REGIONAL GEOLOGIC SETTING

The Williams Fork Mountains are at the extreme southeastern end of the Sand Wash basin, one of several basins within Colorado that contain Cretaceous rocks. The Sand Wash basin is bordered on the east by the Park Range and on the south and west by the White River uplift and the Axial anticline (fig. 7).

Depositional History

Rocks of the Cretaceous lies and Williams Fork Formations constitute the Mesaverde Group. These rocks and the overlying Lewis Shale were deposited during a 5-million-year timespan that began approximately 70 million years ago (Berman and others, 1980). Marine and nonmarine deposition occurred during two major regressive-transgressive phases extensive enough to move the strandline through the area. The first regressive phase began with the strandline situated 25 mi west of Craig, trending northeast to southwest (fig. 8, line 1). The seas regressed eastward out of the study area, and local deposition occurred under nonmarine deltaic conditions. A subsequent transgression moved the strandline back through the area, until the strandline was 10 mi west of Craig (fig. 8, line 3). A second regression moved the strandline back to the east, again resulting in nonmarine conditions prevailing in the study area (fig. 8, line 4). A final westward transgression resulted in the return of marine conditions and moved the strandline west of Craig (fig. 8, line 5).

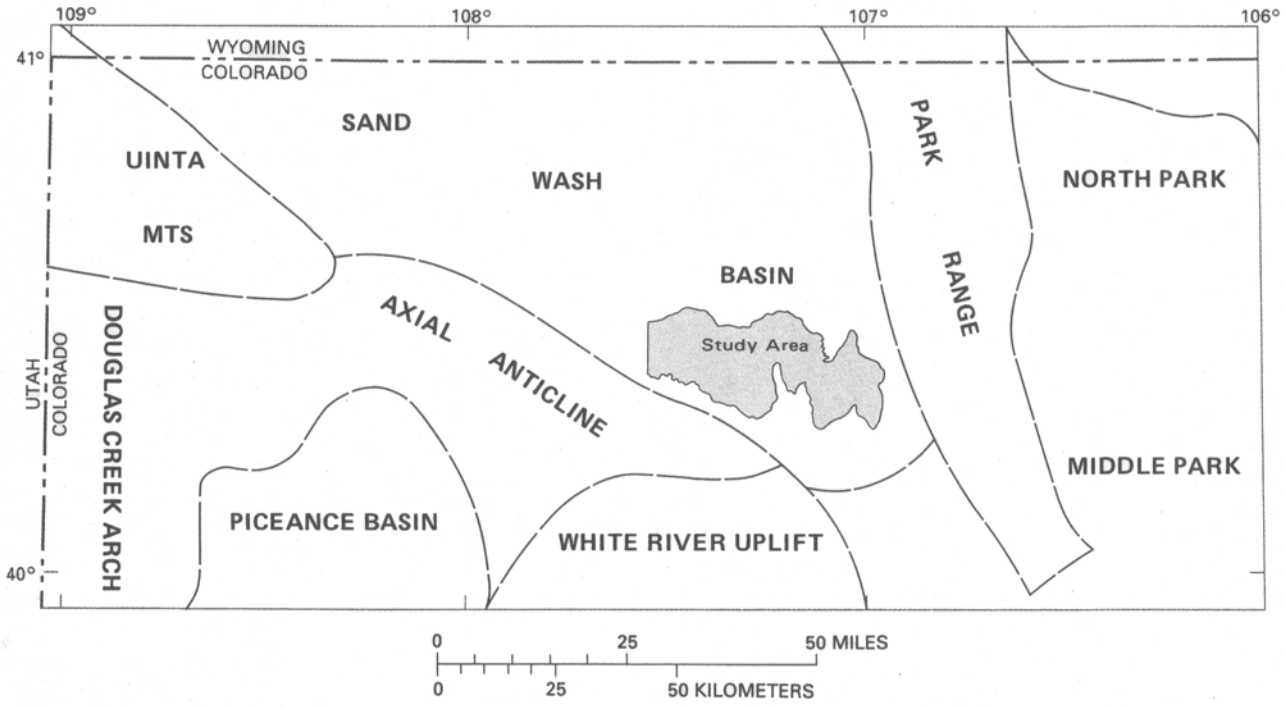

Figure 7.--Regional structural and physiographic setting.

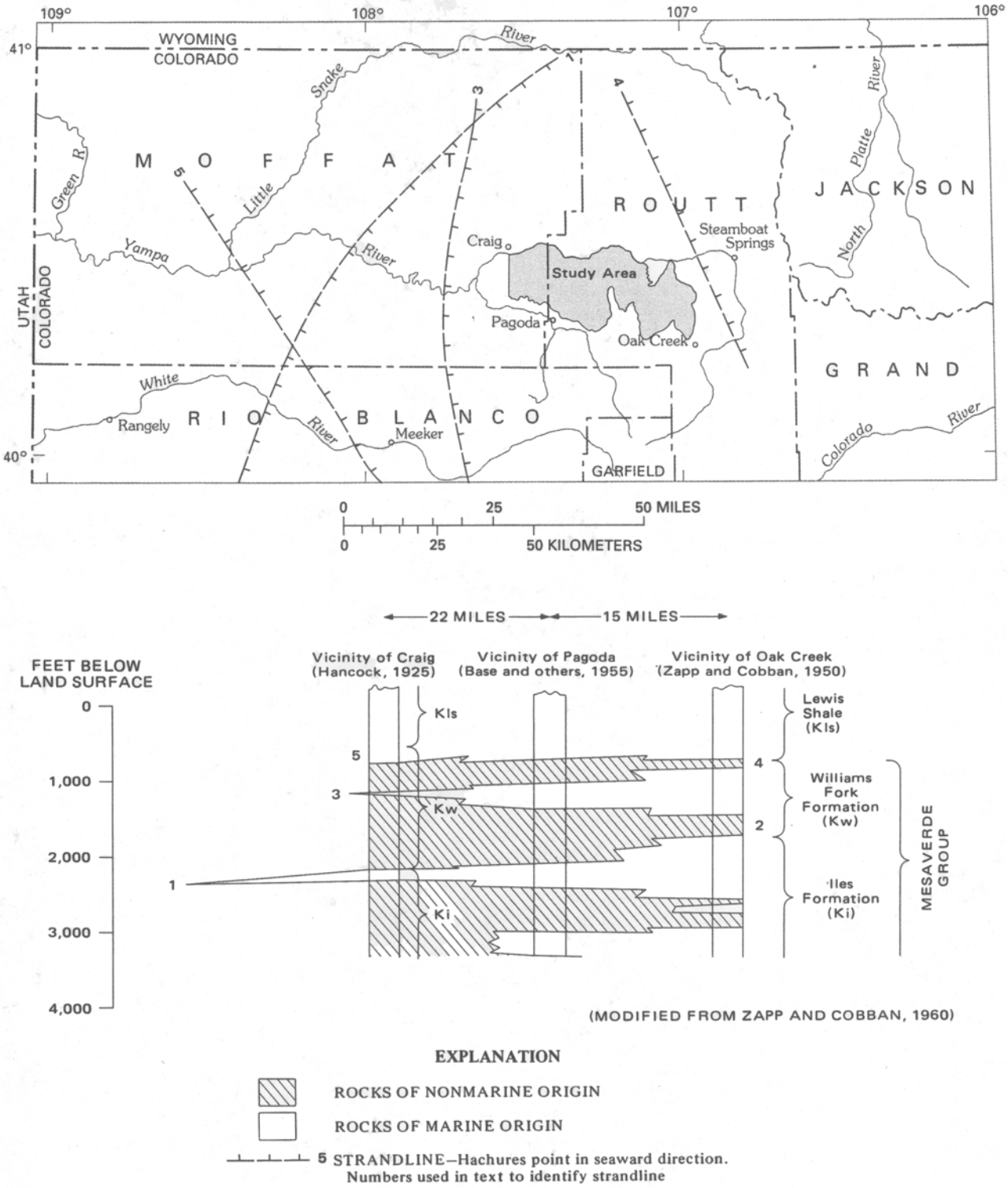

Figure 8.--Strandline boundaries for regressive and transgressive phases during deposition of study area formations.

The resulting stratigraphy has marine deposits that thicken toward the east and nonmarine deposits that thicken toward the west (fig. 8). The thick Trout Creek Sandstone Member of the Iles Formation and Twentymile Sandstone Member of the Williams Fork Formation were formed near the landward margins of the marine rocks at the regressive (upper) boundary of the marine sequence.

Stratigraphy

The multiple migrations of strandlines through the area resulted in stratigraphic relations that are complex and often poorly correlated. Sediments deposited during nonmarine conditions sometimes are of varied lithology, limited lateral continuity, and contain many facies changes. Also, numerous minor transgressive-regressive pulses during deposition produced local strand-line migrations superimposed on the larger phases. The deposits are classified into two thick beach sandstones (the Trout Creek Sandstone Member of the Iles Formation and the Twentymile Sandstone Member of the Williams Fork Formation), three thick marine shales (those underlying the Trout Creek and Twenty-mile Sandstone Members, and the Lewis Shale), and several intervening sections that contain marine and nonmarine rock.

Iles Formation

Trout Creek Sandstone Member

The Trout Creek Sandstone Member is the upper part of the Iles Formation (pl. 1) and is the basal unit studied in this work (fig. 9). Type locality for the Trout Creek Sandstone Member is in the northeastern part of Twentymile Park along Trout Creek (Fenneman and Gale, 1906, p. 26). The unit thickness is fairly consistent, and this bed is considered the most reliable marker bed within the area (Bass and others, 1955, p. 155). The Trout Creek conformably overlies marine shales of the main body of the Iles Formation. The upper contact of the Trout Creek is conformable and very distinct and is the boundary between the Iles and Williams Fork Formations.

The Trout Creek Sandstone Member consists of massive, white to light-gray, moderately well-sorted, fine- to very fine-grained quartz arenite. The sandstone consists of about 90 percent subangular quartz and 10 percent black subangular chert. Individual sandstone grains are undeformed and have tangential grain-to-grain contacts, which indicates that little or no compaction has occurred. The few sedimentary structures present include trough cross-bedding and planar laminations Ryer, 1977). Widely spaced fractures were present in some outcrops. Silica cementation normally is present but varies in amount at different locations. As a result, samples range from friable to well indurated; almost all surface samples are moderately to well indurated. Core samples generally are well indurated. Sandstone thicknesses reported in the literature seem to indicate a regional eastward thickening, from 75 ft at Pagoda (Konishi, 1959) to 132 ft in the vicinity of Oak Creek (Kucera, 1959); however, local variation in thickness is substantial. For example, the sandstone isolith map (fig. 10) indicates a sandstone thickness of less than 100 ft in the north-central part of Twentymile Park; thickness increases to 140 ft or

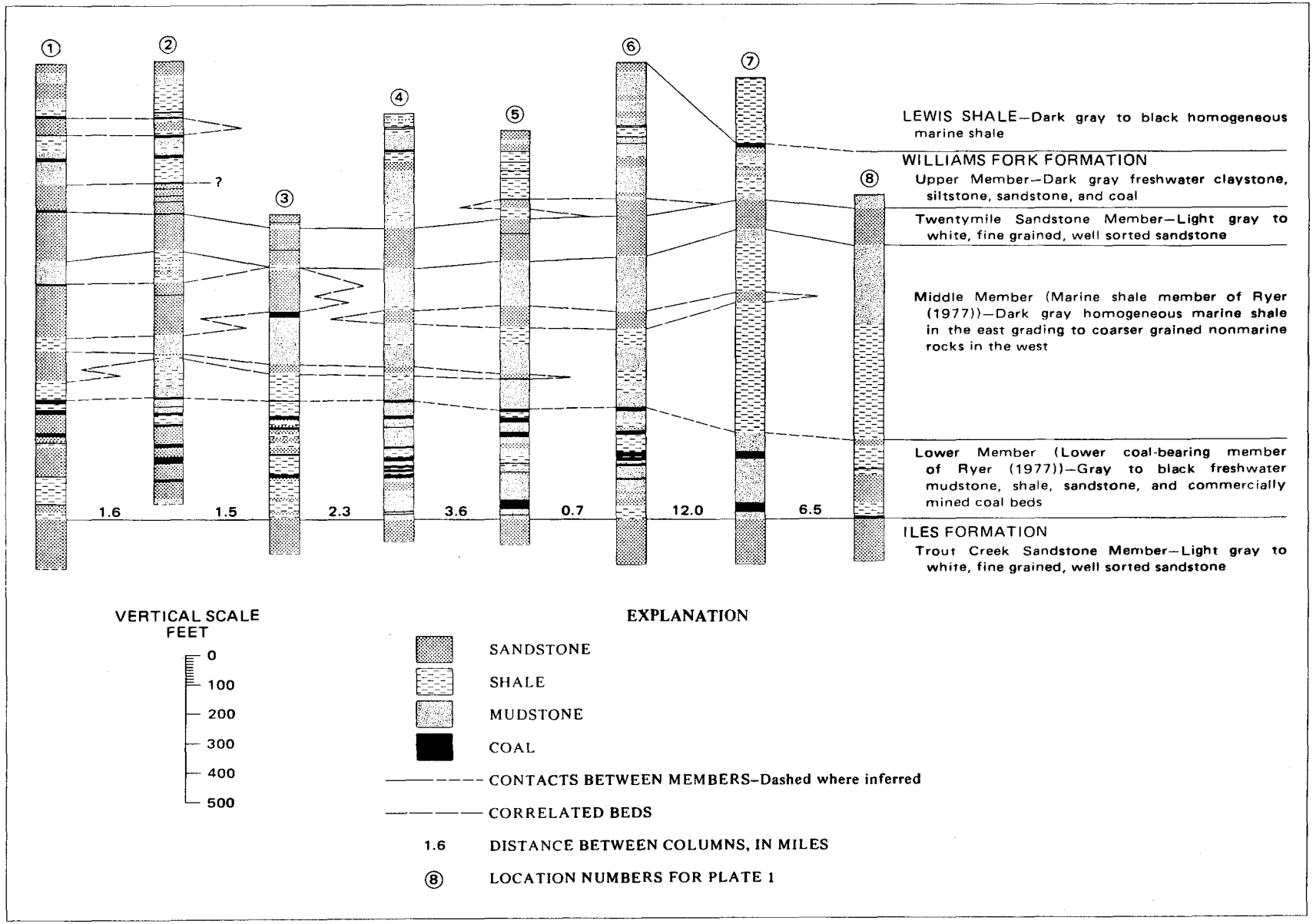

Figure 9.-- Composite stratigraphic columns.

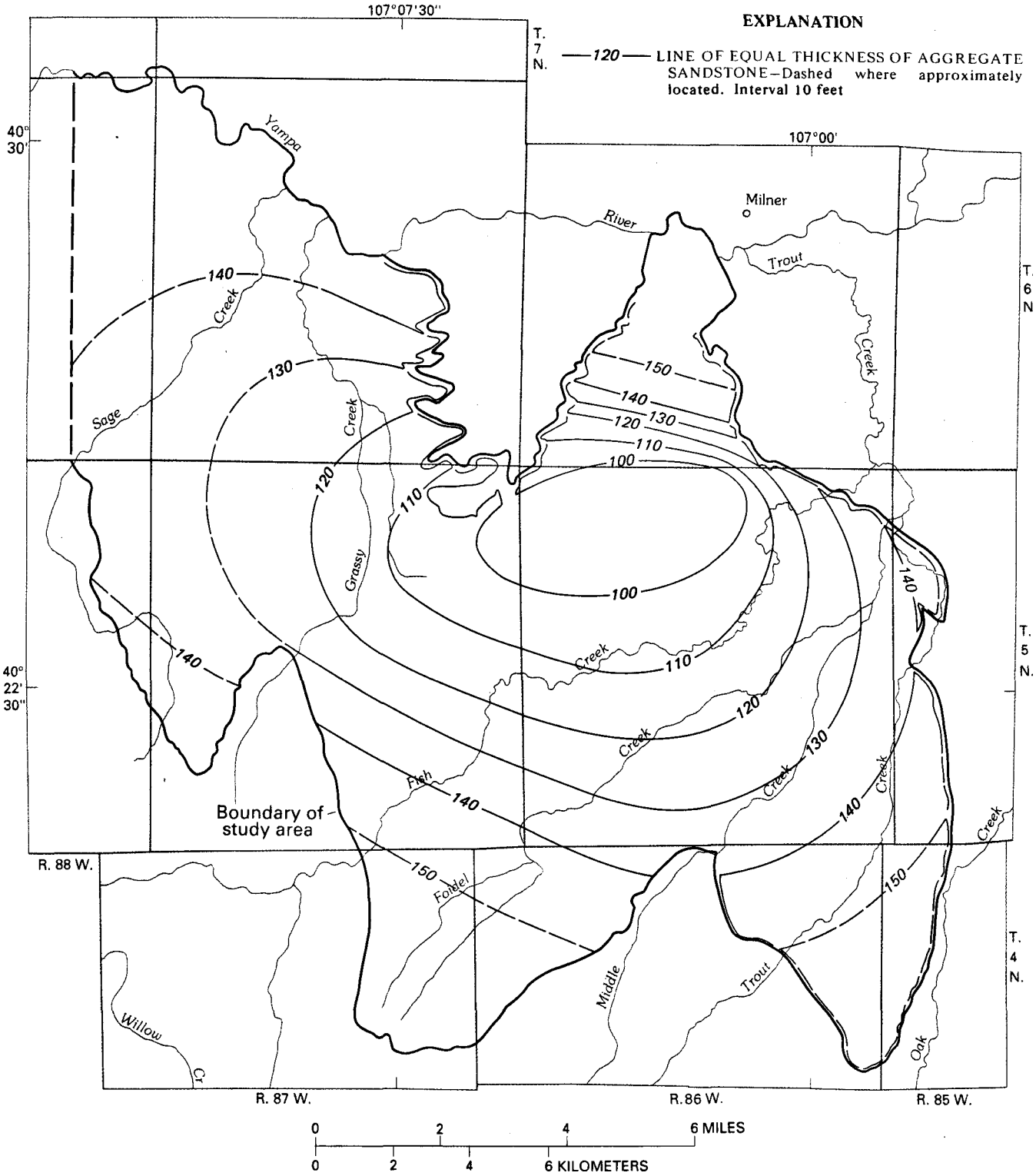

Figure 10.--Aggregate sandstone thickness of the Trout Creek Sandstone Member of the Iles Formation in the eastern part of the study area.

more near the northern and southern outcrops. Data are inadequate to map sandstone thickness in the western part of the study area, and the regional trend in thickness is uncertain.

Williams Fork Formation

Most of the rocks exposed in the study area are part of the Williams Fork Formation (pl. 1). Rocks of the Williams Fork Formation were first named by Hancock (1925). The upper and lower formational contacts are conformable. The lower contact, with the Iles Formation, is distinct and is easily identified by the relatively coarse grain size and presence of black chert in the underlying Trout Creek Sandstone Member (Ryer, 1977). The upper contact, with the Lewis Shale, is transitional; the criteria used by Bass and others (1955) for separating the two formations are unknown. The sediments underlying the contact are nonmarine; the Lewis Shale is marine. The transitional zone between the two is about 10 ft thick, defining a relatively narrow zone in which to place the actual contact. The thickness of the Williams Fork Formation ranges from 1,100 ft at Mount Harris to 2,000 ft at the western study area boundary (Bass and others, 1955, p. 157). The increase in thickness occurs at the top of the formation where the formation thickens and the Lewis Shale thins. The Williams Fork Formation in the study area originally was classified in three segments (Bass and others, 1955); however, the fourfold classification used by Ryer (1977) is more representative and is used here. The four segments are the lower coal-bearing member (hereinafter referred to as the lower member), the middle shale member (hereinafter referred to as the middle member), the Twentymile Sandstone Member, and the upper member (fig. 9).

Lower member

The lower member contains extensive reserves of bituminous coal (Bass and others, 1955). The lower boundary is the distinct contact between the underlying Trout Creek Sandstone Member of the Iles Formation, a beach deposit, and the finer grained deposits of the lower member (Ryer, 1977). In the eastern part of the study area, the upper contact is between the nonmarine sandstones and mudstones of this member and the overlying marine shales. In the western part of the study area, where the overlying marine shale is absent, the contact is arbitrarily set approximately 50 ft above the uppermost thick coal seam (fig. 9). The dominant lithologies are gray to black siltstones, silty, fine-grained sandstones, and limey shales interbedded with coal seams. Toward the west, the section becomes sandier and coalbeds tend to be thinner and more numerous. The thickness of this member ranges from 300 ft in the east to 450 ft in the west, primarily because of facies changes across the area. In the eastern part of the area, data enable mapping, and the total sandstone thickness in this member ranges from 100 to 200 ft, thickening to the west (fig. 11). Shale thickness ranges from 100 to 200 ft, thickening to the east (fig. 12).

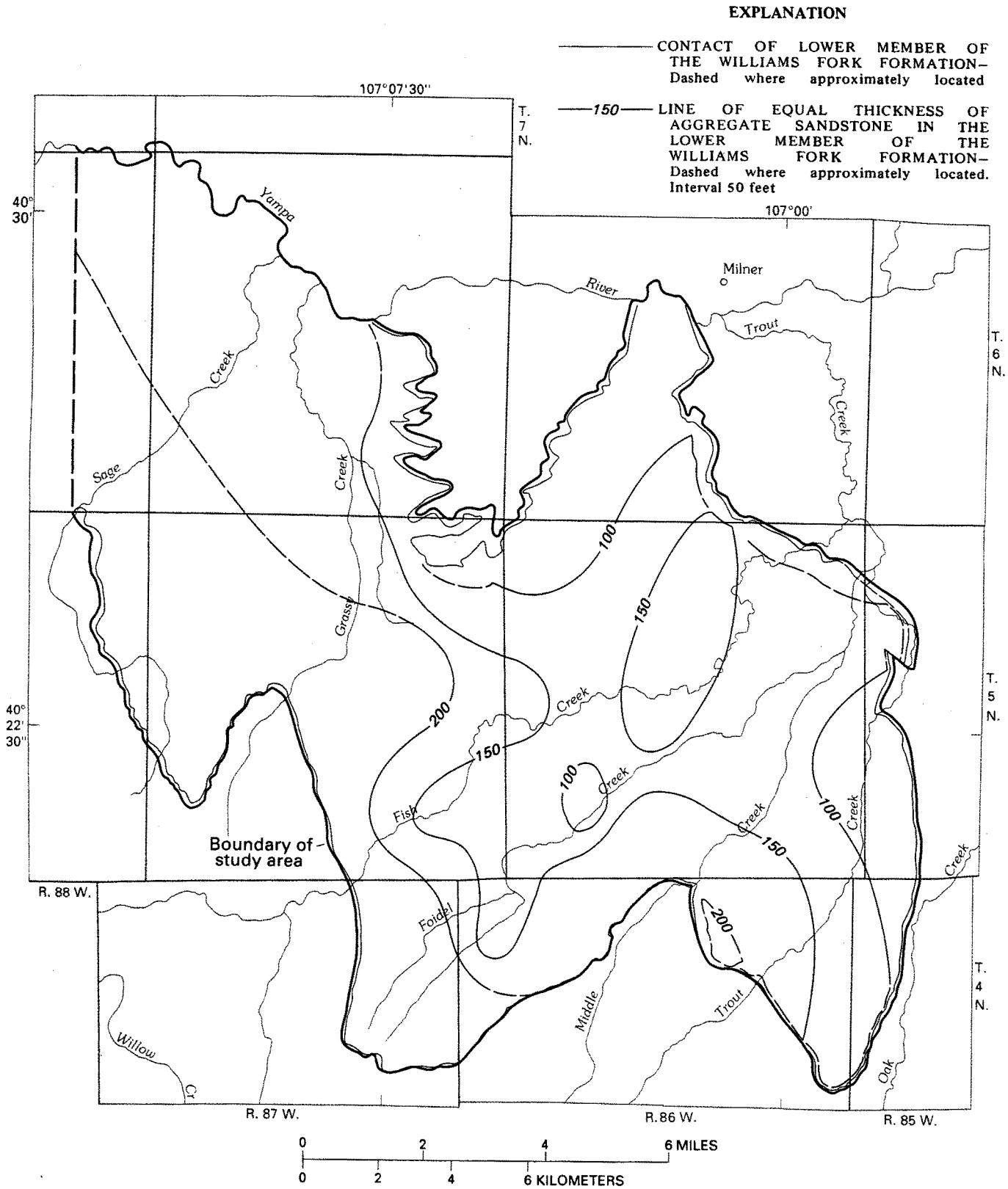

Figure 11.--Aggregate sandstone thickness of the lower member of the Williams Fork Formation in the eastern part of the study area.

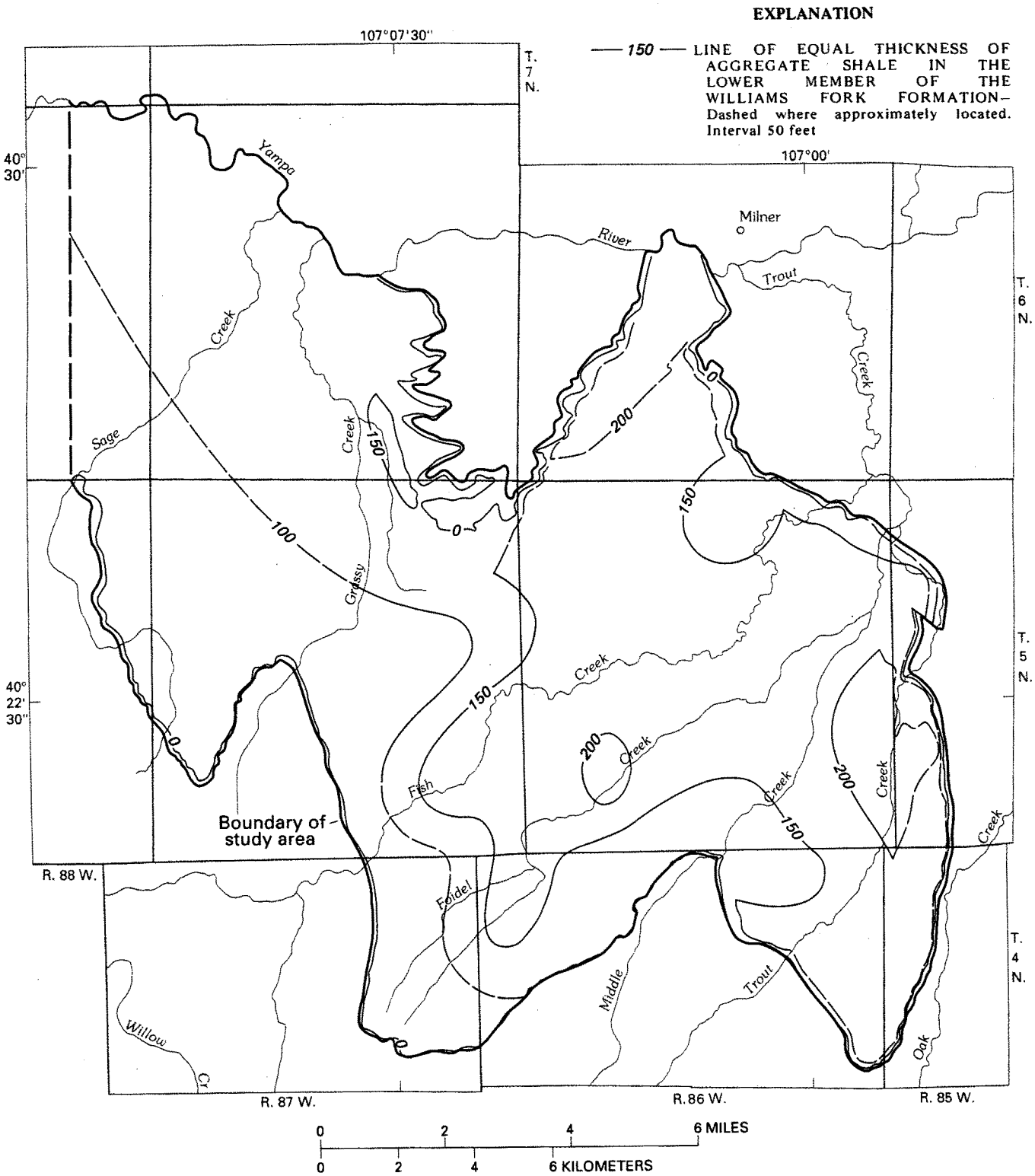

Figure 12.--Aggregate shale thickness of the lower member of the Williams Fork Formation in the eastern part of the study area.

Coal within this interval is mined extensively in the eastern part of the study area. Three seams—the Wolf Creek, the Wadge, and the Lennox—are extensive and continuous enough to have been named. The Wolf Creek coal is located 40 to 100 ft above the top of the Trout Creek Sandstone Member. This Seam ranges from 0 to 18 ft in thickness over short horizontal distances and is of poor quality because of shale stringers. The Wolf Creek seam currently is not extensively mined. The Wadge coal seam lies 230 ft above the Trout Creek. It is a clean, continuous coalbed that ranges in thickness from 6 to 14 ft. This is the major source of coal at the three large operating open-pit mines and the one large underground mine in the eastern part of the study area. The Lennox seam is about 60 ft above the Wadge seam. It is about 4 ft thick and has been eroded away throughout most of the uplifted margin of the eastern area.

West of Hayden Gulch, coal seams in this member are thinner, more numerous, and generally not accessible by strip mining. Much less is known about these coals; therefore, correlation of the Wolf Creek, Wadge, and Lennox coals is not well defined west of Hayden Gulch.

Middle member

The middle member of the Williams Fork Formation is defined by the underlying contact with the lower member and an upper transitional, conformable contact with the overlying Twentymile Sandstone Member. Lithology of the middle member varies from marine shale in the eastern part of the study area to nonmarine gray siltstone, silty sandstone, and brown sandstone in the western part of the study area. There are few coal seams in this interval, and those present generally occur in the middle of the member in the far western part of the study area. Several sandstones 30 to 100 ft thick are present in the western part of the area. Thickness of this member ranges from 600 ft in the east to 450 ft in the west, primarily because of a facies change and stratigraphic climbing of the overlying Twentymile Sandstone Member. The middle member generally is 500 to 600 ft thick in the eastern part of the area (fig. 13). Outcrops of marine shale generally are less resistant than the outcrops of sandstone in the overlying and underlying units; the shales generally erode to form broad, gently sloping landforms. Shale thickness increases gradually across such outcrops.

Twentymile Sandstone Member

The Twentymile Sandstone Member, first named by Fenneman and Gale (1906), is very similar in appearance and origin to the Trout Creek Sandstone Member (Bass and others, 1955, p. 153); it is a white to light gray, moderately well-sorted, fine- to very fine-grained quartz arenite. The unit contains about 90 percent subangular quartz and 10 percent black, subangular chert and is moderately to well indurated. The cementing agent primarily is silica in the harder samples and clay in the softer samples. Tangential grain-to-grain contacts of outcrop samples indicate that little or no compaction has occurred. Thickness and character of the Twentymile Sandstone Member are more varied than in the underlying Trout Creek Sandstone Member. In the eastern part of the study area, the

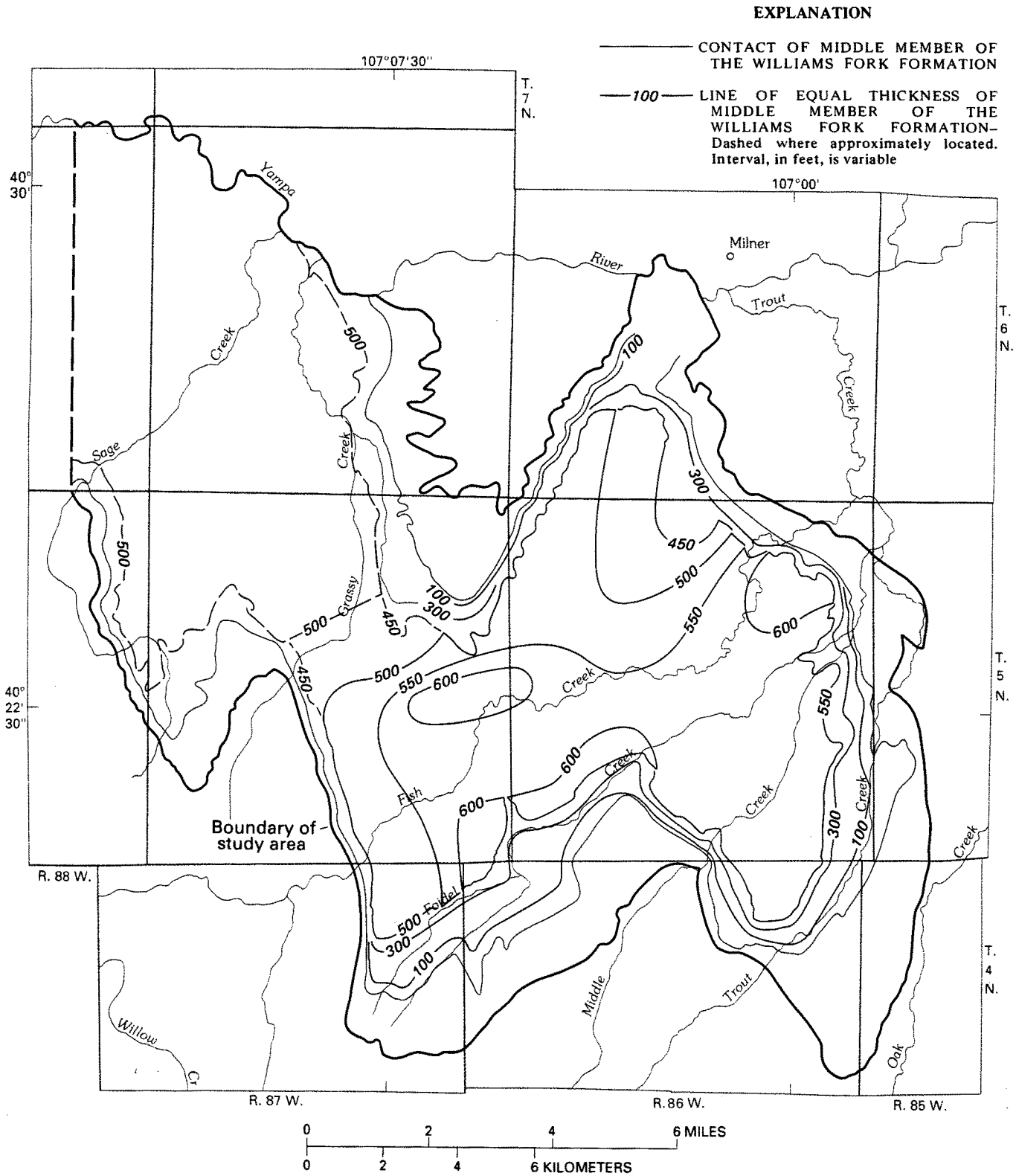

Figure 13.--Thickness of the middle member of the Williams Fork Formation in the eastern part of the study area.

Twentymile Sandstone Member has an average thickness of about 100 ft and ranges in thickness from 80 to 180 feet. This large range and the seemingly random distribution of thickness preclude isopach mapping. The lower transitional contact between the beach sand of the Twentymile and the underlying marine shales is moderately well defined. The upper contact with the siltstones and fine-grained sandstones of the upper member is less well defined. In the western part of the area, the thickness is about 100 feet; however, rocks above and below the Twentymile Sandstone Member tend to be coarser silty sandstones or sandstones that produce poorly defined boundaries, particularly at the base.

Upper member

The upper member of the Williams Fork Formation includes all rocks between the top of the Twentymile Sandstone Member and the base of the Lewis Shale. Rocks in this member primarily are dark-gray mudstones, siltstones, and limey shales interbedded with sandstones 20 to 30 ft thick. Coal seams, some thick enough to be mined, occur near the top of the member in the east and from the base through the middle of the interval in the west. Thickness of the upper member increases from 300 ft in the east to 850 ft in the west. The combined thickness of the upper member and the Twentymile Sandstone Member is about 420 ft in Twentymile Park.

Lewis Shale

The Lewis Shale (pl. 1) is a dark-gray to black, homogeneous marine shale deposited during the last regional transgression (Zapp and Cobban, 1960). Erosional remnants of the lower part of the formation are located near the axis of the synclinal basin in Twentymile Park. A narrow outcrop of shale connects these exposures with the more extensive exposures located to the southeast of Hayden and Craig. The total thickness of the shale varies markedly throughout the area because of erosional thinning. In Twentymile Park, maximum thickness is about 700 ft; in the smaller synclinal basin to the west, a maximum thickness of about 500 ft is attained (fig. 14). The full stratigraphic thickness of the Lewis Shale is present only locally in the area east of Craig where the shale is conformably overlain by the Lance Formation. The shale attains a maximum thickness of about 2,300 ft in this area.

Lance Formation

The Lance Formation (pl. 1) is a transitional marine-deltaic sequence of interbedded gray shale and buff to tan, soft, fine-grained sandstone and a few coal beds (Bass and others, 1955). The only exposure of the formation in the study area occurs south of the Yampa River to the east of Craig, where it attains a maximum thickness of 300 to 400 ft.

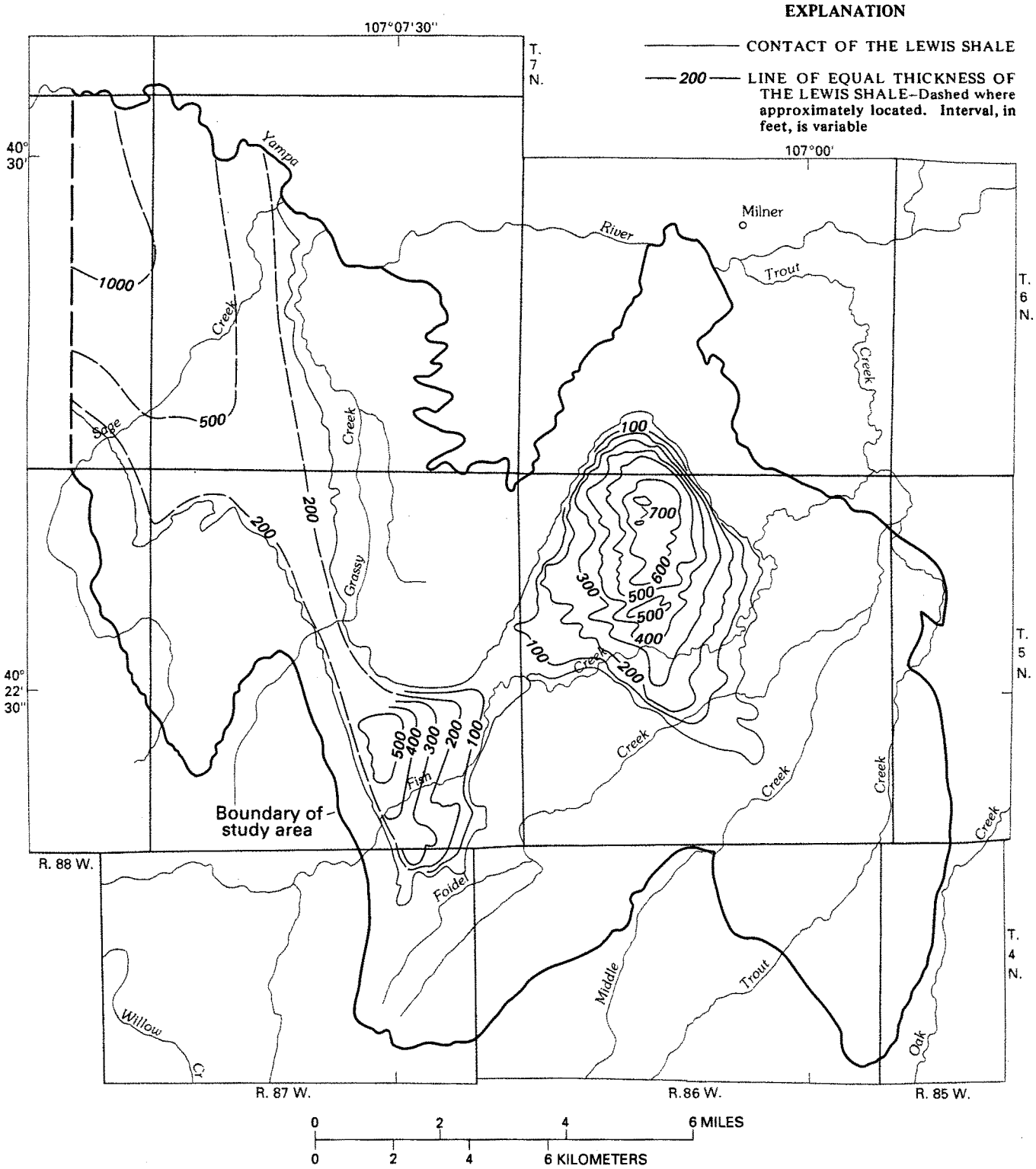

Figure 14.--Thickness of the Lewis Shale in the eastern part of the study area.

Structure and Faulting

Principal structural features within the study area are a result of the Laramide orogeny. This structural folding and mountain-building event began in Late Cretaceous time, 65 to 70 million years ago, and continued intermittently into late Eocene time (Tweto, 1980). The orogeny moved the epicontinental sea from Colorado for the final time. The resulting regional structure is shown in figure 7.

The major structure in the study area, the Hayden syncline (fig. 15), is the farthest southeastern extension of the Sand Wash basin. The Hayden syncline is located just east of Hayden, Colo. Smaller structures in the study area can be divided into eastern and western forms. These differing structural forms are important because they affect topography, vegetation, surface drainage, and ground-water movement.

The structural form of the study area from Hayden Gulch (about 10 mi southwest of Hayden) to the western boundary is basically a homocline dipping to the northeast at a 10 to 15˚ angle. One fold, the Buck Peak anticline (pl. 1), occurs in the far northwestern area. The structure of this anticline does not extend to the surface. The Buck Peak anticline axis trends north–west, parallel to regional strike, and oblique to minor fold axes in the west. Relief on this fold is estimated at 400 to 500 ft. A fault occurs just south of and parallel to the fold axis. Several smaller folds of similar alignment also are present.

The structural form of the area east of Hayden Gulch has a different origin and configuration. The primary tectonic feature affecting this regionis the north-south trending Park Range (fig 7). Secondary structures, superimposed on the regional structure, complicate the structure in the eastern part of the study area.

Three generally north-south trending synclines are the principal secondary structures. The westernmost, here termed the Sage Creek syncline, is a northward-plunging asymmetrical syncline, underlying Sage Creek Reservoir. The asymmetry produces 50 to 60˚ dips and a northwestern strike in outcrops along the steeper western flank and 10 to 20˚ dips and a northeastern strike along the eastern flank (pl. 1). The second syncline seems to be a southward extension of the larger Hayden syncline. It also is northward plunging and asymmetrical. Outcrops on the western flank strike north to northwest and dip 50 to 60˚; those on the eastern flank strike east to northeast and dip 10 to 25˚. The Twentymile Park syncline is the largest and easternmost of the three synclines. It is a triple-plunging syncline that forms a small structural basin underlying Twentymile Park. The northward plunging southern limb is asymmetrical. Outcrops strike northeast and dip 20 to 35˚ along the eastern flank. The southward-plunging northern limb is symmetrical, although offset by faulting. Both flanks dip 10 to 35˚ to the southeast or southwest. The northernmost part of the syncline again plunges to the north, although structural features in this area are poorly defined.

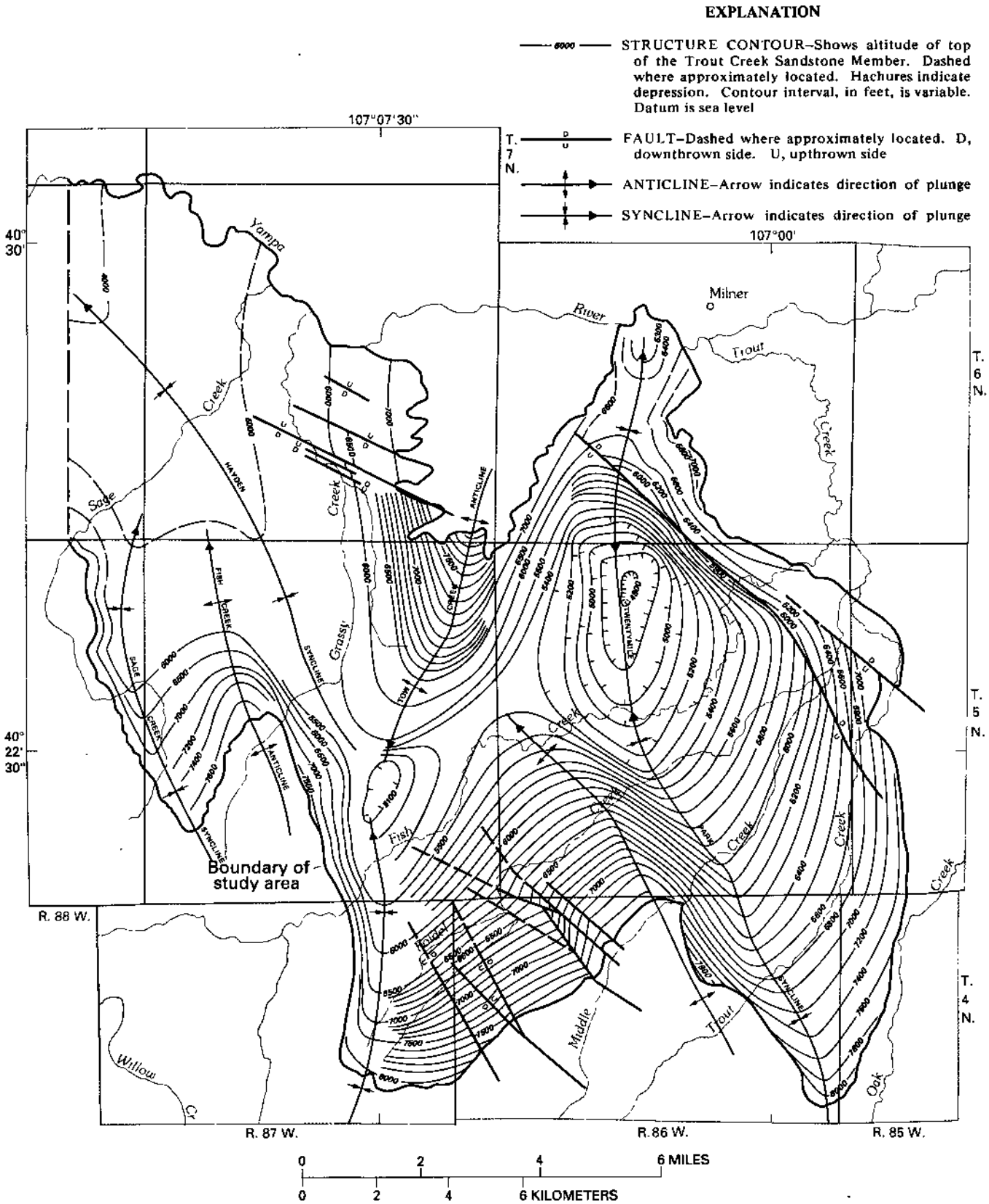

Figure 15.--Structural altitude of the top of the Trout Creek Sandstone Member of the Iles Formation in the eastern part of the study area.

Three principal anticlines occur in conjunction with the synclines in the eastern part of the area (pl. 1). The Tow Creek anticline plunges toward the southwest and is the largest of the four anticlines; it has 3,000 ft of vertical relief. The Tow Creek anticline has been stripped to its core in the Mancos Shale, which underlies the Mesaverde Group, hydraulically isolating its eastern and western flanks. The Sage Creek and Fish Creek anticlines are subparallel anticlines southeast of Hayden; both plunge northward. Of the two, the Sage Creek anticline is larger, tighter, and has more vertical relief. The eastern flanks of all three anticlines are much steeper than the western flanks. Outcrops on the eastern flanks commonly dip 30 to 60˚; those on the western flanks commonly dip 10 to 20˚. The steep-ended flanks resulted from compressive stresses produced by the north–south trending Park Range as it formed east of the study area.

Faults are more common east of Dry Creek. Although Bass and others (1955) mapped several surficial fault traces on the western flank of the Tow Creek anticline and to the northeast and south of Twentymile Park, many more faults are known to exist in the subsurface. Difficulty in identifying fault offset and orientation from lithologic or geophysical logs precluded most additional mapping. Numerous northwest-trending faults located south of Twentymile Park exhibit vertical offset of less than 100 ft, as measured in the dip slope south of Foidel Creek. Some of these offsets may result from strike-slip movement on the dip slope as indicated by slickenslides observed in coal mines in this area (Richard Tifft, Twentymile Coal Co., oral commun., 1985). Vertical offset ranges from 0 to 400 ft along the fault, or fault zone, located within the study area to the northeast of Twentymile Park. In addition to offset, faulting in this area has created an extensively fractured zone of rock within or between several fault planes that parallel the fault trace shown on plate 1.

Structural warping and faulting in the eastern part of the study area is indicated by the configuration and lateral extent of the bedrock formations. The top of the Trout Creek Sandstone Member has 3,200 ft of structural relief, between the trough of the Twentymile Park syncline and the southern outcrops of the formation (fig. 15). The basin underlying Twentymile Park contains two structural lows, one on the Twentymile syncline, the other at the southern end of the Tow Creek anticline. The combination of structure and topography produces an irregular, contorted outcrop line that delineates the limit of the water-yielding units considered in this study. The deformed and faulted structure of the Trout Creek Sandstone Member in the Iles Formation is expressed in the structure map of the base of the Twentymile Sandstone Member in the Williams Fork Formation (fig. 16). Structural relief on this surface exceeds 1,700 ft. The two structural low areas in the Trout Creek Sandstone Member also are evident in the structure of the base of the Lewis Shale (fig. 17). Maximum structural relief on the Lewis Shale is about 1,000 ft.

CLIMATIC CONDITIONS

All surface water and ground water in the study area is the result of precipitation. Changes in climatic conditions such as precipitation, temperature, wind, and evaporation can cause large and rapid changes in streamflow and more gradual changes in ground-water flow. The changes