficult to use consistently over wide areas of the basin (Soister, 1978b; Crifasi, 1992; Raynolds, 1997). With the goal of presenting information from a genetic standpoint, two unconformity-bounded sequences of strata were defined by Raynolds (1997); these sequences are separated by a mature paleosol series representing a regional unconformity. The lower sequence is termed D1 (D standing for Denver) and is bounded at its base by the unconformity at the base of the conglomeratic Arapahoe Formation as defined southwest of Denver by Eldridge (1896). These conglomerate beds lie unconformably on the Laramie Formation and contain the first coarse crystalline clastics derived from the uplifted Front Range. The top of the D1 sequence is delimited by a strongly weathered unconformity marked by a regional paleosol first identified by Soister and Tschudy (1978). The D2 sequence is bounded at its base by the top of the regional paleosol. The D2 sequence is bounded at its top by an unconformity separating D2 strata from the overlying Castle Rock Conglomerate and Wall Mountain Tuff, which is also known as the "Castle Rock Rhyolite" (Trimble and Machette, 1979).

Thus, the rock units discussed in this report are (in ascending order from oldest to youngest): the Pierre Shale, the Fox Hills Sandstone, the Laramie Formation, and the overlying D1 and D2 sequences. The D1 sequence is comprised of the Arapahoe Formation and portions of both the Denver Formation and the Dawson Arkose. The D2 sequence is comprised of most but not all of the Dawson Arkose.

Above the Pierre Shale, these same strata are divided into four hydrostratigraphic units, which are, in ascending order, the Laramie-Fox Hills, Arapahoe, Denver, and Dawson aquifers (fig. 3). The Pierre Shale is considered to be the basal confining unit of the bedrock aquifers in the Denver Basin.

Preliminary evidence of westward thickening and increased sandstone abundance in the Laramie Formation suggests it may have accumulated during a transitional time as the Denver Basin was starting to subside, yet before there was significant relief established on the Front Range. The Laramie Formation contains coal beds that have been extensively mined around the periphery of the Denver Basin. Core samples from these coal beds were analyzed for isotopic characteristics by R.A. Zielinski of the USGS and results are shown in table 1.

Above the Laramie Formation, the D1 and D2 sequences accumulated during times when there was developing relief in the Front Range area. Because they accumulated contemporaneously with the orogenic activity, the sequences are termed synorogenic.

Figure 2 shows the general outcrop pattern of the aquifers. The bedrock geology of the Denver Basin is shown in figure 4, and the thickness of the synorogenic strata is shown in figure 5. Figure 6 shows a generalized cross-section of the principal aquifers in the Denver Basin and figure 7 shows a geological cross section across the upper portion of the Denver Basin.

Sequence of Events During Drilling

Surface casing was set on February 24, 1999, and the first 70 ft were drilled using an auger tool. Core drilling commenced on the morning of March 1, 1999. We acquired 2.5-inch-diameter core in 5-foot segments using a split tube, wire line system. Drillers worked in 12-hour shifts and DMNS staff worked in 8-hour shifts, as drilling proceeded around the clock.

Drilling continued for 11 days at a rate of about 132 feet per day until a depth of approximately 1,460 ft followed by a pause of a few days for rig repair. Drilling started again on March 14, 1999, to a depth of 1,880 ft at a rate of approximately 70 feet per day.

At 1,880 ft, in the upper portion of the Fox Hills Sandstone, both rig and hole problems were encountered that persisted for 11 days. Steel casing was installed to a depth of 1,797 ft to stabilize the hole and drilling started again on April 1, 1999. A portion of the Laramie Formation was re-drilled as coring proceeded to a total depth of 2,256 ft at a rate of approximately 75 feet per day. Total depth was reached on April 6, 1999.

Geophysical logs were obtained in a series of three runs. The logging suite consisted of caliper, gamma ray, spontaneous potential, resistivity, compensated density and full waveform sonic logs. Because of difficulties in getting the lightweight resistivity tool down the hole, a 452-ft-segment of hole between 1,412 and 1,864 ft has no resistivity log coverage.

The well was developed for approximately six hours using a bailer immediately following completion of the well. Efforts to obtain uncontaminated water samples from deep aquifers were not successful as the pH of all samples indicated extensive contamination by drilling fluids. Later, a series of temperature profiles were measured in the fluid-filled well.

The core hole was completed as a monitoring well with 2-inch-diameter steel casing set in the Denver aquifer to a total depth of 734 ft on April 20, 1999. Figure 8 shows how the monitoring well is constructed. Screen intervals in the well were placed adjacent to prominent sand layers in the Denver aquifer. Blank intervals are adjacent to layers composed primarily of mudstone.

CORE LOG AND DESCRIPTION

Graphic Core Log

The core was photographed and described as it was collected in Kiowa. Grain size, color, and stratigraphic features were recorded on site. Later the core descriptions were reviewed and edited at the USGS Core Research Center to ensure that there was a uniform style of description and observation. The nomenclature of the cored units is shown in figure 3 and a graphic core log is shown as figure 9. The cored units are described in table 2.

Stratigraphy and Lithology

Beneath 58 ft of unconsolidated alluvium deposited by Kiowa Creek, the core enters the upper sequence of synorogenic strata termed D2. The D2 sequence is comprised of 282 ft of alternating sandstone and mudstone layers. The sandstone layers typically have abrupt bases and gradational tops and the mudstone units show weak soil development. The top of the paleosol series that separates the D2 sequence from the underlying D1 sequence occurs at a depth of 340 ft. The paleosol series is 14 ft thick and is described in detail in a subsequent section of this report.

Beneath the paleosol, D1 strata occur to a depth of 1,648 ft. These strata are characterized by alternating sandstone and mudstone layers with a significant proportion of lignite between 430 and 1,130 ft. At the base of D1, a one-foot-thick gravelly sandstone bed represents the basal conglomerate of the Arapahoe Formation. The sandstone beds in D1 typically have abrupt bases and gradational tops and the intervening mudstone units show weak soil development.

Beneath the D1 sequence the Laramie Formation occurs to a depth of 1,851 ft. The Laramie Formation is generally shaly with few significant sandstone beds and has a series of coal beds near its base.

Beneath the Laramie Formation, the Fox Hills Sandstone occurs from 1,851 ft down to a depth of about 2,120 ft. The Fox Hills Sandstone is composed of massive quartz-rich sandstone beds that become increasingly shaly downwards into the Pierre Shale. The transition into the Pierre Shale is picked at approximately 2,120 ft and coring was completed in the Pierre Shale at a total depth of 2,256 ft. The Pierre Shale is a dark, well-bedded shale with invertebrate fossils. The bedding fabric is commonly disrupted by bioturbation.

As mentioned, the sandstone beds cored in D1 and D2 have sharp erosive bases and transitional tops and the intervening mudstone beds often show evidence of soil formation. These sandstone beds are interpreted to be of fluvial origin. The sandstone mineralogy suggests that the D1 rivers drained a mixed terrain of granitic and volcanic rocks whereas the D2 sandstone beds indicate a granitic source area. The Laramie Formation mudstone beds also show signs of soil formation and, together with the coal beds near the base, suggest floodplain and mire environments. The massive quartz-rich sandstone beds of the Fox Hills Sandstone represent the near-shore and beach facies deposited as the Cretaceous Interior Seaway retreated from the Denver Basin area. The underlying fossiliferous Pierre Shale beds are interpreted to have been deposited in a marine environment.

ANALYSES OF CORE SAMPLES

Geohydrology

Hydrologic studies were conducted to determine the nature and quality of the bedrock aquifers in the vicinity of the Kiowa core hole. Previously, most such analyses in the Denver Basin had been conducted from shallow wells or outcrops.

Samples from the Kiowa core consist of whole core segments typically 20-30 cm long. Sample intervals were chosen by the USGS based on the lithology of the core in each aquifer. Samples were coated in jewelry wax to keep the core moist and consolidated. The samples were analyzed at the Colorado State University Hydrogeology Lab for hydraulic conductivity, porosity, specific yield, and grain-size. The results are summarized below and appear in more detail in the Master's thesis of Laura Lapey (2001).

a. Hydraulic conductivity

Laboratory determination of vertical hydraulic conductivity was conducted in accordance to American Society for Testing and Materials (ASTM) Standard D 2434-68. A constant head permeameter was built for the coarse-grained samples (fig. 10). The waxed core samples were cut into 7-12 cm sections using a water-lubricated rock saw. Three-inch PVC caps fitted with gravel and screen were attached with wax to each end of the sample. De-aired tap water is forced into the bottom of the permeameter under a natural gradient and the rate at which the water exits through the sample is measured. Experiments were conducted approximately 15 hours after flow started. At least three runs were used to determine the hydraulic conductivity of each sample.

De-aired tap water was used for the hydraulic conductivity experiments to ensure that no air filled the pore spaces. The water was subjected to a vacuum of 25 mm Hg for two hours until the air bubbles ceased. A large carboy fitted as a Mariotte bottle was used for constant head control.

The samples were also de-aired by placing them under a 25mm Hg vacuum for 20 minutes before water was allowed to enter the sample (ASTM D 2434-68). The sample remained under vacuum until flow was achieved.

Hydraulic conductivity (K) is calculated using Darcy's Law:

$$K = Q\Delta L / A\Delta h$$

Where: Q = water discharge rate; ΔL = sample length; A = sample area; Δh = change in head

Fine-grained samples were tested using a falling head permeameter, where the amount of water entering the sample is measured instead of the rate at which water exits the sample (fig. 11). The PVC caps are fitted with a porous stone and screen to prevent silt and clay from washing out of the sample. The same procedures are followed as described above.

The hydraulic conductivity for this method is calculated by:

$$K = aL/At \ln (h_0/h_1)$$

Where: a = area of the manometer; L = sample length; A = sample area; t = time; h_0 = initial head; h_1 = final head

Preferential flow of water between the sample and the wax walls was a concern. After each test, food coloring was injected into the inflow tube and allowed to circulate through the sample. If the dye stained the outer edges of the core, the sample was re-waxed and tested again.

Several samples were tested using an air permeameter, designed by Arthur Corey at the Colorado State University Porous Media Lab. The air permeameter measures the permeability of the sample to air, which must then be converted to water permeability or hydraulic conductivity. The air permeameter is used for samples that are too fine-grained for the falling head permeameter.

A one-inch diameter plug is drilled from the core sample using a drill press and dried in an oven at 105° C for 24 hours. The plugs are then placed in the chamber to be tested in the air permeameter. A diagram of the air permeameter is shown in figure 12. Air is forced through the sample, and the rate of outflow is measured using a soap film flowmeter, which measures the flux directly. The gradient is fixed at the air pressure manometer to the approximate length of the sample before the test begins and the change is recorded during each test run.

The air permeability (k) is calculated by:

$$k = \{V/A*t\} * \{\mu*\Delta L/\Delta P*g\}$$

Where: V = volume of flow meter (cc); g = gravity; A = sample area; ΔP = change in pressure; t = time (sec); ΔL = change in length; μ = air viscosity

Air permeability (k) is then converted to water permeability or hydraulic conductivity (K). This is accomplished by:

$$K = (k*\rho_w*g)/\mu_w$$

Where: K = Hydraulic conductivity ρ_w = density of water
k = intrinsic permeability (air) μ_w = viscosity of water
g = gravity

To prevent air from flowing between the sample and the chamber walls, the air permeameter was designed with a rubber sleeve, which was held against the outer circumference of the sample with a pneumatic pressure of between 5-20 psi (Brooks and Corey, 1964).

The hydraulic conductivity data results of the Kiowa core samples can be found in table 3.

b. Specific yield and porosity

Laboratory determination of specific yield is conducted in accordance to ASTM Standard D 2335-68 and with the use of the same laboratory methods used by David McWhorter on the Castle Pines core project. The equipment consists of standard pressure plate apparatus manufactured by the Soil Moisture Equipment Company, Inc. Ceramic pressure plates with 1, 3, 5, and 15-bar entry pressures are utilized, and pressure is supplied using a Soil Moisture air compressor and/or cylinders of compressed nitrogen.

Samples are approximately 6 cm in diameter and were sectioned into duplicate 2 to 3 cm increments. The jeweler's wax coating remains around the sample to maintain its shape. The waxed core cylinder is then wrapped in a brown paper towel, which is secured at the top with a rubber band. The purpose of the towel is to keep the sample contained so an accurate weight is obtained. Duplicate samples are labeled "a" and "b" and are typically sectioned adjacently in the core sample.

Before samples are placed in the pressure chamber, they must be completely saturated. This is accomplished by natural saturation in de-aired water for twenty-four hours followed by one hour in an evacuation chamber at a vacuum of 20 mm Hg. The saturated samples were wiped of excess water, weighed, and placed on a previously saturated porous plate in the pressure chamber. The saturated weight will be used to calculate porosity.

To maintain good hydraulic connectivity between the sample and the porous plate, a lead weight was placed on top of each sample. This ensures that the sample makes good contact with the plate. The pressure chamber must remain humid to prevent the samples from drying out. To accomplish this, wet paper towels are placed on top of the samples.

The procedure consists of determining the weight of the samples at each desired capillary pressure (suction), which for this experiment includes 0.5, 1, 3, 5, and 13.5 bars. An equilibration weight is necessary in order to proceed to the next desired pressure. Equilibration periods of 48 hours are used for pressures of one bar or less and at least 72 hours are required for 3-13.5 bars. After the samples are weighed at 13.5 bars, they are oven-dried at 45° C for 96 hours. The standard 105-degree drying temperature was not used due to the low melting temperature of the wax (McWhorter and Garcia, 1990).

Each sample is contained in wax and wrapped in a paper towel. The water contained on the wax and towel must be subtracted from each of the sample weights. A test sample, containing just wax and towel, is run with each round of samples. The weight (W) of the test sample at each pressure level is subtracted from the dry weight of the test sample. This value constitutes the rough weight of water retained by each sample held by the wax and towel alone.

$$\mathbf{W_{test} = W_{test\ at\ pressure} - W_{test\ dry}}$$

The volumetric water content of the samples at 13.5 bars is considered to be the specific retention (McWhorter and Garcia, 1990). It is calculated by determining the volume of pore water and dividing by the bulk volume of the sample.

The volume of pore water retained by the sample at 13.5 bars is the sample weight minus the gross dry weight minus the test weight divided by the mass density of water, which is assumed to be 1 g/cm^3 in all cases.

$$\theta_{vol} = [W_{sample\ 13.5\ bars} - W_{sample\ dry} - W_{test}] / \rho_{water}$$

Porosity is calculated in a similar manner by taking the saturated sample weight minus the dry weight divided by the mass density of water, and dividing that by the bulk volume of the sample.

$$\phi = [(W_{saturated\ sample} - W_{dry\ sample}) / \rho_{water}] / V_{sample}$$

The specific yield is then obtained by taking the calculated porosity value minus the calculated specific retention value.

$$S_y = \phi - S_r$$

The volumetric water content at each pressure level is measured. Duplicate samples should have similar retention curves, and if they do not, there is a problem. One common problem is not achieving good hydraulic connection between the porous plate and the sample. If this occurs, the retention curve on the graph is a straight line.

The results for the porosity and specific yield data for the Kiowa core can be found in table 4.

c. Grain-size analysis

Each of the samples was gently crushed with a mortar and pestle, dried in an oven at 105° C, and mechanically sieved according to ASTM Standard D 422. The sieve sizes in millimeters used for this experiment range from 0.0526 to 16. The finer-grained, more consolidated samples require more crushing than the medium-grained sandy samples.

Between 200-300 grams of each sample were sieved. The particles remaining on each sieve were weighed and recorded. The percent of the total sample volume was then calculated by:

(weight determined on sieve / total sample weight) x 100

This is then used to calculate the percent finer by summing all percent totals finer than a particular sieve size. For example, if zero grams of sample remained on the 16mm sieve, the percent total would be zero and the percent finer would be 100 percent.

The percent finer was graphed against sieve size in millimeters. From the graph, D30, D50, and D90 can be determined for each sample. For example, D30 represents the grain-size at which 30 percent of the sample is finer by weight.

The grain size analysis data is presented in table 5.

Paleosol Series in the Kiowa Core

Description

The Kiowa core contains the mature paleosol series recognized by Soister and Tschudy (1978), which separates the synorogenic sediments in the Denver Basin into two unconformity-bounded sequences termed D1 and D2. The paleosol series in the core is 14 ft thick and occurs at a depth of 340 to 354 ft. Nine stratigraphic units are identified based on grain size, mineralogy, and pedogenic features (fig. 13). The nine units collectively are 90 percent mudstone and 10 percent sandstone with a significant portion of core lost.

Pedogenic features characterizing the paleosol sequence are slickensides, mottles, root traces and casts, and ped-like features. Pedogenic structures were determined by hand sample analysis under a binocular microscope. Slickensides are prevalent in three of the nine units and are often intersecting. Mottles are present in two of the nine units and are red, dark gray, and moderate yellowish brown in color. Mottle sizes varied from 3-10 cm in diameter. Root traces are present in one of the nine units in the core and are associated with red and yellow mottles. The traces are vertical and horizontal in nature and are clay-filled. In general root traces are small with diameters of 5 mm or less. Polypedon structures in the paleosol are often bounded by slickensides and provide planes of weakness causing samples to break into ped-like fragments.

Color variations in the paleosol sequence are determined using a Munsell color chart and span a range from light gray N7 to medium bluish gray 5B 5/1 to a dark reddish brown 10R 3/4. The most common color is gray. One unit is brightly colored with reds and yellows.

The micromorphology of the paleosol sequence was analyzed using thin sections made from each unit. Distinctive features include clay skins, disrupted fabrics, alluvial clay, patchy iron-oxide impregnations, and sphaerosiderite crystals, a morphologically distinctive form of siderite. There is also a lack of organic material within the paleosol interval. Analytical results are summarized below; further interpretations are developed in the University of Colorado Master's thesis by Farnham (2001).

X-ray Diffraction and X-ray Fluorescence

The mineralogy of the paleosol sequence was determined using a Scintag Powder X-ray Diffraction (XRD) machine at the University of Colorado at Boulder. The XRD machine uses x-rays generated by a copper filament to bombard samples and determine the spacing of the crystal lattices of atoms. Each mineral has a unique set of lattice spacings that cause the x-rays to reflect at specific angles. The whole rock mineralogy is determined by grinding a sample of the unit to be tested into a powder. The powder is then placed into a sample holder. It is then placed onto a target in the XRD machine and bombarded by x-rays through a range of angles (2-70 degrees). The x-ray reflections are measured and matched with known patterns for minerals.

In order to determine the clay mineralogy the clay fraction must first be separated out. This is done by placing a sample of rock in a test tube, mixing it with de-ionized water and sodium phosphate (a deflocculating agent), agitating the sample, then letting the heavier fractions settle out. The topmost fluid is pipetted out and dripped onto a ceramic tile to dry. The clay fraction is left on the tile as a film. The tile is run through the XRD after air-drying.

The weight percent of major oxides is determined using x-ray fluorescence (XRF). XRF analysis was performed at the geology lab at the University of Colorado at Boulder. The ratios of major oxides are used to determine the change in clay content, degree of weathering, and translocation of iron or other selected minerals through a paleosol profile.

The whole rock mineralogy of the paleosol sequence is dominated by quartz and the 1:1 dioctahedral clay mineral kaolinite [$Si_4Al_4O_{10}(OH)_8$] and the 2:1 dioctahedral layered silicate smectite [$Al_2Si_4O_{10}(OH)_2$]. Other significant components are the iron carbonate siderite [$FeCO_3$] found in nodular and single crystal form, and minor amounts of the layered silicate illite [$KAl_4(Si_7AlO_{20})(OH)_4$]. The clay mineralogy is primarily kaolinite and smectite although the uppermost units (5-9) contain less than 2 percent smectite and minor amounts of illite. Results of the x-ray diffraction analysis are presented in figure 14. Results of the clay sized x-ray diffraction analysis are presented in figure 15. Results of the XRF whole-rock analyses are presented in figure 16.

Palynology

Fossil pollen and spores (palynomorphs) are often preserved in fine-grained, organic-rich sedimentary rocks because of the durability of these fossils. Analysis of palynological assemblages recovered from a sequence of rocks can provide insight into floral changes through time. These changes can be used to determine the age of the rocks and the nature of the vegetation present at the time of deposition.

Methods

Samples of mudstone, carbonaceous shale, and lignite were collected from the core for palynological analyses. Samples were generally small (about 15-25 gm). They were shipped to Global Geolab Ltd. in Medicine Hat, Alberta, where they were processed using standard palynological procedures. Slides were shipped back to Denver and scanned for biostratigraphically useful taxa.

Results

Samples were analyzed for the purposes of locating the Cretaceous-Tertiary (K-T) boundary, constraining the age of the prominent paleosol that marks the D1-D2 boundary, and developing a reference pollen biostratigraphy section for the Denver Basin.

In general, palynological recovery from the Kiowa core is good. Most samples submitted for processing yield well-preserved palynomorph assemblages. This is primarily due to the fresh, un-weathered character of the material recovered from the core. Rock samples from natural exposures are often oxidized and palynomorph recovery is in general far better from core samples.

Little evidence of mixing of older fossils into younger rocks was observed in samples below 426 ft in the Kiowa core. Samples above 426 ft contain some reworked fossils, including marine dinoflagellates reworked from rocks of Cretaceous age. However, the relative abundance of reworked specimens is lower than is found in samples from the western part of the Denver Basin. The palynostratigraphic zonation above the K-T boundary is based primarily on the first appearances of members of the *Momipites-Caryapollenites* lineage; first appearances are not affected by reworking.

Table 6 contains a list of all samples collected from the Kiowa core for palynological analysis. The table also summarizes palynostratigraphic presence/absence data. Table 7 lists age-diagnostic fossils that have been observed to date in the Kiowa core.

a. Cretaceous-Tertiary boundary

The palynological K-T boundary was located in the Kiowa core based on the extinction of Cretaceous pollen species, including species of the genera *Proteacidites* and *Aquilapollenites,* which are genera that characterize the *Wodehouseia spinata* Assemblage Zone (Nichols and others, 1982). In sequences where reworking is not a problem, fossils of these genera occur in uppermost Cretaceous rocks but disappear precisely at the K-T boundary.

Based on palynological assemblages, the K-T boundary occurs in the Kiowa core below 878 ft 4.5 in and above 880 ft 2 in. Because a small interval of core was lost at this depth, a K-T boundary claystone was not located and more precise positioning of the boundary in the Kiowa core is not possible. The estimated position of the boundary in the core will be used to aid in locating natural exposures of the boundary interval along the eastern margin of the Denver Basin.

One aspect of palynological assemblages across the K-T boundary is the presence of a fern-spore abundance anomaly (“fern spike”). In many K-T boundary sections in the Western Interior, assemblages immediately above the boundary contain very high percentages of fern spores, sometimes approaching 100 percent of a single species. R.H. Tschudy first reported and later fully described this anomalous abundance of fern spores in the Raton Basin of southern Colorado and New Mexico (Orth and others, 1981; Tschudy and others, 1984). Since his initial observations, this anomaly has been reported from many additional localities to the north and south of the Denver Basin. Tschudy interpreted the high abundance to represent recolonization of a devastated landscape following the K-T boundary event. The sample just below the missing interval of the K-T boundary in the Kiowa core contains about 50 percent fern spores and the sample just above this interval contains about 75 percent fern spores. Although these data are inadequate to make a definitive interpretation, they suggest the presence of a fern-spore abundance anomaly in the Denver Basin.

b. Age of paleosol

The paleosol series that demarcates the D1-D2 contact in the Denver Basin was recovered in the Kiowa core. Palynological samples were analyzed from the interval containing the paleosol in an attempt to constrain the age of rocks immediately above and below the paleosol.

The stratigraphically highest sample below the base of the paleosol that yielded a good palynological assemblage comes from a depth of 411 ft (71 ft below the top of the paleosol). This sample contains three species of the fossil pollen genus *Momipites*. Two of these species (*M. leffingwellii* and *M. inaequalis*) suggest that the assemblage is from Zone P1 of Nichols and Ott (1978). However, the third species (*M. dilatus*) does not appear until Zone P3 in the Raton Basin (Fleming, 1990). One other specimen in the assemblage may be referable to *M. wyomingensis*, but it is too poorly preserved for positive identification. Based on this evidence, the assemblage is tentatively assigned to Zone P2 of Nichols and Ott, but could be as young as Zone P3 of Nichols and Ott (middle Paleocene).

The stratigraphically lowest samples above the paleosol that yielded good assemblages come from depths of 332 ft and 327 ft (8 and 13 ft above the top of the paleosol, respectively). Both of these assemblages contained several species in the *Momipites-Caryapollenites* lineage, including *Momipites ventifluminis*, *Caryapollenites veripites* and *Caryapollenites inelegans*. In addition, both samples contain rare specimens of *Platycarya platycaryoides*.

In the Bighorn Basin of Wyoming, the earliest occurrence of *Platycarya platycaryoides* is found near the base of Wasatchian strata in rocks currently determined to be earliest Eocene in age (Wing, 1998). Abundant specimens of *Platycarya platycaryoides* are found about 500 meters higher in the

Bighorn Basin, still in strata of early Eocene age (Wing, 1998). Based on a comparison with the Bighorn Basin, the presence of rare specimens of *Platycarya platycaryoides* in the Kiowa core samples indicates an earliest Eocene age for the strata immediately above the paleosol.

The paleosol is thus bracketed between rocks of middle Paleocene and earliest Eocene age. This interpretation supports the hypothesis that the paleosol represents a major unconformity. Unfortunately, it is very unlikely that palynomorphs can be recovered from the paleosol itself due to its oxidized nature.

c. Biostratigraphic zonation of the Kiowa core

Based on palynological assemblages, the Kiowa core can be divided into three broad zones. The lowermost zone is Cretaceous in age and extends from about 880 ft to the bottom of the core. The upper part of this zone is Maastrichtian in age (latest Cretaceous, based on presence of fossil pollen species of the *Wodehouseia spinata* Assemblage Zone) but the precise age of the lowermost part of the core has not been determined based on palynology. The middle zone of the core is early to middle Paleocene in age from 878 ft to about 352 ft (base of the paleosol). Above the paleosol, the upper zone of the core is early Eocene in age. This suggests that some of the middle part and the upper part of the Paleocene are missing due to an unconformity, which is marked by the paleosol. The age of the uppermost parts of the core cannot be determined due to poor recovery of palynomorphs, but it is presumably Eocene or younger.

d. Paleoecology

In addition to biostratigraphic interpretations, palynological assemblages provide some insight into the vegetation that was present in the Denver Basin during the Late Cretaceous and early Tertiary. In combination with fossil leaf data gathered elsewhere in the basin, this information can be used to reconstruct the vegetation of the area during the Late Cretaceous and early Tertiary. Preliminary observations from the Kiowa core samples allow general interpretations of the vegetation.

Paleocene palynological assemblages below the paleosol contain numerous species indicative of wet habitats, such as *Azolla* (a water fern), other ferns, *Sphagnum* (sphagnum moss), and *Isoetes* (quillwort). Palynological data support the interpretation of high rainfall that is indicated by leaf assemblages (Ellis and Johnson, 1999). The Eocene assemblages from just above the paleosol are markedly different. They contrast with the Paleocene assemblages in that they contain fewer fern spores, more angiosperm pollen, and higher percentages of pollen referable to a group of gymnosperms, all of which produce similar pollen—the Taxodiaceae, Cupressaceae, and Taxaceae.

The Denver Basin appears to have been located on a paleobiogeographic boundary between the northern and southern parts of the Western Interior. During the early Tertiary, the northern part of the Western Interior included a significant abundance of taxodiaceous elements (e.g., bald cypress). These trees were rare to absent in the southern part of the Western Interior. Samples from the Kiowa core suggest that taxodiaceous trees were present in greater abundance than in the Raton Basin but in lesser abundance than in basins to the north such as the Powder River Basin. In addition, it appears that taxodiaceous trees increased in abundance from Paleocene to Eocene time in the Denver Basin.

Paleomagnetism

Methods

The Kiowa core was extensively sampled for a paleomagnetic analysis. Oriented samples for analysis were collected from each 5-ft core storage tube that contained suitable undamaged and well-oriented rock. This resulted in a complete suite of 327 samples collected from the 399 core tubes of the primary hole, and an additional 51 samples from the 97 core tubes of the secondary hole. Not all these samples are to be used for paleomagnetic analysis, but the full suite of samples collected provides a reference collection of archived samples to meet the needs of present and future analysis.

The paleomagnetic subsamples were prepared from a 2- to 3-inch slice, or full round, cut from the original core. The full round was cut with a diamond saw into four subsamples that were then dry-sanded into cubes, nominally 1-inch square, suitable for measurement in the cryogenic magnetometer. The samples were collected this way because the core sediments were generally too fractured or poorly indurated for the subsamples to be taken by drilling small diameter cores out of the full round. All the subsamples were cut from the full round aligned to an arbitrary witness mark. The core itself is unoriented, and the actual field declination is not known, but with the witness mark the four subsamples from each level could be compared for within-site consistency. The subsamples were labeled "a" through "d", and are referred to as such below, and in Table 8.

All demagnetization and measurement was carried out at the Scripps Institution of Oceanography in a magnetically shielded room, with an ambient field of 200nT. The magnetic measurements were made on a CTF three-axis cryogenic magnetometer. Thermal demagnetization was carried out in air in two high-capacity custom-built ovens modeled after a type developed at the Lamont-Doherty Geological Laboratory. The susceptibility of the samples was measured using a Bartington MS2 susceptibility meter. Progressive demagnetization by both thermal and alternating-field (AF) methods was carried out in steps until the magnetization intensity fell below noise level, or below approximately 8% of the natural remnant magnetization (NRM), or until the measured directions became erratic, or when the low-field bulk magnetic susceptibility increased more than one order of magnitude, indicating alteration of magnetic minerals.

Since there are no published reports of paleomagnetic analyses from the synorogenic strata of the Denver basin, the paleomagnetic analysis was carried out on a series of pilot samples using different methods of stepwise demagnetization and data analysis.

a. Stepwise thermal demagnetization

The first suite of pilot samples was taken at a 20- to 50-ft spacing from 68 stratigraphic levels that ranged from the top to the bottom of the core. Three to four subsamples from each level were measured using a stepwise thermal demagnetization regime of 11 steps (NRM, 125^{o}, 150^{o}, 175^{o}, 200^{o}, 225^{o}, 250^{o}, 250^{o}, 275^{o}, 300^{o}, 325^{o}, 350^{o} C). In no case was there more than a small fraction of the natural remanent magnetization (NRM) remaining after 350^{o}C and in many cases the data became scattered after treatment to about 250 to 300^{o}C. Susceptibility measurements indicate that the scatter probably results from alteration of magnetic mineralogy during thermal demagnetization. The data from the 206 samples processed in this manner were not satisfactory as few samples achieved a consistent or stable direction. The exact reason for the failure of this thermal demagnetization process is not fully understood at present, but will be studied further in the future.

b. Combined thermal and stepwise alternating-field demagnetization

A second suite from 57 stratigraphic levels, totaling 217 subsamples (labeled a through d and listed in Table 8) were collected at mean stratigraphic interval of 38 ft. Ranging from the top to the bottom of the core, the stratigraphic spacing ranged from a maximum of 161 ft across the Fox Hills sandstone, to a minimum of 2.5 ft at the critical Pierre Shale interval at the bottom of the core.

A pilot set of 20 samples (76 subsamples) were collected from the top to the bottom of the core and processed in a single run using a combined thermal and alternating field (AF) demagnetization procedure. The samples were measured at room temperature (NRM), then heated in two steps at 125 and 150°C to remove any hydrous iron oxides that may be carrying a spurious signal, and finally subjected to five step-wise alternating field demagnetization steps of 5.0mT, 7.5mT, 10.0mT, 12.5mT, and 15.0mT. Statistical analysis of these samples showed that a consistent remnant magnetization could be measured. This is believed to be a primary detrital remnant magnetization (DRM) representative of the original paleomagnetic field at the time the samples were deposited.

A final set of 34 stratigraphic levels (93 subsamples) were collected from levels in the core where there were gaps in the paleomagnetic sampling sequence, or where there was some doubt as to the polarity of the interval. The samples were run using the same combined thermal and alternating field (AF) demagnetization procedure.

c. Stepwise alternating-field demagnetization

A third suite from 12 stratigraphic levels (46 subsamples) was processed using just a stepwise AF demagnetization procedure with no thermal steps. No difference could be observed in the DRM from adjacent samples demagnetized with and without the two thermal steps, so the remaining samples from 25 stratigraphic levels were demagnetized the same way in six AF steps (NRM, 5.0mT, 7.5mT, 10.0mT, 12.5mT, and 15.0mT). By the 15.0mT step almost all the samples were completely demagnetized.

Results

Because the core only has up-down orientation data, the measured declination that was aligned with the arbitrary witness mark could only be used to compare the orientation of subsamples measured from within a single stratigraphic level. But in this way the within-site orientation could be subjectively used to evaluate the consistency of the subsamples from each level.

The inclination data from the AF demagnetized samples were processed in a spreadsheet, and a simple mean calculated for each subsample from three to four individual demagnetization steps that maintained a consistent orientation. If there were not at least three samples successfully measured from each stratigraphic level, then the data were discarded and are not shown. Samples were lost due to operator error, and breakage. If there were three or four samples then a mean inclination for those stratigraphic levels could be calculated. The calculated mean inclinations for each stratigraphic level are shown in Table 8. If the range of inclinations at each stratigraphic level did not lie in the same hemisphere then the data were discarded from further analysis and a mean was not calculated for that level (see Table 8). The mean inclination for each stratigraphic level and the inclinations of each individual subsample (a through d) are plotted versus downhole depth in figure 17.

Overall the data are quite consistent. There are 31 levels with a positive mean inclination, and 18 levels with a negative or reversed inclination. The mean positive (normal) inclination throughout the entire core is 52.4 ° and the mean negative (reversed) inclination is –41.1 °. The calculated standard deviations for both positive and negative inclinations are the same at 13.4 °, and the inclination values have an almost identical range from, and +74.3 ° to +22.1 °, –73.2 ° to –14.7 ° respectively. The conclusion that can be drawn from these data are that the normal and reversed inclinations are only approximately antipodal to one another, because the reversed directions are in general some 11^o shallower than the normal directions.

When all the data were plotted in the inclination diagram shown in figure 17, there was one level that contained an anomalous single-site reversed sample. Adjacent samples were run and were found to be normal in polarity. The core sample from this level is believed to have been inverted at some point during sample handling. The discarded level is clearly identified in Table 8 by the label “REMOVED” in the mean inclination column and was removed from further analysis.

A single reversed sample was measured in an area of mixed polarity near the bottom of the core at 2147 ft. This interval lies at the level where the paleoenvironment shifted from the marine to terrestrial as the Cretaceous Seaway regressed from the western interior of the US. At the same level at Red Bird, Wyoming, there is a similarly anomalous interval that corresponds to the nearshore marine environment. At Red Bird this level is glauconitic and almost certainly has been overprinted. In the Kiowa core this interval has been extensively re-sampled and re-measured, but has been found to contain multiple levels of mixed polarity. In the interpretation shown in figure 17 the top of C31r is projected to lie at approximately 2100 ft, and in the future additional samples will be measured from this interval to try and better define the polarity.

Reversal sequence

Visual inspection of figure 17 shows that there are nine distinct polarity intervals in the full length of the Kiowa core. In figure 17 they are labeled from R1 to R5, and from N1 to N4.

a. Mixed polarity interval R1 to R2

The basal reversal, R1, is defined by two reversed levels that lie close to the base of the Kiowa core. This level contains a normal polarity interval N1, which is an interval of mixed polarity made up of four normal samples and four inconsistent samples for which no average direction could be ascertained (see label 1, fig. 17).

At this stratigraphic level the core lies just below the distinctive sandstone facies of the Fox Hills, in the uppermost part of the Pierre Shale. In surface exposures along the western edge of the Denver basin the top of the Pierre Shale is known to lie in the ammonite range zones of *Baculites clinolobatus* and *Hoploscaphites birkelundi*. Magnetostratigraphic analysis of the Red Bird section in eastern Wyoming (Hicks and others, 1999) has shown that *B. clinolobatus* lies in the middle of C31r and the top of this ammonite range zone at Red Bird has been dated isotopically at 69.57 ± 0.37 Ma (Hicks and others, 1999).

The top of the R2 interval is projected to lie at about 2110 ft in the core and its position is known to within ± 38 ft (Table 8). The age control from the ammonite biostratigraphy indicates that this reversal is the top of C31r, which has been dated at 69.01 Ma by extrapolation from isotopically dated ash beds in the Red Bird magnetostratigraphic section (Hicks and others, 1999; labeled 5, fig. 17). Plotted on figure 17 (label 2) are the ages for *B. clinolobatus* (69.57 Ma), the extrapolated age of the top of C31r (69.01 Ma), and the age of the top of C31r after the time scale of Cande and Kent (1995; 68.737 Ma; time scale referred to as CK95 in the following text). The extrapolated age of the boundary and the age estimate of CK95 are very close, lying within 0.27 Myr of each other.

b. Normal polarity interval N2

The normal polarity interval above R2 ranges from the uppermost part of the Pierre Shale at 2110 ft through the Fox Hills and overlying Laramie to a level of 1182 ft in the lower third of the D1 synorogenic stratigraphic interval (see label 3, fig. 17). The total thickness of the N2 polarity interval is 928 ft, and the top can be placed with a precision of ± 21.2 ft (Table 8). The N2 interval is bracketed above and below by two calibration points. As defined in the section above the ammonite range zones of *B. clinolobatus* and *Hoploscaphites birkelundi* define the age of the Maastrichtian marine sediments of the Pierre Shale at the base of the N2 interval. The K-T boundary interval has been placed palynologically in the core at between 878-880 ft and lies above N2 in a reversed polarity interval R3 (see label 4, fig. 17). The K-T boundary has been dated at 65.51 Ma (Hicks and others, 2001).

In this time period between 69.01 and 65.51 Ma there are two possible normal intervals that can be correlated to N2, C30n and C31n. But they are separated by only a very short reversed polarity interval, C30r, which is only 125,000 years in duration (Cande and Kent, 1995). Because it is so short, C30r is rarely encountered in terrestrial magnetostratigraphic sequences, therefore N1 most likely ranges from the base of C31n to the top of C30n and C30r is not found in the sequence. The sedimentation rate for this interval is calculated at approximately 292 ft/Myr of compacted sediment (Table 8).

c. Reversed polarity interval R3

The reversed polarity interval R3 lies in the middle of the D1 synorogenic strata interval (fig. 17) and ranges from 1182 ft to 879 ft, an interval of 303 ft of core. The Cretaceous/Tertiary boundary in the Kiowa core has been placed palynologically at between 878 and 880 ft, which conclusively identifies R2 as C29r. The K-T boundary is known globally to lie within the upper half of C29r (D'Hondt and others, 1996). In the Kiowa core the boundary lies within 2 ft of the projected top of R2 at 879 ft, and the reversal boundary R3/N3 is known to within ± 7 ft, meaning that the K-T boundary and the top of the C29r reversal are indistinguishable (Table 8).

Our conclusion is that the K-T boundary, as defined palynologically in the Kiowa core, lies at the top of C29r. This indicates that there may have been a hiatus or a period of erosion in the earliest Paleocene in this part of the Denver Basin (fig. 17) which removed at least 300 kyrs of C29r.

A revised age estimate for the K-T boundary interval of 65.51 ± 0.10 Ma (see label 4, fig. 17) has been obtained by normalizing the most recently published isotopic dates for the boundary to a standard monitor age of 28.02 Ma for the Fish Canyon Tuff and 28.32 Ma for the Taylor Creek Rhyolite. Orbital chronology gives very precise estimates for the duration of C29r that range from 570 kyr to 673 kyr, but the most modern published estimate (D'Hondt and others, 1996) assigns an age of 603 ± 26 kyr for the whole of C29r, with 333 ± 20 kyr from the base of C29r and the K-T boundary, and 270 ± 17 kyr for the interval from the K-T to the top of the chron. By extrapolating from the palynological K-T boundary to the base of C29r and employing the 333 kyr precessional age for the interval of C29r that lies below the K-T, the age of the C30n/C29r reversal is estimated to be 65.84 Ma (fig. 17).

The calculated sedimentation rate for this interval is approximately 911 ft/Myr of compacted sediment (Table 8), which is a 300% increase over the underlying interval defined by N2. The implication is that the Fox Hills, Laramie and the lower part of the Dawson (D1) accumulated at a relatively low and steady rate as the Cretaceous Seaway regressed from the region, and that there was a marked increase in sedimentation rate near the end of the Maastrichtian in the middle part of the D1 as the Laramide orogeny developed along the Rocky Mountain front and subsidence accelerated in the adjacent foreland basin.

d. Normal/reversed/normal polarity interval N3 to N4

N3 lies in the upper half of the D1 synorogenic strata and ranges from 879 ft to a projected level of 628 ft with a precision of ± 39 ft, an interval of 251 ft. The two polarity reversals N3/R4 and R4/N4 define a short reversed interval in the upper part of the D1 sequence (see label 5, fig. 17). The top of N4 coincides almost exactly with the position of the D1/D2 paleosol that has been logged at 340 to 354 ft in the core (fig. 17).

The top of N4 is projected to lie at 351 ft which coincides exactly with the paleosol level and the contact of D1 and D2 (see label 6, fig. 17). This indicates that the N4/R5 reversal is an artifact caused by either a hiatus or active period of erosion at the level of the paleosol. Therefore both the base and top of this N3/R4/N4 interval are marked by hiatuses or erosional levels. The interval is bounded by the age of the K-T boundary below, and above by an isotopic age of 64.13 Ma obtained from an ash that lies just beneath the level of the paleosol (fig. 17).

This interval can be broadly correlated to that part of the GPTS that spans from C29n to C28n. The CK95 geomagnetic polarity time scale (GPTS) that ranges from the Maastrichtian through the Paleocene was calibrated using an age for 65.0 Ma for the K-T boundary. For this reason their age interpolation for the interval from C29n to C28n is approximately 0.5 Myr less than we would estimate. In figure 17 we show the age estimates for the CK95 time scale assuming that the sequence N3/R4/N4 corresponds to C29n through C28n. The CK95 time scale assigns an age that is somewhat older than the age we have measured, which is based on the 64.13 Ma isotopic age beneath the paleosol and extends to the base of C29n which is dated at 65.24 Ma (shown by the black hashed line in fig. 17). This age for the base of C29n is derived from the age of the K-T (65.51 Ma) and the precessional age of the upper part of C29r (333 kyr). The difference between this estimate and CK95 increases up section. The problem is compounded by the fact that there is an indeterminate amount of time missing from the K-T boundary hiatus and from the overlying paleosol. Nevertheless the reversal pattern measured does correspond well to the C29n to C28n interval, and this is the interpretation that we show in figure 17.

e. Reversed polarity interval R5

R5 extends from the top of the D1/D2 paleosol at approximately 351 ft to the uppermost sample measured in the core at 83 ft. R5 lies wholly within the Dawson (D2) stratigraphic interval. As the base of R5 lies on a hiatus or even an erosional disconformity, marked by the deep weathering profile of the paleosol sequence, and the top of the reversal is not found, then R5 is a fragment of a currently unidentified reversed polarity interval. This polarity interval is tentatively correlated to some part of C24r based on an Eocene age for D2 cited by Soister (1978b).

Conclusions

The Kiowa core is dominated by terrestrial sediments, and we have measured a number of hiatuses or disconformities (fig. 17) that are invariably part of a terrestrial sedimentary sequence. But our preliminary conclusions indicate that the core can be correlated with a high degree of confidence to that part of the GPTS that ranges from the top of C31r to C24r, or from the Maastrichtian to the Early Eocene. Thus the core encompasses a time period of approximately 15 million years from 69 to 54 Ma.

If the sequence is plotted on a time rather than a stratigraphic scale, then the amount of time missing in the sequence becomes apparent (fig. 18). This figure is based on the interpretation and ages described above and in figure 17. There is an obvious diachroneity between the isotopic age obtained below the paleosol and the age estimate for this polarity interval based on CK95. This is to be resolved in future studies of the ash layer and by a recalibration of the time scale to a revised K-T boundary age of 65.51 Ma.

Mineralogy and Petrography

Methods

Thin sections and Scanning Electron Microscope (SEM) photomicrographs of sandstone samples from the Kiowa core were used to determine the character and likely source terrain for the sandstone layers. Table 9 contains data derived from point-count analysis of over 40 thin sections made from sandstones from the core and figure 19 illustrates a representative SEM view of the disaggregated sand grains.

Results

a. Texture

Average visible mean grain sizes increase consistently upwards from a low value of 0.09 mm in the Pierre Shale sandstones to 0.18 mm in the Fox Hills Sandstone, 0.35 mm in the Laramie Formation (only one sample), 0.37 mm in the D1 sequence, and 0.56 mm in the D2 sequence. However, although grain sizes vary over only a limited range in the Pierre Shale (0.06 to 0.1 mm) and Fox Hills Sandstone (0.07 to 0.35 mm), they display wide variations in the D1 (0.09 to 1.5 mm) and D2 sequences (0.15 to 1.5 mm).

Average visible sorting levels are relatively consistent in the Pierre Shale (average of 0.42 phi and range from 0.38 to 0.45 phi) and Fox Hills Sandstone (average of 0.45 phi and range from 0.38 to 0.6 phi). The only sample from the Laramie Formation has a sorting value of 0.45 phi. Average sorting values increase significantly in D1 (0.63 phi), and D2 (0.79 phi) but range widely in both units (0.4 to 1.1 phi in the D1 sequence and 0.5 to 1.2 phi in the D2 sequence).

Grain size is commonly a major control on composition with certain components being relatively abundant in the finer size ranges while others dominate the coarser size ranges. Typically feldspars, dolomite, and micas tend to be concentrated in the coarse silt to fine sand size ranges, whereas quartz and rock fragments (including chert) tend to be most abundant in the coarser size ranges. To evaluate the influence of provenance on sandstone composition, grain size controls must be taken into account.

b. Composition

Quartz-feldspar-lithic proportions: The quartzose content is highest in sandstone beds in the Fox Hills Sandstone (72 percent) and the Pierre Shale (63 percent). Quartzose content drops off to only 30 percent in the Laramie Formation (based on one sample) and then increases to 51 percent in the D1 sequence and to 55 percent in the D2 sequence. The feldspathic content is approximately the same in the Fox Hills and Pierre (14 and 13 percent respectively), increases slightly in the Laramie (14 percent), increases in the D1 sequence (18 percent), then increases significantly in the D2 sequence (33 percent). Lithic components are moderately high in the Pierre (24 percent), about half that in the Fox Hills (11 percent), quite high in the Laramie (56 percent, only one sample), high in the D1 sequence (31 percent) and low in the D2 sequence (12 percent).

Quartzose components: Monocrystalline quartz is relatively high in both the Fox Hills and Pierre (51 and 46 percent respectively), low in the Laramie (21 percent), and moderate in the D1 and D2 sequences (35 and 36 percent, respectively). Polycrystalline quartz (all grains with greater than 1 crystal subunit) content is low in the Pierre (3 percent) and much higher in the Fox Hills (8 percent). The larger amount of polyquartz in the Fox Hills may be largely attributable to the increased average grain size of these sandstones. Polyquartz is low in the Laramie (4 percent, only one sample), moderate in the D1 sequence (6 percent), and highest in the D2 sequence (10 percent). Higher levels of average polyquartz tend to correlate strongly with increased grain size in most units. The relatively high polyquartz content in the Fox Hills compared to the coarser D1 and D2 sandstones is probably produced by a greater input of low-grade metasediments during deposition of this unit.

Chert content is highest in the Fox Hills (8 percent) and Pierre (7 percent) with the reduced content in the latter probably attributable to the finer average grain size of these sandstones. Chert is low in the Laramie (3 percent) but only one sample was available for comparison. Chert is higher in the D1 sequence (4 percent) reflecting a stronger sedimentary source than in the Laramie. Sandstones in the D2 sequence average only 0.1 percent chert, reflecting the very low sedimentary input for this unit. It is possible that some of the chert in the D1 is actually finely crystalline polyquartz rather than chert.

Feldspathic components: Plagioclase content is comparable in the Fox Hills (4 percent) and Pierre (5 percent) with the higher content in the latter probably related to the finer grain size of these sandstones. Surprisingly, plagioclase is absent in the Laramie (based on one sample), which may reflect the relatively silicic and potassium-rich nature of the volcanics sourcing this sandstone. Plagioclase is minor in the D1 sequence (3 percent), and this may also reflect a high silicic/potassium-rich volcanic source for many of the sandstones in this unit. In the D2, sequence plagioclase jumps to 8 percent and indicates a more basic composition for the plutonics sourcing this unit. Potassium feldspar is moderate in the Fox Hills (8 percent) and Pierre (7 percent) and significantly higher in all three of the younger units (averages of 12 percent in both the Laramie and the D2 sequence). The much higher potassium feldspar content in the upper three units reflects the higher input of locally sourced potassium feldspar-bearing volcanics and plutonics for these sandstones. Granitic fragments increase consistently from less than 1 percent in the Pierre to 3 percent in the D1 sequence. Granitic fragment content jumps to 11 percent in the D2 sequence, strongly reflecting the high plutonic input for these sandstones.

No gneiss fragments were encountered in any of the sandstones analyzed. This strongly suggests that high-grade metamorphics typical of the Front Range foothills north of the Castle Rock area were not a source of debris for any of the sandstones studied.

Lithic components: Total ductile grain (micas, mudstone fragments etc.) content varies widely between units. It is high in the Pierre (13 percent) largely due to its high content of micas and organic fragments. Ductiles are much lower in the Fox Hills (7 percent) with most being micas, organic fragments, and shale/mudstone/argillite fragments. Ductiles increase to 12 percent in the D1 sequence as a result of a high content of micas and mud/clay pellets. They are also high in the D2 sequence sandstones (11 percent) due largely to their high mica content.

Carbonate fragments are absent in the D2 sequence and Laramie sandstones, and comprise only a minor component of most D1 sandstones (1 percent) and Fox Hills sandstones (2 percent). However, they are considerably more abundant in sandstones of the Pierre (6 percent) with much of this increase possibly reflecting the decreased grain size of these sandstones and increased sedimentary input in the

Pierre-Fox Hills interval. All of the carbonate grains encountered are dolomite fragments. Heavy minerals are trace components in most samples.

Volcanic fragments are virtually absent in D2 sandstones (1 percent) and only a very minor component in the Fox Hills (2 percent) and Pierre (2 percent). They are much more abundant in the D1 sequence (17 percent) and Laramie (50 percent, only one sample). The very low content of these components in D2 reflects the lack of volcanic input during deposition of these sandstones.

c. Trends within stratigraphic units and with grain size

Chert content tends to increase from the base of the Pierre, where it is 3 percent, into the lower Fox Hills, where it reaches a high of 12 percent. It then decreases rapidly in the lower part of D1, where it is absent in a sample at a depth of 1528 ft. The decreasing trend is not entirely consistent as minor stratigraphic variations occur within this interval. The decrease in chert content in the lower part of D2 occurs despite the increased grain size of the sandstone in the upper Fox Hills and lower part of D1. Chert commonly exhibits a very strong positive correlation with grain size; for example, this relationship has been observed in the Permian through Lower Jurassic sandstone of the Alaska North Slope, Lower Cretaceous conglomerate and sandstone in the Alberta Basin, and in the Lower Cretaceous Frontier Formation of the Green River and Wind River Basins (M.D. Wilson, pers. comm., 2000). Such a relationship is not observed in the bulk of the sandstone penetrated in the Kiowa well, suggesting that provenance rather than grain size is the stronger influence on the composition of these sandstones. Chert content increases in the middle portion of D1 (at depths of 937 to 1,350 ft) to 14 percent and 21 percent in two samples. It then decreases to very low levels (less than 1-2 percent) in the upper part of the D1 sequence at depths of 429 to 619 ft. Chert is absent in the uppermost D1 sample, and in all but the uppermost D2 samples, where it occurs in trace amounts (0.5 percent). Chert may have been derived from reworking of clastics in Mesozoic and Paleozoic rocks and from the lower Paleozoic carbonates in the Pikes Peak area.

Carbonate fragments (dolomite fragments only) are absent in all but one sample (0.5 percent at a depth of 524 ft) down to a depth of 623 ft. Dolomite content then increases to 4-7 percent in two samples at depths of 852 and 976 ft. Dolomite is also present in trace to very minor amounts (1-2 percent) in samples at 1,177 and 1,246 ft, although two samples at depths of 1,060 and 1,061 ft are devoid of dolomite. Dolomite is absent throughout the lower part of D1 and the Laramie and upper Fox Hills down to a depth of 1,963 ft. At this depth it is present in significant amounts (3-9 percent), and also in all deeper samples. The simultaneous occurrence of large amounts of chert and minor dolomite in the medial portion of the D1 sequence suggests that unroofing of lower Paleozoic carbonates may have occurred at this time. The presence of chert in lesser amounts in deeper zones in the D1 sequence, but lack of dolomite, may indicate that these sandstones were derived from overlying Paleozoic and Mesozoic strata containing relatively modest to low chert content. The combined occurrence of minor to moderate chert and dolomite in the lower Fox Hills and Pierre suggest that these sandstones were derived from a chert-bearing, carbonate-rich source terrain such as the upper Paleozoic sedimentary rocks in the Sevier thrust belt, in Utah and Wyoming.

The percentage of volcanic fragments varies significantly in the section analyzed. Only trace to very minor amounts of silicic volcanics occur in the D2 sequence and no basic volcanics are present in any of the D2 sequence samples. Silicic volcanics are present in trace to minor amounts in the Fox Hills and Pierre samples and basic volcanics occur in trace to very minor amounts in only one sample in each of these two units. Silicic volcanics dominate many lithic-rich sandstones in the D1 sequence and the Laramie Formation sample. These sandstones tend to occur in the lower D1 (1,458-1,635 ft) and in the uppermost D1 (368-524 ft). Volcanic content is low however, in the finer grained sandstones throughout D1 regardless of stratigraphic position (0.06-0.15 mm average visible mean grain size).

Basic volcanics are absent in many D1 sequence samples but tend to occur in trace to very minor amounts in samples containing large amounts of silicic volcanics. The low content of basic volcanics throughout the section suggests that silicic volcanics were the main type of volcanic sourcing the sandstones analyzed. The silicic volcanics tend to contain large amounts of very fine sanidine (?) and quartz and appear to have phenocrysts scattered sparsely through a cryptofelsitic groundmass. Phenocrysts in the silicic volcanic fragments tend to be primarily plagioclase and biotite, though occasionally opaque heavy minerals, apatite, and possible amphibole phenocrysts are present. The more unstable phenocrysts tend to be altered to smectite or dissolved. Mafic constituents of these fragments are typically minor components and have been altered to smectitic or chloritic clays. Most of these silicic volcanics are probably rhyolites or dacites.

Apatite Fission Track Analysis

Ten samples were taken from the Kiowa core for fission track analysis at the New Mexico Institute of Mining and Technology. Fission tracks are microscopic crystal lattice disruptions caused by radioactive fission events. The crystal lattice disruptions are made visible by acid etching. In the mineral apatite these lattice disruptions anneal at about 60-70° C. By counting the number of tracks and the amount of radioactivity present in a given crystal (together with an assumed decay rate), one can compute the time elapsed since the rock cooled below the annealing temperature (Kelley and Chapin, 1997).

The samples from the Kiowa well (fig. 20a) indicate an age of cooling that generally ranges from 54 to 70 million years, ages that correspond to the Laramide orogeny. Some apatite crystals give significantly older dates (see for example samples from 1,394 and 1,715 ft). These older ages are thought to have been derived from crystals eroded from the crest of the uplifting Rocky Mountains.

Zircon Fission Track Analysis

Ten samples were mounted in Teflon, polished, and etched in NaOH/KOH at 230^{o}C for the times shown in table 10. Age histograms are shown in figure 20b. The samples contained zircon populations that had various etching characteristics. The mounts were cut in half and each half was etched for a different amount of time in an attempt to attain optimum etch conditions for each population. In this set of samples, mounts 1 and 2 were etched for the same amount of time.

The zircons were placed in a reactor package with Fish Canyon zircon age standards and Corning (CN-5) fission-track glass standards. The ages were calculated using the zeta calibration (422 ± 67 for zircon). The neutron flux for the reactor run was determined from glass standards and the accepted ages of the zircon standards.

When the samples were counted, the mounts were systematically scanned. Each grain encountered was evaluated. In many cases the zircon grain was metamict; in other words the grains were so old that radiation damage has destroyed the crystal structure. These grains were likely derived from the Proterozoic basement. Many of these grains are subhedral, although rounded metamict grains were observed in D1 sediments below 1395 ft. Some grains were over-etched and some were under-etched, and thus not dateable. Mounts that were etched for a short amount of time in order to best etch old zircons had large numbers of unetched grains, while other mounts etched for longer times to reveal the tracks in younger grains had many over-etched grains. Datable grains are well-polished and etched, so that tracks parallel to the c-axis are easily detectable. The number of metamict grains, likely reflecting the contribution from the basement or recycled Proterozoic grains, as well as the number of over-etched, under-etched, and dateable grains from each mount is recorded in table 10. The relative percentage of volcanic grains, distinctive yellow euhedral to brownish-yellow subhedral grains with high uranium concentrations and fission-track ages in the 60-90 Ma range is also indicated. The relative percentage of metamict versus volcanic grains varies throughout the D1 package.

TEMPERATURE LOGGING

Temperatures were measured in the Kiowa well for two reasons. First, temperature data in the southern Denver Basin are scarce and the effects of the aquifers on the temperature distribution in the basin are not well documented. Second, evaluation of the temperatures in the well is needed for proper interpretation of apatite fission-track data from the core samples.

Methods

Temperatures in the Kiowa well were measured four times. The temperature measurements were obtained using equipment calibrated in meters while most core and drilling data were measured in feet. Thus, measurements discussed here are reported in the units used during data acquisition. A conversion table is provided at the beginning of this report.

The first logging run took place about 24 hours after the last section of core had been extracted from the well, about an hour after the geophysical logs were run (table 11 and fig. 21). Drilling a well disturbs the ambient temperatures of the rocks. Fluids used during drilling heat up the upper section of a drill hole and cool the deeper portions of a well. Consequently, immediately after drilling, the temperatures in the borehole are out of thermal equilibrium, and it can take up to a year for the temperatures to return to normal.

Although the Kiowa well was out of thermal equilibrium, temperature logging commenced immediately after drilling because the well was going to be plugged back to a depth of 734 ft. The first temperature log was measured by taking readings every 5 m using a calibrated thermistor attached to about 2,500 m of cable. The thermistor was lowered into the well using a hand crank. Data from the top 1,837 ft were collected inside the drill pipe and temperatures were measured in open hole below that point. The drill pipe was left in the hole above the top of the Fox Hills Sandstone to keep the hole from collapsing during logging. The fluid level in the hole was about 15 m below the ground surface at the time of logging.

The hole was completed as a monitoring well by setting casing to a depth of 734 ft in late April 1999. The upper part of the well was re-logged approximately three months after the initial logging run using a truck-mounted system. Data were collected every 0.1 m (table 12 and fig. 22). The water level in the hole was ~100 m at the time of second logging run. Monitoring equipment in the hole prevented logging below a depth of 157 m. The well was logged a third and fourth time at 5 to 10 m intervals using the hand-crank logging equipment approximately six months and one year after the well was completed. The water level was at a depth of about 100 m during the third and fourth logging runs.

Results

The temperature and geothermal gradient data from the four logging runs are shown in figures 21 and 22. The temperature data from the April 6, 1999 run are surprisingly smooth, given the fact that the hole was just disturbed by drilling and logging. Fluids moving around at the base of the drill pipe caused the rather large disturbance at a depth of 560 m (figures 21 and 22). The relatively high geothermal gradients in the interval between 220 m to 260 m correspond to an interval containing many lignite beds.

The truck-mounted logging system has a hard time equilibrating in air, so there is an offset in the temperatures measured on July 6, 1999 at the water table. Note that, below the water table, the temperatures apparently decreased 3°C in the upper part of the well between the April 1999 and July 1999 runs. This observation may be due to a real cooling effect or it may reflect a difference in calibration between the two pieces of equipment used to make the measurements. Temperatures recorded during the third and fourth runs are cooler than those recorded during the first run, as expected, but are significantly warmer than those recorded during the second run in July 1999. Since the well was not disturbed between July 1999 and October 1999, it is likely that the differences in temperature recorded are due to calibration. Despite the absolute differences in temperatures recorded in different logging runs, the relative differences in temperature (i.e., the geothermal gradient) measured by the two systems track each other fairly well, particularly at depths below 120 m. The higher gradient recorded at a depth of 140 m is in an interval of mudstone and minor lignite, whereas lower gradients recorded in intervals above and below this point are in silty mudstone intervals. Mudstone facies dominate the sediments below 155 m. The well cooled only about 0.1°C between October 1999 and April 2000; thus the fourth log represents a near-equilibrium log.

The initial, non-equilibrium log of the Kiowa well was compared with a partially equilibrated log from the Castle Pines well to the west (Robson and Banta, 1993) (fig. 23). The temperatures in the Kiowa well are nearly 9°C warmer than the Castle Pines well at a depth of 680 m. The deeper portions of the Kiowa well are not as far out of equilibrium as the shallower sections, and the deeper parts of the well will warm during equilibration after interacting with relatively cooler drilling fluids during the equilibration process. A discrepancy in calibration between the logging equipment used in the Castle Pines well and that used in the Kiowa well is a consideration, but there are differences in geothermal gradient between the two wells. The average gradient for the Kiowa well is approximately 31°C/km while the gradient in the Castle Pines well is only 17°C/km. The temperature and gradient distribution may be related to the hydrology of the Denver basin. The Castle Pines well is closer to the recharge part of the basin, and has cooler temperatures and lower gradients, while the Kiowa well may have been heated by waters discharging eastward after the waters were warmed in the deeper parts of the basin.

RADIOMETRIC DATING

Two outcrops east of the Kiowa core were sampled for radiometric dating of mineral grains (sanidine) obtained from beds of altered volcanic ash. These radiometric dates are extrapolated into the subsurface to constrain the interpretation of the paleomagnetic signature in the Kiowa core.

The radiometric dates together with relevant constants are reported in table 13. The mineral grains dated at 64.13 ± 0.21 Ma are from an ash bed located at 39° 24.93' N, 104° 20.26' W on the Haas Ranch, and the grains dated at 65.03 ± 0.25 Ma are from an ash bed located at 39° 16.53' N, 104° 15.47' W on the north side of State Highway 86.

GEOPHYSICAL LOGGING

The geophysical logging was carried out by the Colog Division of Layne Geosciences, Inc. The logging was conducted in three separate runs. The first run spanned from the surface to a depth of 562 ft and was run on March 24, 1999. The second run spanned depths from 550 to 1,797 ft and was run on March 31, 1999. The final logging run spanned depths from 1,797 to 2,256 ft and was run on April 6, 1999.

The following tools were run: caliper, gamma ray, spontaneous potential, resistivity, compensated density, and full waveform sonic. There is a section of hole between 1,412 and 1,864 ft where no resistivity log is available because the lightweight sensor was not able to reach the entire logged interval. A set of logs is included as Plate 1. Selected log traces are portrayed on figure 9 where log data can be directly compared to both core lithology and the core sampling program.

SEISMIC LINE

R.J. Grundy and Associates at EnviroSeis obtained a short seismic line adjacent to the core hole in Kiowa. The seismic line was obtained using Vibroseis techniques and runs from the core location site, east to the county road, then north for about a mile along the side of the road. Selected reflectors are identified on the seismic line. The seismic line is included as Plate 2.