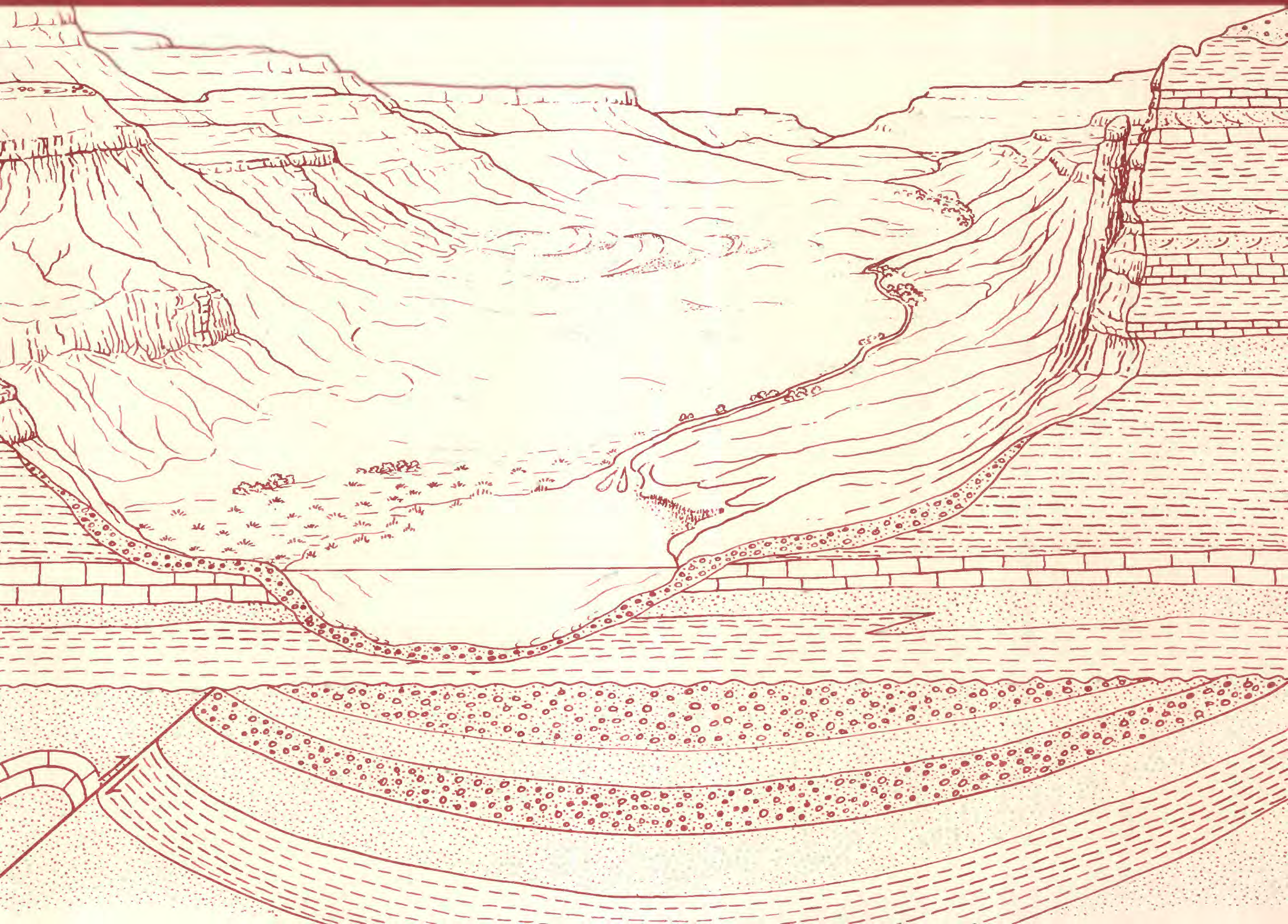
Miocene Cooling in the Southwestern Powder River Basin, Wyoming—Preliminary Evidence from Apatite Fission-Track Analysis

U.S. GEOLOGICAL SURVEY BULLETIN 1917–O



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Chapter O

Miocene Cooling in the Southwestern Powder River Basin, Wyoming—Preliminary Evidence from Apatite Fission-Track Analysis

By NANCY D. NAESER

A multidisciplinary approach to research studies of sedimentary rocks and their constituents and the evolution of sedimentary basins, both ancient and modern

U.S. GEOLOGICAL SURVEY BULLETIN 1917

EVOLUTION OF SEDIMENTARY BASINS—POWDER RIVER BASIN

U.S. DEPARTMENT OF THE INTERIOR
MANUEL LUJAN, JR., Secretary

U.S. GEOLOGICAL SURVEY
Dallas L. Peck, Director

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Miocene Cooling in the Southwestern Powder River Basin, Wyoming—Preliminary Evidence from Apatite Fission-Track Analysis

By Nancy D. Naeser

Abstract

The thermal history of the southwestern Powder River Basin of Wyoming was studied using results of fission-track analysis of detrital apatite separated from sandstone in the Upper Cretaceous Lewis Shale (youngest), Parkman Sandstone Member of the Mesaverde Formation, Shannon Sandstone Bed of the Steele Member of the Cody Shale, and Frontier Formation (oldest). The samples were recovered from depths of 1,974–3,809 m (6,478–12,498 ft) in 11 drill holes in Campbell, Johnson, and Converse Counties. In most of the section apatite was totally or almost totally annealed after burial in the basin and subsequently cooled about 12 Ma. In at least part of the section, temperatures required to produce observed fission-track ages and track lengths are substantially higher than those predicted by combining estimated post–mid-Miocene erosion (~630 m, 2,070 ft) and present-day gradients (about 27°C/km, 1.5°F/100 ft). Either the amount of total erosion since about 12 Ma is greater than estimated, or geothermal gradients in basin are higher than estimated (or were higher in the past), or factors such as movement of high-temperature fluids through the basin have contributed to maximum paleotemperatures experienced by the Upper Cretaceous sandstone reservoirs.

INTRODUCTION

A thick sequence of Upper Cretaceous open-marine to shallow-marine and fluvial, coastal-plain units was deposited in the Powder River Basin of Wyoming and Montana during alternating periods of westward transgression and eastward regression of the epicontinental sea that occupied a broad area of the central United States and Canada during much of the Cretaceous. The onset of Laramide deformation led to final eastward withdrawal of the sea in the latest Cretaceous (middle Maastrichtian) and deposition of a thick sequence of uppermost Cretaceous to Tertiary (Paleocene through Miocene) nonmarine sediments. Upper Cretaceous strata thicken from about 1,220 m (4,000 ft) at the northern margin of the Powder River Basin to about 3,050 m (10,000 ft) at the southern margin. Tertiary rocks thin from about 1,891 m (6,200 ft) in the northern part of the basin to about 1,624 m (5,330 ft) in the south. Extensive erosion thought to have begun about 10 Ma has removed most of the Oligocene and Miocene rocks, making it difficult to estimate the original thickness of Tertiary rocks deposited in the basin. About 825 m (2,700 ft) of the Tertiary section may have been removed in the north and 630 m (2,070 ft) in the south (Merewether and others, 1976; Nuccio, 1990).

The Cretaceous section contains thick sandstone intervals (including the Parkman Sandstone Member of the Mesaverde Formation, Shannon Sandstone Bed of the Steele Member of the Cody Shale, and Frontier Formation sampled for the present study) that are prime reservoirs for oil and gas production in this prolific basin. Geochemical evidence indicates that sometime during the Tertiary oil migrated updip and upsection along Laramide structures into these reservoirs, primarily from deeply buried Cretaceous source-rock shale in the western part of the basin (Strickland, 1958; Merewether and Claypool, 1980; Momper and Williams, 1984; Nuccio, 1990).

Understanding the thermal history of the Powder River Basin is important in establishing the timing of the petroleum generation, migration, and accumulation. The temperature history and thermal maturity of selected horizons have been investigated using a variety of methods including organic geochemistry, vitrinite reflectance, Rock-Eval pyrolysis, time-temperature index (TTI) modeling, and kinetic modeling based on the reactions of organic matter during thermal maturation (Merewether and Claypool, 1980; Momper and Williams, 1984; Nuccio, 1990). The results of these studies indicate a complex thermal history that varies from one part of the basin to another and that has been controlled by fluid flow as well as by temperature variations related to burial and erosion.

In the present study, the thermal history of rocks in the southwestern part of the Powder River Basin, along and to the east of the basin axis, was interpreted using fission-track analysis of detrital apatite. The apatite was separated from core samples of Upper Cretaceous sandstone recovered from the Lewis Shale (youngest), Parkman Sandstone Member of the Mesaverde Formation, Shannon Sandstone Bed of the Steele Member of the Cody Shale, and Frontier Formation (oldest) at depths of 1,974–3,809 m (6,478–12, 498 ft) in 11 drill holes in Campbell, Johnson, and Converse Counties, Wyoming (fig. 1).

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METHODS

Fission-Track Analysis

Fission tracks are zones of intense damage formed when fission fragments travel through a solid. Several naturally occurring isotopes fission spontaneously, but only ^{238}U has a sufficiently short fission half-life (9.9×10^{15} yr) to produce significant numbers of spontaneous tracks over a time period of geologic interest (Fleischer and others, 1975).

A number of common minerals contain trace amounts of uranium. Because ^{238}U fissions spontaneously at a constant rate, fission tracks can be used to date these minerals. The age of a mineral is calculated by determining the number of spontaneous tracks intersecting a polished surface of the mineral and the amount of uranium that produced those tracks. The techniques used in dating have been developed by physicists and geologists since the early 1960's and are reviewed in Fleischer and others (1975), C.W. Naeser (1976, 1979a), and N.D. Naeser and others (1989).

If a mineral containing spontaneous fission tracks is heated to sufficiently high temperature, the damage zone undergoes progressive shortening and ultimately disappears, leading to a reduction in the number of observable tracks and thus to an anomalously young fission-track age. Different minerals undergo this annealing over different temperature ranges. The temperature range for any given mineral depends on the duration of heating: the shorter the time the mineral is heated, the higher the temperature required to anneal its tracks.

More research has been devoted to determining the annealing kinetics of apatite than of any other mineral. Information has been gained both from laboratory heating experiments (for example, C.W. Naeser and Faul, 1969; Märk and others, 1973; Zimmermann and Gaines, 1978; Crowley, 1985; Green and others, 1985, 1986; Crowley and Cameron, 1987; Laslett and others, 1987; Duddy and others, 1988; Green, 1988; Green, Duddy, Laslett, and others, 1989; Crowley and others, 1990, 1991; Donelick and others, 1990; Hughes and others, 1990; Donelick, 1991) and by observing the annealing behavior of apatite in drill holes in areas where the thermal history of the rocks is reasonably well known (C.W. Naeser, 1979a, 1981; Gleadow and Duddy, 1981) (fig. 2). A topic that has received considerable attention in recent years is the effect of chemical composition on annealing temperatures of apatite. It is now known that the annealing susceptibilities of F-, Sr-F-, and OH-apatite are so similar that all can be approximated by F-apatite data. Chlorapatite, however, is significantly more resistant to annealing; at fixed heating times in the laboratory, it anneals at temperatures as much as 30°C (54°F) higher than other apatite varieties (Crowley and Cameron, 1987; Crowley and others, 1990; Hughes and others, 1990). Similar variation in annealing temperatures related to chlorine content is observed in drill-hole samples (Green and others, 1985; Green, Duddy, Gleadow, and Lovering, 1989). Available information indicates that apatite suites are typically so dominated by fluorapatite containing insignificant amounts of chlorine (Berry and Mason, 1959; Deer and others, 1962; N.D. Naeser and others, 1987) that most samples can be interpreted using fluorapatite annealing temperatures. For example, fluorapatite was used in all of the laboratory studies shown in figure 2, and analyses by K.D. Crowley (Miami University, oral commun., 1988) indicate that the apatite analyzed from at least two of the drill holes shown in figure 2 is F-apatite or F-OH-apatite containing little or no chlorine. As a practical matter, evidence suggests that the presence or absence of significant concentrations of chlorine can be determined indirectly from the etching characteristics of fission tracks (Crowley and others, 1990). Chlorapatites seem to etch more rapidly than other apatite varieties, producing characteristic broad tracks.

The most complete set of empirically derived annealing temperatures presently available indicates that fluorapatite is effectively totally annealed (yields a zero age) at temperatures that range from about 105°C (220°F) for relatively long-term heating of about 100 million years duration to 150°C (300°F) for a heating interval of about 100,000 yr (C.W. Naeser, 1981) (fig. 2).

Thermal History of Basins

The annealing of fission tracks in apatite and the resulting effect on fission-track age and track lengths have been widely used to reconstruct the thermal history of sedimentary basins (reviewed in N.D. Naeser, 1989, and N.D. Naeser and others, 1989). Fission tracks

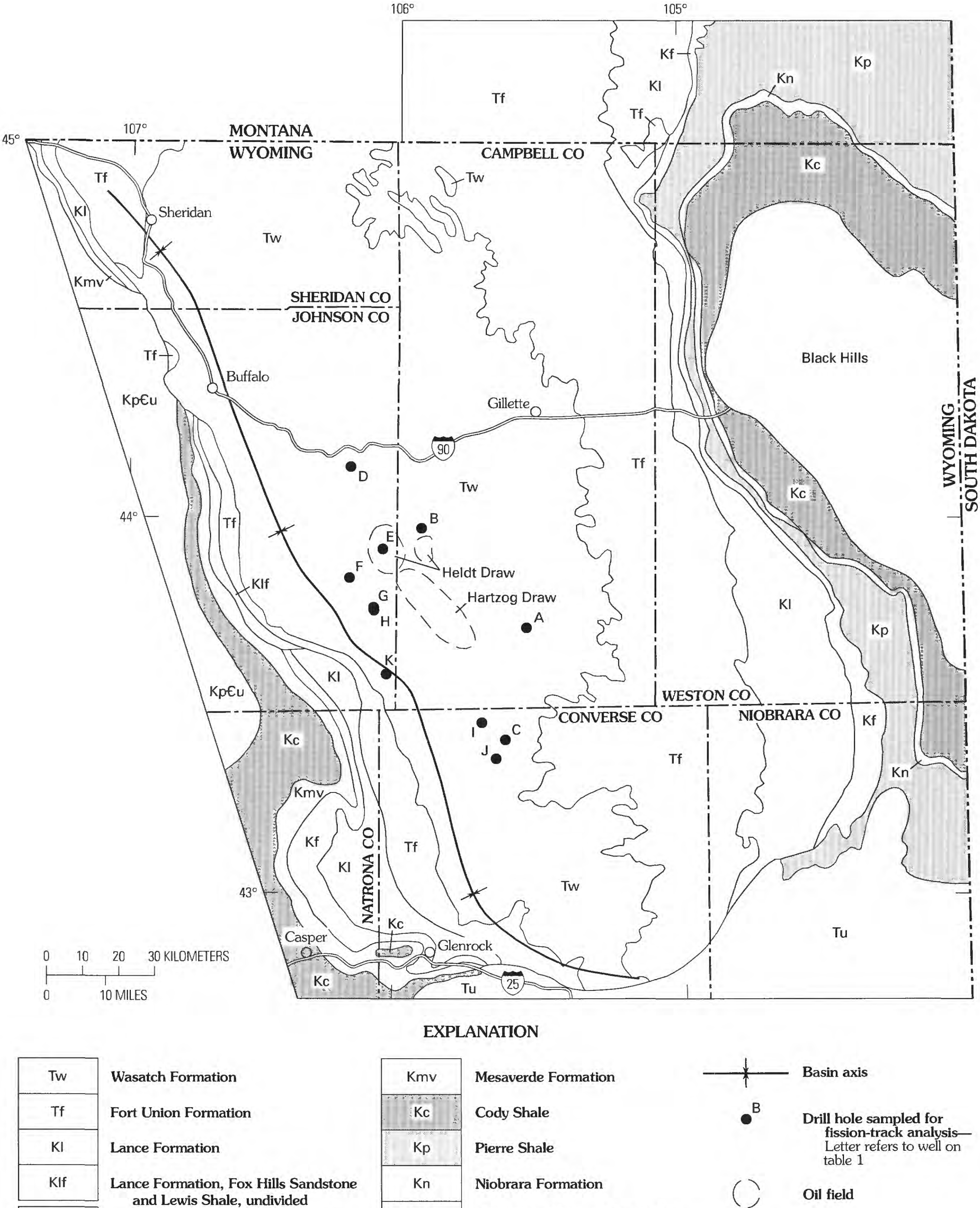

Figure 1. Map showing location of drill holes (solid lettered circles) sampled for fission-track analysis, southwestern Powder River Basin, Wyoming. Location data for drill holes are given in table 1. Geology of Black Hills not shown. Modified from Hansley and Whitney (1990).

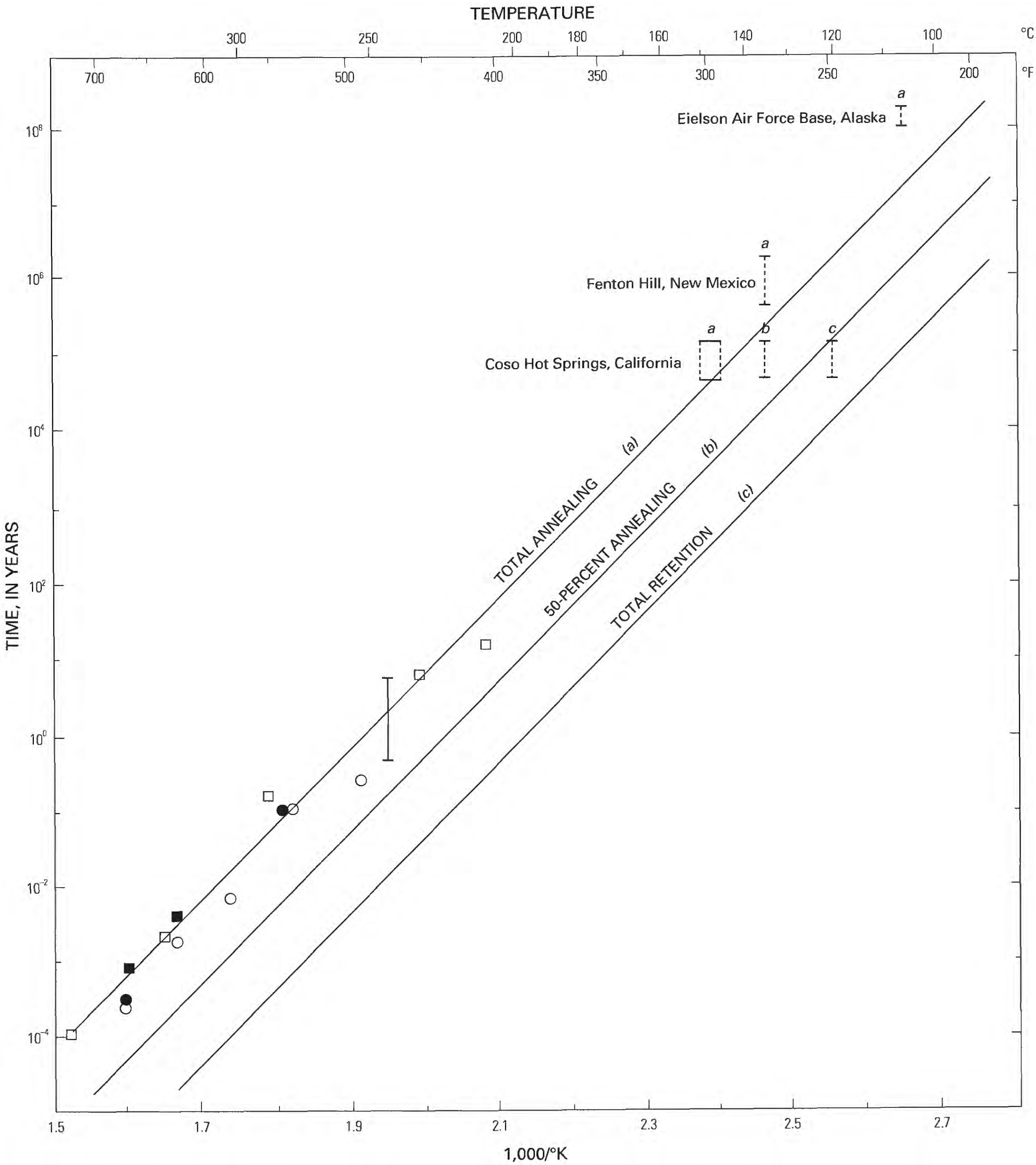

Figure 2. Temperatures required to anneal fission tracks in apatite over heating durations ranging from short-term laboratory experiments to long-term geologic heating. Modified from Sanford (1981, fig. 2). Temperatures for geologic annealing (dashed vertical bars) were determined by dating apatite in drill holes in three areas where the approximate duration of heating is known (C.W. Naeser, 1981). Circles and squares indicate the temperature-time conditions predicted for total annealing using the fading rates determined by the laboratory work of C.W. Naeser and Faul (1969) (open circles), Reimer (1972) (solid circles), Märk and others (1973) (open squares), and Zimmermann and Gaines (1978) (solid squares). Extrapolation of the laboratory data (solid lines) is based on the rate constant for fission-track annealing determined from a least-squares fit of the laboratory data (Zimmermann and Gaines, 1978). The solid vertical bar is the 95 percent confidence interval for the least-squares fit. Letters on the solid lines and dashed vertical bars identify data for (*a*) total annealing of fission tracks, (*b*) 50 percent annealing, and (*c*) total retention.

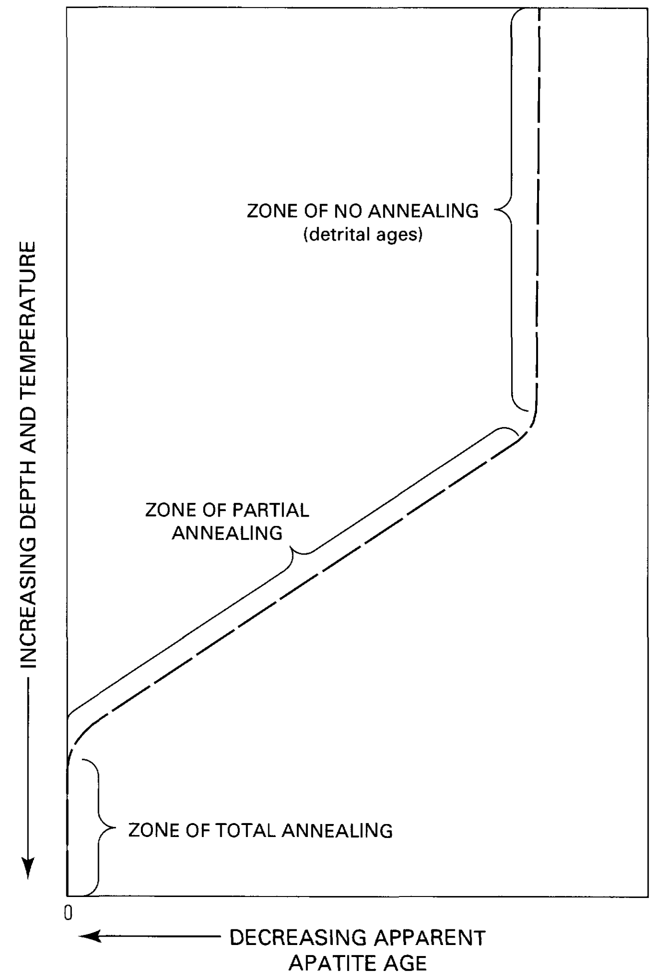

Figure 3. Expected decrease in apparent apatite fission-track age with increasing temperature and depth in a sedimentary sequence at the time of maximum burial heating. The temperature at which the apatite age decreases to zero depends on the duration of time the rocks have been heated near their present temperature (fig. 2). Drill-hole and extrapolated laboratory data (fig. 2) suggest that the zone of partial annealing covers a 30°C–35°C (54°F–63°F) temperature interval. Modified from C.W. Naeser (1979b).

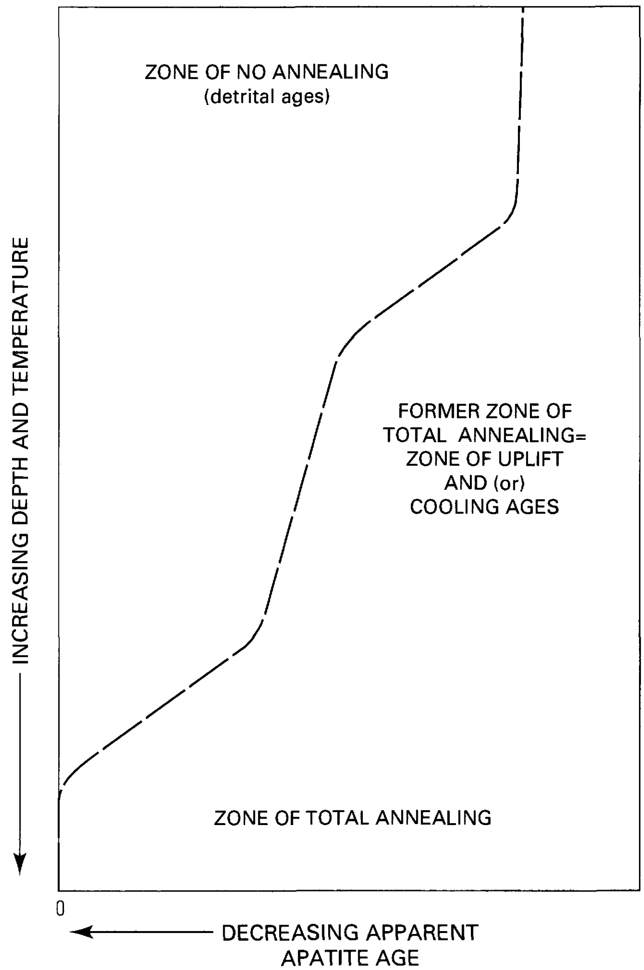

Figure 4. Expected distribution of apparent apatite fission-track ages in sedimentary rocks after uplift and (or) cooling of the sedimentary sequence (compare with fig. 3). Modified from C.W. Naeser (1979b).

provide information on the thermal history of sediments from deposition and burial through uplift and erosion for a temperature range that coincides with hydrocarbon generation and a number of other low- to moderate-temperature reactions in sedimentary basins (such as clay diagenesis and conodont color alteration) (Hood and others, 1975; Waples, 1980; N.D. Naeser and others, 1989). Fission tracks also define localized temperature anomalies such as those related to intrusions and to high-temperature fluid flow in a basin. Figures 3 and 4 illustrate the trends of depth versus apatite age for sedimentary sequences that are at their maximum burial temperatures and have cooled below maximum paleotemperatures, respectively.

In a sedimentary sequence at maximum burial temperatures (fig. 3), the ages of apatites from shallow rocks at relatively low temperatures are not affected by annealing during burial of the sediments (zone of no annealing). The ages of individual apatite grains in these rocks reflect the age(s) of the source rocks for the detrital grains. In a given sample, the apatite grains can be of widely differing ages. They may be equal in age to the stratigraphic age of the rock, as in the case of grains derived from contemporaneous volcanism, but much more commonly the grains are older and the composite apatite age (see below) for the sample is thus older than the stratigraphic age of the rock. The composite apatite ages calculated for individual samples in the zone of no annealing may remain relatively constant with depth (as depicted in fig. 3), but more commonly they vary, reflecting the variation in ages of detrital grains dated in any given sample.

Below the zone of no annealing, in rocks subjected to progressively higher temperatures due to deeper burial, apatite undergoes partial annealing and gives progressively

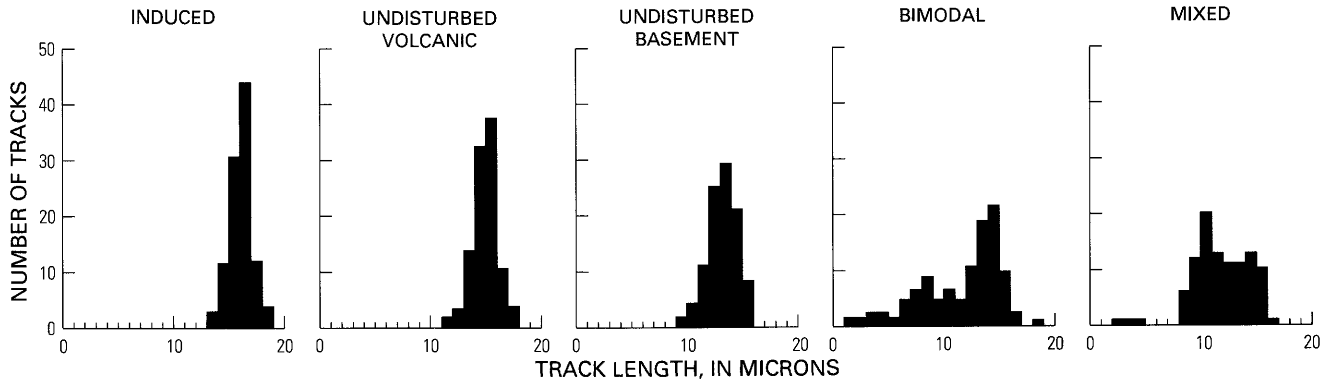

Figure 5. Horizontal, confined track-length distributions in apatite for various thermal histories including typical induced, undisturbed volcanic (from rocks that have undergone rapid cooling and remained at low temperatures), undisturbed basement (from rocks that have undergone slow continuous cooling from deep crustal to ambient surface temperatures), and mixed (thermally disturbed). The bimodal distribution is a special case of the mixed distribution in which two separate components, reflecting a two-stage thermal history, can be readily identified. All track lengths were measured on polished surfaces essentially parallel with the crystallographic *c*-axis and are not corrected for measurement bias (Laslett and others, 1982). Modified from Gleadow, Duddy, Green and Lovering (1986).

younger ages (zone of partial annealing). Within this zone, the apparent apatite ages become younger than the stratigraphic age of the rock and finally decrease to zero at the depth where the temperature for total annealing is attained for a sufficient time (see fig. 2) (zone of total annealing).

The annealing data in figure 2 suggest that the zone of partial annealing, in which there is an obvious decrease in apatite age due to annealing, covers a temperature interval of only about 30°C–35°C (54°F–63°F) for heating times on the order of 10^5–10^8 yr. Note that the actual temperatures covered by this zone depend, as does the temperature for total annealing, on the duration of heating. At a temperature of 105°C (221°F), for example, apatite heated for 10^8 yr is totally annealed, whereas apatite heated for only 10^5 yr or less is still in the zone of no annealing where there is little or no age reduction due to annealing (as observed, for example, in parts of the Los Angeles Basin; N.D. Naeser and others, 1987, 1990).

As a sedimentary sequence cools, in response to uplift and erosion or to a decrease in the geothermal gradient, apatite from the zone of total annealing once again begins to accumulate tracks and record a fission-track age (fig. 4). The recorded apatite age, the slope of the depth (or temperature) versus age plot, and the thickness of the zone of cooling ages give information on the time, rate, and amount of cooling, respectively.

Fission-track lengths in apatite are also a sensitive recorder of thermal history because each track in a given apatite forms at a different time and thus is exposed to a different fraction of the apatite's thermal history (for example, Gleadow and Duddy, 1981, 1982; Duddy and Gleadow, 1982; Gleadow and others, 1983; Crowley, 1985; Gleadow, Duddy, Green, and Hegarty, 1986; Gleadow, Duddy, Green, and Lovering, 1986; Duddy and others, 1988; Green, Duddy, Gleadow, and Lovering, 1989; Green, Duddy, Laslett, and others, 1989). Apatite in volcanic and related rocks that cool rapidly and remain at low temperatures has a narrow, symmetric track-length distribution, with mean track length of about 14.0–15.6 μm and standard deviation of the distribution of about 0.8–1.2 μm. More complex thermal histories produce more complex distributions. In the progression from undisturbed volcanic to mixed thermal histories, mean track length decreases, standard deviation of track-length distribution increases, and the complexity of the form of the track-length distribution increases (figs. 5, 6) (Gleadow, Duddy, Green, and Lovering, 1986).

Detrital apatites in a sedimentary rock can have any one or a combination of these distributions, depending on the thermal history of the parent rocks from which they were derived. As detrital apatite is buried and heated to progressively higher temperatures in a basin, tracks that were present when the apatite was deposited in the basin, as well as new tracks that form during burial, shorten in response to the heating.

In the simplest case of apatite derived from quickly cooled (undisturbed volcanic) parent rocks and undergoing relatively simple burial, apatite at shallow depths (low temperatures) has typical undisturbed volcanic track-length distribution. As temperature increases, mean track length decreases and the spread (standard deviation) of the track-length distribution increases (fig. 7). The increased spread is caused both by anisotropic annealing of tracks in apatite (tracks parallel with the *c*-axis of apatite shorten more slowly than tracks at high angles to the *c*-axis) and by the fact that even though existing tracks are being shortened by annealing, new (long) tracks continue to form in the apatite. The spread is accentuated in apatite suites that have a wide range in F/Cl composition because of the composition-related differences in apatite annealing susceptibility, as discussed above (Gleadow, Duddy, Green, and Hegarty,

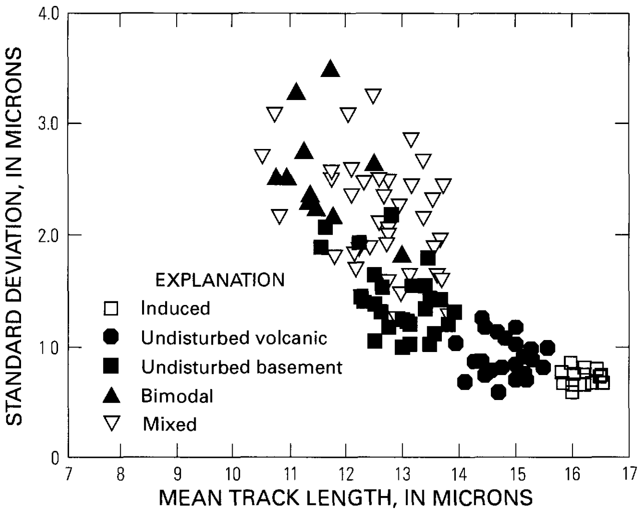

Figure 6. Relationship between standard deviation and mean track length for the various track-length distributions shown in figure 5. Note that bimodal distributions are much broader (have larger standard deviations) than distributions of undisturbed samples. The mean length and standard deviation of mixed distributions span the range of the bimodal and undisturbed basement samples. Modified from Gleadow, Duddy, Green, and Lovering (1986).

1986; Gleadow, Duddy, Green, and Lovering, 1986; Green and others, 1986).

In the more general case, the actual variation in mean length, standard deviation, and distribution of confined track lengths with depth in any given basin reflects the interplay among (1) the pre-basin (parent-rock) thermal history(s) experienced by the detrital apatite grains, (2) the postdepositional (basin) thermal history, and (3) the range of (F, Cl) composition in the apatite population and its consequent effect on annealing rates. Data from a number of basins are given in Gleadow, Duddy, Green, and Lovering (1986).

Laboratory Procedures

In the present study, 13 samples for fission-track analysis were taken from core samples of Upper Cretaceous sandstone recovered from 11 drill holes in the southwestern Powder River Basin (fig. 1, table 1). Apatite was separated from the crushed core samples using heavy liquid and magnetic separation techniques (N.D. Naeser and others, 1989, fig. 10.7). Grains coarser than about 74 µm (200 mesh; very fine sand size) were used for dating. In all samples, the fraction lighter than methylene iodide was treated with a bromoform–methylene iodide mix (sp gr=3.037) to improve segregation of apatite from contaminating grains. Three samples (PR–10, PR–12, and 83NN1) also required hand picking to isolate the apatite.

Apatite was dated by the external detector method, using a low-uranium-content muscovite as the detector. Samples were counted at × 1,000–1,500 magnification using a × 100 oil immersion lens (C.W. Naeser, 1976, 1979a; N.D. Naeser and others, 1989). Thermal neutron fluence was determined from a calibrated muscovite detector covering a glass dosimeter[1] placed at the top and bottom of each irradiation tube. The fluences were calibrated against the copper value determined by the National Bureau of Standards (Carpenter and Reimer, 1974), and the fluence for each sample was calculated by interpolation between the values determined for the standards. This method of fluence determination, if used in conjunction with a fission-decay constant of 7.03×10^{-17} yr^{-1} (Roberts and others, 1968) and the laboratory procedures followed in the U.S. Geological Survey fission-track laboratory, has been shown to consistently yield fission-track ages that are concordant with K-Ar ages of coexisting phases in rapidly cooled (volcanic and hypabyssal) rocks (C.W. Naeser and others, 1977).

Apatite fission-track ages were calculated for each of the Powder River Basin samples (tables 2, 3) by using the sum of the spontaneous and induced tracks counted in the individual grains in the sample to calculate the values for spontaneous track density (ρ_s) and induced track density (ρ_i), respectively, in the fission-track age equation (Price and Walker, 1963; C.W. Naeser, 1967). The uncertainty in the age was calculated by combining the Poisson errors on the spontaneous and induced track counts and on the track counts in the detector covering the dosimeter (McGee and others, 1985). These methods are commonly used to calculate age and uncertainty in fission-track dating, but they may not be strictly applicable to sedimentary rock samples in which the detrital grains were most likely derived from more than one age population. The age calculated from the ages of individual detrital grains in a sedimentary rock is in fact a composite age and has no real meaning in a stratigraphic sense.

Track lengths were measured in transmitted light at × 1,500 magnification using a × 100 oil immersion lens and a Summagraphics MacTablet digitizing tablet and projection tube calibrated against a stage micrometer (1 unit=0.01 mm). Only well-etched horizontal confined tracks in grains with polished surfaces approximately parallel with the crystallographic *c*-axis were measured. Reported track lengths (table 4, fig. 10) are actual measurements, not corrected for length-measurement bias (Laslett and others, 1982).

Present-Day Temperatures

Present-day temperatures of the analyzed samples are difficult to determine because the only temperature data

[1]USGS glass standard calibrated against National Bureau of Standards glass standard SRM 963 containing 0.832±0.002 ppm U.

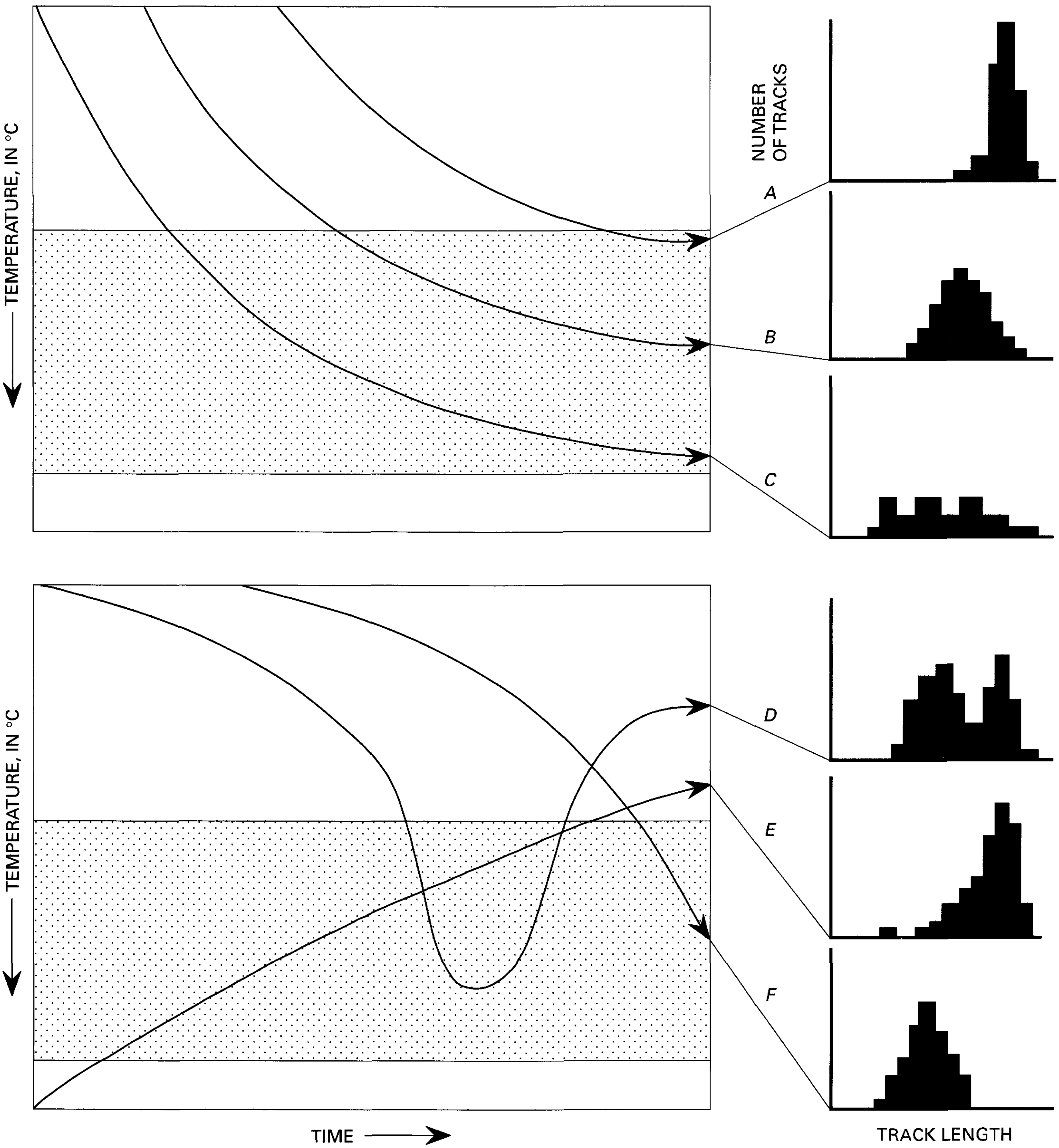

Figure 7. Temperature-time paths and resulting apatite track-length distributions for rocks of varying thermal history. Diagrams *A–C* show distributions resulting from simple progressive burial of undisturbed volcanic apatite (fig. 5) to different levels in the zone of partial annealing (stippled). Diagrams *D–F* show distributions for more complicated thermal histories including (*D*) a past thermal event (bimodal distribution), (*E*) slow cooling, and (*F*) recent heating. Modified from Gleadow and others (1983).

available from the sampled wells are bottom-hole temperatures (BHT) (two depth-temperature pairs from well I; one BHT from all other wells) based on measurements made as many as 14 hr, but generally less than 5 hr, after circulation. Obtaining corrected equilibrium temperatures for the samples is further complicated by the combined problem that the sampled wells are rather widely scattered and temperature gradients are known to vary significantly from one

Table 1. Location, depth, stratigraphic position, and present-day temperature of analyzed drill-core samples of Upper Cretaceous sandstone, southwestern Powder River Basin, Wyoming
[Well letters refer to locations shown on figure 1]

Sample	Well	Depth below surface (feet)	Depth below surface (meters)	Stratigraphic unit	Present-day temperature[1] (°C)
PR–1	A	6,478	1,974	Lewis Shale	64
PR–4	B	7,499	2,286	Parkman Sandstone Member[2]	72
PR–5	A	7,500	2,286	Parkman Sandstone Member[2]	72
83NN1	C	8,183	2,494	Parkman Sandstone Member[2]	78
PR–6	D	8,599	2,621	Shannon Sandstone Bed[3]	82
83NN3	E	9,366	2,855	Shannon Sandstone Bed[3]	88
83NN2	E	9,387	2,861	Shannon Sandstone Bed[3]	88
PR–7	F	9,687	2,953	Shannon Sandstone Bed[3]	91
PR–8	G	9,901	3,018	Shannon Sandstone Bed[3]	93
PR–9	H	9,955	3,034	Shannon Sandstone Bed[3]	93
PR–10	I	11,611	3,539	Frontier Formation	107
PR–11	J	12,337–12,340	3,760–3,761	Frontier Formation	113
PR–12	K	12,498	3,809	Frontier Formation	114

Location of wells

A. Ladd Petroleum Good No. 1 (NE¼SW¼ sec. 18, T. 43 N., R. 72 W.)
B. Texaco Skyline No. AK–1 (NCT–1) (NE¼NE¼ sec. 1, T. 46 N., R. 76 W.)
C. MWJ Production Smith Federal No. 27–15 (SW¼SE¼ sec. 27, T. 40 N., R. 73 W.)
D. Southland Royalty Beaver Creek Federal No. 1–1 (sec. 1, T. 48 N., R. 78 W.)
E. Davis Oil Heldt Draw No. 10 (SW¼SE¼ sec. 36, T. 46 N., R. 77 W.)
F. Webb Resources Federal No. 25–D (SE¼SE¼ sec. 25, T. 45 N., R. 78 W.)
G. Southland Royalty Van Irvine No. 3 (sec. 22, T. 44 N., R. 77 W.)
H. Southland Royalty Van Irvine No. 2 (NE¼SE¼ sec. 27, T. 44 N., R. 77 W.)
I. Ensearch Exploration Federal Moore Sheep No. 1–3 (sec. 3, T. 40 N., R. 74 W.)
J. Woods Petroleum Dilts Government No. 7–1 (SW¼NE¼ sec. 7, T. 39 N., R. 73 W.)
K. Oil Development of Texas Moore No. A–1 (SW¼SW¼ sec. 22, T. 42 N., R. 77 W.)

[1]Based on average gradient of 27.3°C/km (1.5°F/100 ft) for southern Powder River Basin; see text for discussion.
[2]Of the Mesaverde Formation.
[3]Of the Steele Member of the Cody Shale.

area to another of the southern Powder River Basin, locally over short distances (for example, Buelow and others, 1986, sheet 3).

Nuccio (1990) adopted a present-day gradient of 29.2°C/km (1.6°F/100 ft) for the southern Powder River Basin, based on Geothermal Survey of North America Subcommittee (GSNAS) (1976). In the area of the wells sampled for the present study (fig. 1), the GSNAS map indicates that gradients vary from >21.9°<25.5°C/km (>1.2°<1.4°F/100 ft) to >29.2°<32.8°C/km (>1.6°<1.8°F/100 ft). These gradients are based on bottom-hole temperature measurements that were corrected for thermal disequilibrium using a correction procedure developed from a comparison of bottom-hole and equilibrium temperatures in 602 selected West Texas and Louisiana wells.

The southern part of the present study area (wells C, I, J, and K, fig. 1) is covered in more detail by the thermal gradient study of Buelow and others (1986). Their conductive thermal modeling (based on thermal (equilibrium) logs from 60 wells, average thermal conductivities, and regional heat flow values) indicates an average gradient of 25.2°C/km (1.38°F/100 ft) for the southernmost Powder River Basin, in good agreement with the average gradient of 24.4°C/km (1.34°F/100 ft) that they derived from 6,100 uncorrected bottom-hole temperature measurements. Superimposed on this average background gradient are areas in which gradients are significantly higher.

In the specific areas of wells sampled in the present study, the geothermal gradient maps of GSNAS (1976) and Buelow and others (1986, sheet 3) are generally comparable, although they differ in details of the thermal gradient contouring. The rather generalized gradient contours, particularly on the GSNAS map, the lack of equilibrium measurements made directly in the sampled wells, and the highly variable nature of gradients in the Powder River Basin make it risky to try to assign specific gradients to individual wells. Accordingly, a mean gradient of about 27.3°C/km (1.5°F/100 ft) was calculated from gradients shown on the maps of GSNAS and Buelow and others in the area of the 11 sampled wells, and this gradient was used to calculate the corrected temperatures given in table 1 and figure 8. Actual gradients undoubtedly vary from this value in several of the sampled drill holes. For example, the geothermal map of GSNAS indicates that gradients of from

Table 2. Fission-track age of detrital apatite in drill-core samples of Upper Cretaceous sandstone, southwestern Powder River Basin, Wyoming

[Table gives data for all grains counted, including grains containing broad tracks (see text). Locations of samples described in table 1 and shown in figure 1. Number in parentheses is number of tracks counted]

Sample[1]	Number of grains counted	Track density: Spontaneous (ρ_s) ($\times 10^6$t/cm^2)	Track density: Induced[2] (ρ_i) ($\times 10^6$t/cm^2)	Neutron fluence[3] (ϕ) ($\times 10^{16}$n/cm^2)	Chi-squared (χ^2) probability[4] (percent)	Age[5] (Ma)
PR-1	7	0.469 (39)	7.74 (322)	1.26 (1,945)	1	45.5±7.8[6]
PR-4	9	0.070 (11)	6.86 (542)	1.22 (1,945)	46	7.4±2.3
PR-5	8	0.198 (27)	5.40 (369)	0.530(2,301)	5	11.6±2.3
83NN1	12	0.169 (78)	4.33 (998)	1.09 (3,723)	<1	25.3±3.0[6]
PR-6	10	0.024 (4)	3.68 (306)	1.21 (1,945)	49	4.7±2.4[6]
83NN3	17	0.114 (37)	2.44 (396)	1.07 (3,723)	21	29.7±5.1[6]
83NN2	4	0.063 (3)	2.79 (67)	1.08 (3,723)	3	14.4±8.5
PR-7	5	0.043 (2)	2.30 (53)	1.16 (1,945)	16	13.1±9.4
PR-8	11	0.049 (10)	2.61 (268)	1.18 (1,945)	6	13.2±4.3[6]
PR-9	6	0.059 (7)	3.03 (180)	1.17 (1,945)	78	13.6±5.3[6]
PR-10	11	0.068 (8)	4.25 (249)	0.858(2,901)	87	8.2±3.0
PR-11	5	<0.021 (0)	1.81 (43)	1.14 (1,945)	--	0
PR-12	8	0.010 (2)	4.77 (462)	1.12 (1,945)	52	1.5±1.0[6]

[1]Listed in order of increasing depth.

[2]Reported induced track density is twice the measured density.

[3] See text for method used to determine neutron fluence (ϕ).

[4]Measure of the probability that all individual grains counted in a sample are from a single age population; values of $P(\chi^2)<5$ percent are generally taken as an indication of a real spread in single grain ages (Galbraith, 1981; Green, Duddy, Gleadow, and Lovering, 1989).

[5]Calculated from fission-track age equation (Price and Walker, 1963; C.W. Naeser, 1967), using sums of the spontaneous and induced track counts obtained for all grains counted in the sample and the following values: $\lambda_D=1.551\times10^{-10}$/yr; $\lambda_F=7.03\times10^{-17}$/yr (Roberts and others, 1968); $\sigma=580\times10^{-24}$ cm^2; $I=7.252\times10^{-3}$. Standard error (±1) calculated by combining Poisson errors on spontaneous and induced counts and on counts in detector covering dosimeter (McGee and others, 1985).

[6]Sample contains grains with anomalously broad tracks that suggest anomalously high chlorine content. Age recalculated without these grains is given in table 3.

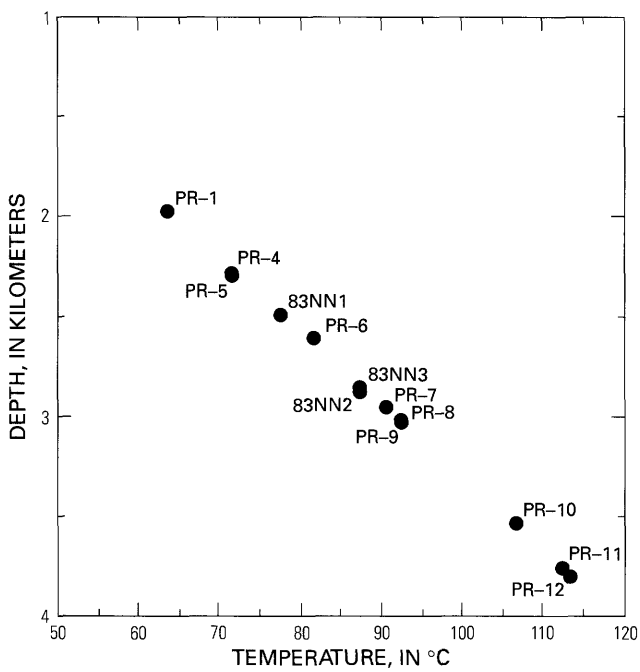

Figure 8. Depth and present-day temperature (corrected) of samples collected for fission-track studies from drill holes in the southwestern Powder River Basin. Sample information is given in table 1. Method used to correct temperatures is explained in the text.

21.9°C/km to 25.5°C/km (1.2°F/100 ft–1.4°F/100 ft) may exist in the general area of wells E, F, G, H, and K. Both GSNAS (1976) and Buelow and others (1986) indicate that gradients approach or exceed 29.2°C/km (1.6°F/100 ft) in the general area of wells C, I, and J. The latter wells are close to three wells for which Merewether and Claypool (1980, wells 1–3) reported corrected gradients of from about 29°C/km to 32°C/km (1.59°F/100 ft–1.76°F/100 ft).

RESULTS

Apatite Ages

Apatite fission-track ages were determined for all 13 samples. Although apatite composition was not determined directly in the analyzed samples, a qualitative estimate of chlorine content in apatite can be made, as noted earlier, from the width of etched fission tracks; tracks in chlorine-rich apatites seem to etch faster and thus are broader. Most of the samples used in this study were first counted in the early 1980's, before the role of composition in controlling annealing temperatures was fully appreciated. Subsequent re-examination of the dated apatites showed that several grains having anomalously wide tracks, and thus probably containing significant amounts of chlorine, were included in

Table 3. Corrected fission-track age of detrital apatite in drill-core samples of Upper Cretaceous sandstone, southwestern Powder River Basin, Wyoming

[Data from table 2 have been corrected to eliminate grains with anomalously wide tracks (and therefore presumably with anomalously high chlorine content) (see text). Locations of samples described in table 1 and shown in figure 1. Number in parentheses is number of tracks counted]

Sample[1]	Number of grains counted	Track density: Spontaneous (ρ_s) (×10⁶t/cm²)	Track density: Induced[2] (ρ_i) (×10⁶t/cm²)	Neutron fluence[3] (ϕ) (×10¹⁶n/cm²)	Chi-squared (χ^2) probability[4] (percent)	Age[5] (Ma)
PR–1	6	0.421 (30)	8.42 (300)	1.26 (1,945)	34	37.6±7.3
PR–4	9	0.070 (11)	6.86 (542)	1.22 (1,945)	46	7.4±2.3
PR–5	8	0.198 (27)	5.40 (369)	0.530(2,301)	5	11.6±2.3
83NN1	10	0.130 (51)	4.53 (892)	1.09 (3,723)	<1	18.5±2.7
PR–6	9	0.020 (3)	3.77 (280)	1.21 (1,945)	37	3.9±2.3
83NN3	13	0.081 (18)	2.50 (279)	1.07 (3,723)	14	20.5±5.0
83NN2	4	0.063 (3)	2.79 (67)	1.08 (3,723)	3	14.4±8.5
PR–7	5	0.043 (2)	2.30 (53)	1.16 (1,945)	16	13.1±9.4
PR–8	9	0.036 (6)	2.75 (229)	1.18 (1,945)	25	9.2±3.8
PR–9	4	0.063 (5)	3.59 (143)	1.17 (1,945)	69	12.2±5.6
PR–10	11	0.068 (8)	4.25 (249)	0.858(2,901)	87	8.2±3.0
PR–11	5	<0.021 (0)	1.81 (43)	1.14 (1,945)	--	0
PR–12	7	0.006 (1)	4.89 (404)	1.12 (1,945)	38	0.8±0.8

[1]Listed in order of increasing depth.

[2]Reported induced track density is twice the measured density.

[3] See text for method used to determine neutron fluence (ϕ).

[4]Measure of the probability that all individual grains counted in a sample are from a single age population; values of $P(\chi^2)<5$ percent are generally taken as an indication of a real spread in single grain ages (Galbraith, 1981; Green, Duddy, Gleadow, and Lovering, 1989).

[5]Calculated from fission-track age equation (Price and Walker, 1963; C.W. Naeser, 1967), using sums of the spontaneous and induced track counts obtained for all grains counted in the sample and the following values: $\lambda_D=1.551\times10^{-10}$/yr; $\lambda_F=7.03\times10^{-17}$/yr (Roberts and others, 1968); $\sigma=580\times10^{-24}$ cm²; $I=7.252\times10^{-3}$. Standard error (±1) calculated by combining Poisson errors on spontaneous and induced counts and on counts in detector covering dosimeter (McGee and others, 1985).

the initial counts. To rigorously compare track size, tracks widths (maximum axis of the pit formed by the intercept of the etched track and the polished grain surface) were measured in all of the dated grains. Grains having anomalously wide tracks were discarded from the analysis. This exercise probably eliminated most of the chlorine-rich apatite; however, because a quantitative correlation between track width and chlorine content is not yet available, it is possible that in some samples not all of the chlorine-rich grains were excluded.

Table 2 gives data for all grains originally counted, including grains having anomalously wide tracks. Table 3 gives recalculated data, excluding the grains having anomalously wide tracks. The ages from table 3 are plotted in figure 9 and discussed below.

The composite apatite age calculated for each of the 13 samples (table 3, fig. 9) and all but a few of the individual apatite grain ages are significantly younger than the stratigraphic ages of the units from which they were collected (that is, the ages are younger than the stratigraphic ages and do not overlap them at two standard deviations); thus, there has been significant postdepositional annealing of apatite in all of the Upper Cretaceous sandstone units sampled in the southwestern Powder River Basin. The composite ages vary from 37.6±7.3 Ma (±one standard deviation) in the shallowest sample (Lewis Shale, sample PR–1) to zero (totally annealed) in the deeply buried Frontier Formation (sample PR–11).

A notable feature of the apatite fission-track data is the apparent lack of decrease in age in samples PR–4 through PR–10 (fig. 9). Within analytical uncertainty, the composite ages calculated for individual samples are constant in this 1,253-m-thick, 35°C (4,112 ft, 63°F) interval (from 2,286 m, 72°C (7,499 ft, 162°F) to 3,539 m, 107°C (11,611 ft, 225°F)). The composite age calculated from the 82 grains counted in samples PR–4 through PR–10 is 12.7±1.2 Ma. The arithmetic mean of the 10 composite sample ages is 11.9 ±1.6 Ma.

Apatite Track Lengths

Track lengths were measured in six samples (fig. 10, table 4); the remaining samples did not contain sufficient apatite for track-length measurements. Mean track length in all samples is less than 12 µm, and the standard deviation of the track-length distribution is 1.62 µm or more. Samples PR–4 and PR–5 have positively skewed length distributions and few short tracks (no tracks shorter than 8 µm). As downhole temperature increases, mean track length decreases, standard deviation of the track-length distribution and the number of short tracks generally increase, and track-length distributions are generally negatively skewed.

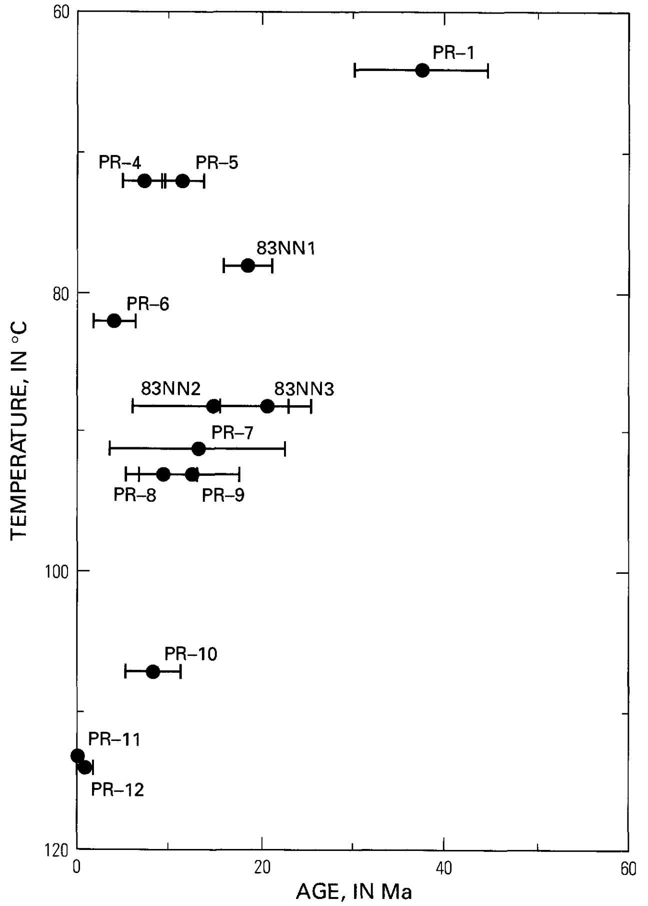

Figure 9. Present-day temperatures (corrected) and fission-track ages (±one standard deviation) for detrital apatites from drill-core samples of Upper Cretaceous sandstones in the southwestern Powder River Basin. Sample information is given in table 1; fission-track data are given in table 3.

Samples 83NN3 and 83NN2 are separated by only 6 m (21 ft) in drill-hole E and have essentially the same present-day temperature and similar apatite age and mean track length. Samples PR–4 and PR–5 are from different drill holes but are at the same temperature and yield similar ages and mean track lengths; the same is true of samples PR–8 and PR–9. Within each of these three pairs, the samples most likely have very similar thermal histories. Complications in several of the track-length distributions (for example, the hint of bimodality in sample PR–4) disappear when the distributions are combined for each of the three pairs (fig. 10), suggesting that the "complications" may be, at least in part, artifacts of the relatively small number of tracks that could be measured in most of the samples.

DISCUSSION

Age and track-length data indicate that throughout the sampled section apatite has been annealed. Over the depth and temperature interval from sample PR–4 through sample

Table 4. Horizontal confined fission-track lengths in detrital apatite from drill-core samples of Upper Cretaceous sandstone, southwestern Powder River Basin, Wyoming

[Locations of samples described in table 1 and shown in figure 1. Track-length distributions shown in figure 10]

Sample number	Number of tracks measured	Mean track length[1] (μm)	Standard deviation of track-length distribution
PR–4	29	11.66±0.33	1.75
PR–5	20	11.76±0.38	1.69
83NN3	58	10.80±0.30	2.25
83NN2	11	10.11±0.49	1.62
PR–8	4	9.84±0.98	1.97
PR–9	5	9.28±1.47	3.29

[1]±one standard error.

PR–10 the apatites record ages of about 12 Ma. Age and track-length data are consistent with the interpretation that all of these rocks were heated to temperatures sufficiently high to totally or almost totally anneal the apatite and subsequently cooled about 12 Ma. This interpretation is supported both by the general lack of variation in fission-track age in a relatively wide temperature interval and by modeling of the age and track-length data, using a modeling program based on Laslett and others (1987). The exact time and rate of cooling cannot be determined precisely because of (1) the possibility that apatite in some samples was not totally annealed prior to Miocene cooling, (2) the large analytical uncertainty associated with the apatite ages, (3) the possibility that data from chlorine-rich grains have been included in the analyses of some samples, affecting both the observed ages and track lengths, and (4) the fact that the deeper samples in particular are at sufficiently high temperatures to have undergone some degree of annealing since cooling from maximum paleotemperatures. Regarding the last factor, modeling indicates that reduction in track lengths has occurred over the past 12 Ma, but the effect of postcooling annealing on the fission-track ages is less obvious. Several laboratories (for example, Kamp and Green, 1990) correct apatite fission-track ages that supposedly have been lowered by annealing by assuming a 1:1 ratio between reduction in track length and fission-track density in the early (low temperature) stage of annealing (Green, 1988). However, the relationship between length and density may not be a simple 1:1 ratio. Evidence from both drill-hole and laboratory data suggests that as much as a 20 percent reduction in measured lengths may occur with little or no effect on the fission-track age (C.W. Naeser and others, 1989). Until the length:density relationship is resolved, any age correction based on track lengths should be viewed with caution.

Heating of Upper Cretaceous sandstone intervals in the southwestern Powder River Basin and subsequent Miocene cooling may reflect (1) a relatively simple thermal history of

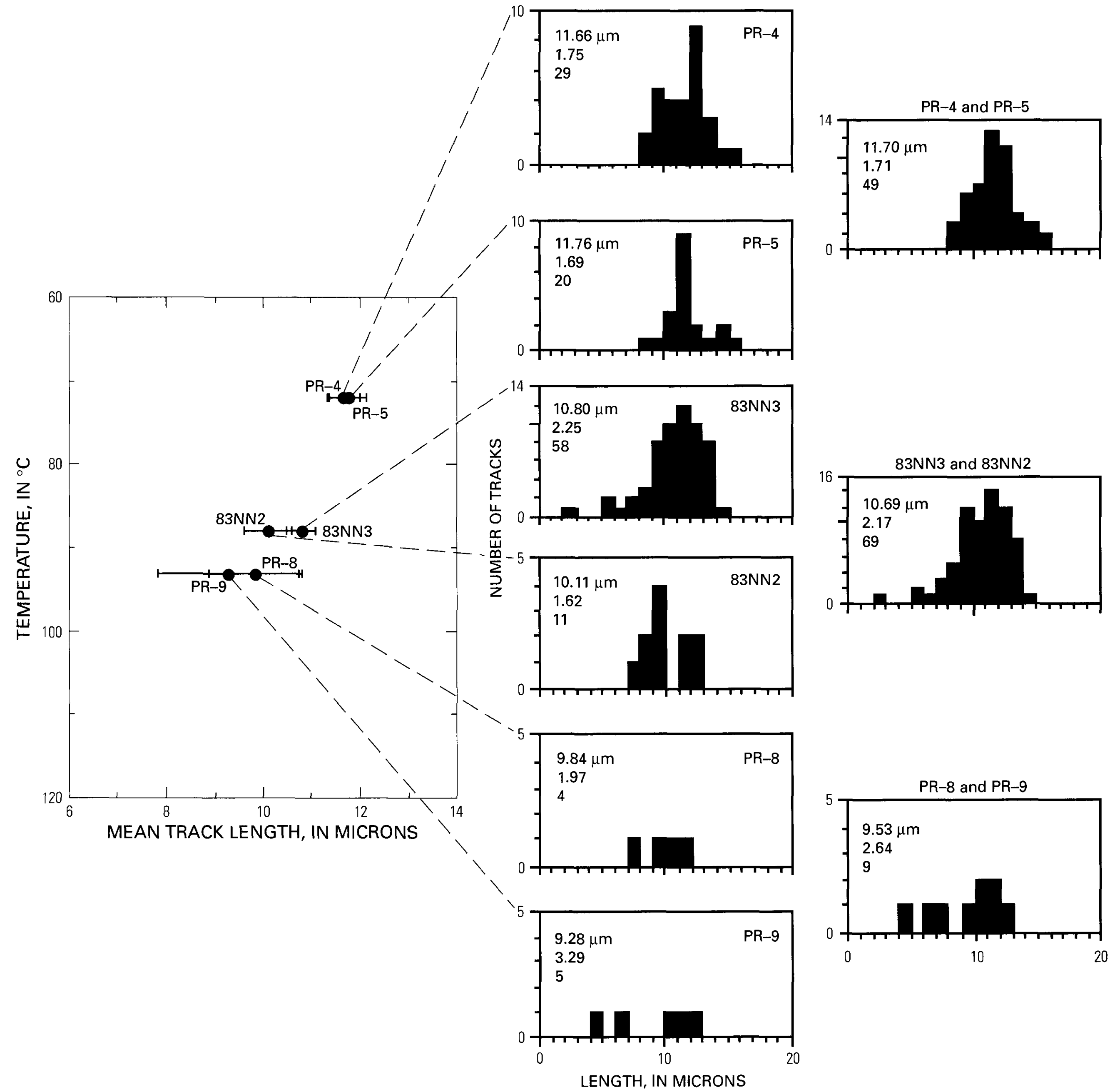

Figure 10. Present-day temperatures (corrected), mean length plus or minus the standard error of the mean, and track-length distributions of selected apatite samples, southwestern Powder River Basin. Each histogram lists (from top to bottom) mean length, standard deviation of the track-length distribution, and number of tracks measured. Composite track-length distributions obtained by combining track-length measurements for samples PR–4 and PR–5, 83NN3 and 83NN2, and PR–8 and PR–9 are also shown. Sample information is given in table 1.

burial heating followed by uplift and erosion or (2) a more complex thermal history in which burial, uplift, and erosion have been combined with the thermal effects of fluid flow. Although the timing of cooling indicated by the fission-track data is compatible with the suggested timing of major Miocene uplift and erosion in the southwestern Powder River Basin (Nuccio, 1990, and others), preliminary data suggest that the estimated amount of uplift and erosion is not sufficient by itself to account for the cooling indicated by fission-track data.

The estimate of Nuccio (1990) of 630 m (2,070 ft) of post–mid-Miocene erosion, combined with the gradient of 27.3°C/km (1.5°F/100 ft) adopted in the present study, translates into cooling of 17°C (31°F). The slightly higher gradient of 29.2°C/km (1.6°F/100 ft) used by Nuccio still allows for cooling of only 18°C (33°F). In contrast, the fission-track data suggest that in at least part of the section the rocks have cooled by 35°C (63°F) or more. Several approaches can be used to estimate amount of cooling from the fission-track data. If we assume that the observed pattern of apatite ages (fig. 9) reflects cooling caused entirely by uplift and erosion, then, by analogy with figure 4, the apatite ages indicate cooling of a minimum of 35°C (63°F) since about 12 Ma. Alternatively, modeling the temperatures required to produce the observed ages and track lengths, for the effective heating time indicated by burial-history plots for the rocks (Nuccio, 1990, fig. 8), suggests that for samples PR–4, PR–5, PR–1, and PR–6 about 40°C–45°C (72°F–81°F) cooling is required. The amount of cooling in other samples is more problematic. Observed ages and track lengths of samples 83NN3, 83NN2, PR–8, and PR–9, for example, could be produced by burial, uplift, and erosion under a gradient equal to or slightly greater than the mean gradient of 27.3°C/km (1.5°F/100 ft) adopted herein. However, if gradients in the vicinity of drill holes E, G, and H are in fact lower than 27.3°C/km (see discussion under section on present-day temperatures), then total cooling in these samples may be comparable to that indicated for PR–4 and PR–5. Therefore, the fission-track data indicate that if post–mid-Miocene cooling in the Powder River Basin is related entirely to uplift and erosion, then either the amount of erosion in at least part of the basin has been greater than the 630 m (2,070 ft) estimated by Nuccio or the geothermal gradients have been higher. Cooling of 35°C (63°F) or more requires removal of a minimum of about 1,300 m (4,265 ft) of section since the onset of Miocene erosion or a geothermal gradient of at least 33.3°C/km (1.8°F/100 ft) prior to the onset of erosion, or some appropriate combination of gradients and erosion between these extremes and the presently accepted values. Higher geothermal gradients are probably the more likely explanation because most workers in the Powder River Basin consider it unlikely that more than 630 m of post-mid-Miocene erosion has occurred (V.F. Nuccio, U.S. Geological Survey, written commun., 1991).

An alternative explanation is that the high temperatures required for annealing were not entirely related to burial heating. Additional heat (over and above that provided by burial) may have been supplied by high-temperature fluids moving through the sandstone intervals. A unique solution to fluid temperature and duration of fluid movement cannot be determined from the fission-track data because of the trade-off between time and temperature in annealing (fig. 2); modeling the passage of fluids as a temperature spike superimposed on the burial history of Nuccio (1990, fig. 8) results in a spectrum of scenarios that could have produced the observed fission-track ages and track-length distributions. For example, in samples PR–4 and PR–5 the observed annealing could be produced by the passage of fluids of about 140°C through the sandstones in a period of a million years, by even more rapid passage of higher temperature fluids, or by more prolonged flow of lower temperature fluids.

The temperature history and thermal maturity of selected horizons in the southwestern Powder River Basin have been investigated using organic geochemistry, vitrinite reflectance, Rock-Eval pyrolysis, time-temperature index (TTI) modeling, and modeling of the kinetic reactions of organic matter during thermal maturation (Merewether and Claypool, 1980; Momper and Williams, 1984; Nuccio, 1990). The major thrust of these studies has been to establish thermal maturity and source-rock potential of units in the basin and timing of petroleum generation and reservoir accumulation. Data suggest that expulsion of oil from the dominant source bed in the basin (the Upper Cretaceous Mowry Shale) began in the late Paleocene or early Eocene in the deep southwestern part of the basin and continued through much of the Miocene as the oil-generation front moved updip and upsection (Momper and Williams, 1984). The Upper Cretaceous Steele Member of the Cody Shale (which includes the Shannon Sandstone Bed sampled in the present study; table 1) is thought to have begun oil generation sometime between the middle to late Eocene (47 to 38 Ma) and the late Miocene (10 Ma) (Nuccio, 1990) (see below).

The effect of the high temperatures indicated by fission-track analysis on petroleum generation and migration depends to some extent on the origin and timing of the temperature increase. If high temperatures resulted from deeper burial and (or) higher gradients, then their effects on petroleum maturation will have been more pronounced than if they resulted from what may have been very transient, and to some extent localized, fluid flow.

An important factor to consider in interpreting the thermal history and maturation of the Powder River Basin is that vitrinite reflectance in Upper Cretaceous rocks in the southwestern part of the basin is anomalous as compared to most other thermal indicators. Merewether and Claypool (1980) determined vitrinite reflectance and geochemical data from shale and minor siltstone and sandstone recovered from the Frontier Formation and Cody Shale at depths of 3,780.6–3,879.9 m (12,404–12,729 ft) in three drill holes near the axis of the basin (near drill-holes C, I, J, table 1, fig. 1) and at depths of less than 320 m (1,050 ft) on the southwestern flank of the basin. Vitrinite reflectance[2] is generally greater near the axis of the basin than on the flank (about 0.6 percent near the axis versus about 0.5 percent on the southwestern flank), but the difference is not sufficient to explain the difference in thermal maturity indicated by organic geochemical data (for example, by temperature of rate of maximum pyrolytic yield). In the Steele Member of

[2]Reported values are mean (or mode) of many readings for each sample, measured at random optical orientation under immersion oil.

the Cody Shale, immediately below and approximately at the Shannon Sandstone Bed horizon, vitrinite reflectance (R_m) values "are remarkably consistent and do not seem to increase with increasing depth" (Nuccio, 1990, p. A10); R_m varies from 0.47 to 0.66 percent and averages 0.56 percent in the interval from 2,153 to 3,581 m (7,065–11,750 ft). The vitrinite reflectance data, together with Rock-Eval pyrolysis (T_{max} and production index) data, indicate that in the southwestern Powder River Basin the Steele Member is immature to mature and was not heated to temperatures sufficiently high to begin oil generation (that is, it did not attain an R_m of about 0.60–0.65 percent) until at or near the time of maximum burial (estimated by Nuccio to be 10 Ma). In contrast, time-temperature index modeling and modeling of the kinetic reactions of organic matter during thermal maturation indicate that the rocks were heated to temperatures sufficiently high to begin significant oil generation much earlier, between 47 and 38 Ma (assuming type II kerogen). Nuccio (1990) suggested that the true maturity and timing of generation may be somewhere between the extremes indicated by the vitrinite reflectance/Rock-Eval data and kinetic modeling.

Most kinetic models that relate vitrinite reflectance and maximum temperature (Dickinson, 1989, appendix 1) equate the mean 0.56 percent R_m value for the Steele Member (Nuccio, 1990) with a peak paleotemperature of about 90°C, a significantly lower temperature than indicated by the fission-track data. A possible explanation for part of the discrepancy between maximum temperatures indicated by vitrinite reflectance and fission-track annealing is that, if annealing of the apatite was partly caused by high-temperature fluid flow through sandstone, then vitrinite reflectance, which is generally measured in finer grained, less permeable horizons, may have been less affected by the higher temperatures. A constraint on this explanation is the fact that vitrinite reflectance is low even in drill holes where fission-track and vitrinite reflectance samples were collected in close proximity to one another. For example, in drill-hole E (table 1) (drill-hole B626 of Nuccio, 1990, table 2), fission-track sample 83NN2 is bracketed by vitrinite samples from carbonaceous shale that were collected within only 0.6 m (2 ft) of the fission-track sample and yet yielded typically low values of 0.56 percent R_m. At this time, the reason for the discrepancy between vitrinite reflectance and most other thermal indicators in the southwestern Powder River Basin is not fully understood.

SUMMARY

Apatite fission-track data for Upper Cretaceous sandstone recovered from drill holes in the southwestern Powder River Basin indicate that in much of the Upper Cretaceous section apatite was totally or almost totally annealed after burial in the basin and subsequently cooled about 12 Ma. In at least part of the section the temperatures required to anneal the apatite are substantially higher than those predicted by combining the estimated post-mid-Miocene erosion (about 630 m, 2,070 ft) and present-day geothermal gradients. The fission-track data thus indicate that either (1) total erosion since about 12 Ma has been greater than estimated (probably the least likely explanation), (2) geothermal gradients in basin are higher than indicated by estimates of present-day temperatures (or have been higher in the past), or (3) factors other than burial heating and erosion have contributed to maximum temperatures experienced by the Upper Cretaceous sandstone reservoirs. For example, movement of high-temperature fluids through the sandstone, combined with the thermal effects of burial heating, could explain the observed degree of apatite annealing.

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