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U.S. GEOLOGICAL SURVEY**

**Preliminary investigations of the distribution
and resources of coal in the
Kaiparowits Plateau, southern Utah**

by

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EXECUTIVE SUMMARY

This report on the coal resources of the Kaiparowits Plateau, Utah is a contribution to the U.S. Geological Survey's (USGS) "National Coal Resource Assessment" (NCRA), a five year effort to identify and characterize the coal beds and coal zones that could potentially provide the fuel for the Nation's coal-derived energy during the first quarter of the twenty-first century. For purposes of the NCRA study, the Nation is divided into regions. Teams of geoscientists, knowledgeable about each region, are developing the data bases and assessing the coal within each region. The five major coal-producing regions of the United States under investigation are: (1) the Appalachian Basin; (2) the Illinois Basin; (3) the Gulf of Mexico Coastal Plain; (4) the Powder River Basin and the Northern Great Plains; and (5) the Rocky Mountains and the Colorado Plateau. Six areas containing coal deposits in the Rocky Mountain and Colorado Plateau Region have been designated as high priority because of their potential for development. This report on the coal resources of the Kaiparowits Plateau is the first of the six to be completed.

The coal quantities reported in this study are entirely "resources" and represent, as accurately as the data allow, all the coal in the ground in beds greater than one foot thick. These resources are qualified and subdivided by thickness of coal beds, depth to the coal, distance from known data points, and inclination (dip) of the beds. The USGS has not attempted to estimate coal "reserves" for this region. Reserves are that subset of the resource that could be economically produced at the present time.

The coal resources are differentiated into "identified" and "hypothetical" following the standard classification system of the USGS (Wood and others, 1983). Identified resources are those within three miles of a measured thickness value, and hypothetical resources are further than three miles from a data point. Coal beds in the Kaiparowits

Plateau are laterally discontinuous relative to many other coal bearing regions of the United States. That is, they end more abruptly and are more likely to fragment or split into thinner beds. Because of these characteristics, the data from approximately 160 drill holes and 40 measured sections available for use in this study are not sufficient to determine what proportion of the resources is technologically and economically recoverable.

The Kaiparowits Plateau contains an original resource of 62 billion short tons of coal in the ground. Original resource is defined to include all coal beds greater than one foot thick in the area studied. None of the resource is recoverable by surface mining. However, the total resource figure must be regarded with caution because it does not reflect geologic, technological, land-use, and environmental restrictions that may affect the availability and the recoverability of the coal. At least 32 billion tons of coal are unlikely to be mined in the foreseeable future because the coal beds are either too deep, too thin to mine, inclined at more than 12°, or in beds that are too thick to be completely recovered in underground mining. The estimated balance of 30 billion tons of coal resources does not reflect land use or environmental restrictions, does not account for coal that would be bypassed due to mining of adjacent coal beds, does not consider the amount of coal that must remain in the ground for roof support, and does not take into consideration the continuity of beds for mining. Although all of these factors will reduce the amount of coal that could be recovered, there is not sufficient data available to estimate recoverable coal resources. For purposes of comparison, studies of coal resources in the eastern United States have determined that less than 10 percent of the original coal resource, in the areas studied, could be mined economically at today's prices (Rohrbacher and others, 1994).

INTRODUCTION

Purpose and scope

An assessment of the distribution and resources of coal in the Kaiparowits Plateau of southern Utah is presented in this report. Results of the Kaiparowits Plateau study include a preliminary delineation of thick coal deposits and a coal resource estimate that can serve as a baseline for other efforts to further assess the coal resource in terms of its availability and recoverability. The Kaiparowits Plateau project is part of the United States Geological Survey's National Coal Resource Assessment project that was initiated in 1994. The goal of the National Assessment is to characterize the resource potential and quality of coal for the entire Nation, with emphasis on those coals that may be of importance during the first quarter of the next century. The Kaiparowits Plateau is one six priority areas within the Rocky Mountains and Colorado Plateau region. The Kaiparowits Plateau contains about 1.5 percent of the Nation's total coal resource in the lower forty-eight States, if compared to the figures of Averitt (1975).

The assessment of the Kaiparowits Plateau is based on data from geologic mapping, outcrop measurements of stratigraphic sections, and drilling that has been conducted in the region since the late 1960's. Deposits of coal are contained within the John Henry Member of the Straight Cliffs Formation, and although the distribution of coal has been well documented on outcrop, its distribution in the subsurface has remained largely unknown due to the proprietary status of company data. However, recently released company drill-hole data and drilling by the U.S. Geological Survey provide new insight into the subsurface aspects of these coals. We have integrated these recently released data with additional published geologic data to construct coal correlation charts and maps that show various aspects of coal distribution in the Kaiparowits Plateau. These data are stored digitally and manipulated in a Geographic Information System to calculate coal resources within a variety of spatial parameters that are useful for land-use planning. Coal resources reported in this investigation are for total in-place coal in the John Henry Member and do not indicate the amount of coal that can be economically mined from the Kaiparowits Plateau.

Methods

In order to assess the coal resources of the Kaiparowits Plateau, we have created digital files for various geologic features within the plateau. These spatial data are stored, analyzed, and manipulated in a Geographic Information System (GIS) using ARC/INFO software developed by the Environmental Systems Research Institute, Inc. Spatial data that require gridding for the generation of contour and isopach maps are processed using Interactive Surface Modeling (ISM) [Dynamics Graphics, Inc.]. Contour lines generated in ISM are then converted into ARC/INFO coverages using a program called ISMARC which we received from the Illinois State Geological Survey. We have also collected and created additional coverages in ARC/INFO that define various geographic boundaries within the vicinity of the Kaiparowits Plateau. Integrating these various coverages allows us to calculate coal resources and characterize coal distribution within a variety of geologic and geographic parameters that can be selected according to an individual's needs. The following paragraphs discuss procedures used to produce the various coverages used in the assessment.

Lithologic and stratigraphic data

Lithologic and stratigraphic data are based on our interpretations of geophysical logs from 139 company coal test holes and 22 oil and gas holes as well as published descriptions from 6 U.S. Geological Survey drill holes and 46 measured stratigraphic sections. Drill hole data have been provided by 5M, Inc., PacificCorp Electric Operations, Andalex Resources, Oryx Energy Company, the Bureau of Land Management, and the Petroleum Information Corp. All data point localities are shown on plate 1 (fig. A). Data are identified in appendix 1, and lithologic and stratigraphic interpretations for each data point are also provided in appendix 1.

Lithologic interpretations on geophysical logs were made from a combination of natural-gamma (gamma ray), density, resistivity, and neutron logs and company descriptions of core and drill-hole cuttings. Sandstone was interpreted from a moderate-response on natural gamma and resistivity logs. Mudrock was interpreted from a high natural gamma and a low resistivity response. Coal was interpreted from a low natural gamma and density response and a high resistivity and neutron response. Coal bed

thicknesses were interpreted from density logs whenever possible and recorded to the nearest 1 foot; coal beds less than 1 foot thick were not included in the assessment. Thicknesses of more than one coal bed have been combined if an intervening parting is thinner than either the overlying or underlying bed of coal according to methods of Wood and others (1983, p. 31, 36) and the thickness of the parting is not included.

Stratigraphic interpretations were based on lithologic stacking patterns in each drill hole and on correlations to cores and outcrops where coeval rocks have been measured and described. Some stratigraphic interpretations were based on lithologic descriptions from published measured sections and from texts in geologic reports. Stratigraphic correlations were difficult using original geophysical log traces because they were recorded using various scales and deflection patterns. In order to make the best correlations, all geophysical logs were digitized and plotted using uniform scales and deflection patterns. Selected digitized log traces are shown in correlation charts on plate 1 (figs. C, D, and E).

Geologic maps

ARC/INFO coverages for geologic features include the locations of stratigraphic boundaries, faults, fold axes, and areas where strata are inclined at various ranges of dip. These data were digitized using ARC/INFO. Geologic contacts, fold axes, and faults were digitized at a 1:125,000-scale from a geologic map of the Kaiparowits coal-basin area (Sargent and Hansen, 1982). The base of the Drip Tank Member was digitized from a 1:100,000-scale geologic map of Kane county (Doelling and Davis, 1989). The range-of-dip map was compiled at a 1:125,000-scale from structure contour lines and from dip measurements published on 1:24,000-scale geologic maps of the Kaiparowits Plateau.

Geographic boundaries

ARC/INFO coverages for geographic boundaries were imported from existing public domain data bases. Township boundaries were obtained from a 1:24,000-scale Public Land Survey System (PLSS) coverage produced by the Automated Geographic Reference Center (AGRC) in Salt Lake City, Utah. Towns and roads were obtained from 1:100,000-scale Digital Line Graphs created by the U.S. Geological

Survey EROS Data Center in Sioux Falls, South Dakota. Areas of surface ownership were digitized from 1:100,000-scale quadrangles by the Bureau of Land Management and Geographic Approach to Planning (GAP) in 1993. Areas of coal ownership were obtained from 1:100,000-scale digital compilations from the former U.S. Bureau of Mines Inventory of Land Use Restraints program and the PLSS coverage. County and State lines were obtained from 1:100,000-scale Topologically Integrated Geographic Encoding and Referencing (TIGER) files produced by the U.S. Bureau of the Census in 1990. Surface topography was obtained from a 1:250,000-scale U.S. Geological Survey Digital Elevation Model of the Escalante quadrangle.

Location

The Kaiparowits Plateau is located in the southwestern part of the Colorado Plateau province and occupies parts of Kane and Garfield Counties between the towns of Escalante, Henrieville, and Glen Canyon City, in southern Utah (fig. 1). In this report, any further use of the word "plateau" refers to the Kaiparowits Plateau. The northern boundary of the Kaiparowits Plateau merges with the Aquarius Plateau and is arbitrarily delineated by the Paunsaugunt fault, volcanic rocks of Tertiary age, and the 112° line of longitude (fig. 1). Elsewhere, the edge of the Kaiparowits Plateau is defined by the base of Upper Cretaceous strata (fig. 1). The Kaiparowits Plateau covers approximately 1,650 square miles; it extends 65 miles north to south, 20 miles across its northern boundary, and 55 miles across its southern boundary. The plateau is a dissected mesa that rises as much as 6,500 feet above the surrounding terrain. Elevations range from about 4,000 feet above sea level in the south near Lake Powell (fig. 1) to about 9,800 feet above sea level in the north near the Aquarius Plateau; some erosional remnants in the northern part of the plateau are as high as 10,450 feet above sea level. The landscape is defined by four sets of cliffs and benches that form a step-like topography between the Aquarius Plateau and Lake Powell (Sargent and Hansen, 1980). The Straight Cliffs form a prominent escarpment that extends northwest to southeast along the plateau's eastern flank; the escarpment is as high as 1,100 feet along Fiftymile Mountain (fig. 1). The northern part of the plateau contains lands within Dixie National

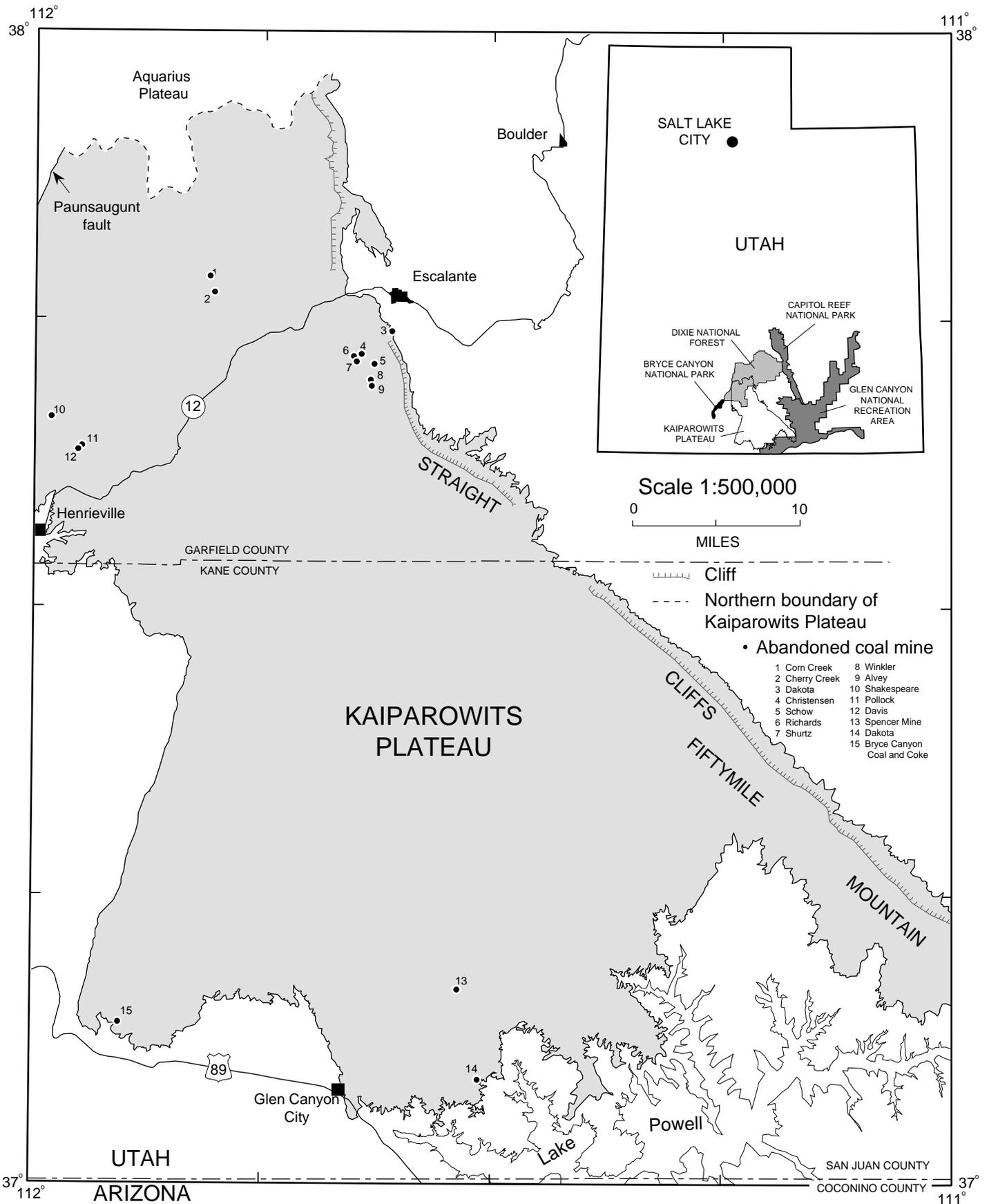


Figure 1. -- Location of Kaiparowits Plateau, Utah, east of 112° of longitude. The plateau is delineated by the base of Upper Cretaceous rocks except along its northern boundary where it merges with the Aquarius Plateau. Inset map shows the location of the Kaiparowits Plateau with respect to nearby National Forests, Parks, and Recreational Areas.

Table 1. Coal mining history in the Kaiparowits Plateau, Utah. Total coal production at each mine is estimated from average annual production reported in Doelling and Graham (1972). Mine and 7.5' quadrangle locations (queried where uncertain) are shown on figures 1 and 2, respectively. Table is modified from Doelling and Graham (1972).

Mine	Location quadrangle	7.5' or formation	Producing coal zone of production	Years production (short tons)	Estimated total
Alvey	NW1/4 sec. 12, T. 36 S., R. 2 E.	Canaan Creek	Alvey coal zone	1952-1962	12,000
Bryce Canyon Coal and Coke	NE1/4 sec. 21, T.42 S., R. 1 W.	Fivemile Valley	Dakota Formation	1939-1970? Intermittent	1,000
Cherry Creek Christensen	SE1/4 sec. 8, T. 35 S., R. 1 E. SW1/4 sec. 36, T. 35 S., R. 2 E.	Griffin Point Canaan Creek	Alvey coal zone Christensen coal zone	1962-1964 1893-1930	420 100
Corn Creek	SE1/4 sec. 5, T. 35 S., R. 1 E.	Griffin Point	Rees coal zone?	unknown	unknown
Davis	NE1/4 sec. 36, T. 36 S., R. 2 W.	Pine Lake	Henderson coal zone	1952-1953	100
Dakota Coal Mine	NE1/4 sec. 30, T. 35 S. R. 3 E.	Dave Canyon	Dakota Formation	unknown	unknown
Dakota Coal Mine	NW1/4, sec. 7, T. 43 S., R. 4 E.	Lone Rock	Dakota Formation	Abandoned, 1913	145
Pollock	SE1/4 sec. 25 ?, T. 36 S., R. 2 W.	Pine Lake	Henderson coal zone	1920-1925	unknown
Richards	SE1/4, sec. 35, T. 35 S., R. 2 E.	Canaan Creek	Christensen coal zone	1913-1928	15,000
Shakespeare	NW1/4 sec. 23, T. 36 S., R. 2 W.	Pine Lake	Henderson coal zone	1952-1964	5,800
Shurtz	SW1/4 sec. 35, T. 35 S., R. 2 E.	Canaan Creek	Christensen coal zone	1913-1928	1,500
Schow	SW1/4 sec. 36, T. 35 S., R. 2 E.	Canaan Creek	Christensen coal zone	unknown	unknown
Spencer	SW1/4 sec. 3, T. 42 S., R. 3 E.	Tibbet Bench	Christensen coal zone ?	1910-1913	115
Winkler	NW1/4 sec. 12, T. 36 S., R. 2 E.	Canaan Creek	Alvey coal zone	1920's	unknown

Forest, and the southern boundary of the plateau contains lands within the Glen Canyon National Recreation area (fig. 1). Bryce Canyon and Capitol Reef National Parks are located west and east of the plateau, respectively (fig. 1).

Previous geologic studies and mining activity

Coal in the Kaiparowits Plateau region was first mined by settlers in the late 1800's near the town of Escalante, and small mines produced coal for local needs until the early 1960's. Locations of the abandoned mines and adits are shown on figure 1. Production figures from Doelling and Graham (1972, p. 71) shown on table 1 indicate that less than 50,000 short tons of coal have been mined from the Kaiparowits Plateau.

Although coal investigations were first reported in the Kaiparowits Plateau by Gregory and Moore (1931), it was not until the early 1960's that energy companies expressed an interest to commercially develop coal in the region. Since then, coal leases

have been held by at least 23 companies (Doelling and Graham, 1972, p. 98-99), and about 1,000 company coal test holes have been drilled in the plateau (Jim Kohler, U.S. Bureau of Land Management, 1991, oral communication). Plans were made in 1965 to develop a 5,000-megawatt coal-burning power plant but were revised in the mid 1970's to a 3,000-megawatt generating plant after controversy over environmental issues (Sargent, 1984, p. 8). Construction plans were finally discontinued because of government action and pending lawsuits over environmental concerns (Sargent, 1984). Currently, only a few companies retain coal leases in the area.

The U.S. Geological Survey conducted investigations to study the geology and assess the region's coal resources. Stratigraphic investigations resulted in formal divisions of some Upper Cretaceous and Tertiary strata (Peterson, 1969b; Bowers, 1972, respectively). Other sedimentological investigations demonstrated the detailed relationships between coal-bearing continental and related marine strata and provided sequence stratigraphic divisions for the Upper

Cretaceous rocks (Shanley and McCabe, 1991; Shanley and others, 1992; McCabe and Shanley, 1992; Hettinger and others, 1994; Hettinger, 1995). Information obtained from coal drilling projects was reported by Zeller (1976, 1979) and Hettinger (1993, 1995). Geologic maps were published at scales of 1:24,000 for twenty-five 7.5' quadrangles within the plateau (fig. 2), at 1:125,000 for the entire Kaiparowits Plateau (Sargent and Hansen, 1982), and at 1:250,000 for the Escalante 1x2 degree quadrangle (Hackman and Wyant, 1973).

The U.S. Geological Survey has also published a series of 1:125,000 scale maps that address geologic factors that may affect coal mining within the Kaiparowits Plateau. Results of these studies were summarized by Sargent (1984). These maps show drainage patterns and stream-flow data (Price, 1978), water quality (Price, 1977a, 1979), ground-water availability (Price, 1977b), scenic features and landforms (Carter and Sargent, 1983; Sargent and Hansen, 1980, respectively), surficial and bedrock geology (Williams, 1985; Sargent and Hansen, 1982, respectively), geologic cross sections (Lidke and Sargent, 1983), and total coal thickness and overburden (Hansen, 1978a, b, respectively).

Geologic investigations by the Utah Geological and Mineralogical Survey have also resulted in significant publications. Seven 7.5' quadrangles in the southern part of the plateau were published by the Utah Geological and Mineralogical Survey at a 1:31,680 scale as a result of cooperative investigations with the U.S. Geological Survey (fig. 2). A comprehensive assessment of geology and coal resources in the Kaiparowits Plateau was published by Doelling and Graham (1972); that report includes geologic maps, published at a scale of 1:42,240, and measured coal thicknesses in twenty-seven 7.5' quadrangles in the plateau (fig. 2). The geology of Kane County, Utah, was reported by Doelling and Davis (1989) and includes a 1:100,000 scale geologic map that covers the southern part of the Kaiparowits Plateau. Coal resources for the southern part of the plateau are described by Blackett (1995).

Coal resources of the Kaiparowits Plateau have been estimated by Averitt (1961), Peterson (1969b), and Doelling and Graham (1972) and include coals in the John Henry and Smoky Hollow Members of the Straight Cliffs Formation as well as the Dakota Formation. Initially, Averitt (1961) estimated that the Kaiparowits Plateau contained 3 billion tons of

coal. Coal discoveries made during the 1960's resulted in higher estimates, and Peterson (1969a, p. 219) estimated the potential coal resource for the plateau to be about 40 billion tons for beds greater than 1 foot thick and less than 3,000 feet deep. Doelling and Graham (1972, p. 102-106) stated that most of the coal in the plateau is minable only by underground methods, and they reported a coal reserve of about 15 billion tons for all beds greater than 4 feet thick and less than 3,000 feet deep. Both Peterson (1969a, p. 221) and Doelling and Graham (1972, p. 102) estimated that about 4 billion tons of coal could be mined. Coal resource estimates were also reported in 12 of the 7.5' quadrangles in the plateau (appendix 2) by Doelling and Graham (1972) and by the U.S. Geological Survey. These resource estimates total only about 11 billion short tons of coal, but they are generally determined for limited bed thicknesses and limited areas in each quadrangle.

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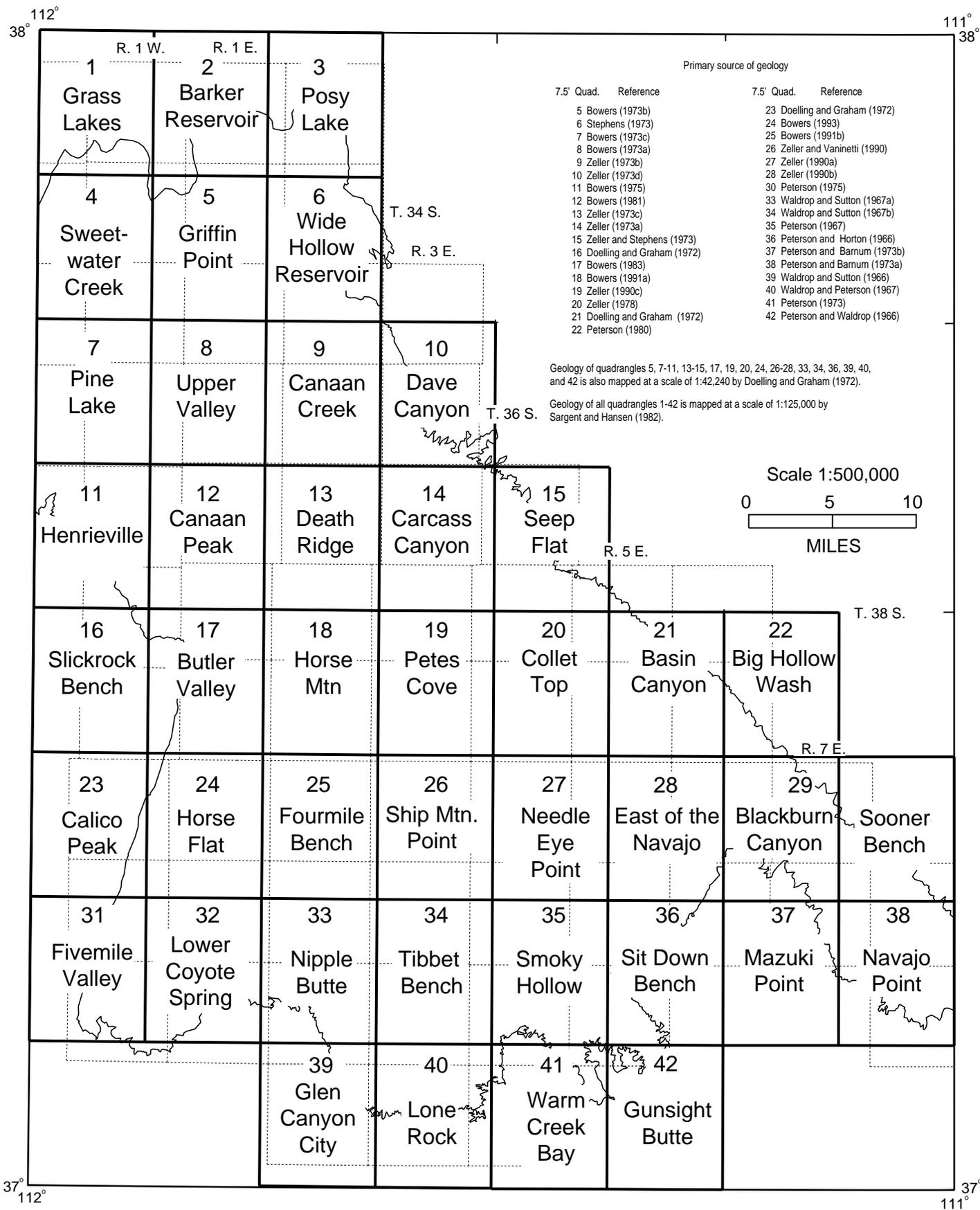


Figure 2. -- Index map for 7.5' quadrangles and townships in the Kaiparowits Plateau. Published geologic maps for each quadrangle are referenced in the inset.

Table 2. Stratigraphic summary of Upper Cretaceous and Tertiary strata in the Kaiparowits Plateau, Utah. Lithologic descriptions and depositional interpretations are based on Sargent and Hansen (1982), Bowers (1972), Peterson (1969a, b) and Shanley and McCabe (1991).

Age	Formation	Thickness (ft)	Description and depositional interpretation
Miocene	Osiris Tuff	0-600	Gray, purplish-gray and red-brown welded ash-flow tuff. Volcanic.
Eocene and Paleocene	Wasatch Fm	1,350-1,650	<u>Variegated Sandstone Member</u> Red, pink, and purplish-gray, very fine to coarse-grained sandstone, mudrock and minor conglomerate (0-600 ft). Fluvial. <u>White Limestone Member</u> Light-gray to white, crystalline limestone and minor mudrock (0-600 ft). Lacustrine. <u>Pink Limestone Member</u> Gray, tan, white, pink or red, fine-grained clastic limestone, mudrock, sandstone, and minor conglomerate.(0-900 ft). Fluvial.
Paleocene?	Pine Hollow Fm	0-450	Lavender to red and gray mudrock and limestone with coarse-grained, pebbly sandstone in lower part. Low energy fluvial and lacustrine.
Paleocene? and Late Cretaceous	Canaan Peak Fm	0-900	Gray, tan, and brown conglomerate, conglomeratic sandstone, and minor gray and red mudstone. High energy fluvial.
Late Cretaceous	Kaiparowits Fm	600-3,000	Greenish- and bluish-gray, fine-grained, silty sandstone with subordinate beds of mudrock and limestone. Low energy fluvial (meandering river) and floodplain.
	Wahweap Fm	900-2,600	Light-gray and brownish-orange, fine- to medium-grained sandstone interbedded with gray mudrock and shale. Upper part is dominantly sandstone. Fluvial and floodplain.
	Straight Cliffs Fm	1,000-2,000	<u>Drip Tank Member</u> (140-400 ft) Light-gray, medium- to coarse-grained sandstone, conglomeratic sandstone, and minor mudrock. Braided river. <u>John Henry Member</u> (600*-1,500 ft) Light-gray to brown, very fine to medium-grained sandstone; minor coarse-grained and conglomeratic sandstone; olive-gray, brown, and black mudrock, and coal. Nearshore marine, estuarine, paludal, and alluvial. *Thickness based on subsurface data. <u>Smoky Hollow Member</u> (20-300 ft) Upper part is light-gray, medium- to coarse-grained and pebbly sandstone (Calico bed). Lower part is fine-grained sandstone, mudrock, and coal. Braided river (Upper part), coastal plain and paludal (lower part). <u>Tibbet Canyon Member</u> (60-185 ft) Yellowish-gray and grayish-orange, fine- to medium-grained sandstone with siltstone and mudrock in lower part. Estuarine and nearshore marine.
	Tropic Shale	600-900	Gray shale with thin beds of siltstone and fine-grained sandstone in upper part. Offshore marine.
	Dakota Formation	15-250	<u>Upper member</u> (0-68) Light-brown, fine-grained to fine-grained sandstone interbedded with gray mudrock. Coastal plain, brackish water, and nearshore marine. <u>Middle member</u> (4-76) Gray to brown, very fine grained to fine-grained sandstone interbedded with yellowish-green mudrock, carbonaceous mudrock and coal. Low energy fluvial, floodbasin, and paludal. <u>Lower member</u> (0-66) Gray to brown conglomerate and fine- to coarse-grained, pebbly sandstone and minor carbonaceous mudrock. High energy fluvial.

GEOLOGIC SETTING

General stratigraphy of Cretaceous and Tertiary strata of the Kaiparowits Plateau

Geologic cross sections by Lidke and Sargent (1983) indicate that as much as 7,500 feet of Upper Cretaceous strata and 3,000 feet of Tertiary strata underlie the Kaiparowits Plateau. Upper Cretaceous strata include, in ascending order, the Dakota Formation, Tropic Shale, and Straight Cliffs, Wahweap, Kaiparowits, and Canaan Peak (lower part) Formations (table 2). Paleocene strata include the Canaan Peak (upper part), Pine Hollow, and Wasatch (lower part) Formations (table 2). Eocene strata include the middle and upper part of the Wasatch Formation (table 2) and Miocene rocks are in the Osiris Tuff (table 2). The Dakota Formation, Tropic Shale, and Straight Cliffs Formation are exposed along the margins of the plateau but are buried by younger strata in the plateau's central areas (fig. 3). Thicknesses, lithologies, and depositional settings for Cretaceous and Tertiary strata in the plateau are summarized in table 2; additional sedimentological, stratigraphic, paleontological, and palynological data are provided in publications cited in table 3.

Coal in the Kaiparowits Plateau is contained in the Dakota Formation and the Smoky Hollow and John Henry Members of the Straight Cliffs Formation (table 2). The deposits of coal in the upper part of the Smoky Hollow Member and John Henry Member are described in detail throughout the remainder of this report. Coals in the Dakota Formation and lower part of the Smoky Hollow Member are described only briefly here, because they are generally thin, lenticular, and too deep to be mined in the foreseeable future. The basal 25 feet of the Smoky Hollow Member contains as many as four beds of coal that are generally less than 2 feet thick; coal beds are as much as 3 feet thick in the Wide Hollow Reservoir quadrangle and range from 4 to 5 feet thick in the Lone Rock and Smoky Hollow quadrangles (fig. 2). Coal is found in the Dakota Formation along all areas of outcrop except in the Seep Flat quadrangle (fig. 2). The Dakota Formation contains as many as seven lenticular beds of coal that are generally less than 2 feet thick; however, some coal beds are 4-6 feet thick in the Dave Canyon, Henrieville, and Wide Hollow Reservoir quadrangles (fig. 2). The quality

of coal in the Dakota Formation is not well known, but proximate and ultimate analyses of a coal sample from the Dakota Coal Mine in the Lone Rock quadrangle (table 1), reported by Waldrop and Peterson, (1967), yielded 11,370 Btu/lb on a moist, mineral-matter-free basis and an apparent rank of subbituminous A using the Parr Formula described in American Society for Testing and Materials (1995).

Detailed stratigraphy of the Upper Cretaceous Straight Cliffs Formation

During the Late Cretaceous, the region now occupied by the Kaiparowits Plateau was located at a paleolatitude of about 41° N. (Irving, 1979; Beeson, 1984) on the western margin of the Western Interior Seaway (fig. 4). Shorelines were oriented approximately N.45°W. - S.45°E. (Peterson, 1969b; Shanley, 1991, Roberts and Kirschbaum, 1995) (fig. 4). Sediment deposited in the region of the Kaiparowits Plateau was supplied from the Sevier Highlands, located 100 miles to the west (Peterson, 1969a). Approximately 1,100-1,600 feet of strata were assigned to the Straight Cliffs Formation by Gregory and Moore (1931). The formation was initially mapped along the plateau's southern flank and divided into lower and middle members and an upper sandstone member (fig. 5). The middle member contains a minor coal zone (that includes a white sandstone marker bed), a major coal zone, and an upper barren zone (fig. 5).

Peterson (1969b) formally divided the Straight Cliffs Formation, in ascending order, into the Tibbet Canyon, Smoky Hollow, John Henry, and Drip Tank Members (table 2, fig. 5). Outcrops of the John Henry and Drip Tank Members are shown in figure 3. Peterson (1969a, b) interpreted the Tibbet Canyon and Smoky Hollow Members as a regressive stratigraphic succession, of middle to late Turonian age, consisting of shallow marine and beach deposits in the Tibbet Canyon Member and coal-bearing coastal plain strata and braided river deposits in the Smoky Hollow Member. Braided river deposits are contained in the Calico bed (fig. 5) located in the upper part of the member. Peterson (1969a, b) interpreted that the Calico bed was truncated by an unconformity (fig. 5) of late Turonian to early Coniacian age. However, the unconformity has not been recognized on the western flank of the plateau, and Shanley and

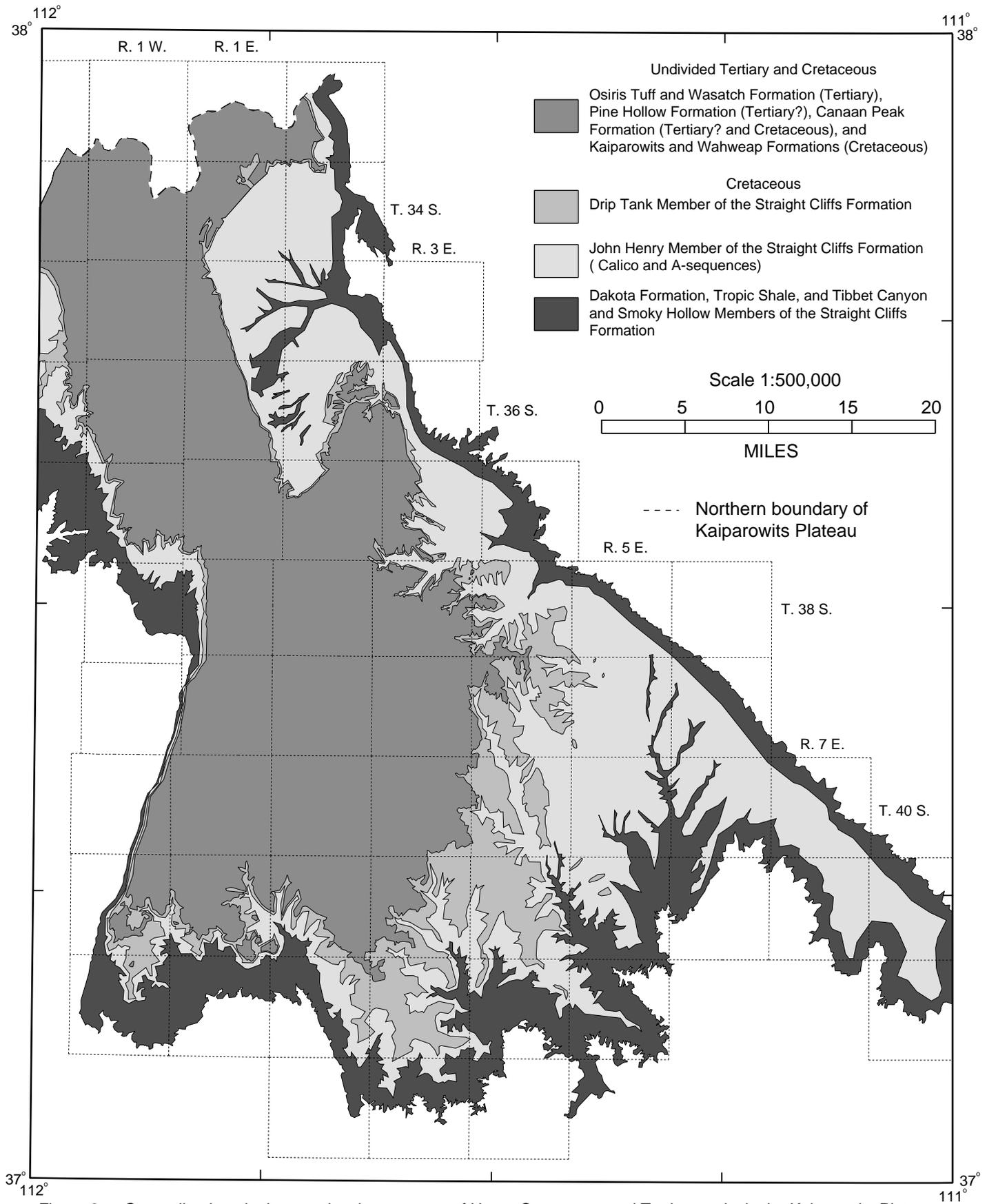


Figure 3. -- Generalized geologic map showing outcrops of Upper Cretaceous and Tertiary rocks in the Kaiparowits Plateau. At the mapped scale, outcrops of the John Henry Member of the Straight Cliffs Formation are nearly identical with outcrops of the Calico and A-sequences. Geologic map is modified from Sargent and Hansen (1982).

Table 3. Geologic publications regarding Upper Cretaceous and Tertiary strata in the Kaiparowits Plateau, Utah.

Formation	Authors of investigation and references
Wasatch, Pine Hollow, and Canaan Peak Fms.	Bowers (1972)
Kaiparowits Fm.	Lohrengel (1969)
Wahweap Fm.	Peterson (1969a), Eaton (1991)
Straight Cliffs Fm.	Peterson (1969a, b), Orlansky (1971), Doelling and Graham (1972), Vaninetti (1978), Johnson and Vaninetti (1982), Eaton (1991), Shanley (1991), Shanley and McCabe (1991), Shanley and others (1992), McCabe and Shanley (1992), Hettinger and others (1994), Hettinger (1995), Nichols (1995)
Tropic Shale and Dakota Fm.	Lawrence (1965), Peterson (1969a), May and Traverse (1973), Gustason (1989), Eaton (1991), Kirschbaum and McCabe (1992)

others (1992) have reinterpreted it as a ravinement surface cut by marine transgression. The John Henry Member is early Coniacian to late Santonian in age (Eaton, 1991) and consists of coal-bearing continental beds that grade eastward into a vertical stack of near-shore marine strata (Peterson, 1969a, b). Shoreface sandstones are named A through G (fig. 5) and are the dominant lithology along the Straight Cliffs escarpment. Continental strata within the John Henry Member contain coal in the lower, Christensen, Rees, and Alvey coal zones (fig. 5) as defined by Peterson (1969a, b). The Drip Tank Member is constrained to a late Santonian or early Campanian age (Eaton, 1991) and consists of sandstone that is interpreted to have been deposited in a fluvial environment (Peterson, 1969a, b).

The nomenclature of Peterson (1969b) has been applied to most areas mapped in the southern and eastern parts of the Kaiparowits Plateau. However, on the western flank of the plateau, the formation is simply divided and mapped into lower and upper parts (fig. 5). The lower part contains a basal marine sandstone (fig. 5) that is equivalent to the Tippet Canyon Member, and a white marker sandstone (fig. 5) equivalent to the Calico bed. The upper part contains the Henderson coal zone (fig. 5) (defined by Robison, 1966) at its base and is capped by a thick massive sandstone (fig. 5) that is equivalent to the Drip Tank Member. Strata between the white marker sandstone and thick massive sandstone are equivalent to the John Henry Member. Correlations between the various units and members are shown in figure 5 and are based on Doelling and Graham (1972) and Bowers (1973c, 1975, 1983, 1993). In this report, all further references to the nomenclature of Peterson

(1969b) include equivalent strata throughout the Kaiparowits Plateau.

Recent stratigraphic and sedimentological investigations by Shanley and McCabe (1991) have resulted in the identification of four unconformity-bounded sequences within the Straight Cliffs Formation. The unconformities are located in the Tippet Canyon Member, near the base of the Calico bed, within the A-sandstone, and near the base of the Drip Tank Member. The unconformities are named the Tippet, Calico, A-, and Drip Tank sequence boundaries, respectively, and each overlying sequence is named after its basal unconformity (figs. 5, 6). The sequence boundary unconformities are recognized by facies that have shifted abruptly basinward over regional surfaces of erosion. The basinward facies shifts are characterized by fluvial and estuarine strata juxtaposed over finer grained coastal plain and shoreface deposits (fig. 6) and are documented by Shanley (1991), Shanley and others (1992), and Hettinger and others (1994). Deposition in each sequence is interpreted to be controlled by fluctuations in base-level. Each sequence boundary unconformity is interpreted to have been cut during a fall in base-level, and each overlying sequence is deposited during a subsequent rise in base-level. During the initial stages of base-level rise, incised valleys are backfilled by fluvial, estuarine, and shoreface strata that are capped by a maximum marine flooding surface; these successively deepening upward successions are interpreted as transgressive systems tracts (TST) (fig. 6). Overlying aggradational and progradational deposits of marine, coal-bearing coastal plain, and alluvial strata are deposited during a slower rate of base-level rise and

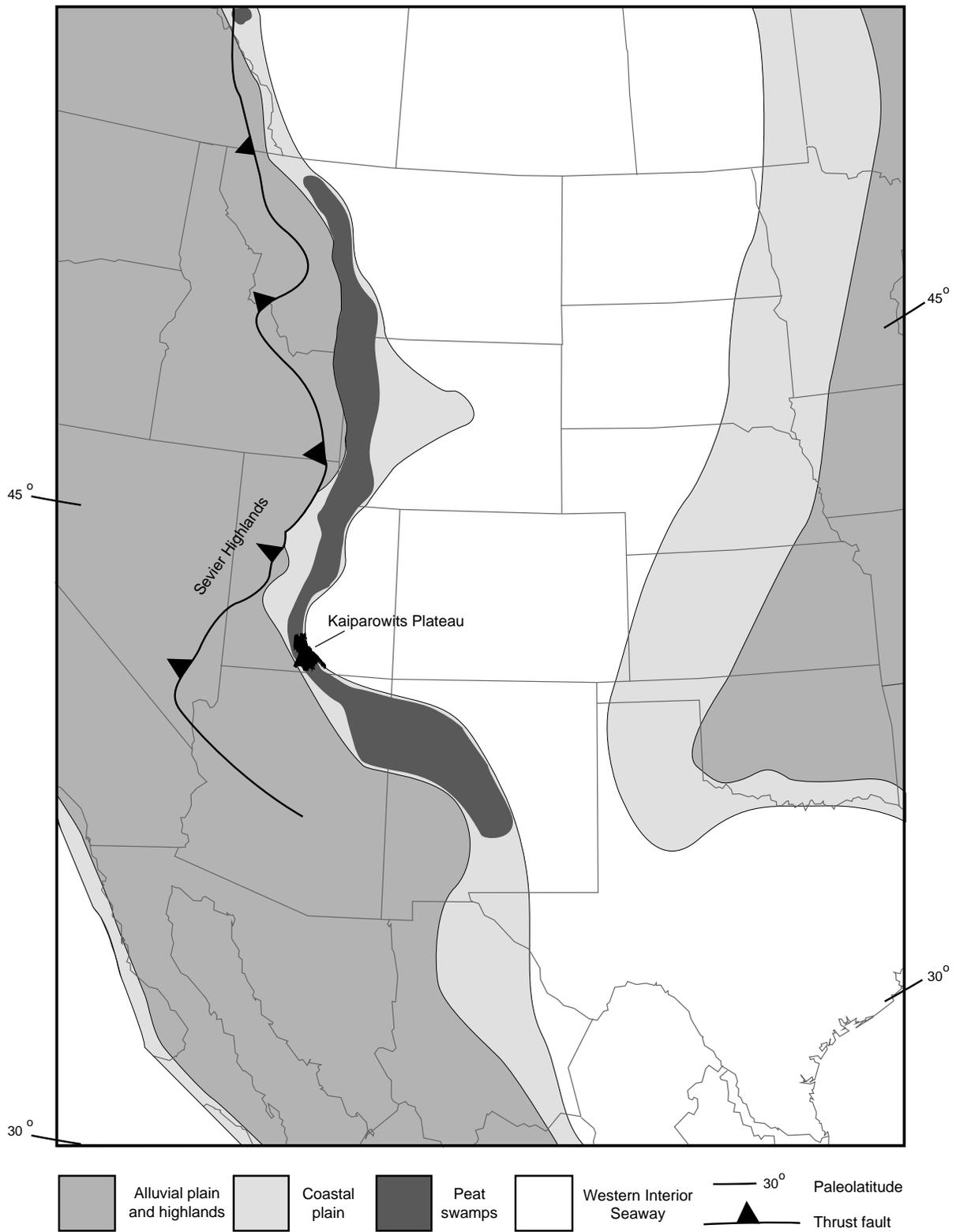


Figure 4. -- Paleogeographic map of the central part of North America during the Coniacian and Santonian Stages (88.5-83.5 ma.) of the Cretaceous Period. The Kaiparowits Plateau is shown in relation to shorelines, coastal plains, and peat swamps associated with the Western Interior Seaway; deposits from these depositional systems are preserved in the Straight Cliffs Formation. Map is modified from Roberts and Kirschbaum (1995).

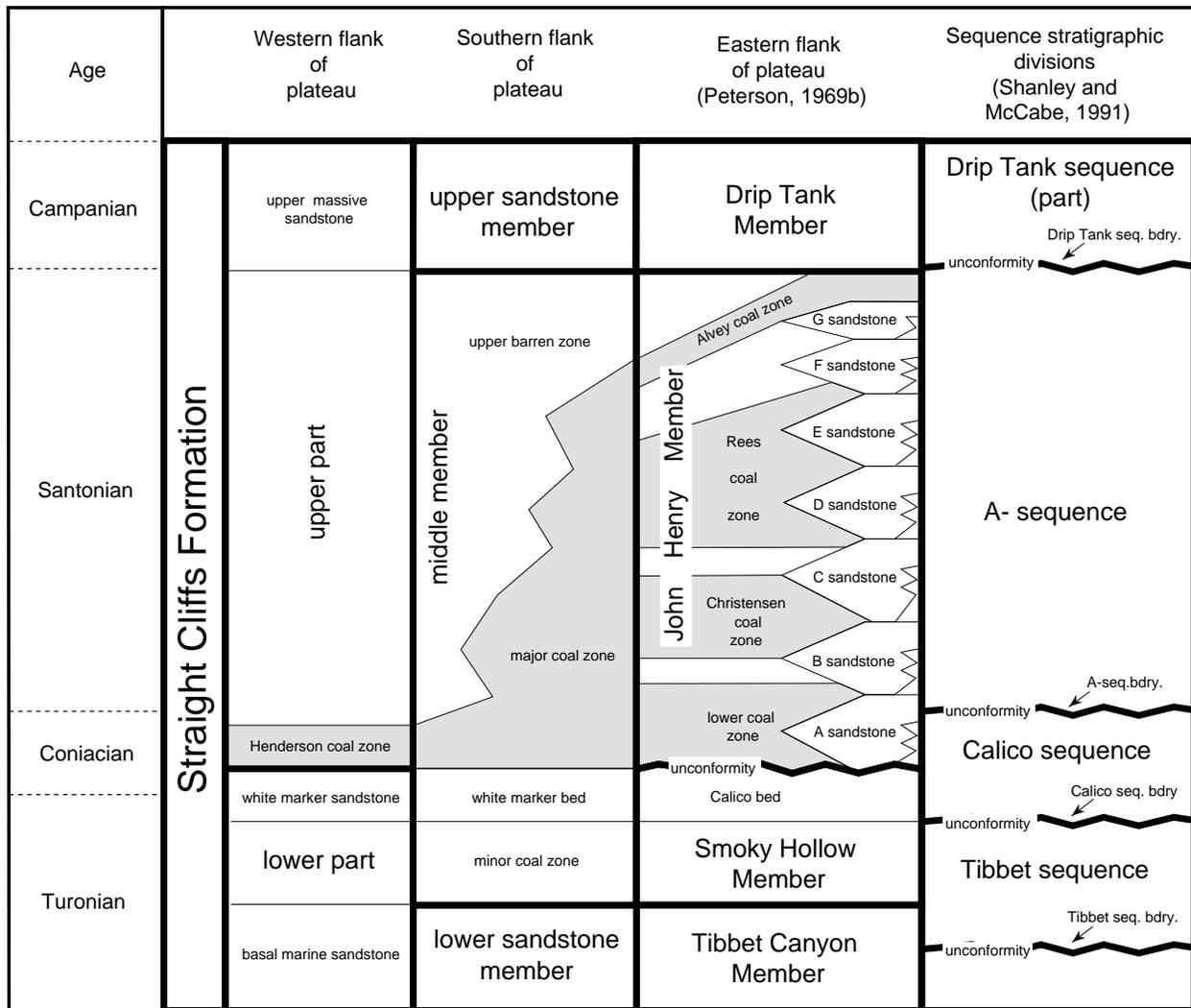


Figure 5. -- Stratigraphic divisions of the Straight Cliffs Formation used for mapping and stratigraphic studies in various parts of the Kaiparowits Plateau. Position of age boundaries are approximate.

are interpreted as highstand systems tracts (HST) (fig. 6).

The Calico and A-sequences contain all of the coal within the John Henry Member and upper part of the Smoky Hollow Member (figs. 5, 6). The Calico and Drip Tank sequence boundaries are easily recognized on geophysical logs and are useful correlative horizons throughout the plateau. Examples of geophysical log signatures and core descriptions for the Calico and A-sequences are given in figure 7. The Calico sequence boundary is recognized by a high natural gamma response (fig. 7) that is produced by a thick paleosol beneath the Calico bed (Hettinger, 1995). The Drip Tank sequence boundary is interpreted at or near the base of blocky log signatures (fig. 7) that are a response to thick sandstone in the

basal part of the Drip Tank sequence (Hettinger, 1995). The logs and cores shown in figure 7 provide the basis for interpreted depths to the Calico and Drip Tank sequence boundaries that are given for other drill holes in the plateau in appendix 1. Down-hole depths to the Calico and Drip Tank sequence boundaries are used to construct isopach maps that portray the thickness and deformation of coal-bearing strata.

The Calico and A-sequences underlie an area of about 1,300 square miles within the Kaiparowits Plateau. Their lines of outcrop are nearly identical to those of the John Henry Member at the scale mapped in figure 3. The Calico and A-sequences have a combined thickness of approximately 600-1,600 feet (fig. 8); about 75-400 feet of strata are in the Calico sequence and 525-1,200 feet of strata are in the

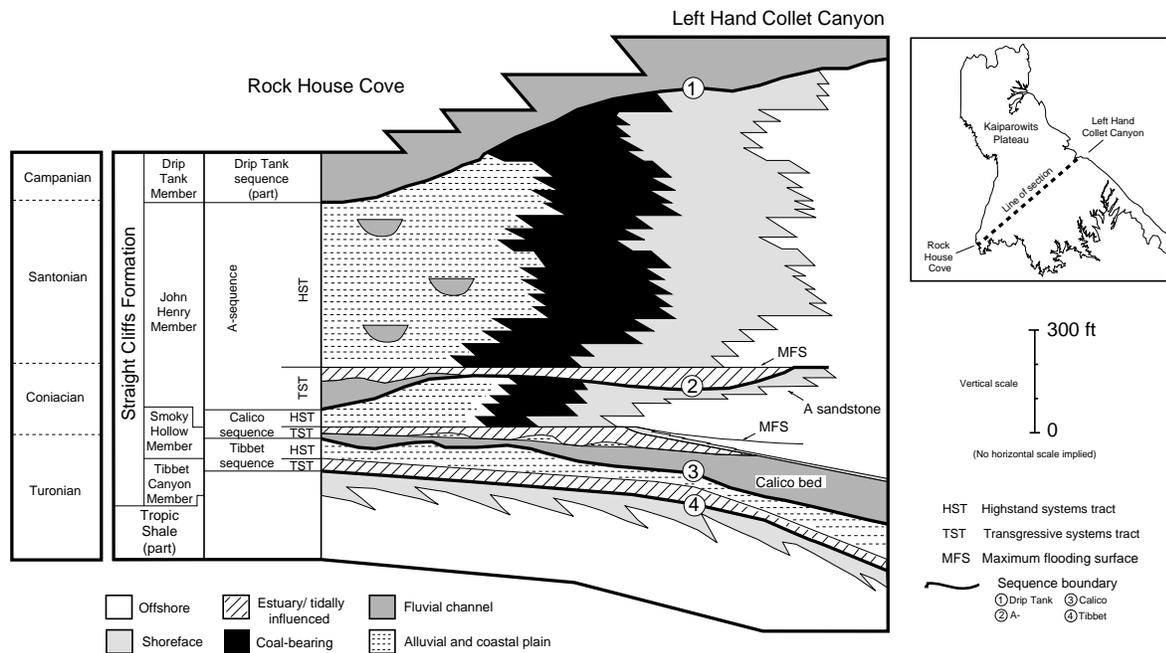


Figure 6. -- Sequence stratigraphic correlations and facies relationships in the Straight Cliffs Formation and upper part of the Tropic Shale. Line of section extends from Left Hand Collet Canyon to Rock House Cove (inset) and is perpendicular to paleoshorelines. Sequence stratigraphic divisions are compared to formal stratigraphic nomenclature. Diagram is modified from Shanley (1991). Position of age boundaries are approximate.

A-sequence. The combined sequences are 750-850 feet thick throughout much of the southwestern and south-central parts of the plateau and gradually thicken in the northern parts of the plateau. The sequences are thickest near the Straight Cliffs escarpment, where they contain thick aggradational stacks of shoreface sandstone and mudrock; conversely, the sequences are thinnest in the central part of the plateau, where they contain the greatest amount of mudrock and coal. These thickness variations were probably controlled, in part, by the differential compaction of sandstone, mudrock, and peat. Thicknesses of the Calico and A-sequences are based on interpretations of geophysical logs from 149 drill holes, 36 measured sections, and 7 control points listed in appendix 1. Thicknesses from measured sections are based on the stratigraphic interval between the base of the Calico bed and base of the Drip Tank Member. Thicknesses at the control points are based on general stratigraphic information published in geologic maps.

Structure

Strata within the Kaiparowits Plateau are inclined along numerous northerly trending folds that plunge into a deep central basin containing the Table Cliffs,

Last Chance, and Coyote Creek-Billie Wash synclines (fig. 9). The northeastern flank of the central basin is defined by the westwardly dipping limb of the Dutton monocline, and its western flank is defined by eastwardly dipping limbs of the Johns Valley anticline and East Kaibab monocline (fig. 9). Strata are inclined by less than 6° throughout most of the plateau (fig. 9). However, beds dip as much as 25° along a westwardly dipping homocline near the town of Escalante, 30° on the eastern limb of the Johns Valley anticline, 45° along the Dutton monocline, and 80° along the East Kaibab monocline (fig. 9). Areas where strata are inclined 0° to 6°, 6° to 12°, 12° to 25°, and greater than 25° are also shown in figure 9 and are based on recorded strikes and dips in the field and structure contour lines published in geologic maps referenced in figure 2. Dips in the Posy Lake, Five Mile Valley, and Lower Coyote Spring quadrangles (fig. 2) are based on photographic interpretations by Detterman (1956), McQueen and Ray (1958), and McQueen (1958).

There are relatively few faults in the Kaiparowits Plateau; most are located around its peripheral areas (fig. 9) and displacements are generally insignificant related to the potential mining of the coal (Doelling and Graham, 1972). Faults having significant

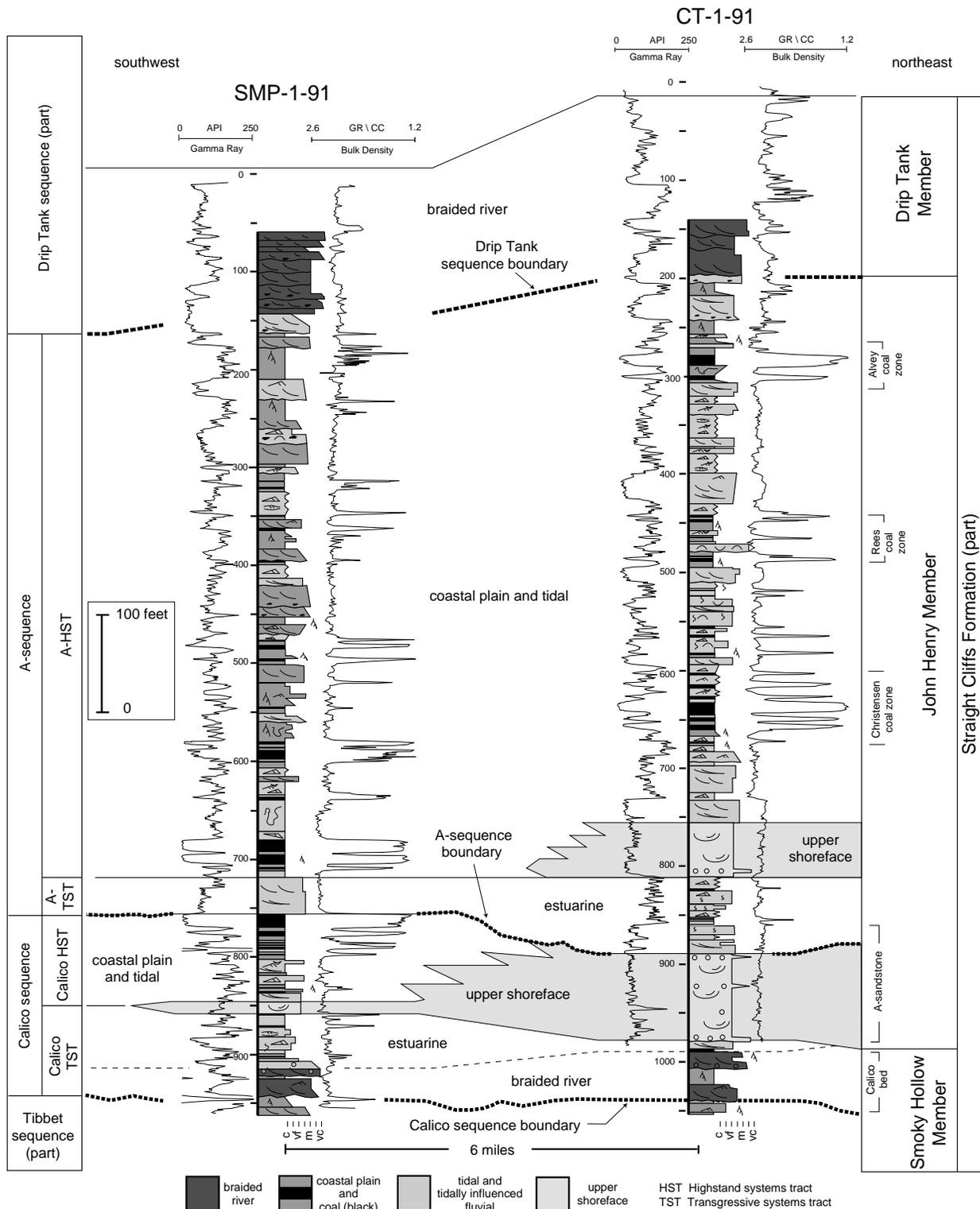


Figure 7. -- Responses of gamma ray and bulk density logs to lithologies in the Calico and A-sequences. Lithologies and geophysical logs are from cores CT-1-91 and SMP-1-91 (localities 5 and 6, respectively on plate 1). Explanations for grain size abbreviations (c, vf, m, vc) and symbols used for sedimentary structures are given on plate 1. Diagram is modified from Hettinger (1995).

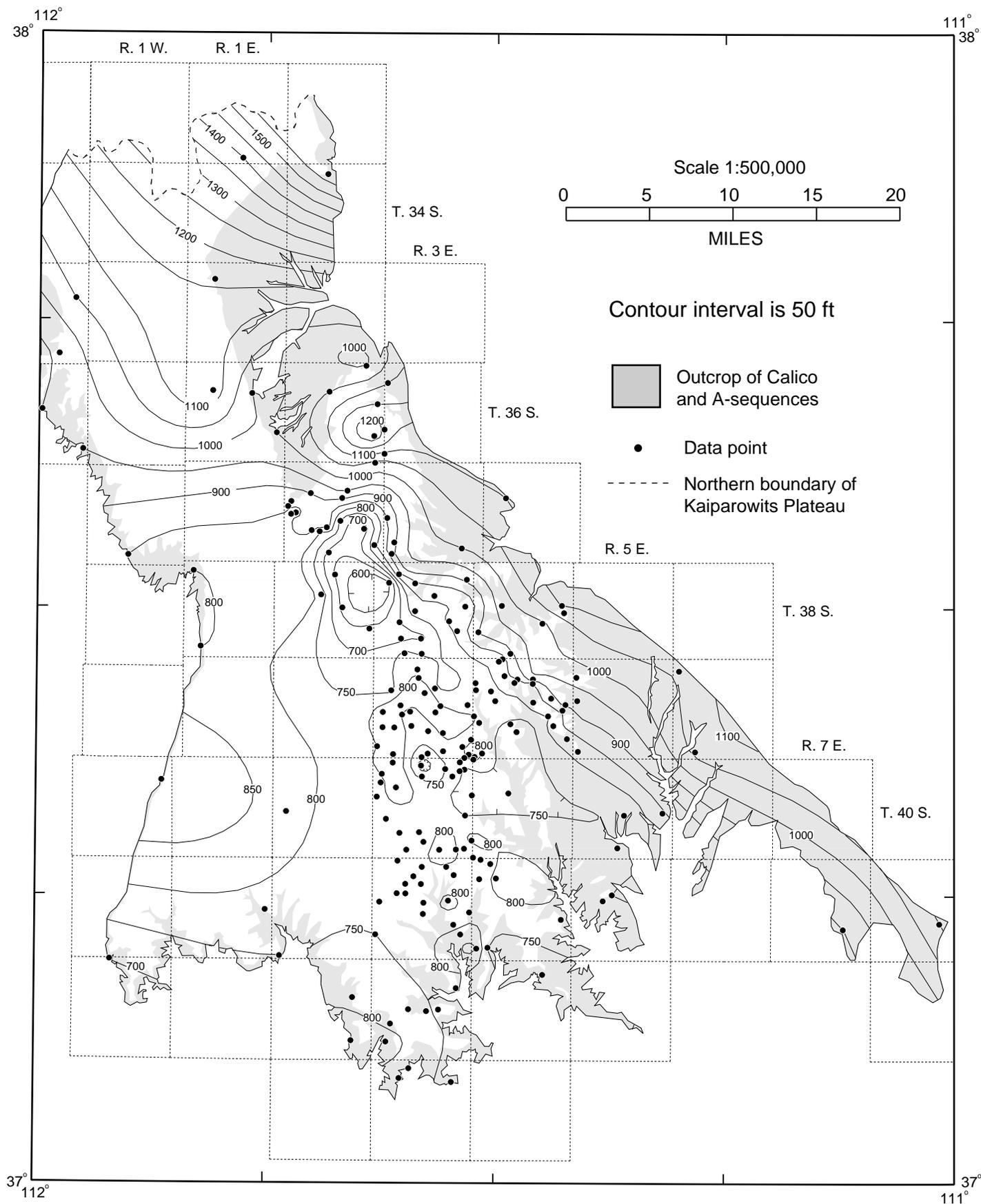


Figure 8. -- Isopach map showing the combined thickness of the Calico and A-sequences. Thicknesses are based on 192 data points. Data points are identified on figure A of plate 1 and the thickness of the combined sequences at each data point is given in appendix 1.

displacement include the northeast-trending Paunsaugunt fault and the bounding faults of the Jake Hollow graben, located along the plateau's northern margin (fig. 9). The Paunsaugunt fault has as much as 2,000 feet of displacement and truncates all coal-bearing strata along the northwestern flank of the plateau (Doelling and Graham, 1972). The Jake-Hollow graben extends about 6 miles, is 0.5-1.0 mile wide, and has as much as 500 feet of displacement (Bowers, 1973b). Northeast-trending faults on the west-central flank of the plateau near Henrieville (fig. 9) have a strong right-lateral strike-slip component and 200-250 feet of vertical displacement (Bowers, 1983). Further south, the East Kaibab monocline is cut by numerous southeast-trending faults (fig. 9) that have only minor displacement (Bowers, 1983, 1993). The southern margin of the plateau contains several additional northwest-trending faults that extend less than 10 miles and have less than 50 feet of displacement (Peterson, 1967; Waldrop and Sutton, 1967a; Zeller, 1990a).

Deformation of coal-bearing strata in the Calico and A-sequences is shown on a structure contour map of the Calico sequence boundary (fig. 10). The sequence boundary is 4,500-9,000 feet above sea level on outcrop and 2,000 feet above sea level in the Table Cliffs syncline (fig. 9). The structure contour map reflects most of the major folds shown in figure 9 and indicates that the folds are not related to compaction of coal-bearing strata. The map is based on measured elevations of the sequence boundary at 64 drill sites, estimated elevations at 102 drill sites (appendix 1), and subcrop elevations inferred at 50-100 feet below the mapped base of the John Henry Member around the entire perimeter of the plateau. Estimated elevations of the Calico sequence boundary at drill sites are made where drilling was terminated less than a few hundred feet above the sequence boundary and are based on correlations to nearby drill holes where the sequence boundary was penetrated.

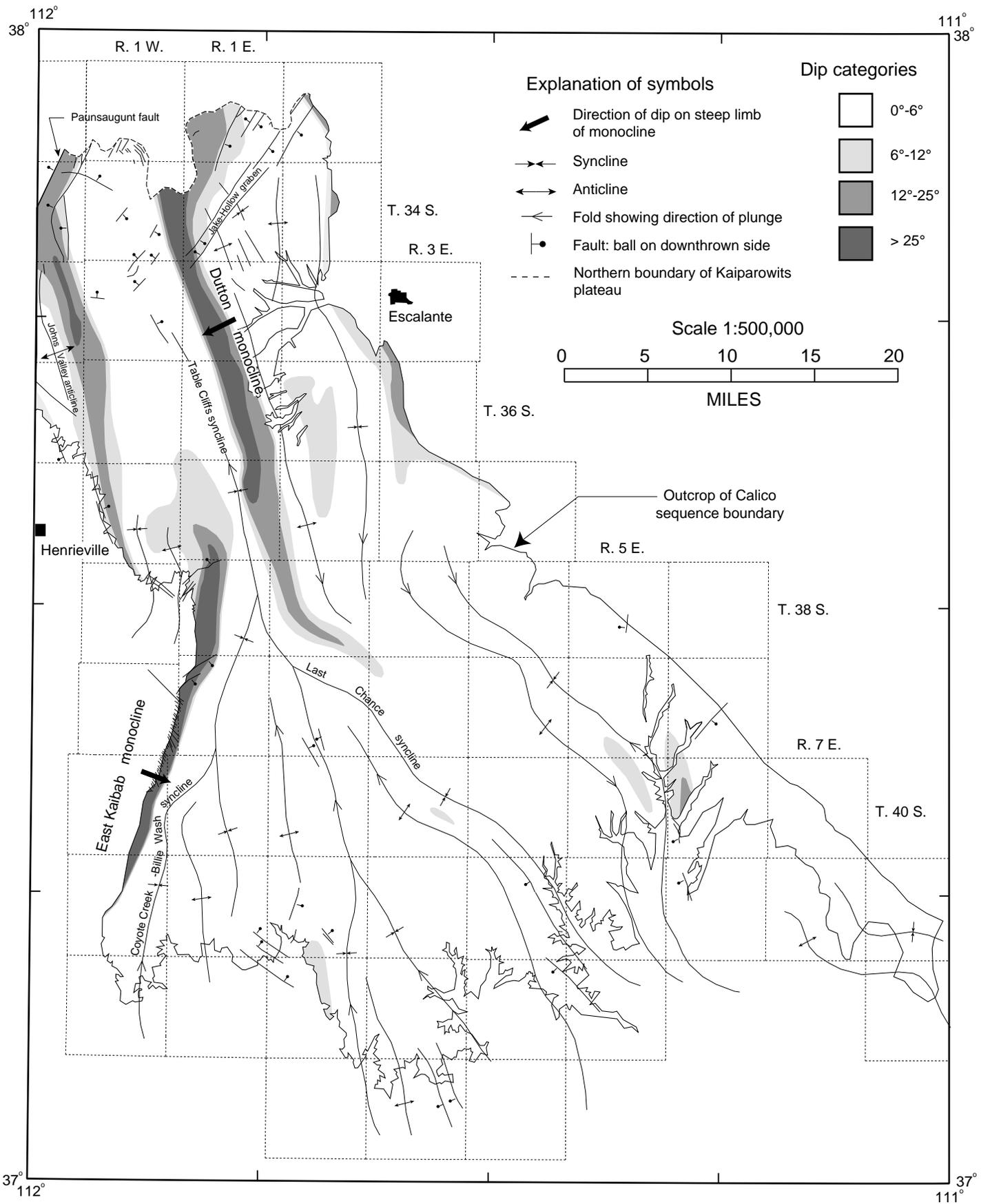


Figure 9. -- Structural features and inclination of strata within the Kaiparowits Plateau. Inclinations of strata are based on geologic mapping referenced in figure 2 are shown in categories that range from 0°- 6°, 6°- 12°, 12°- 25°, and > 25°. Fold axes and faults are from Sargent and Hansen (1982).

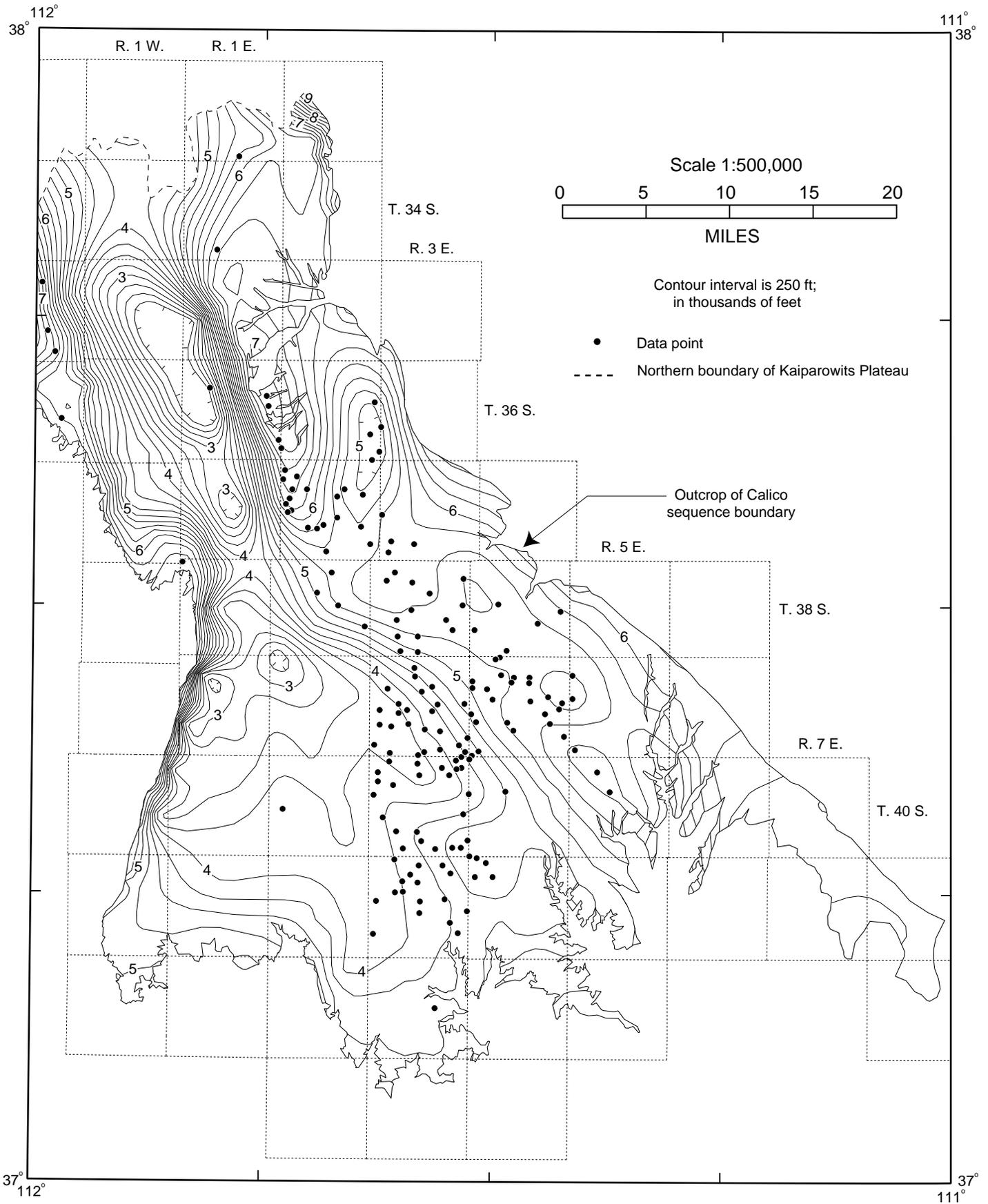


Figure 10. -- Structure contour map of the Calico sequence boundary. Sequence boundary elevations are based on 166 drill sites. The Calico sequence boundary occurs from 50-100 ft below the John Henry Member, therefore an inferred elevation of the sequence boundary was used at numerous locations along the outcrop where the John Henry Member was mapped. Data points are identified on figure A of plate 1 and sequence boundary elevations are provided in appendix 1.

COAL DISTRIBUTION, QUALITY, AND RESOURCES IN THE CALICO AND A-SEQUENCES

The Calico and A-sequences (figs. 5, 6) contain coal in the Henderson coal zone, the lower coal zone, and the Christensen, Rees, and Alvey coal zones. The Henderson and lower coal zones are in the Calico sequence, and the Christensen, Rees, and Alvey coal zones are in the A-sequence (fig. 5). We describe these coals in sequence stratigraphic context because, unlike formational contacts of the John Henry Member, the Calico and Drip Tank sequence boundaries provide excellent marker horizons that can be traced on geophysical logs throughout the plateau.

Coal distribution

Coal-bearing strata in the Calico and A-sequences extend as much as 60 miles from north to south and 30 miles from east to west across the plateau. Outcrop investigations reveal that coal is within distinct zones along the peripheral areas of the plateau. On the eastern flank of the plateau, the coal-bearing interval is 500-700 feet thick. Coals are in the lower coal zone, and the Christensen, Rees, and Alvey coal zones that intertongue with, and pinch out eastward into, thick deposits of shoreface strata in the A-sequence (fig. 5). The coal-bearing interval thins to less than 50 feet on the plateau's western flank where the only coals are within the Henderson zone (fig. 5) in the Calico sequence. Southwestward thinning of coal-bearing strata is seen in outcrops on the plateau's southern flank. The full extent of the coal-bearing interval is revealed only by drill-hole data collected from the plateau's interior region where the net coal accumulation is greatest. These data show that the distinct coal zones located along the peripheral areas of the plateau tend to merge and lose their identity in the subsurface of the plateau's interior. The following paragraphs provide a summary of coal distribution based on outcrop investigations and a detailed analysis of their distribution in the subsurface.

Coal distribution in outcrops

Outcrop investigations cited in figure 2 provide maps and measurements for coal beds within several distinct coal zones located along the peripheral margins of the plateau. Published coal thickness data

from outcrops are summarized for each 7.5' quadrangle in appendix 3. In general, coal beds in the Kaiparowits Plateau have been reported to split and pinch out rapidly on outcrop and are difficult to trace because they are commonly burned and covered by slope wash and talus. Coals are extensively burned, and are still burning, in parts of the East of Navajo, Needle Eye Point, Smoky Hollow, and Sit Down Bench quadrangles (fig. 2). Baked rocks in these areas may extend more than 200-300 feet into the subsurface (Peterson and Horton, 1966; Peterson, 1967). The Henderson zone is 5-50 feet thick on outcrop and contains as much as 29 feet of coal on the northwestern flank of the plateau in the Pine Lake quadrangle (fig. 2). Coals in the Henderson zone thin to the south and pinch out completely on the southwestern flank of the plateau in the Horse Flat quadrangle (fig. 2). The lower zone is exposed only on the southern flank of the plateau, where it is as much as 40 feet thick and contains as many as four beds of coal that are 1-7 feet thick. The lower zone is split by the A-sandstone and the upper split is exposed in the East of Navajo and Needle Eye Point quadrangles (fig. 2). Outcrops of the Christensen zone are 70-130 feet thick and contain as many as six beds of coal that are 1-30 feet thick. The Rees zone is 70-200 feet thick in outcrops and contains as many as seven beds of coal that are 1-20 feet thick. Outcrops of the Alvey zone are 40-160 feet thick and have as many as eight beds of coal that are 1-20 feet thick. These collective coal zones contain as much as 70 feet of net coal in outcrops located in the Sit Down Bench and Smoky Hollow quadrangles (fig. 2); the coal beds thin to the west and less than 3 feet of coal remains in the Nipple Butte quadrangle (fig. 2).

Coal distribution in the subsurface

A broad three-dimensional view of coal distribution throughout the subsurface of the Kaiparowits Plateau is demonstrated in three correlation diagrams shown on plate 1 (figs. C, D, and E) and a net coal isopach map shown in figure 11. The geographic distribution of net coal in the Calico and A-sequences (fig. 11) is based on coal measurements from 158 drill holes and 45 measured sections listed in appendix 1. Cross sections A-A' and B-B' are oriented perpendicular to paleoshorelines; A-A' extends 25 miles northeast from Tibbet Canyon to Left Hand Collet Canyon (fig. B on pl. 1). Cross section B-B'

extends 11 miles northeast from the plateau's interior region to Alvey Wash (fig. B on pl. 1). Cross section C-C' is oriented nearly parallel to paleoshorelines; it is located 9-12 miles southwest of the Straight Cliffs escarpment and extends a distance of 19 miles (fig. B on pl. 1). Stratigraphic control for the cross sections is provided by measured sections at Alvey Wash (map number 177), Left Hand Collet Canyon (map number 196), and Tibbet Canyon (map number 211) and by core collected from CT-1-91 and SMP-1-91 (map numbers 5 and 6, respectively); map numbers are shown on plate 1 (fig. A). The measured section at Alvey Wash was published by Zeller (1973d), measured sections at Left Hand Collet Canyon were published by Peterson (1969a) and Shanley (1991), and the measured section at Tibbet Canyon was published by Shanley (1991). Cores CT-1-91 and SMP-1-91 are described in Hettinger (1995).

The net coal isopach map (fig. 11) and cross sections (figs. C, D, E on pl. 1) demonstrate that variations in net coal accumulation in the Calico and A-sequences are related to the distance from the paleoshorelines that the original peat accumulated. Along the Straight Cliffs escarpment, highstand deposits of both sequences are dominated by shoreface sandstone and mudrock and contain only minor beds of coal. As viewed along depositional dip in cross sections A-A' and B-B', thick coals are located immediately landward (southwest) of the shoreface sandstone pinch-outs. Shoreface sandstones in the Calico sequence extend about 15 miles southwest into the plateau's interior region, and thick beds of coal are not found in the Calico sequence along the eastern part of the plateau. In contrast, aggradational stacks of shoreface sandstone in the A-sequence pinch out within 1-7 miles of the escarpment. Measured sections in Alvey Wash (Zeller, 1973d) and Left Hand Collet Canyon (Shanley, 1991) show that within 2.5 miles of the escarpment the A-sequence contains about 30 feet of net coal in the Christensen, Rees, and Alvey coal zones. The coal zones are separated by thick clastic wedges consisting of shoreface sandstone. These clastic wedges thin and change facies to the southwest; their thinning is accompanied by an increase in net coal. Eventually, the coal zones merge and their boundaries become indistinct. A drill-hole core collected 5 miles from the escarpment at CT-1-91 reveals that the A-sequence contains 61 feet of net coal in beds that are as much as

11 feet thick (Hettinger, 1995); clastic strata in the A-sequence are dominantly tidal and coastal plain in origin and include some shoreface deposits.

Areas where net coal accumulations exceed 100 feet are located approximately 8-15 miles southwest of the Straight Cliffs escarpment (fig. 11) and are viewed along depositional strike in cross section C-C'. As much as 160 feet of net coal is contained in a 500-600 foot thick interval and coal beds are as much as 59 feet thick. Net coal accumulations of 150-160 feet have been drilled at map localities 8, 9, 12, 13, 101, and 108 (fig. A on pl. 1), which are located about 10-12 miles southwest of the escarpment. Core SMP-1-91 shows that these areas contain thick coal beds in both the Calico and A-sequences; clastic strata are mostly tidal and fluvial in origin, although some shoreface deposits remain in the Calico sequence (Hettinger, 1995). Coal beds in areas of maximum accumulation are concentrated in pods that extend laterally for about 1-3 miles. The pods eventually split into distinct coal zones that can be traced for several miles. Examples of pods are seen at locality 13 (B-B', C-C') between the depths of 1,595 and 1,670 feet and at locality 22 (B-B') between the depths of 1,315 and 1,472 feet. Within the areas of overall thick coal accumulation, several localities have a relative paucity of coal; as little as 70 feet of net coal was drilled at localities 15, 87, 94, and 152 (fig. A on pl. 1). Geophysical logs from these localities show a marked increase in sandstone as compared to nearby areas, and coal correlations are tentative. Although not proven, these areas may represent localities of northeast-flowing paleofluvial systems.

The net coal isopach map (fig. 11) and cross section A-A' (fig. C on pl. 1) show that net coal accumulations and coal bed thicknesses decrease southwest of the areas of maximum accumulation. A measured section described in Tibbet Canyon, located 22 miles southwest of the Straight Cliffs escarpment, shows that the A-sequence contains about 20 feet of net coal in beds that are all less than 3 feet thick, and only a few minor beds of coal remain in the Calico sequence (Shanley, 1991). The measured section also reveals that clastic deposits of both sequences are predominantly alluvial and, to a lesser degree, tidally influenced in origin (Shanley, 1991). Still further southwest at Rock House Cove (fig. B on pl. 1), both highstand deposits are entirely alluvial in origin and contain no coal (Shanley, 1991).

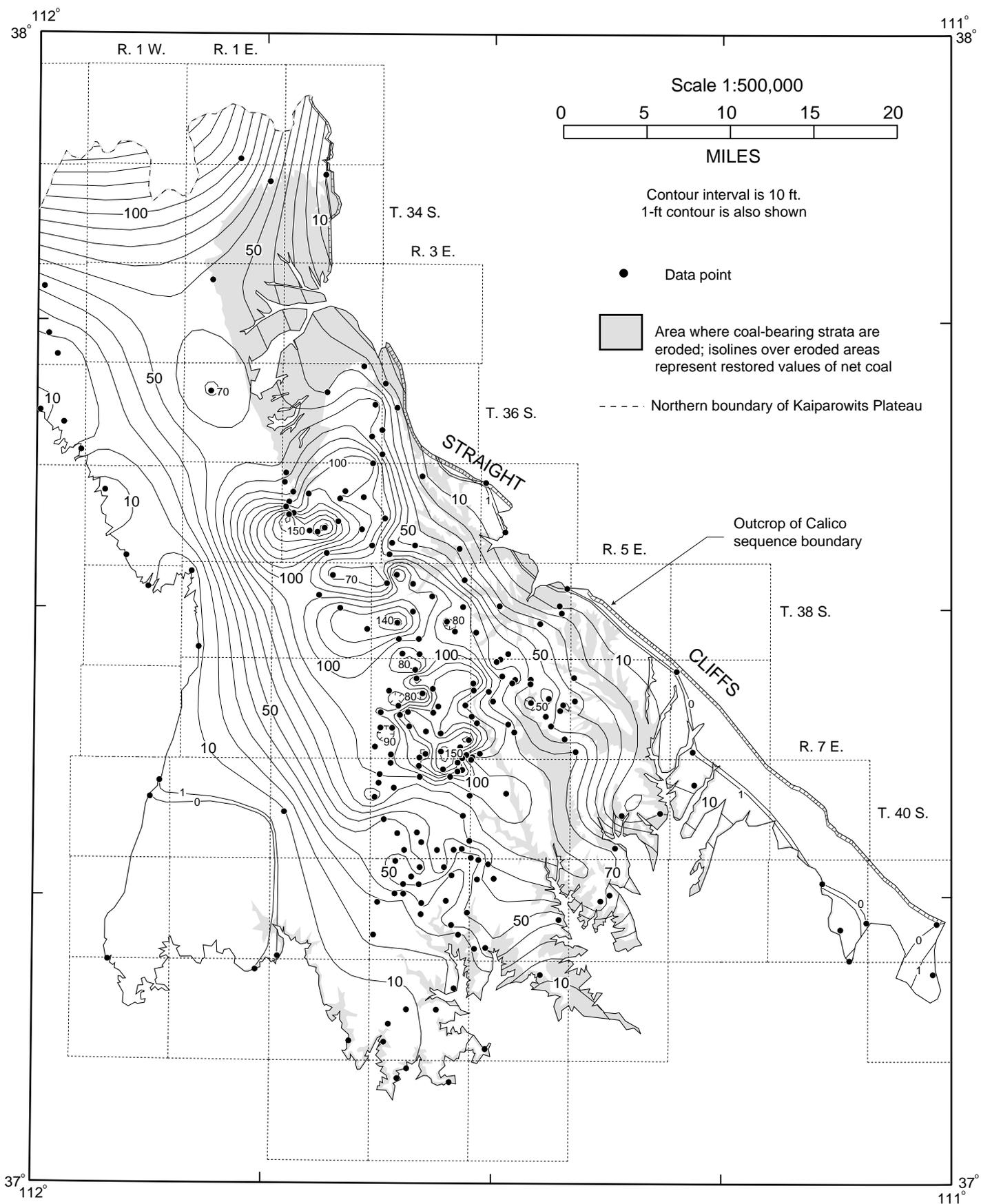


Figure 11. -- Isopach map of net coal in the Calico and A-sequences. Net coal values represent all coal beds that are more than 1 foot thick and are determined from 209 data points listed in appendix 1; data points are identified on figure A of plate 1. Isolines over areas where coal-bearing strata are eroded (gray stipple) represent restored values.

The profile of net coal distribution in the Calico and A-sequences is shown by two graphs (fig. 12). Graph A-A' (fig. 12A) is constructed along depositional dip using the same drill-hole data shown in cross section A-A' (fig. C on pl. 1), and graph C-C' (fig. 12B) is constructed along depositional strike using the same drill-hole data shown in cross section C-C' (fig. E on pl. 1). The vertical axis in each graph shows the net coal accumulation recorded at drill holes along the line of section, and the horizontal axis records the distance between drill holes. Both graphs also show net coal accumulations within bed thickness categories of 1-3.4, 3.5-14.0, and greater than 14.0 feet; bed thicknesses are based on data provided in appendix 1. Graph A-A' shows that coal distribution, as viewed along depositional strike, takes on the shape of a bell curve, in which thin coal beds and net coal accumulations of less than 20 feet are located along the flanks of the curve and thick coal beds and maximum coal accumulations of as much as 150 feet occupy the center of the curve. Graph C-C' shows that along depositional strike, areas of thick coal accumulation take on the shape of a more sinuous curve, in that three distinct areas having thick coal beds and net coal accumulations of 120-160 feet are separated by two areas where net coal accumulations are only 60-70 feet and thick beds are absent.

Coal quality

Coals in the Kaiparowits Plateau are reported to be subbituminous C to high-volatile bituminous A in rank (Doelling and Graham, 1972, p. 93). Proximate and ultimate analyses are provided from about 100 coal samples collected from abandoned mines and outcrops located throughout the plateau (Doelling and Graham (1972, p. 123-127). Analyses of coal from core DH-1 are also provided by Doelling and Graham (1972, p. 126) (information by Bowers (1973c) indicates that DH-1 is located 150 feet northwest of map number 151 (fig. A on pl. 1) in T. 35 S., R. 2 W.). Additional quality data are reported for coals collected from three cores (K-1-DR, CT-1-91, and SMP-1-91) drilled by the U.S. Geological Survey; the cores are collected from localities 4, 5, and 6, respectively (fig. A on pl. 1). Proximate and ultimate analyses of samples collected from K-1-DR are reported by Zeller (1979) and Affolter and Hatch (1980); analyses of samples collected from CT-1-91 and SMP-1-91 are provided by Brenda Pierce (U.S. Geological Survey, unpub. data, 1996).

Ranges in values for proximate and ultimate analyses, as well as moist, mineral-matter-free BTU/lb and apparent rank, are reported in table 4 for coal collected from cores. We have also determined arithmetic means from proximate and ultimate analyses reported in Doelling and Graham (1972, p. 123-127) for samples collected from mines and outcrops. Arithmetic means and apparent ranks calculated from these average values are reported in table 5; the range of proximate and ultimate values is summarized in appendix 3. Apparent ranks determined from samples collected from cores range from subbituminous B to high-volatile A bituminous coal (table 4). The apparent rank of samples collected from outcrops and mines (as determined from average values of proximate and ultimate analyses) ranges from subbituminous B to high-volatile C bituminous coal (table 5).

Coal Resources

The Kaiparowits Plateau contains an estimated original coal resource of 62.3 billion short tons (table 6) within the Calico and A-sequences. That original coal resource includes all coal beds that are greater than 1 foot thick, as deep as 8500 feet, and within an 850 square mile area where the entire coal-bearing interval is preserved (fig. 11). Coal tonnages are calculated using the methodology of Wood and others (1983) and are determined by multiplying the estimated volume of coal by its average density. The volume of coal in the Calico and A-sequences is a product of its net thickness and its areal extent as shown in figure 11. The average density of bituminous coal is 1,800 short tons per acre-foot (Wood and others, 1983, p. 22). An average bituminous rank is assumed for coal in the Calico and A-sequences, based on analyses from mines and cores summarized in tables 4 and 5 and appendix 3. The original resource area shown in figure 11 contains most areas where State and Federal coal leases and Federal coal prospect permits were issued prior to 1972, as shown in Doelling and Graham (1972, p. 100-101). Doelling and Graham (1972, p. 106) reported that underground mining is the most likely method for extracting coal in the plateau, and although all localities within the reported resource area would have to be mined by underground methods, much of the coal is too deep or too thin to be economically mined in the foreseeable future.

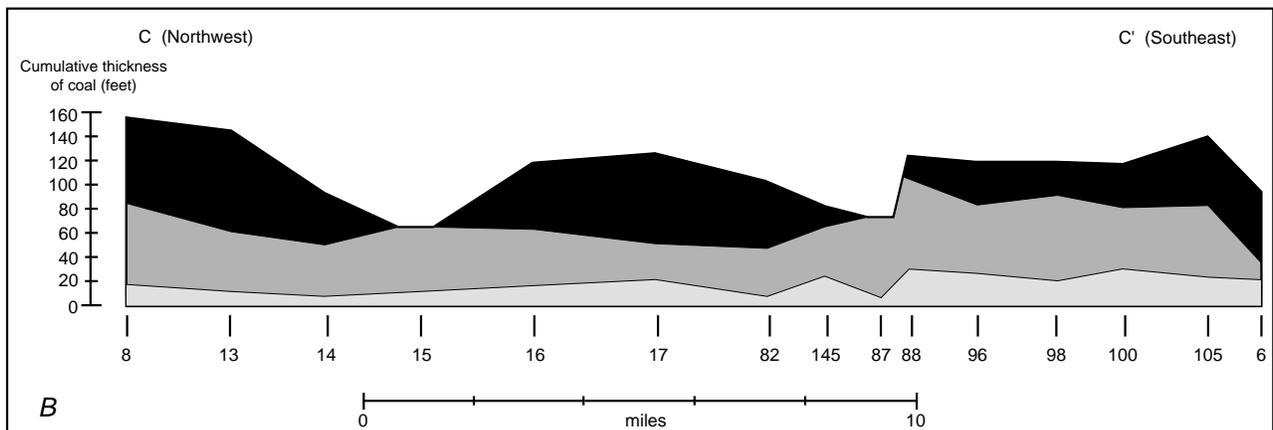
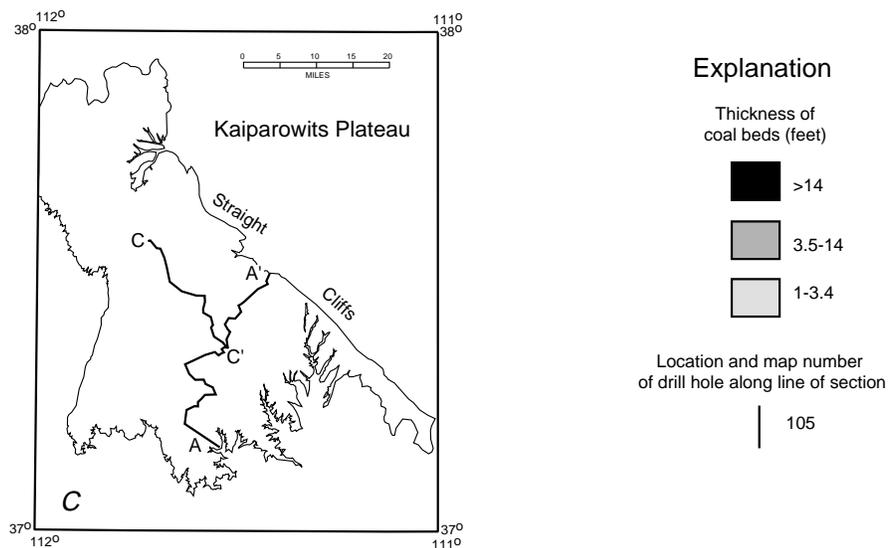
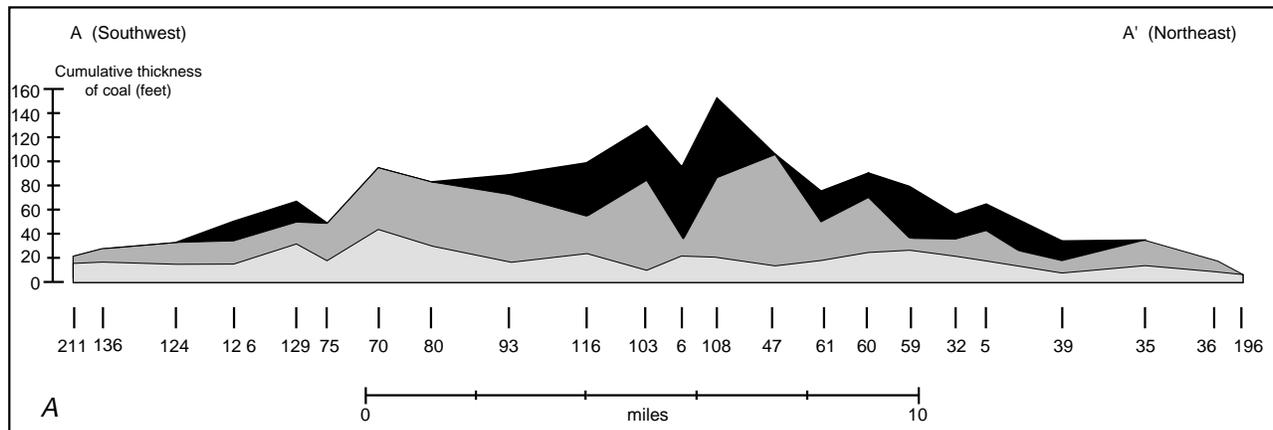


Figure 12. -- Coal distribution in the Calico and A-sequences. *A*, shows coal distribution along A-A', which trends perpendicular to the paleoshorelines. *B*, shows coal distribution along C-C', which trends parallel to the paleoshorelines. Horizontal axes show distance between drill holes; vertical axes show the cumulative coal thicknesses for beds that range from 1-3.4, 3.5-14.0, and greater than 14 feet thick. *C*, shows the locations of A-A' and C-C'; stratigraphic correlations are shown in figures C and E of plate 1. Drill hole locations are shown on figure A of plate 1; coal bed thicknesses are listed in appendix 1.

Table 4. Coal quality summary for samples collected from cores of the Calico and A-sequences in the Kaiparowits Plateau, Utah. Coal zone queried where uncertain. Apparent rank calculated using the Parr formula (American Society for Testing and Materials, 1995).

Coal zone	Moisture %	Volatile Matter %	Fixed Carbon %	Ash %	Sulfur %	Heating value Btu/lb	Moist-, Mineral-Matter-Free Heating value Btu/lb	Apparent Rank
Coals sampled from core K-DR-1 (map no. 4, figure A on plate 1)								
Alvey (2 samples)	19.7-20.4	34.7-35.1	37.0-37.7	7.2-8.2	1.0	9,440-9,510	10,240-10,440	Subbituminous B
Rees (3 samples)	15.6-18.4	29.6-35.0	29.9-36.3	10.3-24.9	0.6-0.7	7,640-9,280	10,450-10,460	Subbituminous B
Christensen (3 samples)	19.7-21.1	33.3-34.7	39.8-40.9	4.4-5.8	0.5-0.6	9,830-9,860	10,320-10,520	Subbituminous A and B
Coals sampled from core SMP-1-91 (map no. 6, figure A on plate 1)								
Rees ? (6 samples)	8.2-9.7	41.7-43.9	41.8-44.7	2.7-8.2	0.4-0.7	11,488-12,381	12,390-12,760	High volatile C Bituminous
Rees (17 samples)	0.7-7.8	27.9-50.7	24.9-45.4	4.3-42.5	0.5-2.3	6,962-12,387	12,700-13,710	High volatile B and C Bituminous
Christensen (13 samples)	5.5-7.9	35.3-44.5	34.6-48.0	2.3-24.7	0.3-1.0	9,464-12,477	12,360-13,590	High volatile B and C Bituminous
lower (15 samples)	4.5-7.1	35.4-46.5	32.1-45.5	3.5-26.4	0.4-2.3	9,002-12,620	12,610-16,720	High volatile A, B, and C Bituminous
Coals sampled from core CT-1-91 (map no. 5, figure A on plate 1)								
Christensen (23 samples)	8.5-15.5	34.5-41.1	34.8-4.6	3.7-17.6	0.4-2.2	9717-11721	11,110-12,590	Subbituminous A to High volatile C Bituminous
Coals sampled from core DH-1 (150 ft northeast of map no. 151, figure A on plate 1)								
Henderson (5 samples)	9.4-18.9	32.4-38.2	26.4-35.6	8.4-29.9	NR	9,740-10,300	11,010-11,350	Subbituminous A

Additional coal resources underlie the Kaiparowits Plateau's eastern and southern flanks where the coal-bearing interval is partially eroded. The eroded areas are shown in gray stipple in figure 11. Coal resources were not calculated in these areas because the resources would have to be determined from individual beds based on their outcrop geometry and thicknesses. Unfortunately, most coals in these areas are mapped in zones rather than individual beds, and recorded coal thickness cannot be applied to specific coal beds. In addition, the zones are commonly burned and covered by slope wash over large outcrop areas, making resource determinations difficult

if not impossible. However, coal tonnage estimates have been made previously for many of the 7.5' quadrangles that contain the eroded areas, and these estimates are reported in appendix 3.

The original resource is reported in identified and hypothetical reliability categories that are based on the distance that the resource is calculated from a data point. Identified resources are located within a 3-mile radius of a data point and hypothetical resources are located beyond a 3-mile radius from a data point (Wood and others, 1983). Although confidence levels have not been established for these reliability categories, they reflect decreased levels of

Table 5. Coal quality summary for samples collected from mines and outcrops within the Calico and A-sequences in the Kaiparowits Plateau, Utah. Arithmetic means are reported for moisture, volatile matter, fixed carbon, ash, sulfur, and heating value and are based on proximate and ultimate analyses from about 100 samples reported in Doelling and Graham (1972, p. 123-127). Moist- and mineral-matter-free heating values and apparent ranks are determined from these average values. Apparent rank calculated using the Parr formula (American Society for Testing and Materials, 1995).

Coals collected from mines								
Coal zone	Moisture %	Volatile Matter %	Fixed Carbon %	Ash %	Sulfur %	Heating value Btu/lb	Moist-, Mineral-Matter-Free Heating Value Btu/lb	Apparent Rank
Alvey	16.4	38.4	38.0	7.3	0.6	9,350	10,150	Subbituminous B
Rees	5.0	41.4	48.7	5.0	0.7	11,600	12,270	High volatile C Bituminous
Christensen	6.7	39.2	44.2	7.3	2.1	11,600	12,640	High volatile C Bituminous
Henderson	18.7	39.1	36.5	8.6	1.0	9,260	10,210	Subbituminous B
Coals collected from outcrops								
Coal zone	Moisture %	Volatile Matter %	Fixed Carbon %	Ash %	Sulfur %	Heating value Btu/lb	Moist-, Mineral-Matter-Free Heating Value Btu/lb	Apparent Rank
Alvey	11.3	40.2	41.7	6.6	0.9	10,310	11,110	Subbituminous A
Rees	10.3	41.0	39.3	9.2	1.1	9,250	10,280	Subbituminous B
Christensen	10.9	38.8	43.1	7.2	0.9	10,390	11,280	Subbituminous A
Henderson	20.5	36.1	37.1	8.3	0.9	9,000	9,890	Subbituminous B

accuracy for calculated resources based on their distance from a data point. Approximately 47.2 billion short tons of coal (76 percent of the original resource) is calculated for areas located less than 3 miles from a data point and is therefore considered to be an identified resource (table 6). About 15.1 billion short tons of coal (24 percent of the original resource) is calculated for areas that are located more than 3 miles from a data point and are considered to be a hypothetical resource (table 6). Identified and hypothetical resource areas are shown in figure 13 and are based on the distribution of 209 coal data points; the hypothetical resources areas generally reflect where coal measurements are lacking because coals are either thin or deeply buried.

Coal resources were reported for areas in the Kaiparowits Plateau where coal is owned by the Federal Government, as well as for areas that underlie Kane and Garfield Counties and for each 7.5' quadrangle and township. Areas of Federal coal ownership are shown

in figure 14. County locations are shown in figure 1; township and 7.5' quadrangle locations are shown in figure 2. Of the 62.3 billion short tons of coal reported for the original resource, approximately 57.2 billion short tons (92 percent) are Federally owned; of the remaining 5.1 billion short tons, 4.7 billion tons underlie areas where the surface is owned by the State, and 0.3 billion tons underlie areas where the surface ownership is private. Approximately 27.7 billion short tons of coal are within Garfield County and 34.6 billion tons are within Kane County (table 6). Coal resources within each 7.5' quadrangle and township are reported in appendix 2. Coal resources reported within these more restricted areas are useful because they can be compared to resource estimates made in the previous investigations cited in figure 2.

Geologic restrictions to coal availability

In order to better quantify the original coal resource of the Calico and A-sequences, various aspects of coal

Table 6. Coal resources (in millions of short tons) in the Calico and A-sequences in the Kaiparowits Plateau, Utah. Resource reliability categories are defined in Wood and others (1983). Areas having identified resources are within a 3-mile radius of a data point and areas having hypothetical resources are beyond a 3-mile radius from a data point. Resources represent all areas of the plateau where the entire coal-bearing section is preserved (fig. 12) and are calculated using an average density of 1800 short tons per acre-foot for all coal beds thicker than 1 foot. Resources are reported in overburden and reliability categories for each county.

		ESTIMATED COAL RESOURCES (in millions of short tons)					
County	Reliability	Overburden (thickness in feet)					Total
		0-1,000	1,000-2,000	2,000-3,000	3,000-6,000	> 6,000	
Garfield	Identified	2,780.2	6,629.7	3,143.8	4,381.6	76.2	17,011.5
	Hypothetical	61.2	364.3	1,320.4	7,296.9	1,659.1	10,701.9
	Subtotal	2,841.4	6,994.0	4,464.2	11,678.5	1,735.3	27,713.4
Kane	Identified	13,227.0	9,219.5	7,672.7	77.3	0	30,196.5
	Hypothetical	304.5	150.7	3,326.7	618.7	0	4,400.6
	Subtotal	13,531.5	9,370.2	10,999.4	696.0	0	34,597.1
Total		16,372.9	16,364.2	15,463.6	12,374.5	1,735.3	62,310.5

distribution were investigated, including overburden, coal bed thickness, and dip of strata.

Overburden

Maximum overburden overlying coal in the Calico and A-sequences has been delineated utilizing the topography of the Calico sequence boundary (fig. 10) and surface elevations imported from a 1:250,000 Digital Elevation Model constructed by the U.S. Geological Survey. Maximum overburden lines are shown on the resultant map, figure 15, at 1,000, 2,000, 3,000, and 6,000 foot intervals. The maximum overburden map indicates that coals in the Calico and A-sequences are less than 2,000 feet deep in all areas of the Kaiparowits Plateau except for the central basin, where maximum overburden ranges from 2,000 to 8,500 feet. Estimated coal resources are calculated in overburden categories of 0-1,000, 1,000-2,000, 2,000-3,000, 3,000-6,000, and greater than 6,000 feet by integrating the overburden map (fig. 15) with the net coal isopach map (fig. 11). Coal resources in each category are reported in table 6. About 32.7 billion short tons of coal are under less than 2,000 feet of overburden, 48.2 billion short tons

of coal are under less than 3,000 feet of overburden, and 14.1 billion short tons of coal are under more than 3,000 feet of overburden.

In order to check the accuracy of the overburden map shown in figure 15, it was compared to an overburden map constructed for the Christensen coal zone by Hansen (1978b). The two maps generally compare favorably in most areas of the Kaiparowits Plateau; minor discrepancies are attributed to generalities in the Digital Elevation Model and the use of different horizons. However, overburden differences of as much as 500 feet are found in the northeastern part of the plateau in the Griffin Point quadrangle (fig. 2) where overburden is affected by the Jake Hollow graben (fig. 9). Additionally, our overburden values are as much as 1,000 feet too thick in the extreme northeastern part of the plateau (central part of the Posy Lake quadrangle, fig. 2), where thick successions of shoreface strata are located between the lowermost beds of coal and the Calico sequence boundary.

Coal bed thickness

The Calico and A-sequences contain as many as 30 beds of coal that range from 1 to 59 feet in

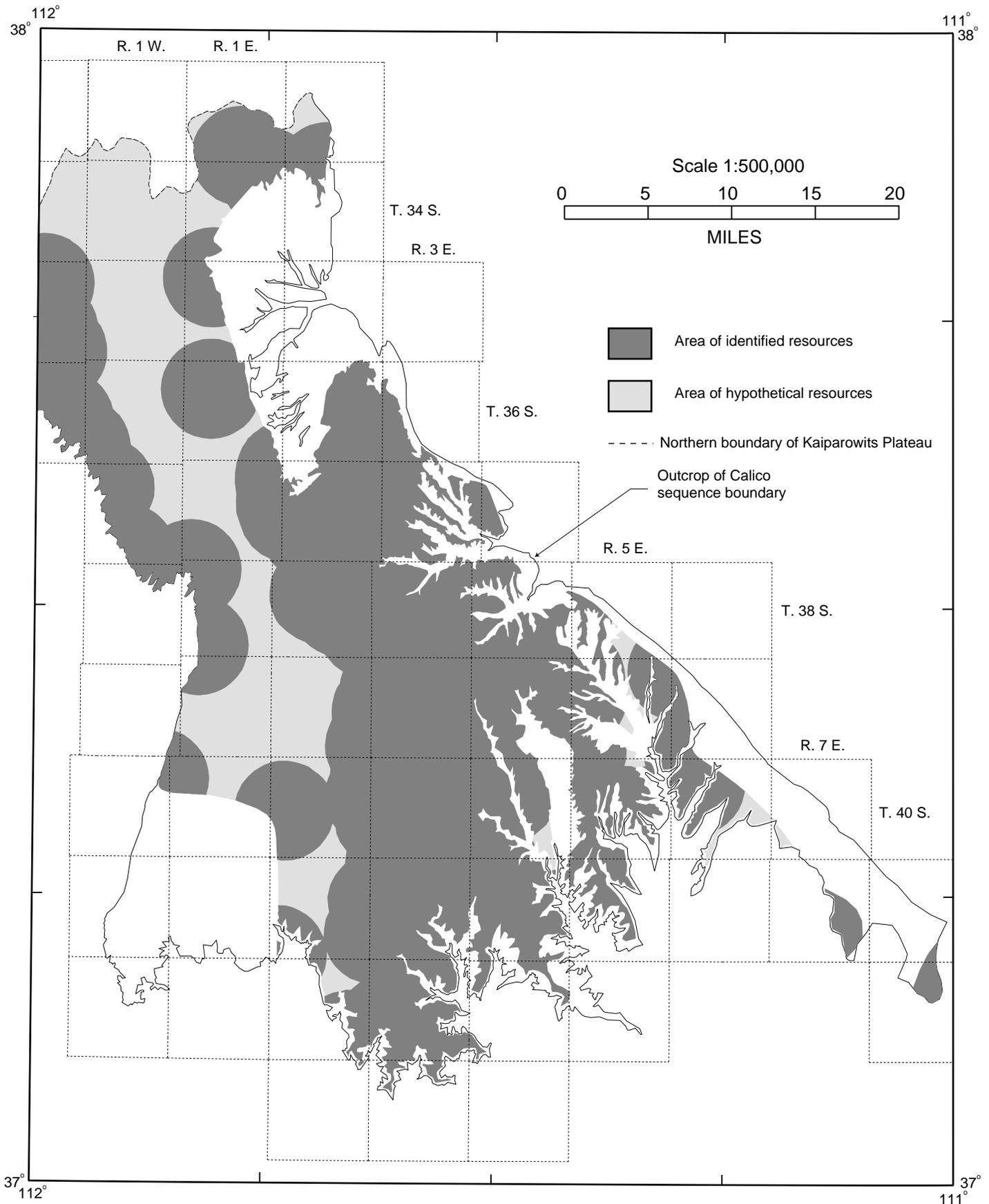


Figure 13. -- Map showing areas of reliability for coal resources in the Calico and A-sequences. Areas having identified resources are within a 3-mile radius of a data point and areas having hypothetical resources are beyond a 3-mile radius from a data point; areas are based on 209 data points shown in figure 11 and apply only to localities underlain by the total coal-bearing interval where coal beds are greater than 1 foot thick.

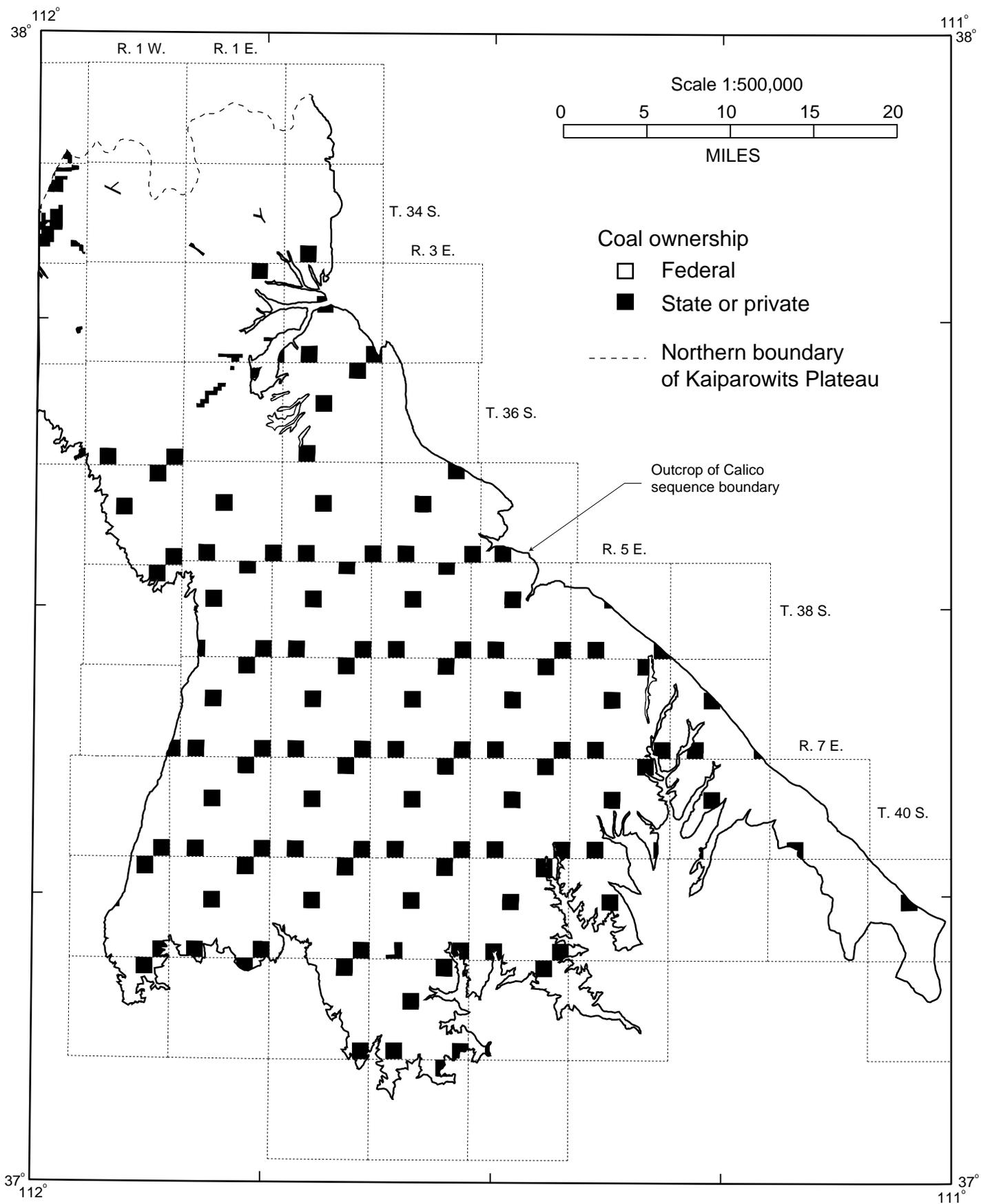


Figure 14. -- Mineral ownership for areas underlain by the Calico and A-sequences.

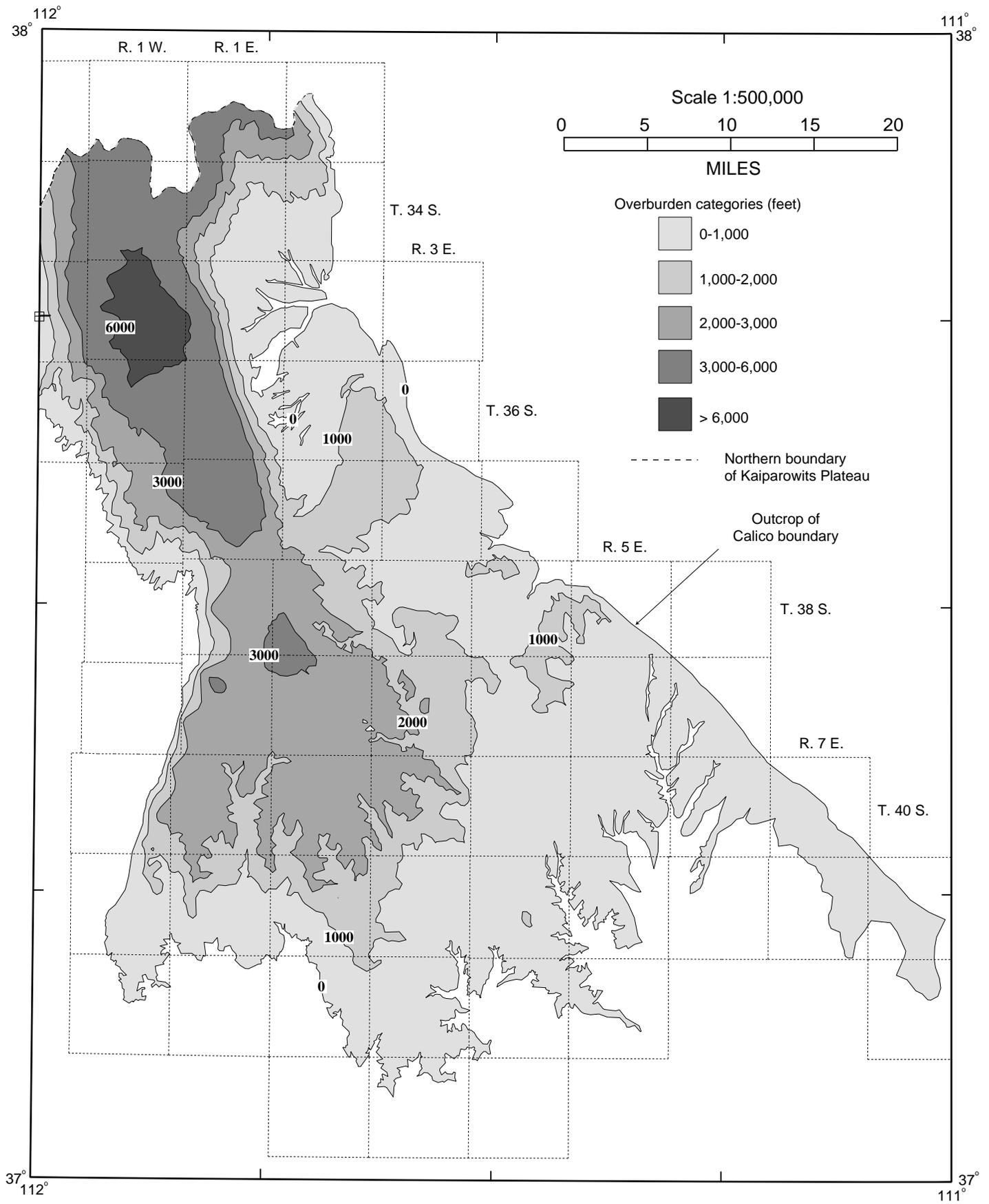


Figure 15. -- Overburden on the Calico sequence boundary. Thickness categories show range of maximum overburden above coal in the Calico and A-sequences.

thickness. In order to better understand the distribution of these coal beds, we have constructed a series of isopach maps that show net coal in bed thickness categories of 1.0-2.4, 2.5-3.4, 3.5-7.4, 7.5-14.0, 14.1-20.0, and greater than 20.0 feet (figs. 16A-21A), respectively. The number of coal beds within each thickness category is shown in figures 16B-21B, respectively. Each isopach map has been constructed using coal data listed in appendix 1. The estimated coal resource in each thickness category is listed in table 7. However, the sum of coal tonnages from each individual thickness category in table 7 is only 55 billion tons, about 12 percent less than the 62 billion short tons reported in table 6 for the original coal resource. This discrepancy appears because the area mapped for each coal thickness category is slightly underestimated, because an artificial value of “zero” was assigned to data points that lack coal within the specified bed thickness category. The discrepancy is relatively minor, and the isopach maps and reported tonnages in each category provide a reasonable estimation of coal distribution by bed thickness.

Coal beds less than 3.4 feet thick are widely distributed across the entire resource area. As many as 22 coal beds range from 1 to 2.5 feet in thickness and have a maximum net accumulation of 30 feet (fig. 15A, B). As many as nine coal beds range from 2.5 to 3.4 feet in thickness, and the maximum net accumulation in this category is 27 feet (fig. 17A, B). Approximately 11 billion short tons of coal are in beds that range from 1 to 3.4 feet in thickness (table 7).

Coal beds between 3.5 and 4.1 feet in thickness are also distributed widely throughout the plateau, but they occupy a slightly smaller area than do coals in the thinner categories. As many as nine beds of coal range from 3.5 to 7.4 feet in thickness, and these beds have a maximum net accumulation of 65 feet (fig. 18A, B). As many as seven beds of coal are 7.4-14.1 feet thick, and these beds have a maximum net accumulation of 66 feet (fig. 19A, B). Approximately 28 billion short tons of coal are in beds that range from 3.5 to 14.1 feet in thickness (table 7).

Coal beds greater than 14.1 feet thick occupy an elongated area situated in the central region of the Kaiparowits Plateau (figs. 20A, 21B). The elongated area is about 20 miles wide in the northern part of the plateau and narrows to about 10 miles wide in the plateau’s southern areas. As many as four coal beds range from 14.1 to 20.0 feet in thickness and have a maximum net accumulation of 71 feet (fig.

Table 7. Estimated coal tonnages (in billions of short tons) in beds ranging from 1-2.4, 2.5-3.4, 3.5-7.4, 7.5-14.0, 14.1-20.0, and greater than 20.0 feet in thickness within the Calico and A-sequences, Kaiparowits Plateau, Utah. Thickness categories used here are standard for estimating resources of bituminous coal (Wood and others, 1983). Tonnage estimates are calculated using an average density of 1800 short tons per acre-foot for coal and represent all areas of the plateau where the entire coal-bearing section is preserved.

Coal bed thickness in feet	Estimated tonnage (in billions of short tons)
1-2.4	7
2.5-3.4	4
3.5-7.4	15
7.5-14.0	13
14.1-20.0	8
> 20.0	8

20A, B). Coal beds greater than 20.0 feet thick occupy an area along the northern part of the plateau as well as several areas that are 2-17 miles long and 3-9 miles wide in the central regions of the plateau (fig. 21A). As many as three beds of coal are greater than 20.0 feet thick, and as much as 59 feet of coal is contained in 1 bed (fig. 21A, B). Approximately 16 billion short tons of coal are in beds that range from 14.1 to 59 feet in thickness (table 7). However, current longwall mining technology can economically extract no more than 14 feet of coal from beds of any thickness (Timothy J. Rohrbacher, U.S. Geological Survey, oral commun., 1996). Therefore, only about 5 billion short tons of coal are actually available for mining from these thicker beds. This 5 billion ton figure does not account for any restriction to mining other than bed thickness and is determined by treating each mapped bed shown in figures 20B and 21B as if it was only 14 feet thick.

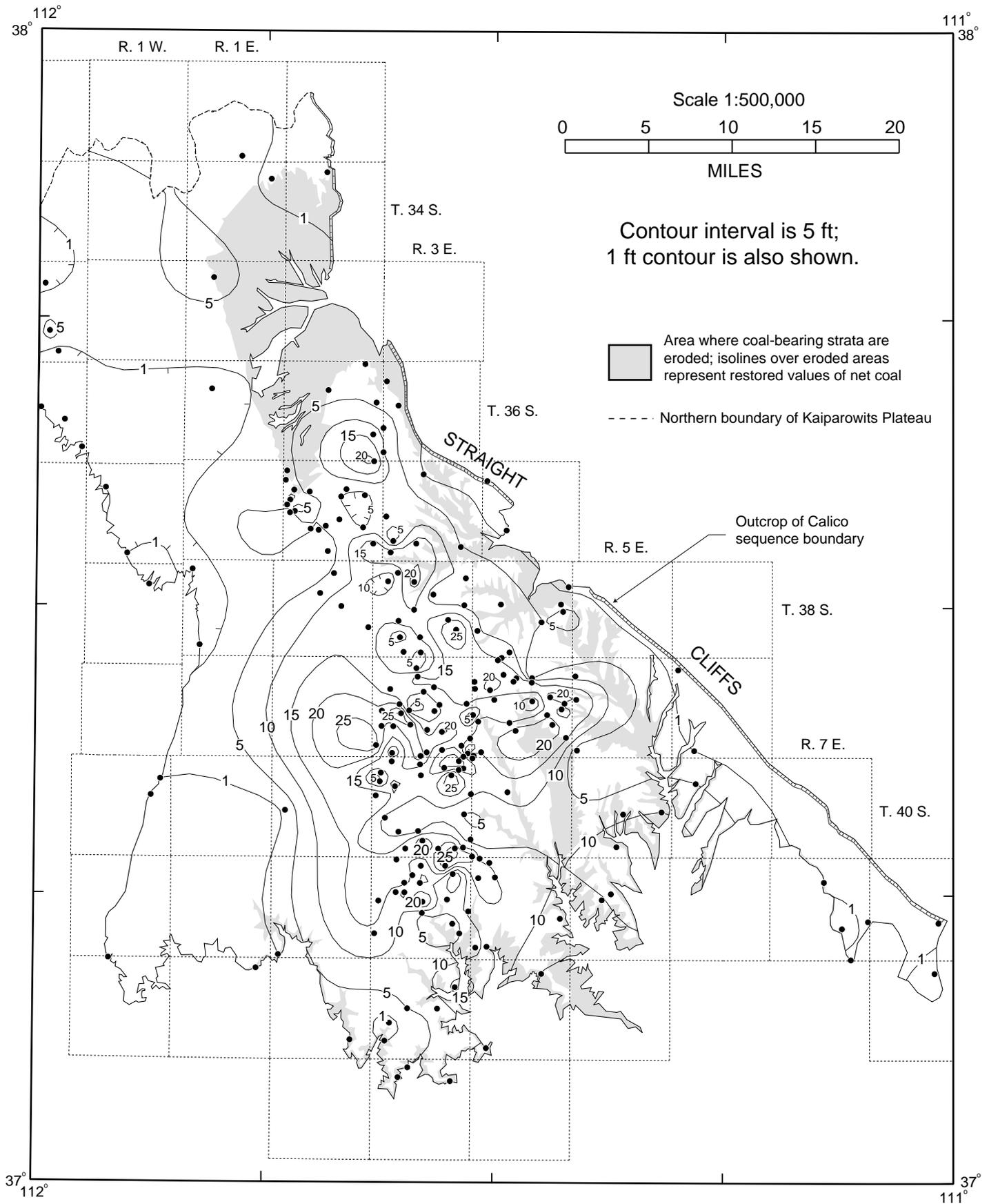


Figure 16A. -- Distribution of 1.0-2.4 foot thick coal beds in the Calico and A-sequences. Isopach map showing net coal in beds 1.0-2.4 feet thick.

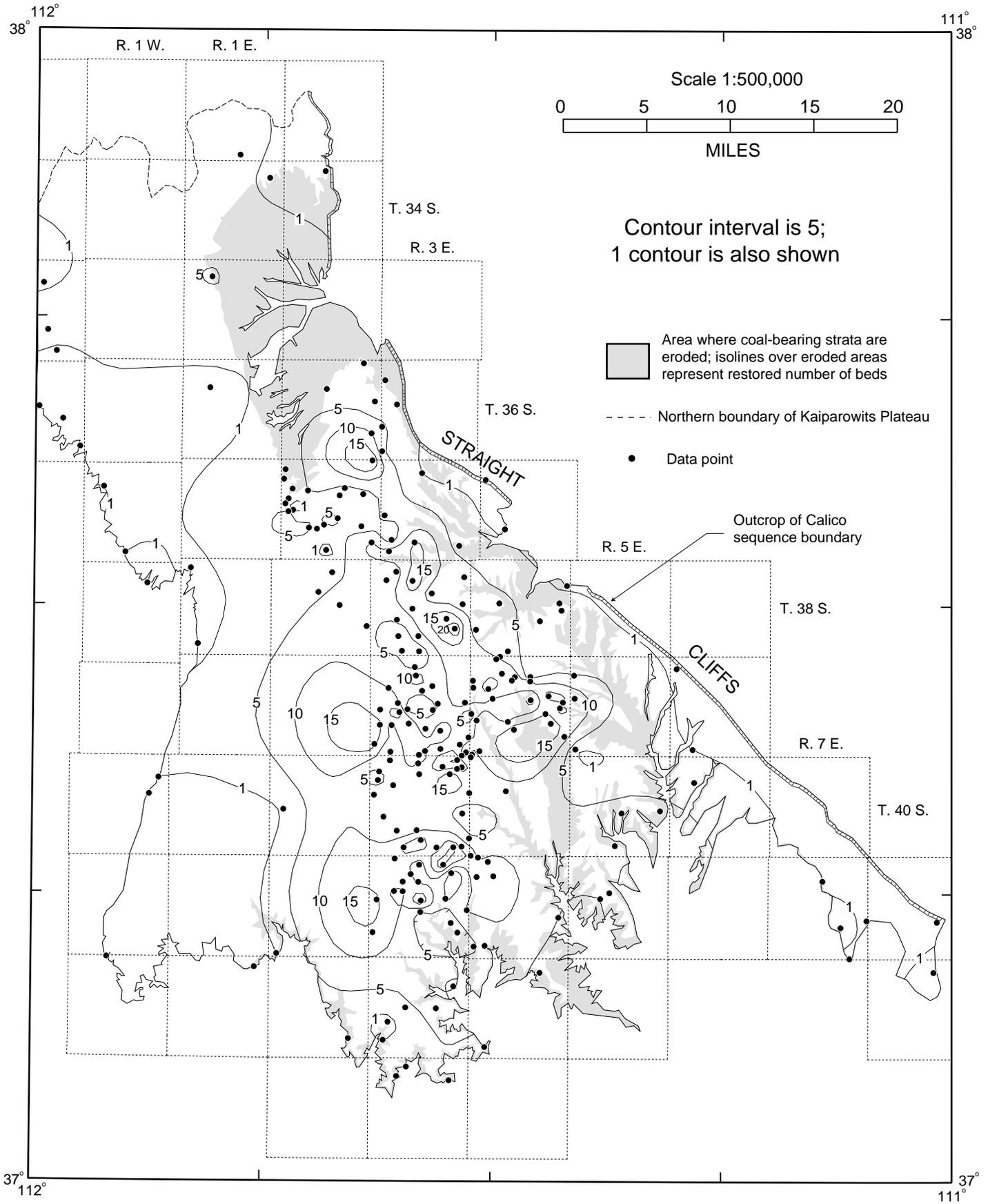


Figure 16B. -- Distribution of 1.0-2.4 foot thick coal beds in the Calico and A-sequences. Isopleth map showing the number of coal beds that are 1.0-2.4 feet thick.

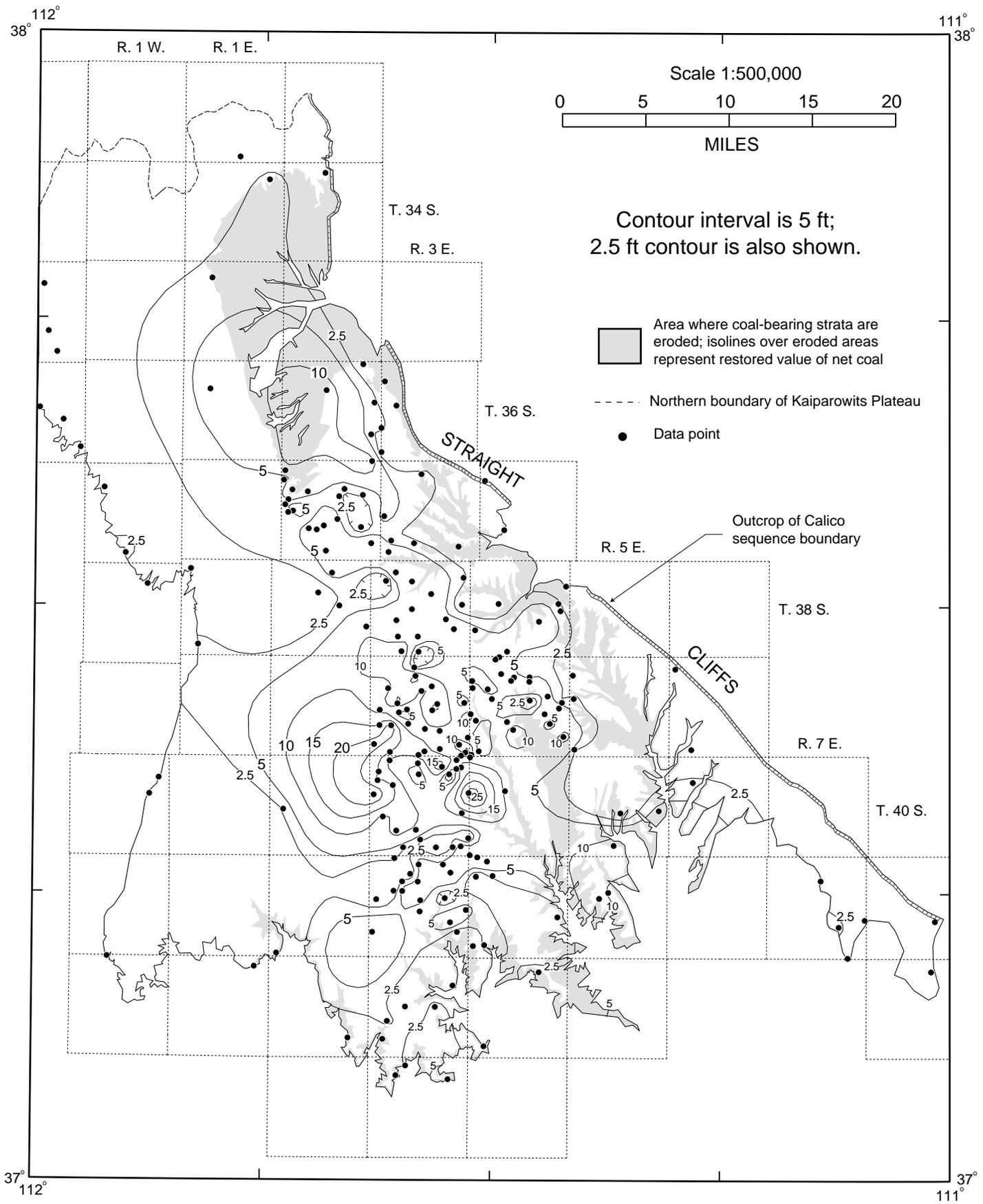


Figure 17A. -- Distribution of 2.5-3.4 foot thick coal beds in the Calico and A-sequences. Isopach map showing net coal in beds 2.5-3.4 feet thick.

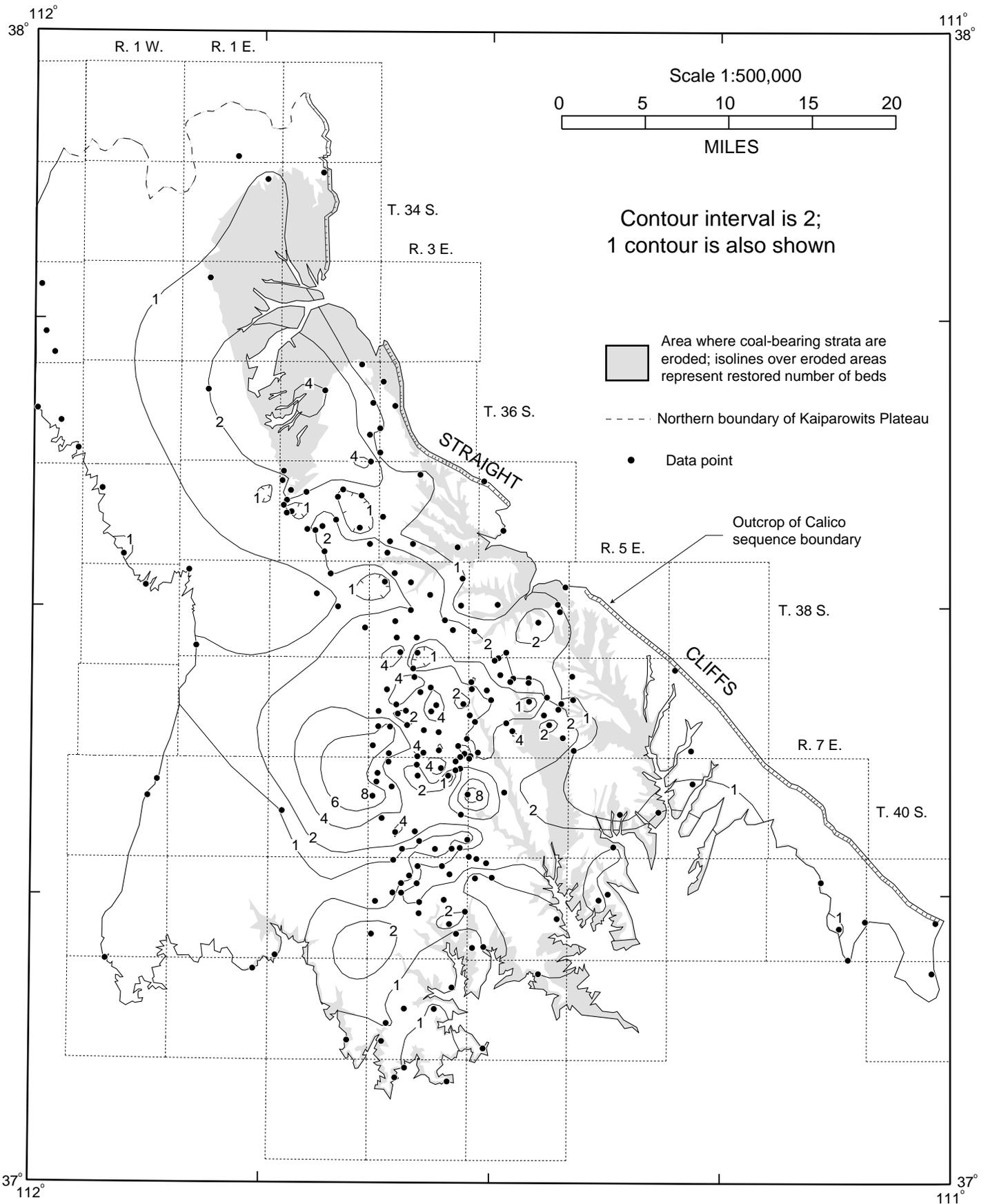


Figure 17B. -- Distribution of 2.5-3.4 foot thick coal beds in the Calico and A-sequences. Isopleth map showing the number of coal beds that are 2.5-3.4 feet thick.

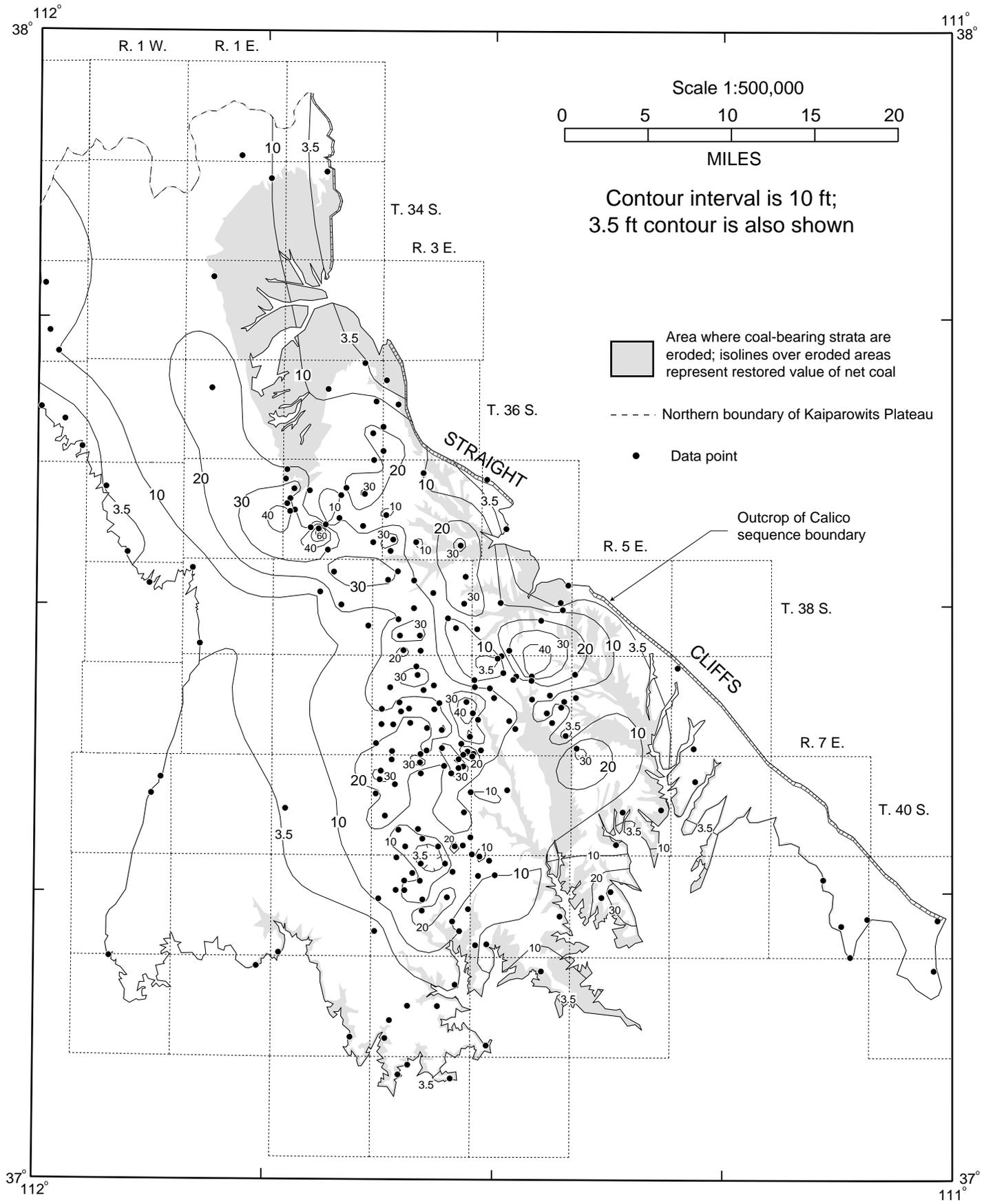


Figure 18A. -- Distribution of 3.5-7.4 foot thick coal beds in the Calico and A-sequences. Isopach map showing net coal in beds 3.5-7.4 feet thick.

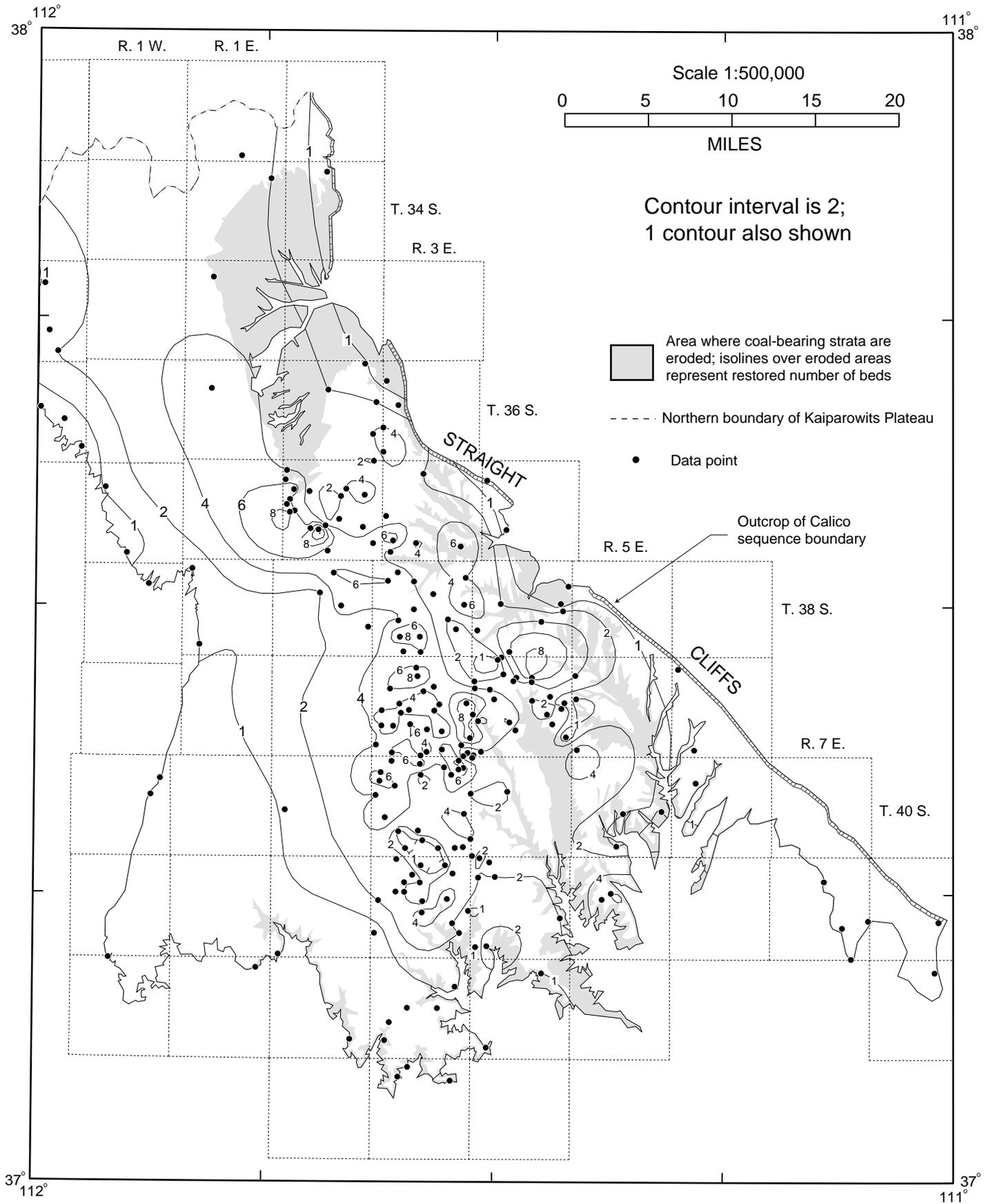


Figure 18B. -- Distribution of 3.5-7.4 foot thick coal beds in the Calico and A-sequences. Isopleth map showing the number of coal beds that are 3.5-7.4 feet thick.

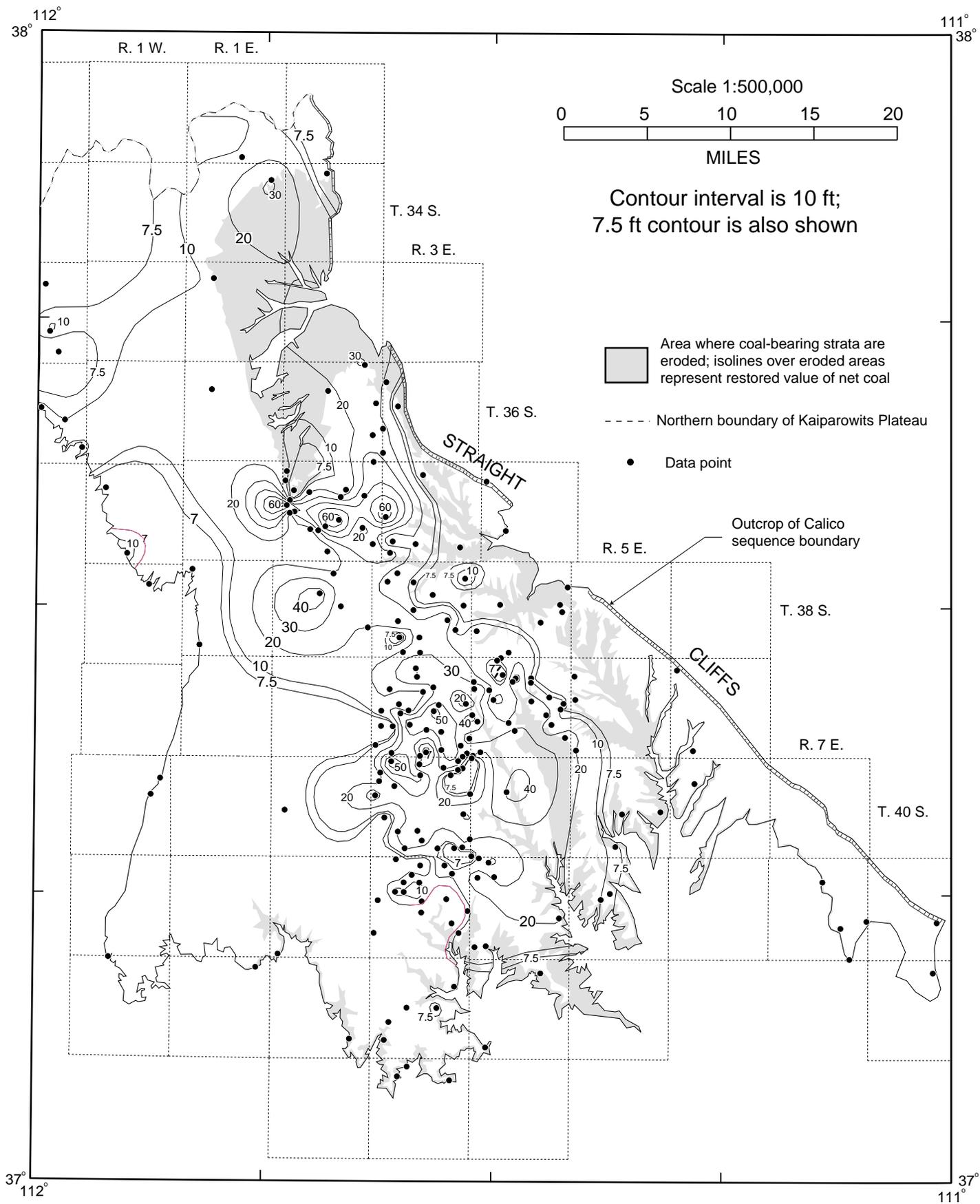


Figure 19A. -- Distribution of 7.5-14.0 foot thick coal beds in the Calico and A-sequences. Isopach map showing net coal in beds 7.5-14.0 feet thick.

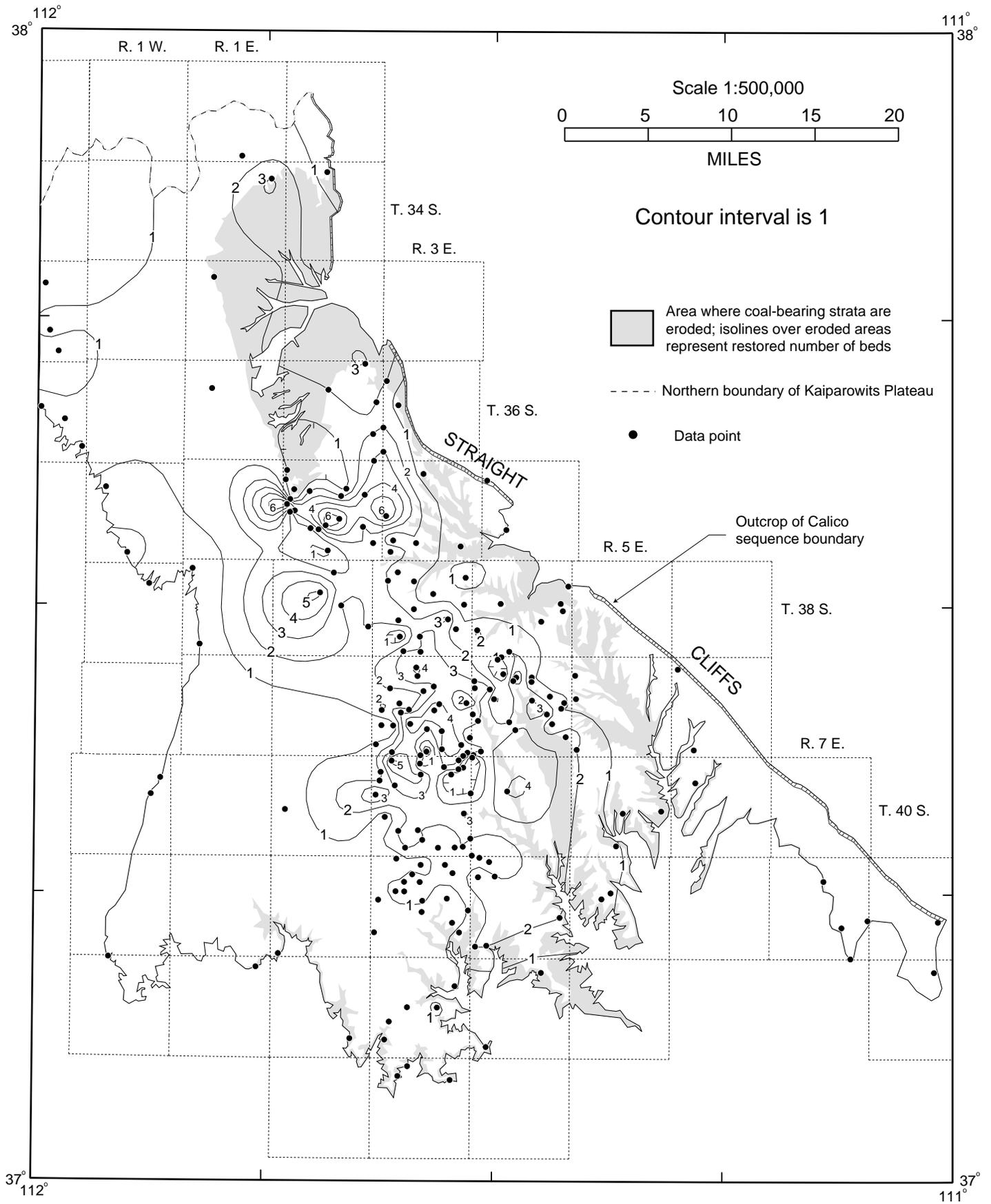


Figure 19B. -- Distribution of 7.5-14.0 foot thick coal beds in the Calico and A-sequences. Isopleth map showing the number of coal beds that are 7.5-14.0 feet thick.

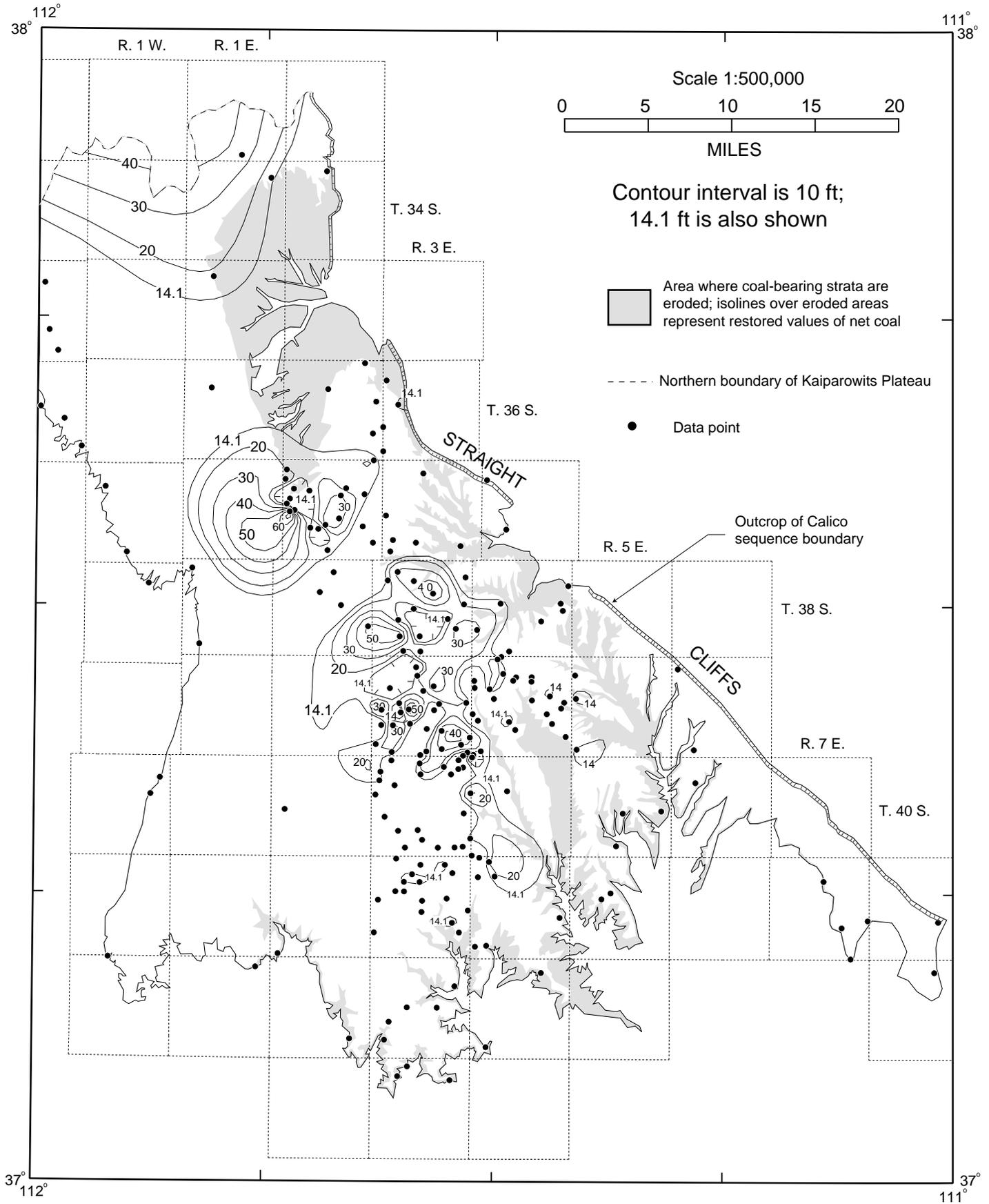


Figure 20A. -- Distribution of 14.1-20.0 foot thick coal beds in the Calico and A-sequences. Isopach map showing net coal in beds 14.1-20.0 feet thick.

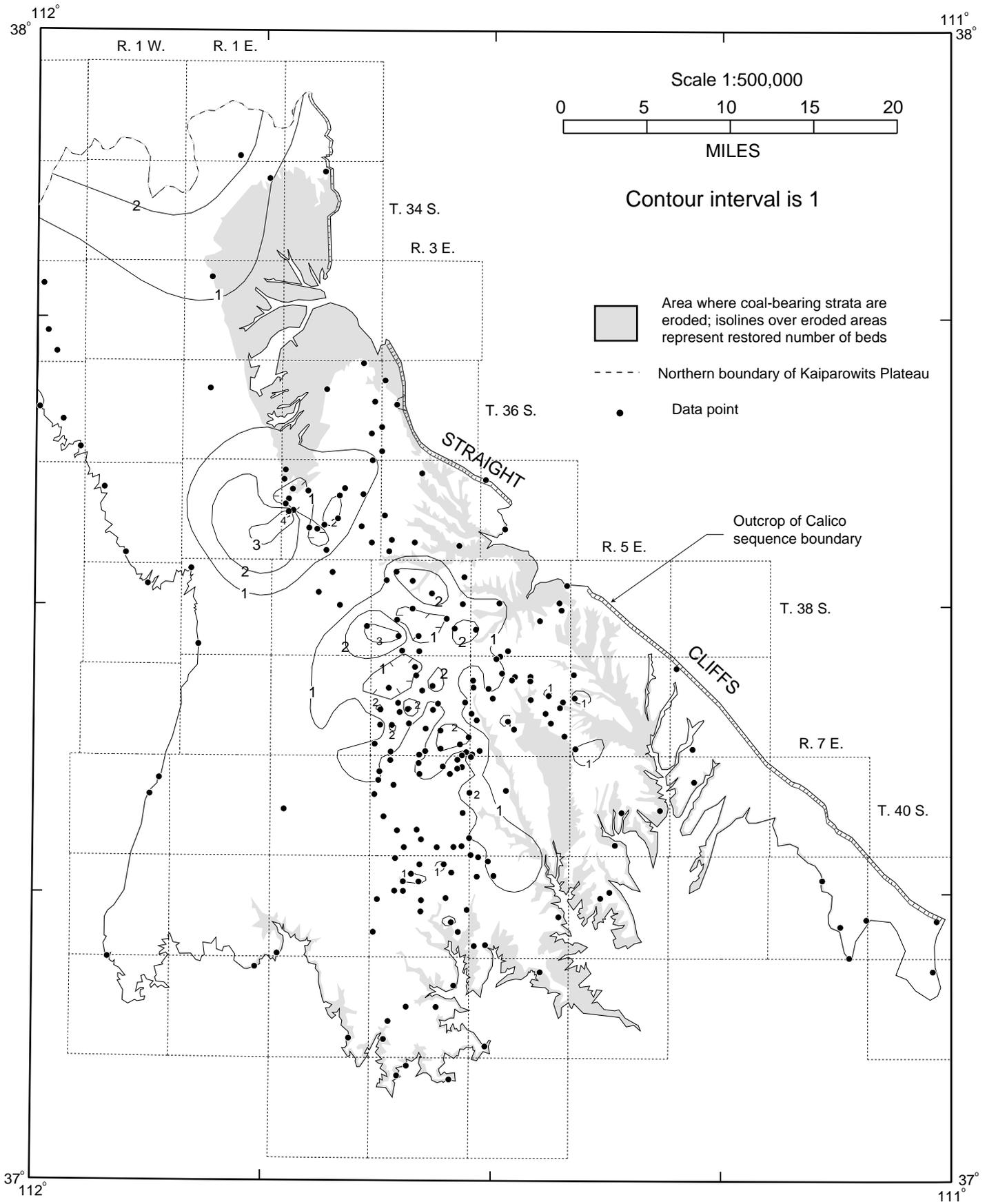


Figure 20B. -- Distribution of 14.1-20.0 foot thick coal beds in the Calico and A-sequences. Isopleth map showing the number of coal beds that are 14.1-20.0 feet thick.

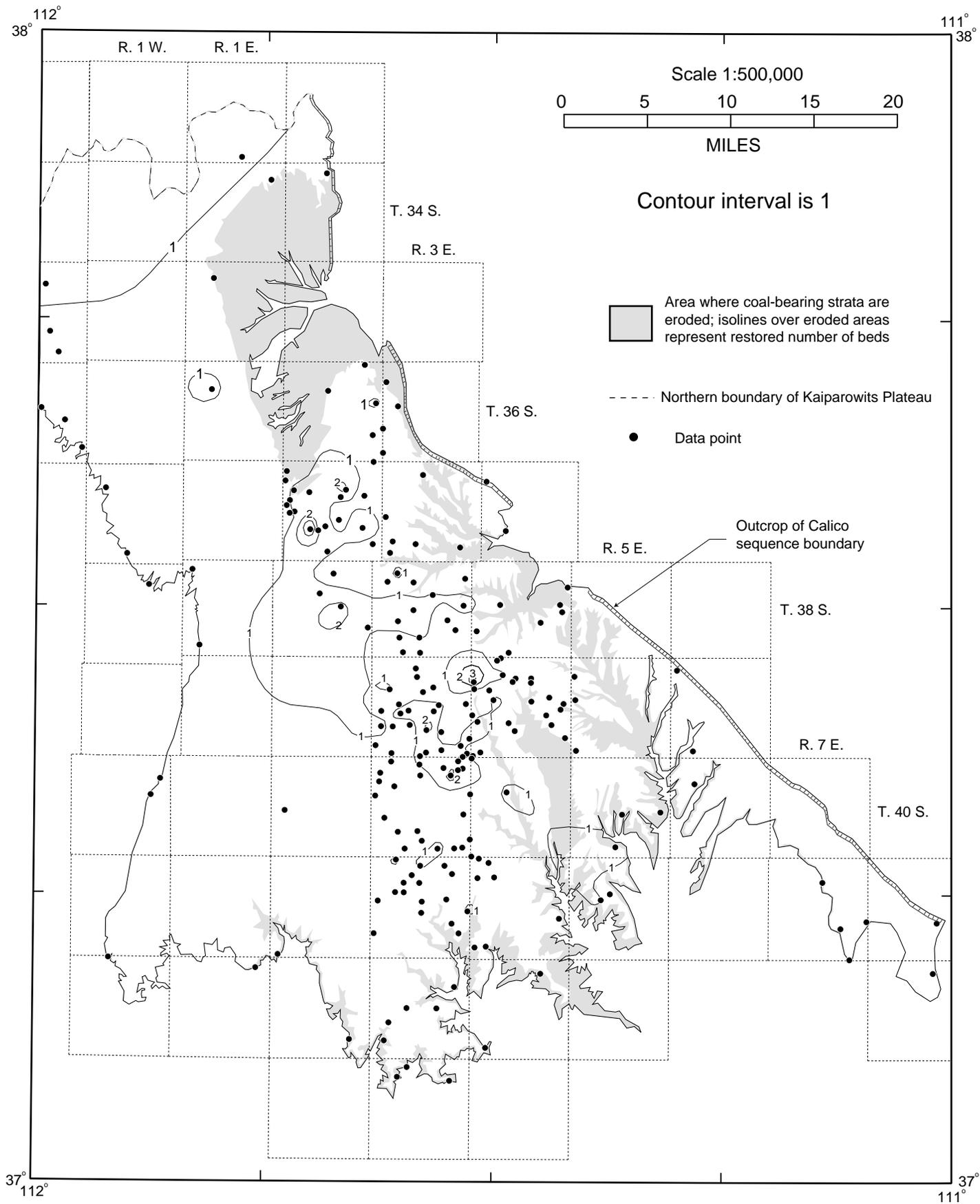


Figure 21B. -- Distribution of coal beds that are greater than 20.0 feet thick in the Calico and A-sequences. Isopleth map showing the number of coal beds that are greater than 20.0 feet thick.

Dip of strata

Based on studies conducted by the former U.S. Bureau of Mines between 1985 and 1993, underground mining is most efficient in areas where strata are inclined by less than 6°; underground mining is difficult where strata are inclined between 6° and 12° and it is not feasible where strata are inclined more than 12° (Timothy J. Rohrbacher, U.S. Geological Survey, oral commun., 1996). Inclinations of strata are shown in figure 9 for ranges of 0° to 6°, 6° to 12°, 12° to 25°, and greater than 25°. Coal resources within each category of inclination are calculated by integrating the dip-of-strata map (fig. 9) with the net coal isopach map (fig. 11). Approximately 49.8 billion short tons of coal are contained in strata that are inclined by less than 6°, 5.6 billion short tons are in strata that dip between 6° and 12°, and 6.9 billion short tons of coal are in strata that dip more than 12°. These tonnages comprise 80, 9, and 11 percent of the original resource, respectively.

COAL RESOURCE SUMMARY

Although the Calico and A-sequences contain an original coal resource of 62.3 billion short tons, this large resource figure must be regarded with caution, because it does not reflect economic, land-use, environmental, technological, and geologic restrictions that may affect its availability and recoverability. Peterson (1969a) estimated that only 10 percent of the coal in the Kaiparowits Plateau could be recovered with the technology of that time. Similar estimates for the Appalachian coal region (Rohrbacher and others, 1994) also indicate that less than 10 percent of an original coal resource can be mined and marketed at a profit.

Land-use and environmental considerations that may affect the economics or availability of coal in the Kaiparowits Plateau include the impact of mining and coal utilization on air and water quality in nearby National Parks and Recreational Areas, regional populations, grazing, and land subsidence above mined areas (Sargent, 1984). These issues may be significant; in 1976, several companies dropped their plans to construct a coal-burning power plant in the region due to Government actions and pending lawsuits over environmental issues (U.S. Bureau of Land Management, 1976; Sargent, 1984).

At least 32 billion short tons of coal are not likely to be mined in the foreseeable future because of geologic and technological restrictions that included overburden, dip of strata, and coal bed thickness. Physical and economic constraints generally limit current longwall and continuous mining to depths of less than 3,000 feet, to strata that are inclined by less than 12°, and to coal beds that are more than 3 feet thick; additionally, only 14 feet of coal can be mined from beds of any thickness (Timothy J. Rohrbacher, U.S. Geological Survey, oral commun., 1996). These overburden and bed thickness limits are supported by a summary given for 81 current longwalls operated in the United States by 30 companies (Merritt and Fiscor, 1995, p. 32-38). Approximately 18 billion short tons of coal are not likely to be mined because they are in areas where overburden is greater than 3,000 feet or where strata are inclined by more than 12°. Coal tonnages in these areas are calculated by integrating the dip of strata, net coal isopach, and overburden maps (figs. 9, 11, 15, respectively). An estimated additional 14 billion short tons of coal are not likely to be mined from the remaining areas of the Kaiparowits Plateau because they are in beds that are less than 3.4 feet thick (11 billion tons) or cannot be extracted from beds that are more than 14 feet thick (3 billion tons). These coal tonnages are determined by integrating the overburden and dip-of-strata maps with resources determined from coal isopach maps (figs. 16A, 17A) and bed maps (figs. 20B, 21B).

Approximately 30 billion short tons of coal are in areas of the Kaiparowits Plateau where geologic conditions are more favorable for current underground mining technology (fig. 22). These beds of coal are in areas where overburden is less than 3,000 feet thick and strata dip less than 12°. The coal tonnage is estimated for all beds of coal that are more than 3.5 feet thick, and coal tonnages in beds that are thicker than 14 feet thick are calculated as if they are only 14 feet thick. These coal tonnages do not reflect potential land-use or environmental restrictions, nor do they account for additional coal that cannot be mined due to the discontinuity of coal beds, coal that may be destroyed by the mining of adjacent strata, or coal that must be left in the ground for roof support.

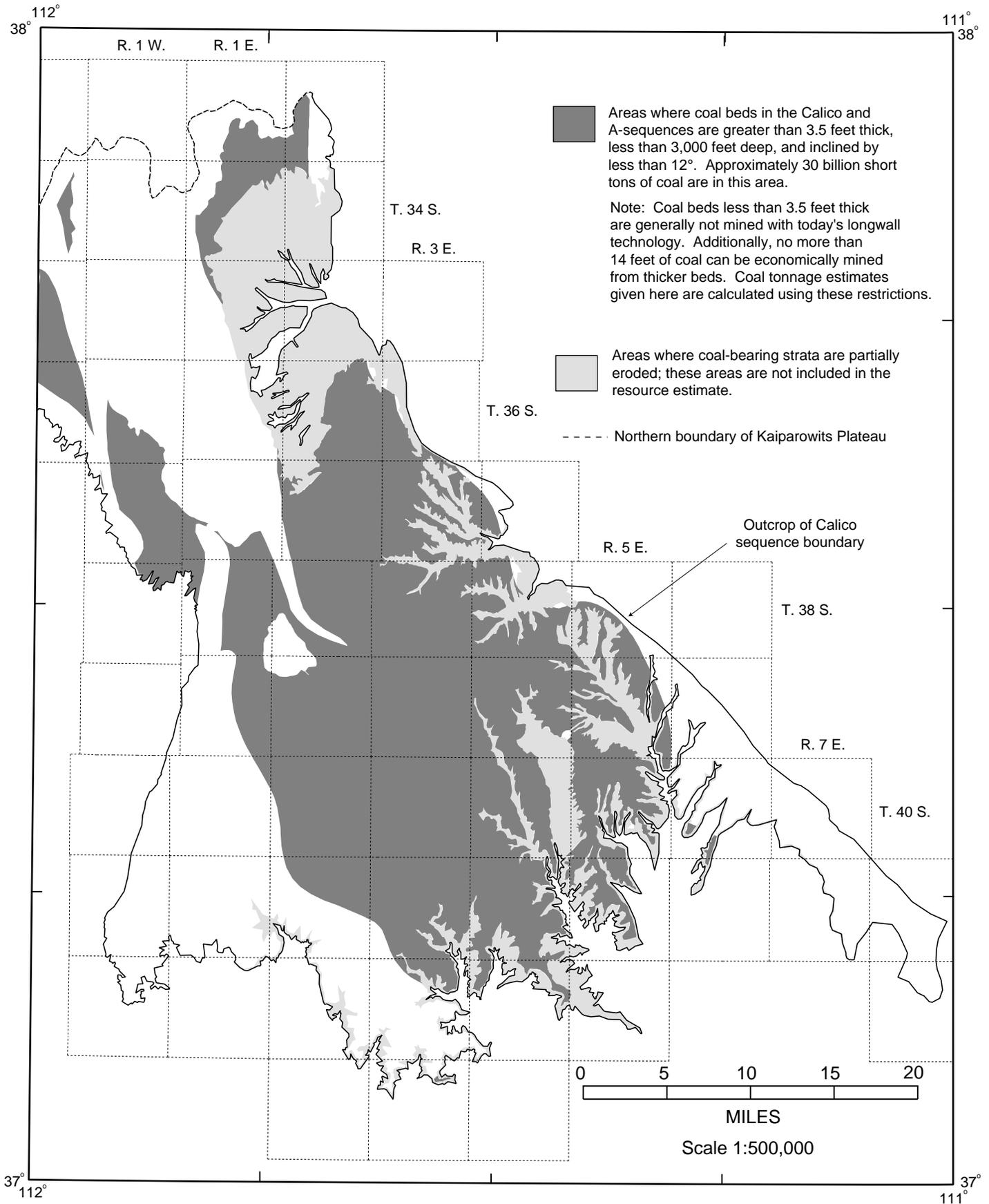


Figure 22. -- Map of the Kaiparowits Plateau showing areas (dark gray stipple) where coal beds are: 1) greater than 3.5 feet thick, 2) under less than 3,000 feet of overburden, and 3) inclined by less than 12° of dip. Areas where coal-bearing strata are partially eroded (light gray stipple) are not addressed in this investigation.

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