Stratigraphic Framework, Structure, and Thermal Maturity of Cretaceous and Lower Tertiary Rocks in Relation to Hydrocarbon Potential, Crazy Mountains Basin, Montana

By Ronald C. Johnson, Thomas M. Finn, David J. Taylor, and Vito F. Nuccio

Chapter A

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Chapter B

Basin Structure from Two-Dimensional Seismic Reflection Data, Crazy Mountains Basin, Montana

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Chapter C

Thermal Maturity and Petroleum Generation History of Cretaceous and Tertiary Source Rocks, Crazy Mountains Basin, Montana

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Abstract

The Crazy Mountains Basin in south-central Montana, a sparsely explored deep basin with a complex depositional and structural history, was investigated for basin-centered gas accumulations. The basin formed largely in response to thrust loading along the Helena salient, an eastward bulge in the Sevier orogenic belt just west of the deep basin trough, in Late Cretaceous (Maastrichtian) and Paleocene time. Drilling is too sparse to detect the presence of a basin-centered gas accumulation, so other Rocky Mountain basins serve as analogs as many contain Cretaceous and Paleocene source rocks similar to those in the Crazy Mountains Basin, and have demonstratable large basin-centered gas accumulations. Based on analogous comparisons, a basin-centered gas accumulation probably began to develop in the Crazy Mountains Basin during the later stages of basin subsidence, near the end of the Paleocene, due to burial heating. Thermal maturities were elevated further by an Eocene igneous event that produced intense heating in the vicinity of stocks and dikes as well as a low-grade, more regional heating across much of the basin. This heating event is similar to one that affected the Raton Basin in Colorado and New Mexico in Oligocene and Miocene time, which elevated thermal maturities but left the coalbed methane and basin-centered gas accumulation largely intact, and appears to have increased gas content in the coal beds. We suggest that a basin-centered gas accumulation is still present in the deeper parts of the Crazy Mountains Basin away from Eocene intrusions.

Introduction

The Crazy Mountains Basin is a northwest-trending structural and sedimentary basin of about 7,800 mi^2 in south-central Montana. It is bounded on the southwest by the Beartooth Mountains and Gallatin Range, on the west by the Bridger Range, on the northwest by the Big Belt Mountains, on the north by the Little Belt Mountains, and on the southeast by the Pryor Mountains (fig. 1). The basin is separated from the Bighorn Basin to the south by the Nye-Bowler lineament, a northwest-trending zone of faulting and anticlinal development (figs. 1 and 2). The Crazy Mountains Basin is one of the deeper Rocky Mountain basins and contains an estimated thickness of more than 30,000 ft of Phanerozoic rocks (Kent, 1972, his fig. 1). Upper Cretaceous and lower Tertiary rocks compose the majority of this thick Phanerozoic section. Roberts (1972) estimated that there was about 10,300 ft of Cretaceous strata and more than 6,600 ft of Paleocene strata in the Livingston area, near the basin axis in the western part of the basin.

Many excellent structural and stratigraphic studies of the Upper Cretaceous and lower Tertiary strata in the Crazy Mountains Basin have been published in the past. With a few exceptions, these studies have concentrated on outcrops and incorporated little subsurface information. This report presents a detailed subsurface investigation of the basin to assess the potential for a basin-centered gas accumulation in the basin.

For this investigation, available information from each of the 269 drill holes occurring within and adjacent to the Crazy Mountains was studied and a file of formation tops was compiled (table 1). Nearly all of these wells were drilled on relatively shallow structures along the Nye-Bowler lineament and along the eastern and northern flanks of the basin, with only a few having been drilled in the deeper areas. Several key intervals were isopached to better understand the basin's depositional and structural history. Four detailed subsurface cross sections (*A–A′* through *D–D′*) were constructed to determine the subsurface distribution characteristics and correlation of the Cretaceous and Tertiary strata and to evaluate their potential for containing a basin-centered gas accumulation (pls. 1–4). In addition, partial sections of Upper Cretaceous rocks were described in detail in the northern and southwestern parts of the basin (pl. 5).

Geology of Basin-Centered Gas Accumulations

Extensive basin-centered or continuous gas accumulations have been identified in most Rocky Mountain basins that formed during the Laramide Orogeny (Late Cretaceous

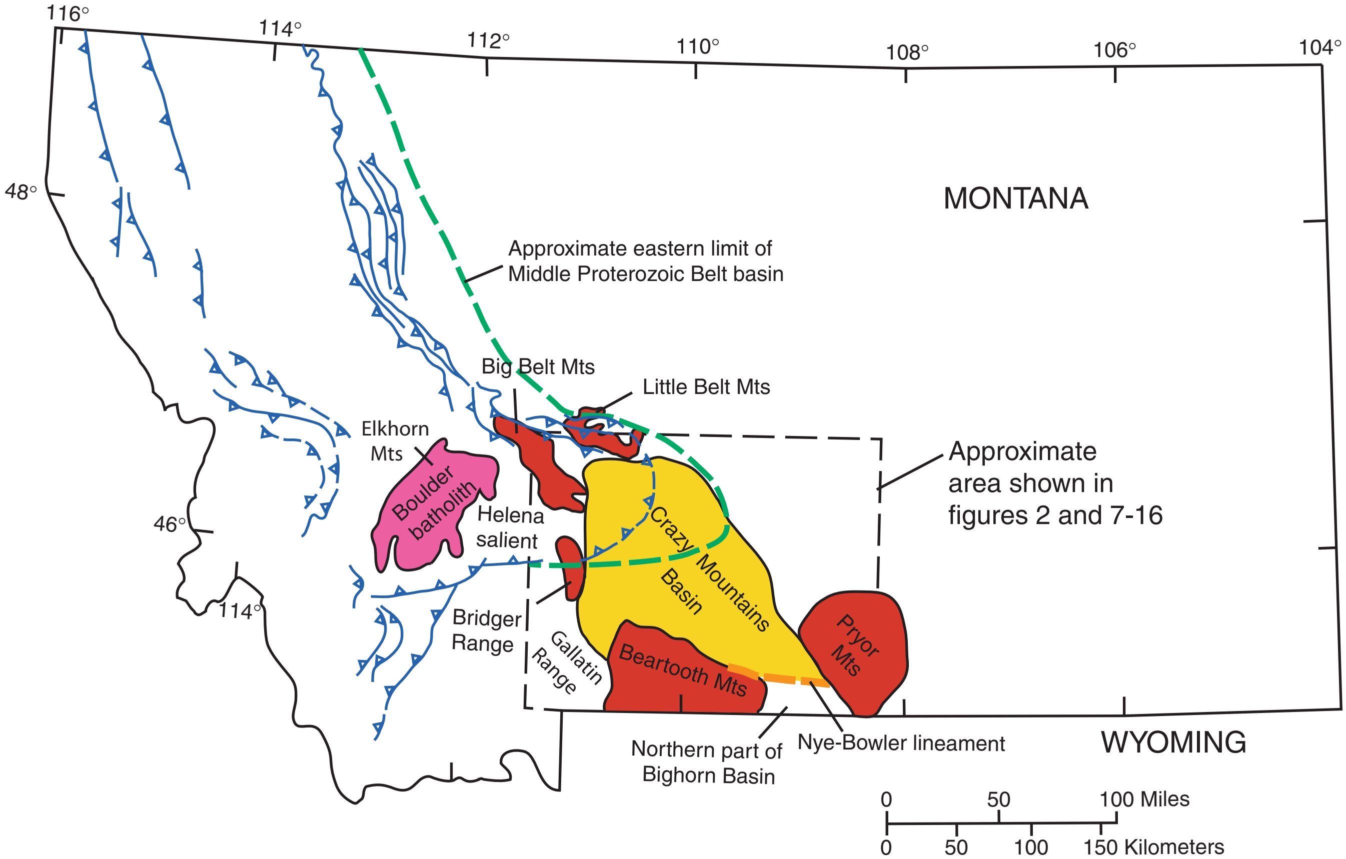

Figure 1. Location of Crazy Mountains Basin and surrounding uplifts in south-central Montana. Location of thrust faults modified from Kulik and Schmidt (1988). Eastern limit of Middle Proterozoic Belt basin modified from Woodward (1981).

through Eocene). Reservoirs within this type of gas accumulation typically have low permeabilities (in-situ permeability to gas of 0.1 millidarcy [mD] or less) and are commonly referred to as tight gas reservoirs (Spencer, 1989). These accumulations differ from conventional gas accumulations in that they: (1) cut across stratigraphic units, (2) commonly occur structurally down dip from more permeable water-filled reservoirs, (3) have no obvious structural and stratigraphic trapping mechanism, and (4) are almost always either overpressured or underpressured. The abnormal pressures of these reservoirs indicate that water in hydrodynamic equilibrium with outcrop is not the pressuring agent. Instead, hydrocarbons within the tight reservoirs are thought to provide the pressuring mechanism (Spencer, 1987).

Masters (1979) was one of the first to study these unique accumulations, which occur down dip from more permeable, water-wet rocks. Masters (1979) proposed that gas generated in the deep, thermally mature areas of sedimentary basins, with low-permeability reservoir rocks, is inhibited from migrating upward along bedding and out of the basin by a capillary seal. Masters (1979) pointed out that low-permeability rocks (<1 mD), with 40 percent water saturation, are only three-tenths as permeable to gas as they are to water, and at 65 percent water saturation, the rock is almost completely impervious to the flow of gas. The concepts for the development of basin-centered gas accumulations in the Rocky Mountains have been further refined by a number of workers such as Jiao and Surdam (1993), Meissner (1980, 1981, 1984), McPeek (1980), Law (1984), Law and others (1979, 1989), Law and Dickinson (1985), MacGowan and others (1993), Spencer and Law (1981), Spencer (1985, 1987), and Yin and Surdam (1993).

In general, the conceptual models indicate that overpressuring, which is commonly encountered in these basin-centered accumulations, is the result of volumetric increases during gas generation in source rocks that are interbedded with the sandstone reservoir rocks. Law (1984) suggested that migration distances from source rock to reservoir rock in the basin-centered gas accumulation of the Greater Green River Basin of Wyoming, Colorado, and Utah are generally less than a few hundred feet. Much of the water that originally filled the pore spaces in the potential reservoirs is driven out by hydrocarbons (Law and Dickinson, 1985). According to Law and Dickinson (1985), the capillary seal is activated as gas replaces water in the pore space, and hence the basin-centered gas accumulations seal themselves as they form. These seals are so efficient that they may be able to maintain abnormally

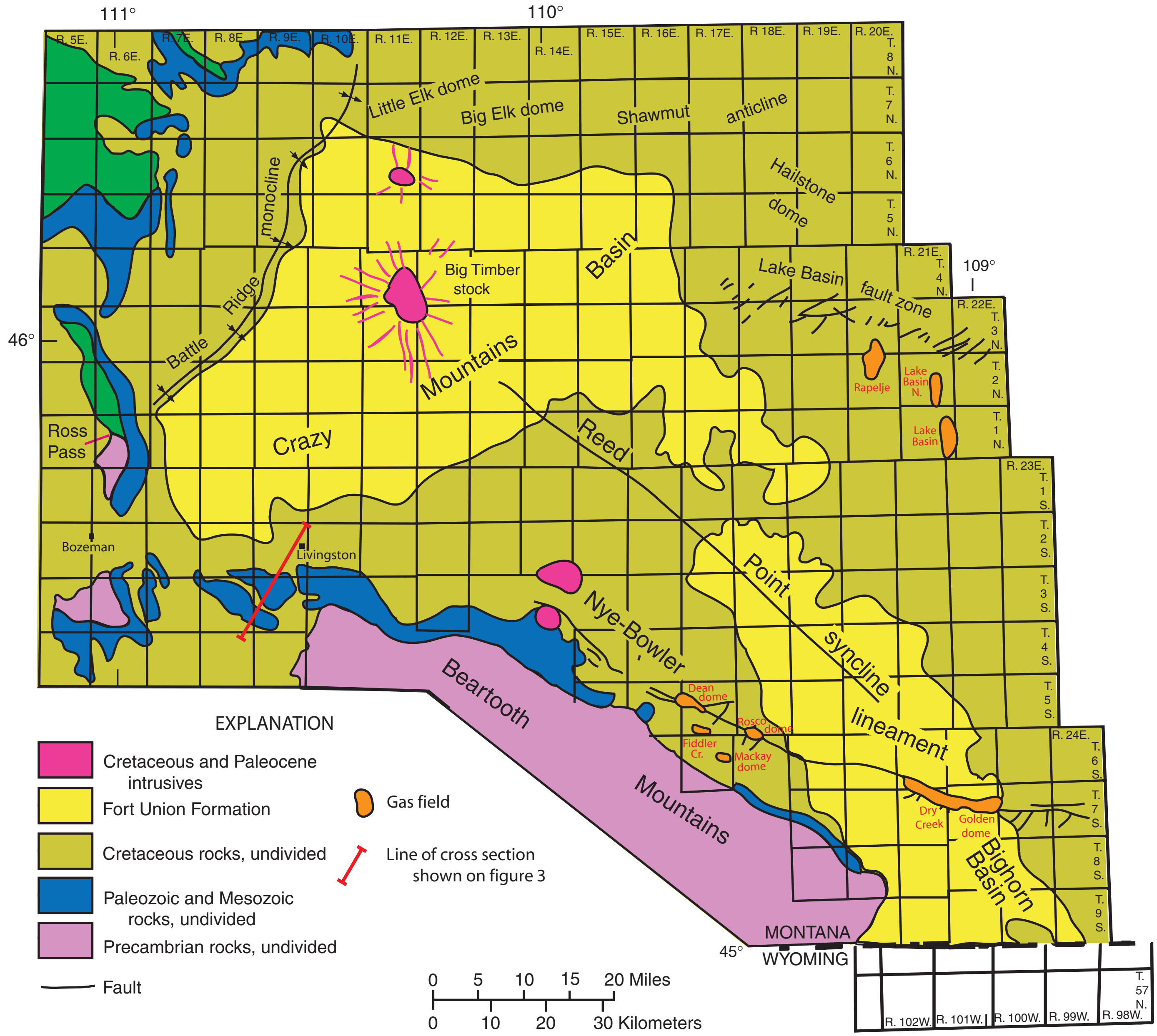

Figure 2. Generalized geology of Crazy Mountains Basin, Montana, showing major structural features and oil and gas fields.

high pressures for tens of millions of years after gas generation has ceased (MacGowan and others, 1993).

Regional Geologic Setting of the Crazy Mountains Basin

The Crazy Mountains Basin is the northernmost of the sedimentary basins in the central Rocky Mountain region that is at least partly defined by “Laramide” uplifts. The basin lies in a complex structural area that was impacted by both Cordilleran “thin-skinned” thrust tectonics (Jurassic through early Eocene) and Laramide basement-involved “thick-skinned” tectonics (Cretaceous through late Eocene). Cordilleran tectonics is characterized by thrust faults that are propagated largely along bedding planes within the cratonic sedimentary cover and usually do not involve the underlying Precambrian crystalline rocks. Thick-skinned Laramide tectonics, in contrast, is characterized by uplift along high-angle thrust and reverse faults that cut across both the sedimentary cover and the underlying Precambrian crystalline rocks. Thrust loading is thought to be the dominant reason that subsidence occurred in both types of terranes (Price, 1973; Jordan, 1981; Beaumont, 1981; Beck, 1985; Beck and others, 1988). In sedimentary basins such as those in the Rocky Mountain region, the response to thrust loading can generally be considered as nearly instantaneous (Jordan, 1981). Thus, uplift histories can be deduced by studying the subsidence histories of the basins that form adjacent to the uplifts.

The Cordilleran tectonic belt stretched from north to south across much of the west-central part of the North American continent, whereas Laramide tectonism was confined largely to the central Rocky Mountain region. Armstrong (1968), who originally recognized the two contrasting tectonic styles, believed that there was little overlap in time between Cordilleran thin-skinned tectonism, which he believed ended in the Campanian, and thick-skinned Laramide tectonism, which he dated as starting the Maastrichtian. Subsequent detailed studies, however, demonstrated that both Cordilleran-style and Laramide-style tectonism proceeded together throughout much of Cretaceous and Paleocene time. Schwartz and DeCelles (1988) cited evidence that Laramide-style uplifts in southwestern Montana, west of the Crazy Mountains Basin, had prolonged uplift histories that began near the beginning of the Cretaceous. There is considerable evidence that Laramide-style tectonism actually preceded Cordilleran-style tectonism in some areas such as southwest Montana (see, for example, Perry and others (1988)).

The Crazy Mountains Basin lies along the southeast edge of an extensive eastward bulge in the Cordilleran overthrust belt known as the Helena salient (fig. 1). The north and south margins of the salient are bound by complex outward-thrusting fault systems that have strike-slip components consistent with the concept that the entire salient has been transported considerably east of the main part of the overthrust belt. The Battle Ridge monocline (fig. 2), which cuts northeastward across the western part of the Crazy Mountains Basin, is part of the southeast terminus of this salient (Garrett, 1972). Seismic data indicate that the monocline is underlain by a southeast-directed thrust fault (Garrett, 1972); however, some left-lateral movement along the fault is also suspected (Garrett, 1972; Woodward, 1981, 1983). Rocks as young as the uppermost Cretaceous and Paleocene Fort Union Formation are deformed over the Battle Ridge monocline (Skipp and McGrew, 1968; Skipp and McMannis, 1971), indicating that movement on the thrust fault persisted at least into the late Paleocene. The structurally deepest part of the Crazy Mountains Basin formed in front of this fault, and the thrust block appears to have overridden part of the deep trough of the basin (Garrett, 1972, his figure 3). The Battle Ridge monocline is generally not thought to mark the western boundary of the basin, however, as Upper Cretaceous rocks persist for a considerable distance west of the monocline to the flanks of the Bridger Range and Big Belt Mountains (figs. 1 and 2). This area is also generally included in the Crazy Mountains Basin (Thom, 1957, his figure 1).

Several workers have noted that the eastern limit of the Cordilleran overthrust belt in Montana and Wyoming closely follows the eastern limit of Middle Proterozoic Belt Supergroup sedimentary rocks (Harris, 1957; Harrison and others, 1974; Woodward, 1981). The Belt Supergroup thickens to the west from a wedge edge to at least 23,000 ft. The Helena salient occurs in an area where Belt Supergroup rocks extend eastward in an embayment (Harris, 1957). These rocks consist largely of slates and argillites through which bedding-plane faults can easily propagate (Harris, 1957, p. 25). To the east, where Belt Supergroup rocks are not present, Phanerozoic sedimentary rocks directly overlie crystalline basement. The comparatively shallow crystalline basement east of the Belt Supergroup basin is thought to have acted as a buttress against the eastward propagation of thin-skinned thrusts (Berry, 1943; Robinson, 1963). The southern limit of Belt Supergroup sedimentary rocks is exposed near Ross Pass in the Bridger Range just west of the Battle Ridge monocline (figs. 1 and 2) (McMannis, 1955). To the north, Belt Supergroup rocks are present; however, to the south, Precambrian rocks are characterized by Archean igneous and metamorphic rocks. The Battle Ridge monocline lines up with Ross Pass (fig. 2), and the alignment is thought to approximately mark the boundary between thin-skinned Cordilleran thrusting to the north and basement-involved Laramide faulting to the south (Lageson and others, 1983).

Laramide-style uplifts also impinge on the Crazy Mountains Basin. The Beartooth Mountains, to the southwest (figs. 1 and 2), are a Laramide-style uplift with a complex structural history. The southern part of the Bridger Range to the west of the Crazy Mountains Basin has also been affected by Laramide-style tectonism (Lageson and others, 1983), and the Little Belt Mountains, north of the basin, are bounded by Laramide-style thrusts. Although minor movement of the Beartooth uplift may have occurred as early as Late Jurassic (Schwartz and DeCelles, 1988), major uplift on the Beartooth Mountains probably began in Paleocene time. Fission track dating by Giegengack and others (1998) indicated that the Beartooth Mountains were actively rising from 61 Ma in early Paleocene time to 52 Ma in early Eocene time. Previous interpretations (for example, Foose and others, 1961) suggested that vertical tectonics was mainly involved in the uplift of the Beartooth Mountains. More recent interpretations, aided by seismic and deep drilling information, indicate that thrust faulting played a major role in uplift (see Blackstone, 1986).

An apparent reversal in thrust direction has been mapped on the surface in the northeast flank of the Beartooth Mountains. The southeast segment of this mountain front has been thrust over the northwest margin of the Bighorn Basin along southwest-dipping thrust faults. Bonini and Kinard (1983), using gravity data, estimated approximately 12 km (7.5 mi) of overhang along this fault zone just northwest of Red Lodge, Mont. In contrast, to the northwest along the northeast flank of the Beartooth uplift, the thrusting appears to be reversed with southwest thrusting toward the Beartooth uplift along northeast-dipping thrust faults (Skeels, 1939). These thrust faults can be traced to the northwest into the Livingston area where they plunge off the northwest flank of the Beartooth uplift and into the Crazy Mountains Basin, creating a series of northwest-plunging anticlines (Roberts, 1966; Robbins and Erslev, 1986). Lammers (1937) and Skeels (1939) suggested that these unusual thrusts formed late in the development of the Beartooth uplift after an earlier near-vertical uplift phase. Robbins and Erslev (1986), on the other hand, suggested that the surface thrusts in this area are secondary backthrusts created as the main fault, a hidden, low-angle thrust fault, peeled up wedge-shaped slabs of Precambrian and Phanerozoic rock as it plowed northeastward into the Crazy Mountains Basin (fig. 3). They (Robbins and Erslev) suggested that this “master fault” is needed to explain the major elevation difference between the Beartooth uplift and the adjacent Crazy Mountains Basin. Wise (1997) suggested that (1) variations in the structural strength of the Precambrian basement are largely responsible for the perplexing style of faulting along the northeast front of the Beartooth Mountains; and (2) much of the structural complexities along the northeast Beartooth front can be related to the inability of thrust faults to propagate through the Precambrian Stillwater lopolith in the northwestern part of the front.

The Nye-Bowler lineament divides the Crazy Mountains Basin to the north from the Bighorn Basin to the south. This structural lineament is a complex zone of faulting and folding that extends along a linear trend from the Beartooth Mountains on the northwest to the Pryor Mountains on the southeast (figs. 1 and 2). These faults and folds are thought to be the surface expression of basement faults along which both lateral and vertical movement has occurred (Wilson, 1936). Most surface faults trend parallel to the lineament, but there are also some minor transverse (northeast-trending) faults (fig. 2). These two sets of faults had complex histories, which commonly included a reversal of displacement direction (Wilson, 1936). Northeast-trending faults are thought to have formed as a result of lateral movement along the main basement fault (Wilson, 1936). The Nye-Bowler lineament intersects the Beartooth front near the area where thrusting direction changes from northeast to southwest as previously described. Wilson (1936) believed that movement on the lineament began during deposition of the Upper Cretaceous Bearpaw Shale and continued through deposition of the Paleocene Lebo Shale of the Fort Union Formation based on a thinning of these units along the crest of the lineament. Drilling subsequent to Wilson’s study generally does not show a thinning of these units along the structure, thus casting doubt on the timing of movement that will be discussed in more detail later. The youngest preserved unit involved in the folding along the lineament is the Lebo Shale, indicating that movement continued into Paleocene time.

There are significant differences between the eastern and western parts of the Nye-Bowler lineament. The eastern part consists of a single line of complex, highly faulted anticlines that trend about N. 80° W. As the lineament approaches the Beartooth uplift to the west, the trend changes to about N. 70° W. to more closely parallel the trend of the uplift. Anticlines along the western part of the lineament are much less faulted than those to the east, and appear to follow three closely spaced linear trends instead of one. These western anticlines are relatively simple, asymmetric structures, with steep southwest flanks and gentle northeast flanks. These folds were probably formed by southwest-thrusting faults at depth (Ames, 1991), similar to those that occur along the flank of the nearby Beartooth uplift.

Cretaceous and Lower Tertiary Strata in the Crazy Mountains Basin

The Cretaceous through Paleocene stratigraphic nomenclature used in this report for the Crazy Mountains Basin is shown in figure 4. A comparison is made between the nomenclature used here and that used by Keefer and others (1998) for the Bighorn Basin just south of the Crazy Mountains Basin, which reflects the names commonly used in north-central Wyoming. The change from Wyoming nomenclature in the Bighorn Basin to Montana nomenclature along the Nye-Bowler lineament and the Crazy Mountains Basin is also shown in cross section *A–A′* (pl. 1), which extends southward into the northern part of the Bighorn Basin in Wyoming. The Cretaceous through Paleocene strata in the Crazy Mountains Basin contain little evidence for major unconformities, and the uppermost Cretaceous-Paleocene contact appears conformable throughout the basin (fig. 4). As a result, the Crazy Mountains Basin has been used as a reference area for a continuous representation of uppermost Cretaceous and Paleocene nonmarine fossils (Hartman, 1989; Hartman and Krause, 1993). The mapped contact for the base of the Fort Union Formation only approximately corresponds to the Cretaceous-Tertiary boundary in the basin. In the Livingston area, Roberts (1972) mapped the base of the Fort Union at a distinctive, mappable lithologic break but found Cretaceous fossils in the lower part of his Fort Union. In the northern part of the basin the Bear Formation, a distinctive sandy unit named by Simpson (1937), conformably overlies the less sandy Hell Creek Formation. The upper part of that formation was dated paleontologically as earliest Paleocene, so the undated lower part may be uppermost Cretaceous (Hartman, 1989, p. 171).

Upper Cretaceous Campanian and Maastrichtian strata in the western part of the Crazy Mountains Basin are predominantly volcanic, preventing identification of many of the stratigraphic subdivisions used farther east in the basin and in eastern Montana. The local stratigraphic name, Livingston Group (Roberts, 1963), is applied to these rocks (fig. 4), which are equivalent to (in ascending order) the Claggett Shale, Judith River Formation, Bearpaw Shale, and Hell Creek Formation. Weed (1893, p. 21) originally applied the name Livingston Formation to these rocks, and Iddings and Weed (1894) and Weed (1899) assigned all Upper Cretaceous strata younger than the Eagle Sandstone to the Livingston Formation throughout most of the Crazy Mountains Basin. A number of different local schemes have been used to subdivide the Livingston Group in various parts of the basin. For a summary of the history of the usage of the terms Livingston Formation and Livingston Group and the subdivisions thereof, see Roberts (1972) and Skipp and McGrew (1972).

Kootenai Formation

The Kootenai Formation is a nonmarine sequence of Early Cretaceous age that unconformably overlies the Upper

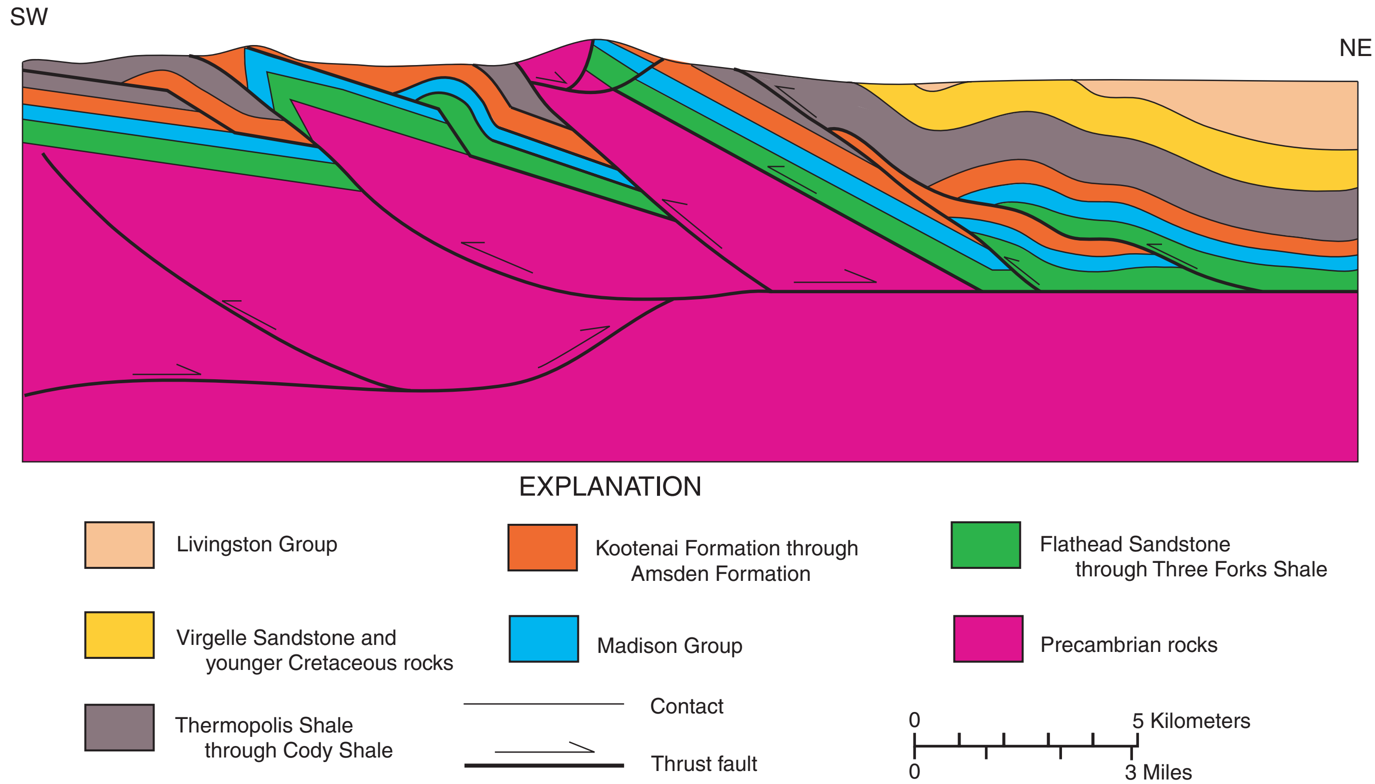

Figure 3. Balanced structural cross section across southwest flank of Crazy Mountains Basin near Livingston, Mont. From Robbins and Erslev (1986, their fig. 10a).

Jurassic Morrison Formation throughout the Crazy Mountains Basin (fig. 4, pls. 1–4). It is equivalent to that part of the Cloverly Formation below the Rusty Beds Member in the Bighorn Basin south of the Crazy Mountains Basin (fig. 4, pl. 1). The Kootenai is equivalent to the Dakota Sandstone in other parts of the Rocky Mountain region and was originally mapped as Dakota Sandstone west of Livingston by Iddings and Weed (1894). Calvert (1912) later correlated the unit with the Kootenai Formation near Great Falls, Mont. The formation is divided into two units: (1) a basal conglomerate, conglomeratic sandstone, and coarse-grained sandstone called the Pryor Conglomerate Member, and (2) an unnamed upper member of sandstone, variegated mudstone, limestone, and tuff (Roberts, 1972). The Pryor Conglomerate Member was named for exposures at the base of the Pryor Mountains, southeast of the Crazy Mountains Basin (fig. 1), by Hares (1917), who considered it a member of the Cloverly Formation. Roberts (1965) made the Pryor in the Crazy Mountains Basin a member of the Kootenai Formation. The Pryor Conglomerate Member occurs throughout much, if not all, of the Crazy Mountains Basin. It has been described in exposures along the southwest margin of the basin (Richards, 1957; Roberts, 1972) and along the west margin of the basin (McGrew, 1977a, b, c, d; Skipp, 1977; Skipp and others, 1999) and was identified in all of the wells that penetrated the Kootenai Formation on the cross sections constructed for this report (pls. 1–4). It varies from about 20 to 190 ft thick along the lines of cross section. The unnamed upper member overlies the Pryor Conglomerate Member and is composed of variegated red, purple, green, and gray mudstone, lenticular sandstone, limestone, and tuff (Roberts, 1972, his sections 1–3) and varies from about 13 to 250 ft thick along the lines of cross section. The age of the Kootenai in the Crazy Mountains Basin is thought to be Early Cretaceous Aptian-Albian (Dyman and others, 1995).

Fall River Sandstone

The Fall River Sandstone is generally considered to have formation status in south-central Montana (Dyman and others, 1995) and consists of “brownish-gray, thin-bedded, argillaceous, fine-grained quartz sandstone” in the Crazy Mountains Basin area (Lopez, 2000; Berg and others, 2000). It is found throughout the Crazy Mountains Basin area and forms a distinctive high-resistivity marker on electric logs (pls. 1–4). It is equivalent to the Rusty Beds Member of the Cloverly Formation in the Bighorn Basin to the south (fig. 4, pl. 1).

Thermopolis Shale

The Thermopolis Shale was originally defined by Lupton (1916) for exposures near Thermopolis, Wyo., along the south margin of the Bighorn Basin. The formation was deposited during the first major incursion of the Cretaceous seaway into the middle of the North American continent. It varies in thickness from about 290 to 460 ft along the cross sections

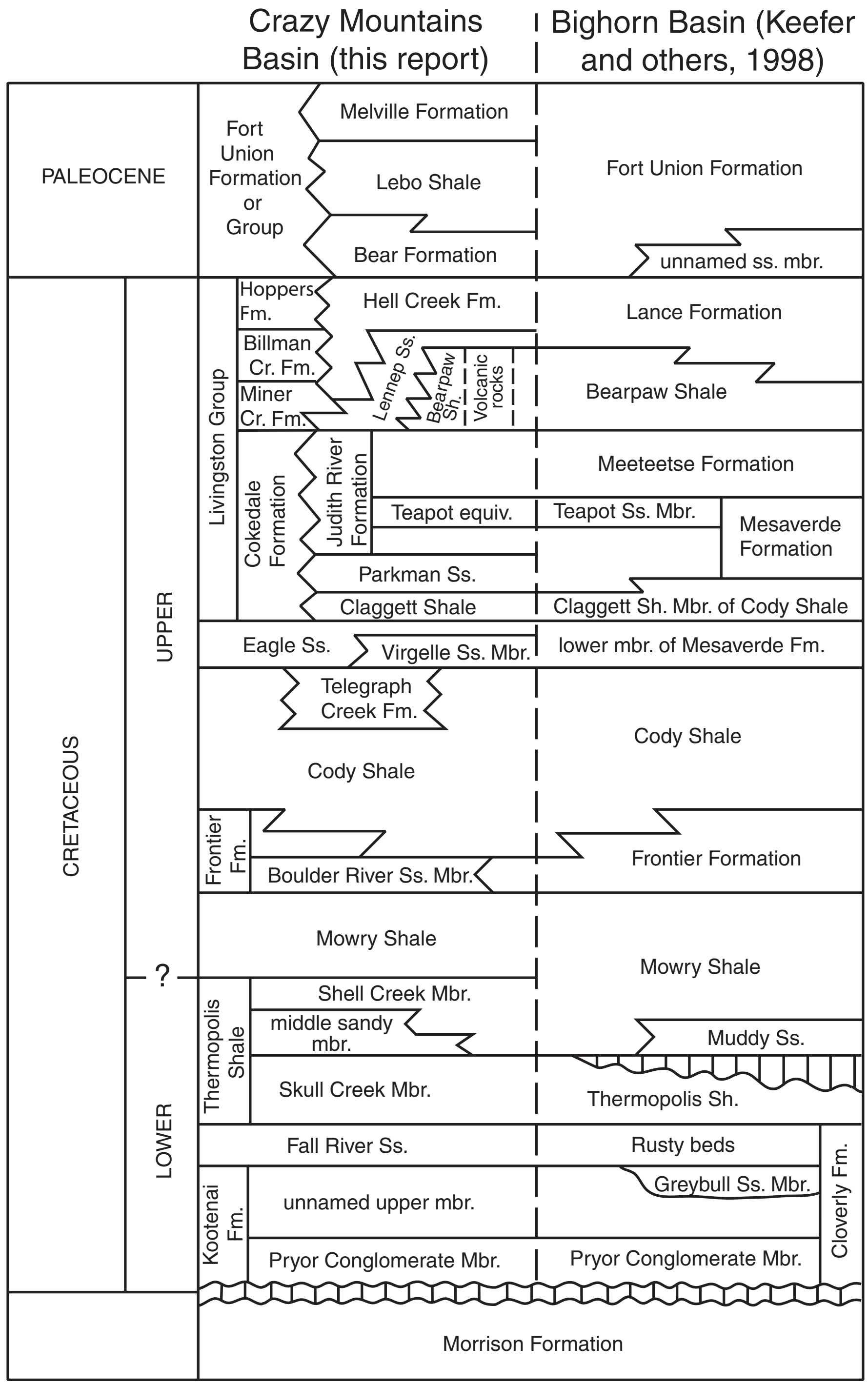

Figure 4. Generalized stratigraphic chart of Cretaceous and older Tertiary rocks, Crazy Mountains Basin, Montana, and Bighorn Basin, Montana and Wyoming. Abbreviations: Cr., Creek; Fm., Formation; Mbr., Member; Sh., Shale; Ss., Sandstone; equiv., equivalent.

(pls. 1–4). Porter and others (1993) subdivided the Thermopolis at Pine Creek anticline, northeast of the Crazy Mountains Basin, into three members—in ascending order, the Skull Creek Member, the middle sandy member, and the Shell Creek Member (fig. 4), and these member designations will be used here. In the Bighorn Basin to the south, the use of the name Thermopolis Shale is more restricted stratigraphically than in the Crazy Mountains Basin, generally being applied to just the lower part or Skull Creek Member (fig. 4) (Keefer and others, 1998). The middle sandy member of the Thermopolis Shale includes thin coarsening-upward sandstones of probable nearshore marine origin (pls. 2–4). These sandstones are approximately in the same stratigraphic position as the Muddy Sandstone in the Bighorn Basin to the south (fig. 4, pl. 1; Keefer and others, 1998, their pl. 1). The Muddy Sandstone was deposited in a series of paleovalleys cut into the underlying Skull Creek Member and Thermopolis Shale during a major regional drop in relative sea level in Early Cretaceous Albian time (Weimer, 1984). During maximum regression, the shoreline stood just south of the Montana-Wyoming State line, in the northernmost part of the Bighorn Basin (fig. 5). Thus, continuous marine deposition probably occurred in the Crazy Mountains Basin during the time period represented by the Muddy Sandstone.

The Shell Creek Member consists of soft black shale deposited in an offshore marine setting. It varies from about 20 to 80 ft thick in the subsurface throughout most of the Crazy Mountains Basin; locally in the subsurface it could not be recognized (pls. 1 and 2). In the eastern part of the basin, it thickens from 325 to 405 ft at the expense of the underlying middle sandy member (pls. 2 and 4). The type section of the Shell Creek Member is 6 mi northwest of Greybull in the Bighorn Basin to the south; in that basin, however, the Shell Creek was included in the overlying Mowry Shale (Keefer and others, 1998).

Roberts (1972) divided the Thermopolis Shale into three informal members in the Livingston area in the southwestern part of the Crazy Mountains Basin: a lower sandstone member, a middle shale member, and an upper sandstone member. The lower sandstone member of Roberts (1972) is approximately equivalent to the Fall River Sandstone, his middle shale member is approximately equivalent to the Skull Creek Member, and his upper sandstone member is approximately equivalent to the middle sandy member here.

Mowry Shale

The Mowry Shale is a distinctive organic-rich, resistant, dark-gray, siliceous shale with abundant fish scales and bentonitic layers deposited after a major transgression of the Cretaceous seaway in late Albian time (fig. 6). It varies in thickness from about 460 to 690 ft along the lines of cross section (pls. 1–4). The formation was deposited during a period of unusually intense volcanic activity, and the distinctive siliceous nature of shales in the Mowry is the result of the alteration of volcanic ash (Rubey, 1929). The Mowry was originally named by Darton (1904) for exposures on Mowry Creek northwest of Buffalo, Wyo., and occurs throughout Wyoming and parts of adjacent States (fig. 6). It is approximately equivalent to the Blackleaf Formation farther west in Montana (Porter and others, 1993). Source for the volcanic ash is probably eruptions related to emplacement of the Idaho batholith in central Idaho and the Boulder batholith in southwestern Montana (Christiansen and others, 1994). The contact with the underlying Shell Creek Member of the Thermopolis Shale is conformable. The contact with the overlying Frontier Formation is also conformable and placed by Roberts (1972) in the Livingston area at the base of the Boulder River Sandstone Member of the Frontier Formation. That member, or its equivalent, was used as the base of the Frontier Formation on the cross sections (pls. 1–4). Coarsening-upward sandstones of probable nearshore marine origin occur in about the upper half of the Mowry Shale in the western part of the Crazy Mountains Basin (pls. 1–4). These sandstones, which also occur in Wyoming south of the Crazy Mountains Basin (fig. 6), thin toward the east and are not present in the eastern part.

Frontier Formation

The Frontier Formation conformably overlies the Mowry Shale throughout the Crazy Mountains Basin and was deposited in offshore marine, nearshore marine, coastal plain, and valley fill settings. The Frontier varies from 0 to 550 ft thick in the wells used in the cross sections and includes at least four discrete sandstones (pls. 1–4). All four, however, are rarely present at any given locality, and all are locally absent in the northeastern part of the basin where they appear to have graded into gray shales of the Cody Shale (pl. 3, well C-4); there, the overlying Cody Shale directly overlies the Mowry Shale. Knight (1902, p. 721) originally named the Frontier Formation for exposures near Kemmerer in southwestern Wyoming; the name was later used in the Crazy Mountains Basin by Cobban and Reeside (1952b), Garbarini (1957), and Roberts (1965). Roberts (1972) described the Frontier Formation in the Livingston area as 415 ft of conglomerate, sandstone, siltstone, and shale with thin intervals of carbonaceous shale and coal. Roberts (1972) did not observe any bentonites in the Frontier near Livingston, although bentonites are common in other parts of south-central Montana.

Deposition of the Frontier Formation in the Rocky Mountain region spans the interval from near the beginning of Late Cretaceous Cenomanian time into the early Coniacian (Cobban and Reeside, 1952b; Dyman and others, 1994), a period of nearly 10 m.y. (Obradovich, 1993). Overall subsidence rates are, therefore, low in areas such as the Crazy Mountains Basin, where the Frontier Formation is no more than a few hundred feet thick. As a result, relatively minor fluctuations in base level due to changes in sea level and regional uplift created significant and widespread hiatuses. Merewether and others (1975, 1998) described several hiatuses within the Frontier Formation in the Bighorn Basin to the south, including one that separates Cenomanian strata below from latest Turonian strata above, a span of approximately 5.1–5.7 m.y. In the Madison Range, southwest of the Crazy Mountains Basin, Tysdal (1991) described two unconformities, the lower one separating lower shoreface sandstones in the lowest part of the formation from delta-plain deposits above. These delta-plain deposits contain early Cenomanian fossils and are unconformably overlain by delta-front deposits containing an early middle Turonian fauna. A hiatus between Cenomanian and Turonian rocks is widespread in the central Rocky Mountain region (Merewether and Cobban, 1986). Porter and others

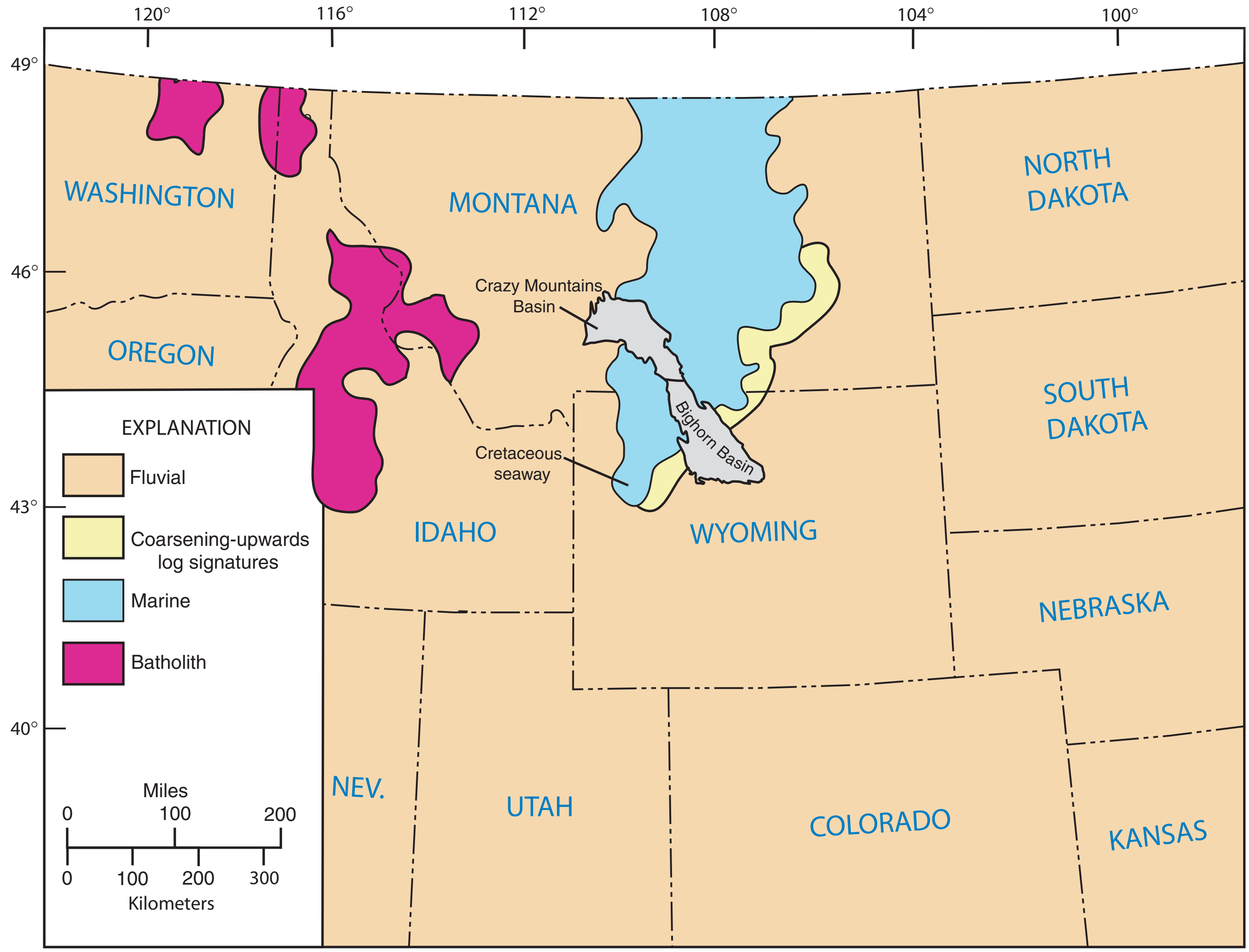

Figure 5. Paleogeographic map showing depositional settings at maximum sea level lowstand during deposition of Muddy Sandstone, central Rocky Mountain region. Simplified from Dolson and others (1991).

(1993) traced the Cenomanian-Turonian unconformity in the Madison Range into a layer of small cobbles at a sharp contact in the lower part of the Belle Fourche Shale at Pike Creek anticline in central Montana (the anticline is east of the pinch out of the Frontier Formation). The position of this unconformity in the Crazy Mountains Basin, which lies between the Madison Range and Pike Creek anticline, is uncertain.

The base of the Frontier Formation in the Crazy Mountains Basin is placed at the base of a prominent 100-ft-thick sandstone named by Richards (1957) the Boulder River Sandstone Member of the Colorado Shale for exposures in the Boulder River Valley east of Livingston. Roberts (1965) later designated the Boulder River Sandstone Member as the basal member of the Frontier Formation. The Boulder River Sandstone Member occurs in all but the southeastern and northeastern parts of the Crazy Mountains Basin (fig. 7). Roberts (1972) described the Boulder River Sandstone in the Livingston area as having a uniform thickness of 115–120 ft. In his measured section 10 (pl. 2, section S-2), the Boulder River Sandstone Member is 119 ft thick and consists of poorly sorted, very fine grained to conglomeratic, locally crossbedded sandstone. Maximum thickness along the lines of cross section is about 125 ft (pl. 3, well C-9). In geophysical logs, the Boulder River Sandstone generally appears to coarsen upwards (see, for example, pl. 1, sections A-22 and A-23), suggesting a nearshore marine origin; in thick intervals, however, the upper part appears to fine upwards (see for example pl. 3, well C-8).

A widespread sandstone occurs from about 190 to 375 ft above the base of the Frontier Formation (pls. 1–4). This sandstone is 33 ft thick and lies 287 ft above the base of the Frontier Formation in Roberts' (1972) measured section 10 near Livingston (pl. 2, measured section S-2). He (Roberts) described the unit as a poorly sorted, crossbedded, conglomeratic sandstone. This sandstone was traced in the subsurface throughout the southwestern part of the basin and pinches out along an irregular boundary toward the northeast (fig. 8). The description of Roberts (1972) indicates that it could be a valley fill sandstone and that a hiatus might occur at the base;

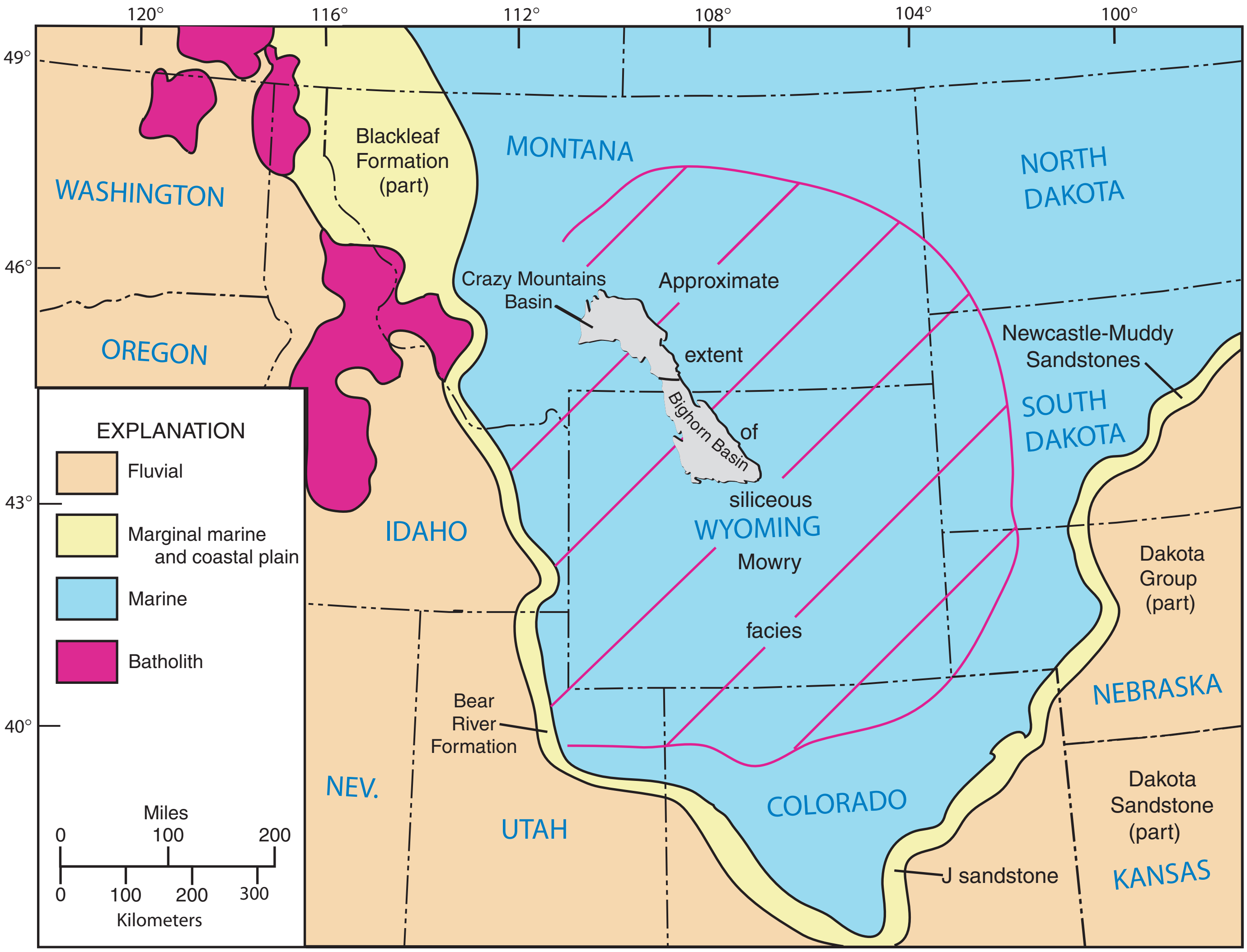

Figure 6. Location of Cretaceous shoreline and facies distributions during maximum extent of Mowry Shale, central Rocky Mountain region. From Reeside and Cobban (1960), Davis (1970), and Burtner and Warner (1984).

however, geophysical logs are interpreted to indicate that it is a coarsening-upwards sandstone of nearshore marine origin over much of its extent.

Cody Shale

The Cody Shale overlies the Frontier Formation with apparent conformity and interfingers with marginal marine rocks of the overlying Telegraph Creek Formation and Eagle Sandstone. Locally, where the Frontier is absent in the subsurface in the northern part of the basin (pl. 3), the Cody Shale is shown to directly overlie the Mowry Shale; hence Frontier-equivalent strata there would be more properly referred to the Belle Fourche Shale as is the case at Pike Creek anticline northeast of the Crazy Mountains Basin (Porter and others, 1993). However, the term Belle Fourche Shale has not apparently been used before in the Crazy Mountains Basin. The Cody Shale ranges from about 720 to 2,090 ft thick along the lines of cross section (pls. 1–4); however, much of this variation is due to the presence or absence of both the overlying Telegraph Creek Formation and the underlying Frontier Formation rather than to true variations in thickness. The Cody Shale consists of medium- to dark-gray and brown shale, and silty and sandy shale deposited in an offshore marine setting. The formation was named by Lupton (1916) for exposures near Basin, Wyo., and included shale and sandy shale between the Frontier Formation and overlying Mesaverde Formation. It was applied to roughly stratigraphic equivalent rocks in the Crazy Mountains Basin area by several workers (see, for example, Cobban and Reeside, 1952a, their pl. 1, section 103; Roberts, 1972); however, the name Colorado Shale has also been applied to this interval (Cobban and Reeside, 1952a, their pl. 1, sections 104, 105; Richards, 1957).

In the southwestern part of the basin, the Cody Shale is subdivided into a lower shale member, the Eldridge Creek Sandstone Member, and an upper shale member (Roberts, 1964, 1972). Roberts (1972) described the Eldridge Creek as a shallow-water marine sandstone deposited during a marine regression. It was identified only in the western part of cross

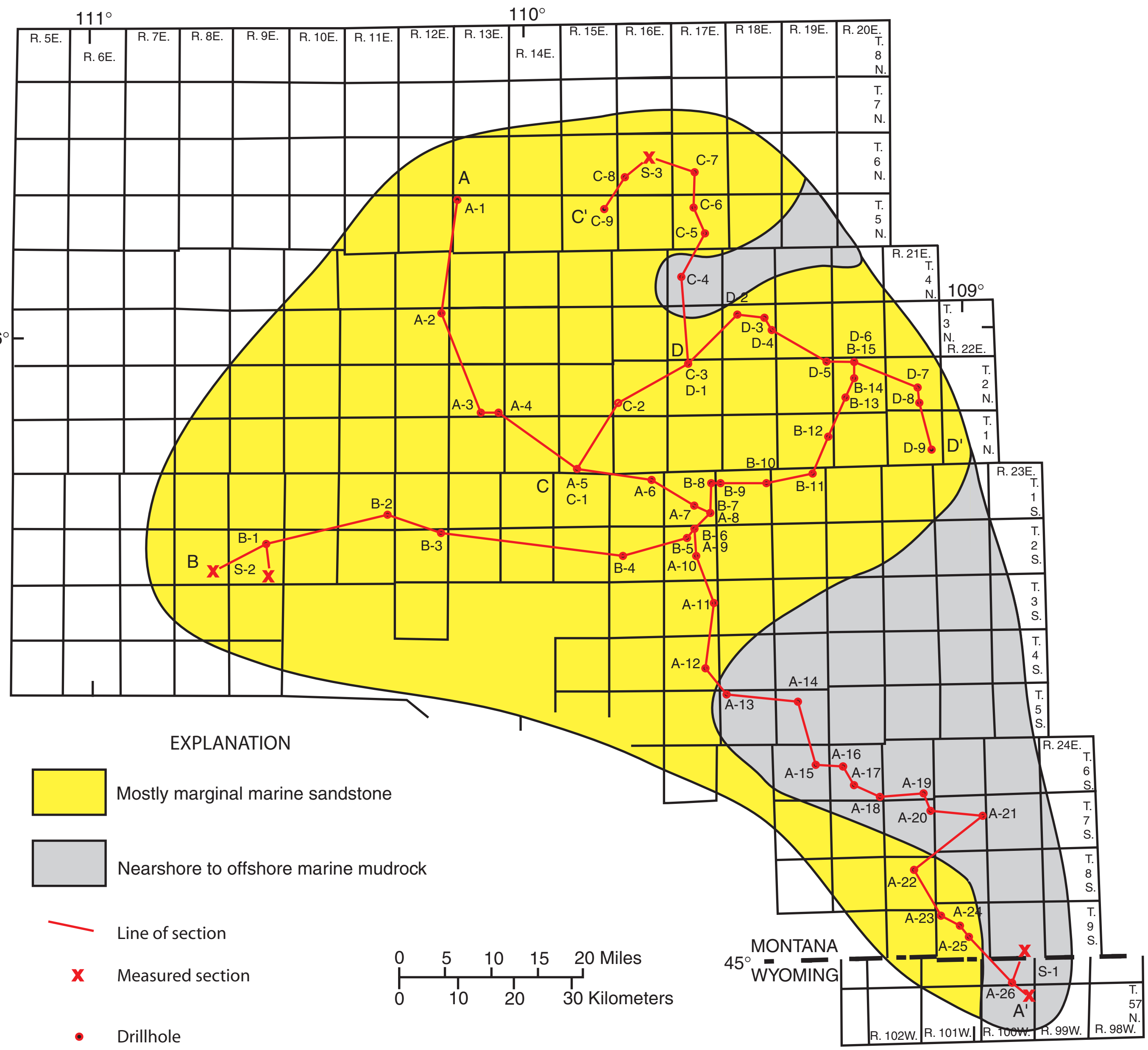

Figure 7. Approximate extent of Boulder River Sandstone Member of Upper Cretaceous Frontier Formation, Crazy Mountains Basin, Montana.

section *B–B′* (pl. 2, sections S-2, B-1, B-2), where it varies from 7 to 130 ft thick. It appears to pinch out to the east and northeast.

Telegraph Creek Formation

The Telegraph Creek Formation was named by Thom (1922, p. 38) for exposures at the head of Telegraph Creek southeast of Billings, Mont. The formation is a zone of interbedded shallow-water sandstone, siltstone, and shale that is transitional between the marine shales below and the marginal marine to nonmarine rocks above. Knappen and Moulton (1931) applied the name to strata near Park City, Mont., along the east margin of the Crazy Mountains Basin; however, their Telegraph Creek appears to be largely younger than the type section (Roberts, 1972, p. C29). The formation has been mapped in the southwestern part of the Crazy Mountains Basin by Wilson (1934), Skeels (1939), Garbarini (1957), and Roberts (1972), and along the east margin of the basin by Knappen and Moulton (1931). It can be recognized locally in the subsurface where it is slightly more resistant on electric logs than the underlying less silty and sandy marine shales (pls. 1–4). In the cross sections, the Telegraph Creek is shown only where it could be readily distinguished from the underlying Cody Shale using available well logs. The lower contact is gradational and the upper contact is the base of the overlying Eagle Sandstone. Cobban and Reeside (1952a) assigned a Late Cretaceous Santonian age to the Telegraph Creek Formation in

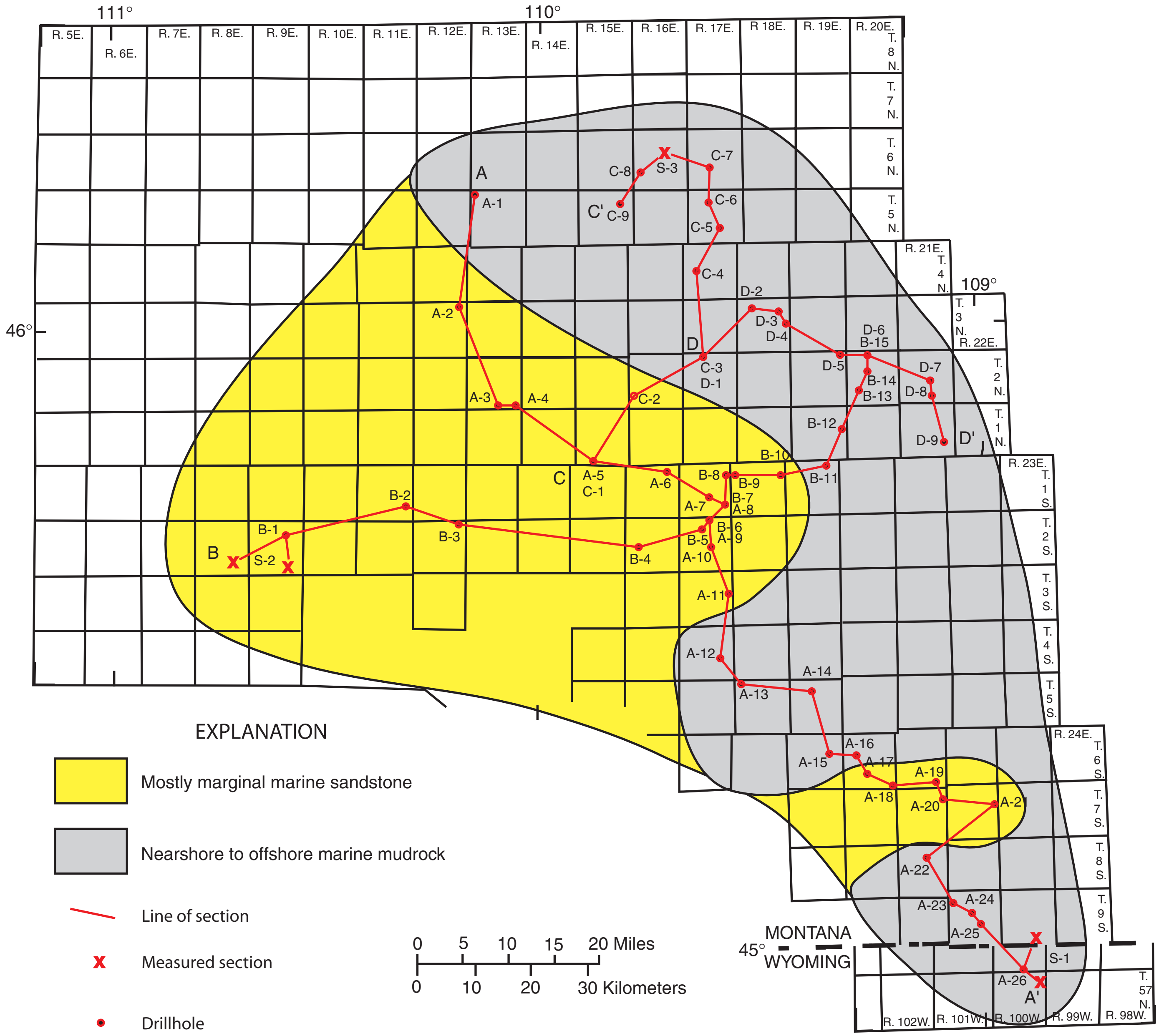

Figure 8. Approximate extent of pebbly sandstone of Upper Cretaceous Frontier Formation, Crazy Mountains Basin, Montana, as defined by Roberts (1972).

the Livingston area. Roberts (1972, p. C30) described sandstones in the Telegraph Creek as consisting of predominantly quartz, with lesser amounts of potassium feldspar, plagioclase, and chert. Heavy minerals include magnetite, zircon, tourmaline, biotite, apatite, augite, garnet, and hornblende.

A persistent sandstone of probable nearshore marine origin, the Elk Basin Sandstone, is present in the upper part of the Telegraph Creek and equivalent strata in the southernmost part of the Crazy Mountains Basin. The member was named by Hares (1917) for exposures in Elk Basin in the northernmost part of the Bighorn Basin near the Wyoming-Montana State line. Thicknesses vary from about 50 to 80 ft in the southern part of the Crazy Mountains Basin, and it merges with the Eagle Sandstone about 18 mi north of the State line (pl. 1, wells A-18, A-19). At its type locality, the Elk Basin Sandstone occurs in the late Campanian *Scaphites hippocrepis* zone (Roberts, 1972). A sandstone in approximately the same stratigraphic position is present in the northeastern part of the basin and was mapped by Knappen and Moulton (1931) as Elk Basin; however, according to Roberts (1972, p. C30), the sandstone is older and occurs in the late Santonian *Desmoscaphites bassleri* zone. This may be the sandstone labeled “Elk Basin? Ss. equivalent” on plates 3 and 4. The sandstone is between 0 and 70 ft on the Shawmut anticline measured section (pl. 5) and consists of fine-grained to very fine grained sandstone with horizontal beds and trough crossbeds as high as 3 ft. In thin section, this sandstone consists of mainly quartz and chert with minor plagioclase, potash feldspar, and dark, very fine grained rock fragments.

Eagle Sandstone

The Eagle Sandstone was deposited during a major regression of the Cretaceous shoreline in early Campanian time. The formation was named by Weed (1899) for exposures at the mouth of Eagle Creek about 100 mi north of the north margin of the Crazy Mountains Basin. At the type locality, it was subdivided into three units: (1) an upper, thin-bedded sandstone, (2) a middle, coal-bearing unit, and (3) a lower, persistent sandstone unit. The lower sandstone unit was later named the Virgelle Sandstone Member of the Eagle Sandstone by Bowen (in Stebinger, 1914) for exposures near the town of Virgelle, about 12 mi northwest of the type locality for the Eagle. Age of the Eagle in the northern Rocky Mountain region is early Campanian (Gill and Cobban, 1966; Dyman and others, 1994). It has been mapped on the surface throughout the Crazy Mountains Basin (Handcock, 1918; Knappen and Moulton, 1931; Roberts, 1972; Skipp and Hepp, 1968; Skipp and McMannis, 1971; McGrew, 1977a, b, c). The Virgelle Sandstone Member is generally not mapped separately, although many workers have recognized it in outcrop (Handcock, 1918; Knappen and Moulton, 1931). The only mineable coal in the Crazy Mountains Basin occurs in the Eagle Sandstone in the vicinity of Livingston (Roberts, 1966, 1972). The formation is overlain by the marine Claggett Shale in all but the southwest corner of the Crazy Mountains Basin, and the upper contact is generally placed at the top of the highest nonmarine bed (Roberts, 1972, p. C31). Thickness along the lines of cross section, excluding the Livingston area, ranges from about 60 to 300 ft.

In the Livingston area, in the southwest corner of the basin, where the Claggett has graded into nonmarine rocks, Roberts (1972) placed the top of the Eagle at the lithologic change where volcanic detritus becomes abundant. Thus defined, the formation in the Livingston area is considerably thicker than elsewhere in the basin (pl. 2, section S-2), ranging from 515 to 860 ft and averaging 640 ft. Roberts (1972, p. C31) also noted that the Eagle near Livingston was about twice as thick as it is a few miles to the north and east. Relations shown on cross section *B–B′* (pl. 2) indicate that the Eagle near Livingston includes the lateral equivalent of the Parkman Sandstone as well as the overlying Claggett Shale. Roberts (1972, his fig. 13) included three major sandstone units, each of which is overlain by a coaly interval, in a reference section near Livingston. The lower sandstone is the marginal marine Virgelle Sandstone Member. Oyster and *Inoceramus* shells were found in the middle of the second sandstone indicating that it is marginal marine as well. According to Roberts, this middle sandstone lenses out to both the east and west. Depositional setting of the upper sandstone is less certain, but it does contain worm tubes or pelecypod burrowings, possibly indicating a marginal marine origin. Roberts (1972) described sandstones in the Eagle Sandstone near Livingston as sourced mainly by plutonic and metamorphic rocks, but fragments of andesite are also present, and pebbles of microporphyritic and fine-grained andesite occur locally in the Virgelle Member.

The Eagle Sandstone, along the lines of cross section (pls. 1–4), consists mainly of marginal marine sandstone, but fluvial and coastal plain rocks occur in its upper part in the southern part of the basin (pl. 1, wells A-19 through A-21, A-23 through A-26, S-1). Based on geophysical logs, little coal appears to occur in the Eagle along the lines of section. The Superior 22-25 Windsor well in sec. 25, T. 1 S., R. 11 E. (pl. 2, well B-2; table 1, no. 92), 12 mi northeast of Livingston, has two 6-ft coal beds in the Eagle, and thin (>3 ft) coal beds occur in the fluvial and coastal plain facies in the upper part of the Eagle in the southernmost part of the basin. At the Shawmut anticline measured section (pl. 5), the formation is 295 ft thick and can be divided into three units: (1) a 45-ft-thick basal fine-grained to very fine grained sandstone that is probably the Virgelle Sandstone Member, (2) a middle part composed of interbedded poorly exposed fine-grained to very fine grained sandstone and gray, fissile shale, and (3) an upper 25-ft-thick, fine-grained to very fine grained sandstone. The Virgelle is horizontal bedded and trough crossbedded with foresets as high as 3 ft; one set of 2-ft-high planar crossbeds was observed. The upper surface of the Virgelle is burrowed. Sandstones in the middle part are 2–11 ft thick, horizontal and flaser bedded, and burrowed. The upper sandstone has trough crossbeds 3 ft or higher and lenticular clayey rip-up zones.

Claggett Shale Through Teapot Sandstone Member of the Mesaverde Formation and Its Equivalent Interval

This complex interval of intertonguing marginal marine sandstone, marine shale, and coastal plain deposits occurs throughout the Crazy Mountains Basin and consists of, in ascending order, the Claggett Shale, the Parkman Sandstone, and the lower part of the Judith River Formation to the top of the Teapot Sandstone Member equivalent. The interval spans about 17 ammonite zones, from *Baculites mclearni* at the base to *Baculites reesidei* at the top (Gill and Cobban, 1966), a time span estimated by Obradovich (1993, his fig. 2) to be about 8–9 m.y. The interval generally ranges from about 700 to 900 ft thick along the lines of cross section (pls. 1–4) for a sedimentation rate after compaction of only about 100 ft per m.y. Such a slow rate of sedimentation likely created several minor regional hiatuses resulting from eustatic changes in sea level, as well as more local hiatuses resulting from tectonism and autocyclic sedimentation processes. Correlations of individual marginal marine sandstones in this interval were difficult, possibly because of these multiple hiatuses, and the correlations shown on the cross sections are probably greatly simplified. Reconstructions of shoreline positions by Gill and Cobban

(1973) indicated that the shoreline was largely stationary in the area of the Crazy Mountains Basin during most of this time period, trending generally east-west through the northern part of the basin. Thus, there is a gradation from nonmarine rocks to marine shale within much of this interval over a short lateral distance to the north, but existing drillhole information is inadequate to define the stratigraphic relations in detail.

The Claggett Shale was originally named by Hatcher and Stanton (1903) for a 400-ft-thick sequence of marine shales and sandstones overlying the Eagle Formation and underlying the Judith River Formation near old Fort Claggett at the mouth of the Judith River about 100 mi north of the north margin of the Crazy Mountains Basin. The Claggett has been mapped along the north margin of the basin (Handcock, 1918), the east margin (Knappen and Moulton, 1931), and in the southern part (Andrews and others, 1947). The Claggett grades into nonmarine rocks toward the southwest and is not present in the Livingston area along the southwest basin margin (Roberts, 1972). Maximum Claggett transgression in the area occurred during the Baculites sp. (weak flank ribs) through *Baculites mclearni* ammonite zones of the early Campanian (Gill and Cobban, 1973, their fig. 14), when the shoreline trended northwest-southeast along the southwest basin margin (fig. 9). The lower part of the Claggett Shale is bentonitic throughout its extent in Montana and Wyoming, indicating that volcanism was occurring at that time. Typically this bentonitic interval is a zone of low resistance on resistivity logs. A regionally significant bentonitic marker, the Ardmore Bentonite Bed, occurs near the base of this bentonitic zone (Gill and Cobban, 1966, their pl. 3). The Ardmore is labeled along the southern part of cross section *A–A′* (pl. 1) and has been dated at Elk Basin in the northernmost Bighorn Basin, just south of the Crazy Mountains Basin (pl. 1, section S-1), at 80.54±0.55 Ma (Obradovich, 1993, p. 383–384).

At the Shawmut anticline measured section, the Claggett Shale is composed of 307 ft of well-exposed, fine-grained to very fine grained sandstone ledges as much as 20 ft thick separated by thick mostly covered intervals; fissile gray mudstone is sporadically exposed in these intervals (pl. 5). Sandstones display horizontal to low-angle bedding, trough crossbedding to 3 ft, and hummocky bedding, and were probably deposited in a nearshore marine setting.

The Parkman Sandstone overlies the Claggett Shale and was named for exposures near the town of Parkman, Wyo., just south of the Montana State line, along the west-central margin of the Powder River Basin (Darton, 1906; Wegemann, 1918). In the vicinity of the Crazy Mountains Basin, the name is commonly applied to marginal marine sandstone or sandstones above the Claggett Shale or equivalent rocks (Roberts, 1972, his fig. 2; Skipp and McGrew, 1977, their fig. 4). Early workers in the Crazy Mountains Basin, however, did not recognize the Parkman Sandstone and assigned all marginal marine and nonmarine rocks between the Claggett Shale and the Bearpaw Shale to the Judith River Formation (Handcock, 1918; Knappen and Moulton, 1931). In the basin, the Parkman Sandstone is usually considered to be a separate formation (Gill and Cobban, 1966, their pl. 3, Hardin section; Roberts, 1972, his fig. 2; Gill and Burkholder, 1979, their sections 2 and 3).

The Parkman Sandstone is present throughout all but possibly the northeast corner of the Crazy Mountains Basin, occurring along about a 50- to 65-mi-wide northwest-southeast-trending zone (fig. 10). In the southwestern part, the Parkman grades into nonmarine rocks in the Eagle Sandstone and Cokedale Formation as used by Roberts (1972) (pl. 2, fig. 10). Along the lines of cross section, the Parkman is a complex interval that can include from one to three marginal marine sandstones and thin tongues of marine shale (pls. 1–4). Marine shale tongues occur within the Parkman along a 30- to 36-mi-wide belt across the center of the Crazy Mountains Basin (fig. 10).

Correlations of the Parkman Sandstone in the northeastern part of the basin are problematical. Here the Parkman is separated from the overlying Teapot Sandstone Member equivalent by less than 150 ft of nonmarine strata (pls. 2–4) and in places appears to intertongue and merge with the Teapot (pl. 4, wells D-1 through D-3). Well control is too sparse to resolve these complexities, and detailed surface mapping is lacking.

Gill and Burkholder (1979) identified the Parkman Sandstone at Shawmut anticline, in the northeastern part of the basin and seaward of the pinch out of the Parkman shown on plate 3. Stratigraphic relations shown on cross section *C–C′* (pl. 3) indicate that that their Parkman may in part be equivalent to the Teapot, which overlies the Parkman. Gill and Burkholder (1979), however, identified *Baculites compressus* in the Bearpaw Shale about 800 ft above the top of their Parkman Sandstone, which is a baculite zone that is older than the Teapot equivalent but consistent with this sandstone being the Parkman. They described the interval from the Cody Shale through their Parkman Sandstone at approximately the same locality as the Shawmut anticline section in this study, and the descriptions of the sections presented by Gill and Burkholder (1979) and the one presented in this report are similar (compare section S-3 on pl. 3 and Shawmut anticline section on pl. 5). The overlying strata are not exposed at this locality, and Gill and Burkholder offset about 4.5 mi to the southwest to describe that interval. Thus, the ammonites identified by Gill and Burkholder (1979) were not from the same locality that is described in detail here. As previously discussed, rapid lateral facies changes occur in this area making offsets of this magnitude in measured sections risky, and more detailed surface work is needed to resolve this apparent discrepancy between the physical stratigraphy and ammonite zonation.

Although the name Teapot is not generally used in Montana, the Teapot Sandstone Member or its equivalent could be traced throughout much of the Crazy Mountains Basin where it occurs in the lower part of the Judith River Formation (pls. 1–4). The presence of the Teapot in at least the eastern part of the basin has apparently long been common knowledge as it was correctly labeled by well-site geologists on numerous electric logs from the 1950s and 1960s kept in the Montana

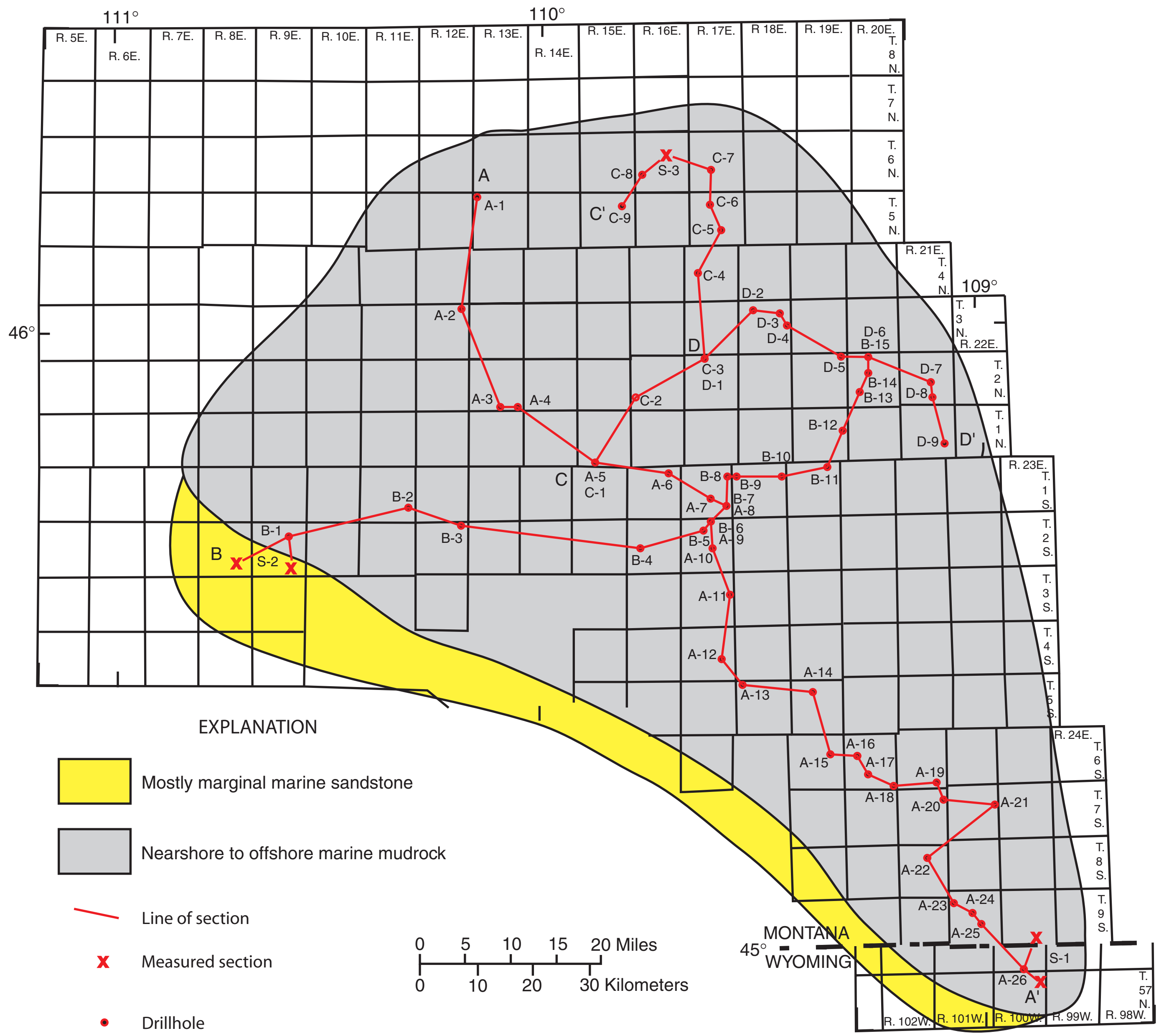

Figure 9. Approximate extent of Upper Cretaceous marine Claggett Shale, Crazy Mountains Basin, Montana.

State records. The Teapot and its equivalents represent an extensive braid-plain deposit that developed throughout much of western Wyoming in latest Campanian through earliest Maastrichtian time. The braid-plain deposits, which created a large eastward bulge in the Cretaceous shoreline, grade to the north, east, and south into marginal marine rocks and then into marine shale (Gill and Cobban, 1973). In the vicinity of its type section in the southern Powder River Basin, the Teapot is considered a deltaic complex that is both underlain and overlain by marine shales (Curry, 1976a, b).

The Teapot is locally missing possibly due to faulting in the northernmost part of the Bighorn Basin to the south (Johnson and others, 1998b) and is missing in the Elk Basin measured section on cross section *A–A′* (pl. 1). It appears to be missing in two drillholes along the Nye-Bowler lineament, which separates the Bighorn and Crazy Mountains Basins (pl. 1, wells A-19 and A-20). The Teapot equivalent is shown as marginal marine sandstone along the lines of cross section (pls. 1–4) although it may include some braid-plain deposits as well. As previously discussed, correlations between the Teapot equivalent and the underlying Parkman Sandstone are poorly understood in the northeastern part of the Crazy Mountains Basin.

Judith River Formation

In the eastern part of the Crazy Mountains Basin, the nonmarine sequence above the Parkman Sandstone and below the Bearpaw Shale is assigned to the Judith River Formation

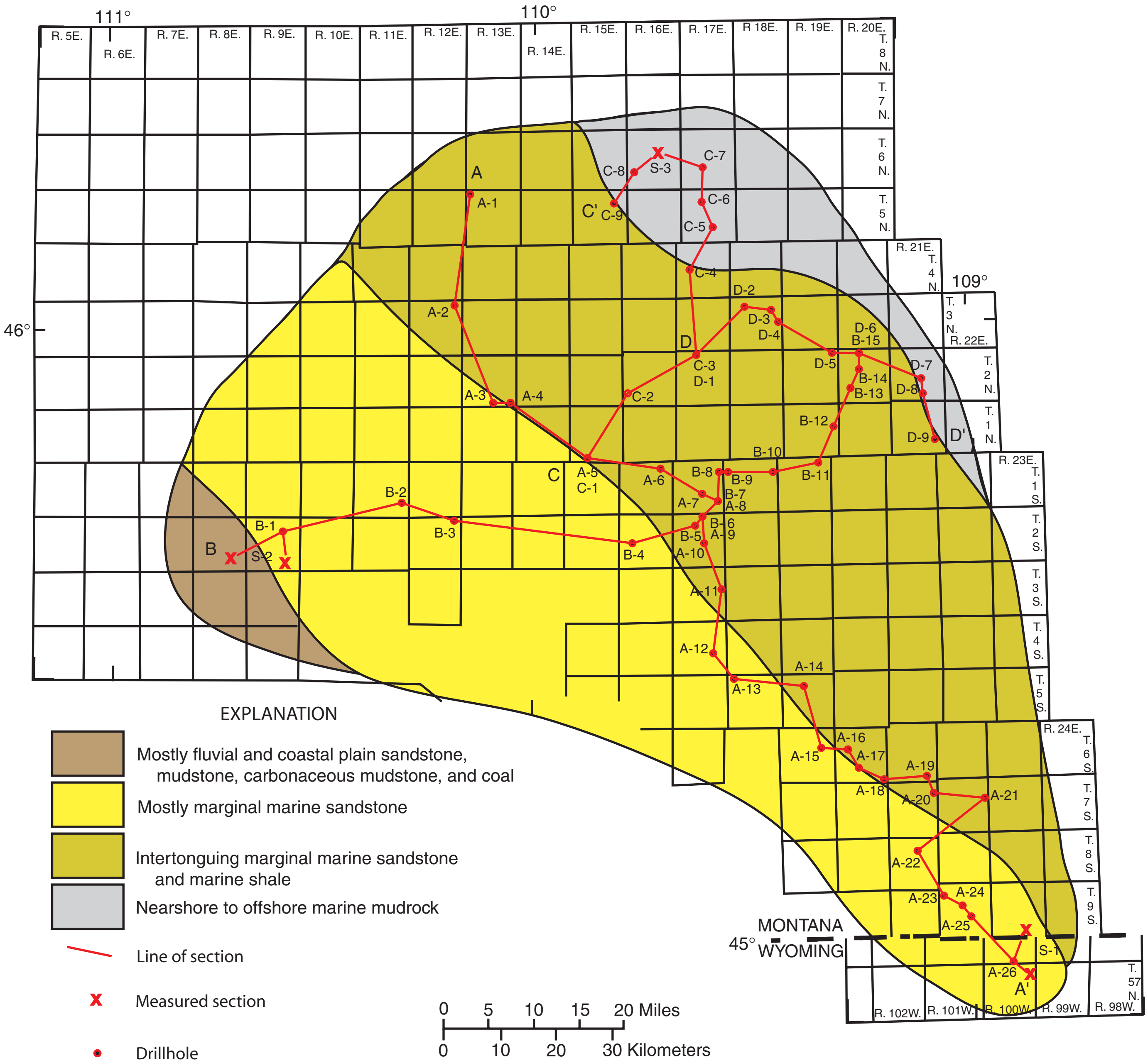

Figure 10. General depositional settings during deposition of Upper Cretaceous Parkman Sandstone, Crazy Mountains Basin, Montana.

(fig. 4) (Gill and Cobban, 1966, pl. 3, Hardin section; Roberts, 1972, fig. 2; Gill and Burkholder, 1979, secs. 2 and 3). The Judith River includes the Teapot Sandstone equivalent and grades into the Livingston Formation in the southwestern part of the basin. In the northwestern part of the Powder River Basin to the east, the underlying Parkman Sandstone is considered a member of the Judith River (Merewether, 1996), whereas farther to the south, in that part of the west margin of the Powder River Basin in northeast Wyoming, the Parkman Sandstone is considered a formation and includes the marginal marine Parkman as defined in the Crazy Mountains Basin as well as the overlying nonmarine rocks (Darton, 1906; Wegemann, 1918; Thom and others, 1935; Gill and Cobban, 1966). The overlying Bearpaw Shale, which defines the top of the Judith River, grades to the southwest into nonmarine rocks and is not present in the southwest half of the basin (fig. 11). Southwest of the pinch out of the Bearpaw, the Judith River is lumped with the overlying Hell Creek Formation or is included in the Livingston Group.

Along the lines of cross section, the Judith River varies from about 650 to 1,050 ft thick and consists of rocks deposited in marginal marine and coastal plain settings (pls. 1–4). At Shawmut anticline, only 463 ft is exposed, including a 40-ft-thick marginal marine Teapot equivalent or Parkman Sandstone at the base (pl. 5). Sandstones above the basal sandstone are as much as 22 ft thick with trough crossbeds, clay ripups, and lateral accretion. The upper part is poorly exposed with thin, small-scale trough crossbedded sandstone of possible

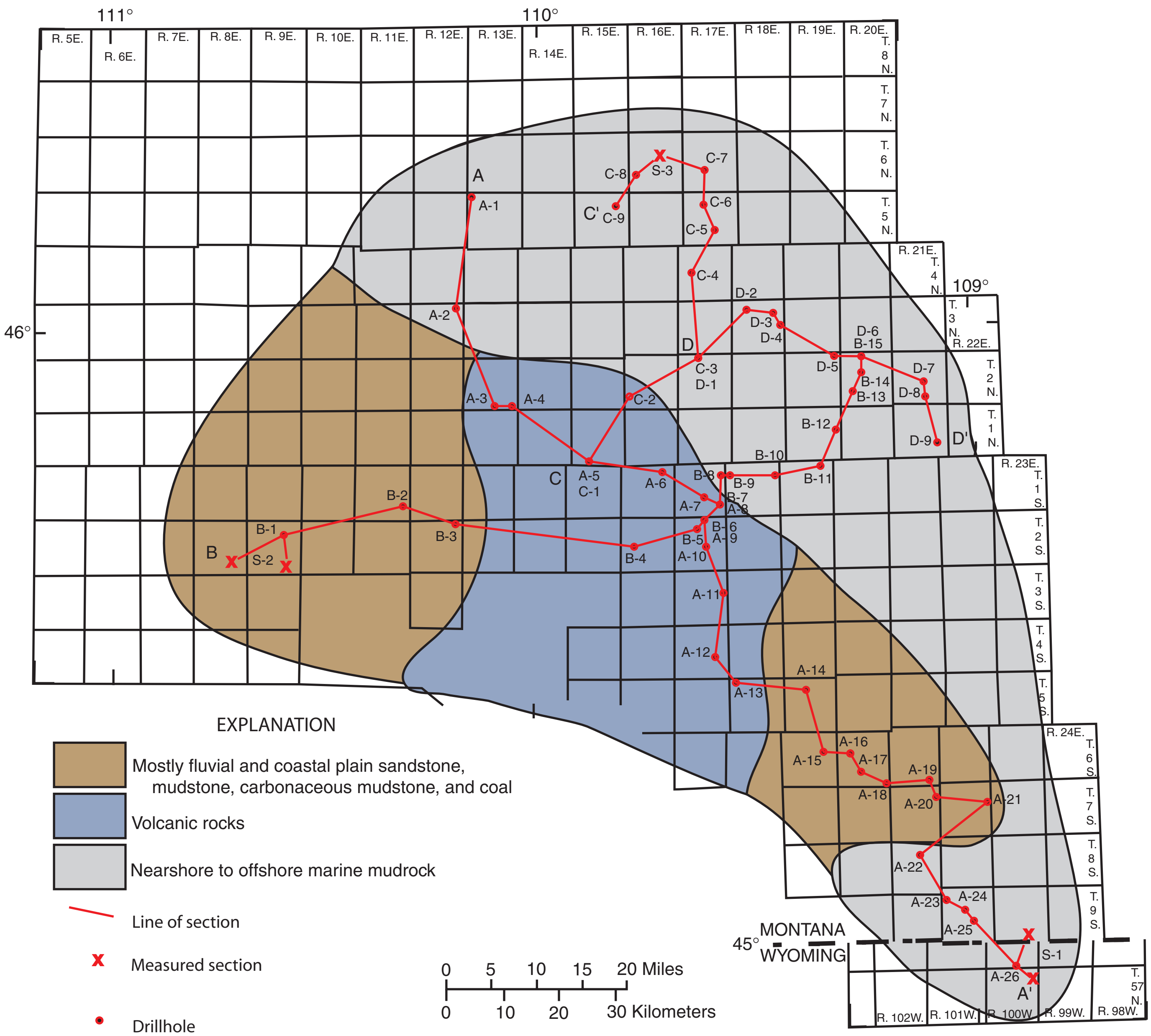

Figure 11. Generalized depositional settings during maximum transgression of Upper Cretaceous Bearpaw Shale, Crazy Mountains Basin, Montana.

crevasse splay origin separated by thick covered intervals. Crossbeds from the Judith River at Shawmut anticline indicate a southeast flow direction (pl. 5).

Bearpaw Shale

The Bearpaw Shale occurs above the Judith River Formation and below the Hell Creek Formation throughout the northwest half of the basin. It wedges out into nonmarine rocks of the Judith River Formation and Livingston Group to the southwest. The term Bearpaw Shale, which was first used by Hatcher and Stanton (1903), is applied to this Upper Cretaceous shale in eastern Montana and Alberta, Canada, to the north, and in parts of the Powder River and Bighorn Basins in northern Wyoming. It is in part equivalent to the Lewis Shale farther south in Wyoming. The Bearpaw interfingers and wedges out into coarse volcaniclastic sediment north of a Late Cretaceous volcanic center south of Livingston, along the southwest flank of the Beartooth uplift (pls. 1–4, fig. 11). The base of the Bearpaw varies from about 400 to 820 ft above the top of the Teapot equivalent along the lines of cross section.

Lennep Sandstone

The Lennep Sandstone is a regressive marginal marine unit overlying the Bearpaw Shale and is approximately equivalent to the Fox Hills Sandstone to the south in Wyoming. It is overlain by the nonmarine Hell Creek Formation. It intertongues with the Bearpaw Shale near its pinch out toward the southwest in the Crazy Mountains Basin and grades into nonmarine rocks of the undifferentiated Judith River and Hell Creek Formations a short distance southwest of the pinch out of the Bearpaw (pls. 1–4). The name Lennep Sandstone was applied by Stone and Calvert (1910, p. 747) to the "dark-colored tuffaceous sandstone intercalated with dark shale" at the top of the Bearpaw Shale and base of the Lance Formation, and was named for Lennep Station along a now abandoned railroad line just north of the Crazy Mountains. The Lennep varies from 40 to 300 ft thick along the lines of cross section (pls. 1–4). At Shawmut anticline, the Lennep is 49 ft thick and composed of fine-grained to very fine grained sandstone with ophiomorpha burrows, low-angle cross strata, and trough cross strata less than 1 ft high (pl. 5).

Hell Creek Formation

The Hell Creek Formation is composed of nonmarine varicolored mudstone and sandstone overlying the Lennep Sandstone in the northwest half of the basin where the Bearpaw Shale is present. It is named for exposures along Hell Creek north of Jordan, Mont. The formation varies in thickness from about 1,580 to 2,810 ft along the lines of cross section (pls. 1–4). About 525 ft of Hell Creek is exposed at Shawmut anticline, and this interval is composed predominantly of green and gray mudstone with a few very fine grained to medium-grained, trough-crossbedded, probable fluvial channel sandstones from 14 to 28 ft thick and fine-grained to very fine grained, ripple-drift laminated, probable splay sandstones from 0.5 to 4 ft thick. Lateral accretion was observed in some of the channel sandstones.

Livingston Group

Upper Cretaceous and lower Tertiary rocks in the western and southwestern parts of the Crazy Mountain Basin contain a considerable amount of andesitic volcanic debris. The earliest evidence for volcanic detritus in the vicinity of the Crazy Mountains Basin area from this volcanic activity appears to be lenses of andesitic material in the Cody Shale just below the base of the Eagle Sandstone in the northern part of the Bridger Range just west of the basin (Stone and Calvert, 1910, p. 752, their pl. IV). The Eagle can be recognized throughout the area whereas younger units are mapped as the volcanic-rich Livingston Group (Roberts, 1972). Andesitic material entered the Crazy Mountains Basin area in large quantities after deposition of the Eagle and continued into the Paleocene. According to Skipp and McGrew (1972) the Upper Cretaceous rocks above the Eagle Sandstone along the west margin of the basin include as much as 40 percent brecciated and nonbrecciated flows, vitric tuffs, and welded tuffs along the extreme west margin of the Crazy Mountains Basin. The approximate limits where several stratigraphic units have a "noticeably andesitic character" were studied by McMannis (1955, 1957).

This volcanic-rich sequence was assigned to the Livingston Formation by Weed (1893, p. 21) for exposures near Livingston, Mont., in the southwestern part of the basin. Weed (1893, p. 34–35) believed that the Livingston was separated from older rocks by a regional unconformity. The lack of Bearpaw, Judith River, and Claggett strata in the vicinity of Livingston was thought to be the result of truncation of these units prior to deposition of the Livingston (Weed, 1893, p. 34–35; Knowlton, see Stone and Calvert, 1910, p. 751). Stone and Calvert (1910, p. 752, pl. IV) demonstrated, however, that the Livingston graded laterally into the Claggett, Judith River, Bearpaw, Lennep, Lance, and Lebo to the north and east in the Crazy Mountains Basin.

The volcanic detritus appears to be coming from two main sources: (1) the Elkhorn Mountains, west of the Crazy Mountains Basin (Billingsley, 1915; Berry, 1943; McMannis, 1955; Klepper and others, 1957); and (2) a volcanic center along the southwest margin of the basin about 30 mi southeast of Livingston (figs. 2 and 11) (Weed, 1893, p. 29; Vhay, 1939; Parsons, 1942, 1958; Garbarini, 1957; McMannis, 1957; Richards, 1957). The Elkhorn Mountains Volcanics are andesitic and thought to be an extrusive phase of the Boulder batholith (Robinson and others, 1969; Klepper and others, 1971). The Livingston volcanics are also andesitic and thought to have been sourced by volcanic vents in the vicinity (Parsons, 1942). The Livingston volcanic field was studied in detail by Parsons (1942), who believed that the source was several small breccia pipes within the volcanic field. Intrusive volcanic plugs and a small laccolith about 5 mi across also occur within the field (figs. 2 and 11). Parsons (1942) collected fossil leaves and stems that were dated as approximately the age of the Judith River Formation in central Montana. Garbarini (1957) mapped part of the Livingston volcanic center and subdivided the volcanic sequence into two informal members: (1) a lower member of tuff, volcanic sandstone, and volcanic mudstone, and (2) an upper member of volcanic breccia. As with earlier workers, Garbarini believed that nearby breccia pipes were the source of the volcanics. The lower member grades downward into the underlying Eagle Sandstone.

The Elkhorn Mountains Volcanics have been dated from 78 Ma to 73 Ma (Robinson and others, 1969; Chadwick, 1981). This is somewhat younger than the Livingston volcanic center, which has been dated at 82 Ma (Marvin and Dobson, 1979) and is the oldest dated volcanic center in southwestern Montana (Chadwick, 1981). Age of this volcanic center is about the same as the lower Campanian *S. hippocrepis II* ammonite zone which has been dated at 81.7±0.34 Ma (Obradovich, 1993). Roberts (1972, fig. 2) estimated that the Eagle Sandstone near Livingston fell within the *S. hippocrepis* zone of the lower Campanian. Thus the first occurrence of volcanic detritus in the Crazy Mountains Basin, just below the Eagle Sandstone, is about the same age as the Livingston volcanic center but significantly older than the oldest dated volcanic rocks in the Elkhorn Mountains. Detailed stratigraphic studies along the west margin of the basin have found that, as in the Livingston area, there is a minor amount of volcanic debris in the Eagle Sandstone followed by a flood of volcanic detritus above (Skipp and McGrew, 1977). Clearly both centers added volcanic detritus to the basin but the relative importance of the two sources through time has not been studied in detail.

Roberts (1963, 1972) divided the Livingston Group in the Livingston area into four formations—in ascending order, the Cokedale, Miner Creek, Billman Creek, and Hoppers Formations. All of these units are considered to be nonmarine. The Cokedale Formation is equivalent to strata extending from the top of the Eagle Sandstone to the base of the Lennep Sandstone and is composed of siltstone and sandstone and lesser amounts of mudstone, tuff, bentonite, and lignite (Roberts, 1972, p. C36). The Miner Creek, Billman Creek, and Hoppers Formations grade to the northeast into the Hell Creek Formation (Roberts 1972, his fig. 2). According to Roberts (1972, p. C36–C37), the Miner Creek Formation is composed of alternating beds of sandstone and siltstone; the Billman Creek consists of red, purple, and green mudstone with some tuff, bentonite, and sandstone; and the Hoppers Formation is composed of sandstone and conglomerate interbedded with some siltstone, mudstone, and tuff.

During the present study, two partial sections of the Livingston Group were measured where it is exposed along Interstate 80 east of Livingston (pl. 5). The sections are east of the area where Roberts (1972) mapped and subdivided the Livingston Group into its four formations and in an area where the Livingston was mapped by Richards (1957) as a single formation. At the first locality, 14 mi east of Livingston, 475 ft of the Livingston Group was described beginning about 700–800 ft above the top of the Teapot Sandstone equivalent. At the second locality, 15 mi east of Livingston, 285 ft was described beginning about 1,600–1,700 ft above the top of the Teapot equivalent.

The first section consists of very fine grained to medium-grained sandstones interbedded with gray mudstone (pl. 5). Sandstones are composed mainly of quartz, chert, detrital carbonate, and some fine-grained, highly altered volcanic rock fragments. They are predominantly discrete channel sandstones from 5 to 28 ft thick, but a 120-ft-thick multistory channel sandstone unit occurs in the middle of the outcrop, which includes at least three scour surfaces, one of which included subangular chert pebbles to 0.5 in. Discrete sandstones commonly display lateral bar accretion with mudstone drapes confined mainly to the upper parts of the bars. All channel sandstones are predominantly trough crossbedded. Trough crossbeds indicate a northward flow direction, away from the volcanic center to the south.

The second section (pl. 5) is lithologically distinct from the first, being composed almost entirely of medium- to coarse-grained conglomeratic sandstone with abundant andesitic and basaltic clasts as much as 2 ft across. Multiple rooted zones and scour surfaces were observed. Sandstones are horizontal to low angle crossbedded and trough crossbedded. Rare, interbedded mudstones are olive green. Trough crossbeds again indicate a northward flow direction away from the volcanic center to the south.

Fort Union Formation or Group

The Fort Union is considered a group in the northern part of the Crazy Mountains Basin and a formation elsewhere; it is the youngest stratigraphic unit preserved in the basin. In the Livingston area, Roberts (1972) placed the contact between the Livingston Group and the Fort Union Formation at the lithologic change from volcanic clasts in conglomerates in the uppermost part of the Livingston to sedimentary clasts derived from Precambrian, Paleozoic, and Mesozoic formations in the Fort Union. He (Roberts, 1972, p. C51) believed that the clasts in the Fort Union were coming from the Bridger uplift just west of the basin and that the Fort Union was conformable with the underlying Cretaceous Livingston Group in the Livingston area. A considerable thickness of the lower part of the Fort Union in the Livingston area appears to be Cretaceous in age, as Roberts (1972) collected Cretaceous pollen 750 ft above the base of the Fort Union and probable Tertiary pollen 1,625 ft above the base; he measured a total of 6,615 ft of Fort Union strata in the Livingston area.

In the northern part of the basin, the Fort Union Group conformably overlies the Hell Creek Formation and is subdivided into three formations—in ascending order, the Bear Formation, Lebo Shale, and Melville Formation (Simpson, 1937; Stow, 1946; Hartman and others, 1989). According to Hartman and others (1989) and Hartman and Krause (1993), the Bear Formation varies from about 373 to 610 ft thick and consists predominantly of buff to gray, fine-grained calcareous sandstone, siltstone, and gray, dark-green, and brown shales. The sandstones are rarely thicker than 6.5 ft and can be either fining-upward or coarsening-upward units. The Bear Formation was given separate formation status by Simpson (1937) because it contained no diagnostic vertebrate fossils and could not be assigned to either the Hell Creek or Fort Union Formations. The lower 80 ft of the Bear contains fragmentary dinosaur remains that he (Simpson, 1937) interpreted as being reworked from the underlying Hell Creek Formation. Later work indicated that the Bear may be largely early Paleocene in age (Hartman, 1989). In the subsurface, the Bear Formation is difficult to distinguish from the underlying Lance Formation and overlying Lebo Shale, and its stratigraphic position as shown on cross section *A–A′* (pl. 1) is questionable.

The overlying Lebo Shale consists of dark-olive-green mudstone and sandstone and is about 1,350 ft thick (Simpson, 1937). It was originally referred to as the Lebo Andesitic Member of the Fort Union Formation by Stone and Calvert (1910, p. 746–747) and was named for exposures along Lebo Creek in T. 6 N., R. 13 E. in the northern part of the basin. It was tentatively identified in the subsurface during the present investigation throughout much of the Crazy Mountains Basin (pls. 1 and 3). Near its type section in the northern part of the Crazy Mountains Basin, the Lebo Shale is middle Paleocene in age (Hartman, 1989). In the subsurface in that area the Lebo

Shale appears to be relatively sandy, and therefore difficult to distinguish from the underlying Bear Formation and overlying Melville Formation. In the southern part of the Crazy Mountains Basin and the northern part of the Bighorn Basin to the south, the Lebo Shale is a distinctive largely fine-grained unit (Hickey, 1980), represented by low resistivity on electric logs (pl. 1), above a thin basal Fort Union sandy interval. Johnson and others (1998, their pl. 2) described the lower part of the Lebo Shale in detail at Elk Basin where it consists mainly of dark-gray carbonaceous mudstone, thin coal beds, and lenticular, fluvial channel sandstones. There, the basal Fort Union sandstone unit is 240 ft thick and composed of fine to coarse conglomeratic, trough-crossbedded sandstone, and gray mudstone. Nichols (1998) reported middle Paleocene P4 zone pollen from the lowermost part of the Lebo Shale at Elk Basin, and Cretaceous and early Paleocene P1 or P2 zone pollen from the basal Fort Union sandstone. The Cretaceous pollen in this case is interpreted to be reworked.

The Melville Formation is the youngest unit in the Fort Union Group and is as much as 5,000 ft thick (Hartman and Krause, 1993). It was named by Simpson (1937) for exposures near the town of Melville in the northwestern part of the Crazy Mountains Basin and is composed of a basal buff-colored sandstone overlain by about 5,000 ft of olive-green shales and sandstones (Hartman and Krause, 1993). The Melville is present only in the northern part of the basin and could not be distinguished from the underlying Lebo Shale on geophysical logs.

Potential Hydrocarbon Source Rocks in the Crazy Mountains Basin

Possible source rocks in the Crazy Mountains Basin include (1) organic-rich marine shale intervals in the Lower Cretaceous Thermopolis Shale and Mowry Shale and the Upper Cretaceous Cody Shale, and (2) coals and carbonaceous shales in the Upper Cretaceous Eagle Sandstone and Judith River Formation, and the Paleocene Lebo Shale and Melville Formation. The Thermopolis and Mowry occur throughout the Crazy Mountains Basin. Total organic carbon (TOC) values of as high as 1.0 percent and Tmax values of from 440 to 460 were reported by Burtner and Warner (1984) for these formations, indicating that they are organically rich enough to be considered potential source rocks, and that they are within the oil window. Samples were collected from the marginal areas of the basin where the Mowry and Thermopolis occur at relatively shallow depths (4,100–6,035 ft). The source rock potential of the Cody Shale has not been investigated in the Crazy Mountains Basin. Hagen and Surdam (1984), however, reported TOC values as high as 4.42 percent for the Cody in the Bighorn Basin to the south, indicating excellent source rock potential, and it is likely that similar organic-rich intervals occur in the Cody in the Crazy Mountains Basin.

Coal has been mined from the Upper Cretaceous Eagle Sandstone in the Livingston area along the southwest margin of the basin and in the Elk Basin area in the northernmost part of the Bighorn Basin to the south. Significant coal appears to be present in these formations only in the vicinity of Livingston in the southwestern part of the basin and along the Nye-Bowler lineament in the southeastern part of the basin. Thin (<2 ft thick) coals and carbonaceous shale are, however, present in the Eagle and Judith River throughout the basin.

The Paleocene Melville Formation is approximately equivalent to the Tongue River Member of the Fort Union Formation in the Powder River Basin to the east and southeast. The Tongue River Member contains vast deposits of lignite and subbituminous coal (Fort Union Coal Assessment Team, 1999) that are being extensively mined, and also being drilled extensively for coalbed methane. Only carbonaceous shale and thin coal beds occur in the Melville where it is exposed in the northern part of the Crazy Mountains Basin; however, more coal may occur in the formation in the subsurface. Geophysical logs for the E.R.E.C. Western Region no. 23-6 American Fork well in sec. 6, T. 5 N., R. 13 E., in the north-central part of the basin, indicate that numerous thin (>5 ft thick) coal beds occur in the Melville Formation and possibly the underlying Lebo Shale at depths of about 1,800–4,000 ft. Only minor carbonaceous shale and lignite were reported in cuttings taken at depths of 2,180–2,190 ft and 2,580–2,590 ft from probable Melville strata in the Chevron-Sonat-CIG 1 Van Cleve well in sec. 1, T. 3 N., R. 12 E. about 12 mi south of the E.R.E.C. 23-6 well (pl. 1, well no. A-2). However, coal fragments were reported in cuttings from the Chevron no. 1 Sonat-Largent well in sec. 3, T. 4 N., R. 10 E., about 15 mi southwest of the 23-6 well, starting at 2,250 ft and continuing to 7,740 ft. Geophysical logs suggest that there may be numerous thin (>5 ft) coal beds throughout this interval.

Hydrocarbon Production in the Crazy Mountains Basin

To date, only shallow hydrocarbon production from conventional reservoirs has been established in the Crazy Mountains Basin. Several fields produce from closed anticlinal structures along the Nye-Bowler lineament, which forms the southern boundary of the basin (fig. 2). Dean dome produces oil and gas from the Greybull Sandstone Member of the Cloverly Formation (Lower Cretaceous) at a depth of 2,800–2,900 ft (Ames, 1985a). Dry Creek field produces oil and gas from the Greybull (average depth 5,470 ft) and lower part of the Cloverly Formation (average depth 5,670 ft), and mainly gas from the Upper Cretaceous Frontier (average depth 4,000–4,520 ft), Telegraph Creek, Virgelle (average depth 2,170 ft), Judith River (average depth 1,320 ft), and Bearpaw (Cully, 1985a). Fiddler Creek field produces minor oil from the Lower Cretaceous Greybull (average depth 2,300 ft) and lower part of the Cloverly Formation (average depth 2,550 ft)

(Washburn, 1985). Golden dome field produces gas and oil from the Greybull (average depth 5,850 ft), Frontier (average depth 4,400–4,760 ft), Virgelle (average depth 2,610 ft), Eagle (average depth 2,270 ft), and Judith River (average depth 1,650 ft) (Cully, 1985b). Mackay dome produces oil and gas from the lower part of the Cloverly Formation (average depth 3,550–4,100 ft) and Greybull (average depth 3,400–3,900 ft) (Ames, 1985b). Rosco dome produces oil from the lower part of the Cloverly Formation (2,954 ft) (Warchola, 1985).

Several small gas fields occur in the northeastern part of the basin (fig. 2). These fields include Lake Basin field, which produces gas from the Eagle Sandstone (average depth 1,100 ft) (Jones, 1985), and Lake Basin north field, which produces gas from the Eagle Sandstone (average depth 1,019 ft) and Frontier Formation (average depth 2,868 ft) (Grauman, 1985). Rapelje field produces gas from the Eagle Sandstone (average depth 1,100–1,250 ft) and Judith River Formation (average depth 550 ft) (Oleson, 1985).

Isotopic studies of gases from the Dry Creek and Golden dome fields by Johnson and Keighin (1998) indicate that the gases in these fields are probably composed of mixed thermogenic and biogenic gases. They (Johnson and Keighin, 1998) suggested that the thermogenic component migrated vertically from deeper, more thermally mature source rocks whereas the biogenic component was generated by microbes that were introduced into the formations along with groundwater after regional uplift began about 10 Ma. The vertical migration of thermogenic gas into these shallow reservoirs demonstrates that source rocks have generated gas in the deeper parts of the basin. Vertical migration of gases out of deep basin-centered gas accumulations and into shallow conventional traps has been demonstrated in many Rocky Mountain basins including the Bighorn Basin of Montana and Wyoming (Johnson and Keighin, 1998), the Wind River Basin of Wyoming (Johnson and Rice, 1993; Johnson and others, 1994; Johnson and Keighin, 1998), the Piceance Basin of Colorado (Johnson and Rice, 1990), and the Uinta Basin of Utah and Colorado (Rice and others, 1992; Johnson and others, 1994). The presence of vertically migrated gas in the marginal areas of the Crazy Mountains Basin indicates that a basin-centered gas accumulation may be present at depth.

Implication of Present Investigation on the Structural Development of the Crazy Mountains Basin

For the present study, two structure contour maps and three isopach maps were constructed to better understand the structural development of the basin. Structure contour maps were constructed on the base of the Lower Cretaceous Kootenai Formation (fig. 12) and the top of the Upper Cretaceous Teapot Sandstone Member and its equivalent (fig. 13). Isopach intervals are (1) top of the Mowry Shale to the top of the Virgelle Sandstone Member of the Eagle Sandstone (fig. 14), (2) top of the Virgelle Sandstone Member of the Eagle Sandstone to the top of the Teapot equivalent (fig. 15), and (3) top of the Teapot equivalent to the base of the Lebo Shale (fig. 16). The maps were constructed from available drillholes, surface mapping, and seismic information; subsurface tops are listed in table 1. Surface mapping was used to help define anticlinal and synclinal axes and general structural dip and include Richards (1957), Skipp and McGrew (1968), Skipp and Hepp (1968), Roberts (1972), McGrew (1977a, b, c, d), Skipp (1977), and Skipp and others (1999). Seismic data from Taylor (Chapter B, this CD-ROM) were used to define general structural configuration. The structure of the deep trough of the basin shown on the structure contour maps (figs. 12 and 13) is generally similar but is more generalized than that shown on cross sections constructed from surface data alone by Skipp and others (1999). For example, Skipp and others (1999) interpreted the upturned, east-dipping southwest margin of the basin to be cut by numerous relatively small scale imbricate thrusts, whereas the structure is shown on the structure contour maps as a single unbroken fold. Intrusions in the basin, such as the Big Timber stock (fig. 2), are interpreted on the structure contour maps to crosscut strata without any doming or faulting. This is clearly a simplification but there is no drilling or seismic data available to ascertain structural complexities around the intrusions.

Structure contour maps of the Crazy Mountains Basin indicate that maximum subsidence along the basin trough during Cretaceous and early Tertiary time is roughly comparable to that in Laramide basins in Wyoming to the south. The top of the Teapot equivalent varies from about 1,500 to 3,000 ft above sea level throughout much of the eastern part of the basin to more than 10,000 ft below sea level along the deep trough of the Crazy Mountains Basin (fig. 13). This indicates that about 11,500–13,000 ft of differential subsidence occurred between the eastern part of the basin, which has little structural relief, and the basin trough after deposition of the Teapot equivalent. The depth of the basin trough is roughly comparable to that of the Bighorn Basin to the south, where the top of the Teapot occurs at an elevation of about 11,000 ft below sea level along the trough (Johnson and Finn, 1998b), and the Wind River Basin in central Wyoming where the top of the Teapot occurs at a depth of about 13,000 ft below sea level (Johnson and others, 1996, pl. 1). Low-amplitude anticlines and synclines in the southern part of the basin, adjacent to the Beartooth uplift, are present on the Teapot-equivalent structure contour map (fig. 13) but not on the Kootenai Formation structure contour map (fig. 12). These structures are formed largely by detached shale masses in the Cody Shale (Stone, 1983). Detachment surfaces are typically bentonitic shales in the Cody Shale, Frontier Formation, and Mowry Shale above the Kootenai stratigraphic level. He (Stone, 1983) suggested that the blind thrusts were produced by “synclinal squeezing” in front of the Beartooth uplift but noted that gravitational gliding may have also played a role.

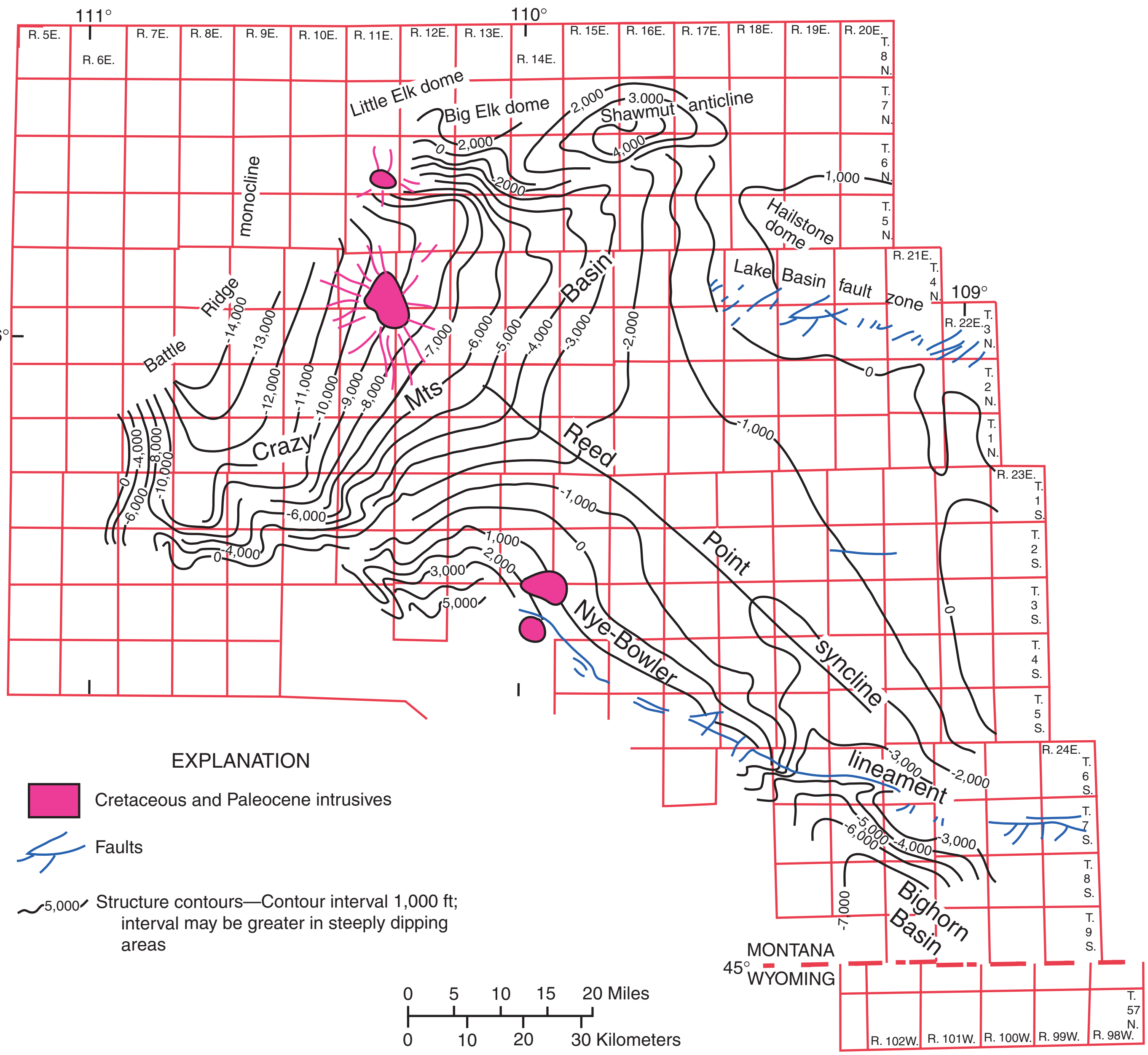

Figure 12. Structure contour map on base of Lower Cretaceous Kootenai Formation, Crazy Mountains Basin and northernmost part of Bighorn Basin, Montana. Contour interval 1,000 ft.

The timing of basin subsidence can be studied using isopach maps. The interval from the top of the Mowry Shale to the top of the Virgelle Sandstone Member of the Eagle Sandstone (fig. 14) varies from less than 1,400 ft in the northern part of the basin to more than 2,100 ft in the western and southern parts. The isopached interval spans the time period from late Albian through early Campanian. Control for the isopach map in the western part of the basin is sparse as none of the wells near the deep basin trough penetrated this entire interval. However, the entire interval is preserved on the overthrust belt west of the Battle Ridge monocline where a thickness of 2,138 ft was measured in a well in sec. 27, T. 6 N., R. 8 E. This compares favorably with thicknesses of 2,100 ft and 2,150 ft estimated from cross sections published by McGrew (1977a) in the Sixteen NE 7.5-minute quadrangle a few miles southwest of the drillhole. Many of the wells examined contain fault-repeated intervals in the Frontier Formation and Cody Shale; these wells were not used to construct the isopach map. Most of the wells with repeated sections occur in the southern part of the basin where Stone (1983) identified blind thrusts involving the Cody Shale and underlying Frontier Formation. Several of the wells with repeated sections are north and west of the area defined by Stone, indicating that there may be blind thrusts that were not recognized. No attempt was made to isopach the interval along the Nye-Bowler lineament because nearly all wells along that trend

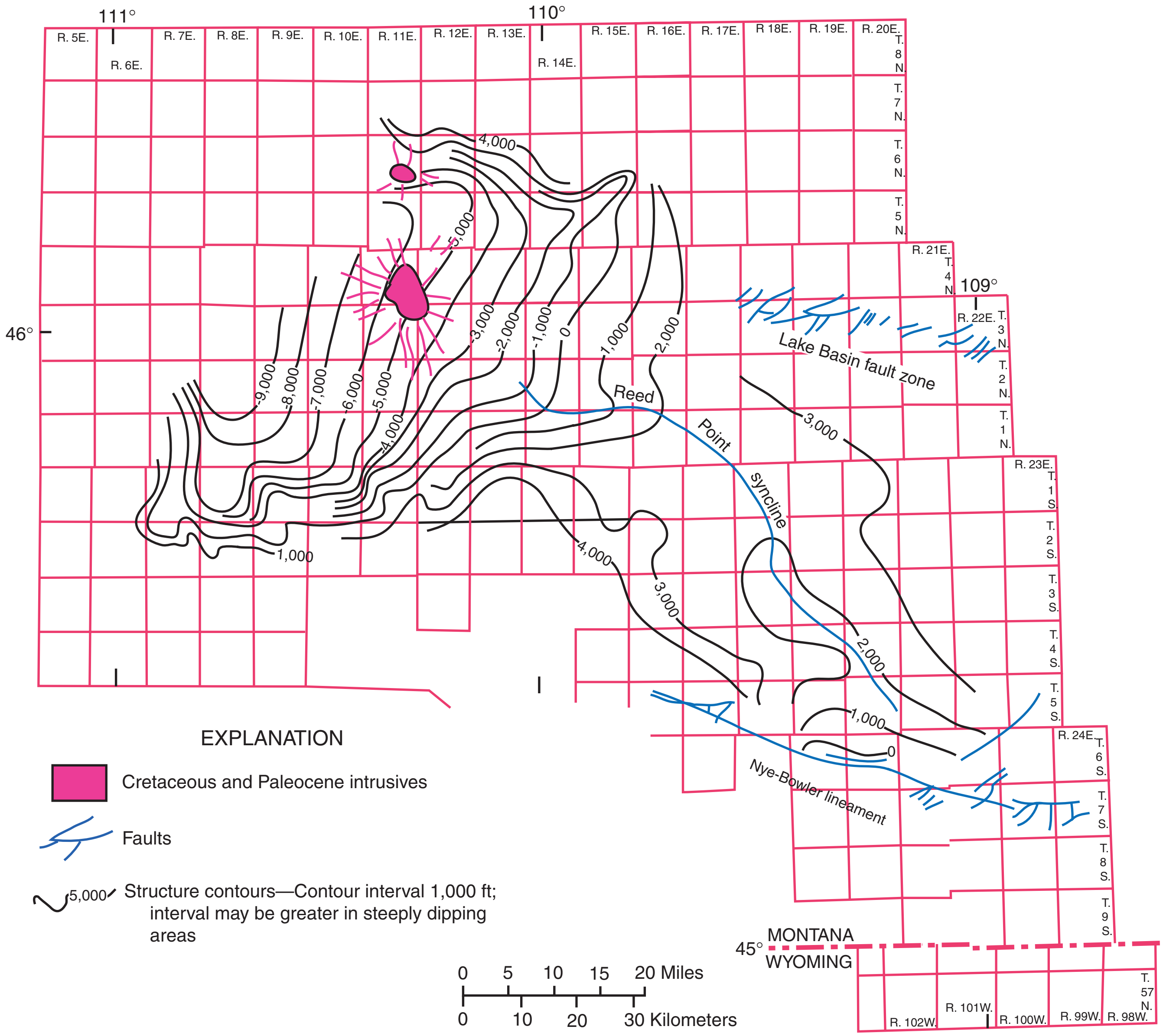

Figure 13. Structure contour map on top of Upper Cretaceous Teapot Sandstone Member of Mesaverde Formation and Teapot equivalent, Crazy Mountains Basin and northernmost part of Bighorn Basin, Montana. Contour interval 1,000 ft.

intersected some faulting. The isopach map thickens somewhat toward the trough of the Crazy Mountains Basin but also thickens generally toward the Beartooth uplift. In general, the isopach map shows little indication of a trough developing in the vicinity of the Crazy Mountains Basin during deposition of strata between the top of the Mowry Shale and the top of the Virgelle Sandstone Member of the Eagle Sandstone.

The next interval isopached, from the top of the Virgelle Sandstone Member of the Eagle Sandstone to the top of the Teapot equivalent, varies from less than 800 ft in the southeastern part of the basin to more than 1,100 ft adjacent to the Beartooth uplift and appears to thicken only slightly toward the basin trough. This Upper Campanian sequence is more than 1,300 ft thick adjacent to the Beartooth uplift in the northernmost part of the Bighorn Basin, just to the south (fig. 15).

The interval from top of the Teapot equivalent to the base of the Lebo Shale, in contrast, thickens markedly from 2,000 to 2,500 ft in the eastern part of the basin to 7,000 ft and possibly as much as 10,000 ft along the basin trough (fig. 16), indicating from 5,000 to 8,000 ft of differential subsidence along the basin trough. Comparing this to the total amount of structural relief on the top of the Teapot (11,500–13,000 ft) indicates that the trough of the basin formed largely during this time period, which is largely Maastrichtian but includes a comparatively thin interval of rocks representing Paleocene time. In the southern part of the basin the interval includes as much as 250 ft of Paleocene basal sandstone of the Fort Union Formation, and in the northern part it includes the Bear Formation, an interval as much as 800 ft thick that is in part Maastrichtian and in part Paleocene. The thickness of this

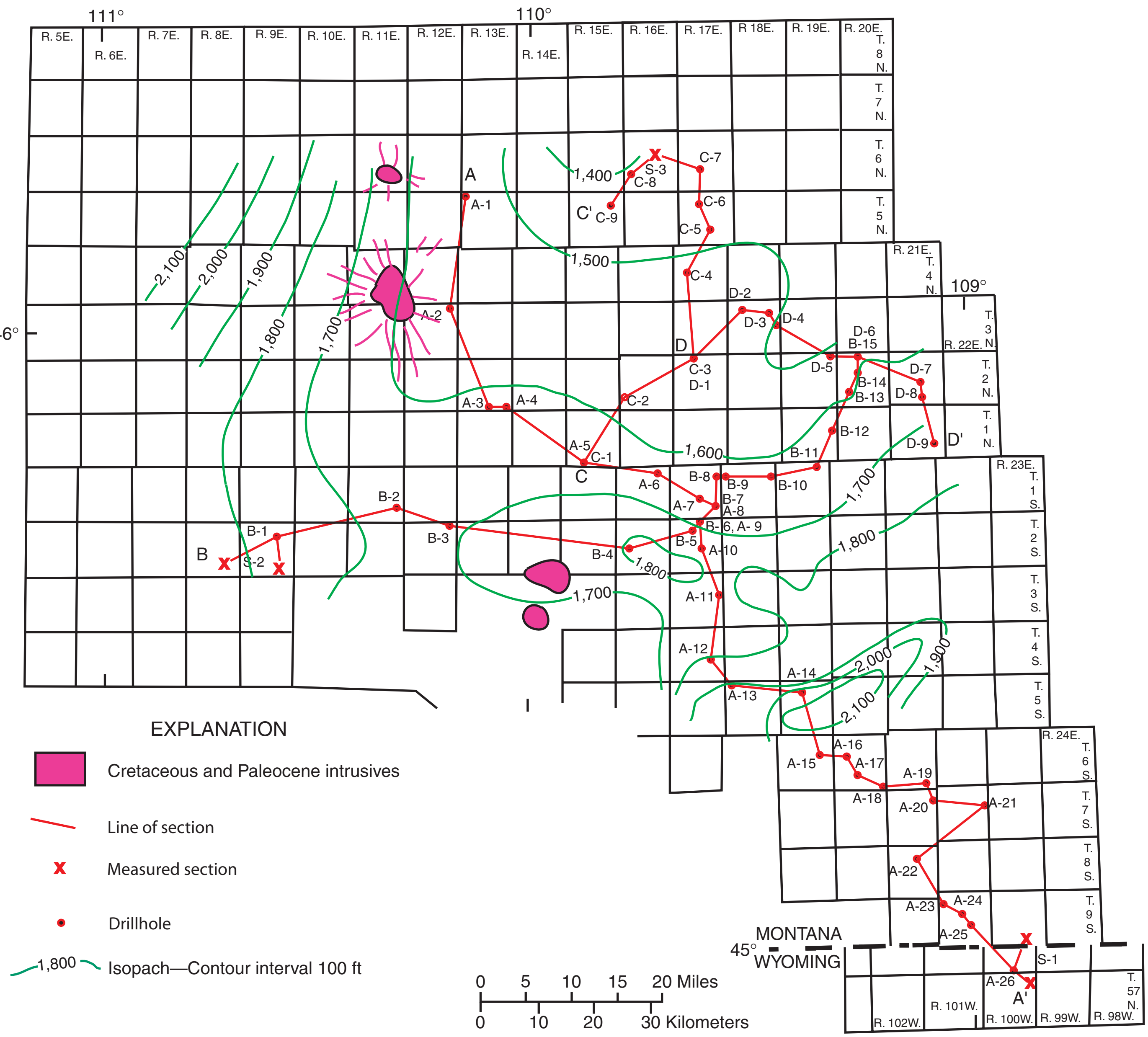

Figure 14. Isopach map of interval from top of Lower Cretaceous Mowry Shale to top of Upper Cretaceous Virgelle Sandstone Member of Eagle Sandstone, Crazy Mountains Basin, Montana. Contour interval 100 ft.

isopached interval along the basin trough is only approximate, being based primarily on surface mapping and surface sections. A thickness of 7,200 ft was estimated in the vicinity of Livingston in the southwest corner of the basin from surface sections described by Roberts (1972). Although the Teapot equivalent was not identified in the Livingston area, it appears to trace into Roberts' measured section at Livingston at about 4,300 ft above the base (pl. 2, Canyon Mountain composite surface section). Roberts (1972) measured 6,000 ft of Cretaceous Livingston Group above that horizon. In addition, a considerable thickness of the overlying Fort Union Formation is Maastrichtian in age. Roberts (1972) reported Cretaceous pollen 750 ft above the base of the Fort Union and probable Tertiary pollen 1,625 ft above the base. If it is assumed that the Cretaceous-Tertiary boundary occurs halfway between these two pollen sites, then there is roughly 1,200 ft of Cretaceous Fort Union Formation at Livingston. Thus, the measured thickness of the interval from the top of the Teapot equivalent to the Cretaceous-Tertiary boundary is about 7,200 ft where exposed in the Livingston area. Skipp and others (1999) showed the thickness from the top of the Judith River to the base of the Fort Union at between about 9,000 and 10,000 ft on their cross sections along the west margin of the basin north

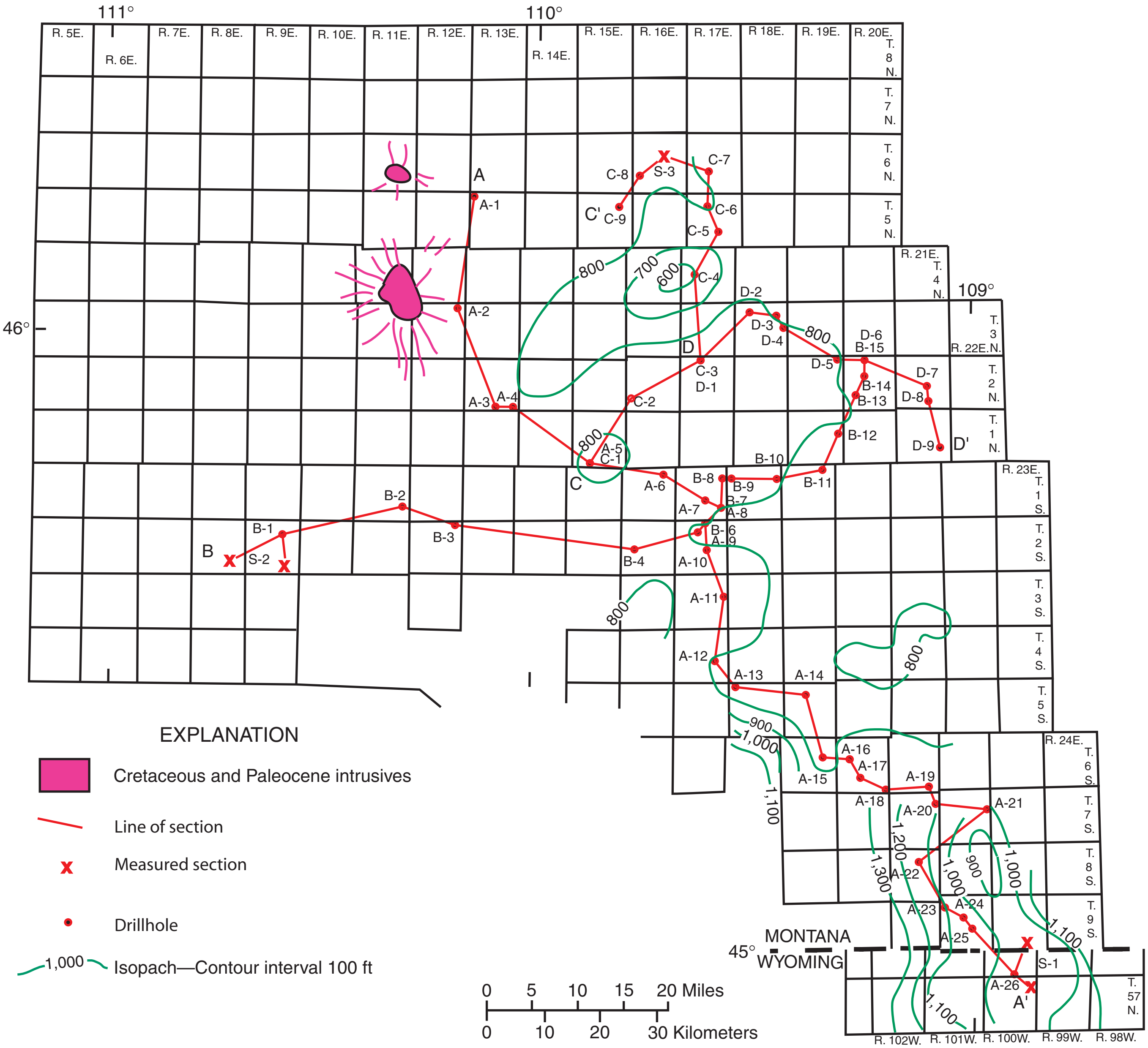

Figure 15. Isopach map of interval from top of Upper Cretaceous Virgelle Sandstone Member of Eagle Sandstone to top of Teapot Sandstone Member of Mesaverde Formation and Teapot equivalent, Crazy Mountains Basin and northernmost part of Bighorn Basin, Montana. Contour interval 100 ft.

of Livingston. The top of the Teapot equivalent there probably occurs within the upper part of the Judith River.

The trough of the Crazy Mountains Basin, therefore, appears to have formed largely in Maastrichtian time. This contrasts with the trough of the Bighorn Basin to the south that formed largely in Paleocene and Eocene time. Figure 17 is a map of the central Rocky Mountain region, modified from Johnson (2001), showing (1) thicknesses of selected largely Maastrichtian intervals, including that of the Maastrichtian isopach map presented in figure 16 and (2) age of oldest Paleocene rocks preserved. The isopach map of Maastrichtian rocks shown in the Bighorn Basin, which extends from the top of the Teapot Sandstone Member to the base of the Fort Union Formation, displays only a slight thickening toward the trough of the basin (fig. 18). The overlying Paleocene Fort Union Formation, in contrast, thickens generally toward the basin trough from less than 5,000 ft to more than 9,000 ft (fig. 18).

The contrast in styles of development of the Crazy Mountains and Bighorn Basins adjacent to the Beartooth uplift is apparent on the structure contour map on the top of the Teapot Sandstone Member and its equivalent. There is no evidence that a trough ever formed in the Crazy Mountains Basin adjacent to the uplift. The top of the Teapot dips gently away from the Beartooth uplift southwest of the Crazy

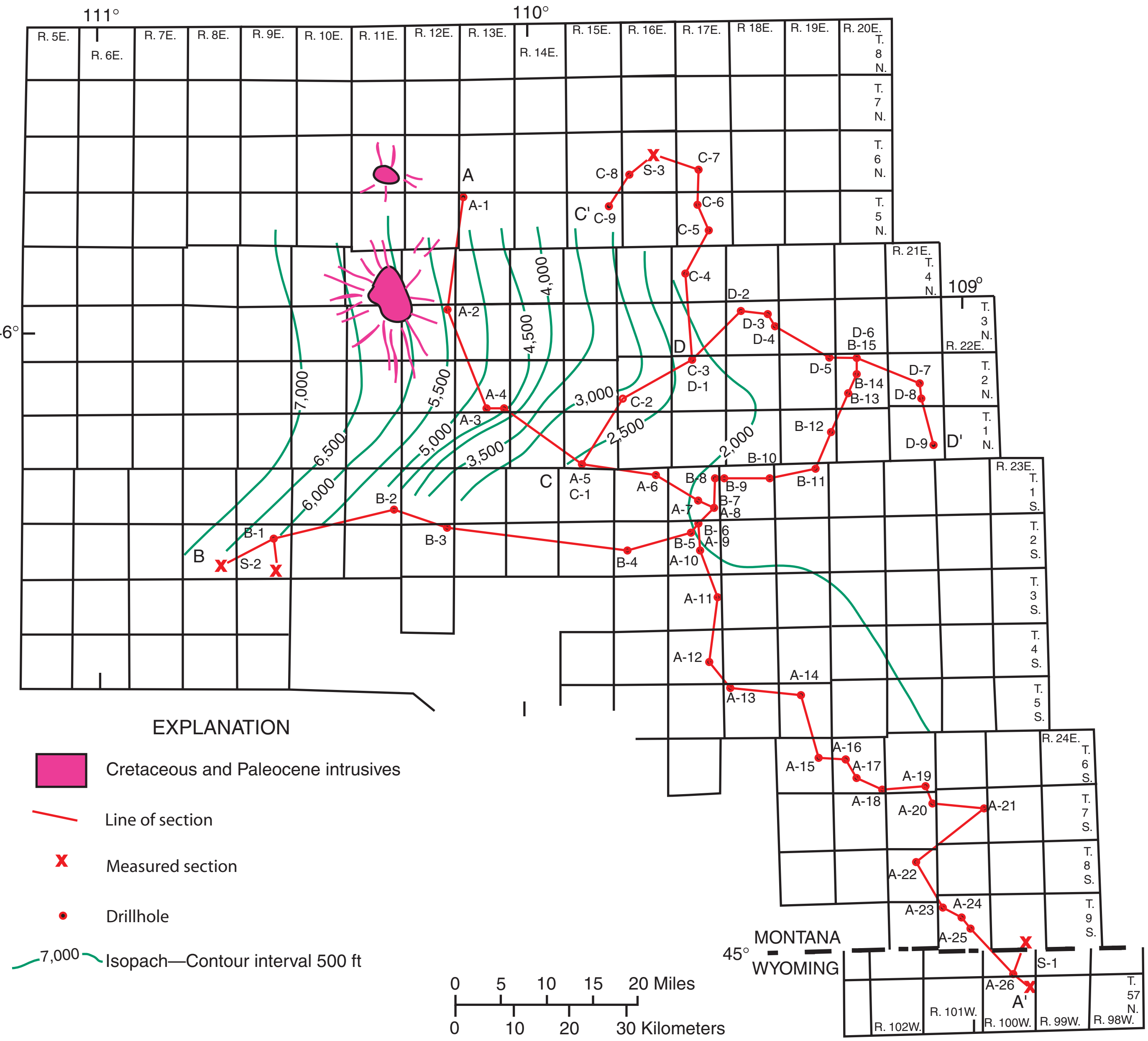

Figure 16. Isopach map of interval from top of Upper Cretaceous Teapot Sandstone Member and its equivalent to base of Paleocene Lebo Shale, Crazy Mountains Basin, Montana. Contour interval 500 ft.

Mountains Basin, from an elevation of about 6,000–7,000 ft along the mountain front to about 1,500 ft in the trough in the southern part of the basin (fig. 13). In the northern part of the Bighorn Basin, in contrast, a deep trough formed adjacent to the northeast, thrust-faulted margin of the Beartooth uplift (fig. 13), where the top of the Teapot reaches depths of more than 5,000 ft below sea level. The lack of subsidence in the Crazy Mountains Basin adjacent to the Beartooth Mountains may be related to the contrasting structural styles along the Beartooth uplift north and south of the Nye-Bowler lineament. The southwest flank of the Crazy Mountains Basin appears to be thrusted over the northwest flank of the Beartooth Mountains along a series of back thrusts (fig. 3) whereas the northwest flank of the Bighorn Basin appears to be overridden by the Beartooth Mountains thrust block.

Defining Basin-Centered Gas Accumulations in Rocky Mountain Basins

Basin-centered hydrocarbon accumulations are typically abnormally overpressured or abnormally underpressured with respect to regional hydrostatic gradients, and evidence for such pressure conditions is commonly cited as evidence that

Table 1. Depths in feet to selected stratigraphic horizons for Upper Cretaceous and lower Tertiary strata in Crazy Mountains Basin, Montana.

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ID	Operator	well name	twnsp	rng	sec.	1/4 sec.	KB	Jm	Kpr	Kk	bKgb	Kgb	Kd	Kcv	Kt	Kmd	clyspr	bKf	Kf	Kvg	Ktp	bKbp	bTful	coal	ID
1	Vanderbilt Res.	1 Shay	1 N	15 E	33	SW NW	4115	5815	5756	5560			5450		5240		4576	4605	4050	2320	1540			0	1
2	S.O.C. Develop.	1 Pederson	1 N	16 E	12	NW NE	5060	*6500		6192			6073		5853		5205	5305	4930	3688	2805	2350		0	2
3	Shenandoah Oil	1 Adkisson	1 N	17 E	1	SE NW	5082	*6220											4650	3450	2613	2205		0	3
4	MCOR 0&G	1-22 Lukkes	1 N	17 E	22	NW SE	4632	5840	5800	5635			5515		5300		4660	4770	4430	3074	2220	1782		8 bp	4
5	Aston & Fair	1 B.N.	1 N	18 E	7	NW NW	5018	*6100							5570		4918	5040	4545	3360	2528	2150		0	5
6	Champlin Pet.	1 Svenson 33A	1 N	18 E	8	NW SE	5006	*6090									4895	5034	4620	3320	2465	2170		0	6
7	U.S. Smelting	1 Pelton	1 N	19 E	13	SE SE	4941	5430	5395	5203			5095		4885		4256	4322		2618	1838	1425			7
8	Balcron Oil	21-6 Zindler	1 N	20 E	6	NE NW	4418													1862	1052	645		0	8
9	Belco Pet.	1 Zindler	1 N	20 E	18	SE NE	4789	*5255												2430	1650	1290		0	9
10	Johnson Oil	1 State	1 N	20 E	36	SW SW	4766	*5230					4895		4630		4000	4087		2295	1515	1110		0	10
11	L.H. Smith	1-Nordahl	1 N	21 E	2	SW NW	3992	*3960					3630		3350		2789	2880		1100	356			0	11
12	Dawson-Cramer	1 Kaufman	1 N	21 E	14	SE SE	4091	*4030					3700		3420		2870	2946		1150	410			0	12
13	West Gas	1-23 Hepp	1 N	21 E	23	SW NE	4155	*4065					3735		3453		2900	2980		1170	435			0	13
14	Great Basin	1 Hepp	1 N	21 E	23	NE SE	4173	*4100					3770		3488		2930	3010		1203	468			0	14
15	Oroco Oil	2 Keating-Hepp	1 N	21 E	25	SW NW	4172	*4060					3745		3467		2900	2999		1210	403			0	15
16	S.O.C. Develop.	1 Keating Ranch	1 N	21 E	26	NE NE	4196	4105	4071	3890			3775		3494		2938	3024		1220	470			0	16
17	Waggoner Expl.	1 Yellowstone Gr.	1 N	22 E	3	SE SW	3944	3900	3850	3666			3563		3355		2714	2805		915	215			0	17
18	Montana Power	4-11 Eastlick	1 N	22 E	11	NW NW	4012	3905	3860	3676			3575		3360		2726	2813		948	238				18
19	Montana Power	12-22 Leuthold	1 N	22 E	22	NW SW	4020	3845	3805	3645			3540				2700	2780		938	195			0	19
20	Harken O&G	1 Burns	2 N	13 E	34	NW SW	4768	9350	9310	9100			8990		8735		8022	8070	7710	6393	5555	4900	?	0	20
21	Gulf Oil	1 Big Timber	2 N	13 E	36	NW SE	4549	8840	8800	8590			8470		8235		7537	7580	7235	5903	5093	4437	?	8 e	21
22	West Gas	1-23 Arneson	2 N	15 E	23	NE NE	4586	*6900												3940	3072	2560		0	22
23	Molen Drilling	1-23 Fee	2 N	15 E	23	SE NW	4606	*6700												4003	3074	2593		0	23
24	Stanolind Pet.	1 Rapstad	2 N	15 E	31	SE SW	4120						6010				5150			3470	2610				24
25	Kissingern Pet.	8-30 Bookout	2 N	16 E	30	SE NE	4350	6410	6380	6180			6070		5854		5190	5310		3646	2820	2220		0	25
26	SOC Develop.	1 State	2 N	17 E	4	SE NW	4962	5980	5930	5732			5624		5424		4800	4842		3275	2448	1810		0	26
27	Farmers Union	11-1Wodrich	2 N	19 E	1	NE SW	4133	4245	4222	3976			3860		3653		2970	3060		1424	610			0	27
28	Shoreline Pet.	1 C. Christenson	2 N	19 E	3	NW NW	4160	*4255									2980	3070		1440	608				28
29	Shoreline Pet.	1 C.F. Kirchner	2 N	20 E	4	NE SW	4021	4015	3975	3795			3670		3472		2770	2870		1225	420			2 e	29
30	North. Nat. Gas	1 State "C"	2 N	20 E	16	NW	4063	4115	4075	3876			3765		3555		2853	2967		1295	482				30
31	US Smelting	1 Gee	2 N	20 E	29	NW NW	4107	4215	4167	3965			3855		3650		2968	3070		1380	600				31
32	Tenneco Oil	1 Flanagan	2 N	21 E	10	NW SE	3954	*3955									2740	2866		1127	350			0	32
33	North. Nat. Gas	1 Copulos	2 N	21 E	15	NW SE	3959	*3905									2696	2803		1055	310				33
34	Phillips Pet.	1 Copulos	2 N	21 E	18	NW SE	3957	*4105									2885	2994		1278	528				34
35	Superior Oil	71-22 Copulos	2 N	21 E	22	NE NE	3990	3955	3905	3730			3624		3350		2742	2870		1100					35
36	Holland-America	1 Castle	2 N	21 E	22	NW SE	4079	4030	3985	3800			3693		3415		2812	2930		1164	392				36
37	North. Nat. Gas	1 Nelles "A"	2 N	21 E	27	NW SE	3998	*3890									2762	2875		1110	350				37
38	West Gas	7-34 Dannenberg	2 N	21 E	34	SW NE	4054	4030	3990	3810			3700		3420		2822	2945		1162	398				38
39	Holland-America	1 L.L. Gray	2 N	21 E	34	NW SE	4041	4025	4000	3800			3693		3416		2817	2930		1162	404				39
40	SCAT Drilling	1 State	3 N	7 E	36	SE SW	5640	*8200												4926	3580			10 e	40
41	Amoco Prod.	1 McCombs	3 N	8 E	14	NW NE	5145																		41
42	Amoco Prod.	1 Robinson Rn.	3 N	8 E	31	NW NE	5490													4308	?			0	42
43	Chevron	1 Sonat Van Cleve	3 N	12 E	1	NW SW	5900	*13590													9672	9095			43
44	B. N. Inc.	13-32 Otter Cr.	3 N	15 E	32	NW SW	4500	*7150												4588	3820	3208		0	44
45	West Gas	5-8 Cremer	3 N	18 E	8	SW NW	4597	*4715												1903	1070	462		0	45
46	Texaco Inc.	1 B. R. Cremer	3 N	18 E	8	NE NE	4883	4200	4150	3945			3845		3640		2987	3080		1660	840				46
47	Balcron Oil	B.N. 43-11	3 N	18 E	11	NE SE	4579	4090	4060	3851			3737		3520		2833	2920		1412	617			3 e	47
48	Balcron Oil	Stimpson 14-13	3 N	18 E	13	SE SW	4418	3850	3797	3620			3500		3278		2602	2695		1135				0	48
49	Chevron USA	1 Sonat Largent	4 N	10 E	3	SW SE	6824																		49
50	West Gas	15-23 Cremer	4 N	16 E	23	SW SE	5098	*6700													3307	2920			50

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51	Concept Res.	12-4 Gugler	4 N	17 E	12	NE NE	4475	*4200					3840		3577		2910	2980	2680	1410	695			0	51
52	West Gas	13-17 Cremer	4 N	17 E	17	SW SW	4734	5000	4960	4735			4635		4418		3752	3810		2208	1620	1026		0	52
53	Cities Service	1 Cremer	4 N	17 E	17	SE NE	4854	4960	4910	4690			4590		4380		3750								53
54	Flank Oil Co.	1 Gjerde	5 N	8 E	24	NW SW	6151	3430	3395	3180			3046		2705			2220							54
55	Amoco Prod.	1 Gjerde	5 N	8 E	24	NW SW	6163	3368	3330	3185			3040		2705			2250	1660						55
56	Amoco Prod.	1 Kiff Ranch	5 N	9 E	7	SE SE	6558	3735	3705	3395			3255		2953										56
57	E.R.E.C.	Amer. Fork 23-6	5 N	13 E	6	NE SW	5736	*14000												11256	10400	9563			57
58	J.C. Trahan	Invest. Royal. 1	5 N	13 E	15	SE NW	?	?																	58
59	Montana Power	10-11 Cooney	5 N	15 E	11	NW SE	4726	7770	7754	7490			7357		7035		6435	6552		4973	4110	3465	1085	0	59
60	Concept Res.	9-12 Berg	5 N	17 E	9	NW SW	4363	*4385												1635	834			0	60
61	West Gas	2-27 Livestock	5 N	17 E	27	NW NE	4246	*4360												1503	738	217		0	61
62	Sinclair O&G	1 P.A. Sieg	5 N	18 E	2	SW NW	4104	2965	2915				2590		2365			1718	1680						62
63	Concept Res.	5-4 Tierney	5 N	18 E	5	NW NW	4147	3130	3060	2865			2730		2415			1910	1540						63
64	Amoco Prod.	1-R Kiff Ranch	6 N	8 E	27	SE SW	5610	6970	6950	6660			6550		6115		5546	5744							64
65	Amoco Prod.	1 Kiff Ranch	6 N	8 E	27	SE SW	5606										5516	5692		3380	2270				65
66	Naftzger, Barker	1 Glennie	6 N	14 E	20	NE NW	5113	3220	3190	2900			2790		2584		1970			590					66
67	L. Barker Jr.	1 State	6 N	15 E	2	SE NW	4818	445																	67
68	Montana Power	1-30 Cooney	6 N	16 E	30	NE NE	4550	7210	7160	6895			6800		6505		5914	6020	5870	4450	3507	3017	2202	0	68
69	Cities Service	1 Cooney	6 N	16 E	30	NE SE	4664	7320	7270	7005			6880		6570		5972	6070	5785	4527	3720	3113			69
70	Balcron Oil	1 Cooney	6 N	16 E	30	SE SE	4670														3785	3120			70
71	Amer. Climax	31-13 Cooney	6 N	16 E	31	SW SW	4702	*7400									6100			4640	3780	3230		0	71
72	Texaco Inc.	1 NP-H (NTC-1)	6 N	17 E	1	NW SE	3911	1990					1560		1340		640	750							72
73	Balcron Oil	1Storfa	6 N	17 E	11	NE NE	3921	1800					1370		1158		470	567							73
74	J.B. Brown	11-2 Storfa	6 N	17 E	11	NE NE	3960	1840					1405		1195		510	610							74
75	Texaco Inc.	1 H.K. Griffith	6 N	17 E	12	NE NW	3914	1820					1395		1180		492	595							75
76	J.B. Brown	12-2 Griffith	6 N	17 E	12	NE NW	3907	1800	1740				1376		1160		477	575							76
77	J.B. Brown	12-6-17 Griffith	6 N	17 E	12	NW SW	3982	1845	1800				1403		1195		520	595							77
78	H.D. Hadley	21-14 Gaarder	6 N	17 E	21	SE SW	4214	*4530									3230	3310		1743	948				78
79	Texota Oil	1 Baker	6 N	18 E	15	NW NW	4183	3460	3380				3053		2830		2148	2216		678					79
80	Seaboard Oil Co.	43-22 State	6 N	18 E	22	SE NW	3869	3065	3005				2670		2452		1867	1800		320					80
81	West Gas	9-34 State	6 N	18 E	34	SE	4045	*2935									1670								81
82	Concept Res.	28-8 Golden Valley	6 N	19 E	28	SE NE	3895	2880	2840	2643			2510		2254		1616	1667	1320						82
83	Seaboard Oil	2-20 Ice	6 N	20 E	20	NW NW	3661	2955		2690			2575		2320										83
84	Medders Oil	1 Keefer-Rusmak	6 N	20 E	27	NE NE	3845	2870		2620			2505		2238										84
85	Elenburg Expl.	1 Fiske	6 N	20 E	33	NW SW	4022	2800	2740				2420		2150			1635	1250						85
86	W.D.I. Norris	1 Federal	7 N	13 E	28	NE SE	5164	1445	1385				970		720										86
87	Montana Power	3-18 Anderson	7 N	16 E	8	NE NW	4309	1860					1380		973										87
88	Pan Am Pet.	1 State-C	7 N	17 E	36	NW SW	3987	1935	1877				1506		1285		577	685							88
89	Mon-O-Co. Oil	1 Erickson	7 N	18 E	24	NW NW	3927	2240	2165				1893				1016	1115							89
90	Cities Service	A-1 Shawmut-BN	7 N	19 E	9	SW NE	3973	*2493					2145		1924		1317	1360							90
91	Mon-O-Co. Oil	1 N.P.R.R.	7 N	19 E	19	NW NW	4075	2538	2480				2190		1947		1330	1400							91
92	Superior Oil	22-25 Windsor	1 S	11 E	25	SE NW	4697	6000	5820	5610			5485		5230		4650	4830	4320	1830	1050			12 e	92
93	Amerada/Mobil	1 Hoefle-Govt.	1 S	16 E	2	SW SW	4444	5792	5753	5554			5405		5210		4570		4190	2912	2100				93
94	Concept Res.	6-12 Fraser	1 S	17 E	12	SE SW	4207													2829	1845	1030		0	94
95	McCulloch Oil	1-22 Mayo	1 S	17 E	22	NE SE	4186	5605	5568	5390			5250		5040		4372	4483	4135	2740	1945	0			95
96	McCulloch Oil	1-25 Bare	1 S	17 E	25	NW NW	3846	5295	5240	5070			4950		4730		4100	4175	3840	2432	1622			0	96
97	Montana Power	7-33 Bue	1 S	17 E	33	SW NE	3822	5140	5090	4875			4780		4566		3930			2237	1432			0	97
98	Belco Pet.	1 Nellie Van Oosten	1 S	18 E	1	SE SW	4125	*5385													1715	812			98
99	Mountain States	7-1 Stevens	1 S	18 E	7	NE NE	4062	5465											3980	2645	1796	880		0	99
100	Shell Oil	12-12 Schmitt	1 S	18 E	12	SW NW	4071	5325	5270	5090			4975		4760		4095		3790	2478	1660	845		0	100

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101	Belco Pet.	1 Bokma	1 S	19 E	2	SW NW	4531	*5465												2530	1800	907			101
102	Belco Pet.	1 Nelson	1 S	20 E	34	NE NE	4407	*5035												2143	1410			0	102
103	Shenandoah Oil	1-A Keating Ranch	1 S	21 E	4	NE SE	4230	4406	4370	4180			4070		3860		3213	3315		1462	710			0	103
104	Concept Res.	1-16 State	1 S	21 E	16	NE	4204	*4500					4105		3888		3250	3344		1487	742			0	104
105	Shoreline Pet.	1 Keating, etal	1 S	21 E	21	NE NW	4181	*4501									3310	3400		1558	758				105
106	Great Northern	1 Lackman	1 S	22 E	15	SE SW	3807	*3509					3310		3100		2462	2550		640					106
107	Y.V.C. Inc.	1 Lackman	1 S	22 E	24	SE NE	4171	*3855							3235		2596	2686	2237	770				0	107
108	Great Northern	2 Lackman	1 S	22 E	29	NW NW	3817	*3820									2652	2737		843					108
109	J. Burns Brown	2 Lackman	1 S	22 E	30	SE NE	3888	*3920									2750	2832	2410	940				5 e	109
110	Sohio Pet.	1-3 Moats	2 S	6 E	1	NE NW	5234	9550	9520	9290			9150		8695		8282		7430	5836	4716			3 e	110
111	Montana Power	1 Strong	2 S	9 E	11	SE SW	4684	6100	6065	5800			5663		5332		4583	4825	4420	2680	1873				111
112	Montalban	1 Larkin Bros.	2 S	11 E	27	NE SE	6286	3670	3608	3392			3244		2932		2372	2370	4194						112
113	Amer. Minerals	1 Burlington N.	2 S	12 E	1	NE NE	4939	4350	4310	4105			3970		3725		3100	3133	2785	1418	603			0	113
114	Sun Expl.	12-14 Federal	2 S	15 E	12	SE SW	5316													3020	2120				114
115	Mountain States	8-11 Strobel	2 S	16 E	8	NE SW	4542	*5340											3750	1903	1020			2 e	115
116	Sun Expl.	10-2 Hausserman	2 S	16 E	10	NW NE	4183	*5300		5552			4933		4620		4055		3660	1897	1035			0	116
117	Amoco Prod.	1 Mothershead	2 S	16 E	20	NW NE	4396	4970	4920	4760			4622		4310		3743	3800	3350	1920	1068			2 e	117
118	Sun Expl.	32-7X 2	S	16 E	32	SW NE	4677	5400	5369	5200			5049		4860		4177	4261	3870	2405	1528			0	118
119	Montana Power	8-2 Booth	2 S	17 E	2	SE NE	4027	*5420									4230	4310	3850	2005	1230			0	119
120	Montana Power	7-3 Mysse	2 S	17 E	3	SW NE	4246	*5580									4387	4460	4010	2710	1940			0	120
121	Mountain States	9-12 Bue	2 S	17 E	9	NW SW	4050	*5450					5130		4916		4257	4340	3895	2282	1486			0	121
122	True Oil	41-22 Swift	2 S	17 E	22	NE NE	4736	6210	6164	5990			5864		5660		5004	5080	4610	3255	2450			0	122
123	Mayco Expl.	32-20 Daggett	2 S	19 E	20	SW NE	4240	5750	5710	5536			5420		5197		4587	4573	4250	2867	2087	1300		2 e	123
124	Concept Res.	1-27 Federal	2 S	19 E	27	NE NE	3993	*5340												2450	1630	845		0	124
125	J. P. Dever	1 L.B. Habein	2 S	19 E	32	NW SW	4413	*6050												3130	2345	1498			125
126	Continental Oil	1 Govt.	2 S	19 E	33	SE NE	4384	5910	5870	5710			5584		5370		4740		4360	3000	2225	1345			126
127	Sinclair O&G	1 State	2 S	19 E	36	NW NE	3776	5095	5047	4830			4714		4487		3920		3510	2106	1320	518		0	127
128	J.H. Snowden	1 Vander Mulen	2 S	20 E	23	NE SW	3697	*4530												1600	778				128
129	Gulfstream Pet.	1 Garnet Cary	2 S	21 E	11	SE SE	4252	4380	4346	4150			4050		3890		3245	3292		1393	632			0	129
130	SOC Develop.	1 Bertha Peterson	2 S	21 E	11	SW SE	4231	4380	4360	4155			4054		3850		3262	3297	2873	1400	604			0	130
131	Halbert	1 Peterson	2 S	21 E	12	SE SE	4390	4430	4405	4205			4103		3890		3305	3340	2935	1442	660				131
132	J-W Oper.	1 Bertha Peterson	2 S	21 E	15	NE NE	4276	*4510									3394	3425	3010	1530	772			0	132
133	Snowden	1 Murane	2 S	21 E	19	SE SW	3891	4540	4500	4330			4220		4010		3440	3410	2985	1580	785				133
134	Daube Expl.	1-7 Kober Farms	2 S	22 E	7	SE SW	4319	4326	4298	4130			4005		3790		3205	3240	2820	1340	555				134
135	Montalban Oil	1 NP	3 S	12 E	5	SW SE	5760	1775	1720				1340		1040			520							135
136	Amerada Pet.	1 P.E. Hedrick	3 S	16 E	11	NW SE	5262	6210	6190	5970			5860		5544		4955	5053	4599	3210	2423	vol.	vol.		136
137	Shoreline Pet.	1 Govt.	3 S	16 E	29	NW SE	5418	5545	5500	5355			5182		4974		4268	4445		flt.	vol	vol.	vol.		137
138	Smokey Oil Co.	31-35 Bailey	3 S	16 E	35	NE NW	5379	*5750		5522			5400		5194		4520	4610	4157	2908	2147	vol.	vol.		138
139	True Oil	32-13 Ostrum	3 S	17 E	13	SW NE	4559	6210	6170	5995			5860		5650		4970	5054	4590	3205	2345				139
140	Alantic Richfield	1-23 Knee Tremb.	3 S	20E	23	SW SE	4601	5750	5704	5525			5400		5190		4590	4700	4203	2755	2003	1232			140
141	J-W Operating	1 C.H. Thompson	3 S	21 E	8	NE SW	3810	*4530									3340			1180	550				141
142	Klabzuba Oper.	1 Skibstad	3 S	21 E	30	NE SW	4199	5180	5148	4986			4855		4630		4033	4117	3626	2150	1353	743			142
143	J-W Operating	1 H.A. Lenning	3 S	21 E	32	SW NE	4474	5345	5302	5143			5025		4803		4208	4250	3840	2330	1285	730			143
144	J-W Operating	1 G.A. Golden	3 S	22 E	21	NE SW	4017	*3825										2692							144
145	Deerfield Oil	1 Bain-Federal	3 S	23 E	29	SW NW	3912	*2805		2545			2435		2210			1640	1145						145
146	McAlester Fuel	1-A Cooper	3 S	23 E	34	SW SW	3652	*1990					1585		1365										146
147	Shoreline Pet.	1 Govt.	4 S	15 E	3	SW SE	5982	4770	4725	4520			4406		4190		3530	3590		vol.	vol.	vol.	vol.		147
148	Anadarko Prod.	Fed. "AD" 1-25	4 S	15 E	25	NE NE	5144	3255	3190		3016	2980	2863	2863	2650		1900	1990	1610						148
149	Gulf Oil	1 Carlisle	4 S	16 E	15	NE SE	4687	4095	4060	3850			3738		3525		2800	2950		1165				5 e	149
150	Montana Power	1-36 State	4 S	16 E	36	NW NW	5307	4150	4105				3770		3560		2850	2960	2330	1150					150

Table 1. Depths in feet to selected stratigraphic horizons for Upper Cretaceous and lower Tertiary strata in Crazy Mountains Basin, Montana.—Continued

[twnsp, Township; rng, Range; sec., Section. KB, Kelly bushing elevation, in feet. Abbreviations of stratigraphic horizons: Jm, Jurassic Morrison Formation; Kpr, Pryor Conglomerate Member of Cretaceous Kootenai Formation; Kk, Cretaceous Kootenai Formation; bKgb, base of Greybull Sandstone Member of Cretaceous Cloverly Formation; Kgb, Greybull Sandstone Member of Cretaceous Cloverly Formation; Kd, Cretaceous Dakota Formation; Kcv, Cretaceous Cloverly Formation; Kt, Cretaceous Thermopolis Shale; Kmd, Cretaceous Muddy Sandstone; clyspr, Clayspur bentonite; bKf, base of Cretaceous Frontier Formation; Kf, Cretaceous Frontier Formation; Kvg, Virgelle Sandstone Member of Cretaceous Eagle Sandstone; Ktp, Cretaceous Teapot Sandstone Member and its equivalent; bKbp, base of Cretaceous Bearpaw Shale; bTful, base of Tertiary Fort Union Formation. Coal thicknesses (in feet) estimated from geophysical logs; abbreviations of coal-bearing formations: bp, Bearpaw Shale; e, Eagle Sandstone; jr, Judith River Formation; m, Meeteetse Formation; Tfu, Fort Union Formation]

ID	Operator	well name	twnsp	rng	sec.	1/4 sec.	KB	Jm	Kpr	Kk	bKgb	Kgb	Kd	Kcv	Kt	Kmd	clyspr	bKf	Kf	Kvg	Ktp	bKbp	bTful	coal	ID
151	Sunray Oil	1 White Deer	4 S	17 E	13	SE NW	4587	*5740		5494			5375		5164		4502	4558	4205	2768	1958			3 e	151
152	Phillips Pet.	1 Pearson "A"	4 S	17 E	19	NW SE	4783	4375	4330	4156			4020		3810		3100	3220	2704	1100	250				152
153	Cockrell Corp.	23-1 Johnson	4 S	17 E	23	NE SE	4797	5350	5315	5130			5000		4787		4085	4220	3800	2250	1380	vol.		0	153
154	McCulloch Oil	Redle 1-1	4 S	19 E	1	NE NE	4130	6040	5988	5823			5700		5484		4850	4972	4483	2990	2233	1405		0	154
155	Arco Expl. Co.	1-6 Deadpan Draw	4 S	19 E	6	SW SE	4413	6715	6682	6500			6370		6164		5498	5660	5090	3710	2920			5 e	155
156	Texas Co.	1 Unit	4 S	19 E	10	SE NW	4608	6770	6725	6565			6445		6230		5708		5170	3760	3030				156
157	Continental Oil	1 Dickinson	4 S	19 E	20	NE NW	4362	*5900												flt.	flt.				157
158	Tyler-Forest	Arthum 35-16	4 S	19 E	35	SE SE	4811	7350									6230		4335	flt.	flt.				158
159	North. Nat. Gas	NP 1-A	4 S	20 E	9	NW SE	4584																		159
160	Energy Reserves	1 J. Rouane	4 S	20 E	14	NW NE	4608	*6165									5035		4620	2920	2165	1575		2 e	160
161	J.P. Deaver	Strat. test #2	4 S	20 E	14	SW SW	4723	*6435												3380	2548	1860	270		161
162	Arco Expl. Co.	Grayburg 1-20	4 S	20 E	20	SE NW	4718	6745	6710	6570			6420		6210		5580	5546	5205	3690	2862	2240	710	0	162
163	Amoco Prod. Co.	D.O. Baldwin	4 S	20 E	22	NW NE	4742													3240	2375			2 e	163
164	McCulloch Oil	1-6 Krueger	4 S	21 E	6	NW NW	4697	5840					5507		5293		4686		4302	2840	1812	1300		0	164
165	Energy Reserves	1 Clyde Finley	4 S	21 E	11	NE SE	4536	5060	5007	4853			4726		4510		3937	3900	3470	1990	1195	797		0	165
166	Energy Reserves	1 Anderson	4 S	21 E	12	NE NW	4218	4610	4580	4420			4297		4035		3495	3540	3040	1564	755			0	166
167	J.W. Operating	1 USA-15	4 S	21 E	15	NE NE	4728	5440	5400	5253			5125		4903		4340	4285	3908	2404	1606	1115		3 e	167
168	McCulloch Oil	1-5 Descheemacker	4 S	22 E	5	SW SW	3993	4045	4008	3860			3723		3420			2955	2463						168
169	Breuer & Curran	1 A. Olson	4 S	23 E	2	NW NE	3454	*1350		1120			980		755			170							169
170	Breuer & Curran	2 Olsen	4 S	23 E	2	NW NW	3474	*1530					1164		945			370							170
171	Alco O&G	1 Knox Gibson	4 S	23 E	2	SE SW	3500	*1430					1065		840			255							171
172	L.A. Garner	1 Schoessier	4 S	23 E	4	SW NE	3592	*2000					1632		1417			842							172
173	Y.V.C. Inc.	1 Newton	4 S	23 E	21	NE NE	3678	*2010		1760			1640		1410			840	360						173
174	Mule Creek Oil	1-434 Govt. Hill	5 S	16 E	4	NE SE	5125	2610	2550		2340	2320	2205	2205	1968										174
175	E. Amer. Energy	1 Ostrum	5 S	16 E	12	SE SE	5249	2755	2720		2512	2480	2372	2372	2170			1540	1147						175
176	E. Amer. Energy	1 Rickman	5 S	16 E	13	NE NW	5287	2360	2310		2120	2087	1971	1971	1770			1140	755						176
177	L. Barker Jr.	2 Kennedy-Bahr	5 S	16 E	13	SE NE	5274	2300	2260		2053	2020	1920	1920	1690			1120	650						177
178	Turner Smith	7-15 Weast	5 S	17 E	7	SW SE	5175	3010	2973		2772	2750	2636	2636	2413		1712	1810	1392						178
179	E. Amer. Energy	3 Kelier	5 S	17 E	17	NW SW	5209	2670	2630		2413	2377	2272	2272	2065		1356	1440	1032						179
180	Farmers Union	12X-17 Larson	5 S	17 E	17	SW NW	5241	*3010			2760	2720	2616	2616	2400		1680	1773	1360						180
181	Farmers Union	34-17 Larson	5 S	17 E	17	SW SE	5460	*3010			2760	2743	2640	2640	2410		1773	1850	1383						181
182	Tyler Oil Co.	2 Orr	5 S	17 E	18	SE SE	5255	2400	2352		2144	2107	2003	2003	1790		1057	1145	611						182
183	L. Barker Jr.	1 Tyler-Orr	5 S	17 E	18	NW SE	5291	2330	2280		2080	2055	1943	1943	1740	1700	1062		650						183
184	Gary-Williams	20-1 O'Brien	5 S	17 E	20	NE NE	5535	2995	2968		2840	2802	2700	2700	2480		1789	1875	1437						184
185	Turner Smith	21-6R Keller	5 S	17 E	21	SE NW	5835	3560	3535		3305	3285	3180	3180	2975		2225	2353	1882	300					185
186	E. Amer. Energy	1Leithead	5 S	17 E	26	SW NE	5174	3630	3602		3368	3322	3210	3210	3002	2988	2288	2370	1910						186
187	McElroy Ranch	1-30 Govt.	5 S	17 E	30	SE SW	5681	2510	2483		2267	2255	2140	2140	1934		1183	1270	880						187
188	E. Amer. Energy	1 Keller	5 S	17 E	32	SE NE	5541	2400	2378		2170	2135	2036	2036	1845		1188	1210	790						188
189	High Valley Inv.	1 Eggen	5 S	17 E	33	SE SE											1346								189
190	Cockrell Corp.	6-1 Edwards	5 S	18 E	6	SE NE	4726	5260	5220	5030			4896		4680		4023	4127	3640	1878	1053				190
191	E. Amer. Energy	2 George	5 S	18 E	32	NE SW	5388	*3210			2950	2934	2841	2841	2660	2630	1930	2060	1630						191
192	E. Amer. Energy	4 George	5 S	18 E	32	SW SW	5469	2950	2916		2770	2745	2643	2643			2065	2105	1646						192
193	Devel. Services	1 George	5 S	18 E	32	SE SW	5473	2865	2804		2636	2614	2513	2513	2320	2310	1823	1905	1440						193
194	Coquina Oil	1 Ostrum	5 S	19 E	2	SE SW	4914	7680	7617	7446			7340		7120		6500	6570	6037	3757	3165	no	1480	0	194
195	Tipperary O&G	1 H.C. Ostrum	5 S	19 E	9	SE SE	5041	*7960									6790	6845	6285	4450	3580	no	1610	0	195
196	Arco Expl.	1-7 Devil's Tail	5 S	20 E	7	SE NW	4476	7090	7065	6832			6755		6540		5930	6000	5447	3808	3120	no	970	?	196
197	L. Barker Jr.	16-16 State	5 S	20 E	16	SE SE	4468	*7040												3855	3125	no	918	5 e	197
198	McCulloch Oil	1-11 Kelly	5 S	21 E	11	NE NW	4267	5445	5410	5293			5121		4910		4195	4366	3840	2350	1570	795		4 e	198
199	Great Northern	31-11 Devries	5 S	21 E	11	NW NE	4318													2355	1603	808			199
200	Cardinal Pet.	1 Ward	5 S	22 E	26	SW NE	3936	4040		3878			3770		3530			3050	2552						200

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ID	Operator	well name	twnsp	rng	sec.	1/4 sec.	KB	Jm	Kpr	Kk	bKgb	Kgb	Kd	Kcv	Kt	Kmd	clyspr	bKf	Kf	Kvg	Ktp	bKbp	bTful	coal	ID
201	J-W Operating	1 USA-34	5S	22 E	34	SE NW	4109	*4850					4580		4490			3845	3340						201
202	Brown, Pickrell	1 Goodman	5 S	23 E	29	NE NW	3549	*2280		2013			1910		1680										202
203	Tyler Oil Co.	2-16 Henderson	6 S	18 E	2	SE SE	5068	4400	4370		4156	4130	4055	4055	3853	3840	3292	3365	2840	1302	265				203
204	Breuer & Curran	1 Snyder	6 S	18 E	3	NE NW	5078	3360	3320		3104	3094	2986	2986	2785	2774	2134	2240	1746						204
205	Shell Oil	Brown Foothills 1	6 S	18 E	4	NW NW	5240	2510	2460		2300	2270	2180	2180	2035	2026	1410	1475	1103						205
206	E. Amer. Energy	6 George	6 S	18 E	5	NW NE	5425	2830	2799		2672	2625	2557	2557	2434	2420	flt	2000							206
207	MGF Oil Co.	31-27 Nicholson	6 S	18 E	27	NW NE	5405	8870	8837		8602	8607	8504	8504	8313		7628	7668	7323	5450	4293				207
208	Montana Power	7-14 Bowlen	6 S	19 E	14	SW NE	4829	8720	8685		8468	8484	8375	8375	8200	8190	7572	7675		5795	4950		2250	3 e, 5 m	208
209	L. Barker Jr.	8-7 Koski	6 S	20 E	8	SW NE	5021	*8130												5560	4507		2445	2 e	209
210	Cabeen Expl.	1 McCune-Fox Cr.	6 S	20 E	14	NE SE	4961	8690	8644	8460			8340		8150		7508	7686	7073	6120	5050		3010	3 e	210
211	Equity Oil	14-17 Castagne	6 S	20 E	17	SE SW	5050	*9110					8760	8760			7982	8010		6000	5310		3350		211
212	J.W. Pace	1 Jaaksi	6 S	20 E	21	SE SW	5020														5120		3145		212
213	True Oil	11-25 Boyd	6 S	20 E	25	NW NW	5000	*9230												5683	4987		2818	0	213
214	T.C. Huddle, G.N.	1 Olcott	6 S	20 E	25	SE SW	5052	*7610			7386	7360	7263	7263	7036		6318	6383	5843	4000	3523		1128		214
215	Phillips Pet.	1-A Louma	6 S	20 E	28	NW NE	5126	9620	9580		9325	9310	9230	9230	9010		8370	8410	7890	6108	5222		2732		215
216	K.D.Luff	1 Spencer	6 S	20 E	35	NE NW	5184	*8250												4490	3637		1795	3 e	216
217	Tyler Oil Co.	1 Vickers	6 S	20 E	36	NE NW	5091	*7580			7374	7350	7250	7250	6997		6316	6300	5853	3750	2790				217
218	Cotton Pet.	1-7 Matthews	6 S	21 E	7	SW SW	4796	*8210												5026	3932	3818	2452		218
219	Montana Power	16-21 Robinson	6 S	21 E	21	SE SE	4849	8260	8220	8070			7931		7716		7073	7176	6666	5255	4372	no	2516	11 e	219
220	Montana Power	16-22 Robinson	6 S	21 E	22	SE SE	4874	8080	8035				7770		7550		6900	6915	6450	4847	4180	no	1995	10 e	220
221	May Pet.	1-28 Edwards	6 S	21 E	28	SW NE	5062	8655	8624	8490			8320		8104		7462	7570	7052	5360	4555	no	2112	3 e	221
222	Montana Power	13-29 Hamburg	6 S	21 E	29	SW SW	5164										6364	6490	5970	4270		no	2037	6 e	222
223	Montana Power	1-31-6-21 Croft	6 S	21 E	31	SW NE	5137														3600	no	1225		223
224	Montana Power	5-32-6-21 Croft	6 S	21 E	32	SW NW	5275	7175	7073		6870	6855	6750	6750	6535		5883	6003	5477	4630	3785	no	1650	2 jr	224
225	Helmerich & Payne	1-33 Fed. Croft	6 S	21 E	33	NW SW	5276	6900	6890		6600	6580	6480	6480	6280		5658	5738		3388	2490	no			225
226	Empire State	1 - Federal	6 S	21 E	34	NE SE	4505	*8015												4497	3570	no	1002		226
227	Argo Oil	1 NPRR	6 S	21 E	35	NE SW	4517	8125	8034		7900	7830	7723	7723	7490		6895	6945	6447	4630	3743	no	1368		227
228	McAlester Fuel	1 Govt.	6 S	22 E	1	NE NW	3878	3770					3450		3225		2585		2078	flt.	1280	no			228
229	L. Barker Jr.	6-2 Tolman	6 S	22 E	6	NW NE	4380	*5600												3263	2525	no	490	6 e	229
230	Montana Power	1-15-6-22 Rapp	6 S	22 E	15	NE NE	4056	5115	5090	4903			4790		4563		3975	3970	3365	1700	873				230
231	Farmers Union	2X-17 Baker	6 S	22 E	17	NW NE	4864	6785	6754	6584			6474		6270		flt.	5643		4420	3580	no	2117	10 e	231
232	Montana Power	3-29 Formanack	6 S	22 E	29	NE NW	4161										5370		4890	3170	2358	no	no	5 e	232
233	L. Barker Jr.	23-4 Olcott-Foard	7 S	20 E	23	NW NW	5453														6845		4540		233
234	Flare Energy	1-1 BN	7 S	21 E	1	SW NW	4312	*6380							5840		5110	5010	4910	3210	2664	2160	1127		234
235	Montana Power	5-2 Federal	7 S	21 E	2	SW NW	4313													2970	2195	1320			235
236	Montana Power	5 Chapman	7 S	21 E	2	SW SW	4279																		236
237	Ohio Oil	24 Chapman	7 S	21 E	2	SE SW	4197	5510	5396		5220	5210	5107	5107	4885		4244	4350	3754	3277	2550	1630			237
238	Montana Power	1 Dry Creek Deep	7 S	21 E	3	NW NW	4451	5850	5780		5610	5570	5466	5466	5260		4695		4237	2535			335		238
239	Montana Power	16-3 Robinson	7 S	21 E	3	SE SE	4338							3						2610	1760	942			239
240	Montana Power	8-4-7-21 Bowman	7 S	21 E	4	SE NE	4553																		240
241	Montana Power	8-4 Bowman	7 S	21 E	4	SE NE	4553													2650	1768	1150			241
242	Quadra O&G	5-1 Quadra	7 S	21 E	5	NE NE	5170	*6940			6660	6638	6542	6542	6330		5650	5730	5163	3340	2470	1750			242
243	Montana Power	1-10 Mont. Ind.	7 S	21 E	10	NE NE	4273	5630			5375	5350	5240	5240	5030		4382	4460	4000	2480	1696				243
244	Montana Power	4-11 Chapman	7 S	21 E	11	NW NW	4218	*5500			5247	5237	5132	5132	4920		4230	4332	3760	2860	2350	1650			244
245	Montana Power	4-12 Mont. Ind.	7 S	21 E	12	NW NW	4136	*5640	5590		5408	5398	5297	5297	5085		4470		3982	2230	1340	905			245
246	Pubco-Amax	1 Federal	7 S	21 E	14	SW NE	4266										5352		4870	3038	2180	1363			246
247	Montana Power	10-4 Nelson	7 S	22 E	4	NW SE	3998	6905	6820		6637	6612	6513	6513	6305		5900		5427	3753	2880	2155			247
248	Cardinal Pet.	9-7 Federal	7 S	22 E	7	NE SE	4073	5950	5890		5705	5683	5592	5592	5377		4703		4282	2490	1468				248
249	Phillips Pet.	12-8 Federal-M	7 S	22 E	8	NW SW	4027													2697	1790	no			249
250	Montana Power	13-9 Romano	7 S	22 E	9	SW SW	3940	*6830					6480	6480	6270		5692		5253	3445	2575	no	no		250

Table 1. Depths in feet to selected stratigraphic horizons for Upper Cretaceous and lower Tertiary strata in Crazy Mountains Basin, Montana.—Continued

[twnsp, Township; rng, Range; sec., Section. KB, Kelly bushing elevation, in feet. Abbreviations of stratigraphic horizons: Jm, Jurassic Morrison Formation; Kpr, Pryor Conglomerate Member of Cretaceous Kootenai Formation; Kk, Cretaceous Kootenai Formation; bKgb, base of Greybull Sandstone Member of Cretaceous Cloverly Formation; Kgb, Greybull Sandstone Member of Cretaceous Cloverly Formation; Kd, Cretaceous Dakota Formation; Kcv, Cretaceous Cloverly Formation; Kt, Cretaceous Thermopolis Shale; Kmd, Cretaceous Muddy Sandstone; clyspr, Clayspur bentonite; bKf, base of Cretaceous Frontier Formation; Kf, Cretaceous Frontier Formation; Kvg, Virgelle Sandstone Member of Cretaceous Eagle Sandstone; Ktp, Cretaceous Teapot Sandstone Member and its equivalent; bKbp, base of Cretaceous Bearpaw Shale; bTful, base of Tertiary Fort Union Formation. Coal thicknesses (in feet) estimated from geophysical logs; abbreviations of coal-bearing formations: bp, Bearpaw Shale; e, Eagle Sandstone; jr, Judith River Formation; m, Meeteetse Formation; Tfu, Fort Union Formation]

ID	Operator	well name	twnsp	rng	sec.	1/4 sec.	KB	Jm	Kpr	Kk	bKgb	Kgb	Kd	Kcv	Kt	Kmd	clyspr	bKf	Kf	Kvg	Ktp	bKbp	bTful	coal	ID
251	Montana Power	13-10 Federal	7 S	22 E	10	SW SW	3933	6380			6104	6085	6005	6005	5810		5152		4683	3210	2310	no	835		251
252	Montana Power	8-11 Merrill	7 S	22 E	11	SE NE	3859	*5870					5470	5470	5334		4760	4693	4280	2727	1810	no			252
253	Montana Power	2-12-7-22	7 S	22 E	12	NE NE	3828	5885			5614	5600	5493	5493	5266		4675			3595	2670		no		253
254	Montana Power	2-13 Price	7 S	22 E	13	NW NE	3796	*5580			5290	5270	5180	5180	4960		4312	4360	3830	2225	1380				254
255	Montana Power	5-14-7-22 Card.	7 S	22 E	14	SW NW	3925	*6000			5793	5760	5654	5654	5436		4940		4454	2635	1820				255
256	Montana Power	5-14 Gaudima	7 S	22 E	14		3925																		256
257	Montana Power	7X-14 Kuchinski	7 S	22 E	14		4016													2625	1792	1000			257
258	Texaco Inc.	1 A.F. Richardson	7 S	22 E	15	NE NW	3911													2887	1942				258
259	Montana Power	5-16-7-22 State	7 S	22 E	16	SW NW	3940	6525	6490		6267	6240	6147	6147	5920		5250		4772	3420	2492	1830			259
260	Phillips Pet.	8-17 Dry Creek-C	7 S	22 E	17	SE NE	3941	*6530			6246	6223	6130	6130	5914		5302		4888	3152	2280	1487			260
261	Mule Creek Oil	1 Govt.-Smith	7 S	22 E	18	NW NE	4060	6165	6120		5920	5880	5777	5777	5560		4842	4880	4390	2595	1720	853			261
262	Montana Power	7-22 Red Lodge	7 S	22 E	22	SW NE	3863	*6570			6293	6260	6170	6170	5948		5288	5210	4810	3020	2100	1333			262
263	Montana Power	11-7 Sticka	7 S	23 E	7	NE SW	3762	*6010			5728	5707	5612	5612	5400		4725	4636	4210	2420	1452	715			263
264	Montana Power	13-21-7-23	7 S	23 E	21	SW SW	3894	4800			4543	4516	4427	4427	4195		3637		3155	1405	500				264
265	Amoco Prod. Co.	1-10 Bear Creek	8S	21E	10		4485	11550	11515		11310	11295	11204	11204	10990		10390	10378	9897	7975	7193	6402	4904		265
266	Harken O&G	1 Gloria - Federal	9S	22E	7	SW NW	4216				9930	9890	9792	9792	9582			8962	8733	6540	5595	4840	3612		266
267	Trigg Explor.	1-16 State	9S	22E	16	SE NE	4279				8820	8810	8672	8672	8478			7888	7678	5520	4635	3850	2640		267
268	Chambers Explor.	1-22 Chambers-Fed.	9S	22E	22	NW NE	4446													5230	4305	3520	2400		268
269	Nyvatex Oil	2 Federal	9S	22E	26	SW NE	4927	8125	8090		7850	7820	7735	7735	7537	7521									269

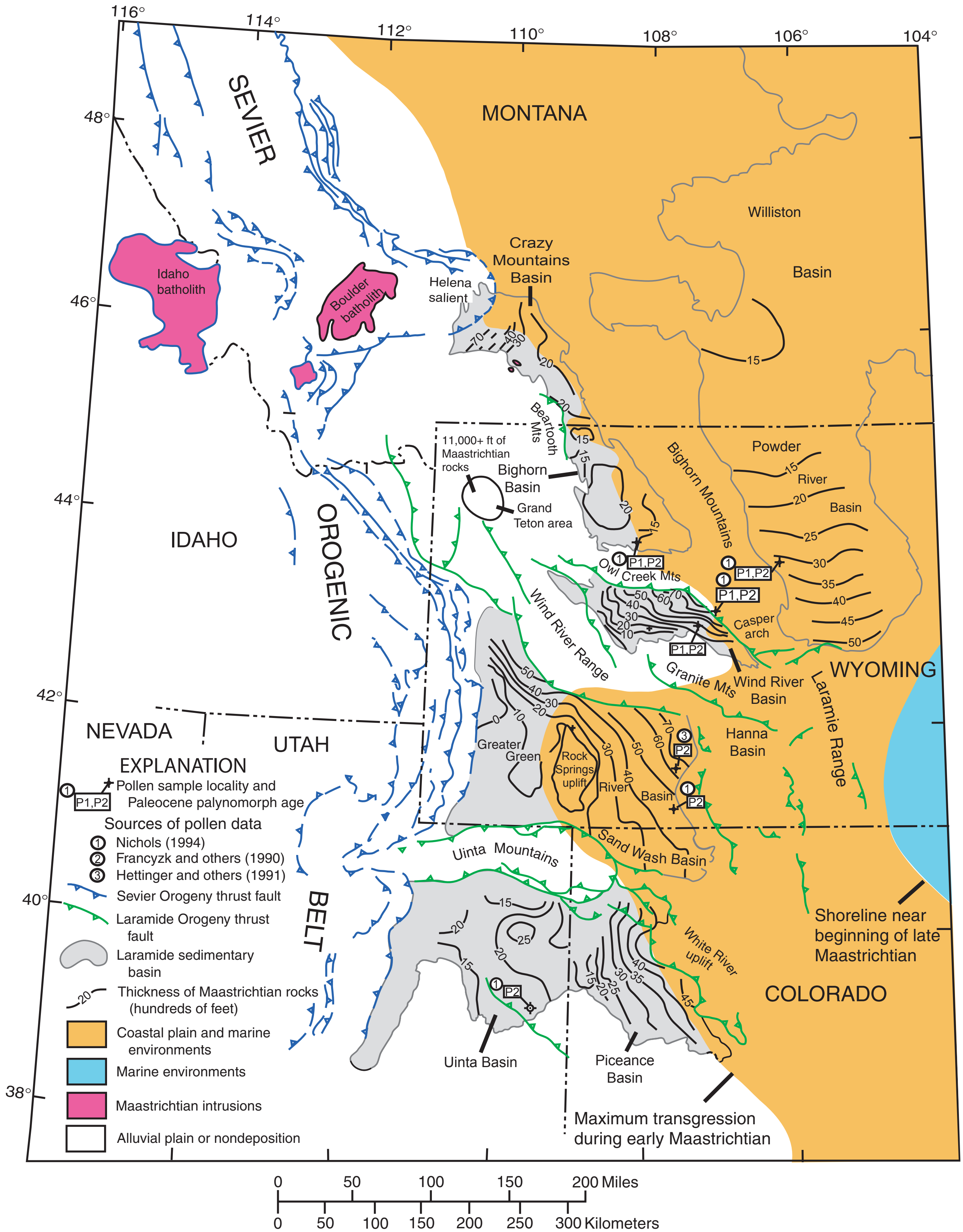

Figure 17. Laramide basins of central Rocky Mountain region. Sources of data listed in legend and keyed to map. Isopached intervals of largely Maastrichtian rocks; isopached intervals vary from basin to basin. Locations shown where early Paleocene pollen (P1 and P2 zones of Nichols and Ott, 1978) have been identified above the Maastrichtian section. Modified from Johnson (2001, his fig. 2).

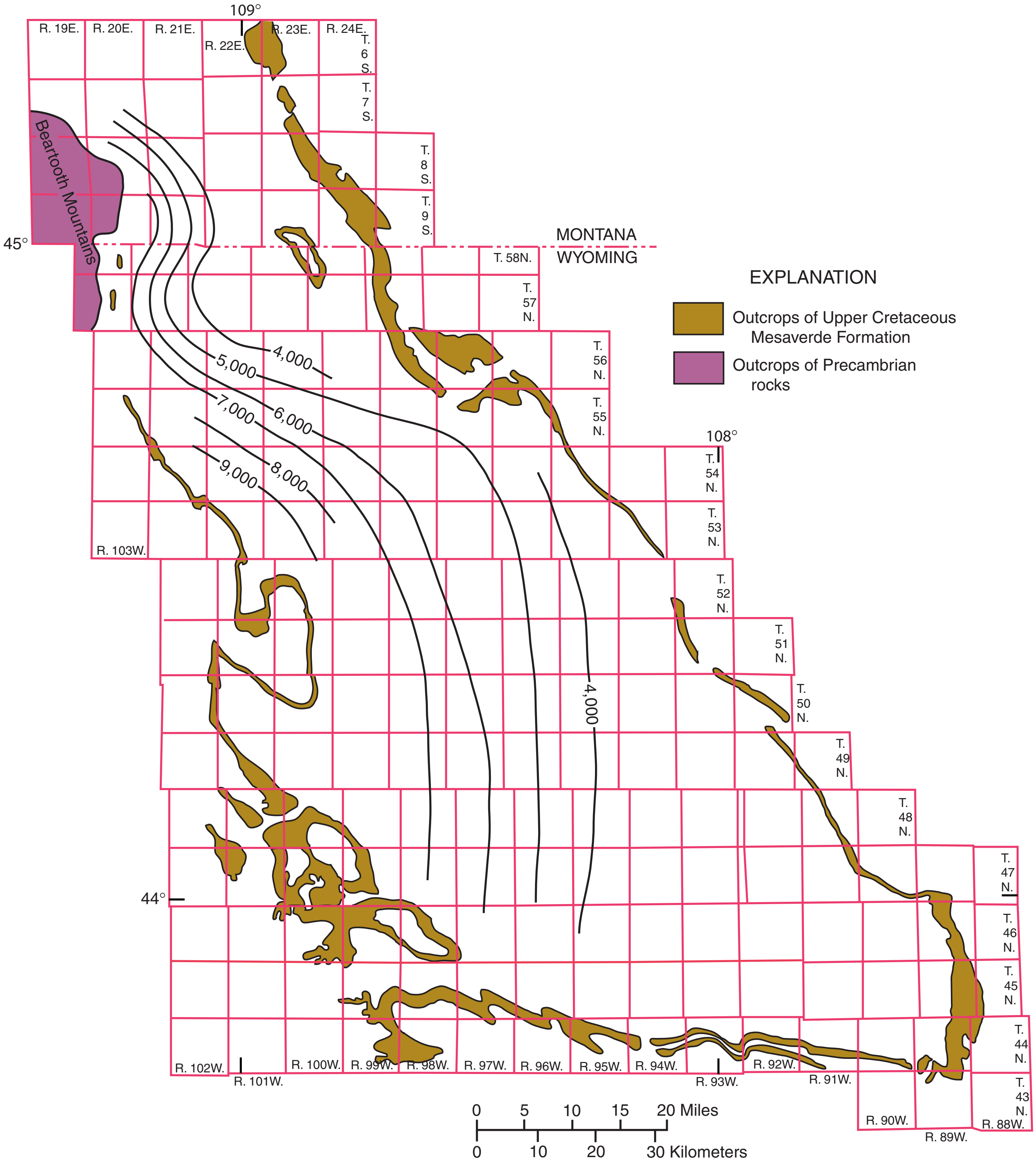

Figure 18. Isopach map of Paleocene Fort Union Formation, Bighorn Basin, Wyoming and Montana. Contour level 1,000 ft. Constructed largely from information in Keefer and others (1998).

a basin-centered accumulation is present. However, reliable formation pressures are extremely difficult to measure in low-permeability (tight) rocks typically found in basin-centered gas deposits. Abnormally high mud weights used while drilling are usually an indication of overpressured rocks, but overpressured intervals can be drilled using normal weight mud if the rocks are extremely tight and unfractured. Drill-stem tests can be used to detect both abnormally high and abnormally low pressures, but the duration of the drillstem test is seldom long enough to detect true formation pressures. Thus, a study of mud weights and drillstem tests will detect some but not all overpressured intervals. Underpressured intervals are even more difficult to detect because they are typically drilled using normal mud weights. Underpressured gas-saturated rocks tend to imbibe water from drilling fluids, hence they are extremely susceptible to formation damage; this damage commonly renders drillstem-test pressure readings unreliable.

Johnson and Finn (1998a) used drillstem tests and mud weights to help define an overpressured basin-centered gas accumulation in the deep trough of the Bighorn Basin, south of the Crazy Mountains Basin. There, the onset of overpressuring appears to occur at about a depth of 14,000 ft in the lower part of the Upper Cretaceous Meeteetse Formation and extends stratigraphically downward to near the base of the Cretaceous interval. Maximum pressure gradients in the Bighorn Basin appear to be about 0.675 pounds per square inch per foot (psi/ft). These gradients are low when compared to the deeper parts of basin-centered gas accumulations in other Rocky Mountain basins such as the Wind River Basin, Greater Green River Basin, and Piceance Basin where fluid pressure gradients as high as 0.8 psi/ft are encountered (Bilyeu, 1978; Spencer, 1989).

Levels of thermal maturity define areas where potential source rocks have generated gas at some time in the past and are commonly used as an indirect method of defining the limits of a basin-centered gas accumulation. Masters (1984, p. 27, fig. 25), in a study of the basin-centered gas accumulation in the Deep Basin of Alberta, indicated that a vitrinite reflectance (Rm) of 1.0 percent corresponds approximately to the limit of the accumulation. In the Piceance Basin of western Colorado, Johnson and others (1987) used an Rm of 1.1 percent to define the limits of the basin-centered gas accumulation. An Rm of from 0.73 to 1.1 percent was used to define a transition zone containing both tight reservoirs (>0.1 mD) and reservoirs with conventional permeabilities. Johnson and others (1996) used these same thermal maturity limits to help define the basin-centered gas accumulation and transition zone in the Wind River Basin in central Wyoming. In the Greater Green River Basin of Wyoming, Colorado, and Utah, Law and others (1989) used an Rm of 0.80 percent to define the top of overpressuring in that basin-centered gas accumulation. In the Bighorn Basin, Johnson and Finn (1998a) found that the 1.1-percent Rm thermal maturity level follows rather closely the areas of overpressuring in the Mesaverde Formation in the northern part of the basin whereas a thermal maturity of somewhat greater than Rm 1.1 percent is required for overpressuring in the southern part.

The rate that source rocks generate gas is directly related to temperature. Spencer (1989) suggested that rates of gas generation need to exceed rates of gas loss in order to maintain abnormally high pressures in Rocky Mountain basin-centered gas accumulations, and that this balance generally occurs at present-day corrected formation temperatures of about 200°F or greater. Law and others (1989) agreed that present-day temperatures can be used as a guide for predicting the onset of overpressuring but cautioned that that information needs to be used in conjunction with other data such as drillstem tests, mud weights, vitrinite data, and gas analysis from mud logs. In the Wind River Basin, Johnson and others (1996) found that the 200°F isotherm fairly closely followed the top of overpressuring in the central part of the basin. In the Bighorn Basin, Johnson and Finn (1998a) found that the onset of overpressuring at the top of the Mesaverde is fairly close to the 225°F isotherm throughout the deep basin trough. The onset of overpressuring at the Upper Cretaceous Frontier Formation level there occurs at a temperature between 200°F and 225°F.

Key Deep Wells in the Crazy Mountains Basin

The Chevron no. 1 Sonat-Largent well in sec. 3, T. 4 N., R. 10 E. (table 1, no. 49) is about 6 mi east of the deepest part of the Crazy Mountains Basin and 7 mi northwest of the Big Timber stock, the largest exposed intrusion in the basin (fig. 2). The well was drilled in 1981 to a depth of 11,436 ft and bottomed in a monotonous sequence of nonmarine Upper Cretaceous rocks of the Livingston Group. It apparently did not reach the Upper Cretaceous Bearpaw Shale, the highest marine shale marker unit in the sequence. The well encountered a number of relatively thin, sill-like intrusive bodies, but the sedimentary rocks do not appear to have been highly baked by intrusive activity in the area. Many sandstones encountered in the well were described by the mud logger at the well site as “unconsolidated.” No drillstem tests or perforations were attempted. Temperature at the bottom of the hole was 191°F (224°F using AAPG correction). Mud weight used at the bottom of the hole was 9.6 pounds. Vitrinite reflectance values ranged from 1.03 percent at 2,280 ft to 2.17 percent at 7,735 ft (Johnson and others, Chapter C, this CD-ROM).

The Chevron-Sonat-CIG 1 Van Cleve well in sec. 1, T. 3 N., R. 12 E. (table 1, no. 43) is about 20 mi east of the deep basin trough and 3.5 mi east of the Big Timber stock (fig. 2; pl. 1, well A-2). The well, drilled in 1980 to a bottom depth of 10,401 ft in the upper part of the Claggett Shale (pl. 1), encountered some sill-like intrusive bodies, but, as in the Sonat-Largent well, the sedimentary rocks encountered were not apparently highly baked. The driller believed that the well bottomed in the Lower Cretaceous Mowry Shale; however, sample descriptions and well logs do not support that interpretation. Based on a comparison with a well in sec. 32, T. 3 N., R. 15 E., about 15 mi southeast, the top of the Bearpaw Shale was encountered at a depth of about 8,420 ft in the no. 1 Sonat well. If this correlation is correct, then the no. 1 Sonat well bottomed in the Eagle Sandstone. Temperature at the bottom of the hole was 192°F (224°F using AAPG correction). Mud weight used at total depth was 9.1 pounds. Vitrinite reflectance values for the well were extremely high, ranging from 2.70 percent at 305 ft to 6.72 percent at 10,370 ft (Johnson and others, Chapter C, this CD-ROM).

The E.R.E.C. Western Region no. 23-6 well in sec. 6, T. 5 N., R. 13 E., in the northern part of the basin (pl. 1, well A-1), was drilled in 1996 to a depth of 11,996 ft, bottoming in the Upper Cretaceous Telegraph Creek Formation. No drillstem tests or perforations were recorded. Temperature at the bottom of the hole was 192°F (225°F using AAPG correction). Mud weight used at total depth was 9.6 pounds. Vitrinite reflectance values ranged from 0.75 percent at 1,900 ft in the Paleocene Melville Formation to 2.15 percent at 10,750 ft in the lowermost part of the Judith River Formation (Johnson and others, Chapter C, this CD-ROM). Numerous thin coals that were encountered in the Paleocene Lebo Shale and Melville Formation at depths from about 1,800 to 4,000 ft were reported to be quite gassy (Steve Van Delinder, Ballard Petroleum, written commun., 1999), with significant amounts of C2+ gases indicating a thermogenic rather than biogenic origin. Numerous gas shows were reported in underlying Cretaceous rocks as well.

The Sohio Petroleum no. 1-3 Moats well in sec. 1, T. 2 S., R. 6 E. (table 1, no. 110) is along the southwest flank of the basin (fig. 2) and was drilled in 1986 to a depth of 14,045 ft. Interpreted formation tops are: top of the Teapot equivalent at 4,716 ft, top of the Virgelle Sandstone Member of the Eagle Sandstone at 5,836 ft, top of the Frontier Formation at 7,430 ft, and top of the Jurassic Morrison Formation at 9,550 ft. The area is structurally complex with highly variable surface strikes and dips (Roberts, 1966, his plate 1) and numerous faults including thrust faults mapped in the vicinity of the drill site (Roberts, 1972, his pl. 1). Skipp and others (1999) showed the Cretaceous section cut by numerous relatively small scale thrust faults on an east-west cross section about 6 mi north of the drill site. It is likely that small-scale thrust faults were encountered in the drillhole, although the thicknesses between the Cretaceous marker horizons listed above are roughly comparable to those in measured sections and other drillholes in the general area (pl. 1). Bottom hole temperature at 10,260 ft, just below the base of the Cretaceous section, was 165°F (197°F using AAPG correction). A mud weight of 9.0 pounds was used to drill through the Cretaceous section. Vitrinite reflectance values for the well vary from 1.54 percent at 5,075 ft to 1.81 percent at 6,005 ft (Johnson and others, Chapter C, this CD-ROM).

Discussion

Although the Cretaceous and Paleocene interval in the Crazy Mountains Basin has many of the elements needed for a basin-centered gas accumulation to form, including adequate source rocks at favorable levels of thermal maturity, drilling to date is insufficient to evaluate the potential. Basin-centered gas accumulations have been identified in virtually all Laramide (Late Cretaceous through Eocene) basins in the Rocky Mountain region, and thus it is likely that a basin-centered accumulation exists in the Crazy Mountains Basin as well. Two analogous basins are proposed that may help in understanding the nature of a proposed basin-centered accumulation in the Bighorn Basin immediately to the south and the Raton Basin in Colorado and New Mexico.

Total subsidence in the Bighorn Basin is about the same depth as that in the Crazy Mountains Basin (Johnson and Finn, 1998a). An overpressured basin-centered gas accumulation appears to be present there along the deep basin trough (Johnson and Finn, 1998a). Hydrocarbon generation history modeling for the Bighorn Basin indicates that thermogenic gas generation, which is required to form a basin-centered gas accumulation, began between 60 and 50 Ma due to burial-related heating while the basin was still subsiding (Nuccio and Finn, 1998). By analogy, source rocks in the Crazy Mountains Basin were probably generating large quantities of thermogenic gas before basin subsidence ended near the end of the Paleocene, and a basin-centered gas accumulation probably began to form near the deep trough of the basin at that time.

Thermal maturities are considerably higher in the Crazy Mountains Basin than in the Bighorn Basin, and much of the difference is probably due to extensive igneous activity (Johnson and others, Chapter C, this CD-ROM) in Eocene time after basin subsidence had largely ceased, which resulted in an increased amount of hydrocarbons being generated by source rocks in the basin. Thermal maturities in the Crazy Mountains Basin are relatively high, with a surface vitrinite reflectance of 0.73 percent or greater over most of the deep trough of the basin and values as high as 2.70 percent near intrusions. Bonini and others (1972) suggested, based on gravity data, that the exposed stocks merge at depth to form a single large laccolith. Heat rising from such an igneous mass (if present) would, however, have almost certainly produced extreme levels of thermal maturities throughout the overlying sedimentary column. Observations, however, show that although there was extreme local heating, heating was only mild on a regional scale.

The igneous history of the Crazy Mountains Basin appears to be similar to that of the Raton Basin of Colorado and New Mexico in Oligocene and Miocene time. The Raton Basin is a Laramide basin of approximately the same size as the Crazy Mountains Basin, and the Cretaceous stratigraphic succession of that basin is generally similar to that in the Crazy Mountains Basin except the Upper Cretaceous continental rocks in the Raton include considerably more coal. Also, the Raton Basin is a comparatively shallow basin, with the base of the Upper Cretaceous coaly interval occurring at an elevation of about 2,500 ft above sea level in the deepest part of the basin trough, whereas the base of the Upper Cretaceous Eagle Sandstone, the lowest coaly interval in the Crazy Mountains Basin, occurs at an elevation of 11,000–12,000 ft below sea level. Like the Crazy Mountains Basin, however, the deep trough of the Raton Basin was intruded by two large stocks and a large number of radiating dikes that produced relatively mild regional heating and extreme heating near intrusions (Tyler and others, 1995). Heating from the dikes, however, was confined to fairly narrow contact zones (Bostick and Pawlewicz, 1984). Despite this intrusive event, the Raton Basin contains a major coalbed methane accumulation, which is currently being developed (Tyler and others, 1995). Gas from the coal beds appears to have migrated into nearby sandstone reservoirs, producing a basin-centered sandstone gas accumulation that is currently underpressured due to uplift and cooling (Johnson and Finn, 2001). The mild regional heating probably improved the economics of coalbed methane development in the basin by increasing the gas content of the coal beds.

It is proposed here that basin-centered gas accumulations are likely present in the Cretaceous and Paleocene strata of the Crazy Mountains Basin away from major intrusions. Accumulations, which would have begun to form during the later stages of basin subsidence in the Paleocene, were highly altered by the Eocene igneous event that accelerated overall gas generation but destroyed parts of the accumulations near intrusive bodies. Source rocks include organic-rich intervals in the Cretaceous Thermopolis Shale, Mowry Shale, and Cody Shale, and coals and carbonaceous shales in the Cretaceous Eagle Sandstone and Judith River Formation and Upper Cretaceous and Paleocene Fort Union Formation or Group. Perhaps the most promising potential is for basin-centered gas accumulations to have formed in the Paleocene Fort Union Formation, as that interval occurs at fairly shallow depths in the basin.

In the western part of the basin, sandstones in the Upper Cretaceous Livingston Group above the Eagle Sandstone include a large percentage of volcanic grains. Alteration of these unstable grains during diagenesis may have largely destroyed porosity and permeability. The best reservoirs in that area may be confined to the Eagle and older strata, and to the overlying Fort Union Formation or Group, which appears to be less volcanic than the intervening Livingston Group (Roberts, 1972).

References Cited

Ames, V., 1985a, Dean Dome Field, *in* Tonnsen, J.J., ed., Montana Oil and Gas Fields Symposium: Montana Geological Society, p. 417–419.

Ames, V., 1985b, Mackay Dome Field, *in* Tonnsen, J.J., ed., Montana Oil and Gas Fields Symposium: Montana Geological Society, p. 743–745.

Ames, V., 1991, Road log Nye-Bowler lineament Billings to Dean, Montana via Red Dome and Red Lodge: American Association of Petroleum Geologists Rocky Mountain Section Meeting, Billings, Mont., Field Trip No. 1 Road Log, p. 3–19.

Andrews, D.A., Pierce, W.G., and Eargle, D.H., 1947, Geologic map of the Big Horn Basin, Wyoming and Montana, showing terrace deposits and physiographic features: U.S. Geological Survey Oil and Gas Investigations Preliminary Map 71, scale 1:126,720.

Armstrong, R.L., 1968, Sevier orogenic belt in Nevada and Utah: Geological Society of America Bulletin, v. 79, p. 429–458.

Beaumont, C., 1981, Foreland basins: Geophysical Journal of the Royal Astronomical Society, v. 55, p. 471–498.

Beck, R.A., 1985, Syntectonic sedimentation adjacent to Laramide basement thrusts, Rocky Mountain foreland; timing of deformation: Ames, Iowa, Iowa State University M.S. thesis, 88 p.

Beck, R.A., Vondra, C.F., Filkins, J.E., and Olander, J.D., 1988, Syntectonic sedimentation and Laramide basement thrusting, Cordilleran foreland; timing of deformation, *in* Schmidt, C.J., and Perry, W.J., Jr., eds, Interaction of Rocky Mountain foreland and the Cordilleran thrust belt: Geological Society of America Memoir 171, p. 465–487.

Berg, R.B., Lopez, D.A., and Lonn, J.D., 2000, Geologic map of the Livingston 30′×60′ quadrangle, southwest Montana: Montana Bureau of Mines and Geology Open-File Report 406, scale 1:100,000.

Berry, G.W., 1943, Stratigraphy and structure at Three Forks, Montana: Geological Society of America Bulletin, v. 54, no. 1, p. 1–30.

Billingsley, Paul, 1915, The Boulder Batholith of Montana: American Institute of Mining Engineers Transactions, v. 51, p. 31–47.

Bilyeu, B.D., 1978, Deep drilling practices, Wind River Basin of Wyoming, *in* Boyd, R.G., ed., Resources of the Wind River Basin: Wyoming Geological Association Guidebook No. 30, p. 13–24.

Blackstone D.L., 1986, Structural geology—Northwest margin, Bighorn Basin, Park County, Wyoming and Carbon County, Montana, *in* Garrison, P.B., ed., Geology of the Beartooth uplift and adjacent basins: Montana Geological Society and Yellowstone Bighorn Research Association Joint Field Conference and Symposium, p. 125–135.

Bonini, W.E., Kelley, W.N., Jr., and Hughes, D.W., 1972, Gravity studies of the Crazy Mountains and the west flank of the Beartooth Mountains, Montana, *in* Lynn, J., Balster, C., and Warne, J., eds., Crazy Mountains Basin: Montana Geological Society 21st Annual Geological Conference, p. 119–127.

Bonini, W.E., and Kinard, R.E., 1983, Gravity anomalies along the Beartooth front, Montana, *in* Boberg, W.W., ed., Geology of the Bighorn Basin: Wyoming Geological Association 34th Annual Field Conference Guidebook, p. 89–94.

Bostick, N.H., and Pawlewicz, M.J., 1984, Paleotemperatures based on vitrinite reflectance of shales and limestones in igneous dike aureoles in the Upper Cretaceous Pierre Shale, Walsenburg, Colorado, *in* Woodward, J.W., Meissner, F.F., and Clayton, J.L., eds., Hydrocarbon source rocks of the Greater Rocky Mountain Region: Rocky Mountain Association of Geologists Guidebook, p. 387–399.

Burtner, R.L., and Warner, M.A., 1984, Hydrocarbon generation in Lower Cretaceous Mowry and Skull Creek shales of the northern Rocky Mountain area, *in* Woodward, J., Meissner, F.F., and Clayton, J.L., eds., Hydrocarbon source rocks of the Greater Rocky Mountain Region: Rocky Mountain Association of Geologists Guidebook, p. 449–467.

Calvert, W.R., 1912, The Livingston and Trail Creek coal fields, Park, Gallatin, and Sweetgrass Counties, Montana: U.S. Geological Survey Bulletin 471–E, p. 384–405.

Chadwick, R.A., 1981, Chronology and structural setting of volcanism in southwestern and central Montana, *in* Tucker, T.E., ed., Guidebook to Southwest Montana: Montana Geological Society Field Conference and Symposium, p. 301–310.

Christiansen, E.H., Kowallis, B.J., and Barton, M.D., 1994, Temporal and spatial distribution of volcanic ash in Mesozoic sedimentary rocks of the Western Interior—An alternative record of Mesozoic Magmatism, *in* Caputo, M.V., Peterson, J.A., and Francyzk, K.J., eds., Mesozoic Systems of the Rocky Mountain Region, U.S.A.: Society of Economic Paleontologists and Mineralogists, Rocky Mountain Section, p. 73–94.

Cobban, W.A., and Reeside, J.B., Jr., 1952a, Correlation of the Cretaceous formations of the Western Interior of the United States: Bulletin of the Geological Society of America, v. 63, p. 1011–1044.

Cobban, W.A., and Reeside, J.B., Jr., 1952b, Frontier Formation, Wyoming and adjacent areas: American Association of Petroleum Geologists, v. 36, no. 10, p. 1913–1961.

Cully, T.G., 1985a, Dry Creek Field, *in* Tonnsen, J.J., ed., Montana Oil and Gas Fields Symposium: Montana Geological Society, p. 441–447.

Cully, T.G., 1985b, Golden Dome Field, *in* Tonnsen, J.J., ed., Montana Oil and Gas Fields Symposium: Montana Geological Society, p. 541–546.

Curry, W.H., III, 1976a, Late Cretaceous Teapot delta of southern Powder River Basin, Wyoming, *in* Laudin, R.B., Curry, W.H., III, and Rung, J.S., eds., Geology and energy resources of the Powder River Basin: Wyoming Geological Association 28th Annual Field Conference Guidebook, p. 21–28.

Curry, W.H., III, 1976b Type section of the Teapot Sandstone, *in* Laudin, R.B., Curry, W.H., III, and Rung, J.S., eds., Geology and energy resources of the Powder River Basin: Wyoming Geological Association 28th Annual Field Conference Guidebook, p. 29–32.

Darton, N.H., 1904, Comparison of stratigraphy of the Black Hills, Bighorn Mountains, and Rocky Mountain Front Range: Geological Society of America Bulletin, v. 15, p. 379–448.

Darton, N.H., 1906, Geology of the Bighorn Mountains: U. S. Geological Survey Professional Paper 51, 129 p.

Davis, J.C., 1970, Petrology of Mowry Cretaceous Shale of Wyoming: American Association of Petroleum Geologists Bulletin, v. 54, p. 487–502.

Dolson, J., Muller, D., Evetts, M.J., and Stein, J.A., 1991, Regional paleotopographic trends and production, Muddy Sandstone (Lower Cretaceous), central and northern Rocky Mountains: American Association of Petroleum Geologists Bulletin, v. 75, no. 3, p. 409–435.

Dyman, T.S., Merewether, E.A., Molenaar, C.M., Cobban, W.A., Obradovich, J.D., Weimer, R.J., and Bryant, W.A., 1994, Stratigraphic transects for Cretaceous rocks, Rocky Mountains and Great Plains Region, *in* Caputo, M.V., Peterson, J.A., and Francyzk, K.J., eds., Mesozoic Systems of the Rocky Mountain Region, U.S.A.: Society of Economic Paleontologists and Mineralogists, Rocky Mountain Section, p. 365–391.

Dyman, T.S., Porter, K.W., Tysdal, R.G., Cobban, W.A., Fox, J.E., Hammond, R.H., Nichols, D.J., Perry,. W.J., Jr., Rice, D.D., Setterholm, D.R., Shurr, G.W., Haley, J.C., Lane, D.E., Anderson, S.B., and Campen, E.B., 1995, West-east stratigraphic transect of Cretaceous rocks in the northern Rocky Mountains and Great Plains regions, southwestern Montana to southwestern Minnesota: U.S. Geological Survey Miscellaneous Investigations Series Map I–2474–A, 1 sheet.

Foose, R.M., Wise, D.V., and Garabini, G.S., 1961, Structural geology of the Beartooth Mountains, Montana and Wyoming: Geological Society of America Bulletin, v. 72, p. 1143–1172.

Fort Union Coal Assessment Team, 1999, National Coal Resource Assessment—1999 resource assessment of selected Tertiary coal beds and zones in the Northern Rocky Mountains and Great Plains Region: U.S. Geological Survey Professional Paper 1625–A, 2 CD-ROMs.

Francyzk, K.J., Pitman, J.K., and Nichols, D.J., 1990, Sedimentology, mineralogy, palynology, and depositional history of some uppermost Cretaceous and lowermost Tertiary rocks along the Utah Book and Roan Cliffs east of the Green River: U.S. Geological Survey Bulletin 1787–N, 27 p.

Garbarini, G.S., 1957, Geology of the McLeod area, Beartooth Range, Montana: Princeton, N.J., Princeton University Ph. D. thesis, pagination unknown.

Garrett, H.L., 1972, Structural geology of the Crazy Mountains Basin, *in* Lynn, J., Balster, C., and Warne, J., eds., Crazy Mountains Basin: Montana Geological Society 21st Annual Geological Conference, p. 113–118.

Giegengack, R., Omar, G.I., and Inman, L.R., 1998, Tectonothermal history of basement-cored mountain ranges flanking the Bighorn Basin—Surrogate evidence of Laramide and post-Laramide uplift and erosion, *in* Keefer, W.R., and Goolsby, J.E., eds., Cretaceous and Lower Tertiary Rocks of the Bighorn Basin, Wyoming and Montana: Wyoming Geological Association Forty-Ninth Annual Field Conference Guidebook, p. 167–178.

Gill, J.R., and Burkholder, R.E., 1979, Measured sections of the Montana Group and equivalent rocks from Montana and Wyoming: U.S. Geological Survey Open-File Report 79–1143, 201 p.

Gill, J.R., and Cobban, W.A., 1966, The Red Bird section of the Upper Cretaceous Pierre Shale in Wyoming: U.S. Geological Survey Professional Paper 393–A, 73 p.

Gill, J.R., and Cobban, W.A., 1973, Stratigraphy and geologic history of the Montana Group and equivalent rocks, Montana, Wyoming, and North and South Dakota: U.S. Geological Survey Professional Paper 776, 37 p.

Grauman, J.E., 1985, Lake Basin, North Field, *in* Tonnsen, J.J., ed., Montana Oil and Gas Fields Symposium: Montana Geological Society, p. 677–679.

Hagen, E.S., and Surdam, R.C., 1984, Matuation history and thermal evolution of Cretaceous source rocks of the Bighorn Basin, Wyoming, *in* Woodward, J., Meissner, F. F., and Clayton, J.L., eds., Hydrocarbon source rocks of the Greater Rocky Mountain Region: Rocky Mountain Association of Geologists, p. 321–338.

Handcock, E.T., 1918, Geology and oil and gas prospects of the Lake Basin Field, Montana: U.S. Geological Survey Bulletin 691–D, 147 p.

Hares, C.J., 1917, Gastroliths in the Cloverly Formation: Washington Academy of Science Journal, v. 7, p. 429.

Harris, S.A., 1957, The tectonics of Montana as related to the Belt Series, *in* Graves, R.W., Jr., ed., Crazy Mountains Basin: Billings Geological Society 8th Annual Field Conference, p. 21–33.

Harrison, J.E., Griggs, A.B., and Wells, J.D., 1974, Tectonic features of the Precambrian Belt basin and their influence on post-Belt structures: U.S. Geological Survey Professional Paper 866, 15 p.

Hartman, J.H., 1989, Stratigraphy of uppermost Cretaceous and Paleocene nonmarine mollusca in the Crazy Mountains Basin, south-central Montana, *in* French, D.E., and Grabb, R.F., eds., Geologic resources of Montana, Volume 1: Montana Geological Society, 1989 Field Conference Guidebook, Montana Centennial Edition, p. 163–172.

Hartman, J.H., Buckley, G.A., Krause, D.W., and Kroeger, T.J., 1989, Paleontology, stratigraphy, and sedimentology of Simpson quarry (early Paleocene), Crazy Mountains Basin, south-central Montana, *in* French, D.E., and Grabb, R.F., eds., Geologic Resources of Montana, Volume I: Montana Geological Society, 1989 Field Conference Guidebook, Montana Centennial Edition, p. 173–184.

Hartman, J.H., and Krause, D.W., 1993, Cretaceous and Paleocene stratigraphy and paleontology of the Shawmut anticline and the Crazy Mountains Basin, Montana—Road log and overview of recent investigations, *in* Hunter, L.D.V., ed., Energy and mineral resources of central Montana: Montana Geological Society 1993 Field Conference Guidebook, p. 71–84.

Hatcher, J.B., and Stanton, T.W., 1903, The stratigraphic position of the Judith River beds and their correlation with the Belly River beds: Science, v. 18, no. 150, p. 211–212.

Hettinger, R.D., Honey, J.G., and Nichols, D.J., 1991, Chart showing correlations of Upper Cretaceous Fox Hills Sandstone and Lance Formation, and lower Tertiary Fort Union, Wasatch, and Green River Formations, from the eastern flank of the Washakie Basin to the southeastern part of the Great Divide Basin, Wyoming: U.S. Geological Survey Miscellaneous Investigations Series Map I–2151, 1 sheet.

Hickey, L.J., 1980, Paleocene stratigraphy and flora of the Clark's Fork Basin, *in* Gingerich, P.D., ed., Early Cenozoic paleontology and stratigraphy of the Bighorn Basin, Wyoming: University of Michigan Paper on Paleontology No. 24, p. 33–49.

Iddings, J.P., and Weed, W.H., 1894, Description of the Livingston sheet [Montana]: U.S. Geological Survey Geologic Atlas Folio 1, 5 p.

Jiao, Z.S., and Surdam, R.C., 1993, Low-permeability rocks, capillary seals, and pressure compartment boundaries in the Cretaceous section of the Powder River Basin, *in* Stroock, B., and Andrew, S., eds., Jubilee Anniversary Field Conference Guidebook: Wyoming Geological Association, p. 297–310.

Johnson, R.C., 2001, Regional stratigraphic setting of the Maastrichtian Lance Formation and equivalent rocks in the central Rocky Mountain region, *in* Robinson, J.W., and Shanley, K.W., eds., Tight gas fluvial reservoirs—A case history from the Lance Formation, Green River Basin, Wyoming: American Association of Petroleum Geologists Annual Meeting, Denver, Colo., Short Course No. 2, 12 p.

Johnson, R.C., Crovelli, R.A., Spencer, C.W., and Mast, R.F., 1987, An assessment of gas resources in low-permeability sandstones of the Upper Cretaceous Mesaverde Group, Piceance Basin, Colorado: U.S. Geological Survey Open-File Report 87–357, 165 p.

Johnson, R.C., and Finn, T.M., 1998a, Is there a basin-centered gas accumulation in Upper Cretaceous rocks in the Bighorn Basin?, *in* Keefer, W.R., and Goolsby, J.E., eds., Cretaceous and Lower Tertiary rocks of the Bighorn Basin, Wyoming and Montana: Wyoming Geological Association Forty-Ninth Annual Field Conference Guidebook, p. 257–273.

Johnson, R.C., and Finn, T.M., 1998b, Structure contour map on the top of the Upper Cretaceous Mesaverde Formation, Bighorn Basin, Wyoming and Montana, *in* Keefer, W.R., and Goolsby, J.E., eds., Cretaceous and Lower Tertiary rocks of the Bighorn Basin, Wyoming and Montana: Wyoming Geological Association Forty-Ninth Annual Field Conference Guidebook, p.197–198.

Johnson, R.C., and Finn, T.M., 2001, Potential for a basin-centered gas accumulation in the Raton Basin, Colorado and New Mexico: U.S. Geological Survey Bulletin 2184–B, 14 p.

Johnson, R.C., Finn, T.M., Keefer, W.R., and Szmajter, R.J., 1996, Geology of Upper Cretaceous and Paleocene gas-bearing rocks, Wind River Basin, Wyoming: U.S. Geological Survey Open-File Report 96–090, 120 p., 3 plates.

Johnson, R.C., Keefer, W.R., Keighin, C.W., and Finn, T.M., 1998, Detailed outcrop studies of the upper part of the Upper Cretaceous Cody Shale and the Upper Cretaceous Mesaverde, Meeteetse, and Lance Formations, Bighorn Basin, Wyoming, *in* Keefer, W.R., and Goolsby, J.E., eds., Cretaceous and Lower Tertiary rocks of the Bighorn Basin, Wyoming and Montana: Wyoming Geological Association Forty-Ninth Annual Field Conference Guidebook, p. 59–78.

Johnson, R.C., and Keighin, C.W., 1998, Origins of natural gases from Upper Cretaceous reservoirs, Bighorn Basin, Wyoming and Montana, and comparison with gases from the Wind River Basin, Wyoming, *in* Keefer, W.R., and Goolsby, J.E., eds., Cretaceous and Lower Tertiary rocks of the Bighorn Basin, Wyoming and Montana: Wyoming Geological Association Forty-Ninth Annual Field Conference Guidebook, p. 233–249.

Johnson, R.C., and Rice, D.D., 1990, Occurrence and geochemistry of natural gases, Piceance Basin, northwest Colorado: American Association of Petroleum Geologists, v. 74, p. 805–829.

Johnson, R.C., and Rice, D.D., 1993, Variations in composition and origins of gases from coal bed and conventional reservoirs, Wind River Basin, Wyoming, *in* Keefer, W.R., Metzger, W.J., and Godwin, L.H., eds., Oil and gas and other resources of the Wind River Basin, Wyoming: Wyoming Geological Association Special Symposium, p. 319–335

Johnson, R.C., Rice, D.D., and Fouch, T.D., 1994, Evidence for gas migration form Cretaceous basin-centered accumulations into lower Tertiary Reservoirs in Rocky Mountain Basins—First Biennial Conference, Natural Gas in the Western United States: Rocky Mountain Association of Geologists and Colorado Oil and Gas Association, 8 p.

Jones, M.K., 1985, Lake Basin Field, *in* Tonnsen, J.J., ed., Montana Oil and Gas Fields Symposium: Montana Geological Society, p. 673–675.

Jordan, T.E., 1981, Thrust loads and foreland basin evolution, Cretaceous, western United States: American Association of Petroleum Geologists Bulletin, v. 65, p. 2506–2520.

Keefer, W.R., Finn, T.M., Johnson, R.C., and Keighin, C.W., 1998, Regional stratigraphy and correlation of Cretaceous and Paleocene rocks, Bighorn Basin, Wyoming and Montana, *in* Keefer, W.R., and Goolsby, J.E., eds., Cretaceous and Lower Tertiary rocks of the Bighorn Basin, Wyoming and Montana: Wyoming Geological Association Forty-Ninth Annual Field Conference Guidebook, p. 1–30.

Kent, H.C., 1972, Review of Phanerozoic history, *in* Mallory, W.W., ed., Geologic atlas of the Rocky Mountain Region: Rocky Mountain Association of Geologists, p. 57–59.

Klepper, M.R., Robinson, G.D., and Ruppel, E.T., 1971, On the nature of the Boulder batholith: Geological Society of America Bulletin, v. 82, p. 1563–1580.

Klepper, M.R., Weeks, R.A., and Ruppel, E.T., 1957, Geology of the southern Elkhorn Mountains, Jefferson and Broadwater Counties, Montana: U.S. Geological Survey Professional Paper 298, 82 p.

Knappen, R.S., and Moulton, G.F., 1931, Geology and mineral resources of parts of Carbon, Bighorn, Yellowstone, and Stillwater Counties, Montana: U.S. Geological Survey Bulletin 822–A, 70 p.

Knight, W.C., 1902, The petroleum fields of Wyoming: Engineering Mining Journal, v. 73, p. 720–723.

Kulik, D.M., and Schmidt, C.J., 1988, Region of overlap and styles of interaction of Cordilleran thrust belt and Rocky Mountain foreland, *in* Schmidt, C.J., and Perry, W.J., Jr., eds., Interaction of the Rocky Mountain Foreland and the Cordilleran Thrust Belt: Geological Society of America Memoir 171, p. 75–98.

Lageson, D.R., Schmidt, C.J., Dresser, H.W., Welker, M., Berg, R.B., and James, H.L., 1983, Road Log No. 1, Bozeman to Helena via Battle Ridge Pass, White Sulphur Springs, Townsend and Toston, *in* Smith, D.L., compiler, Guidebook of the Fold and Thrust Belt, west-central Montana: Montana Bureau of Mines and Geology, Special Publication 86, p. 1–30.

Lammers, E.H.C., 1937, The structural geology of the Livingston Peak area, Montana: Journal of Geology, v. 45, p. 268–298.

Law, B.E., 1984, Relationships of source-rock, thermal maturity, and overpressuring to gas generation and occurrence in low-permeability Upper Cretaceous and Lower Tertiary rocks, Greater Green River Basin, Wyoming, Colorado and Utah, *in* Woodward, J., Meissner, F.F., and Clayton, J.L., eds., Hydrocarbon source rocks of the Greater Rocky Mountain Region: Rocky Mountain Association of Geologists Guidebook, p. 469–490.

Law, B.E., and Dickinson, W.W., 1985, Conceptual model for the origin of abnormally pressured gas accumulations in low-permeability reservoirs: American Association of Petroleum Geologists Bulletin, v. 69, no. 8, p. 1295–1304.

Law, B.E., Spencer, C.W., and Bostick, N.H., 1979, Preliminary results of organic maturation, temperature, and pressure studies in the Pacific Creek area, Sublette County, Wyoming, *in* 5th DOE Symposium on Enhanced Oil and Gas Recovery and Improved Drilling Methods, Tulsa, Oklahoma, Proceedings, v. 3—Gas and Drilling: Tulsa, Okla., Petroleum Publishing Co., p. 1–13.

Law, B.E., Spencer, C.W., Charpentier, R.R., Crovelli, R.A., Mast, R.F., Dolton, G.L., and Wandrey, C.J., 1989, Estimates of gas resources in overpressured low-permeability Cretaceous and Tertiary sandstone reservoirs, Greater Green River Basin, Wyoming, Colorado, and Utah, *in* Eisert, J.L., ed., Gas resources of Wyoming: Wyoming Geological Association Fourteenth Field Conference Guidebook, p. 39–61.

Lopez, D.A., 2000, Geologic map of the Big Timber 30′x60′ quadrangle, south-central Montana: Montana Bureau of Mines and Geology Open File Report 405, scale 1:100,000.

Lupton, C.T., 1916, Oil and gas near Basin, Bighorn County, Wyoming: U.S. Geological Survey Bulletin 621–L, p. 157–190.

MacGowan, D.B., Garcia-Gonzalez, M., Britton, D.R., and Surdam, R.C., 1993, Timing of hydrocarbon generation, organic-inorganic diagenesis, and the formation of abnormally pressured gas compartments in the Cretaceous of the Greater Green River Basin—A geochemical model, *in* Stroock, B., and Andrew, S., eds., Jubilee Anniversary Field Conference Guidebook: Wyoming Geological Association, p. 325–348.

Marvin, R.F., and Dobson, S.W., 1979, Radiometric ages—Compilation B, U.S. Geological Survey: Isochron/West, no. 26, p. 3–32.

Masters, J.A., 1979, Deep basin gas trap western Canada: American Association of Petroleum Geologists Bulletin, v. 63, no. 2, p. 151–181.

Masters, J.A., 1984, Lower Cretaceous oil and gas in western Canada, *in* Masters, J.A. ed., Elmworth case study of a deep basin gas field: American Association of Petroleum Geologists Memoir 38, p. 1–33.

McGrew, L.W., 1977a, Geologic map of the Sixteen NE quadrangle, Meagher, Gallatin, and Park Counties, Montana: U.S. Geological Survey Geologic Quadrangle Map GQ–1384, scale 1:24,000.

McGrew, L.W., 1977b, Geologic map of the Sixteen quadrangle, Gallatin and Meagher Counties, Montana: U.S. Geological Survey Geologic Quadrangle Map GQ–1383, scale 1:24,000.

McGrew, L.W., 1977c, Geologic map of the Ringling quadrangle, Meagher County, Montana: U.S. Geological Survey Geologic Quadrangle Map GQ–1382, scale 1:24,000.

McGrew, L.W., 1977d, Geologic map of the Black Butte Mountain quadrangle, Meagher County, Montana: U.S. Geological Survey Geologic Quadrangle Map GQ–1381, scale 1:24,000.

McMannis, W.J., 1955, Geology of the Bridger Range, Montana: Geological Society of America Bulletin, v. 66, no. 11, p. 1385–1430.

McMannis, W.J., 1957, The Livingstone Formation, *in* Graves, R.W., Jr., ed., 8th Annual Field Conference Guidebook: Billings Geological Society, p. 80–84.

McPeek, L. A., 1980, Eastern Green River Basin—A developing giant gas supply from deep, overpressured Upper Cretaceous sandstone: American Association of Petroleum Geologists Bulletin, v. 64, p. 748–749.

Meissner, F.F., 1980, Examples of abnormal fluid pressure produced by hydrocarbon generation: American Association of Petroleum Geologists Bulletin, v. 64, p. 749.

Meissner, F.F., 1981, Abnormal pressures produced by hydrocarbon generation and maturation and their relation to processes of migration and accumulation: American Association of Petroleum Geologists Bulletin, v. 65, p. 2467.

Meissner, F.F., 1984, Cretaceous and Lower Tertiary coals as sources for gas accumulations in the Rocky Mountain area, *in* Woodward, J., Meissner, F.F., and Clayton, J.L., eds., Hydrocarbon source rocks of the Greater Rocky Mountain Region: Rocky Mountain Association of Geologists Guidebook, p. 401–431.

Merewether, E.A., 1996, Stratigraphy and tectonic implications of Upper Cretaceous rocks in the Powder River Basin, northeastern Wyoming and southeastern Montana: U.S. Geological Survey Bulletin 1917, 92 p.

Merewether, E.A., and Cobban, W.A., 1986, Biostratigraphic units and tectonism in the Mid-Cretaceous foreland of Wyoming, Colorado, and adjoining areas, *in* Peterson, J.A., ed., Paleotectonics and sedimentation in the Rocky Mountain region, United States: American Association of Petroleum Geologists Memoir 41, p. 443–468.

Merewether, E.A., Cobban, W.A., and Ryder, R.T., 1975, Lower Upper Cretaceous strata, Bighorn Basin, Wyoming and Montana, *in* Exum, F.A., and George, G.R., eds., Geology and mineral resources of the Bighorn Basin: Wyoming Geological Association 27th Annual Field Conference Guidebook, p. 73–84.

Merewether, E.A., Tillman, R.W., Cobban, W.A., and Obradovich, J.D., 1998, Outcrop sections of the Upper Cretaceous Frontier Formation, southeastern Bighorn Basin, Wyoming, *in* Keefer, W.R., and Goolsby, J.E., eds., Cretaceous and Lower Tertiary rocks of the Bighorn Basin, Wyoming and Montana: Wyoming Geological Association Forty-Ninth Annual Field Conference Guidebook, p. 31–42.

Nichols, D.J., 1994, Palynostratigraphic correlation of Paleocene rocks in the Wind River, Bighorn, and Powder River Basins, *in* Flores, R.M., Mehring, R.W., and Beck, T.L., eds., Organics and the Rockies field guide: Wyoming State Geological Survey Public Information Circular No. 33, p. 17–29.

Nichols, D.J., 1998, Palynological age determinations of selected outcrop samples from the Lance and Fort Union Formations, Bighorn Basin, Montana and Wyoming, *in* Keefer, W.R., and Goolsby, J.E., eds., Cretaceous and Lower Tertiary rocks of the Bighorn Basin, Wyoming and Montana: Wyoming Geological Association Forty-Ninth Annual Field Conference Guidebook, p. 117–129.

Nichols, D.J., and Ott, H.L., 1978, Biostratigraphy and evolution of the *Momipites-Caryapollenites* lineage in the early Tertiary in the Wind River Basin, Wyoming: Palynology, v. 2, p. 93–112.

Nuccio, V.F., and Finn, T.M., 1998, Thermal maturity and petroleum generation history of Cretaceous and Tertiary source rocks, Bighorn Basin, Wyoming and Montana, *in* Keefer, W.R., and Goolsby, J.E., eds., Cretaceous and Lower Tertiary rocks of the Bighorn Basin, Wyoming and Montana: Wyoming Geological Association Forty-Ninth Annual Field Conference Guidebook, p. 211–231.

Obradovich, J.D., 1993, A Cretaceous time scale, *in* Caldwell, W.G.E., and Kauffman, E.G., eds., Evolution of the Western Interior Basin: Geological Association of Canada Special Paper 39, p. 379–396.

Oleson, N.E., 1985, Rapelje Field, *in* Tonnsen, J.J., ed., Montana Oil and Gas Fields Symposium: Montana Geological Society, p. 933–936.

Parsons, W.H., 1942, Origin and structure of the Livingston igneous rocks, Montana: Journal of Geology, v. 47, p. 1–26.

Parsons, W.H., 1958, Origin, age, and tectonic relationships of the volcanic rocks in the Absaroka-Yellowstone-Beartooth region, Wyoming-Montana, *in* Zieglar, D.L., ed., Beartooth uplift and Sunlight basin: Billings Geological Society, 9th Annual Field Conference Guidebook, p. 36–43.

Perry, W.J., Haley, J.C., Nichols, D.J., Hammons, P.M., and Ponton, J.D., 1988, Interactions of Rocky Mountain foreland and Cordilleran thrust belt, Lima region, southwest Montana, *in* Schmidt, C.J., and Perry, W.J., Jr., eds., Interaction of Rocky Mountain foreland and the Cordilleran Thrust Belt: Geological Society of America Memoir 171, p. 267–290.

Porter, K.W., Dyman, T.S., and Tysdal, R.G., 1993, Sequence boundaries and other surfaces in Lower and Lower Upper Cretaceous rocks of central and southwest Montana—A preliminary report, *in* Hunter, L.D.V., ed., Energy and mineral resources of Central Montana: Montana Geological Society, 1993 Field Conference Guidebook, p. 45–59.

Price, R.A., 1973, Large-scale gravitational flow of supracrustal rocks, southern Canadian Rockies, *in* Delong, K.A., and Scholten, R., eds., Gravity and tectonics: New York, John Wiley and Sons, p. 491–502.

Reeside, J.B., and Cobban, W.A., 1960, Studies of the Mowry Shale (Cretaceous) and contemporary formations in the United States and Canada: U.S. Geological Survey Professional Paper 355, 126 p.

Richards, P.W., 1957, Geology of the area east and southeast of Livingston, Park County, Montana: U.S. Geological Survey Bulletin 1021–L, 438 p.

Rice, D.D., Fouch, T.D., and Johnson, R.C., 1992, Influence of source rock type, thermal maturity, and migration on composition and distribution of natural gases, Uinta Basin, Utah, *in* Fouch, T.D., Nuccio, V.F., and Chidsey, T.C., Jr., eds., Hydrocarbon and mineral resources of the Uinta Basin, Utah and Colorado: Utah Geological Association Guidebook 20, p. 95–110.

Robbins, E.A., and Erslev, E.A., 1986, Basement wedges, back-thrusting and thin-skinned deformation in the northwest Beartooth Mountains near Livingston, Montana, *in* Garrison, P.B., ed., Geology of the Beartooth uplift and adjacent basins: Montana Geological Society and Yellowstone Bighorn Research Association Joint Field Conference and Symposium, p. 111–123.

Roberts, A.E., 1963, The Livingston Group of south-central Montana: U.S. Geological Survey Professional Paper 475–B, p. B86–B92.

Roberts, A.E., 1964, Geology of the Hoppers quadrangle, Montana: U.S. Geological Survey Geologic Quadrangle Map GQ–258, scale 1:24,000.

Roberts, A.E., 1965, Correlation of Cretaceous and lower Tertiary rocks near Livingston, Montana, with those in other areas of Montana and Wyoming: U.S. Geological Survey Professional Paper 525–B, p. B54–B63.

Roberts, A.E., 1966, Geology and coal resources of the Livingston coal field, Gallatin and Park Counties, Montana: U.S. Geological Survey Professional Paper 526–A, 56 p.

Roberts, A.E., 1972, Cretaceous and Early Tertiary depositional and tectonic history of the Livingston area, southwestern Montana: U.S. Geological Survey Professional Paper 526–C, 120 p.

Robinson, G.D., 1963, Geology of the Three Forks, Montana: U.S. Geological Survey Professional Paper 370, 143 p.

Robinson, G.D., Klepper, M.R., and Obradovich, J.D., 1969, Overlapping plutonism, volcanism, and tectonism in the Boulder batholith region, western Montana: Geological Society of America Memoir 116, p. 557–576.

Rubey, W.W., 1929, Origin of the siliceous Mowry Shale of the Black Hills: U.S. Geological Survey Professional Paper 154, p. 153–170.

Schwartz, R.K., and DeCelles, P.G., 1988, Cordilleran foreland basin evolution in response to interactive Cretaceous thrusting and foreland partitioning, southwestern Montana, *in* Schmidt, C.J., and Perry, W.J., Jr., eds., Interaction of Rocky Mountain foreland and the Cordilleran Thrust Belt: Geological Society of America Memoir 171, p. 489–513.

Simpson, G.G., 1937, The Fort Union of the Crazy Mountain field, Montana, and its mammalian faunas: U.S. National Museum Bulletin 169, 287 p.

Skeels, D.C., 1939, Structural geology of the Trail Creek–Canyon Mountain area, Montana: Journal of Geology, v. 47, no. 8, p. 816–840.

Skipp, Betty, 1977, Geologic map and cross section of the Wallrock quadrangle, Gallatin and Park Counties, Montana: U.S. Geological Survey Geologic Quadrangle Map GQ–1402, scale 1:24,000.

Skipp, Betty, and Hepp, Mary-Margaret, 1968, Geologic map of the Hatfield Mountain quadrangle, Gallatin County, Montana: U.S. Geological Survey Geologic Quadrangle Map GQ–729, scale 1:24,000.

Skipp, Betty, Lageson, D.R., and McMannis, W.J., 1999, Geologic map of the Sedan quadrangle, Gallatin and Park Counties, Montana: U.S. Geological Survey Geologic Investigations Series I–2634, scale 1:48,000.

Skipp, Betty, and McGrew, L.W., 1968, Late Paleocene thin-skinned deformation of the western edge of the Crazy Mountains Basin, Montana [abs.]: Geological Society of America Special Paper 115, p. 446–447.

Skipp, Betty, and McGrew, L.W., 1972, The Upper Cretaceous Livingston Group of the western Crazy Mountains Basin, Montana: Montana Geological Society, 21st Annual Field Conference Guidebook, p. 99–106.

Skipp, Betty, and McGrew, L.W., 1977, The Maudlow and Sedan Formations of the Upper Cretaceous Livingston Group on the west edge of the Crazy Mountains Basin, Montana: U.S. Geological Survey Bulletin 1422–B, 68 p.

Skipp, Betty, and McMannis, W.J., 1971, The Sedan quadrangle: U.S. Geological Survey Open-File Report 71–264, 2 sheets.

Spencer, C.W., 1985, Geologic aspects of tight gas reservoirs in the Rocky Mountain region: Journal of Petroleum Technology, July, p. 1308–1314.

Spencer, C.W., 1987, Hydrocarbon generation as a mechanism for overpressuring in the Rocky Mountain Region: American Association of Petroleum Geologists Bulletin, v. 71, p. 368–388.

Spencer, C.W., 1989, Review of characteristics of low-permeability gas reservoirs in western United States: American Association of Petroleum Geologists Bulletin, v. 73, p. 613–629.

Spencer, C.W., and Law, B.E., 1981, Overpressured, low-permeability gas reservoirs in Green River, Washakie, and Great Divide basins, southwestern Wyoming [abs.]: American Association of Petroleum Geologists Bulletin, v. 65, p. 569.

Stebinger, Eugene, 1914, The Montana Group of northwestern Montana: U.S. Geological Survey Professional Paper 90, p. 61–68.

Stone, D.W., 1983, Detachment thrust faulting in the Reed Point syncline, south-central Montana: The Mountain Geologist, v. 20, no. 4, p. 107–112.

Stone, R.W., and Calvert, W.R., 1910, Stratigraphic relations of the Livingston Formation of Montana: Economic Geology, v. 5, no. 7, p. 551–557, 652–659, 741–764.

Stow, M.H., 1946, Dating, sedimentation, volcanism and orogeny in Beartooth Mountain region, Montana, by heavy minerals: Geological Society of America Bulletin, v. 57, p. 675–686.

Thom, W.T., Jr., 1922, Oil and gas prospects in and near the Crow Indian Reservation, Montana: U.S. Geological Survey Bulletin 736–B, p. 35–53.

Thom, W.T., Jr., 1957, Tectonic relationships, evolutionary history and mechanics of origin of the Crazy Mountains Basin, Montana, *in* Graves, R.W., ed., Crazy Mountains Basin: Billings Geological Society 8th Annual Field Conference Guidebook, p. 9–21.

Thom, W.T., Jr., Hall, G.M., and Wegemann, C.H., 1935, Geology of Bighorn County and the Crow Indian Reservation Montana: U.S. Geological Survey Bulletin 856, 200 p.

Tyler, R., Kaiser, W.R., Scott, A.R., Hamilton, D.S., and Ambrose, W.A., 1995, Geologic and hydrologic assessment of natural gas from coal—Greater Green River, Piceance, Powder River, and Raton basins, Western United States: Austin, Texas, Bureau of Economic Geology, Report of Investigations No. 228, 219 p.

Tysdal, R.G., 1991, Depositional environments for strata of composite section of Frontier Formation, Madison Range, southwestern Montana: U.S. Geological Survey Bulletin 1949, 23 p.

Vhay, J.S., 1939, Some features of the Livingston Formation near Nye, Montana: Transactions of the American Geophysical Union, 20th Annual Meeting, pt. 3, p. 433–437.

Warchola, R.J., 1985, Roscoe Dome Field, *in* Tonnsen, J.J., ed., Montana Oil and Gas Fields Symposium: Montana Geological Society, p. 991–993.

Washburn, H.S., 1985, Fiddler Creek Field, *in* Tonnsen, J.J., ed., Montana Oil and Gas Fields Symposium: Montana Geological Society, p. 489–492.

Weed, W.H., 1893, The Laramie and overlying Livingston Formation in Montana: U.S. Geological Survey Bulletin 105, 68 p.

Weed, W.H., 1899, Description of the Fort Benton quadrangle, Montana: U.S. Geological Survey Geologic Atlas, Folio 56, 11 p.

Wegemann, C.H., 1918, The Salt Creek oil field: U.S. Geological Survey Bulletin 670, 52 p.

Weimer, R.J., 1984, Relation of unconformities , tectonics, and sea-level changes, Cretaceous of Western Interior, U.S.A., *in* Schlee, J.C., ed., Interregional unconformities and hydrocarbon accumulation: American Association of Petroleum Geologists Bulletin, v. 68, no. 1, p. 7–35.

Wilson, C.W. Jr., 1934, Geology of the thrust fault near Gardiner, Montana: Journal of Geology, v. 42, no. 6, p. 649–653.

Wilson, C.W. Jr., 1936, Geology of the Nye-Bowler lineament, Stillwater and Carbon Counties, Montana: American Association of Petroleum Geologists, v. 20, no. 9, p. 1161–1188.

Wise, D.U., 1997, Pseudo tear faults at Red Lodge, Montana—Clues to late-stage basin understuffing and tectonics of the Greater Beartooth block, *in* Campen, E.B., ed., 1997 Bighorn Basin Symposium Guidebook: Yellowstone Bighorn Research Association, Wyoming Geological Association, and Montana Geological Association, p. 70–99.

Woodward, L.A., 1981, Tectonic framework of disturbed belt of west-central Montana: American Association of Petroleum Geologists, v. 65, no. 2, p. 291–302.

Woodward, L.A., 1983, Structural geology of the Helena salient—A synopsis, *in* Smith, D.L., compiler, Guidebook of the Fold and Thrust Belt, west-central Montana: Guidebook of the Fold and Thrust Belt, west-central Montana: Montana Bureau of Mines and Geology Special Publication 86, p. 83–87.

Yin, P., and Surdam, R., 1993, Diagenesis and overpressuring in the Almond Sandstone, Mesaverde Group, *in* Stroock, B., and Andrew, S., eds., Jubilee Anniversary Field Conference Guidebook: Wyoming Geological Association, p. 349–357.

Basin Structure from Two-Dimensional Seismic Reflection Data, Crazy Mountains Basin, Montana

By David J. Taylor

Chapter B of

Stratigraphic Framework, Structure, and Thermal Maturity of Cretaceous and Lower Tertiary Rocks in Relation to Hydrocarbon Potential, Crazy Mountains Basin, Montana

By Ronald C. Johnson, Thomas M. Finn, David J. Taylor, and Vito F. Nuccio

Scientific Investigations Report 2004–5091–B

U.S. Department of the Interior
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Basin Structure from Two-Dimensional Seismic Reflection Data, Crazy Mountains Basin, Montana

By David J. Taylor

Abstract

Some 140 miles of multichannel seismic reflection data, acquired commercially in the 1970's, were reprocessed by the U.S. Geological Survey in late 2000 and early 2001 to interpret the subsurface geology of the Crazy Mountains Basin, an asymmetric Laramide foreland basin located in south-central Montana. The seismic data indicate that the northwestern basin margin is controlled by a thrust fault that places basement rocks over a thick (22,000 feet) sequence of Paleozoic and Mesozoic sedimentary rocks to the south. From the deep basin trough, Paleozoic through Tertiary rocks slope gently upward to the south and southeast. The northern boundary of the basin, which is not imaged well by the seismic data, appears to be folded over a basement ridge rather than being truncated against a fault plane. Seismic data along the basin margin to the south indicate that several fault-controlled basement highs may have been created by thin-skinned tectonics where a series of shallow thrust faults cut Precambrian, Paleozoic, and early Mesozoic rocks, whereas, in contrast, Cretaceous and Tertiary strata are folded. The data are further interpreted to indicate that this fault-bounded asymmetric basin contains several structures that possibly could trap hydrocarbons, provided source rocks, reservoirs, and seals are present. In addition, faults in the deep basin trough may have created enough fracturing to enhance porosity, thus developing "sweet spots" for hydrocarbons in basin-centered continuous gas accumulations.

Introduction

The Crazy Mountains Basin is located in south-central Montana just to the north and west of the northernmost part of the Bighorn Basin (fig. 1). The Crazy Mountains Basin is bounded on the south by the Beartooth Mountains, on the southeast by the Pryor Mountains, on the west by the Bridger Range, and on the northwest by the Big and Little Belt Mountains and Helena salient. A series of domes and anticlines are present along the north and northeast boundaries of the basin, and the Lake Basin fault zone is in the northeastern part of the basin (fig. 2). Tertiary Fort Union Formation rocks are present at the surface in the main part of the basin and Cretaceous rocks are present along the edges of the basin (fig. 2). As part of a joint Department of Energy (DOE) and U.S. Geological Survey (USGS) study to assess the Crazy Mountains Basin for deep and continuous gas resources, the USGS purchased 139.5 mi of low-fold two-dimensional seismic data from Seitel Solutions Inc. in 2000. Figure 3 shows the locations of the seismic data used in this study, and key wells located close to the seismic data that were used to guide the interpretation. Comparing the locations of these seismic lines with road maps of the area indicates that the seismic lines were shot primarily along the roads. Some of the wells have sonic log data and were located close enough to the two-dimensional seismic data to be used in the interpretation.

The goal of the seismic interpretation was to supplement and improve knowledge of the overall basin structure, which was previously derived from well data alone. Well data were used to determine the basic geometry of the sedimentary package, but could not be used to accurately determine depths to sedimentary-rock horizons in the deepest part of the basin, the location and geometry of the key faults controlling the edge of the basin, and the location and amount of throw on interior basin faults that control most of the subsurface. The seismic coverage is sparse; however, there are enough data to confirm and modify the well-based interpretations and to shed light on the mechanisms controlling potential gas-bearing structures.

Seismic Data Processing

Dresser Olympic acquired the seismic data used in this study in the summer of 1975 using the Vibroseis method. The frequency of the input sweep was 10–56 Hz (hertz) at a duration of 15 s (seconds). The record length was 20 s, recorded at a sample rate of 4 ms (milliseconds) on a DFS-IV recorder using a 48-channel split spread of receivers. The station interval was 220 ft. Receivers were spaced at each station; a spacing of 660 ft or every third station was used for vibrator

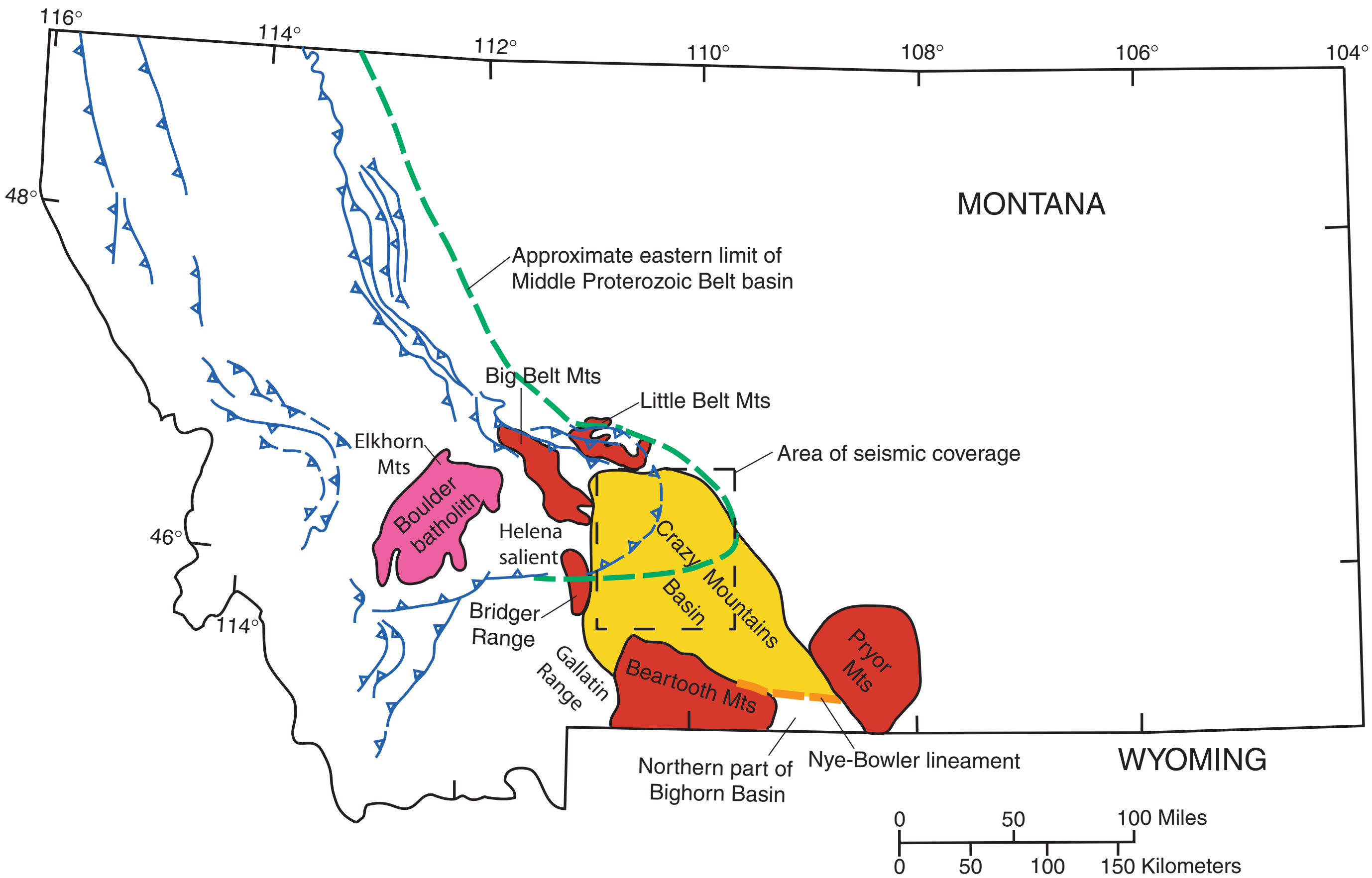

Figure 1. Location of Crazy Mountains Basin and surrounding uplifts in south-central Montana. (Modified from Johnson and Finn, Chapter A, this CD-ROM.)

points. The distance from the shot to the first receiver was 1,540 ft and the distance from the shot to the last receiver on either side of the shot was 6,600 ft. This shooting geometry produced six-fold common depth point (CDP) subsurface coverage.

The processing workflow used by Grant Geophysical Company, outlined in figure 4, yielded a final migrated section capable of being used in a structural interpretation. Note that only a single pass of automatic residual statics was applied to the data after velocity analysis and normal moveout correction. Present-day seismic processing commonly includes multiple passes of surface-consistent automatic residual statics, in conjunction with intermediate velocity analysis, normal moveout correction, and CDP stacking, to try to overcome discontinuities in the data from near-surface effects.

Processing by Grant Geophysical Company used a straight-line geometry definition that does not take into account the effect that a line bend has on the subsurface CDP locations. Straight-line geometry assumes that the CDP locations fall directly beneath the receiver line, but bends in the seismic acquisition line produce a smeared pattern in the CDP locations. Figure 5 is an illustration of the effect that a bend in the shot-receiver line has on the location of the CDP's. Several severe bends in the seismic lines used in this study produced CDP smear (fig. 3).

The unprocessed digital two-dimensional seismic data were reprocessed by the USGS using techniques and software newer than those used in the original 1980 vintage processing; many enhancements to reflection seismic data processing algorithms have been made since 1980. Using version 1998.1 of the Landmark Graphics Inc. ProMAX™ two-dimensional seismic data processing software produced improvement in the final imaging, but the original low-fold data acquisition still did not lend itself to major improvements through reprocessing.

Reprocessing performed by the USGS in 2000 and 2001 used both crooked-line geometry definition and multiple passes of surface-consistent automatic residual statics, velocity analysis, normal moveout correction, and CDP stacking in an effort to produce a more interpretable seismic section. Trace editing, deconvolution, and filtering processes were used by the USGS prior to velocity analysis and initial brute stacking. Because the surface-consistent automatic residual statics are horizon based, the quality of the initial brute stack should be maximized so that the best reflector can be used to define the horizon employed in the statics calculation. Figure 6 shows the workflow used by the USGS to reprocess the seismic data.

A comparison between the original 1980 processing by Grant Geophysical Company and the 2000–2001 reprocessing by the USGS is shown in figure 7. Both examples are from the

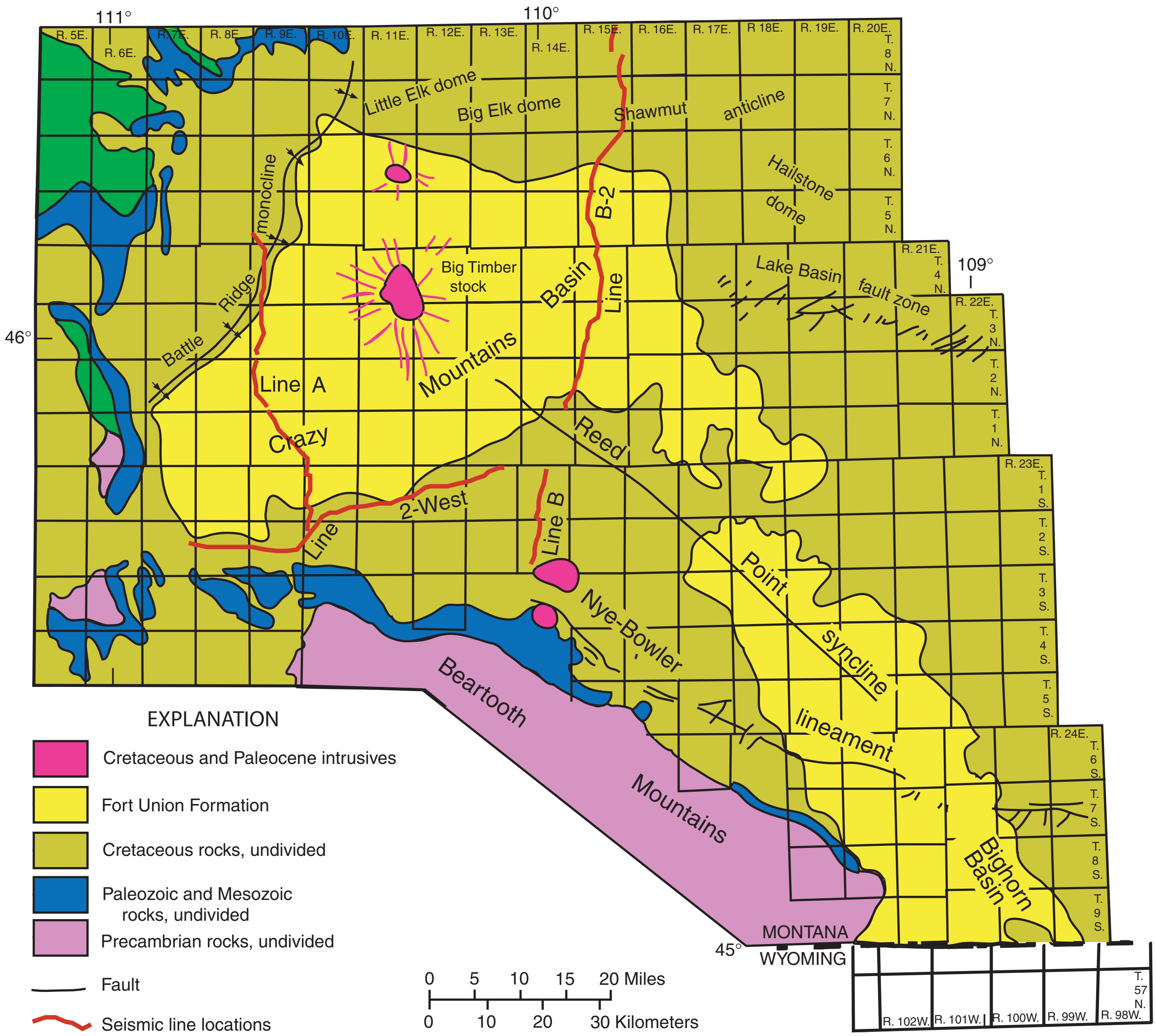

Figure 2. Generalized geology of Crazy Mountains Basin area, Montana, and locations of two-dimensional seismic lines used in this study. (Modified from Johnson and Finn, Chapter A, this CD-ROM.)

same segment of the north-south seismic line A and have been processed through migration. The comparison shows a slight improvement in reflection continuity and fault definition on the USGS processed lines. In both examples, a prominent fault is clearly evident cutting through many of the strong reflections starting at about 1.0 s and ending at about 2.2 s two-way travel time. The Stolt F-K migration performed by the USGS seems to have collapsed many of the diffractions seen on the original 1980 processing, thus making it easier to properly locate the fault.

Several of the seismic lines were shot in segments. Line A, for example, was shot in three segments but the shooting geometry defined in the observer's notes allowed it to be processed as a single line with gaps separating the segments. Because the geometry was defined across the gaps, the distance represented by the gap is accurate. Line B-2 was also shot in segments, but in this case the segments overlapped so the line could be merged and displayed as a single line.

Well-to-Seismic Correlation

Synthetic seismograms were generated using sonic and density log data acquired from wells located close to the seismic lines. If no density log was present, then a reasonable constant value was assumed for the density contribution.

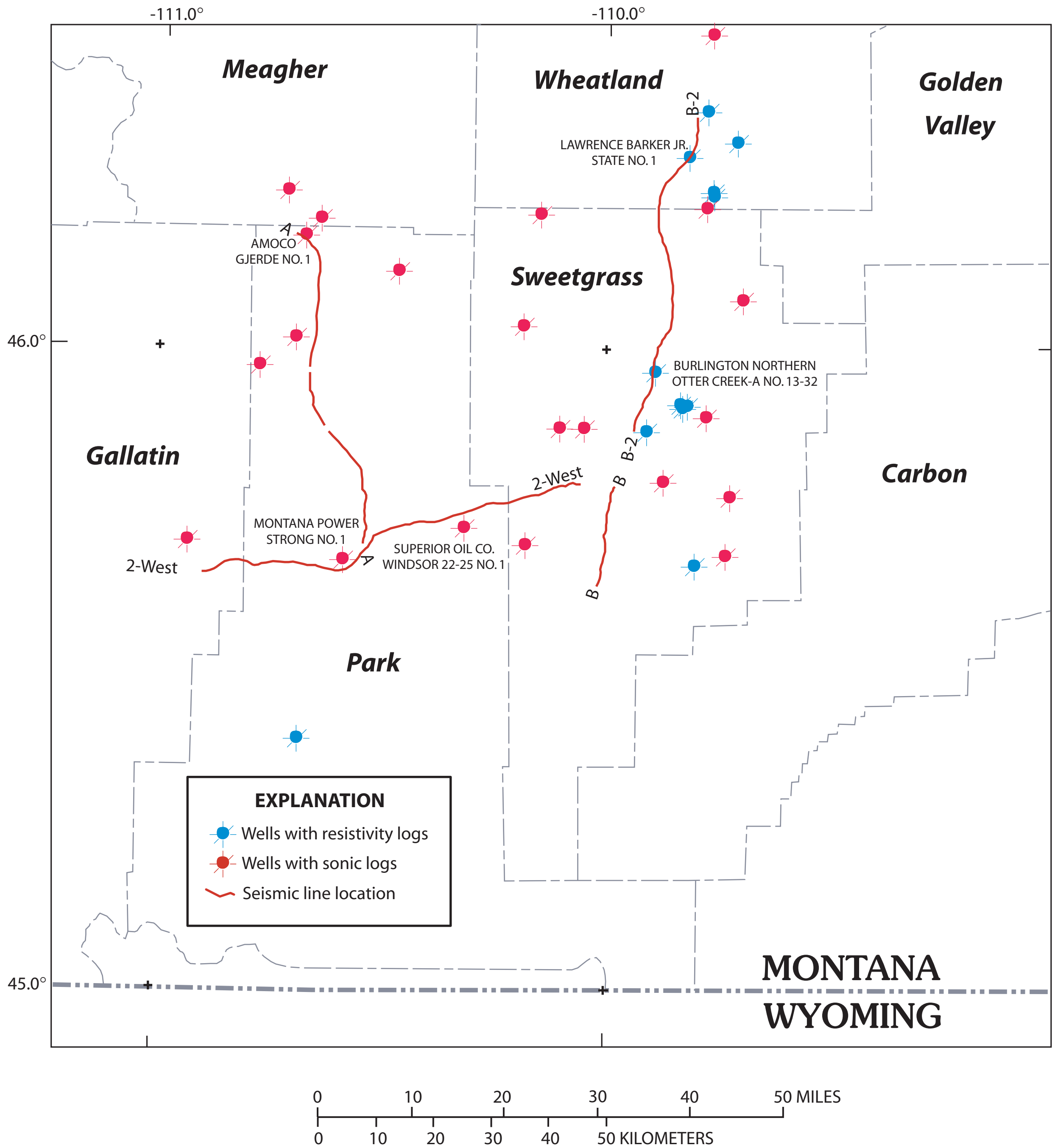

Figure 3. Locations of two-dimensional seismic lines used in this study.

Sheriff's (1991) formula for calculating reflection coefficients is

$$R = (\rho_{n+1} V_{n+1} - \rho_n V_n)/(\rho_{n+1} V_{n+1} + \rho_n V_n)$$

where R=reflection coefficient,
ρ=density log value, and
V=velocity log value.

Once the reflection coefficients are calculated for every log-depth sample, n, then a wavelet is convolved with the reflection coefficient series to produce a synthetic seismic trace. Generally several copies of the synthetic seismic trace are displayed side-by-side to produce a synthetic seismogram.

The synthetic seismograms were created and matched to the adjacent two-dimensional surface seismic data using the Landmark Graphics Inc.–GeoGraphix SeisVision™ software. The resulting time-to-depth relations were used to correlate key geologic horizons penetrated in a well with seismic reflections recorded in two-way travel time on the seismic section. Figure 8 shows a synthetic seismogram generated using the sonic log data from the Superior Oil Co. Windsor 22-25 No. 1 well matched to adjacent two-dimensional surface seismic

Typical Grant Geophysical Company Data Processing Sequence
for
Crazy Mountains Basin Multichannel Seismic Reflection Data

1: Demultiplex and Vibroseis Correlation

2: Binary Gain Removal and Program Gain Curve Application

3: Compute Straight-Line Geometry and Elevation Statics
 Replacement Velocity: 11,000 ft/s
 Datum: 4400 ft

4: Sort from Shot Records to CDP Gathers

5: Deconvolution
 Type: Predictive
 Operator Length: 180 ms
 Design Gate (1): 400–1500 ms
 Design Gate (2): 1500–3400 ms

6: Band Pass Filter (Single Window)
 10–52 Hz

7: Velocity Analysis

8: Normal Moveout Correction

9: First Break Suppression

10: Automatic Residual Statics Calculation and Application
 3-Trace Model
 Window: 800–3300 ms

11: CDP Stack

12: Band Pass Filter (Single Window)
 12–48 Hz

13: Automatic Gain Control (AGC)

14: Wave Equation Migration

Figure 4. Workflow used by Grant Geophysical Company to perform original 1980 industry standard two-dimensional seismic data processing.

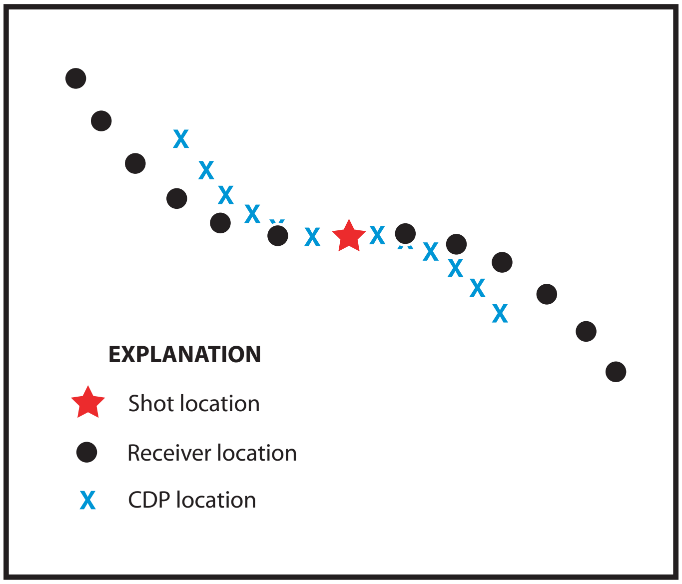

Figure 5. An example of common depth point (CDP) smear pattern caused by a bend in seismic acquisition line. Using crooked-line geometry definition in processing accounts for CDP smear by properly defining bins that allow all CDP locations to be used in stacking process.

data along two-dimensional seismic line 2-West. The synthetic seismogram had to be shifted and then stretched and squeezed in order to attain the best possible match because the well is located 2 mi south of a complex structure present on the seismic line.

An adjusted time-to-depth table was generated from the stretched and squeezed synthetic seismogram and used to position geologic-top markers on the seismic data. The offset in the lines representing formation tops from the sonic log to the actual seismic section in figure 8 is caused by the time adjustments needed to match the synthetic traces to the actual two-dimensional seismic data. Time-to-depth tables were generated to correlate formation tops with seismic reflections, and those markers were then used to interpret horizons on all of the seismic profiles. This procedure was done for several wells located close to the seismic lines that had good sonic log data available. Figure 9 is an example of how this procedure was used to correlate key geologic horizons with seismic reflections between the Windsor 22-25 No. 1 well and two-dimensional seismic line 2-West.

Many of the wells were shallow and did not penetrate lower Paleozoic or Precambrian(?) basement rocks, but they penetrated Cretaceous rocks, which are the main zone of interest in the study. Other wells were located too far away from the seismic lines to provide accurate correlations, even though they penetrated most of the sedimentary section. This limited to about five the number of wells that could be used for interpreting basin structure in conjunction with the seismic data, thus emphasizing the importance of supplementing those sources of data with available surface geologic mapping and stratigraphic studies to improve subsurface interpretations, as indicated in later discussions.

Seismic Interpretation

Seismic line A, the westernmost north-south seismic line, runs through the deepest part of the Crazy Mountains Basin (pl. 1). Using synthetic seismogram time-to-depth table extrapolation from nearby well data and velocity information from the USGS reprocessing, a reasonable depth to acoustic basement was determined. Plate 1 shows that sedimentary rocks reach a maximum two-way travel time of 3.2 s at the northern end of seismic line A, which translates to more than 20,000 ft of sedimentary section measured from a seismic datum of 4,400 ft above sea level.

Seismic line A crosses a large thrust fault that forms the east edge of the Helena salient, a major eastward bulge in the Sevier orogenic belt (fig. 1); the Battle Ridge monocline is the surface manifestation of this fault (fig. 2). This major thrust fault is located just to the north of the deep basin and shows a displacement represented by 900 ms (0.9 s) of two-way travel time at acoustic basement (Precambrian?). At this depth, velocity information from extrapolated sonic logs in the area and velocity analysis generated in the USGS reprocessing indicate that 900 ms (0.9 s) is equivalent to about 8,100 ft of offset. There appears to be a small fault-controlled anticline north of the thrust fault at the northernmost end of the seismic line (pl. 1). This anticline may be one of a series of anticlines present northwest of the Battle Ridge monocline (Garrett, 1972).

Proceeding south out of the deep basin on seismic line A, sedimentary rocks slant upward markedly. Acoustic basement (Precambrian?) is interpreted to rise from its deepest point of 3.2 s on seismic line A to about 1.5 s of two-way travel time. Several other basement-cutting faults just to the south of the major thrust fault appear to produce offsets in Paleozoic, lower Mesozoic, and Cretaceous rocks. Two gaps caused by a discontinuity in shooting seismic line A can be seen on plate 1.

Both sides of another anticline at the southern part of seismic line A seem to be faulted. Near the south end two minor basement faults also displace Paleozoic rocks. Cretaceous strata are not offset, but there is a small rollover structure in these rocks above the faults.

Seismic line 2-West extends generally east-west south of the deep basin trough and nearly intersects the north-south seismic line A except for a small gap of about 0.25 mi (figs. 2 and 3). Garrett (1972, fig. 10) showed that seismic line 2-West crosses several features, such as the Livingston "Shift Zone," the Livingston nose, and the Canyon and Pine Mountain anticlines. The line is oriented at an oblique angle to these features, which may have caused energy to be scattered away from the receivers or to have produced numerous side echoes, resulting in poor-quality data and making the interpretation difficult. Two wells with sonic log data located near

Typical USGS Data Reprocessing Sequence
for
Crazy Mountains Basin Multichannel Seismic Reflection Data

1: SEG-Y Input and Vibroseis Correlation

2: Automatic Gain Control (AGC)
Operator Length: 500 ms

3: Band Pass Filter (Single Window)
5–10–40–45 Hz

4: Compute Crooked Line Geometry

5: Trace Muting
Type: Mute First Breaks

6: Kill Bad Traces

7: Deconvolution
Type: Zero-Phase Spiking
Operator Length: 180 ms
Design Gate Near Offset: 320–5000 ms
Design Gate Far Offset: 1350–5000 ms

8: Band Pass Filter (Single Window)
5–10–42–48 Hz

9: Apply Elevation Statics
Replacement Velocity: 11,000 ft/s
Datum: 4400 ft

10: Velocity Analysis and Normal Moveout Correction

11: CDP Stack (Brute Stack)

12: Max-Power Automatic Residual Statics
7-Trace Pilot Model
Window Length: 500 ms
Iterations: 15
Max Static Allowed: 20 ms

13: Apply Residual Statics

14: Velocity Analysis and Normal Moveout Correction

15: Max-Power Automatic Residual Statics
11-Trace Pilot Model
Window Length: 200 ms
Iterations: 25
Max Static Allowed: 10 ms

16: Apply Residual Statics

17: Velocity Analysis and Normal Moveout Correction

18: CDP Stack (Final Stack)

19: Move to Final Datum

20: Band Pass Filter (Single Window)
5–10–46–52 Hz

21: Automatic Gain Control (AGC)
Operator Length: 500 ms

22: Memory Stolt F-K Migration

23: Band Pass Filter (Single Window)
10–14–42–48 Hz

24: Automatic Gain Control (AGC)
Operator Length: 500 ms

Figure 6. Chart showing workflow used by U.S. Geological Survey to reprocess seismic data in 2000–2001. Note that data were reprocessed using same datum and replacement velocity values as original 1980 processing by Grant Geophysical Company (fig. 4).

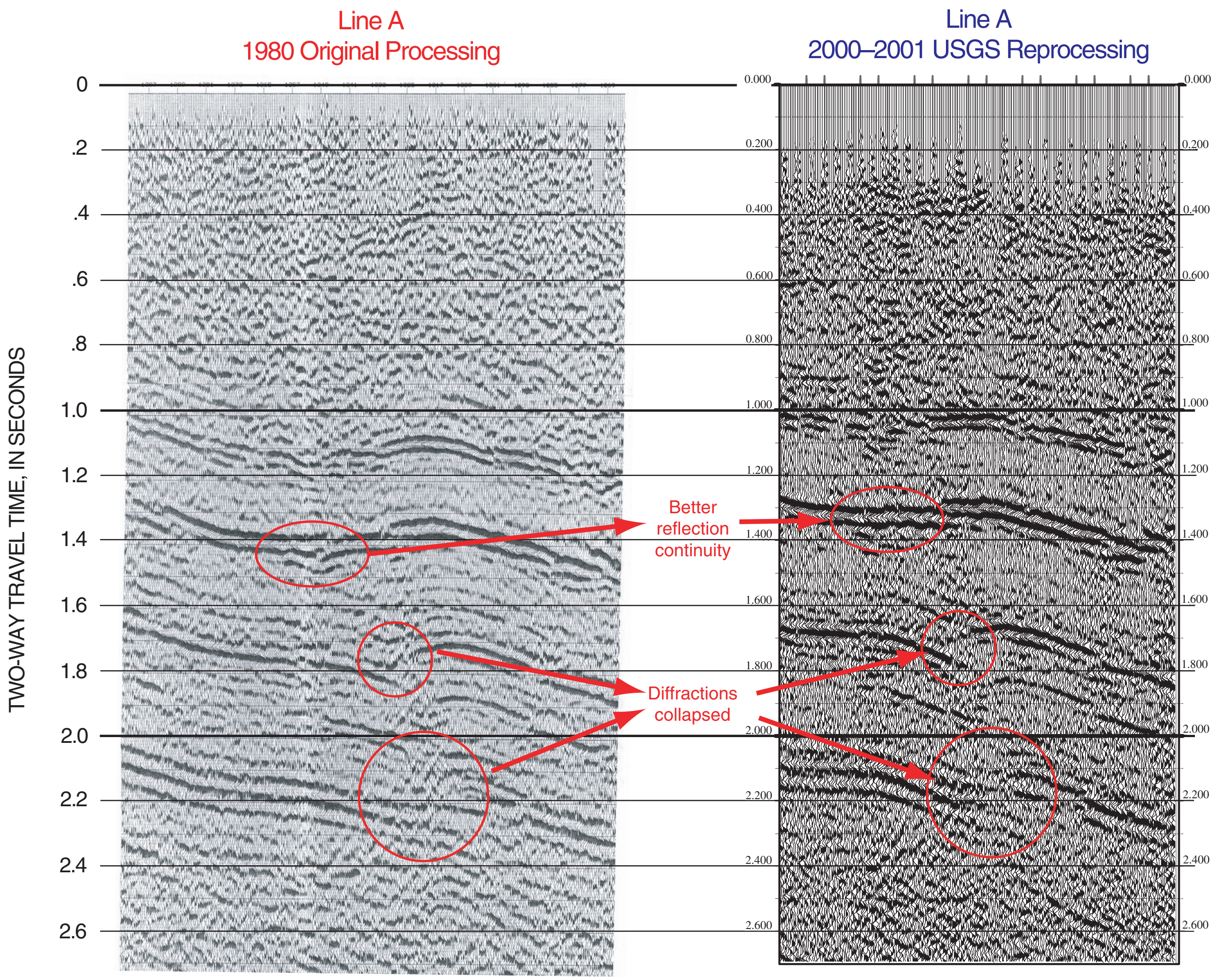

Figure 7. Comparison of original 1980 seismic processing for part of seismic line A by Grant Geophysical Company and same part of seismic line A reprocessed by U.S. Geological Survey in 2000–2001.

seismic line 2-West were used to guide the interpretation (fig. 3). One of these, the Superior Oil Co. Windsor 22-25 No. 1, is located about 2.0 mi south of the seismic line. The other is the Montana Power Strong No. 1, located on a basement high near the town of Livingston across which no seismic acquisition was permitted (shown by the data "gap" in the upper part of seismic line 2-West on plate 2). The interpretation shown on plate 2 incorporates information from the jump-correlation with seismic line A and the synthetic seismogram data prepared from the Superior and Montana Power wells. The interpretation is problematic toward the west end of the line, where the line runs close to the Canyon and Pine Mountain anticlines (pl. 2).

Acoustic basement interpreted on seismic line 2-West is highly faulted; most of these faults penetrate Paleozoic strata and some extend upward into Cretaceous rocks. All of the faults appear to be reverse faults owing to the compressional stress regime. Faulting is complex across an area called the "Shift Zone" (fig. 10, pl. 2) by Garrett (1972), which he described as being an extension of faulting into the Crazy Mountains Basin from the west edge of the Snowy Range block. These faults are interpreted on that part of seismic line 2-West shown in figure 9 and plate 2, and are located on either side of the tie with the Superior Oil Co. Windsor 22-25 No. 1 well.

Seismic line B (pl. 3) is a short south-to-north line between the Beartooth Mountains and the town of Big Timber (fig. 10). Plate 3 shows Paleozoic and Mesozoic strata dipping northward into the basin over acoustic basement (Precambrian?) that is cut by reverse faults, again signifying a compressive stress regime. Faults labeled "Fault-A" and "Fault-B" on plate 3 form a small horst block in acoustic basement and

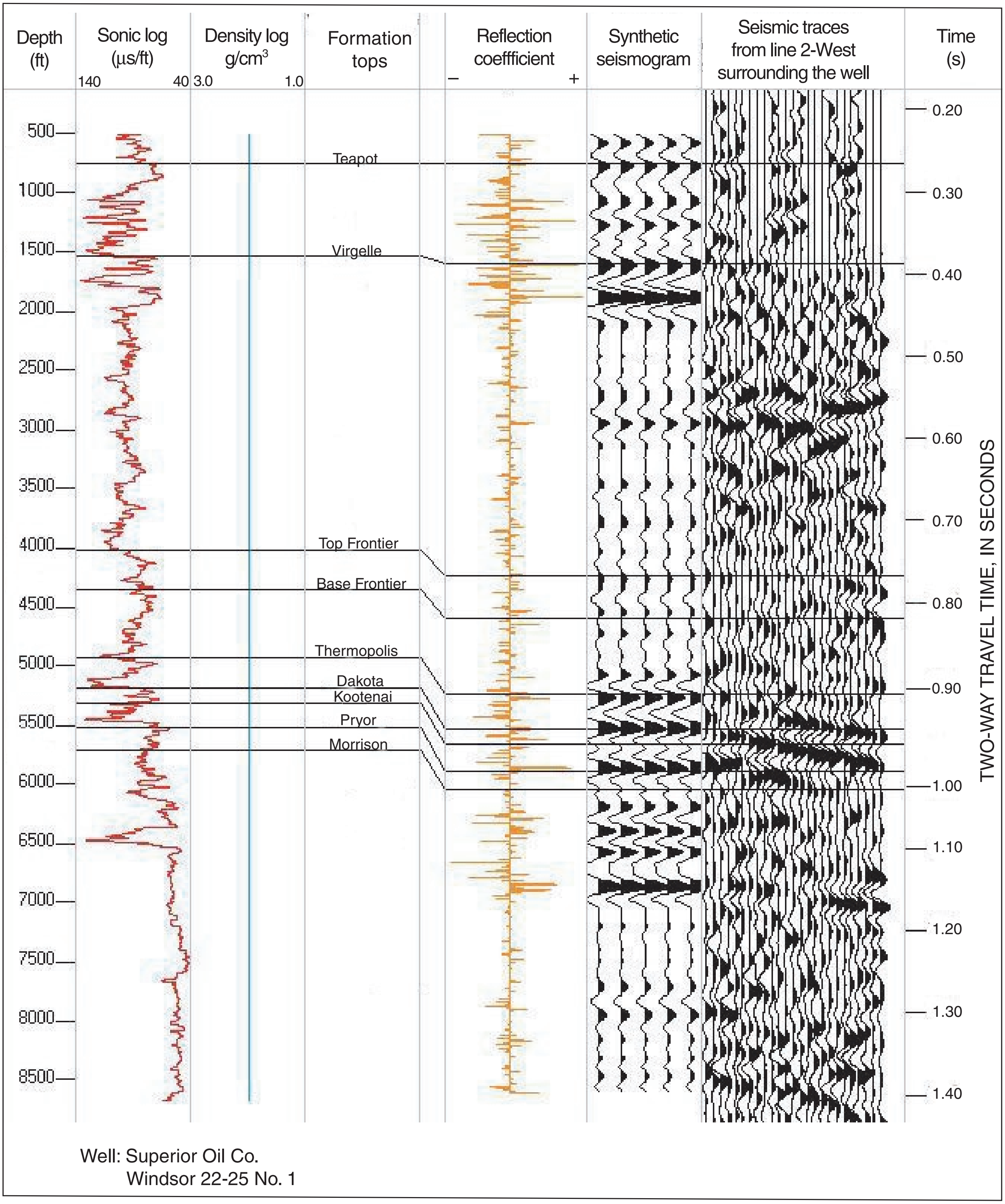

Figure 8. Synthetic seismogram generated using sonic log data from Superior Oil Co. Windsor 22-25 No. 1 well located 2 mi south of seismic line 2-West. Synthetic seismogram has been time adjusted to match actual seismic data taken from line 2-West. Geologic formation tops encountered in well have been inserted and labeled. (See Johnson and Finn, Chapter A, this CD-ROM, for description of geologic formation tops.)

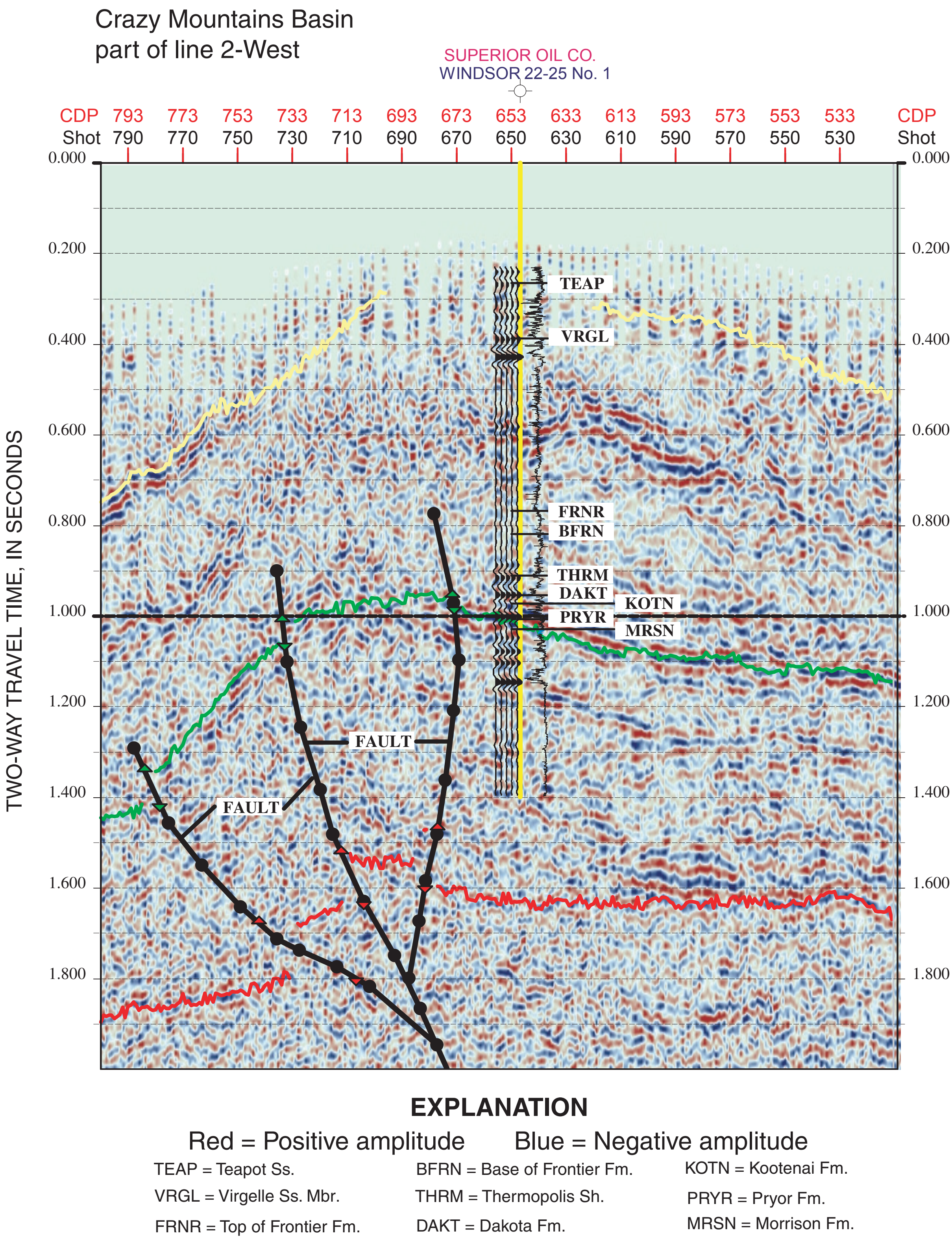

Figure 9. Part of two-dimensional seismic line 2-West showing correlation with synthetic seismogram generated using sonic log data from Superior Oil Co. Windsor 22-25 No. 1 well located 2 mi south of seismic line. Synthetic seismogram (left side) and sonic log (right side) have been inserted on either side of borehole track, and interpreted geologic formation tops have been inserted at proper time based on time-to-depth table produced from matched synthetic seismogram. Several geologic horizons have been interpreted based on correlation between synthetic seismogram and two-dimensional seismic data. Yellow horizon is near top of Cretaceous, green horizon is near base of Cretaceous, and red horizon represents top of acoustic basement (top of Precambrian?).

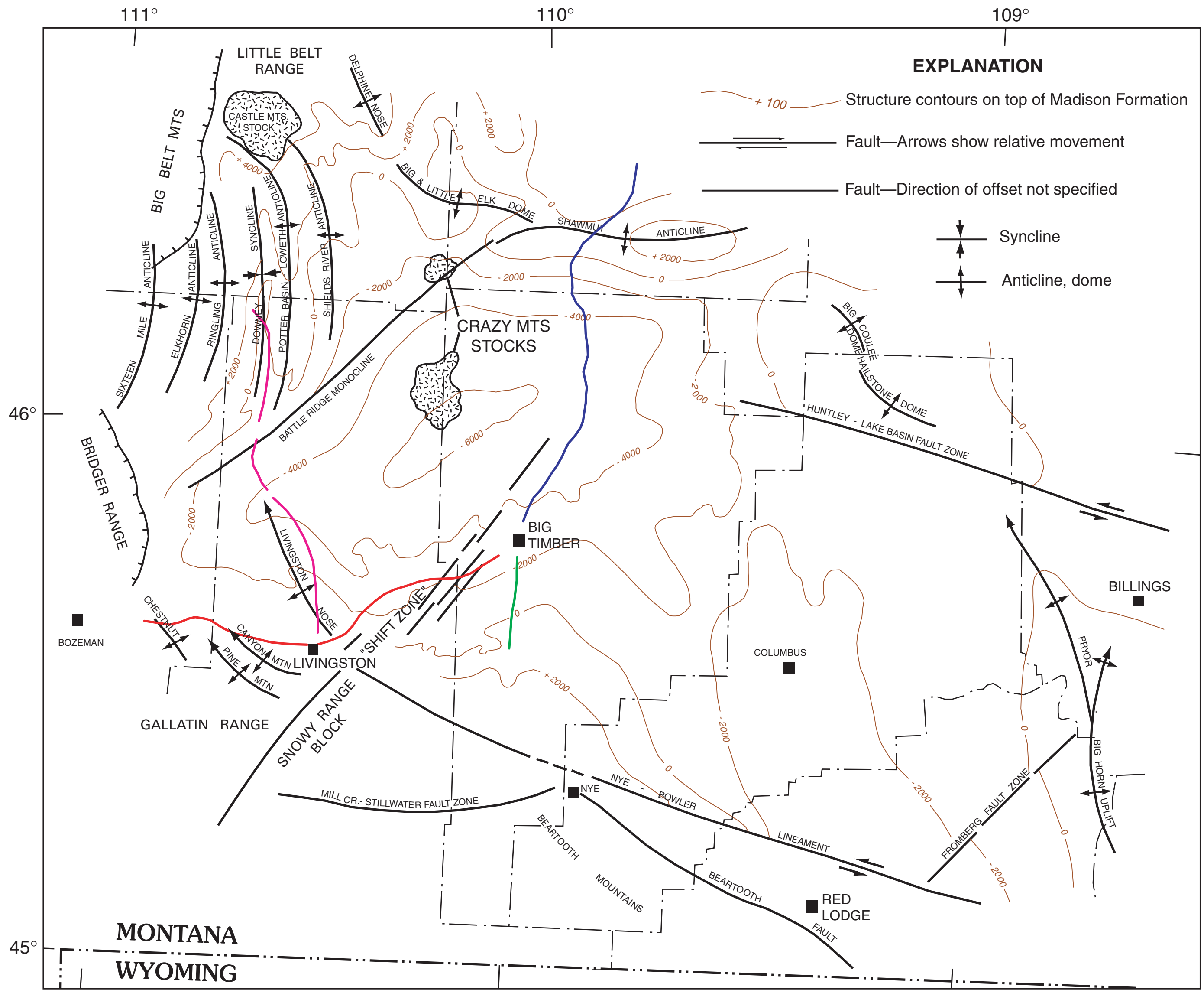

Figure 10. Structural features in Crazy Mountains Basin area (from Garrett, 1972). Approximate location of seismic line 2-West in red, seismic line A in magenta, seismic line B in green, and seismic line B-2 in blue.

cut through part of the overlying strata. The north end of the line is located 1.75 mi east of the end of seismic line 2-West and 6.0 mi southwest of seismic line B-2 (fig. 1).

Seismic line B-2 (pl. 4) was shot in several pieces, producing gaps and overlaps in the acquired data. The line was processed in individual pieces and merged as a single composite line during the interpretation phase. It starts just to the north of the town of Big Timber and ends well to the north of the study area. The USGS purchased all of the line to a point in Wheatland County located just north of the Shawmut anticline (fig. 10). The interpreted line (pl. 4) shows that the gentle northerly dip of acoustic basement (Precambrian?) and the Paleozoic, Lower Mesozoic, Cretaceous, and Paleocene strata are interrupted by the basement-cored Shawmut anticline. These strata all have a relatively uniform seismic thickness south of the Shawmut anticline, where Cretaceous strata are exposed at the surface.

Few structures besides the Shawmut anticline are seen on interpreted seismic line B-2 (pl. 4). A fault-controlled ripple in acoustic basement just to the south of the anticline also corresponds to a line bend, so the geometry of the line may have contributed to the apparent structure in front of the anticline. The south flank of the Shawmut anticline appears to be caused by a bulge in acoustic basement rather than being fault controlled, but the data are ambiguous. Also, there are not enough data on the north side of the anticline to determine whether faults are controlling the structure on that flank. Minor reverse faults along the line to the south, offsetting rocks from acoustic basement (Precambrian?) through Cretaceous, produce a minor drape fold in the overlying, unfaulted strata.

Petroleum Potential

The presence of petroleum in the Crazy Mountains Basin was first noted in 1888, when oil seeps were observed coming from steeply dipping sandstone beds along the Beartooth Mountains front (Hadley, 1972). Exploration began in earnest in the early 1920's and, based on the level of exploration that has taken place since then, it is suspected that most of the major structures have been tested. However, there remains the possibility of additional discoveries in other types of traps. Other reports in this volume (Johnson and Finn, Chapter A; Johnson, Nuccio, and Finn, Chapter C) contain discussions on the possibility for basin-centered continuous gas accumulations in low-permeability sandstones of Cretaceous age in the deep basin trough. If unconventional traps do exist (there are few deep drill holes to test the potential), pathways for migrating gas and reservoir porosities may locally be enhanced within zones of faulting and fracturing as shown on the seismic profiles (pls. 1–4).

Better imaging of the faults and fractures present in the Crazy Mountains Basin might be achieved by enhancing the two-dimensional seismic data through the use of refraction statics. These techniques were not used in either the original processing by Grant Geophysical Company or more recently by the USGS. More advanced seismic studies involving modern three-dimensional acquisition and processing may improve the ability of the seismic method to locate highly fractured areas through the use of coherence technology and seismic attribute mapping.

Conclusions

Combined interpretation of seismic and well data indicates that the Crazy Mountains Basin is markedly asymmetric. Cretaceous, lower Mesozoic, and Paleozoic sedimentary rocks along the east and southeast margins dip gently toward the deep basin into a large basin-bounding thrust fault that may be associated with the Battle Ridge monocline on the west and northwest margins. The acoustic basement (Precambrian?) is highly faulted and predominantly involves reverse movement, indicating that compressional stresses produced both large and small structures in the basin. Lower Mesozoic and Paleozoic sedimentary rocks appear to be of uniform thickness on seismic profiles throughout the basin, whereas the Cretaceous section is thicker near the basin trough (line A) than near the basin margins (lines 2-West, B, and B-2), indicating that the basin began to subside in Late Cretaceous time. Faulting and fracturing in the deep basin interior may have locally enhanced porosities in low-permeability sandstone reservoirs and contributed to the potential for basin-centered gas accumulations.

References Cited

Garrett, H.L., 1972, Structural geology of the Crazy Mountains Basin: Montana Geological Society, 21st Annual Geological Conference Guidebook, p. 113–118.

Hadley, H.D., 1972, A philosophical review with some conclusions concerning the search for oil and gas in the Crazy Mountains Basin, Montana: Montana Geological Society, 21st Annual Geological Conference Guidebook, p. 159–163.

Sheriff, R.E., 1991, Encyclopedic dictionary of exploration geophysics, Third Edition: Society of Exploration Geophysicists, Geophysical References Series No. 1, 376 p.

Thermal Maturity and Petroleum Generation History of Cretaceous and Tertiary Source Rocks, Crazy Mountains Basin, Montana

By Ronald C. Johnson, Vito F. Nuccio, and Thomas M. Finn

Chapter C of

Stratigraphic Framework, Structure, and Thermal Maturity of Cretaceous and Lower Tertiary Rocks in Relation to Hydrocarbon Potential, Crazy Mountains Basin, Montana

By Ronald C. Johnson, Thomas M. Finn, David J. Taylor, and Vito F. Nuccio

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By Ronald C. Johnson, Vito F. Nuccio, and Thomas M. Finn

Abstract

A thermal maturity investigation using vitrinite reflectance and petroleum generation modeling was conducted for the Crazy Mountains Basin, a structurally deep and sparsely drilled sedimentary basin in south-central Montana. The basin formed from Late Cretaceous Maastrichtian through Paleocene time largely as a result of thrust loading along the Helena salient, an eastward bulge in the Cordilleran overthrust belt west of the basin. The deep trough of the basin was extensively intruded by stocks, dikes, and sills in middle Eocene time, after basin subsidence had largely ceased, and the presence of these intrusions has discouraged exploration for hydrocarbons in the basin.

Overall thermal maturity levels are higher than in other Rocky Mountain basins, with surface vitrinite reflectance values ranging from 0.35 to 1.97 percent (most values are between 0.6 percent and 1.1 percent), and subsurface values ranging from 0.73 to 6.72 percent. Thermal maturity levels are highest near the Eocene stocks, but levels are elevated throughout most of the basin, including areas where no Eocene intrusions have been mapped. Variations in surface vitrinite reflectance levels from closely spaced samples collected along transects away from major intrusions indicate that heating, although regional in extent, was also variable.

A pulse of heat in middle Eocene time (51–46 Ma) is required to successfully model the observed vitrinite reflectance values in both the intruded area of the basin and the more marginal areas where little evidence for intrusive activity is present. Petroleum generation modeling for two wells from marginal areas of the basin indicates that gas generation in the coaly intervals in the Upper Cretaceous Eagle Sandstone began in the first well at 63 Ma, peaked at 56 Ma, and largely ended by 40 Ma, whereas in the second well, the onset occurred at 62 Ma, peaked at 54 Ma, and largely ended by 35 Ma. Modeling at one well 6 mi from Big Timber stock, the largest stock in the basin, indicates that gas generation began even earlier, about 66 Ma, peaked at 63 Ma, and largely ended by 54 Ma. Thus, gas generation probably began prior to the middle Eocene intrusive event (51–49 Ma) throughout much of the basin, and the main impact of the intrusive event was to accelerate the rate of gas generation, thereby compressing the period of significant gas generation into a relatively narrow time span.

Introduction

The Crazy Mountains Basin is a northwest-trending, structurally deep sedimentary basin of about 7,800 mi^2 in south-central Montana that formed mainly in Late Cretaceous and early Tertiary time (fig. 1). It is probably the most under-explored basin for hydrocarbons in the Rocky Mountain region, with only shallow hydrocarbon production from anticlinal traps around the basin margins to date, and but few wells drilled near the deep basin trough. This report is part of a series of studies by the U.S. Geological Survey, sponsored by the U.S. Department of Energy National Energy Technology Lab in Morgantown, W. Va., to evaluate the “unconventional” basin-centered gas accumulations found in the deep areas of many Rocky Mountain basins. Reservoirs within this type of gas accumulation typically have low permeabilities (in-situ permeability to gas of 0.1 millidarcy [mD] or less) and differ from conventional gas accumulations in that they (1) cut across stratigraphic units, (2) commonly occur structurally down dip from more permeable water-filled reservoirs, (3) have no obvious structural and stratigraphic trapping mechanism, and (4) are almost always either overpressured or underpressured. Many such accumulations are being actively developed at the present time in several Rocky Mountain basins other than the Crazy Mountains Basin.

This lack of exploration in the Crazy Mountains Basin probably is due in large part to the presence of several sizable igneous stocks as well as numerous dikes and sills in the deep part of the basin (fig. 2). These igneous rocks and associated metasedimentary rocks, forming the core of the Crazy Mountains, are much more resistant to weathering than the surrounding sedimentary rocks. With maximum elevations exceeding 11,200 ft, these mountains tower more than a mile above the surrounding countryside. Recent success at

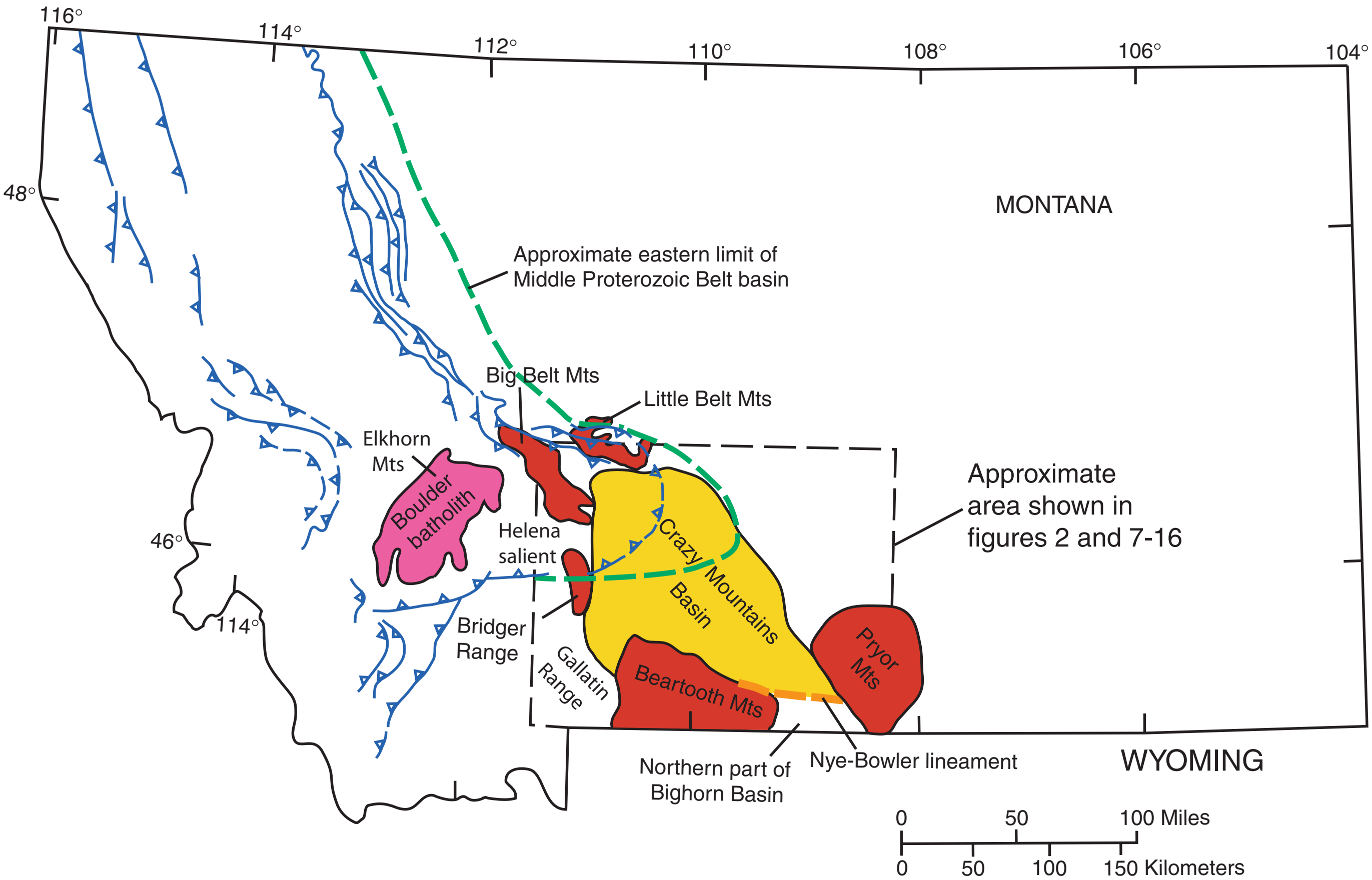

Figure 1. Location of Crazy Mountains Basin and surrounding uplifts in south-central Montana.

developing the coalbed methane resources of the Raton Basin of Colorado and New Mexico demonstrates that the presence of numerous intrusions does not preclude the presence of economic hydrocarbon deposits. Like the Crazy Mountains Basin, the Raton Basin was intruded by stocks and a large number of dikes and sills (Steven, 1975).

Prior to this investigation, the only thermal maturity data published in the basin were Rock-Eval analyses of the Upper Cretaceous Mowry Shale and Lower Cretaceous Skull Creek Member of the Thermopolis Shale from four wells near the margins of the basin; the analyses indicate that these shales were within the oil window (Burtner and Warner, 1984). Apparently no vitrinite reflectance data for the Crazy Mountains Basin have been published, but coal rank information for the Livingston coalfield in the southwestern part of the basin indicated that the coals there were of high volatile bituminous rank (Roberts, 1966). The purpose of this investigation was to obtain both surface and subsurface vitrinite reflectance information in order to better understand the thermal history of the Crazy Mountains Basin. Surface vitrinite reflectance was used to study variations in thermal maturities across the basin whereas subsurface samples were used to study how thermal maturities vary in a vertical sense.

A total of 79 surface vitrinite reflectance samples was collected throughout the basin, 75 of which yielded useful results (fig. 3, table 1). Samples were collected from coal beds, coal lenses in shales and sandstones, and coalified logs, wood fragments, and leaf remains in fluvial channel sandstones. Care was taken to obtain the freshest samples possible. In addition, 14 of the deepest oil and gas exploration wells were extensively sampled for vitrinite reflectance (fig. 5, table 2). Cuttings from these wells are stored at the USGS Core Library in Denver, Colo. A total of 98 vitrinite samples was analyzed from these holes, with depths ranging from 305 ft to 10,750 ft (table 2).

Regional Setting of the Crazy Mountains Basin

The Crazy Mountains Basin in south-central Montana is bounded on the southwest by the Beartooth Mountains and Gallatin Range, on the west by the Bridger Range, on the northwest by the Big Belt Mountains, on the north by the Little Belt Mountains, and on the southeast by the Pryor Mountains (figs. 1 and 2). The basin is separated from the Bighorn Basin to the south by the Nye-Bowler lineament, a northwest-trending zone of faulting and anticlinal development (figs. 1 and 2). The Crazy Mountains Basin is one of

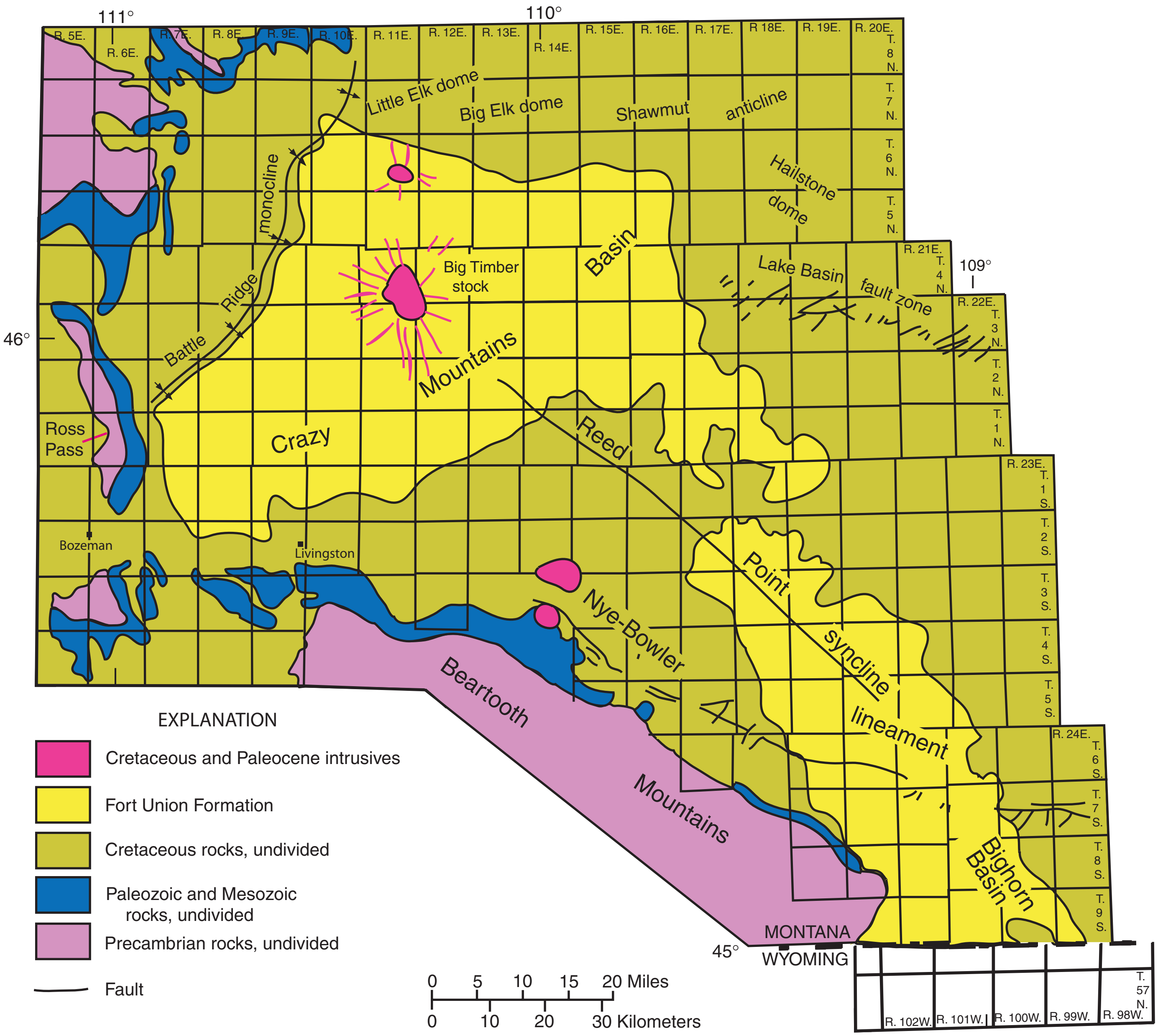

Figure 2. Generalized geology of Crazy Mountains Basin, Montana.

the deeper Rocky Mountain basins, containing an estimated thickness of more than 30,000 ft of Phanerozoic rocks (Kent, 1972, his fig. 1). Upper Cretaceous and lower Tertiary rocks compose the majority of this thick sequence (fig. 4).

The Crazy Mountains Basin is in a structurally complex area that was impacted by both the Sevier (Jurassic through early Eocene) and Laramide (Cretaceous through late Eocene) Orogenies. The Sevier Orogeny was characterized by eastward thrusting along the Sevier orogenic belt. Thrusting occurred in response to active subduction along the west margin of the North American continent. Subsidence, related to thrust loading (Price, 1973; Jordan, 1981; Beaumont, 1981; Beck, 1985; Beck and others, 1988) and possibly subduction-induced mantle flow (Mitrovica and others, 1989; Gurnis, 1992; Stern and Holt, 1994; Pysklywec and Mitrovica, 1998), created the Rocky Mountain foreland basin east of the thrust belt. During Late Cretaceous and Paleocene time, thrusting began in the western part of the orogenic belt and generally progressed eastward with time. Maximum structural and topographic relief occurred along the older, western part of the thrust belt mainly because of repeated periods of passive uplift and the further displacement of older thrust sheets riding “piggy back style” on the hanging walls of younger thrust sheets (DeCelles, 1994). Thrusting along the Sevier orogenic belt is generally thought of as “thin skinned’ because of the low angle of the thrust faults and because the thrusting generally does not involve Precambrian crystalline rocks. This is particularly true in the eastern, younger part of the thrust belt; however,

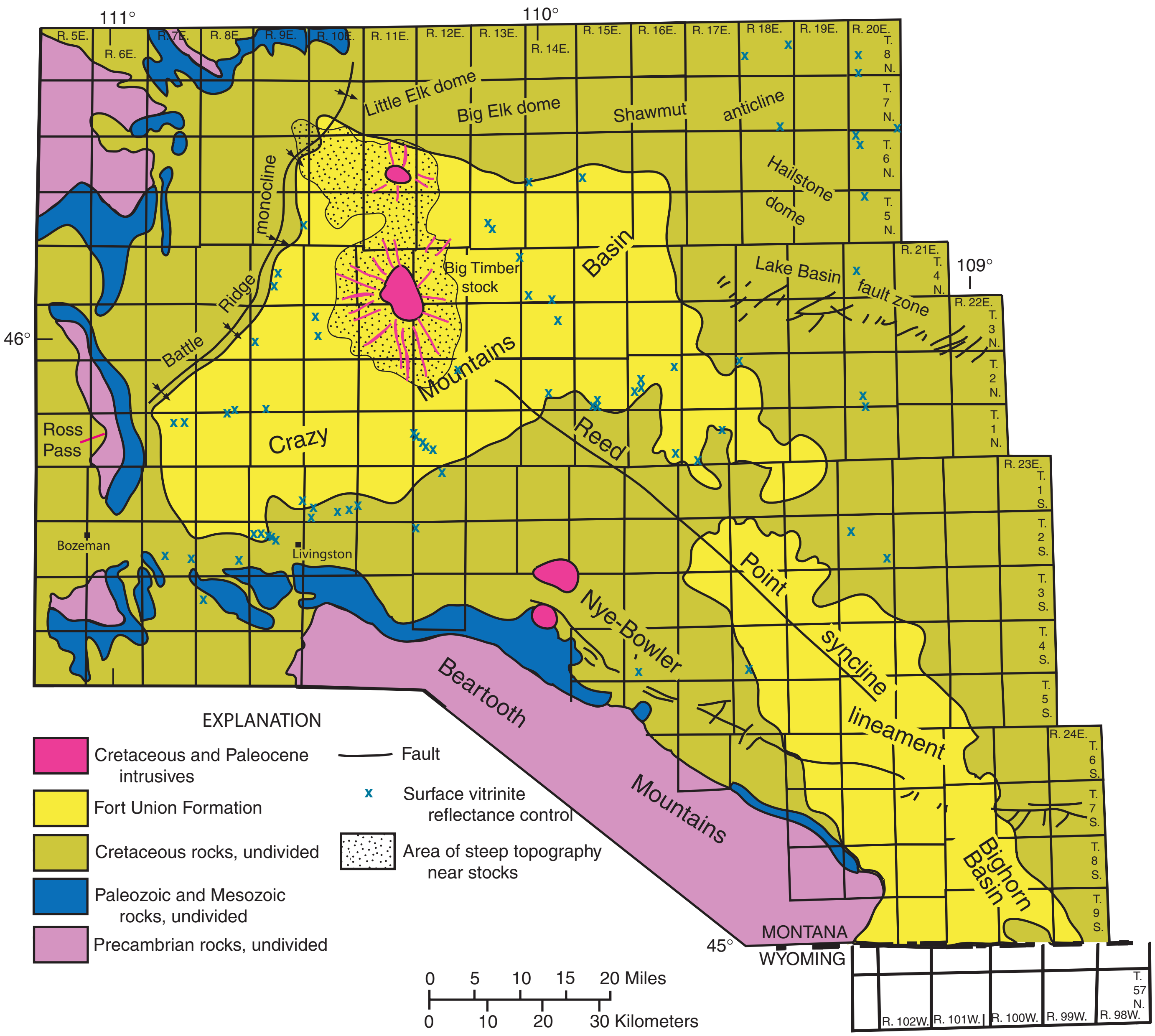

Figure 3. Generalized geology of Crazy Mountains Basin, Montana, showing locations of surface vitrinite reflectance samples and approximate limit of steep topography around Eocene stocks in central part of basin. The area of steep topography may approximately outline the area of hornfels-grade metamorphic rocks.

Precambrian basement is clearly involved in some of the older thrusts to the west. A cross section constructed by DeCelles (1994) across the western part of the thrust belt in north-central Utah, in an area of thickly stacked thrust sheets known as the Wasatch culmination, clearly indicates considerable involvement of Precambrian crystalline rocks in the thrusting.

The Laramide Orogeny, which is characterized by “thick skinned” deformation manifested by reverse faults extending deep into basement rocks, affected only the central part of the Rocky Mountain region where rising Laramide uplifts divided the foreland basin into smaller basins from latest Cretaceous through Eocene time. Several tectonic models related to changes in subduction along the western margin of the North American continent have been proposed to explain why compressional forces of the Laramide were concentrated in this fairly restricted area. The style of deformation appears to have occurred during a time of unusually rapid convergence between the Farallon and North American plates (for summaries, see Hamilton, 1988; Beck and others, 1988).

The Crazy Mountains Basin lies along the southeast edge of an extensive eastward bulge in the Cordilleran overthrust belt known as the Helena salient (fig. 1). The north and south margins of the salient are bound by complex outward-thrusting fault systems that have strike-slip components consistent with the concept that the entire salient has been transported considerably east of the main part of the overthrust belt (Woodward, 1983). The Battle Ridge monocline (fig. 2), which cuts northeastward across the western part of the Crazy Mountains

Table 1. Results of surface vitrinite reflectance investigation.

[R_o, vitrinite reflectance; n, number of readings; s.d., standard deviation. Sample locations shown on figure 3]

Sample ID	Location	Latitude	Longitude	Quadrangle (1:100,000)	Elevation (ft)
98-Mt-1	sw1/4 nw1/4 sec. 29, T. 4 S., R. 18 E.	45° 27' 31"	109° 31' 28"	Red Lodge	4,590
98-Mt-2	nw1/4 ne1/4 sec. 29, T. 4 S., R. 16 E.	45° 27' 52"	109° 46' 22"	Red Lodge	4,920
98-Mt-3	se1/4 nw1/4 sec. 25, T. 2 S., R. 20 E.	45° 37' 57"	109° 12' 42"	Big Timber	3,690
98-Mt-4	se1/4 nw1/4 sec. 8, T. 2 S., R. 20 E.	45° 40' 32"	109° 17' 19"	Big Timber	3,740
98-Mt-5	sw1/4 sw1/4 sec. 33., T. 2 N., R. 20 E.	45° 52' 23"	109° 15' 18"	Big Timber	4,330
98-Mt-6	ne1/4 se1/4 sec. 29, T. 2 N., R. 20 E.	45° 53' 32"	109° 15' 18"	Big Timber	4,085
98-Mt-7	c-s1/2 sec. 17, T. 4 N., R. 20 E.	46° 5' 30"	109° 15' 30"	Harlowton	4,560
98-Mt-8	c-n1/2 ne1/4 sec. 5, T. 5 N., R. 20 E.	46° 13' 14"	109° 13' 24"	Harlowton	4,005
98-Mt-9	ne1/4 sec. 6, T. 6 N., R. 20 E.	46° 18' 34"	109° 15' 30"	Harlowton	3,805
98-Mt-10	ne1/4 ne1/4 sec. 6, T. 6 N., R. 20 E.	46° 19' 6"	109° 15' 24"	Harlowton	3,840
98-Mt-11	nw1/4 nw1/4 sec. 32, T. 8 N., R. 20 E.	46° 24' 44"	109° 15' 24"	Harlowton	3,935
98-Mt-12	nw corner sec. 20, T. 8N. R. 20 E.	46° 26' 30"	109° 15' 24"	Harlowton	3,935
98-Mt-13	nw1/4 nw1/4 sec. 13, T. 8 N., R. 18 E.	46° 27' 46"	109° 25' 12"	Harlowton	4,005
98-Mt-14	nw1/4 ne1/4 sec. 19, T. 8 N., R. 18 E.	46° 26' 42"	109° 30' 48"	Harlowton	4,150
98-Mt-15	sw1/4 nw1/4 sec. 35, T. 7 N., R. 18 E.	46° 18' 24"	109° 26' 27"	Harlowton	3,840
98-Mt-16	ne1/4 ne1/4 sec. 26, T. 2 S., R 8 E.	45° 38' 29"	110° 40' 52"	Livingston	5,170
98-Mt-17	se1/4 sw1/4 sec. 24, T. 2 S, R. 17 E.	45° 38' 34"	110° 48' 18"	Livingston	5,875
98-Mt-18	ne1/4 sw1/4 sec. 21, T. 2 S., R. 7 E.	45° 38' 45"	110° 52' 7"	Livingston	5,380
98-Mt-19	ne1/4 se1/4 sec. 18, T. 3 S., R. 8 E.	45° 34' 24"	110° 47' 2"	Livingston	5,775
98-Mt-20	nw1/4 nw1/4 sec. 6, T. 2 S., R. 12 E.	45° 41' 40"	110° 18' 7"	Livingston	4,365
98-Mt-21	nw1/4 nw1/4 sec. 12, T. 2 N., R. 12 E.	45° 56' 30"	110° 11' 10"	Livingston	5,875
98-Mt-22 (1 of 2)	sw1/4 nw1/4 sec. 22, T. 2 N., R. 14 E.	45° 54' 40"	109° 58' 47"	Big Timber	4,430
98-Mt-22 (2 of 2)	sw1/4 nw1/4 sec. 22, T. 2 N., R. 14 E.	45° 54' 40"	109° 58' 47"	Big Timber	4,430
98-Mt-23 (1 of 3)	c-nl sec. 30, T. 6 N., R. 15 E.	46° 14' 51"	109° 53' 32"	Harlowton	4,990
98-Mt-23 (2 of 3)	c-nl sec. 30, T. 6 N., R. 15 E.	46° 14' 51"	109° 53' 32"	Harlowton	4,990
98-Mt-23 (3 of 3)	c-nl sec. 30, T. 6 N., R. 15 E.	46° 14' 51"	109° 53' 32"	Harlowton	4,990
98-Mt-24	se1/4 se1/4 sec. 36, T. 7 N., R. 20 E.	46° 18' 51"	109° 9' 20"	Harlowton	3,675
99-Mt-1	c sec. 20, T. 3 N., R. 10 E.	45° 59' 47"	110° 30' 27"	Livingston	5,577
99-Mt-2	sw1/4 nw1/4 sec. 8, T. 3 N., R. 10 E.	46° 1' 28"	110° 30' 59"	Ringling	5,676
99-Mt-3	se1/4 sw1/4 sec. 19, T. 3 N., R. 9 E.	45° 59' 29"	110° 39' 23"	Livingston	5,052
99-Mt-4	se1/4 sw1/4 sec. 21, T. 4 N., R. 9 E.	46° 4' 48"	110° 36' 52"	Ringling	5,085
99-Mt-5	se1/4 se1/4 sec. 16, T. 4 N., R. 9 E.	46° 5' 33"	110° 36' 20"	Ringling	5,085
99-Mt-6	se1/4 sw1/4 sec. 24, T. 5 N., R. 9 E.	46° 10' 28"	110° 31' 43"	Ringling	5,906
99-Mt-7	ne1/4 ne1/4 sec. 32, T. 2 N., R. 9 E.	45° 52' 50"	110° 37' 30"	Livingston	4,921
99-Mt-8	sw1/4 se1/4 sec. 35, T. 2 N., R. 8 E.	45° 52' 23"	110° 41' 42"	Livingston	5,052
99-Mt-9	sw1/4 sw1/4 sec. 35, T. 2 N., R. 8 E.	45° 52' 23"	110° 42' 6"	Livingston	5,085
99-Mt-10	sw1/4 sw1/4 sec. 34, T. 2 N., R. 8 E.	45° 52' 23"	110° 43' 21"	Livingston	5,151
99-Mt-11	nw1/4 sw1/4 sec. 2, T. 1 N., R. 7 E.	45° 51' 53"	110° 49' 29"	Livingston	5,546
99-Mt-12	ne1/4 sw1/4 sec. 3, T. 1 N., R. 7 E.	45° 51' 45"	110° 50' 32"	Livingston	5,709
99-Mt-13	ne1/4 nw1/4 sec. 26, T. 1 S., R. 10 E.	45° 43' 29"	110° 27' 27"	Livingston	4,364
99-Mt-14	c-se1/4 sec. 24, T. 1 S., R. 10 E.	45° 43' 43"	110° 25' 50"	Livingston	4,429
99-Mt-15	sw1/4 ne1/4 sec. 10 T. 3 N., R. 14 E.	45° 1' 31"	109° 57' 49"	Harlowton	4,790
99-Mt-16	ne1/4 ne1/4 sec. 31, T. 4 N., R. 14 E.	46° 3' 37"	110° 1' 15"	Ringling	5,249
99-Mt-17	nw1/4 ne1/4 sec. 34, T. 4 N., R. 14 E.	46° 3' 45"	109° 57' 49"	Harlowton	4,921
99-Mt-18	nw1/4 ne1/4 sec. 12, T. 4 N., R. 13 E.	46° 6' 53"	110° 2' 44"	Ringling	5,413
99-Mt-19	sw1/4 sw1/4 sec. 21, T. 5 N., R. 13 E.	46° 9' 51"	110° 6' 39"	Ringling	5,574
99-Mt-20	nw1/4 sw1/4 sec. 21, T. 5 N., R. 13 E.	46° 10' 5"	110° 6' 39"	Ringling	5,574
99-Mt-21	ne1/4 sw1/4 sec. 30, T. 6 N., R. 14 E.	46° 14' 23"	110° 1' 15"	Ringling	5,380
99-Mt-22	sw1/4 nw1/4 sec. 30, T. 7 N., R. 11 E.	46° 20' 15"	110° 24' 8"	Ringling	5,512
99-Mt-23	sw1/4 se1/4 sec. 9, T. 2 S., R. 9 E.	45° 40' 19"	110° 37' 23"	Livingston	4,856
99-Mt-24	sw1/4 se1/4 sec. 9, T. 2 S., R. 9 E.	45° 40' 27"	110° 37' 29"	Livingston	4,856
99-Mt-25	sw1/4 ne1/4 sec. 8, T. 2 S., R. 9 E.	45° 40' 52"	110° 38' 28"	Livingston	4,987
99-Mt-26	nw1/4 nw1/4 sec. 8, T. 2 S., R. 9 E.	45° 40' 52"	110° 38' 53"	Livingston	5,020
99-Mt-27	ne1/4 ne1/4 sec. 7, T. 2 S., R. 9E.	45° 41' 1"	110° 39' 27"	Livingston	5,085
99-Mt-28	se1/4 se1/4 sec. 30, T. 1 S., R. 10 E.	45° 42' 56"	110° 32' 9"	Livingston	4,856
99-Mt-29	se1/4 se1/4 sec. 30, T. 1 S., R. 10 E.	45° 43' 4"	110° 31' 58"	Livingston	4,888
99-Mt-30	se1/4 ne1/4 sec. 24, T. 1 S., R. 9 E.	45° 43' 50"	110° 33' 8"	Livingston	4,987
99-Mt-31	se1/4 sw1/4 sec. 28, T. 1 S., R. 10 E.	45° 42' 56"	110° 30' 0"	Livingston	4,495
99-Mt-32	nw1/4 nw1/4 sec. 3, T. 1 S., R. 12 E.	45° 46' 57"	110° 14' 13"	Livingston	4,528
99-Mt-33	nw1/4 se1/4 sec. 33, T. 1 N., R. 12 E.	45° 47' 20"	110° 14' 19"	Livingston	4,659
99-Mt-34	sw1/4 nw1/4 sec. 28, T. 1 N., R. 12 E.	45° 48' 25"	110° 14' 5"	Livingston	4,593
99-Mt-35	ne1/4 ne1/4 sec. 29, T. 1 N., R. 12 E.	45° 48' 47"	110° 15' 19"	Livingston	4,691
99-Mt-36	ne1/4 ne1/4 sec. 19, T. 1 N., R. 12 E.	45° 49' 24"	110° 16' 19"	Livingston	4,921
99-Mt-37	sw1/4 sw1/4 sec. 18, T. 1N., R. 12 E.	45° 49' 48"	110° 17' 11"	Livingston	4,921
99-Mt-38	se1/4 ne1/4 sec. 13, T. 1 N., R. 11 E.	45° 50' 10"	110° 17' 24"	Livingston	5,085
99Mt-39A	nw1/4 nw1/4 sec. 33, T. 2 N., R. 15 E.	45° 52' 51"	109° 52' 22"	Big Timber	4,528
99-Mt-39B	nw1/4 nw1/4 sec. 33, T. 2 N., R. 15 E.	45° 52' 51"	109° 52' 22"	Big Timber	4,528
99-Mt-40	nw1/4 nw1/4 sec. 33, T. 2 N., R. 15 E.	45° 53' 2"	109° 52' 18"	Big Timber	4,560
99-Mt-41	ne1/4 sw1/4 sec. 28, T. 2 N., R. 15 E.	45° 53' 22"	109° 51' 57"	Big Timber	4,659
99-Mt-42	ne1/4 ne1/4 sec. 19, T. 2 N., R. 16 E.	45° 54' 40"	109° 46' 32"	Big Timber	4,462
99-Mt-43	se1/4 sw1/4 sec. 17, T. 2 N., R. 16 E.	45° 55' 0"	109° 45' 50"	Big Timber	4,364
99-Mt-44	c-el sec. 17, T. 2 N., R. 16 E.	45° 55' 19"	109° 45' 9"	Big Timber	4,347
99-Mt-45	sw1/4 sw1/4 sec. 1, T. 2 N., R. 16 E.	45° 51' 50"	109° 41' 11"	Big Timber	5,019
99-Mt-46	ne1/4 nw1/4 sec. 33, T. 3 N., R. 17 E.	45° 58' 31"	109° 37' 28"	Big Timber	5,020
99-Mt-47	c-wl sec. 6, T. 2 N. R. 18 E.	45° 57' 8"	109° 32' 46"	Big Timber	5,233
99-Mt-48	nw1/4 ne1/4 sec. 14, T. 1 N., R. 17 E.	45° 50' 25"	109° 34' 26"	Big Timber	4,757
99-Mt-49	sw1/4 ne1/4 sec. 32, T. 1 N. R. 17 E.	45° 46' 32"	109° 38' 4"	Big Timber	4,593
99-Mt-50	se1/4 se1/4 sec. 25, T. 1 N., R. 16 E.	45° 48' 26"	109° 40' 24"	Big Timber	4,724
99-Mt-51	sw1/4 sw1/4 sec. 25, T. 1 N., R. 16 E.	45° 48' 26"	109° 41' 5"	Big Timber	4,560

Basin, is part of the southeast terminus of this salient (Woodward, 1983). The deep trough of the basin is adjacent to (east of) the Battle Ridge monocline (fig. 5), and most subsidence occurred in Maastrichtian and early Paleocene time in response to thrust loading during a period of active thrusting on the Helena salient (Johnson and Finn, Chapter A, this CD-ROM).

The northwestern part of the Crazy Mountains Basin was extensively intruded by stocks, sills, laccoliths, and dikes in Eocene time from about 51 to 49 Ma (du Bray and

Table 1. Results of surface vitrinite reflectance investigation.—Continued

Sample ID	Description	Stratigraphic unit	Age	Ro (%)	n	s.d.
98-Mt-1	Very dirty 1 ' coal in a tan ss unit	Hell Creek Fm.	U. Cretaceous	Barren		
98-Mt-2	Coal from old mine site	Probably Judith River Fm.	U. Cretaceous	0.61	30	0.05
98-Mt-3	1/2" thick coaly stringer in carbonaceous shale	Judith River Fm.	U. Cretaceous	0.63	30	0.06
98-Mt-4	Coal stringers in carbonaceous shale	Lennep Ss.	U. Cretaceous	0.49	25	0.05
98-Mt-5	Carbonacous shale with minute coal stringers	Lennep Ss.	U. Cretaceous	0.46	25	0.06
98-Mt-6	Very coaly carbonaceous shale	Judith River Fm.	U. Cretaceous	0.44	25	0.04
98-Mt-7	Coaly stringers in carbonaceous shale	Eagle Ss.	U. Cretaceous	0.52	25	0.07
98-Mt-8	Coaly stringers in carbonaceous shale	Eagle Ss.	U. Cretaceous	0.48	32	0.06
98-Mt-9	Thin coal in carbonaceous shale	Judith River Fm.	U. Cretaceous	0.43	25	0.04
98-Mt-10	3' thick dirty coal	Judith River Fm.	U. Cretaceous	0.59	30	0.05
98-Mt-11	2-3' thick coal	Judith River Fm.	U. Cretaceous	0.59	25	0.05
98-Mt-12	1' thick dirty coal	Judith River Fm.	U. Cretaceous	0.46	30	0.04
98-Mt-13	1' thick coal	Judith River Fm.	U. Cretaceous	0.43	25	0.04
98-Mt-14	1' thick coal	Judith River Fm.	U. Cretaceous	0.63	30	0.06
98-Mt-15	1' thick coal	Probably Eagle Ss.	U. Cretaceous	0.56	30	0.06
98-Mt-16	1' thick coal	Eagle Ss.	U. Cretaceous	0.35	25	0.04
98-Mt-17	Coal >3' thick	Eagle Ss.	U. Cretaceous	0.58	30	0.05
98-Mt-18	Spoil pile from Mountain Side mine	Eagle Ss.	U. Cretaceous	0.47	30	0.06
98-Mt-19	Spoil pile from Mountain House mine	Eagle Ss.	U. Cretaceous	0.48	30	0.08
98-Mt-20	Coaly stringers in 1' thick carbonaceous shale	Livingston Gp.	U. Cret.-Paleocene	0.51	30	0.06
98-Mt-21	Approx. 1"x2" coal pod in black shale	Livingston Gp.	U. Cret.-Paleocene	1.39	30	0.06
98-Mt-22 (1 of 2)	Black mudstone	Livingston Gp.	U. Cret.-Paleocene	Barren		
98-Mt-22 (2 of 2)	Coalified log, 5" x 2-3'	Livingston Gp.	U. Cret.-Paleocene	1.35	30	0.08
98-Mt-23 (1 of 3)	1/4" thick coal bed	Fort Union	Paleocene	0.44	14	0.08
98-Mt-23 (2 of 3)	Carbonaceous shale with coal stringers	Fort Union	Paleocene	0.4	2	0.02
98-Mt-23 (3 of 3)	1/4" thick coal bed	Fort Union	Paleocene	0.46	11	0.06
98-Mt-24	Coal stringers in carbonaceous shale	Judith River Fm.	U. Cretaceous	0.46	30	0.05
99-Mt-1	Coaly debris at base of channel sandstone	Livingston Gp.	U. Cretaceous	0.94	30	0.04
99-Mt-2	Coaly stringer in dark-gray mudstone	Livingston Gp.	U. Cretaceous	0.68	30	0.04
99-Mt-3	Carbonaceous layer below coarse-grained ss.	Livingston Gp.	U. Cretaceous	0.79	30	0.06
99-Mt-4	Weathered coaly debris at base of sandstone	Livingston Gp.	U. Cretaceous	0.64	30	0.04
99-Mt-5	Coaly debris at base of channel sandstone	Livingston Gp.	U. Cretaceous	0.55	32	0.04
99-Mt-6	Carbonaceous layer in baked shale	Livingston Gp.	U. Cretaceous	0.54	30	0.05
99-Mt-7	Carbonaceous plant fragments in dark mudstone	Livingston Gp.	U. Cretaceous	0.77	30	0.04
99-Mt-8	Coaly debris at base of channel sandstone	Livingston Gp.	U. Cretaceous	0.92	30	0.05
99-Mt-9	Coal stringers in carbonaceous shale	Livingston Gp.	U. Cretaceous	Barren		
99-Mt-10	Coal stringers in carbonaceous shale	Livingston Gp.	U. Cretaceous	0.73	30	0.05
99-Mt-11	Coaly debris at base of channel sandstone	Livingston Gp.	U. Cretaceous	0.88	30	0.04
99-Mt-12	6" coal stringer in sandstone	Livingston Gp.	U. Cretaceous	0.67	30	0.04
99-Mt-13	Vein-like filling below sandstone	Livingston Gp.	U. Cretaceous	0.64	30	0.04
99-Mt-14	Coal stringers in carbonaceous shale	Livingston Gp.	U. Cretaceous	0.74	30	0.05
99-Mt-15	Coal stringer in gray shale	Melville Fm.	Paleocene	0.65	30	0.04
99-Mt-16	Carbonized plants in gray shale	Melville Fm.	Paleocene	0.9	30	0.07
99-Mt-17	Coal stringers in carbonaceous shale	Melville Fm.	Paleocene	0.84	40	0.03
99-Mt-18	Coal stringers in carbonaceous shale	Melville Fm.	Paleocene	0.69	30	0.11
99-Mt-19	Coal stringers in carbonaceous shale	Melville Fm.	Paleocene	0.97	32	0.04
99-Mt-20	1" dirty coal approx. 20 ft below sill	Melville Fm.	Paleocene	1.97	30	0.14
99-Mt-21	Coal stringers in carbonaceous shale	Hell Creek Fm.	U. Cretaceous	0.48	30	0.04
99-Mt-22	Coal stringers in carbonaceous shale	Melville Fm.?	Paleocene?	0.87	30	0.05
99-Mt-23	Coaly fragments in sandstone	Hoppers Fm.	U. Cretaceous	0.74	30	0.04
99-Mt-24	Coaly fragments in sandstone	Hoppers Fm.	U. Cretaceous	0.94	30	0.11
99-Mt-25	Coaly fragments in sandstone	Fort Union Fm.	U. Cret.-Paleocene	0.61	30	0.05
99-Mt-26	Coaly fragments in sandstone	Fort Union Fm.	U. Cret.-Paleocene	0.85	30	0.05
99-Mt-27	Coaly fragments in sandstone	Fort Union Fm.	U. Cret.-Paleocene	0.67	17	0.07
99-Mt-28	Coal chips in conglomerate	Hoppers Fm.	U. Cretaceous	0.85	24	0.07
99-Mt-29	Coal chips from base of channel sandstone	Hoppers Fm.	U. Cretaceous	0.72	30	0.07
99-Mt-30	Carbonized plant fragments in sandstone	Fort Union Fm.	U. Cret.-Paleocene	0.87	30	0.04
99-Mt-31	Coaly stringer at base of channel sandstone	Hoppers Fm.	U. Cretaceous	0.65	30	0.04
99-Mt-32	3' long carbonized log in sandstone	Livingston Gp.	U. Cretaceous	0.92	30	0.04
99-Mt-33	Coal chips from base of channel sandstone	Fort Union Fm.	U. Cret.-Paleocene	Barren		
99-Mt-34	Carbonized root in 1' sandstone	Fort Union Fm.	U. Cret.-Paleocene	0.82	30	0.05
99-Mt-35	Coaly fragments in sandstone	Fort Union Fm.	U. Cret.-Paleocene	0.95	30	0.04
99-Mt-36	Carbonized flakes in siltstone	Fort Union Fm.	U. Cret.-Paleocene	0.81	30	0.04
99-Mt-37	Carbonized flakes below channel sandstone	Fort Union Fm.	U. Cret.-Paleocene	1.3	30	0.06
99-Mt-38	6" thick coal pod in sandstone	Fort Union Fm.	U. Cret.-Paleocene	0.95	30	0.04
99Mt-39A	Carbonized plant fragments in sandstone	Bear Fm.	U. Cret.-Paleocene	1.02	30	0.07
99-Mt-39B	1' thick weathered dirty coal pod	Bear Fm.	U. Cret.-Paleocene	0.67	30	0.04
99-Mt-40	Carbonized plant fragments in sandstone	Bear Fm.	U. Cret.-Paleocene	0.75	30	0.06
99-Mt-41	Carbonized plant fragments in sandstone	Bear Fm.	U. Cret.-Paleocene	0.82	30	0.04
99-Mt-42	Carbonized plant fragments in sandstone	Bear Fm.	U. Cret.-Paleocene	0.72	30	0.05
99-Mt-43	0.2" thick coal bed	Bear Fm.	U. Cret.-Paleocene	0.49	30	0.05
99-Mt-44	2" thick coal bed	Bear Fm.	U. Cret.-Paleocene	0.61	30	0.04
99-Mt-45	Carbonized root in siltstone	Bear Fm.	U. Cret.-Paleocene	0.61	30	0.03
99-Mt-46	Thin coaly layer in carbonaceous shale	Bear Fm.	U. Cret.-Paleocene	0.59	30	0.05
99-Mt-47	Coaly flakes from base of channel sandstone	Bear Fm.	U. Cret.-Paleocene	1.06	30	0.07
99-Mt-48	2" thick coal bed	Bear Fm.	U. Cret.-Paleocene	0.53	30	0.03
99-Mt-49	6" thick dirty coal bed	Bear Fm.	U. Cret.-Paleocene	1.41	30	0.09
99-Mt-50	2" thick weathered coal bed	Bear Fm.	U. Cret.-Paleocene	0.49	30	0.04
99-Mt-51	1" thick coal bed	Bear Fm.	U. Cret.-Paleocene	0.49	30	0.03

others, 1993; du Bray and Harlan, 1996). A swarm of largely north-south-trending dikes, exhibiting some radial component, surrounds the Big Timber stock (fig. 2), which is the largest intrusion in this complex (Larsen and Simms, 1972). The two intrusions shown on figure 2 in the southern part of the basin are of Late Cretaceous age (Chadwick, 1981) and are unrelated to this Eocene event. Compositional variations in the Eocene intrusions have been studied in detail by Tappe (1966), du Bray and others (1993), and du Bray and Harlan (1996). The intrusions are unusual in that both strongly alkaline and

Table 2. Results of subsurface vitrinite reflectance investigation.

[R_o, vitrinite reflectance; n, number of readings; s.d., standard deviation. Well locations shown on figure 5]

Well name	Location	Sample depth (ft)	Ro (%)	n	s.d.	Formation	Age
Cities Service 1 Cooney	sec. 30, T. 6 N., R. 16 E.	3,223	0.94	32	0.08	Judith River Fm.	Upper Cretaceous
		3,555	0.96	32	0.05	Judith River Fm.	Upper Cretaceous
		3,775	1.01	32	0.06	Judith River Fm.	Upper Cretaceous
		4,000	0.97	32	0.05	Judith River Fm.	Upper Cretaceous
		4,127	0.98	32	0.06	Claggett Shale	Upper Cretaceous
		4,377	0.97	32	0.06	Eagle Sandstone	Upper Cretaceous
		4,592	0.97	32	0.05	Eagle Sandstone	Upper Cretaceous
		4,627	1.02	32	0.06	Eagle Sandstone	Upper Cretaceous
		4,850	1.02	32	0.06	Eagle Sandstone	Upper Cretaceous
EREC 23-6 American Fork	sec. 6, T. 5 N., R. 13 E.	1,900	0.75	30	0.04	Melville Fm.	Paleocene
		2,265	0.93	30	0.06	Melville Fm.	Paleocene
		3,450	0.89	30	0.06	Melville Fm.	Paleocene
		3,750	1.04	30	0.09	Melville Fm.	Paleocene
		10,750	2.15	30	0.06	Judith River Fm.	Upper Cretaceous
Chevron 1 Sonat-Largent	sec. 3, T. 4 N., R. 10 E.	2,280	1.03	30	0.7	Melville Fm.	Paleocene
		2,395	1.15	35	0.05	Melville Fm.	Paleocene
		2,595	1.16	17	0.09	Melville Fm.	Paleocene
		2,980	1.67	18	0.07	Melville Fm.	Paleocene
		3,290	1.17	24	0.08	Melville Fm.	Paleocene
		3,535	1.15	30	0.08	Melville Fm.	Paleocene
		3,740	1.27	30	0.12	Melville Fm.	Paleocene
		4,245	1.46	30	0.09	Melville Fm.?	Paleocene?
		4,665	1.37	30	0.09	Livingston Group	Upper Cretaceous
		4,980	1.4	30	0.1	Livingston Group	Upper Cretaceous
		5,335	1.75	15	0.09	Livingston Group	Upper Cretaceous
		5,705	1.76	30	0.14	Livingston Group	Upper Cretaceous
		6,190	1.27	30	0.05	Livingston Group	Upper Cretaceous
		6,660	1.55	16	0.07	Livingston Group	Upper Cretaceous
		7,735	2.17	20	0.12	Livingston Group	Upper Cretaceous
Scat 1 State Wilsall	sec. 36, T. 3 N., R. 7 E.	2,460	1.48	30	0.07	Sedan Fm.	Upper Cretaceous
		3,670	0.73	30	0.11	Judith River Fm.	Upper Cretaceous
		3,975	0.77	35	0.06	Judith River Fm.	Upper Cretaceous
		4,175	0.84	35	0.06	Judith River Fm.	Upper Cretaceous
		4,445	0.96	35	0.06	Eagle Sandstone	Upper Cretaceous
		4,645	0.88	35	0.04	Eagle Sandstone	Upper Cretaceous
		4,845	1.13	33	0.09	Eagle Sandstone	Upper Cretaceous
		5,045	1.01	20	0.09	Eagle Sandstone	Upper Cretaceous
		5,245	1.15	30	0.08	Eagle Sandstone	Upper Cretaceous
		5,390	1.08	30	0.07	Eagle Sandstone	Upper Cretaceous
		5,495	1.24	30	0.08	Telegraph Creek Fm.	Upper Cretaceous
		5,585	1.03	11	0.05	Telegraph Creek Fm.	Upper Cretaceous
Amoco 1 Robinson Ranch	sec. 31, T. 3 N., R. 8 E.	3,775	0.96	30	0.04	Judith River Fm.	Upper Cretaceous
		3,955	0.95	32	0.04	Judith River Fm.	Upper Cretaceous
		4,040	1.01	30	0.07	Judith River Fm.	Upper Cretaceous
		4,285	1.08	32	0.06	Judith River Fm.	Upper Cretaceous
		4,385	1.13	32	0.07	Eagle Sandstone	Upper Cretaceous
		4,470	1.12	32	0.07	Eagle Sandstone	Upper Cretaceous
Chevron 1 Sonat-CIG-Van Cleve	sec. 1, T. 3 N., R. 12 E.	305	2.7	32	0.19	Lebo Shale & Melville Fm.	Paleocene
		315	2.79	30	0.13	Lebo Shale & Melville Fm.	Paleocene
		625	2.86	32	0.17	Lebo Shale & Melville Fm.	Paleocene
		980	3.09	30	0.3	Lebo Shale & Melville Fm.	Paleocene
		1,555	3.58	30	0.29	Lebo Shale & Melville Fm.	Paleocene
		1,680	3.55	20	0.23	Lebo Shale & Melville Fm.	Paleocene
		1,905	3.6	29	0.26	Lebo Shale & Melville Fm.	Paleocene
		2,185	3.54	30	0.19	Lebo Shale & Melville Fm.	Paleocene
		2,375	3.33	30	0.13	Lebo Shale & Melville Fm.	Paleocene
		3,025	3.76	30	0.28	Lebo Shale & Melville Fm.	Paleocene
		3,075	3.72	12	0.14	Lebo Shale & Melville Fm.	Paleocene
		3,485	3.82	32	0.21	Lebo Shale & Melville Fm.	Paleocene
		10,370	6.72	29	0.2	Parkman Sandstone	Upper Cretaceous

alkaline-subalkaline phases are present; strongly alkaline rocks are confined mainly to the northern part of the basin and alkaline-subalkaline rocks are confined to the south. This segregat ion appears to be related to differences in basement geology; Precambrian Belt Supergroup sedimentary rocks occur in the north wherever Archean crystalline basement occurs in the south (du Bray and Harlan, 1996). Based on gravity surveys, Bonini and others (1972) suggested that the two stocks shown on figure 2 merge at depth to form one large laccolith that is over 30 mi long in a north-south direction and 12 mi in an east-west direction, with a maximum thickness of about 5 mi. Du Bray and others (1993), in a study of the Big Timber stock, found the surrounding Paleocene Fort Union Formation to be only mildly deformed by the intrusion. They (du Bray and others, 1993) pointed out that there is little density contrast between the intrusive rocks and rocks in the Precambrian basement, hence, the gravity data cannot be used to characterize the shape of the intrusion, and, further, the 3- to 5-mi thickness inferred by Bonini and others (1972) for the Big Timber stock is much greater than is typical for a laccolith.

Du Bray and others (1993) and du Bray and Harlan (1996) found that the hornfels-grade aureole surrounding the Big Timber stock is remarkably wide for such a small intrusion, extending a distance of several miles from the margins of the stock, and suggested that exsolution of fluids from the stock may be responsible for the unusual size of the aureole. These hornfels-grade metamorphic rocks, which form the

Table 2. Results of subsurface vitrinite reflectance investigation.—Continued

Well name	Location	Sample depth (ft)	Ro (%)	n	s.d.	Formation	Age
Gulf Oil 1 Big Timber	sec. 36, T. 2 N., R. 13 E.	4,355	2.07	30	0.1	Volcanic rocks?	Upper Cretaceous
		5,570	2.21	23	0.18	Parkman Sandstone	Upper Cretaceous
		5,725	2.59	30	0.12	Parkman Sandstone	Upper Cretaceous
		6,025	2.59	30	0.14	Eagle Sandstone	Upper Cretaceous
Stanolind 1 Rapstad	sec. 31, T. 2 N., R. 15 E.	3,377	1.96	32	0.11	Claggett Shale	Upper Cretaceous
		3,435	2.02	30	0.11	Claggett Shale	Upper Cretaceous
		3,495	2.16	30	0.16	Eagle Sandstone	Upper Cretaceous
Ranger Pet. 8-30 Bookout	sec. 30, T. 2 N., R. 16 E.	1,325	0.93	34	0.14	Hell Creek Fm.	Upper Cretaceous
		3,555	1.53	30	0.1	Claggett Shale	Upper Cretaceous
		3,835	1.71	15	0.1	Eagle Sandstone	Upper Cretaceous
Vanderbilt 1 Shay	sec. 33, 1 N., R. 15 E.	2,005	0.98	30	0.08	Judith River Fm.	Upper Cretaceous
Shenandoah 1 Adkisson	sec. 1, T. 1 N., R. 17 E.	2,025	0.96	32	0.08	Hell Creek Fm.	Upper Cretaceous
		2,230	0.97	30	0.05	Bearpaw Shale	Upper Cretaceous
		2,490	0.82	8	0.09	Bearpaw Shale	Upper Cretaceous
		2,640	0.96	35	0.08	Judith River Fm.	Upper Cretaceous
		3,515	1.06	30	0.09	Eagle Sandstone	Upper Cretaceous
Sohio 1-3 Moats	sec. 1, T. 2 S., R. 6 E.	5,075	1.41	32	0.09	Judith River Fm.	Upper Cretaceous
		5,575	1.55	32	0.08	Judith River Fm.	Upper Cretaceous
		5,630	1.63	32	0.08	Judith River Fm.	Upper Cretaceous
		5,690	1.57	32	0.07	Judith River Fm.	Upper Cretaceous
		5,790	1.65	32	0.07	Judith River Fm.	Upper Cretaceous
		5,845	1.71	32	0.07	Eagle Sandstone	Upper Cretaceous
		5,875	1.68	32	0.07	Eagle Sandstone	Upper Cretaceous
		5,910	1.74	32	0.07	Eagle Sandstone	Upper Cretaceous
		6,005	1.81	32	0.11	Telegraph Creek Fm.	Upper Cretaceous
American Mineral 1 BN	sec. 1, T. 2 S., R. 12 E.	1,270	1.12	30	0.09	Claggett Shale	Upper Cretaceous
		1,465	0.97	12	0.06	Eagle Sandstone	Upper Cretaceous
Amoco 1 Mothershead	sec. 20, T 2 S., R. 16 E.	1,110	0.74	33	0.1	Judith River Fm.	Upper Cretaceous
		1,230	0.79	40	0.06	Judith River Fm.	Upper Cretaceous
		1,420	0.81	29	0.05	Judith River Fm.	Upper Cretaceous
		1,515	0.8	35	0.09	Judith River Fm.	Upper Cretaceous
		1,625	0.81	32	0.08	Parkman Sandstone	Upper Cretaceous
		1,715	0.9	35	0.08	Claggett Shale	Upper Cretaceous
		1,875	0.99	30	0.1	Claggett Shale	Upper Cretaceous
		1,960	0.89	35	0.07	Eagle Sandstone	Upper Cretaceous
		2,060	0.98	30	0.07	Telegraph Creek Fm.	Upper Cretaceous
		2,165	0.93	30	0.06	Telegraph Creek Fm.	Upper Cretaceous
		2,265	0.92	12	0.09	Telegraph Creek Fm.	Upper Cretaceous
		2,370	0.99	30	0.09	Telegraph Creek Fm.	Upper Cretaceous

elevated flanks around the margins of the Crazy Mountains, are much more resistant to erosion than their nonmetamorphosed sedimentary rock equivalents. The approximate position where the gently dipping pediment surfaces, which cover much of the basin, change into the steep, rugged terrain at the base of the Crazy Mountains is shown on figure 3. This change, which occurs from about 4 to 10 mi away from the margins of the intrusions, may approximately outline the extent of hornfels-grade metamorphism around the stocks. Mineral geobarometer studies by du Bray and Harlan (1996) indicated that the exposed part of Big Timber stock solidified at a depth of about 3 km (9,842 ft). Maximum present-day elevation of the stock is 10,748 ft.

Subsidence along the trough of the Crazy Mountains Basin began near the beginning of Late Cretaceous Maastrichtian time and appears to have largely ceased by the end of the Paleocene and prior to emplacement of the Big Timber stock and associated smaller intrusions (Johnson and Finn, Chapter A, this CD-ROM). The highest preserved outcrops in the vicinity of the stock are nearly flat lying, indicating that little subsidence occurred after deposition of these rocks. This contrasts with most other Laramide basins where subsidence continued to near the end of the Eocene. Present-day elevation of the upper Campanian Teapot Sandstone Member of the Mesaverde Formation and its equivalent (fig. 4) varies from about 3,000 ft above sea level in the nearly flat lying eastern part of the basin to about 9,000 ft below sea level along the basin trough (fig. 5), indicating a total differential subsidence in the basin of about 12,000 ft.

Potential Hydrocarbon Source Rocks

Possible hydrocarbon source rocks in the Crazy Mountains Basin include organic-rich marine shales in the Lower Cretaceous Shell Creek and Skull Creek Members of the Thermopolis Shale and Upper Cretaceous Mowry Shale and Cody Shale, and coals and carbonaceous shales in the Upper Cretaceous Eagle Sandstone and Judith River Formation and Paleocene Lebo Shale and Melville Formation (fig. 4). Possible source rocks in pre-Cretaceous strata were not considered. The Thermopolis Shale and Mowry Shale occur throughout the Crazy Mountains Basin. Burtner and Warner (1984), using cuttings, reported total organic carbon (TOC) values for these intervals to be as high as 1.0 percent and for Tmax values to range from 440°F to 460°F, indicating that they can be

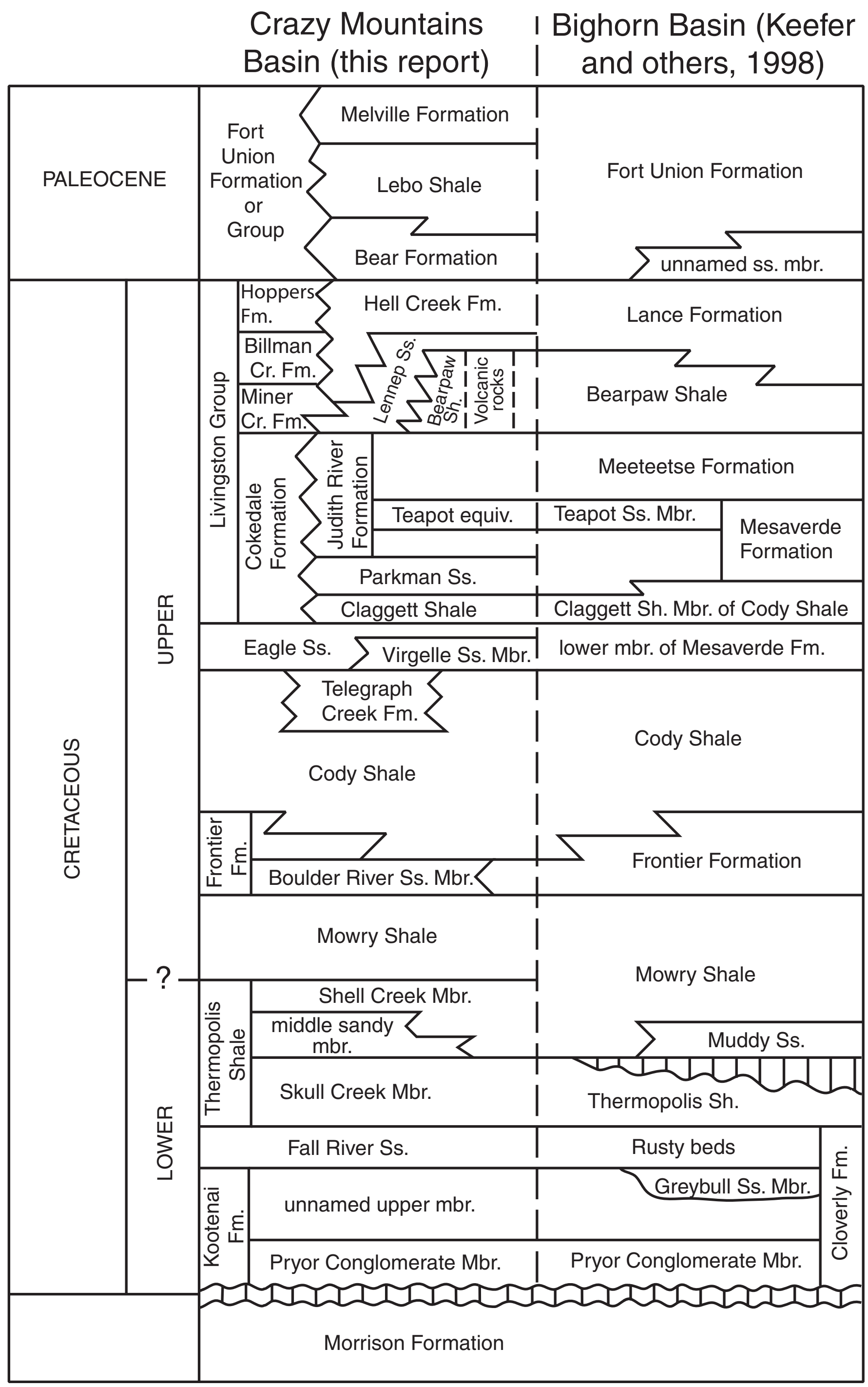

Figure 4. Generalized stratigraphic chart of Cretaceous and older Tertiary rocks, Crazy Mountains Basin, Montana, and Bighorn Basin, Montana and Wyoming. Abbreviations: Cr., Creek; Fm., Formation; Mbr., Member; Sh., Shale; Ss., Sandstone; equiv., equivalent.

considered as potential source rocks and that they are within the oil window. They (Burtner and Warner, 1984) collected samples from only the marginal areas of the basin where the Mowry and Thermopolis occur at the relatively shallow depths of 4,100–6,035 ft. The source rock potential of the Cody Shale has not been investigated in the Crazy Mountains Basin. Hagen and Surdam (1984), however, reported TOC values as high as 4.42 percent for the Cody Shale in the Bighorn Basin to the south, indicating excellent source rock potential, and it is likely that similar organic-rich intervals occur within the Cody in the Crazy Mountains Basin. Coal has been mined from the Upper Cretaceous Eagle Sandstone in the

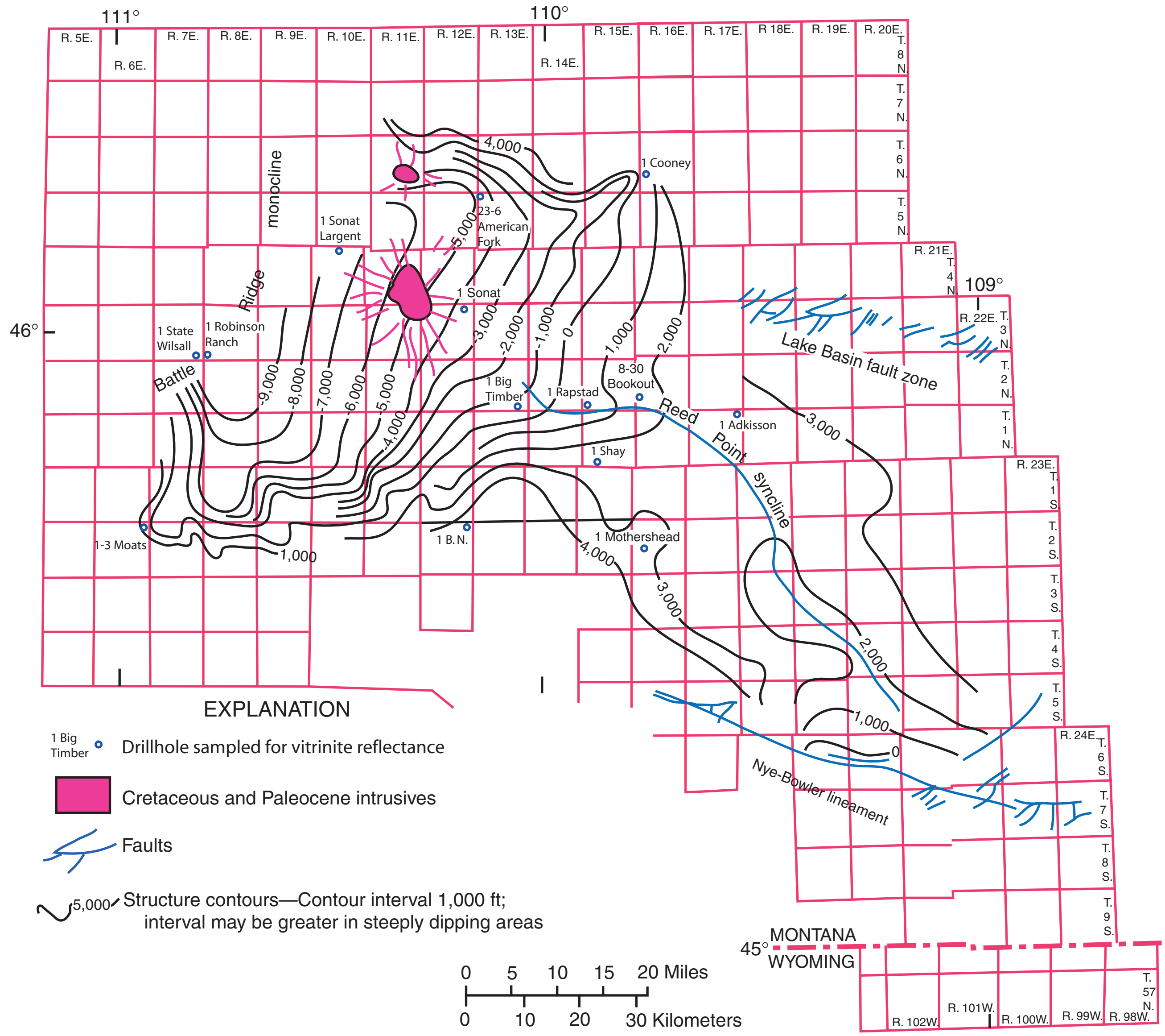

Figure 5. Structure contour map on top of Upper Cretaceous Teapot Sandstone Member of Mesaverde Formation and Teapot equivalent, Crazy Mountains Basin, Montana. Locations of drillholes used for vitrinite reflectance shown. Wells listed in table 2.

Livingston area along the southwest margin of the basin (Roberts, 1966) and in the Elk Basin area in the northernmost part of the Bighorn Basin to the south (Glass and others, 1975). Only thin coals appear to be present in these formations in other parts of the Crazy Mountains Basin (Johnson and Finn, Chapter A, this CD-ROM).

The Paleocene Melville Formation in the Crazy Mountains Basin is approximately equivalent to the Tongue River Member of the Fort Union Formation in the Powder River Basin to the east and southeast, where that member contains vast deposits of subbituminous coals that are being extensively mined as well as being drilled for coalbed methane. Only carbonaceous shale and thin coal beds were observed while sampling the Melville Formation in exposures in the northern part of the Crazy Mountains Basin; however, more coal may occur in the Melville in the subsurface. Geophysical logs for the EREC American Fork 23–6 well in sec. 6, T. 5 N., R. 13 E., in the north-central part of the basin (fig. 5), are interpreted to indicate that numerous thin (<5 ft thick) coal beds occur in the Melville Formation and possibly the underlying Lebo Shale at depths of about 1,800–4,000 ft. Only minor carbonaceous shale and lignite were reported in cuttings taken at depths of 2,180–2,190 ft and 2,580–2,590 ft from probable Melville Formation in the Chevron 1 Sonat-CIG-Van Cleve well in sec. 1, T. 3 N., R. 12 E., about 12 mi south of the 23-6 well (fig. 5). However, coal fragments were reported in cuttings from the Chevron 1 Sonat-Largent well in sec. 3, T. 4 N., R. 10 E., about 15 mi southwest of the 23-6 well (fig. 5) starting at 2,250 and continuing to 7,740 ft. Geophysical logs indicate that there may be numerous thin (<5 ft) coal beds throughout this interval.

Present-Day Geothermal Gradients and Subsurface Temperatures in the Crazy Mountains Basin

Geothermal gradients, calculated from temperatures recorded during logging runs in boreholes drilled for oil and gas, are widely used largely because the information is readily available. Different lithologies, however, conduct heat at varying rates; thus, geothermal gradients cannot be readily converted into heat flow. Because of this lithologic effect, geothermal gradients commonly vary between different logging runs in a borehole. Nonetheless, geothermal gradients are useful in determining present-day temperatures in a sedimentary basin and can be used to reconstruct thermal histories. A correction factor must be applied to the recorded temperatures to compensate for the presence of relatively cool drilling fluids circulating in the borehole while drilling (the American Association of Petroleum Geologists Geothermal Gradient Committee chart was applied here). Present-day geothermal gradients in the Crazy Mountains Basin vary from less than 1.6°F/100 ft to more than 2.6°F/100 ft (fig. 6). The gradients do not noticeably increase toward the intrusions as shown in figure 6, thus there appears to be little if any residual heating left from the volcanism. Geothermal gradients are higher than those in the Bighorn Basin to the south (<1.0°F/100 ft to >1.8°F/100 ft, Nuccio and Finn, 1998) and the Wind River Basin in central Wyoming (<1.4°F/100 ft to 2.0°F/100 ft, Pawlewicz, 1993), but are comparable to those found in the Piceance Basin of Colorado (<1.6° to >2.4°F/100 ft, Johnson and Nuccio, 1986).

Variations in present-day formation temperatures have been used to help define the limits of basin-centered gas accumulations in Rocky Mountain basins. Basin-centered gas accumulations are low-grade deposits that cover large areas in the deeper parts of many basins where gas-prone source rocks are present and permeabilities are low enough to trap the gas. These accumulations are typically either overpressured or underpressured and hence are largely isolated from regional groundwater systems. For a more complete description of basin-centered gas accumulations, see Johnson and Finn (Chapter A, this CD-ROM). Some gas is continuously leaking from these accumulations, and it is thought that present-day gas generation is required to maintain them. Law and others (1979) and Spencer (1989a) found that a temperature of about 190°F to 200°F corresponds to the onset of overpressuring in the basin-centered gas deposit in the Greater Green River Basin of Wyoming and suggested that this overpressuring is caused by present-day gas generation by nearby source rocks. A general relationship between the present-day temperature of about 200°F and the onset of overpressuring was found in the Wind River Basin of Wyoming (Johnson and others, 1996) and the Bighorn Basin of Wyoming and Montana (Johnson and Finn, 1998). At the Multiwell Experiment (MWX) site, a research site sponsored by the Department of Energy to study the basin-centered gas accumulation in the Piceance Basin of Colorado, the onset of overpressuring occurs at a temperature of about 165°F (Spencer, 1989b). Figure 7 shows the areas in the Crazy Mountains Basin where a temperature of 200°F is exceeded at two stratigraphic levels, the base of the Cretaceous strata and the top of the Upper Cretaceous Teapot Sandstone Member and its equivalent. This temperature is exceeded at these stratigraphic levels throughout most of the deep basin area.

Vitrinite Reflectance as a Method of Measuring Thermal Maturity

Vitrinite, a material derived from woody plants that is typically found in coal and carbonaceous shale, is used extensively for studying thermal maturities of potential source rocks and in reconstructing basin thermal histories. Vitrinite reflectance (R_o) is a direct measurement of the proportion of light reflected from a polished vitrinite grain; it is related to the degree of thermal maturity of the rock and can be used to estimate hydrocarbon source rock generation potential. The samples were prepared for R_o analysis by crushing, mounting in epoxy, and polishing. The mean R_o was then measured on a reflected light microscope with a nonrotating stage and randomly oriented indigenous vitrinite grains under oil immersion using plain-polarized incident white light and a 546 nanometer monochromatic filter (technique described in Bostick, 1979, and Bustin, 1986).

Kerogen Types and Related Hydrocarbons

Three general types of kerogen have the potential, under optimum conditions, to generate hydrocarbons: Type I, alginite (sapropelic or lipid rich); Type II, exinite (phytoplankton, zooplankton, waxy, resinous material from land plants, and other microorganisms); and Type III, vitrinite and huminite (terrestrial plant debris) (Tissot and others, 1974). There is no absolute point at which hydrocarbons begin to generate, but it probably begins over a range of R_o values that depend on the specific type of organic matter involved. The following is a brief summary of several models that have been developed relating the generation of hydrocarbons to types of kerogen.

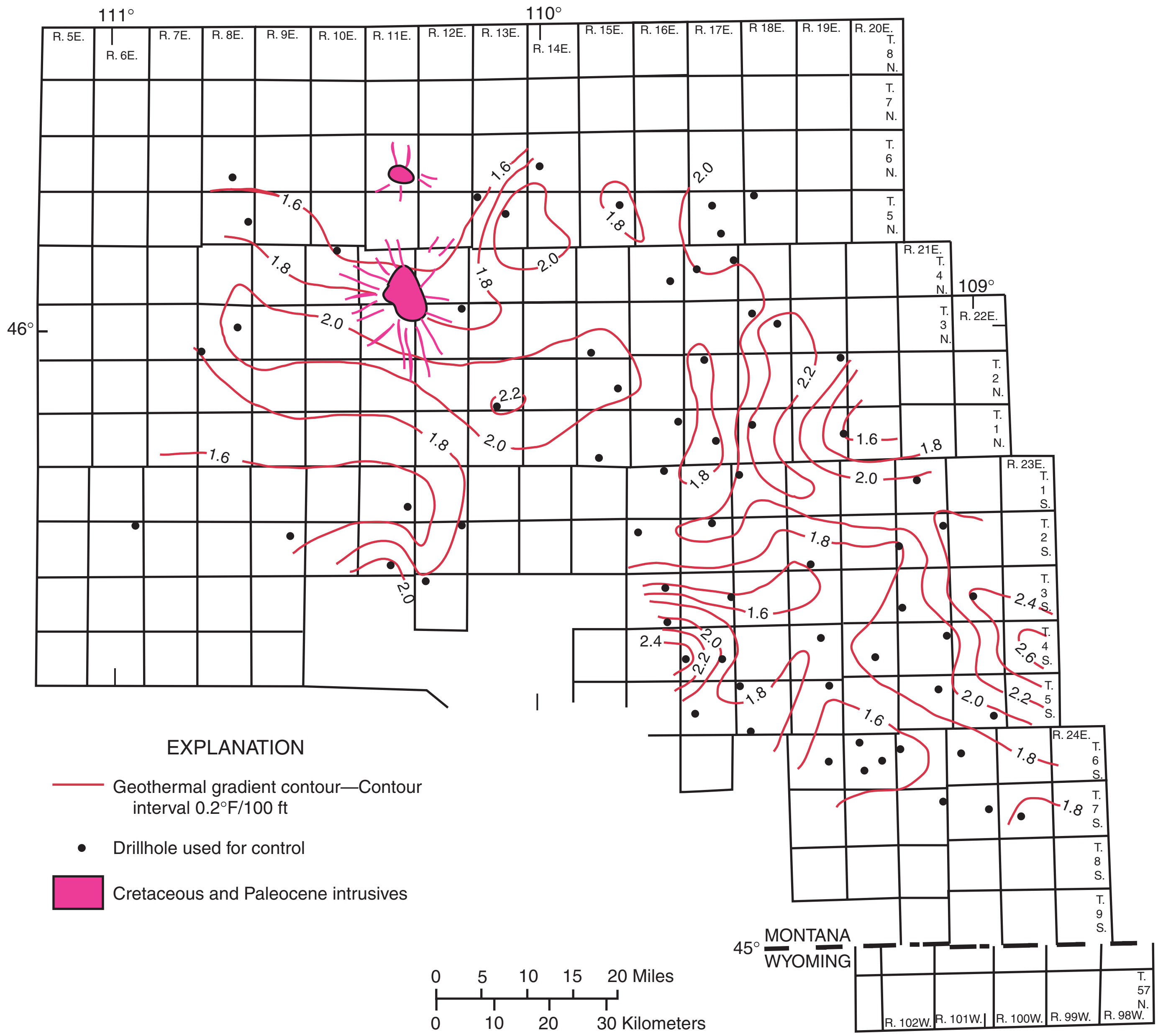

Figure 6. Present-day geothermal gradients, Crazy Mountains Basin, Montana. Gradients have been corrected using the American Association of Petroleum Geologists Geothermal Gradient Committee chart (no reference given) to compensate for effects of cooling due to circulation of drilling fluids.

Type I kerogen is hydrogen rich, is found primarily in marine and lacustrine rocks, and generates mainly oil during catagenesis. The R_o value for the onset of oil generation from Type I organic matter varies depending on the model one chooses. Dow (1977) used 0.50 percent R_o as the onset of oil generation for Type I kerogen, whereas Anders and Gerrild (1984) and Tissot and Welte (1984) used 0.70 percent R_o. Type II kerogen is mainly in marine rocks, but can be present in lacustrine rocks as well, and generates both oil and gas during catagenesis. Waples (1985) stated that oil generation begins at R_o values of about 0.45–0.50 percent for high-sulfur kerogen and 0.60 percent for "typical" Type II kerogen. Huminite and vitrinite, or Type III kerogen, is oxygen rich and hydrogen poor and found mainly in coal, terrestrial shales, and marginal lacustrine and marginal marine rocks, and generates mostly hydrocarbon gases (predominantly methane) during catagenesis. For Type III kerogen, R_o is the best and most widely used measure of thermal maturity. The onset of significant gas generation by Type III organic matter is thought to take place at an R_o value of about 0.73 percent (Juntgen and Karweil, 1966; Juntgen and Klein, 1975), whereas maximum gas generation and expulsion from source rocks take place at an R_o of about 1.10 percent (Meissner, 1984). Wet gas is generated from mixed lacustrine, marine, and terrestrial organic matter and from the thermal cracking of oil between R_o values of 0.80 and 2.0 percent, whereas dry gas

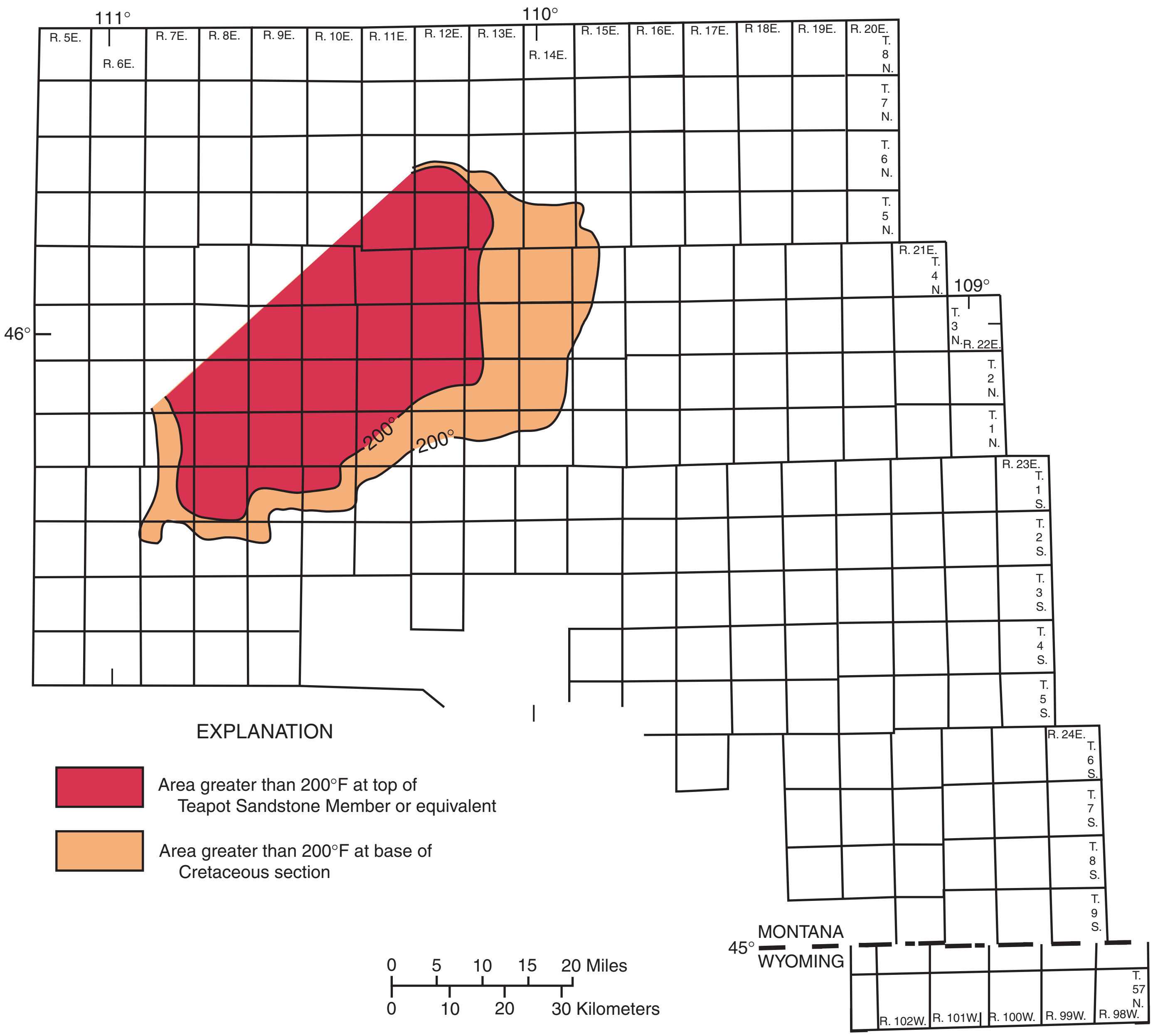

Figure 7. Areas in Crazy Mountains Basin, Montana, where present-day formation temperatures exceed 200°F at two stratigraphic levels—top of Upper Cretaceous Teapot Sandstone Member of Mesaverde Formation and its equivalent, and base of Cretaceous section.

is generated from the thermal cracking of wet gas between R_o values of 1.0 and 3.0 percent (Dow, 1977).

Surface Vitrinite Reflectance Results

Of the 79 surface vitrinite reflectance samples analyzed, 75 yielded meaningful results (fig. 3, table 1) that show R_o values to range from 0.35 to 1.97 percent; the variations across the Crazy Mountains Basin are contoured in figure 8. The area of steep topography surrounding the stocks that form the core of the Crazy Mountains is also plotted on figure 8 to determine if there was any relation between variations in surface R_o values and the abrupt change in topography. As previously discussed, the topographic break may roughly mark the outer limits of the hornfels-grade metamorphic zone around the stocks. Several surface R_o samples were collected from near this rugged area, but none were collected within it. Berg and others (2000) mapped Eocene age dikes, sills, and local areas of hornfels-grade metamorphism south of the Big Timber stock on their geologic map of the Livingston 1° × 2° quadrangle. The southern and western limits of these indicators of igneous activity are shown as a blue dashed line on figure 8.

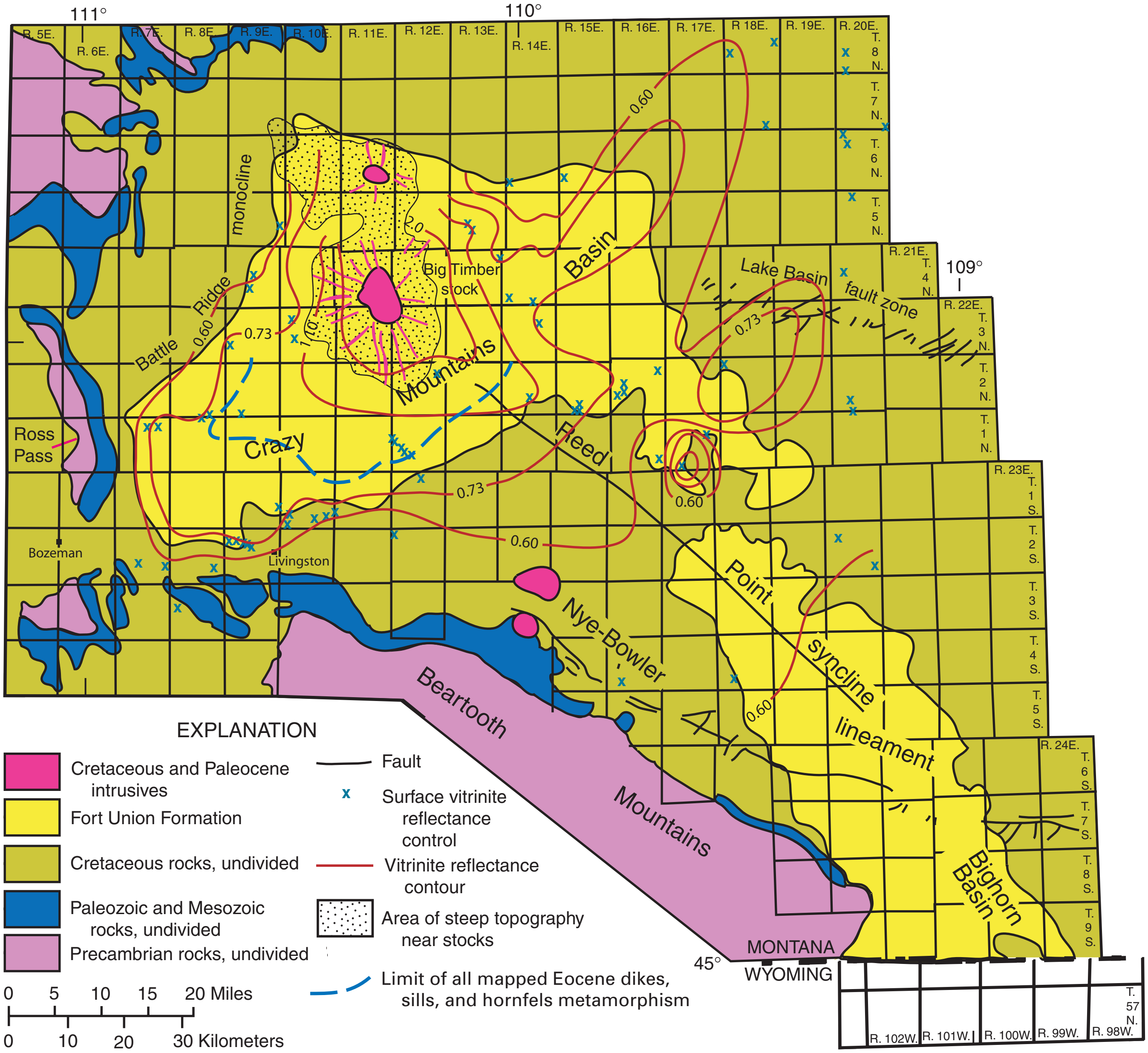

Figure 8. Variations in surface vitrinite reflectance values across Crazy Mountains Basin, Montana. Limit of all mapped Eocene dikes and sills from Berg and others (2000).

Of the 75 surface samples that yielded results, 43 gave R_o values of 0.7 percent or less, 27 gave values of 0.7–1.1 percent, and 5 gave values of 1.1–7 percent (fig. 9). The lowest values, 0.6 percent or less, are confined to the extreme marginal areas of the basin (fig. 8), and are typical surface R_o values for Rocky Mountain basins (see, for example, Nuccio and others, 1996; Nuccio and Finn, 1998; Johnson and Nuccio, 1993). These values are markedly higher than surface R_o values found in other Rocky Mountain basins, except those areas extensively affected by igneous intrusions, such as the central part of the Raton Basin of Colorado and New Mexico (Nuccio and others, 2002) and the southeastern part of the Piceance Basin of Colorado (Johnson and Nuccio, 1993). The area with values of 0.73 percent or greater is highly irregular, extending from 2 to 10 mi beyond the limit of igneous activity in the western parts of the Crazy Mountains Basin, and as much as 30 mi in the eastern part (fig. 8). A generally north-south-trending area with thermal maturity levels of 1.1 percent or greater occurs from about 5 to 12 mi from the Big Timber stock, extending farthest from the stock in a southeast direction (fig. 8). This area of 1.1 percent R_o or greater vitrinite reflectance generally parallels the north-south-trending area of steep topography around the Big Timber stock, but control is sparse particularly in the northern part of the basin, north of the stock.

Samples were taken at relatively close intervals along several transects to study local variations in surface R_o values (figs. 3 and 8). Five samples collected along a 11,000-ft-long

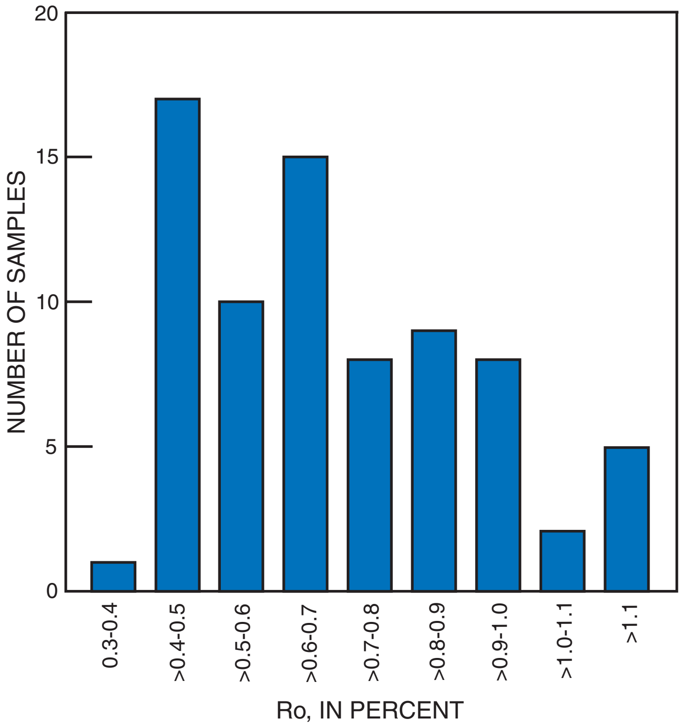

Figure 9. Distribution of surface vitrinite reflectance values values (R_o) in surface samples collected in Crazy Mountains Basin, Montana.

transect in T. 2 S., R. 9 E., just northwest of Livingston (fig. 8) yielded R_o values of from 0.61 to 0.94 percent (table 1, samples 99-Mt-23 through 99-Mt-27). Five samples collected along a 24,000-ft-long transect in T. 1 N., Rs. 11 and 12 E. and T. 1 S., R. 12 E. yielded R_o values of from 0.81 to 0.95 percent (table 1, samples 99-Mt-32, 34, 35, 36, and 38). A sixth sample, sample 99-Mt-37 (table 1), yielded an unusually high value of 1.3 percent. Although sample 99-Mt-37 is only about 1,500 ft from the nearest mapped dike, it is unlikely that this dike is responsible for the high value, inasmuch as contact metamorphic zones near dikes should on average be no greater than the width of the dikes (Bostick and Pawlewicz, 1984). Four samples collected along a 4,000-ft-long transect in T. 2 N., R. 15 E. (fig. 8) gave R_o values of 0.67, 0.75, 0.82, and 1.02 percent (table 1, samples 99-Mt-39a through 99-Mt-41); no intrusions have been mapped near the locality of the sample having the highest value (Lopez, 2000). Three samples collected along a 7,000-ft-long transect just to the east in T. 2 N., R. 16 E. (fig. 8) yielded R_o values of from 0.49 to 0.72 percent (table 1, samples 99-Mt-42 through 99-Mt-44).

Subsurface Vitrinite Reflectance Results

A total of 99 vitrinite samples was analyzed from 14 of the deepest oil and gas exploration wells in the Crazy Mountains Basin (table 2); well locations of these holes are shown in figure 5. Depth of samples ranged from 305 to 10,750 ft, and vitrinite reflectance values ranged from 0.73 to 6.72 percent. Ten of the drillholes yielded sufficient data to construct individual vitrinite reflectance profiles (figs. 10–19). For comparison, the depth to the R_o 1.1 percent level is shown on each profile (in blue). Samples suitable for vitrinite reflectance analysis are commonly restricted to a comparatively thin interval in the drillholes. Estimates of surface R_o values at the well locations were made in order to construct the profiles; however, because such information was seldom available near the drillsites, estimated surface values were derived from the contours on the surface R_o map (fig. 8) and should be considered approximate. Indeed, variations in the slopes of these R_o profiles from well to well are undoubtedly due in part to inaccuracies in estimating surface R_o values at the well sites. "Kinks," or changes in slopes, similar to those described by Law and others (1989), appear to be present in the profiles for the Chevron 1 Sonat-CIG-Van Cleve well (fig. 15), the Scat Drilling 1 State Wilsall well (fig. 13), and possibly the Amoco 1 Robinson Ranch well (fig. 14) and the Sohio 1-3 Moats well (fig. 18). Other profiles also may contain kinks, but there is insufficient data to identify them. Law and others (1989) suggested that (1) the more vertical segments in the kinky, or segmented, profiles are in strata where there was highly efficient convective heat flow, whereas the more sloped segments correspond to intervals where less efficient conduction was the dominant mechanism for heat transfer; (2) intervals dominated by convective heat flow developed directly above expanding basin-centered gas accumulations as water was being displaced upward by gas; and (3) the change from more vertical (convective) to less vertical (conductive) slope in the R_o profiles occurs at a vitrinite reflectance of about 0.8 percent in several Rocky Mountain basins.

A change in profile from a more vertical shallower segment to a less vertical deeper segment, such as those described by Law and others (1989), appears in the profile for the Scat Drilling 1 State Wilsall well at an R_o of about 0.6–0.7 percent (fig. 13); however, more data, particularly in the upper part of the hole, are needed. In the Chevron 1 Sonat-CIG-Van Cleve well, in contrast, the upper slope segment is less vertical than the lower segment, but control is sparse for the lower part of the hole (fig. 15). The model of Law and others (1989) would appear to indicate that convective heat flow dominated in the lower part of the drillhole whereas mainly conduction took place in the upper part. The highest thermal maturities recorded in the basin are in the Chevron 1 Sonat-CIG-Van Cleve well, with an R_o of 2.7 percent at a depth of only 305 ft and an R_o of 6.72 at 10,370 ft in the wellbore (table 2, fig. 15). A possible explanation for this profile is that a convective system, supported by deeper intrusive activity, developed in the interval represented by the lower part of the wellbore. Near-vertical temperature profiles are created by convective cells in modern geothermal systems, such as in the Cerro Prieto geothermal field in Baja California (Barker and others, 1981), whereas a more sloping temperature profile is present above

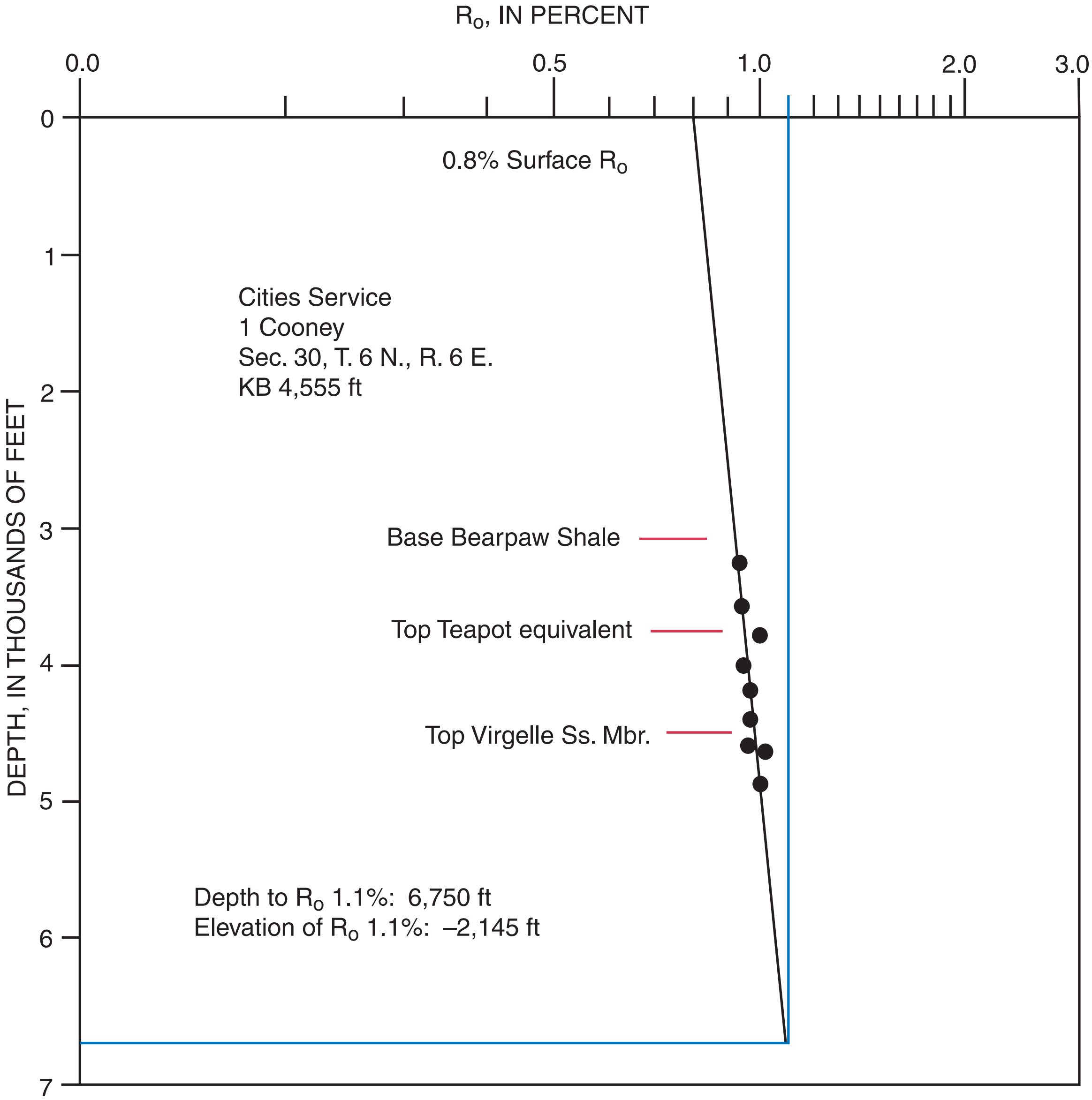

Figure 10. Vitrinite reflectance (R_o) profile for Cities Service 1 Cooney well, located in sec. 30, T. 6 N., R. 16 E. Surface R_o is estimated from surface R_o map (fig. 8). Position of key stratigraphic markers and approximate depth and elevation of R_o 1.1 percent level are shown. KB, 4,555 ft, elevation of Kelly bushing.

the convective cells (fig. 20). temperatures throughout the convective cell, vitrinite reflectance should be fairly constant as well.

Figure 21 shows the estimated R_o levels at the top of the Virgelle Sandstone Member in the Crazy Mountains Basin from both surface and subsurface information. The stratigraphic interval above the Virgelle includes more coal and carbonaceous shale than any other interval; thus it is an important potential source rock for hydrocarbons. Maturity levels vary from less than 0.73 percent (the onset of significant gas generation by Type III or coaly source rocks) around the margins of the basin to more than 2.0 percent throughout the basin trough (fig. 21).

Comparison of Thermal Maturity Levels in the Crazy Mountains Basin with Thermal Maturity Levels in Other Rocky Mountain Basins

A comparison of six vitrinite reflectance profiles from the Crazy Mountains Basin with three profiles from the Bighorn Basin, Montana and Wyoming, and one profile each from the Wind River Basin of Wyoming, the Piceance Basin of Colorado, and the San Juan Basin of Colorado and New Mexico, is shown in figure 22. Because of the high levels of thermal

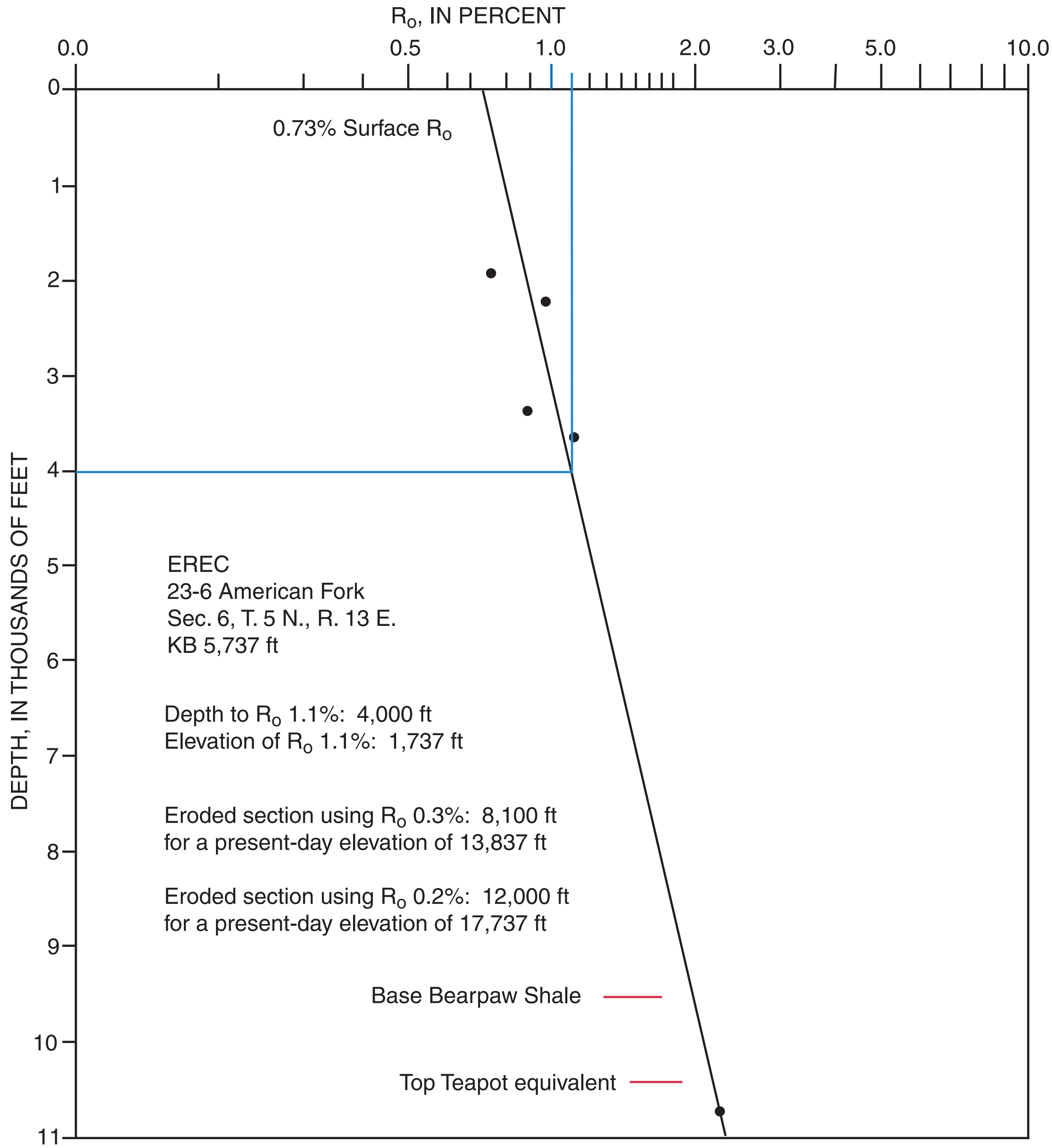

Figure 11. Vitrinite reflectance (R_o) profile for EREC 23-6 American Fork well, located in sec. 6, T. 5 N., R. 13 E. Surface R_o is estimated from surface R_o map (fig. 8). Position of key stratigraphic markers and approximate depth and elevation of R_o 1.1 percent level are shown. Estimates of eroded section were made by extrapolating profile to R_o 0.2 and R_o 0.3 percent levels. KB, 5,737 ft, elevation of Kelly bushing.

maturity in the Crazy Mountains Basin, an attempt was made to find profiles from areas in these other basins with unusually high thermal maturity gradients. The San Juan Basin profile is from the north-central part of the basin and is from Law (1992). The Wind River Basin profile is for the Monsanto 1-5 Bighorn well, a deep well on the Madden anticline, and is from Pawlewicz (1993, fig. 2). The Bighorn Basin profile was constructed using data from Nuccio and Finn (1998) from three wells in the deep trough of the basin. The Piceance Basin profile is from the Multiwell Experiment (MWX) site (Law and others, 1989; Johnson and Nuccio, 1993). In the four basins used in this comparison, thermal maturities at any given depth are lowest in the Bighorn Basin profile and highest in the San Juan Basin and Piceance Basin profiles (fig. 22).

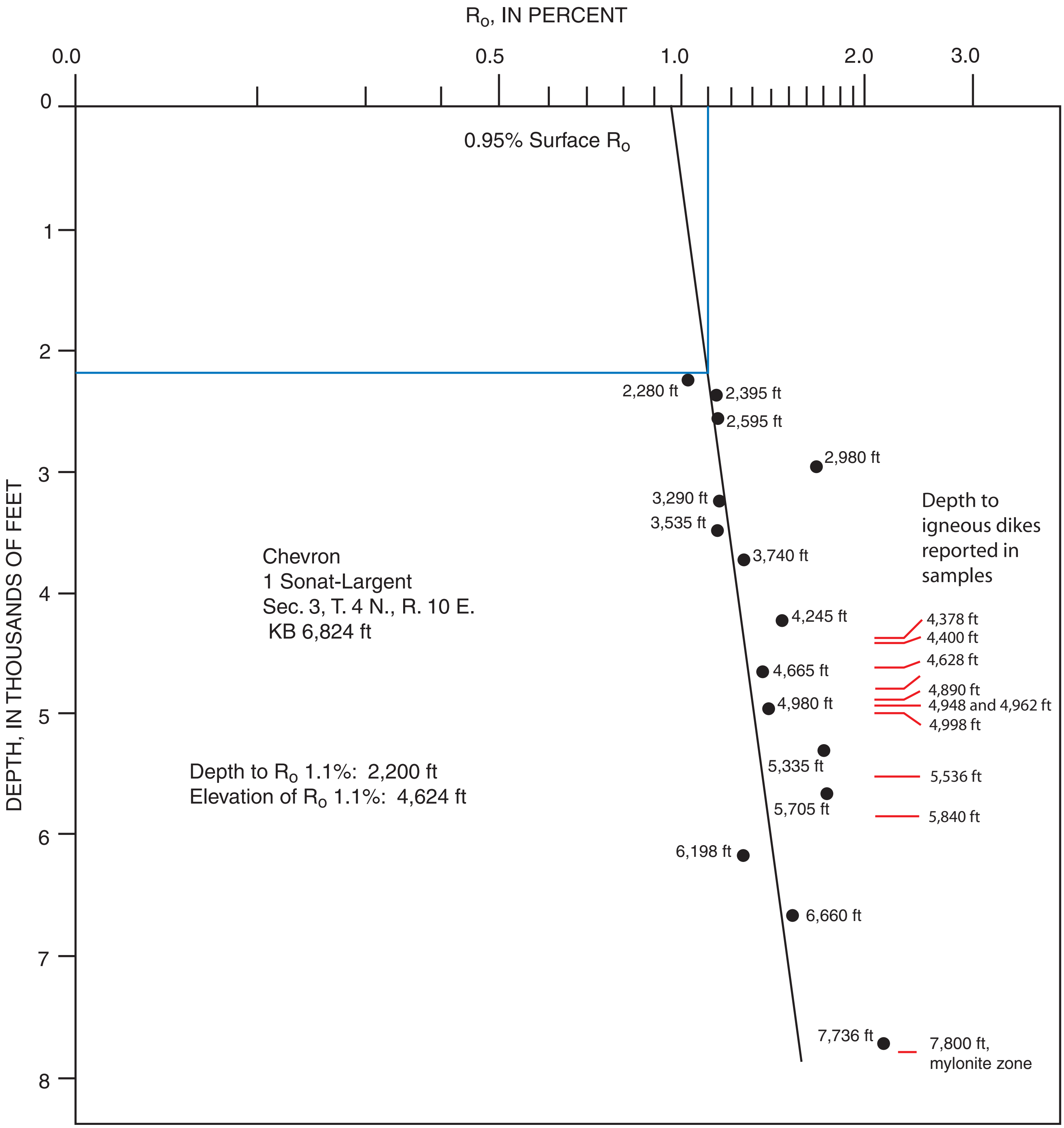

Figure 12. Vitrinite reflectance (R_o) profile for Chevron 1 Sonat-Largent well, located in sec. 3, T. 4 N., R. 10 E. Surface R_o is estimated from surface R_o map (fig. 8). Location of igneous sill and mylonite zone from mud log descriptions. Approximate depth and elevation of R_o 1.1 percent level are shown. KB, 6,824 ft, elevation of Kelly bushing.

When compared with the northern part of the San Juan Basin, thermal maturities in the Crazy Mountains Basin vary from being similar to the San Juan profile, for the least thermally mature area of the basin (the Scat 1 State Wilsall well), to showing much higher maturity for the rest of the basin. Thus, thermal maturities at any given depth are overall noticeably higher in the Crazy Mountains Basin than in these other aforementioned Rocky Mountain basins.

The approximate vertical position of the R_o value of 1.1 percent in the Crazy Mountains Basin was determined

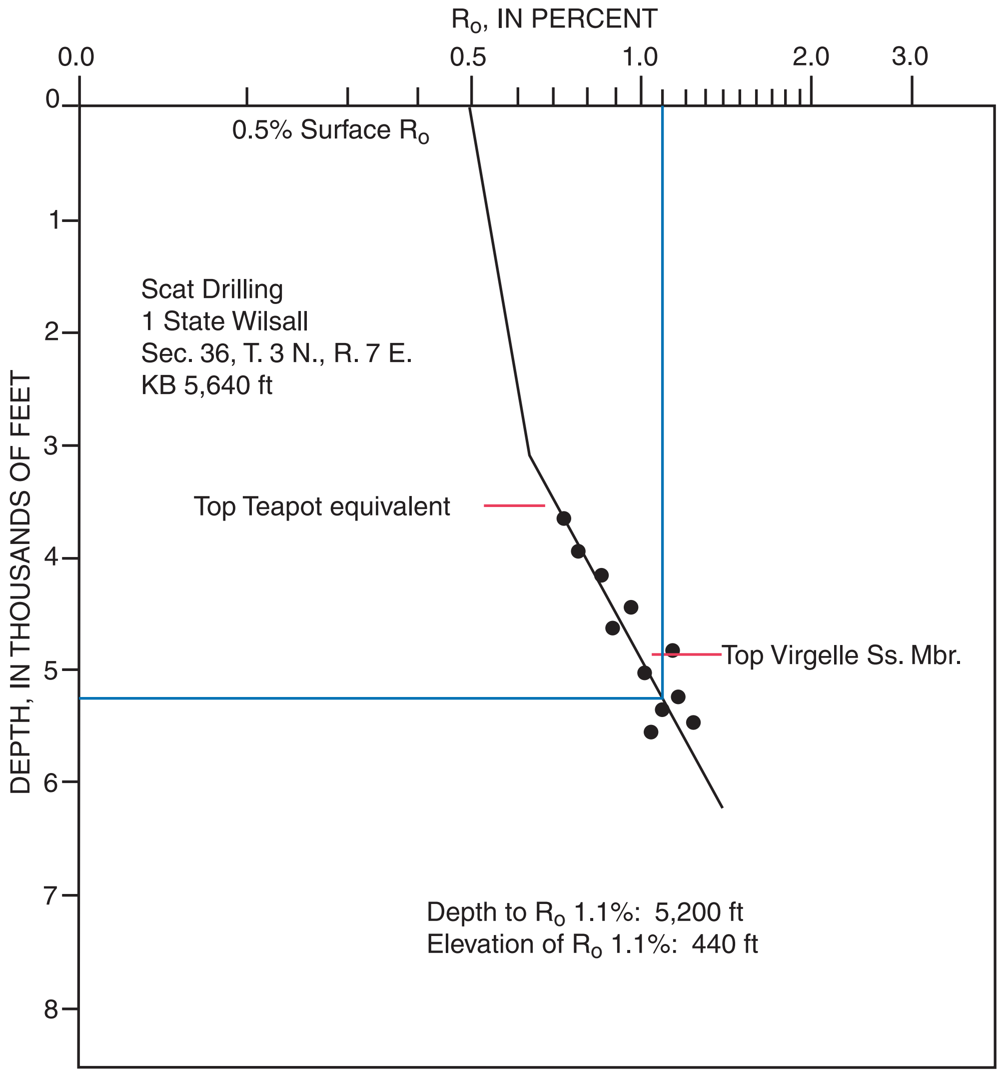

Figure 13. Vitrinite reflectance (R_o) profile for Scat Drilling 1 State Wilsall well, located in sec. 36, T. 3 N., R. 7 E. Surface R_o is estimated from surface R_o map (fig. 8). Position of key stratigraphic markers and approximate depth and elevation of R_o 1.1 percent level are shown. KB, 5,640 ft, elevation of Kelly bushing.

for each of the 10 drillholes for which vitrinite reflectance profiles were constructed (figs. 10–19). The estimated depths or elevations of this thermal maturity level vary from 4,500 ft above wellbore for the Chevron 1 Sonat-CIG-Van Cleve well (surface elevation 5,900 ft), about 6 mi east of the Big Timber stock (fig. 15), to a depth of 6,750 ft for the Cities Service 1 Cooney well (surface elevation 4,555 ft) in the northeastern part of the basin (fig. 10). Elevations of the R_o 1.1 percent thermal maturity level therefore vary from ±10,400 ft above sea level for the Van Cleve well to 2,145 ft below sea level for the 1 Cooney well (fig. 10); elevations of the R_o 1.1 percent level at other wells in the basin vary from 440 ft to 4,549 ft, with the lowest elevations occurring in the marginal areas of the basin. In comparison: (1) approximate elevations of the R_o 1.1 percent level in the Wind River Basin of Wyoming vary from 3,000 to 9,000 ft below sea level (Johnson and others, 1996, fig. 9); and (2) in the Piceance Basin of Colorado, elevations of the R_o 1.1 percent level increase from north to south from 4,000 ft below sea level to 5,000 ft above sea level (Johnson and Nuccio, 1993, their fig. 3), which is attributed to a combination of higher thermal gradients—less than 1.6°F/100 ft in the northern part of the basin to more than 2.4°F/100 ft along the south margin—and increased uplift and beveling toward the south. In contrast to the conditions in the Piceance Basin, present-day geothermal gradients in the Crazy Mountains Basin do not increase toward the high thermal maturity area near the stocks that form the core of the Crazy Mountains (fig. 6).

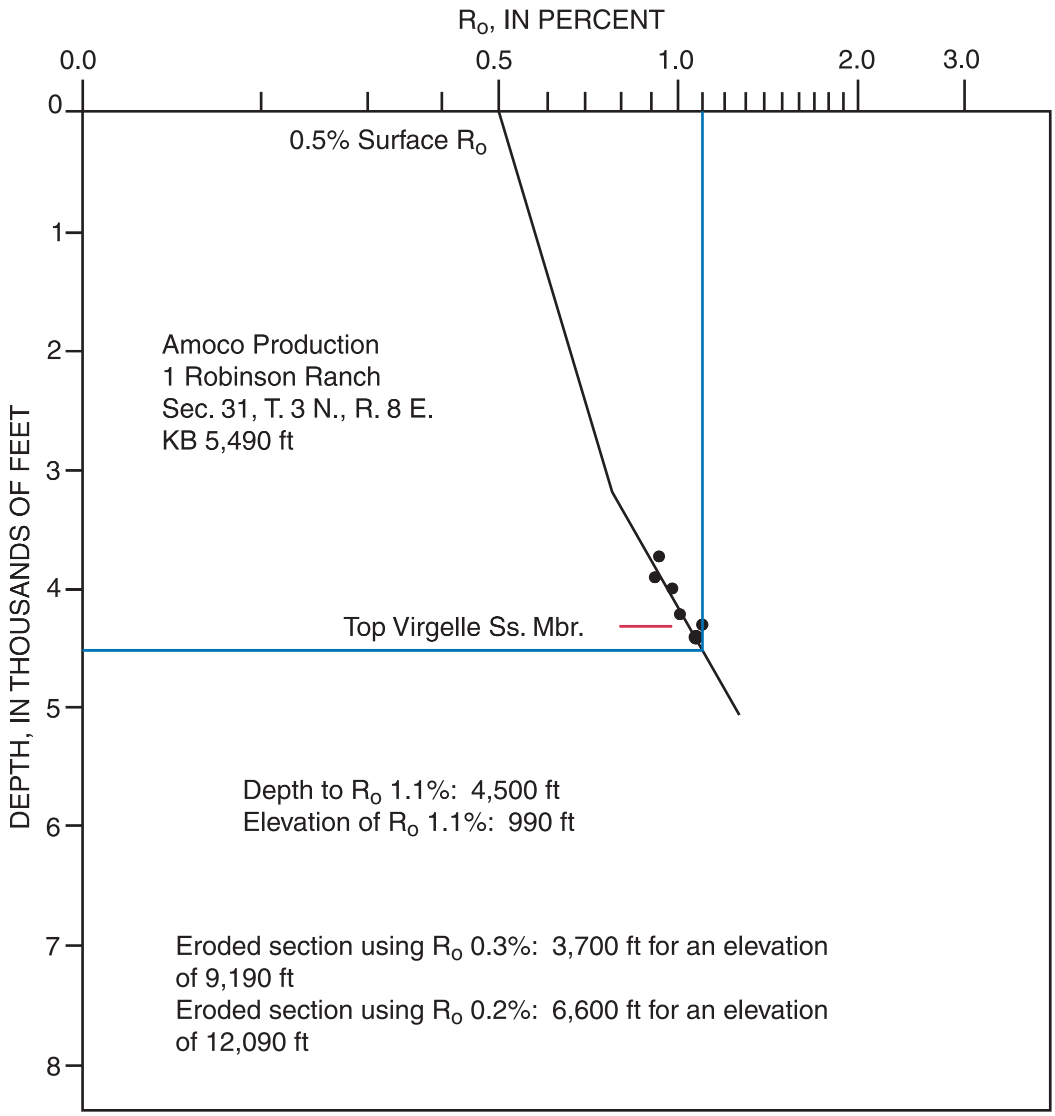

Figure 14. Vitrinite reflectance (R_o) profile for Amoco 1 Robinson Ranch well, located in sec. 31, T. 3 N., R. 8 E. Surface R_o is estimated from surface R_o map (fig. 8). Position of key stratigraphic markers and approximate depth and elevation of R_o 1.1 percent level are shown. Estimates of eroded section were made by extrapolating profile to R_o 0.2 percent and R_o 0.3 percent levels. KB, 5,490 ft, elevation of Kelly bushing.

Overburden Removal in the Crazy Mountains Basin

Estimating the amount of overburden removed from Laramide sedimentary basins such as the Crazy Mountains Basin is critical to reconstructing burial histories and determining the timing of hydrocarbon generation, but such estimates are difficult to make because the entire region, mountains and basins alike, has been uplifted and subjected to extensive downcutting since mid-Miocene time. Remnants of the pre-regional uplift surfaces are still preserved in many basins and on the flanks of adjoining uplifts, however, so reasonable extrapolations of overburden removed since middle Miocene time can be made. These surfaces may be composed of Oligocene through lower Miocene sedimentary and volcanic rocks, or be gently sloping pediments carved into older sedimentary rocks as well as the hard crystalline rocks that form the cores of Laramide uplifts. Once Laramide deformation ended near the close of Eocene time, many thousands of feet of detritus from both local and distant sources accumulated in the Rocky Mountain region, covering all but the highest peaks of these Laramide uplifts (see, for example, Epis and Chapin, 1975; Scott, 1975; Mears, 1993).

No pre-middle Miocene surfaces have been observed in the Crazy Mountains Basin, the youngest preserved unit

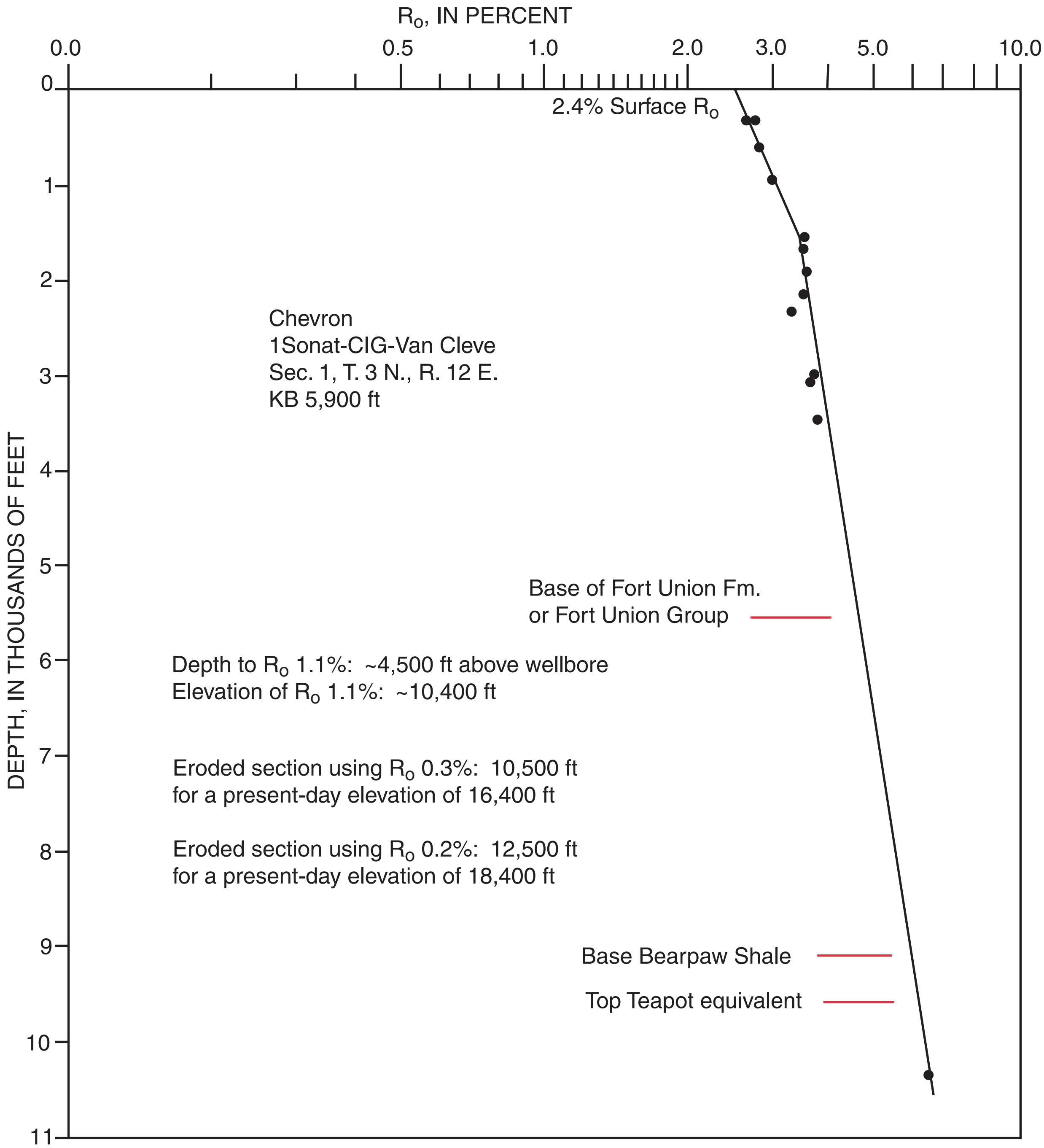

Figure 15. Vitrinite reflectance (R_o) profile for Chevron 1 Sonat-CIG-Van Cleve well, located in sec. 1, T. 3 N., R. 12 E. Surface R_o is estimated from surface Ro map (fig. 8). Position of key stratigraphic markers and approximate depth and elevation of R_o 1.1 percent level are shown. Estimates of eroded section were made by extrapolating profile to R_o 0.2 percent and R_o 0.3 percent levels. KB, 5,900 ft, elevation of Kelly bushing.

appearing to be siltstones, sandstones, and mudstones of the Paleocene Fort Union Formation. Maximum present-day elevations of that formation throughout most of the basin are generally in the 5,000–5,500 ft range, although maximum elevations near the Big Timber stock in the southern part of the Crazy Mountains exceed 11,000 ft where the rocks have been metamorphosed to hornfels grade by the Big Timber stock and are much harder and less easily eroded than non-metamorphosed Fort Union elsewhere in the basin. Crazy Peak, the highest peak in the Crazy Mountains at 11,209 ft, is about 0.6 mi southeast of the margin of the stock and is composed of nearly flat lying Fort Union Formation. The upper age limit of the Fort Union Formation has not been determined in the vicinity of Big Timber stock, but it must be older than

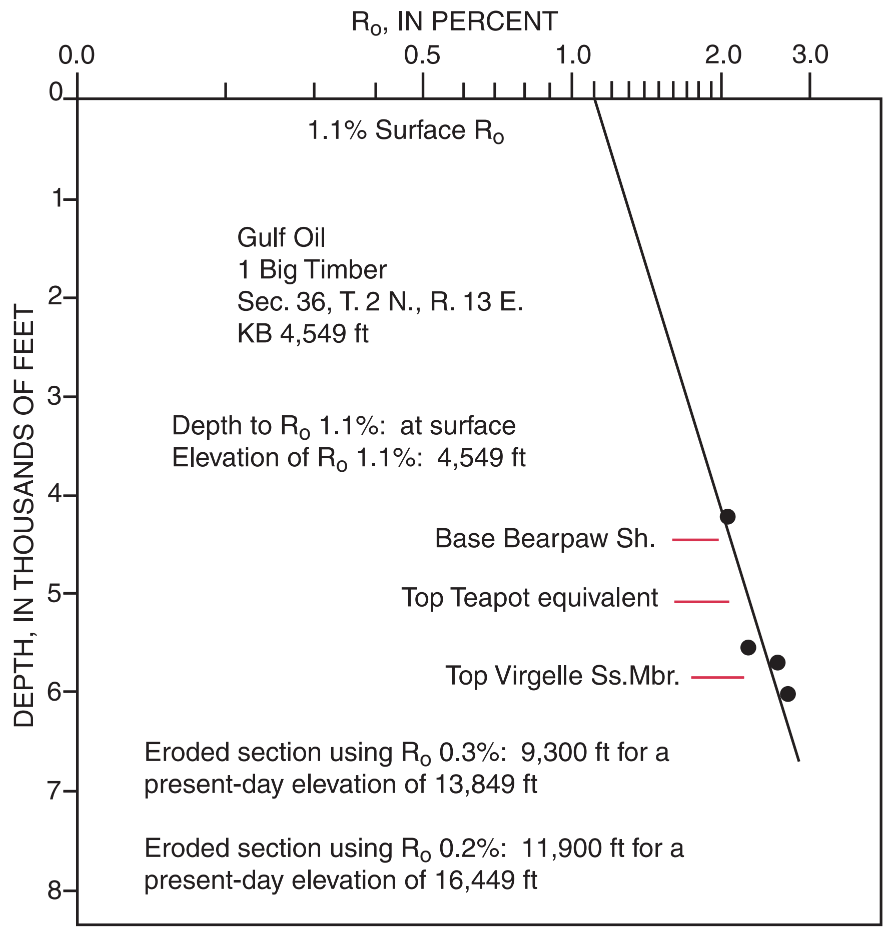

Figure 16. Vitrinite reflectance (R_o) profile for Gulf Oil 1 Big Timber well, located in sec. 36, T. 2 N., R. 13 E. Surface R_o is estimated from surface R_o map (fig. 8). Position of key stratigraphic markers and approximate depth and elevation of R_o 1.1 percent level are shown. Estimates of eroded section were made by extrapolating profile to R_o 0.2 percent and R_o 0.3 percent levels. KB, 4,549 ft, elevation of Kelly bushing.

the intruding stock that has been dated as early middle Eocene (51–49 Ma; du Bray and others, 1993; du Bray and Harlan, 1996). The youngest rocks preserved in uplifts near the Crazy Mountains Basin appear to be the nearly flat lying volcanic rocks and volcanic conglomerates of Eocene age preserved in the Gallatin Range southwest of the Crazy Mountains Basin (fig. 1). No evidence of a pre-middle Miocene maximum aggradation surface has been observed in these outcrops, but their maximum present-day elevation is 10,154 ft. In the Beartooth Mountains south of the Crazy Mountains Basin, Bevan (1925) reported two pediment surfaces preserved in the Precambrian core of that range, a higher, less well developed surface at an elevation of 12,000–12,400 ft, mainly in Montana, and a more continuous surface at about 9,500 ft confined largely to Wyoming.

The Big Timber stock is a 5 × 8 mi elliptical, compositionally diverse intrusion related to an extensive period of Eocene igneous activity in east-central Montana (du Bray and Harlan, 1996). The highest preserved occurrence of intrusive rocks is on Conical Peak at an elevation of 10,748 ft, which is lower than the highest outcrop of the Fort Union Formation (elevation 11,000 ft). One comparatively small mass of intrusive rocks covering about 3 mi^2, the Campfire Lake intrusion, located about 0.6 mi west of the main part of the stock, shows evidence for pressure quenching, indicating a probable venting to the land surface. According to du Bray and others (1993), all of the resulting eruptive material has since been eroded away. Detailed studies on mineral phases in the Big Timber stock led du Bray and Harlan (1996) to conclude that (1) the minerals crystallized at a depth of about 9,850 ft and (2) a like thickness of overburden has been removed by erosion. Adding to the maximum present-day elevation of the stock, 10,748 ft, gives an elevation of nearly 20,600 ft for pre-erosion ground surface over the stock. However, this elevation should not be considered as its elevation during the Eocene, because late Tertiary regional uplift needs to be considered. The entire

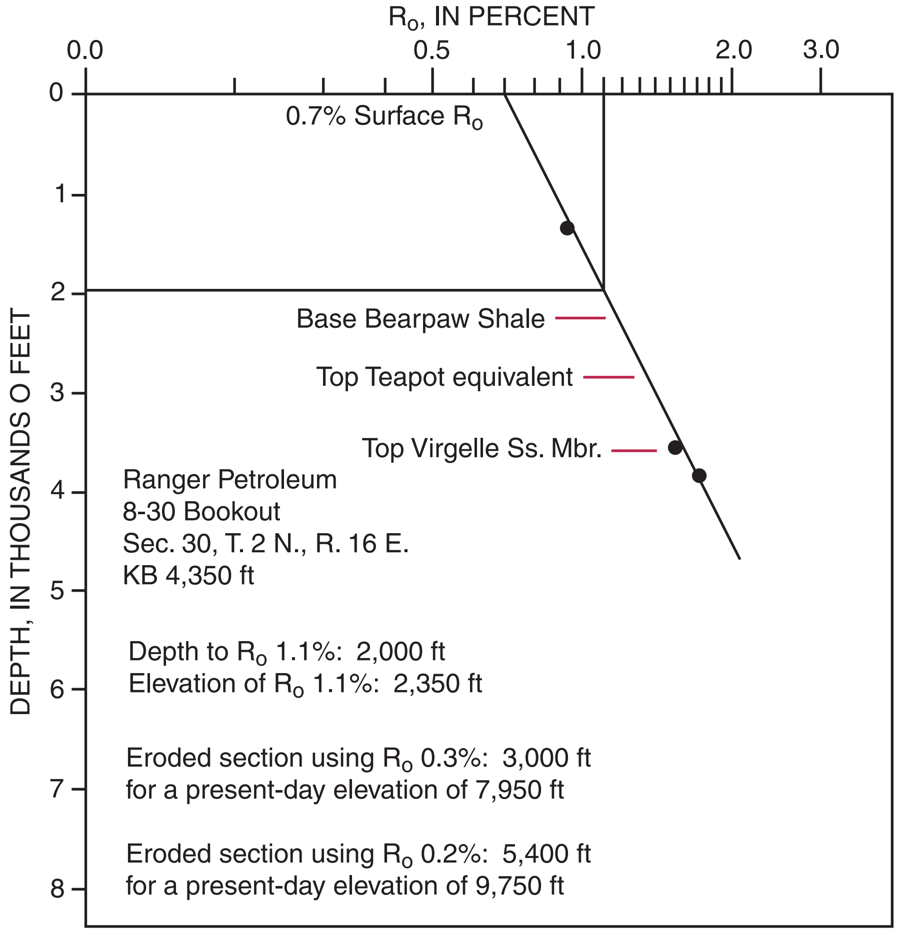

Figure 17. Vitrinite reflectance (R_o) profile for Ranger Petroleum 8-30 Bookout well, located in sec. 30, T. 2 N., R. 16 E. Surface R_o is estimated from surface R_o pt map (fig. 8). Position of key stratigraphic markers and approximate depth and elevation of R_o 1.1 percent level are shown. Estimates of eroded section were made by extrapolating profile to R_o 0.2 percent and R_o 0.3 percent levels. KB, 4,350 ft, elevation of Kelly bushing.

Rocky Mountain region had been regionally uplifted during the late Tertiary. The concept of regional uplift affecting the Rocky Mountain region was originally proposed by Blackwelder (1915, p. 193–210), and has been further developed by many workers since on the basis of faunal evidence indicating that Paleocene strata as well as Eocene, which are now at elevations of 5,000–10,000 ft or more in many basins, were deposited near sea level (MacGinitie, 1953; Leopold and MacGinitie, 1972; Dorf, 1960). Thus the elevation in the vicinity of the stock during Eocene time was probably in the range of 10,000–15,000 ft. As will be discussed later, it seems logical to conclude that, although a certain portion of the 9,850 ft that was presumably eroded off the Big Timber stock consisted of basin-fill sedimentary strata of Paleocene age, a substantial thickness of the eroded material was volcanic debris that once covered the stock and surrounding area and had produced a landform of high elevation above the basin floor.

Estimating Overburden Removed Using Vitrinite Reflectance Profiles

Vitrinite reflectance profiles can be used as an indirect method for estimating the elevation of the surface of maximum aggradation. These estimates are made by extrapolating vitrinite reflectance profiles to the minimum reflectance value for vitrinite that occurs in a shallow near-surface environment. Bustin (1986) reported a near-surface vitrinite reflectance value of 0.15 percent for arctic lignites in an area where little erosion is thought to have occurred. Vitrinite reflectance data from other areas indicate values of 0.2–0.3 percent in the near-surface environment (Dow, 1977; Hunt, 1979; Barker and Pawlewicz, 1986). Johnson and Nuccio (1993) extrapolated vitrinite reflectance profiles to both 0.2 percent and 0.3 percent to estimate overburden removed in the Piceance Basin

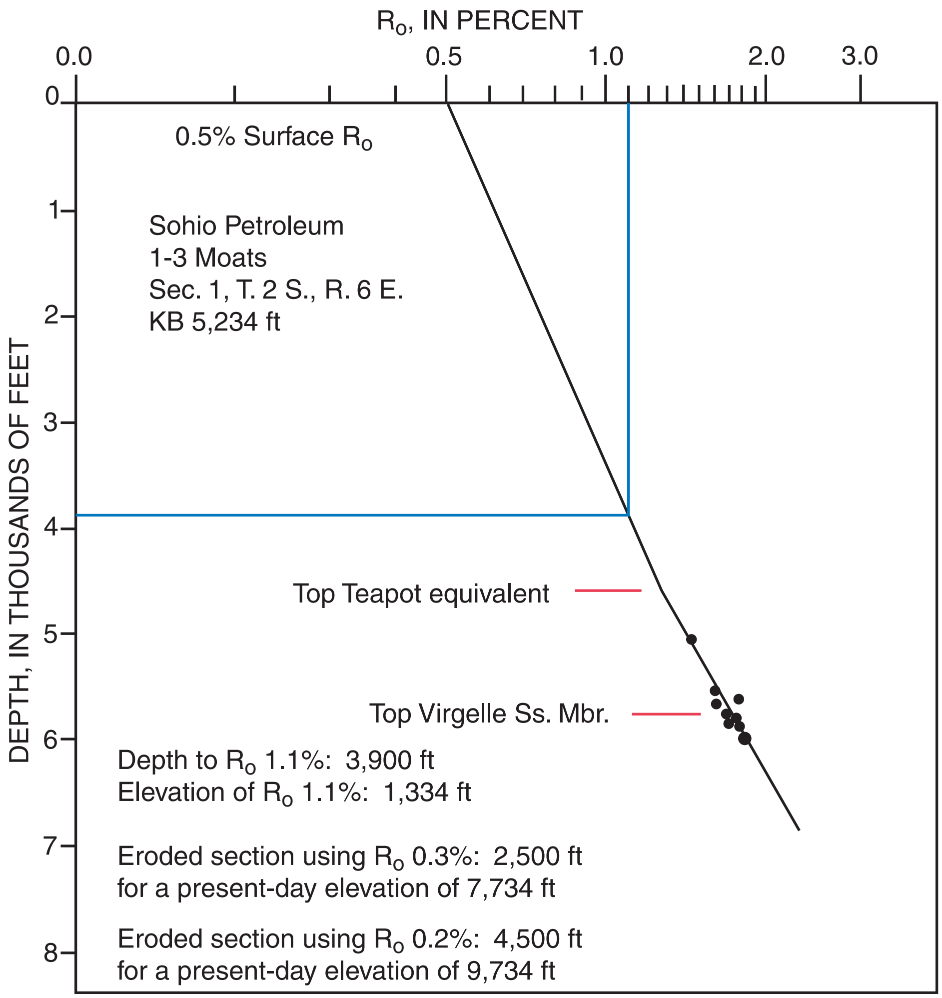

Figure 18. Vitrinite reflectance (R_o) profile for Sohio Petroleum 1-3 Moats well, located in sec. 1, T. 2 S., R. 6 E. Position of key stratigraphic markers and approximate depth and elevation of R_o 1.1 percent level are shown. Estimates of eroded section were made by extrapolating profile to R_o 0.2 percent and R_o 0.3 percent levels. KB, 5,234 ft, elevation of Kelly bushing.

of western Colorado. They found that the two results usually bracketed the present-day 10,000-ft level of that basin, which is the approximate elevation of the erosion surface that is preserved beneath 10-Ma basalts in the basin, and indicates that only a modest amount of section was removed as the erosion surface developed.

These extrapolations require well-constrained vitrinite reflectance profiles inasmuch as a slight change in slope can make a difference of thousands of feet in the extrapolation. In addition, any change in slope or “kink” that may have been present in the eroded part of the profile would be impossible to detect. Estimates of removed overburden extrapolating to both R_o 0.2 percent and R_o 0.3 percent are made for seven of the ten profiles (figs. 11, 14–19). The remaining three profiles are close to vertical and extrapolations to R_o 0.2 percent and 0.3 percent resulted in unreasonable estimates of removed overburden. Four of the most tightly constrained extrapolations are for the Sohio 1-3 Moats well (fig. 18), the Ranger 8-30 Bookout well (fig. 17), the Amoco 1 Mothershead well (fig. 19), and the Chevron 1 Sonat-CIG-Van Cleve well (fig. 15). The first three wells are from the southwest, south, and southeast marginal areas of the basin, and the fourth is near the center, about 6 mi southeast of Big Timber stock. For the three wells around the basin margins, estimates of overburden removed range from 2,500 to 3,200 ft for the 0.3 percent extrapolation and from 4,500 to 5,400 ft for the 0.2 percent extrapolation. Adding these estimates of removed overburden to present-day elevations at the three basin-margin drillsites yielded remarkably similar results, with elevations for the R_o 0.3 percent level from 7,596 to 7,950 ft and for the R_o 0.2

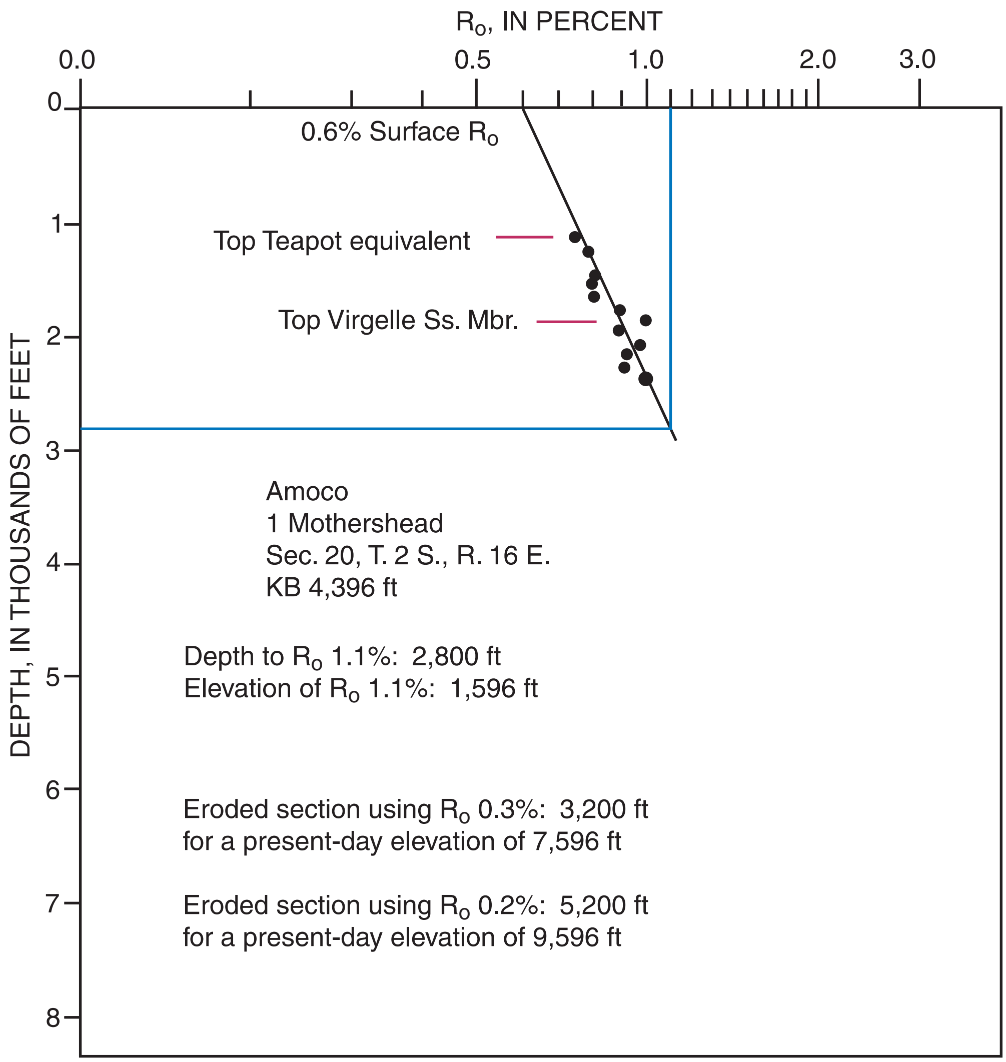

Figure 19. Vitrinite reflectance (R_o) profile for Amoco 1 Mothershead well, located in sec. 20, T. 2 S., R. 16 E. Position of key stratigraphic markers and approximate depth and elevation of R_o 1.1 percent level are shown. Estimates of eroded section were made by extrapolating profile to R_o 0.2 percent and R_o 0.3 percent levels. KB, 4,396 ft, elevation of Kelly bushing.

percent level from 9,596 to 9,750 ft (figs. 17–19). Extrapolations of removed overburden at the Chevron 1 Sonat-CIG-Van Cleve well, in contrast, are 10,500 ft for the R_o 0.3 percent level and 12,500 ft for the R_o 0.2 percent level, which give estimated elevations of 16,400 ft for the R_o 0.3 percent level and 18,400 ft for the R_o 0.2 percent level (fig. 15).

The extrapolations to R_o 0.3 percent for the three wells around the south margin of the basin appear to give unreasonably low amounts of removed overburden (figs. 17–19). The nearly 10,000-ft level of maximum aggradation derived from the extrapolations to R_o 0.2 percent, however, are close to what would be expected if it is assumed that little sediment was deposited in the basin after deposition of the highest outcrops of Fort Union Formation preserved near the Big Timber stock. The approximate 1,000-ft difference between the 10,000-ft level and the highest preserved outcrop of Fort Union along the flanks of the stock could be the result of some doming of sedimentary rocks in the vicinity of the stock and (or) slight errors in the R_o extrapolations.

The extrapolation to R_o 0.2 percent at the Van Cleve well indicates that the ground surface was once at 18,400 ft or more than 7,600 ft higher than the highest preserved outcrop of the Big Timber stock. This is roughly consistent with the 9,850-ft estimate of crystallization depth for mineral phases in the stock by du Bray and Harlan (1996), about 6 mi west of the Van Cleve well. It is unlikely that this eroded interval was largely sedimentary rock, as this like amount of sediment would also have been deposited in the vicinity of the three

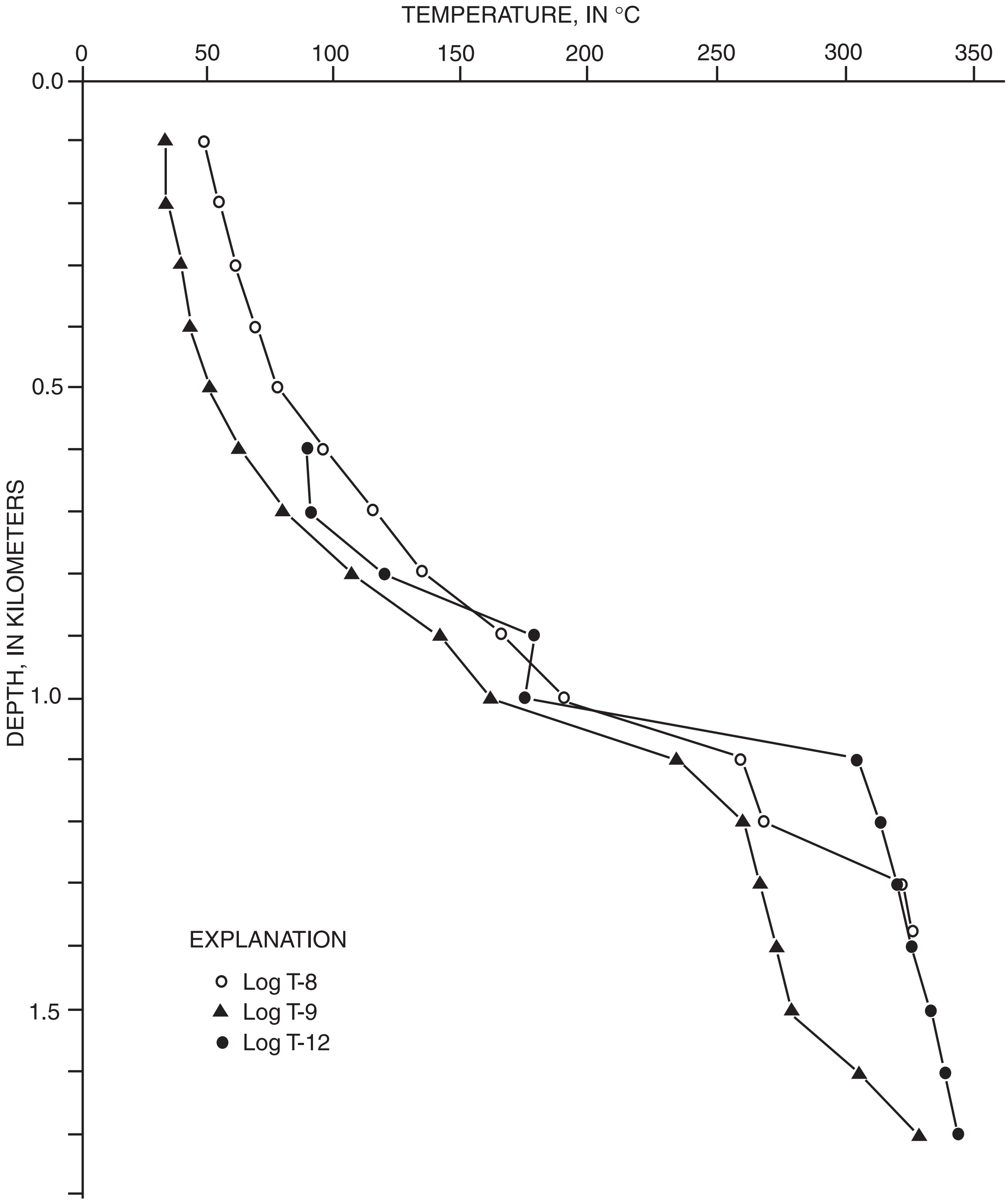

Figure 20. Temperature-depth profiles recorded during three different logging runs for the Cerro Prieto geothermal system, Baja California, Mexico. 1 km = 0.62 mi; °C = (°F–32)/1.8. (From Barker and others, 1981.)

wells used for R_o extrapolations in the marginal areas of the basin, a circumstance for which there is no evidence either there or anywhere else in the Rocky Mountain region. Thus, it is likely that the missing interval was largely volcanic rocks that accumulated in the vicinity of the Big Timber stock.

Burial, Thermal, and Petroleum Generation Modeling

The thermal and petroleum generation history of a basin can be modeled using burial reconstructions. Modeling was

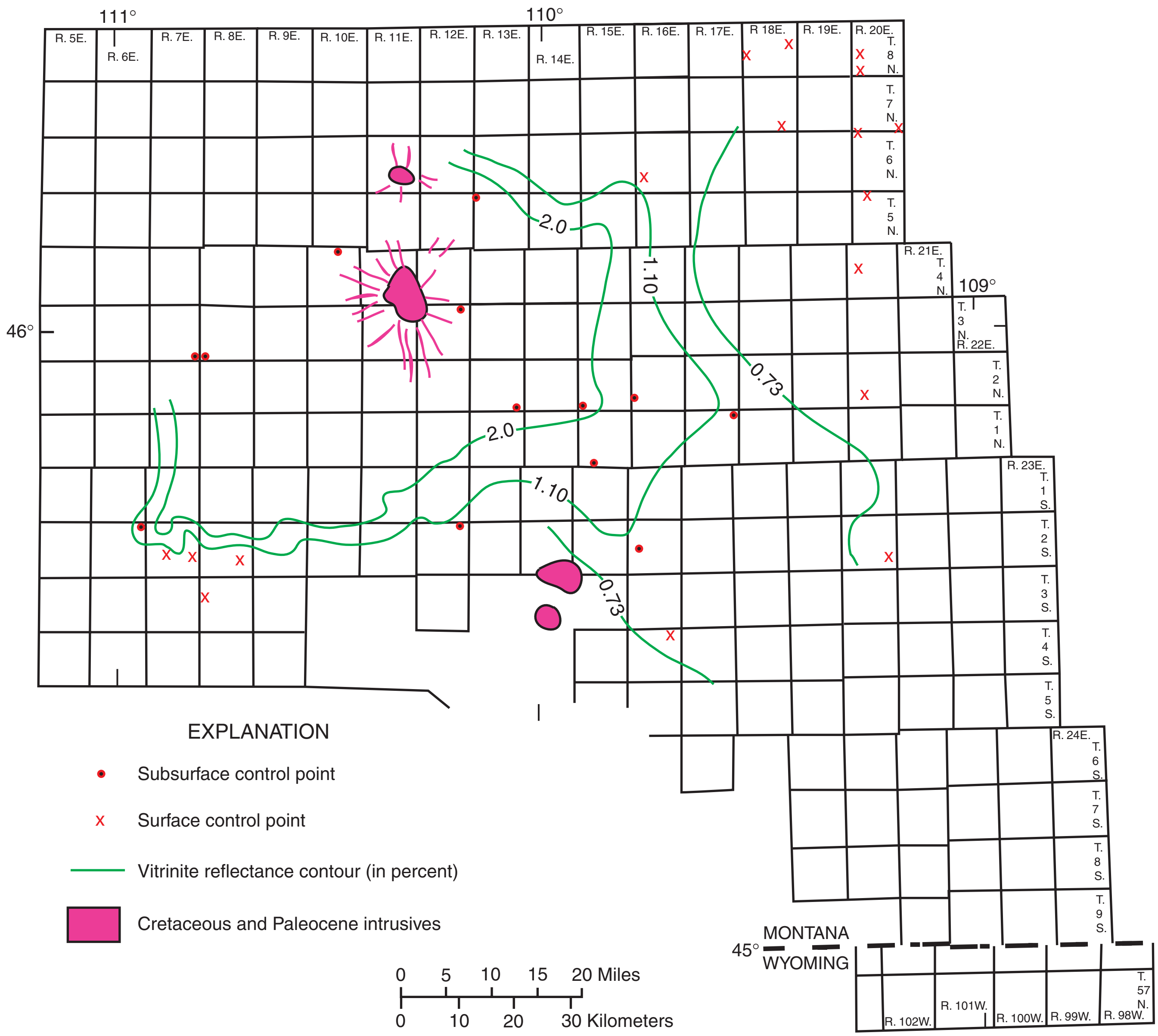

Figure 21. Estimated vitrinite reflectance values for top of Virgelle Sandstone Member of Upper Cretaceous Eagle Sandstone.

attempted for three wells in decreasing distance from the Big Timber stock—the Amoco 1 Mothershead well, Ranger Petroleum 8–30 Bookout well, and Chevron 1 Sonat-CIG-Van Cleve well (fig. 5)—based on source rock kinetics of Lawrence Livermore National Laboratory (LLNL) and the BasinMod program from Platte River Associates. The burial reconstructions used assume continuous deposition from Late Cretaceous through Paleocene time in the basin. Fossil evidence indicates that there are no major time breaks in deposition of this interval (Roberts, 1972; Hartman and Krause, 1993). Age of the Upper Cretaceous Campanian-Maastrichtian boundary (71.3 Ma), Cretaceous-Tertiary boundary (65 Ma), and Paleocene-Eocene boundary (54.8 Ma) are from the Geological Society of America (1999). The Virgelle Sandstone Member of the Eagle Sandstone is within the *Scaphites hippocrepis* ammonite zone (Gill and Burkholder, 1979), which has been approximately dated as 80.5 Ma (Obradovich, 1993). The top of the Teapot Sandstone Member and its equivalent is within the *Baculites reesidei* ammonite zone (Gill and Cobban, 1966), which is one ammonite zone older than the Campanian-Maastrichtian boundary; however, the burial reconstructions assume the Teapot to correlate temporally with this boundary (71.3 Ma). That subsidence in the Crazy Mountains Basin had largely ceased by early Eocene time is evidenced by the nearly flat lying strata mapped as Fort Union Formation adjacent to the Big Timber stock east of the

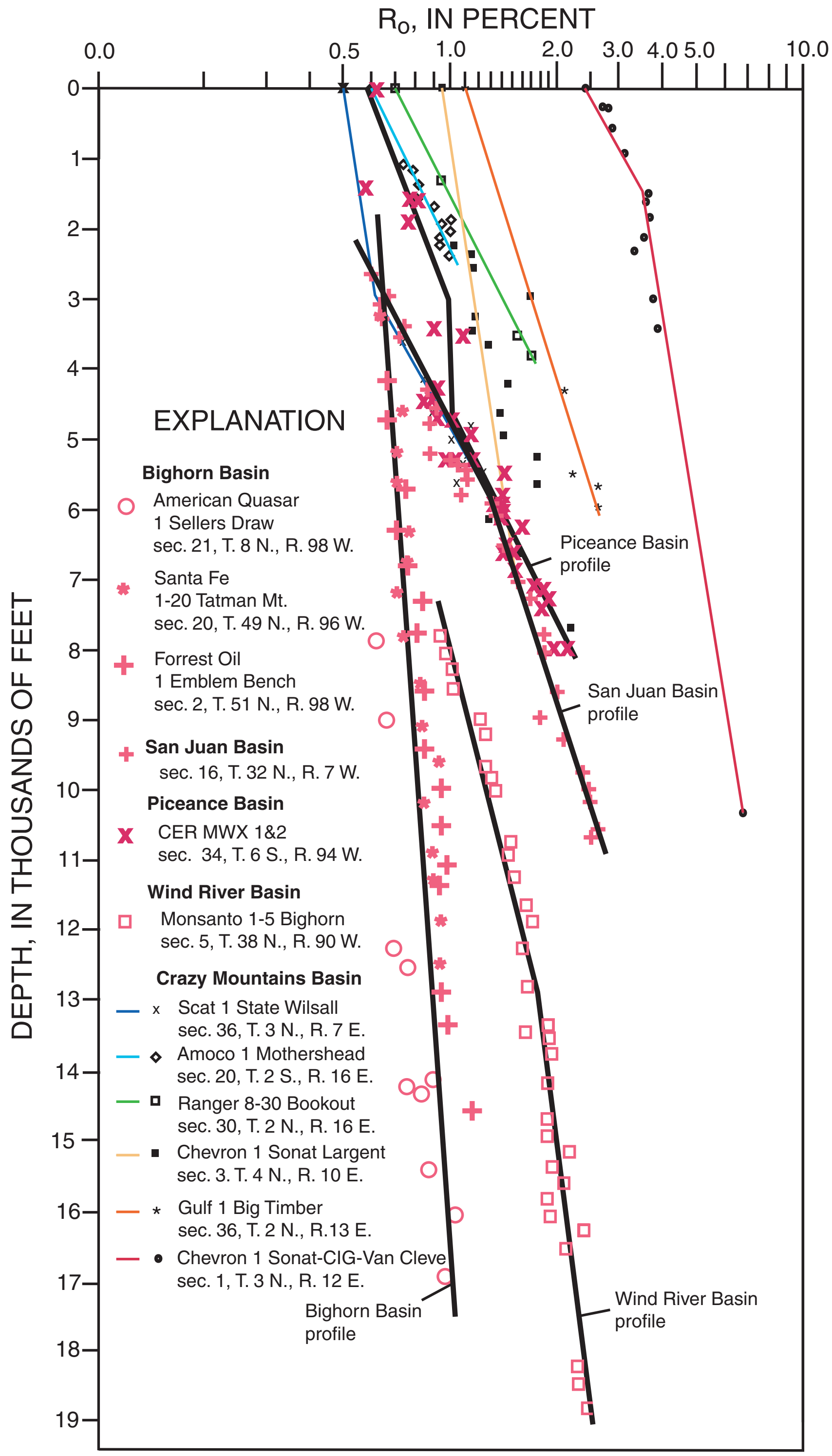

Figure 22. Comparison of six vitrinite reflectance (R_o) profiles from Crazy Mountains Basin with three profiles from Bighorn Basin, Montana and Wyoming, and one profile each from Wind River Basin of Wyoming, Piceance Basin of Colorado, and San Juan Basin of Colorado and New Mexico. San Juan Basin profile is from Law (1992). Wind River Basin profile is from Pawlewicz (1993, fig. 2). Bighorn Basin profile was constructed using data from Nuccio and Finn (1998). Piceance Basin profile is from Law and others (1989) and Johnson and Nuccio (1993).

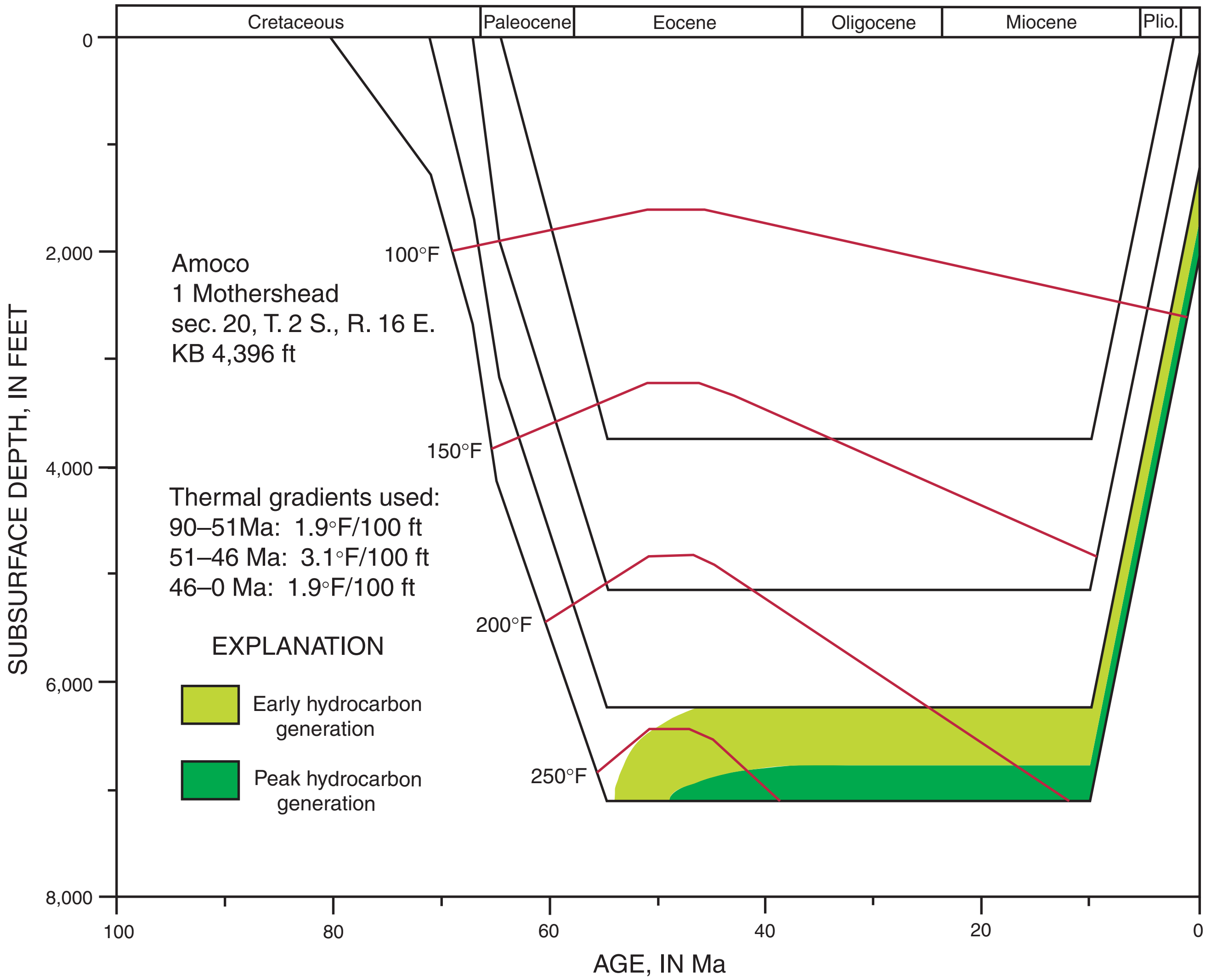

Figure 23. Burial and thermal reconstruction for the Amoco 1 Mothershead well, located in sec. 20, T. 2 S., R 16 E., showing modeled timing of gas generation by coal-bearing Type III source rocks near Upper Cretaceous Virgelle Sandstone Member of Eagle Sandstone. Presently observed vitrinite reflectance values were successfully modeled using a present-day geothermal gradient of 1.9°F/100 ft from 100 to 51 Ma and from 46 Ma to present, and an elevated geothermal gradient of 3.1°F/100 ft from 51 to 46 Ma.

basin trough, which indicates that little downwarping occurred after their deposition. Though undated, these highest outcrops are perceived to be older than the Big Timber stock, which has been dated at 51–49 Ma or early middle Eocene (du Bray and Harlan, 1996). Thus, it is assumed for the purpose of burial reconstructions, that basin subsidence ended at the end of the Paleocene and that no younger strata were deposited above these highest outcrops.

Amoco 1 Mothershead Well

The burial and thermal history of the area around the Amoco 1 Mothershead well is illustrated in figure 23. The present-day R_o value for a single sample in the Eagle Sandstone at a depth of 1,960 ft is 0.89 (fig. 19, table 2), indicating that peak gas generation (R_o about 1.1 percent; Dow, 1977) in these coal-bearing source rocks was never reached. In this area, maximum burial occurred between about 55 and 10 Ma. Uplift and erosion starting about 10 Ma removed approximately 5,200 ft of section. The well is spudded in Upper Cretaceous volcaniclastic rocks (Lopez, 2000) related to a Late Cretaceous volcanic center about 6 mi southwest of the well site. These rocks are approximately time correlative with the Maastrichtian Bearpaw Shale (Johnson and Finn, Chapter A, this CD-ROM). The interval from the top of the Virgelle Sandstone Member to the top of the Teapot in the well is 852 ft thick. The interval from the top of the Teapot Sandstone to the top of the Cretaceous section, from regional structural and stratigraphic relations, is about 2,500 ft, or 1,430 ft above the wellbore. Total thickness of eroded interval, estimated by

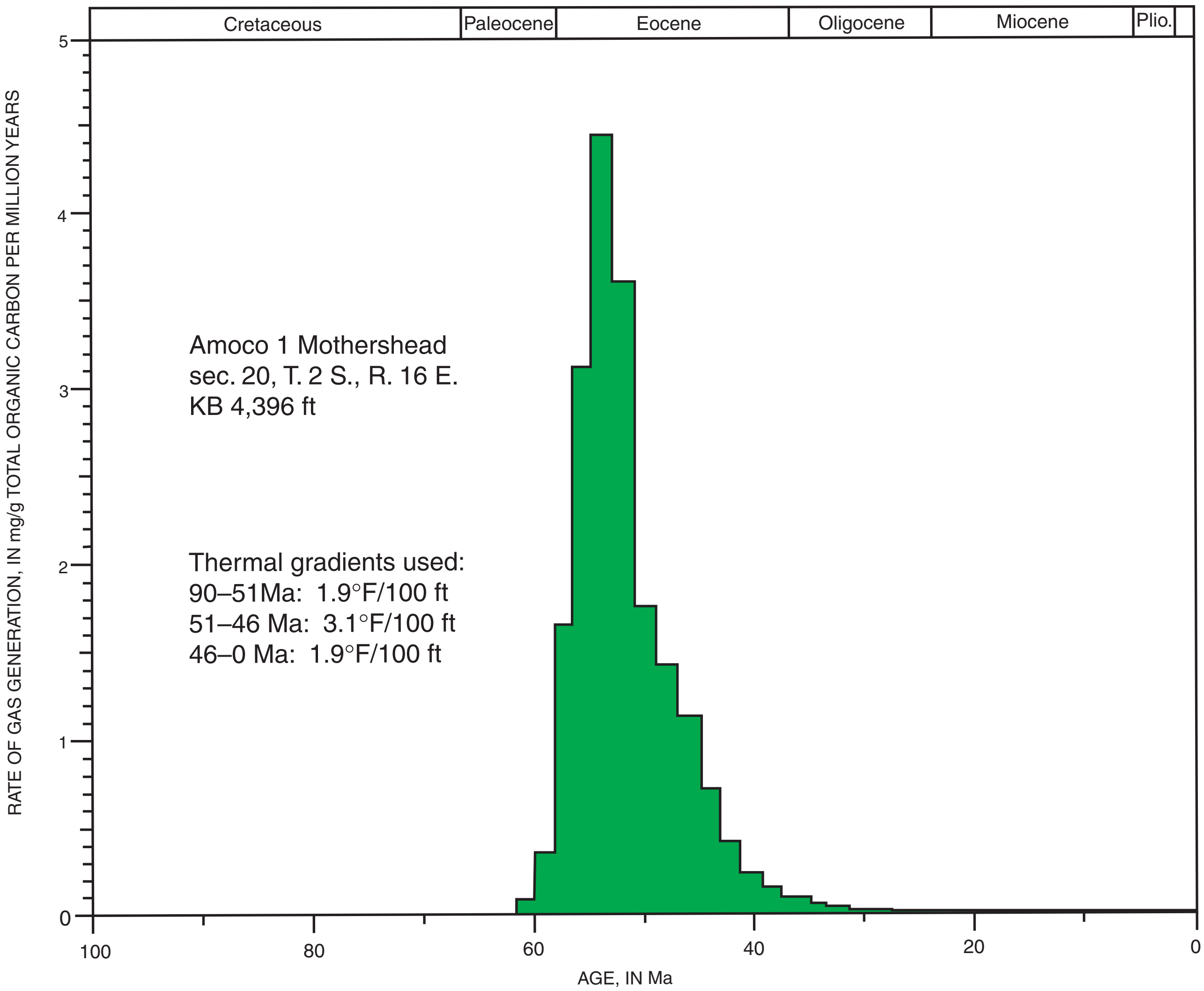

Figure 24. Rate of gas generation in mg/g of total organic carbon through time by coal-bearing Type III source rocks near Upper Cretaceous Virgelle Sandstone Member of Eagle Sandstone for Amoco 1 Mothershead well in sec. 20, T. 2 S., R. 16 E. Peak gas generation occurred at about 53 Ma, and gas generation was largely completed by 23 Ma.

extrapolating the vitrinite reflectance profile to an R_o of 0.2 percent, is 5,200 ft (fig. 19). This eroded interval is assumed to have been all Paleocene Fort Union Formation, although it is likely that at least a part of it was Eocene volcaniclastic rocks. The model assumes 50 percent sandstone and 50 percent mudstone for the entire interval from the Virgelle Sandstone to the surface of maximum aggradation.

Assuming the presently observed thermal gradient of 1.9°F/100 ft for the entire burial period, the model seriously underpredicts the observed R_o values. In order to match the measured vitrinite reflectance values for this well with modeled values, a variable geothermal gradient had to be used that assumes a thermal event related to the period of Eocene igneous activity. The following gradients were then applied: from 90 Ma to 51 Ma—1.9°F/100 ft; from 51 Ma to 46 Ma—3.1°F/100 ft; and from 46 Ma to present—1.9°F/100 ft. Results of the modeling indicate that during maximum burial, the base of the Virgelle Sandstone Member was buried by about 7,100 ft of overburden and reached temperatures as high as 275°F (fig. 23). The model indicates that gas generation from Type III organic matter in the Virgelle began about 60 Ma, peaked at 53 Ma, and then gradually declined until about 23 Ma when generation all but ceased (fig. 24).

Ranger 8–30 Bookout Well

The burial and thermal history of the area around the Ranger 8–30 Bookout well is illustrated in figure 25. Present-day R_o values for two samples from the Eagle Sandstone at present-day depths of 3,555 and 3,835 ft are 1.53 and 1.71 percent, respectively (fig. 17, table 2), indicating that these coal-bearing source rocks have passed through the window for peak gas generation. In this area, maximum burial occurred between about 55 and 10 Ma. Uplift and erosion starting

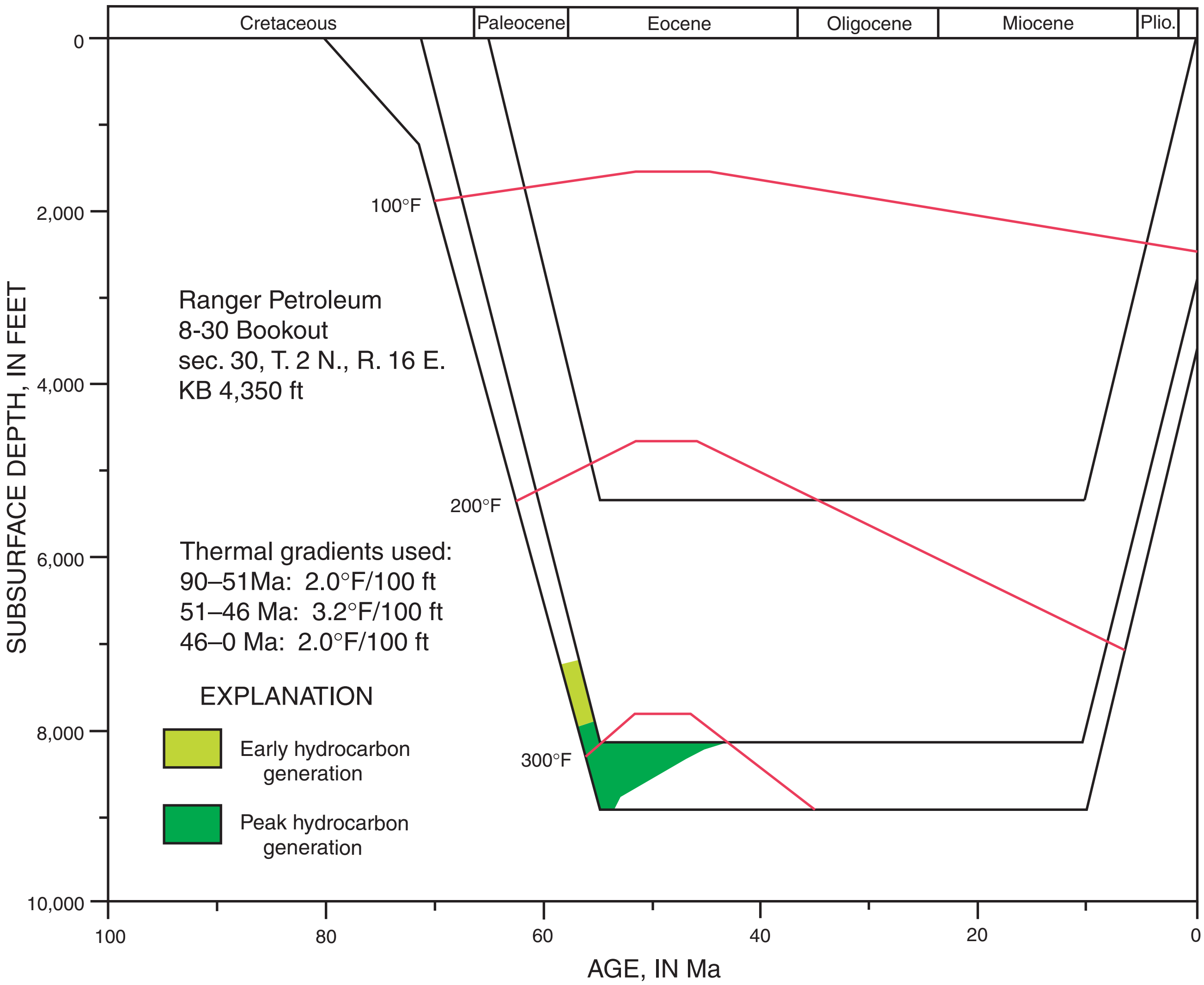

Figure 25. Burial and thermal reconstruction for Ranger Petroleum 8-30 Bookout well, located in sec. 30, T. 2 N., R. 16 E., showing modeled timing of gas generation by coal-bearing Type III source rocks near Upper Cretaceous Virgelle Sandstone Member of Eagle Sandstone. Presently observed vitrinite reflectance values were successfully modeled using a present-day geothermal gradient of 2.0°F/100 ft from 100 to 51 Ma and from 46 Ma to present, and an elevated geothermal gradient of 3.2°F/100 ft from 51 to 46 Ma.

about 10 Ma removed approximately 5,400 ft of section (fig. 17). Geologic mapping in the vicinity of the well indicates that it was spudded just above the contact between the Paleocene Fort Union Formation and the underlying Upper Cretaceous Hell Creek Formation (Lopez, 2000). The burial reconstruction assumes that the well was spudded at the Cretaceous-Tertiary boundary. The interval from the top of the Upper Cretaceous Virgelle Sandstone to the top of the Upper Cretaceous Teapot Sandstone is 785 ft, and the interval from the top of the Teapot Sandstone to the top of the Cretaceous section is 2,770 ft. Extrapolating the R_o profile to an R_o of 0.2 percent indicates that 5,400 ft of strata have been removed (fig. 17). It is assumed that all of these strata were sedimentary rocks of Paleocene age, although it is likely that at least a small part of this eroded interval was Eocene volcaniclastic rocks. The model assumes 50 percent sandstone and 50 percent mudstone for the entire interval from the Virgelle Sandstone to the surface of maximum aggradation.

As with the Mothershead well, using present-day thermal gradient of 2.0°F/100 ft significantly underpredicts the observed vitrinite reflectance values. A variable geothermal gradient also had to be used in this well in order for the modeling to match the measured vitrinite reflectance values. The following gradients were then applied: from 100 Ma to 51 Ma—2.0°F/100 ft; from 51 Ma to 46 Ma—3.2°F/100 ft; and from 46 Ma to present—2.0°F/100 ft. Results of the modeling indicate that during maximum burial, the base of the Virgelle Sandstone was buried to about 9,000 ft and reached

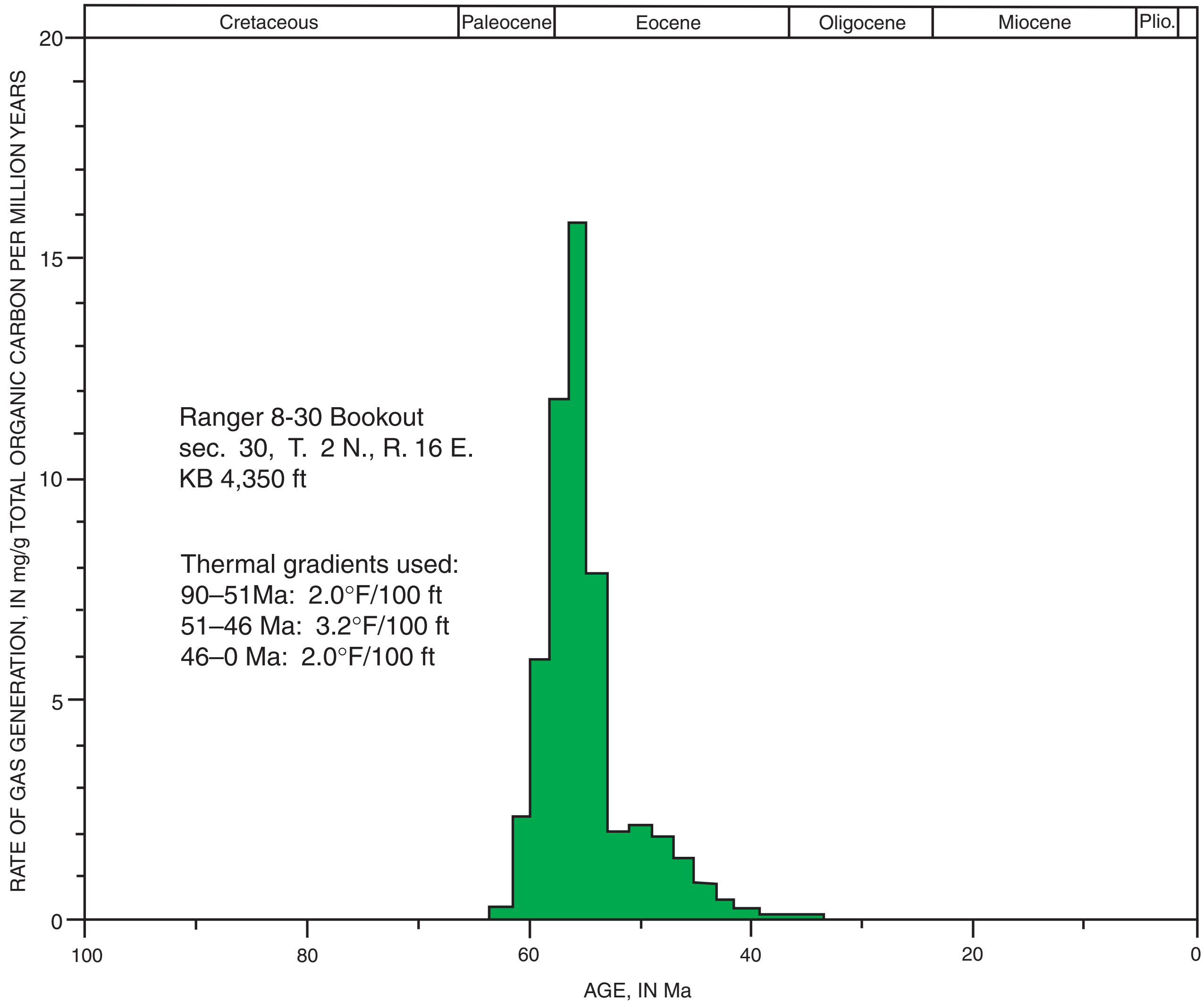

Figure 26. Rate of gas generation in mg/g of total organic carbon through time by coal-bearing Type III source rocks near Upper Cretaceous Virgelle Sandstone Member of Eagle Sandstone for Ranger Petroleum 8-30 Bookout well in sec. 30, T. 2 N., R. 16 E. Peak gas generation occurred at about 55 Ma, and gas generation was largely completed by 40 Ma.

temperatures as high as 325°F (fig. 25). Gas generation from Type III organic matter in the Virgelle began about 62 Ma, peaked at 55 Ma, and largely ended about 40 Ma (fig. 26).

Chevron 1 Sonat-CIG-Van Cleve Well

The burial and thermal history of the area around the Chevron 1 Sonat-CIG-Van Cleve well is illustrated in figure 27. Present-day R_o value for a single sample in the Parkman Sandstone, at a depth of 10,370 ft, is 6.72 percent (fig. 15, table 2), indicating that this sample is well beyond peak gas generation. The well is thought bottom just above the Eagle Sandstone at a depth of 10,401 ft (Johnson and Finn, Chapter A, this CD-ROM). The interval from the bottom of the hole to the top of the Teapot Sandstone Member is 698 ft, and the interval from the top of the Teapot to the base of the Paleocene Fort Union Formation or Group is 4,100 ft. The base of the Fort Union is at a depth of 5,572 ft. The highest preserved Fort Union outcrops are at 11,209 ft at Crazy Peak, near the Big Timber stock and about 3.5 mi west-southwest of the well site. It is assumed that no Fort Union was deposited above this highest outcrop and that some doming of these outcrops occurred during intrusion. For this reconstruction, this present-day elevation for the top of the Fort Union Formation is rounded off to 11,000 ft. Kelly bushing at the well is 5,900 ft. Thus 5,100 ft of Fort Union has been eroded and total original thickness of the Fort Union is estimated to have been 5,100 + 5,572 ft or 10,672 ft. Extrapolating the vitrinite reflectance profile to an R_o of 0.2 percent gave an estimate of 12,500 ft of total rock removed from the drill site (fig. 15). Because 5,100 ft of this estimate is assumed to have been Fort Union sedimentary rocks, the remaining 7,400 ft of missing strata is

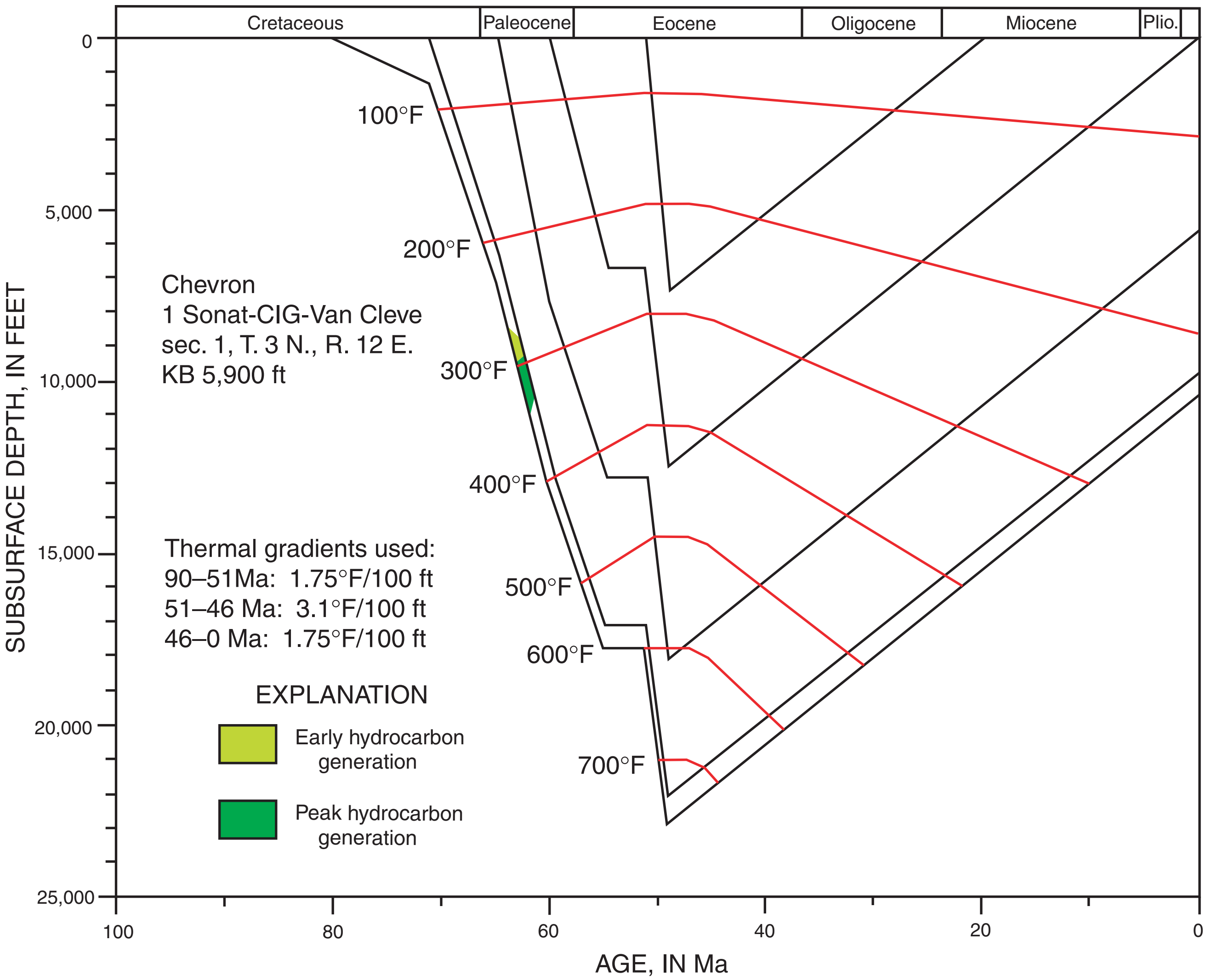

Figure 27. Burial and thermal reconstruction for Chevron 1 Sonat-CIG-Van Cleve well, located in sec. 1, T. 3 N., R. 12 E., showing modeled timing of gas generation by coal-bearing Type III source rocks near Upper Cretaceous Virgelle Sandstone Member of Eagle Sandstone. Presently observed vitrinite reflectance values, except for the R_o 6.72 percent at 10,370 ft, were successfully modeled using a present-day geothermal gradient of 1.75°F/100 ft from 100 to 51 Ma and from 46 Ma to present, and an elevated geothermal gradient of 3.1°F/100 ft from 51 to 46 Ma.

hypothesized to have been volcanic rocks erupted from venting of the Big Timber stock and associated intrusions.

The burial, thermal, and petroleum generation history for the area around this well is notably different than that of the two areas previously described. In this area, maximum burial occurred at 50 Ma. Uplift and erosion, starting at about 50 Ma (fig. 27), or almost immediately after maximum burial, ultimately removed about 12,500 ft of section. Again, a variable geothermal gradient had to be used in order to match the measured vitrinite reflectance values for this well with modeled values. The gradients used were: from 90 Ma to 51 Ma—1.75°F/100 ft; from 51 Ma to 46 Ma—3.1°F/100 ft; and from 46 Ma to present—1.75°F/100 ft. Results of the modeling indicate that during maximum burial, the base of the Virgelle Sandstone Member section was buried to about 23,000 ft and reached temperatures as high as 750°F (fig. 27). Gas generation from Type III organic matter in the Virgelle occurred during a narrow time range beginning about 65 Ma, peaking at 61 Ma, and largely ending about 55 Ma, before the igneous heating event (fig. 28). It should be noted that the modeling program could not match the extremely high vitrinite reflectance value of 6.72 percent in the lower part of the well—a further indication that the area was subjected to an anomalously high heating event.

Discussion

Overall, the Crazy Mountains Basin has the highest levels of thermal maturity in both the surface and subsurface of any

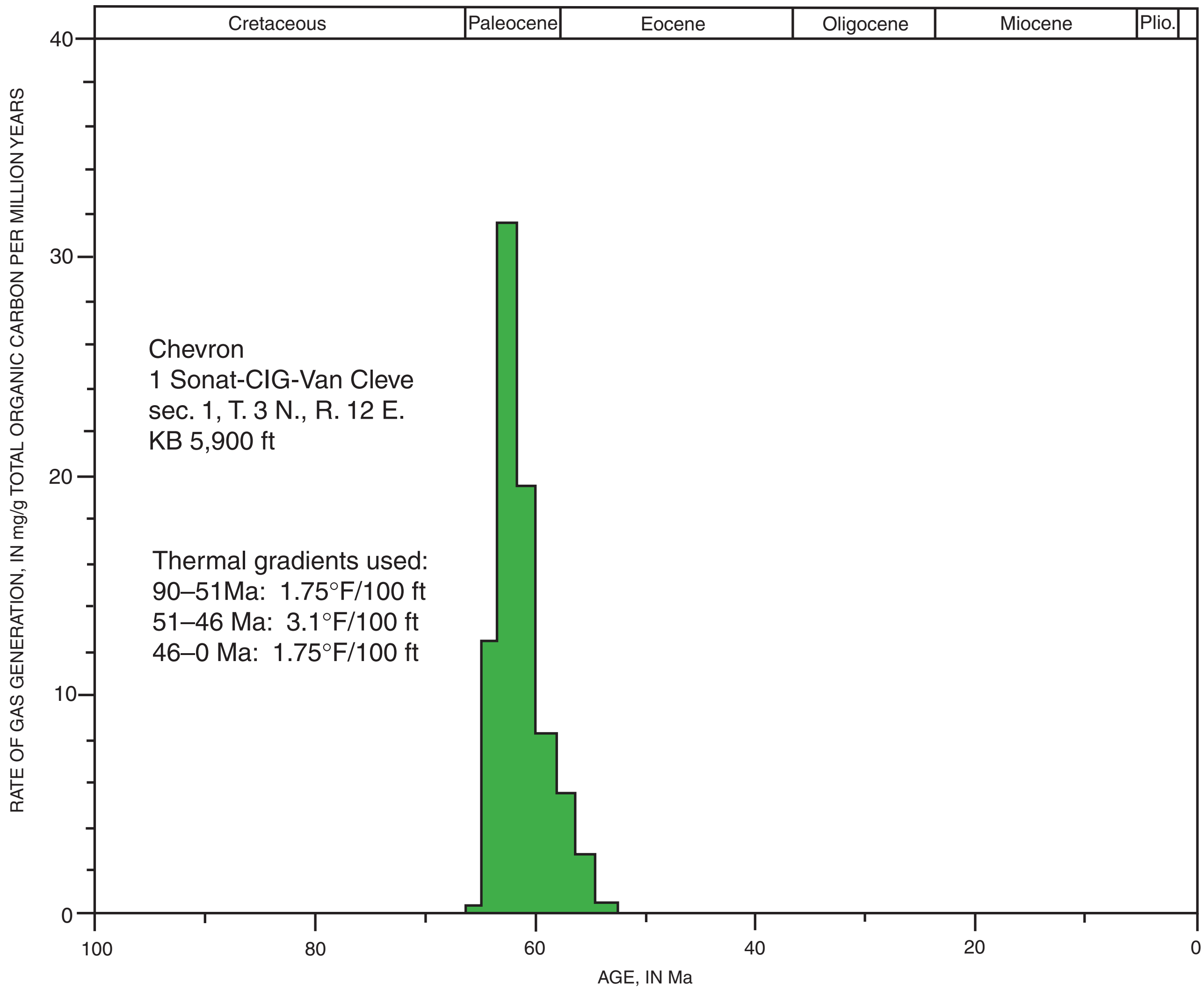

Figure 28. Rate of gas generation in mg/g of total organic carbon through time by coal-bearing Type III source rocks near Upper Cretaceous Virgelle Sandstone Member of Eagle Sandstone for Chevron 1 Sonat-CIG-Van Cleve well in sec. 1, T. 3 N., R. 12 E. Peak gas generation occurred at about 61 Ma, and gas generation was largely completed by 55 Ma.

Rocky Mountain basin for which detailed vitrinite reflectance studies have been published. Surface R_o values appear to be greater than 1.1 percent throughout an area that extends approximately 18–24 mi in an east-west direction and 30 mi in a north-south direction surrounding the Eocene stocks that form the core of the Crazy Mountains. These results are consistent with the earlier work by du Bray and Harlan (1996), who found that the metamorphic aureole around Big Timber stock was remarkably wide for such a small intrusion, with the hornfels-grade metamorphic zone extending a distance of several miles from the margins of the stock. They (du Bray and Harlan, 1996) suggested that exsolution of fluids from the stock may be responsible for the unusual size of the aureole. Elevated vitrinite reflectance values have been determined throughout the southwestern part of the basin and in much of the eastern part, extending well beyond any evidence for influences from middle Eocene igneous activity. Closely spaced samples collected along transects in this large area yielded variable results, indicating that heating also varied on a local scale. The true complexity of this variability cannot be fully understood based on the sparse sampling done for this study, but the results that were achieved indicate that the highest vitrinite reflectance values in this area were found to be not near mapped dikes and sills in all cases. Accordingly, it is suggested that hydrothermal systems that developed over unidentified buried intrusions may be responsible for many of these high values.

Estimates of overburden removed made by extrapolating vitrinite reflectance profiles to an R_o of 0.2 percent gave results ranging from 9,500 to 9,800 ft for the surface elevation of maximum aggradation in three of the most tightly constrained profiles in the marginal areas of the basin away from the Eocene stocks. These results are consistent with regional geology, if it is assumed that a negligible thickness of strata was deposited above the highest preserved outcrops of the Fort Union Formation near the Eocene stocks. Du Bray and Harlan (1996) used detailed mineral studies to estimate that about 9,850 ft of strata was once present over Big Timber stock during its emplacement. Adding this to the maximum present-day elevation of 10,748 ft for the stock gives an elevation of nearly 20,600 ft for the summit of the volcanic cone that built up over the stock, in present-day elevations. As previously discussed, if the 5,000–10,000 ft of probable Miocene to recent regional uplift were subtracted, the volcanic cone over Big Timber stock in middle Eocene time towered about 11,000 ft higher than surrounding areas such as the south margin of the basin where burial reconstructions indicate that little volcanic debris accumulated. As a comparison, Mount St. Helens, prior to the eruptions of 1980, varied in elevation from over 9,800 ft at its peak to about 3,000 ft at the base of the cone about 4 mi away for an elevation of 6,800 ft above the surrounding countryside.

The estimate of 12,500 ft of overburden removed for the Chevron 1 CIG-Sonat-Van Cleve well 6 mi southeast of the Big Timber stock gives an estimate of 18,400 ft elevation for the surface of maximum aggradation in terms of present-day topography. The well is 6 mi from the Big Timber stock, thus the elevation decreased only about 2,200 ft in the 6 mi from the top of the volcano to the vicinity of the Van Cleve well. It should be strongly emphasized that the estimate of overburden removed over the Van Cleve well is highly speculative, for a change in slope or “kink” in the vitrinite reflectance profile in the eroded interval in the profile would make thousands of feet of difference in the estimate of overburden removed. The 11,000-ft difference in elevation between the top of the volcanic cone over the top of Big Timber stock, based on mineral crystallization depths reported by du Bray and Harlan (1996), and the more constrained vitrinite reflectance extrapolations for the wells in the marginal areas of the basin, however, does lead to the tentative conclusion that the middle Eocene volcano over Big Timber stock may have been significantly larger than Mount St. Helens.

Burial reconstruction modeling using present-day geothermal gradients underpredicted measured vitrinite reflectance values at all three drill sites that were modeled. Present-day vitrinite reflectance values can, however, be successfully modeled by applying elevated thermal gradients from 51 to 46 Ma, during the middle Eocene intrusive event, and present-day thermal gradients for the remainder of the burial history, which implies that the high vitrinite reflectance values are related to the igneous activity. One of the wells, the Chevron 1 Sonat-CIG-Van Cleve well, is only about 6 mi southeast of the Big Timber stock, whereas the other two wells, the Ranger 8–30 Bookout well and the Amoco 1 Mothershead well, are in the eastern part of the basin well away from any evidence of middle Eocene igneous activity. This supports the idea that the pulse of heat related to this igneous event extended well beyond the area where intrusions are present at the surface. This contrasts with results from the Bighorn Basin by Nuccio and Finn (1998), who successfully modeled observed vitrinite reflectance values by using present-day thermal gradients throughout the burial histories.

Heating from the middle Eocene igneous event in the Crazy Mountains Basin appears to have largely, if not totally, dissipated. Present-day thermal gradients are higher than those found in the nearby Bighorn Basin and the Wind River Basin in central Wyoming, but comparable to those in the Piceance Basin in western Colorado. In addition, there does not appear to be an increase in thermal gradients toward the stocks near the middle of the basin.

Petroleum generation modeling for the Amoco 1 Mothershead well, the farthest well from the Big Timber stock of the three wells modeled, indicates that gas generation in the coal-bearing intervals in the Upper Cretaceous Eagle Sandstone began at 63 Ma, peaked at 56 Ma, and largely ended by 40 Ma, although gas generation is continuing at a very slow rate today (figs. 23 and 24). The present-day R_o value of 0.89 percent indicates that these source rocks never went through a peak gas generating stage (R_o 1.1 percent) and still retain much of their potential to generate gas. Gas generation has largely ceased due to decreasing temperatures as a result of a drop in thermal gradients at the end of the Eocene intrusive period and regional uplift and removal of overburden during the past 10 million years. In the Ranger 8-30 Bookout well, the second closest well to the intrusion, the onset of gas generation occurred at 62 Ma, peaked at 54 Ma, and largely ended by 35 Ma (figs. 25 and 26). The R_o values of 1.53 and 1.71 percent obtained from samples near the Eagle Sandstone indicate that these source rocks have gone through peak gas generation; thus the effect of the Eocene heating event at this locality was to compress the period of significant gas generation. Modeling at the well only 6 mi from Big Timber stock, and the well closest to the deep trough of the basin, indicates that gas generation began even earlier, about 66 Ma, peaked at 63 Ma, and largely ended by 54 Ma or prior to the Eocene intrusive period (figs. 27 and 28). Burial heating from the overlying sedimentary column was sufficient to drive source rocks along the deep basin trough through the main gas generation window prior to the intrusive event. Gas generation is occurring at only very low levels in the Crazy Mountains Basin today.

References Cited

Anders, D.E., and Gerrild, P.M., 1984, Hydrocarbon generation in lacustrine rocks of Tertiary age, Uinta Basin, Utah—Organic carbon, pyrolysis yield, and light hydrocarbons, *in* Woodward, J., Meissner, F.F., and Clayton, J.L., eds., Hydrocarbon source rocks of the Greater Rocky Mountain Region: Rocky Mountain Association of Geologists Guidebook, p. 513–529.

Barker, C.E., and Pawlewicz, M.J., 1986, The correlation of vitrinite reflectance with maximum temperature in humic organic matter, *in* Buntebarth, G., and Stegena, L., eds., Paleogeothermics: Berlin, Springer-Verlag, p. 79–93, 205–228.

Barker, C.E., Pawlewicz, M.J., Bostick, N.H., and Elders, W.A., 1981, Evolution of the Cerro Prieto geothermal system as interpreted from vitrinite reflectance under isothermal conditions, *in* Proceedings for the third symposium on the Cerro Prieto geothermal field Baja California, Mexico: Lawrence Berkeley Laboratory, University of California, LBL-11967, p. 88–96.

Beaumont, C., 1981, Foreland basins: Geophysical Journal of the Royal Astronomical Society, v. 55, p. 471–498.

Beck, R.A., 1985, Syntectonic sedimentation adjacent to Laramide basement thrusts, Rocky Mountain foreland; timing of deformation: Ames, Iowa, Iowa State University M.S. thesis, 88 p.

Beck, R.A., Vondra, C.F., Filkins, J.E., and Olander, J.D., 1988, Syntectonic sedimentation and Laramide basement thrusting, Cordilleran foreland; timing of deformation, *in* Schmidt, C.J., and Perry, W.J., Jr., eds, Interaction of Rocky Mountain foreland and the Cordilleran thrust belt: Geological Society of America Memoir 171, p. 465–487.

Berg, R.B., Lopez, D.A., and Lonn, J.D., 2000, Geologic map of the Livingston 30′ × 60′ quadrangle, southwest Montana: Montana Bureau of Mines and Geology Open-File Report 406, scale 1:100,000.

Bevan, A., 1925, Rocky Mountain peneplains northeast of Yellowstone Park: Journal of Geology, v. 33, p. 563–587.

Blackwelder, Eliot, 1915, Post-Cretaceous history of the mountains of central western Wyoming: Journal of Geology, v. 23, p. 97–117, 193–217, 307–340.

Bonini, W.E., Kelley, W.N., Jr., and Hughes, D.W., 1972, Gravity studies of the Crazy Mountains and the west flank of the Beartooth Mountains, Montana, *in* Lynn, J., Balster, C., and Warne, J., eds., Crazy Mountains Basin: Montana Geological Society 21st Annual Geological Conference, p. 119–127.

Bostick, N.H., 1979, Microscopic measurements of the level of catagenesis of solid organic matter in sedimentary rocks to aid in exploration of petroleum and to determine formation burial temperatures—A review, *in* Scholle, P.A., and Schluger, P.R., eds., Aspects of diagenesis: Society of Economic Paleontologists and Mineralogists Special Publication No. 26, p. 17–34.

Bostick, N.H., and Pawlewicz, M.J., 1984, Paleotemperatures based on vitrinite reflectance of shales and limestones in igneous dike aureoles in the Upper Cretaceous Pierre Shale, Walsenburg, Colorado, *in* Woodward, J., Meissner, F.F., and Clayton, J.L., eds., Hydrocarbon source rocks of the Greater Rocky Mountain Region: Rocky Mountain Association of Geologists Guidebook, p. 387–392.

Burtner, R.L., and Warner, M.A., 1984, Hydrocarbon generation in Lower Cretaceous Mowry and Skull Creek shales of the northern Rocky Mountain area, *in* Woodward, J., Meissner, F.F., and Clayton, J.L., eds., Hydrocarbon source rocks of the Greater Rocky Mountain Region: Rocky Mountain Association of Geologists Guidebook, p. 449–467.

Bustin, R.M., 1986, Organic maturity of Late Cretaceous and Tertiary coal measures, Canadian Arctic Archipelago: International Journal of Coal Geology, v. 6, p. 71–106.

Chadwick, R.A., 1981, Chronology and structural setting of volcanism in southwestern and central Montana, *in* Tucker, T.E., ed., Guidebook to Southwest Montana: Montana Geological Society Field Conference and Symposium, p. 301–310.

DeCelles, P.G., 1994, Late Cretaceous Paleogene synorogenic sedimentation and kinematic history of the Sevier thrust belt, northeast Utah and southwest Wyoming: Geological Society of America Bulletin, v. 106, p. 32–56.

Dorf, Erling, 1960, Climatic changes of the past and present: American Scientist, v. 48, p. 341–364.

Dow, W.G., 1977, Kerogen studies and geological interpretations: Journal of Geochemical Exploration, v. 7, p. 79–99.

du Bray, E.A., Elliott, J.E., Wilson, A.B., Van Gosen, B.S., and Rosenberg, L.A., 1993, Geologic map of the Big Timber Stock and vicinity, southern Crazy Mountains, Sweet Grass and Park Counties, south-central Montana: U.S. Geological Survey Miscellaneous Field Studies Map MF–2253, scale 1:24,000.

du Bray, E.A., and Harlan, S.S., 1996, The Eocene Big Timber stock, south-central Montana—Development of extensive compositional variation in an arc-related intrusion by sidewall crystallization and cumulate glomerocryst remixing: Geological Society of America Bulletin, v. 108, no. 11, p. 1404–1424.

Epis, R.C., and Chapin, C.E., 1975, Geomorphic and tectonic implications of the post-Laramide, late Eocene erosion surface in the southern Rocky Mountains, *in* Curtis, B.F., ed., Cenozoic history of the southern Rocky Mountains: Geological Society of America Memoir 144, p. 45–75.

Geological Society of America, 1999, Geologic time scale, A.R. Palmer and John Geissman, compilers.

Gill, J.R., and Burkholder, R.E., 1979, Measured sections of the Montana Group and equivalent rocks from Montana to Wyoming: U.S. Geological Survey Open-File Report 79–1143, 202 p.

Gill, J.R., and Cobban, W.A., 1966, The Red Bird section of the Upper Cretaceous Pierre Shale in Wyoming: U.S. Geological Survey Professional Paper 393–A, 73 p.

Glass, B.B., Westervelt, Katherine, and Oviatt, C.G., 1975, Coal mining in the Bighorn coal basin of Wyoming, *in* Exum, F.A., and George, G.R., eds., Geology and mineral resources of the Bighorn Basin: Wyoming Geological Association 27th Annual Field Conference Guidebook, p. 221–228.

Gurnis, M., 1992, Rapid continental subsidence following the initiation and evolution of subduction: Science, v. 255, p. 1556–1558.

Hagen, E.S., and Surdam, R.C., 1984, Maturation history and thermal evolution of Cretaceous source rocks of the Bighorn Basin, Wyoming and Montana, *in* Woodward, J., Meissner, F.F., and Clayton, J.L., eds., Hydrocarbon source rocks of the Greater Rocky Mountain Region: Rocky Mountain Association of Geologists Guidebook, p. 321–338.

Hamilton, W.B., 1988, Laramide crustal shortening, *in* Schmidt, C.J., and Perry, W.J., Jr., eds, Interaction of Rocky Mountain foreland and the Cordilleran thrust belt: Geological Society of America Memoir 171, p. 27–39.

Hartman, J.H., and Krause, D.W., 1993, Cretaceous and Paleocene stratigraphy and paleontology of the Shawmut anticline and the Crazy Mountains Basin, Montana—Road log and overview of recent investigations, *in* Hunter, L.D.V., ed., Energy and mineral resources of central Montana: Montana Geological Society 1993 Field Conference Guidebook, p. 71–84.

Hunt, J.M., 1979, Petroleum geochemistry and geology: San Francisco, Freeman Press, 617 p.

Johnson, R.C., and Finn, T.M., 1998, Is there a basin-centered gas accumulation in Upper Cretaceous rocks in the Bighorn Basin?, *in* Keefer, W.R., and Goolsby, J.E., eds., Cretaceous and lower Tertiary rocks of the Bighorn Basin, Wyoming and Montana: Wyoming Geological Association Forty-Ninth Annual Field Conference Guidebook, p. 257–273.

Johnson, R.C., Finn, T.M., Crovelli, R.A., and Balay, R.H., 1996, An assessment of in-place gas resources in low-permeability Upper Cretaceous and lower Tertiary sandstone reservoirs, Wind River Basin, Wyoming: U.S. Geological Survey Open-File Report 96–262, 204 p.

Johnson, R.C., and Nuccio, V.F., 1986, Structural and thermal history of the Piceance Creek Basin, western Colorado, in relation to hydrocarbon occurrence in the Mesaverde Group, *in* Spencer, C.W., and Mast, R.F., eds., Geology of tight gas reservoirs: American Association of Petroleum Geologists, Studies in Geology No. 24, p. 165–206.

Johnson, R.C., and Nuccio, V.F., 1993, Surface vitrinite reflectance study of the Uinta-Piceance basin area, western Colorado and eastern Utah—Implications for the development of Laramide basins and uplifts: U.S. Geological Survey Bulletin 1787–DD, 38 p. and 2 plates.

Jordan, T.E., 1981, Thrust loads and foreland basin evolution, Cretaceous, western United States: American Association of Petroleum Geologists Bulletin, v. 65, p. 2506–2520.

Juntgen, H., and Karweil, J., 1966, Gasbildung und gasspeicherung in Steinkohlenflozen, Part I and II: Erdol Kohle, Erdgas, Petrochem, v. 19, p. 251–258, 339–344.

Juntgen, H., and Klein, 1975, Entstehung von erdgas gus kohligen sedimenten: Erdol and Kohle, Erdgas, Petrochemie, Erganzungsband, v. 1, p. 52–69.

Kent, H.C., 1972, Review of Phanerozoic history, *in* Mallory, W.W., ed., Geologic atlas of the Rocky Mountain Region: Denver, Colo., Rocky Mountain Association of Geologists, p. 57–59.

Larsen, L.H., and Simms, F.E., 1972, Igneous geology of the Crazy Mountains, Montana—A report of work in progress, *in* Lynn, J., Balster, C., and Warne, J., eds., Crazy Mountains Basin: Montana Geological Society 21st Annual Geological Conference, p. 135–139.

Law, B.E., 1992, Thermal maturity patterns of Cretaceous and Tertiary rocks, San Juan Basin, Colorado and New Mexico: Geological Society of America Bulletin, v. 104, p. 192–207.

Law, B.E., Nuccio, V.F., and Barker, C.E., 1989, Kinky vitrinite reflectance well profiles; Evidence of paleopore pressure in low-permeability, gas-bearing sequences in Rocky Mountain foreland basins: American Association of Petroleum Geologists Bulletin, v. 73, no. 8, p. 999–1010.

Law, B.E., Spencer, C.W., and Bostick, N.H., 1979, Preliminary results of organic maturation, temperature, and pressure studies in the Pacific Creek area, Sublette County, Wyoming, *in* 5th DOE Symposium on Enhanced Oil and Gas Recovery and Improved Drilling Methods, Tulsa, Okla., Proceedings, v. 3, Gas and Drilling: Tulsa, Okla., Petroleum Publishing Co., p. 1–13.

Leopold, E.S., and MacGinitie, H.D., 1972, Development and affinities of Tertiary floras in the Rocky Mountains, *in* Aham, A.G., ed., Floristics and paleofloristics of Asia and eastern North America: Amsterdam, Elsevier Pub. Co., p. 147–200.

Lopez, D.A., 2000, Geologic map of the Big Timber 30′ × 60′ quadrangle, south-central Montana: Montana Bureau of Mines and Geology Open File Report 405, scale 1:100,000.

MacGinitie, H.D., 1953, Fossil plants of the Florissant beds, Colorado: Carnegie Institute Washington Publication 599, Contributions to Paleontology, 198 p.

Mears, B., Jr., 1993, Geomorphic history of Wyoming and high-level erosion surfaces, *in* Snoke, A.W., Steidtmann, J.R., and Roberts, S.M., eds., Geology of Wyoming: Geological Survey of Wyoming Memoir No. 5, p. 609–626.

Meissner, F.F., 1984, Cretaceous and Lower Tertiary coals as source for gas accumulations in the Rocky Mountain area, *in* Woodward, J., Meissner, F.F., and Clayton, J.L., eds., Hydrocarbon source rocks of the Greater Rocky Mountain Region: Rocky Mountain Association of Geologists Guidebook, p. 401–431.

Mitrovica, J.X., Beaumont, C., and Jarvis, G.T., 1989, Tilting of continental interiors by the dynamic effects of subduction: Tectonics, v. 8, p. 1079–1094.

Nuccio, V.F., and Finn, T.M., 1998, Thermal maturity and petroleum generation history of Cretaceous and Tertiary source rocks, Bighorn Basin, Wyoming and Montana, *in* Keefer, W.R., and Goolsby, J.E., eds., Cretaceous and Lower Tertiary rocks of the Bighorn Basin, Wyoming and Montana: Wyoming Geological Association Forty-Ninth Annual Field Conference Guidebook, p. 211–231.

Nuccio, V.F., Finn, T.M., and Johnson, R.C., 1996, Thermal maturity data used for the assessment of gas resources in the Wind River Basin, Wyoming: U.S. Geological Survey Open-File Report 96–064, 57 p.

Nuccio, V.F., Johnson, R.C., and Finn, T.M., 2002, Preliminary surface vitrinite reflectance map of the Raton Basin, Colorado and New Mexico, *in* Schwochow, S.D., and Nuccio, V.F., eds., Coalbed methane of North America, II: Rocky Mountain Association of Geologists, p. 49–52.

Obradovich, J.D., 1993, A Cretaceous time scale, in Caldwell, W.G.E., and Kauffman, E.G., eds., Evolution of the Western Interior Basin: Geological Association of Canada Special Paper 39, p. 379–396.

Pawlewicz, M.P., 1993, Vitrinite reflectance and geothermal gradients in the Wind River Basin, central Wyoming, *in* Keefer, W.R., Metzger, W.J., and Godwin, L.H., eds., Oil and gas and other resources of the Wind River Basin, Wyoming: Wyoming Geological Association Special Symposium, p. 295–305.

Price, R.A., 1973, Large-scale gravitational flow of supracrustal rocks, southern Canadian Rockies, *in* Delong, K.A., and Scholten, R., eds., Gravity and tectonics: New York, John Wiley and Sons, p. 491–502.

Pysklywec, R.N., and Mitrovica, J.X., 1998, Mantle flow mechanisms for the large-scale subsidence of continental interiors: Geology, v. 26, no. 8, p. 687–690.

Roberts, A.E., 1966, Geology and coal resources of the Livingston coal field, Gallatin and Park Counties, Montana: U.S. Geological Survey Professional Paper 526–A, 56 p.

Roberts, A.E., 1972, Cretaceous and early Tertiary depositional and tectonic history of the Livingston area, southwestern Montana: U.S. Geological Survey Professional Paper 526–C, 120 p.

Scott, G.R., 1975, Cenozoic surfaces and deposits in the southern Rocky Mountains, *in* Curtis, B.F., ed., Cenozoic history of the southern Rocky Mountains: Geological Society of America Memoir 144, p. 227–248.

Spencer, C.W., 1989a, Review of characteristics of low-permeability gas reservoirs in western United States: American Association of Petroleum Geologists Bulletin, v. 73, no. 5, p. 613–629.

Spencer, C.W., 1989b, Comparison of overpressuring at the Pinedale anticline area, Wyoming, and the Multiwell Experiment site, Colorado, *in* Law, B.E., and Spencer, C.W., eds., Geology of tight gas reservoirs in the Pinedale anticline area, Wyoming, and the Multiwell experiment site, Colorado: U.S. Geological Survey Bulletin 1886, p. C1–C16.

Stern, T.A., and Holt, W.E., 1994, Platform subsidence behind an active subduction zone: Nature, v. 368, p. 233–236.

Steven, T.A., 1975, Middle Tertiary volcanic field in the southern Rocky Mountains, *in* Curtis, B.F., ed., Cenozoic history of the southern Rocky Mountains: Geological Society of America Memoir 144, p. 75–94.

Tappe, J., 1966, The chemistry, petrology, and structure of the Big Timber igneous complex, Crazy Mountains, Montana: Cincinnati, Ohio, University of Cincinnati Ph. D. thesis, 134 p.

Tissot, B., Durand, B., Espitalie, J., and Combaz, A., 1974, Influence of nature and diagenesis of organic matter in formation of petroleum: American Association of Petroleum Geologists Bulletin 58, p. 499–506.

Tissot, B.P., and Welte, D.H., 1984, Petroleum formation and occurrence, Second Edition: Berlin, Springer-Verlag, 699 p.

Waples, D.W., 1985, Geochemistry in petroleum exploration: Boston, Mass., International Human Resources Development Corporation, 232 p.

Woodward, L.A., 1983, Structural geology of the Helena salient—A synopsis, *in* Guidebook of the fold and thrust belt, west-central Montana: Montana Bureau of Mines and Geology Special Publication 86, p. 83–87.