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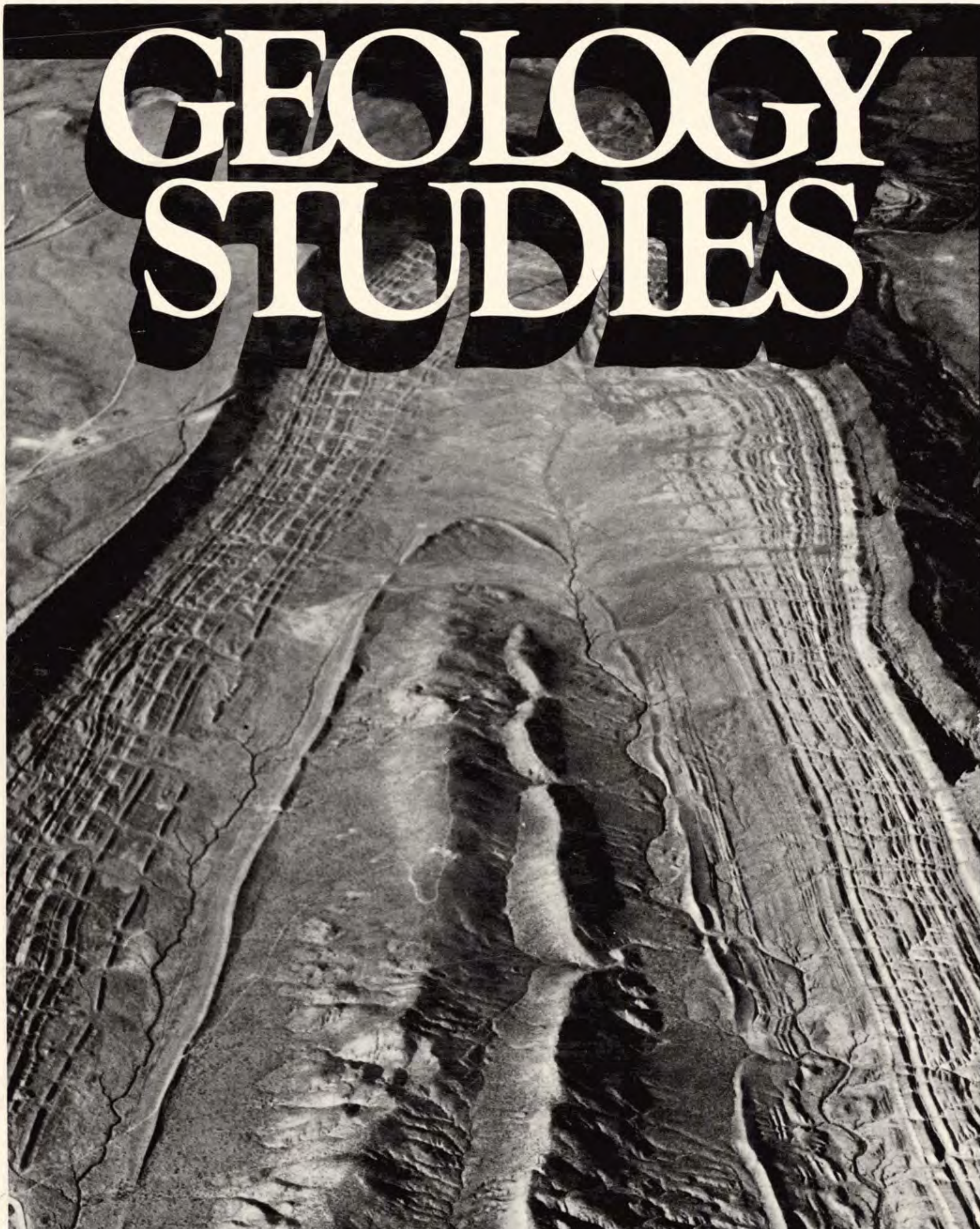

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CONTENTS

THE GLORY OF GOD IS INTELLIGENCE

Cover: Virgin anticline near St. George, Washington County, Utah.

Structure and Stratigraphy of the Co-op Creek Quadrangle, Wasatch County, Utah*

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ABSTRACT.—Detailed mapping of the Co-op Creek Quadrangle reveals the Strawberry Valley Thrust, which is exposed in a window in the quadrangle, to be composed of several major and minor thrust slices. Allochthonous geosynclinal rocks, autochthonous shelf rocks, and synorogenic conglomerates are exposed in the quadrangle. Ages represented are Pennsylvanian through Tertiary. Unnamed synorogenic conglomerates are Paleocene and possibly Eocene.

Several thrust slices, large and small scale folds, normal faults, and small scale deformation features are related to thrusting. Folding occurred contemporaneously with thrusting. Normal faults and gentle folding postdate the thrusting.

Thrusting in the quadrangle is related to the Sevier Orogeny and occurred in latest Cretaceous and Paleocene time. Little evidence was found to clarify problems of amount of displacement and mechanics of thrusting of the allochthon.

The Co-op Creek Quadrangle has definite potential for hydrocarbon accumulations at depth; the best possibility is in the gently folded strata of the autochthon. Both source and reservoir rocks are present.

INTRODUCTION

Detailed mapping of the Co-op Creek Quadrangle has revealed several thrust slices behind the leading edge of the Strawberry Valley Thrust, which is exposed in a window in the quadrangle (fig. 1). This thrust is considered an extension of the Nebo and Charleston-Deer Creek thrusts. It represents the easternmost exposure of the Nebo-Charleston allochthon. The allochthon comprises most of the central and southern Wasatch Mountains.

The rocks of the quadrangle are of three groups: those on the allochthon, which represent a basin or geosynclinal facies; those beneath the thrust, which represent shelf facies; and synorogenic conglomerates, which are a result of tectonics associated with the thrusting and erosion. Ages of rocks represented in the quadrangle are Pennsylvanian through Tertiary, with scattered unconsolidated Quaternary deposits.

Location

The Co-op Creek 7½-minute Quadrangle lies in the east central Wasatch Mountains in a transition area between the Wasatch Mountains and the Uinta Basin (fig. 2). It is approximately 40 kilometers east of Provo, Utah, and the center of the quadrangle is 10 kilometers north of Strawberry Reservoir. U.S. Highway 40 passes through the southwest corner of the quadrangle, and access to the area is gained by several dirt roads and jeep trails.

Previous Work

Previous work in the area has not been extensive. Bissell (1952) mapped the Co-op Creek Quadrangle together with quadrangles to the north, east, and northeast; he modified the stratigraphic terminology of the area in a 1959 paper. Walton (1944), Huddle and McCann (1947), and Garvin (1969) have mapped or studied nearby areas. Many investigators have referred indirectly to the area in dealing with thrusts, but, to my knowledge, no other studies have been done in the Co-op Creek area.

Methods of Investigation

Preliminary work was done in the spring of 1975, and field work was done in July, August, and September 1975. Mapping was done at a scale of 1:24,000, from field investigations and aerial photographs. Stratigraphic sections were measured with steel tape and Brunton compass. The thicknesses of some formations were not measured; they were estimated from aerial photographs. Laboratory work, library research, and writing were done in the fall and winter of 1975-1976.

STRATIGRAPHY

General Statement

The Co-op Creek Quadrangle contains rocks of three groups: geosynclinal rocks which have been thrust over shelf rocks which are in place, and coarse clastic rocks shed off the advancing thrust front. Allochthonous rocks are Pennsylvanian through Jurassic; exposed autochthonous rocks are Cretaceous. Figure 3 shows these two main groups, with Tertiary synogenic deposits atop each one.

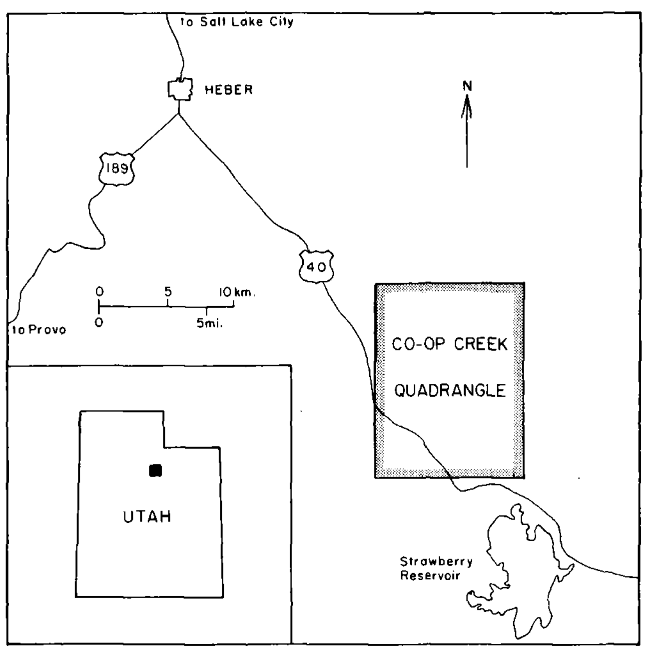

FIGURE 2.—Index map showing location of Co-op Creek Quadrangle.

*A thesis presented to the Department of Geology, Brigham Young University, in partial fulfillment of the requirements for the degree Master of Science, August 1976. James L. Baer, thesis committee chairman.

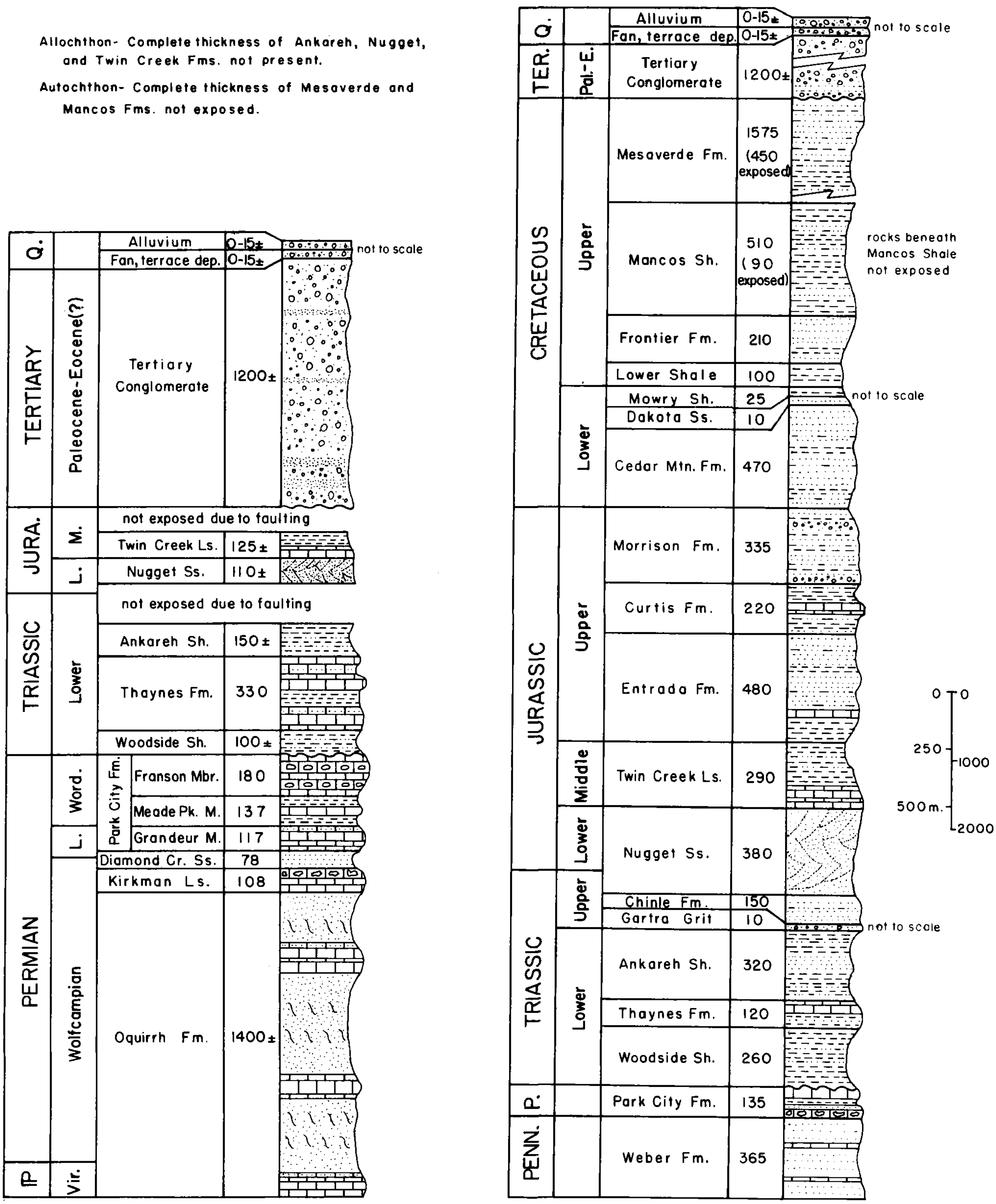

FIGURE 3.—Stratigraphic sections, Co-op Creek Quadrangle. Left section: allochthonous rocks; right section (data from Bissell 1952, 1959): autochthonous rocks.

Of the shelf rocks, only the Mancos and Mesaverde formations are exposed in the quadrangle; the others have been mapped and described in adjacent quadrangles (Bissell 1952, 1959) and are assumed to be present in the subsurface of the Co-op Creek Quadrangle. They may be important in exploring for hydrocarbons in the area and will be discussed later. Tertiary volcanic rocks are present north of the study area (Bissell 1952). Quaternary deposits include stream, fan, terrace, and some glacial deposits.

Pennsylvanian System

Oquirrh Formation.—Pennsylvanian rocks in the Co-op Creek Quadrangle belong to the Oquirrh Formation. Although most of the Oquirrh in the area is Permian, fossil evidence indicates some Upper Pennsylvanian strata are present. The thickness of the Pennsylvanian section is not known, and lack of outcrops obscures the Pennsylvanian-Permian boundary. The total thickness of the Oquirrh in the area is estimated to be 1400 meters, and most of it is Permian.

Fossils which indicate a Pennsylvanian (Virgilian) age are the fusulinid *Triticites cullomensis* (Dunbar and Condra) and the tabulate coral *Syringopora.* They are found in beds of limestone containing fusulinids, corals, bryozoans, foraminifera, and crinoid hash. Several types of crinoid columnals are present, including stellate, circular, and pentagonal forms. In addition to *Syringopora,* poorly preserved rugose corals were also found. These fossils were found in outcrops on the east and west sides of the valley of the Strawberry River, in section 22, T. 2 S, R. 12 W. In addition to limestone, tan and red quartzose sandstone, some of it coarse, characterizes the Pennsylvanian Oquirrh. Outcrops are found along the Strawberry River between Highway 40 and Willow Creek.

Permian System

Permian rocks of the Co-op Creek Quadrangle are Wolfcampian, Leonardian, and Wordian. An unconformity separates Wordian rocks from the Lower Triassic (Armstrong 1968a). Total thickness of Permian rocks is about 2000 meters.

Oquirrh Formation.—Permian rocks of the Oquirrh Formation crop out in the western part of the area, approximately between the west edge of the quadrangle and the Strawberry River, and between U.S. 40 and the northern edge. They are quartzose sandstone and orthoquartzite, with some fossiliferous limestone. Exposures in the higher elevations are usually poor, with float and rubble of sandstone predominant. Orthoquartzite and limestone are generally more resistant and form some good outcrops in roadcuts along Highway 40 and along the Strawberry River north of the highway. As has already been noted, the Oquirrh in the quadrangle is approximately 1400 meters thick, and most of it is Permian.

Limestones are gray and contain beds with abundant fossils, including shell and crinoid fragments, foraminifera, and fusulinids. *Triticites cellamagnus* (Thompson and Bissell), a lower Wolfcampian fusulinid, is abundant in outcrops immediately beyond the western edge of the quadrangle, in sections 10 and 15, T. 6 S., R. 6 E.

Quartzose sandstone and orthoquartzite compose the vast majority of rocks in the section. They are often badly fractured or weather away, covering hillsides with rubble and obscuring outcrops. Quartzose sandstones are medium to coarse grained, sometimes porous and friable, and at times calcareous. Orthoquartzites are hard and tight and appear to comprise most of the clasts in the conglomerates in the eastern part of the area. Colors of sandstones and orthoquartzites include gray, tan, red, and white, with the same variety of colors on weathered surfaces. Dips and bedding are hard to determine, and no sedimentary structures were seen.

In many places a distinctive sandstone unit is seen near the top of the Oquirrh. It is purplish gray and badly weathered. It crumbles and disaggregates easily, and a fresh surface is hard to obtain. The unit weathers to a light cream color and is easily spotted in the field. Below it is a friable calcareous sandstone containing burrows. This unit gives off a strong fetid odor when broken. It also weathers easily, so it usually forms poor outcrops.

The Oquirrh Formation is commonly accepted as marine, but some disagreement exists as to the specific types of marine environments represented (Bissell 1962; Roberts et al. 1965, p. 1934-44). Fusulinids, corals, crinoids, and fossiliferous and hashy limestones, as well as clean sandstone and orthoquartzite comprising Oquirrh rocks in the Co-op Creek Quadrangle, suggest shallow marine deposition.

Thin-section study of fossiliferous limestones of the Oquirrh reveals dead oil in stylolites and fractures and the presence of algae. Some rocks also give off a fetid odor when broken. This information indicates the presence of hydrocarbons in these rocks.

Kirkman Limestone.—The Kirkman Limestone is exposed in a band trending approximately northwest-southeast, running near the mouths of Willow Creek Canyon and Bjorkman Hollow. North of Bjorkman Hollow it is covered by a thrust slice of Oquirrh. To the south, the Kirkman is again covered by an Oquirrh thrust block and also comprises part of that block. The formation is 108 meters thick where measured (see appendix). Fossil evidence (Bissell 1962, p. 34) indicates a middle to late Wolfcampian age for the Kirkman.

The formation is generally composed of two units. The older is brownish gray and gray limestone with thin to thick bedding. It weathers to low ledges and angular rubble, with sometimes a lined or blocky weathered surface which makes the rock resemble a breccia. The second unit is a limestone breccia, with gray limestone clasts in a gray or pinkish gray calcareous matrix. Clasts are often dark, laminated limestone and are usually at least somewhat rounded. They range up to 10-12 centimeters across and are sometimes larger. This unit seems to vary in thickness and cannot be recognized well in some areas. Rocks of both units give off a fetid odor when broken. No fossils were found in the formation.

The environment is marine, probably shallow, and at times restricted, as evidenced by the clasts of dark, laminated limestone in the upper unit. The fetid odor indicates possible hydrocarbon potential, probably as a source rock.

Diamond Creek Sandstone.—The Diamond Creek Sandstone overlies the Kirkman Limestone and occurs in an outcrop band paralleling that of the Kirkman. A section

78 meters thick was measured (see appendix) but the measurement is an approximation because the contact with the Kirkman at that locality is not exposed. Bissell (1952) reported the thickness as 50 meters.

The formation is mostly quartzose sandstone, with some silty beds. Color ranges from white to tan to yellow, with weathered surfaces somewhat darker than the fresh. Bedding is generally thin, with some small-scale cross-bedding. Because the Diamond Creek weathers easily to rounded fragments and sand, it forms a valley between the more resistant Kirkman and Park City formations; therefore exposures are poor to fair. Study of hand samples revealed the rock to be composed of rounded to subrounded, spherical to slightly elongate quartz grains. It is well sorted, with most grains in the medium sand range. Some clay and dark minerals are also present. The rock is porous and friable and contains little or no calcite. No fossils were seen. The evidence suggests a shallow marine environment, such as beach or nearshore. Its composition, grain size and shape, and porosity indicate good potential as a hydrocarbon reservoir rock.

Park City Formation.—The Park City Formation is exposed in two areas in the quadrangle. The first is in a band paralleling that of the Kirkman and Diamond Creek formations. A thrust slice cuts this band roughly in half. Structural interpretation as shown in the cross sections (fig. 1) shows the strata duplicated by the thrust fault, with more of the duplicated section being exposed in the northern part of the band. Where it is cut by thrust or high-angle faults, the Park City is badly brecciated and altered so as to be barely distinguishable. The upper part of the formation is also exposed along the left fork of Co-op Creek, at the leading edge of the thrust.

The Park City Formation (the term *group* is applied in western Utah) was divided into members by McKelvey and others (1956). Member names used in the Wasatch Mountains are Grandeur, Meade Peak, and Franson (Bissell 1962, p. 35). These three members are recognizable in the Co-op Creek Quadrangle and have been distinguished on the stratigraphic column, but not on the geologic map. The Grandeur Member is 117 meters thick; the Meade Peak Member is 137 meters thick, and the Franson Member is 180 meters thick, for a total thickness of 434 meters (see appendix). The section is well exposed near the mouth of Willow Creek Canyon (section 14, T. 2 S, R. 12 W).

The Grandeur Member is composed of limestone, with some sandy limestone and shaly limestone. Rocks are generally a shade of gray or pinkish gray if limestone, light gray to tan or brown if sandy, and greenish gray if shaly. Limestone beds are more resistant and weather to ledges and low outcrops with angular rubble; sandy and shaly units tend to weather to low ledges with sand or dirt. Bedding is not always apparent but is usually thin where visible. Some beds show fractures, calcite veins, and a lined weathered surface, as do parts of the Kirkman. No fossils were found in the Grandeur Member.

The Meade Peak Member contains limestone and shaly limestone with sandy limestone between. The upper and lower units are medium gray to black, fine grained and hard, and have a conchoidal break. They weather to blocky, low ridges. Some shaly beds tend to weather to a cream color, and some are oolitic. Both units are phosphatic and give off a fetid odor when broken. The sandy limestone middle unit is light gray or cream-colored and forms low ledges and float. Some small gastropods were found in this middle unit.

The Franson Member resembles the Grandeur in lithology and color but contains abundant chert. Limestone is generally a shade of gray, but many beds are harder, siliceous, and denser than the Grandeur and contain chert nodules and stringers. More siliceous beds form jagged ledges with a generally pitty surface. Sandy beds are less resistant. Some fossils were found but were poorly preserved and generally unidentifiable. Shell hash, poorly preserved pelecypods or brachiopods, gastropods, and crinoid fragments and hash were seen.

The Park City Formation represents shallow marine sedimentation (Hintze 1973), with the Meade Peak Member deposited by upwelling currents into shallower water (Sheldon et al. 1967). Black shale units of the Meade Peak Member give off a fetid odor when broken as do some rocks in the upper and lower members. There could be possible hydrocarbon source or reservoir rocks at depth.

Triassic System

Triassic rocks in the area represent only early Triassic time. An unconformity separates them from the underlying Permian. Total thickness of Triassic rocks is approximately 580 meters.

Woodside Shale.—The Woodside Shale overlies the Park City Formation unconformably although the unconformity is not readily distinguishable in the study area. It is, however, a well-known regional feature (Clark 1957, p. 2209). The Woodside crops out in the same belt as the Permian section and disappears under thrust blocks to the north and south. In the southern part of the band is a repeated section brought to the surface on a thrust slice. The Woodside also is exposed along the leading edge of the thrust in the left fork of Co-op Creek. No section was measured, but thickness is approximately 100 meters.

The Woodside consists of interbedded red shale, sandstone, and siltstone, with some limestone. Some beds are gray, cream, or brownish red, but red dominates. Weathering quickly reduces the rocks to red soil and shale or siltstone float, so the Woodside forms valleys with few good outcrops. Ripple marks and small-scale cross-bedding are commonly seen, however. Bedding is thin, but silty and sandy units tend to be slightly thicker bedded. No fossils were found in the formation. The Woodside represents deposition on broad, low plains near sea level (Hintze 1973, p. 54).

Thaynes Limestone.—The Thaynes Limestone is probably the most evident of the upper plate formations. It crops out in a band more than three kilometers wide at its widest point and therefore has more good outcrops than any other formation. The rocks are highly folded, and the resistant beds form high vertical and curving ledges visible in several areas, most notably along Willow Creek (section 11, T. 2 S, R. 12 W; fig 4). Thrust slices and folding also expose repeated sequences.

The Thaynes is 330 meters thick in the quadrangle (see appendix). It consists of gray and brownish gray limestone; tan, buff, or light brown sandy limestone; and gray, red, and green shale and shaly limestone. The up-

FIGURE 4.—Resistant ledge in Thaynes Formation, Willow Creek.

per part of the formation contains more sandy and shaly beds than the lower part. Bedding ranges from laminated to thick, with sandy and shaly beds usually thinner. Some shaly beds have small-scale ripple marks.

Limestone beds are more resistant and form ledges and low outcrops with angular float. Sandy and shaly beds tend to form float-covered hillsides with low outcrops. Float is platy but more rounded. Many good outcrops, even of less resistant beds, can be seen along Willow Creek and in Bjorkman Hollow.

The most common fossils found in the Thaynes were pelecypod shells in a hash which occurs in most of the gray limestones in the upper part of the formation. These hash beds form the high ledges seen along Willow Creek and elsewhere (fig. 4). The shells are not identifiable. Other pelecypods were found, including a species of *Monotis,* as well as crinoids (probably *Pentacrinus*), crinoid hash, echinoid spines, bryozoans, and cephalopods (*Meekoceras* or *Columbites*). Some limestones and sandy limestones of the Thaynes were found to contain abundant dead oil.

The Thaynes Formation represents a marine transgression over the low plains of the Woodside (Hintze 1973, p. 54) and is the latest marine deposit in western Utah.

Ankareh Formation.—The Ankareh Formation is exposed in a band contained in the larger belt of Thaynes outcrops. As can be seen from the cross-sections of figure 1, it is in the bottom of a syncline and is not present in its entire thickness. Bissell (1952) noted a thickness of 475 meters, which is a composite from parts measured in different localities. The present mapping and structural interpretation for this formation differ somewhat from that of Bissell; if the present interpretation is correct, the complete thickness is nowhere present in the quadrangle, so a figure of 475 meters would be too high. The estimated thickness is 150 meters.

The Ankareh is quite similar to the Woodside in lithology and topographic expression. It consists of gray, green, red, purple, and tan sandstone, siltstone, and shale. Red is again the dominant color. Some calcareous beds are also present. More sandy units are thicker bedded, but none over 10 centimeters were seen. Small ripple marks and cross-beds are abundant in some outcrops. No fossils were found in the Ankareh.

The formation weathers easily to valleys, and so, as with the Woodside, good outcrops are few. In some areas, beds are highly contorted and squeezed, an effect of the tight folding the formation has undergone.

The Ankareh correlates with upper parts of the Moenkopi Formation (Hintze 1973, p. 56). It probably represents an environment similar to that of the Woodside and was a result of marine regression after the deposition of the Thaynes Formation.

Jurassic System

Jurassic rocks are exposed in the northern part of the area atop thin thrust slices. Only two formations are present, neither one complete. Thickness is approximately 240 meters.

Nugget Sandstone.—The Nugget Sandstone crops out in only two places in the Co-op Creek Quadrangle. Both are in small thrust slices in the north central part of the area. The northernmost is mostly outside the quadrangle. The Nugget consists of white and red quartzose sandstone which weathers reddish-orange. Large-scale cross-bedding is characteristic of the outcrops, but is not well preserved because the outcrops are highly weathered to sand and sandy rubble. Sand is well sorted and has few impurities. Because the outcrops are poor and contacts somewhat obscure, the thickness is hard to determine but is estimated to be 110 meters. The formation is exposed only in thrust slices, and the complete thickness either is not present because of thrusting, or is in the subsurface. Baker (1947) gave a thickness of 440 meters for the Nugget in Spanish Fork Canyon and 460 meters near Heber, Utah. Bissell (1952) noted 380 meters of Nugget on the lower plate northeast of the Co-op Creek Quadrangle. The Nugget is of eolian origin, and is considered late Triassic-early Jurassic.

Twin Creek Limestone.—The Twin Creek Limestone is exposed, as is the Nugget, only in thrust slices in the north central part of the quadrangle. Good exposures are also found just off the map to the north. Exposures are largely fine-grained to micritic limestone and shaly limestone. The best outcrop is found just north of the quadrangle boundary and comprises the following: fine- to coarse-grained gray and purplish gray limestone, with some beds oolitic; fine-grained, gray shaly limestone which weathers light tan; thin-bedded, fine-grained to micritic gray limestone. The total thickness of this outcrop is approximately 40 meters, but total thickness in the quadrangle is estimated to be 125 meters.

Although the formation crops out in a continuous band, good exposures are few, because of the shaly nature of much of the rock. Many exposures are, however, easily distinguished by their light tan to white color on weathered surfaces. Fresh surfaces are mostly medium to dark gray, or grayish tan. Bedding is thin, with shaly units weathering to thin slabs or pencillike fragments. Some beds contain small calcite veins.

A few fossils were found, most notably *Pentacrinus asteriscus* (or *whitei*), and some crinoid hash, pelecypod shell fragments, and burrows. The Twin Creek normally overlies the Nugget conformably and represents a marine invasion. In the Co-op Creek Quadrangle, the incompleteness of the thickness is due to thrusting. Total thicknesses measured in other areas of the allochthon include 335 meters (Baker 1947) and 561 meters (Young 1976), both measured north of Thistle, Utah. Some dead oil was noted in thin sections of oolitic beds of the Twin Creek.

Cretaceous System

Cretaceous rocks in the area are all Upper Cretaceous and belong to the autochthonous shelf facies. Exposures are poor because they are generally covered by later conglomerates, and they weather easily. Total exposed thickness is approximately 540 meters.

Mancos Shale.—Mancos Shale crops out in the extreme northeast corner of the quadrangle, where it is on the up side of a normal fault. Good exposures are found only along the Currant Creek Feeder Canal, which runs northeastward from the right fork of Co-op Creek. Above and below the canal, conglomerate rubble, either in place or weathered, and later fan deposits cover most rock. Because of the poor outcrops, no attempt has been made to differentiate units or measure a section. Bissell (1952) measured the complete thickness of the Mancos east of the Co-op Creek Quadrangle and found it to be 510 meters. Thickness of Mancos exposed in the Co-op Creek Quadrangle is estimated to be 90 meters. These beds are classified as Mancos on scanty fossil evidence and extrapolation of mapping done by Bissell to the north.

Mancos beds are largely shale, with some sandstone and one fossiliferous limestone bed. Exposures of shale can be seen along a creek just north of the quadrangle (section 21, T. 1 S., R. 11 W.). They consist of black, gummy, sticky shale with clay galls, and light gray, pink, and red shale which is also sticky. Outcrops along the Currant Creek Canal (section 28, T. 1 S., R. 11 W.) are cream colored and light gray sandstone which forms low outcrops, one bed (1½ to 2 meters thick) of fossiliferous gray limestone containing large pelecypod shells, more outcrops of black gummy shale, and some tan sandstone and hard calcareous sandstone, with fine (2-3 mm) cross-bedding.

Pelecypod shells resemble the genera *Inoceramus, Ostrea,* or *Exogyra,* all of which are characteristic of the Upper Cretaceous and have been found in the Mancos nearby (Bissell 1952, p. 607-10). Some small plant fragments were also found. Thin sections of the pelecypod shell bed also show dead oil.

Mesaverde Formation.—The Mesaverde Formation in the quadrangle is well exposed only along the Currant Creek Feeder Canal (section 33, T. 1 S., R. 11 W.) and in the gorge formed where this canal empties into Co-op Creek (sections 5, 7, and 8, T. 2 S., R. 11 W.; fig. 5). Slump features are common here because of the nature of the rocks and increased erosion from the canal runoff, and it is sometimes difficult to determine whether beds are in place or not. Dips are generally to the south at 10 to 20 degrees, except near the thrust leading edge where beds were folded up by the thrust movement (fig. 6). Estimated exposed thickness is 450 meters. It represents the upper part of the complete Mesaverde section mapped by Bissell (1952) east of the Co-op Creek Quadrangle and reported to be 1575 meters thick.

Mesaverde rocks change character at approximately the spillway where the canal empties into Co-op Creek. Rocks below this spot are mostly shale, siltstone, and mudstone; those above are sandstone and coarse siltstone. The rock is poorly consolidated to begin with, so weathering quickly destroys it, forming low, rounded outcrops covered by sand, soil, and rubble. Good samples can be found only by digging into this cover.

Rocks below the canal opening are shale, siltstone, mudstone, and sandstone. Color is quite varied, including cream, tan, gray, green, orange, red, and brown. Sandstone beds are generally lighter, shale and mudstone darker. Some of the sandstone is cross-bedded and contains fractures spaced about 75 centimeters apart and trending 10°-190°. Some beds contain mud and clay galls with small flakes of pyrite inside, and very hard limonite concretions and nodules. These rocks have abundant carbonized plant fossils and thin stringers and beds of coal.

Rocks above the canal are quite different, being mostly fine sandstone and siltstone with some shale. They are poorly cemented, quite soft, and friable. Color is still varied: buff, orange, tan, gray, cream, white, and brown are all common. Some beds have sets of cross-strata up to 30 centimeters high. Rocks still dip in a southerly direction. No fossils, concretions, or similar features were seen in these upper rocks.

Tertiary System

Only one Tertiary formation is recognized. It represents synorogenic conglomerates and sandstones shed off the advancing thrust front. Total thickness is approximately 1200 meters.

Tertiary conglomerates.—A review of the literature dealing with central Utah will reveal a definite problem in correlating and determining the ages of the various conglomerate deposits which resulted from orogenic activity and subsequent erosion Conglomerates are exposed in many areas from south of Nephi to north of Salt Lake City (Hintze 1975) and are generally regarded as being synorogenic deposits resulting from folding and thrusting (Burchfiel and Hickox 1972). Rocks exposed in various areas south of the Co-op Creek Quadrangle have been called Indianola (Schoff 1951; Hintze 1973, p. 67; Spieker 1946 and 1949), and Price River or North Horn (Burma and Hardy 1953, Merrill 1972, Pinnell 1972, Spieker 1946, Eardley 1969b). Merrill (1972, p. 76-77) presented a good discussion of the problems encountered with the conglomerates in the Red Narrows area, east of Thistle, Utah.

FIGURE 5.—Mesaverde Formation in right fork of Co-op Creek.

Conglomerates also crop out extensively in the Co-op Creek Quadrangle and areas to the east. Bissell (1952) mapped the conglomerates in the Co-op Creek area as Uinta Formation (Eocene) and Bishop Conglomerate (Miocene), then later (Bissell 1959) considered it all Uinta. Walton (1944) mapped and named the Currant Creek Formation to the east and called it Upper Cretaceous to Eocene. Huddle and McCann (1947), mapping directly east of Bissell's 1952 area, noted 900 to 1500 meters of Currant Creek Formation in their area. Garvin (1969) later studied the Currant Creek Formation and concurred with Walton as to its age. Osmond (1965) said conglomerate deposition in the western Uinta Basin (including the Co-op Creek area) began in late Cretaceous and continued possibly into the Eocene. He further complicated the picture by saying renewed uplift in the area caused erosion and redeposition later in the Tertiary. Walton (1964) implied a genetic relationship between the Currant Creek Formation and the Red Narrows conglomerates by calling the Strawberry thrust sheets the source for both deposits.

I do not think the Co-op Creek conglomerates should be called Uinta. Williams (1950) described the Upper Eocene Uinta as interbedded sandstone and shale which overlie the Middle Eocene Green River Formation. As will be seen later, the conglomerates are probably earlier than the Uinta and may be contemporaneous with the Green River. They should probably not be included in the Currant Creek Formation, either, because of angular discordances and lithologic differences between the two (Bissell 1952; Walton 1944 and 1964; Garvin 1969). Rather than propose a new name, it seems best to call these rocks only Tertiary conglomerates. Actual age will be discussed later.

Conglomerates in the Co-op Creek Quadrangle cover most of the eastern half of the area and much of the southern part. They lie unconformably on the Oquirrh and Thaynes formations above the thrust plane, and on the Mesaverde of the autochthonous block. The thrust leading edge is marked by the boundary of Mesozoic rocks with the conglomerates until it disappears beneath the conglomerates at the fork of Co-op Creek.

Much of the area covered by conglomerate has only poor outcrops and hillsides covered with rounded rubble, but one can easily tell where conglomerates are by riding over the roads and trails. The rubble makes it quite bumpy and even hazardous for a motorcycle rider. There are, however, several good outcrops, the most spectacular being the Red Ledge near the eastern border of the quad-

FIGURE 6.—Mesaverde beds of autochthonous plate folded near thrust leading edge, right fork of Co-op Creek.

rangle (figs. 7 and 8). It is a cliff of conglomerate more than a kilometer long and up to 75 meters high.

These synorogenic deposits are largely conglomerate, with some beds and lenses of fine to coarse sandstone, mostly near the bottom. The sandstone can be seen along Co-op Creek and in Sleepy Hollow to the east. It is red, orange, white, tan, or pink. It is usually clean and fairly well sorted, but poorly indurated, crumbly and porous. Interbeds or lenses of fine conglomerate or siltstone are common, and cross-bedding can sometimes be seen.

Conglomerate dominates all but the lower parts of the section, however, and is approximately 1200 meters thick. It varies somewhat in lithology and color, but not enough to warrant mapping as separate units, as the differences have no definite pattern.

Overall, approximately 80 percent of the clasts are hard sandstone, orthoquartzite, and quartzite, similar to that of the Oquirrh Formation. They are generally well-rounded and range from nearly spherical to moderately elongate (fig. 8). Color ranges from gray, cream, and tan to red. Some clasts are red or white sandstone, some of which is cross-bedded, and occasionally clasts of chert, shale, or siltstone can be seen. Limestone clasts are rare and consist of gray or grayish-brown limestone. One outcrop in the northern part of the quadrangle has a significantly higher proportion of limestone clasts, possibly 10 percent of the total. Overall, clast size ranges from very small to approximately 2 meters across. The average in many places is 15-20 centimeters.

Matrix is composed of sand and silt and is predominantly gray, but in places is red. In fact, the conglomerates of the Red Ledge, while appearing red from a distance, actually contain mostly gray clasts with gray or tan matrix. The red color is imparted by lichen and other plants growing on the rocks. Some outcrops in other areas, however, definitely have a red matrix, and strongly resemble the conglomerates at Red Narrows. The matrix is calcareous in most places.

Dips on the conglomerates are gentle. In the eastern part of the area they are generally to the east at approximately 10 degrees. In the southwest and north, good dips are harder to obtain, but there are some to the north at 10 to 20 degrees.

These conglomerates have a tendency to show bedding, lensing, channeling, and grading, but is it never very distinct or well displayed, or seen on a large scale. Looking at the gross aspects of an outcrop reveals only a crude bedding, with pockets or areas of larger or smaller clasts. On closer inspection, lenses and channels become evident, with some horizontal bedding and crude graded bedding. These features are somewhat indistinct. The easiest feature to see is still layers or lenses of similarly sized clasts next to lenses of clasts of a different size. One good exposure, about 8 meters arcoss and 3 high, has two lenses of medium-sized conglomerate on the left and a large lens of coarse conglomerate on the right. Above and beneath is coarse sand to fine conglomerate. In this case, medium size clasts are 10-12 centimeters across.

The only fossils found in the conglomerates are in limestone clasts and are poorly preserved.

Quaternary System

Two types of unconsolidated Quaternary deposits are recognized. Total thickness varies but probably is not more than 30 or 40 meters in any one locality.

Fan and terrace deposits.—Fan and terrace deposits can be seen in the lower elevations of the valleys of Strawberry River and Co-op Creek (in the southern part of the quadrangle) and in the extreme northeast corner. In places they merge with stream gravels, but are otherwise distinct, forming a broad, gently sloping, hilly plain from the hills or mountains of the higher elevations down to the stream deposits. In some places, downcutting of the stream has cut into the fan deposits, forming low cliffs. These deposits are frequently associated with normal faults, with fan deposits developing on the top of the downdropped fault blocks.

These deposits probably represent both erosion and weathering of the Tertiary conglomerates and deposition of eroded material brought down from higher elevations. Some fan-shaped deposits can be recognized, but hilly or terraced slopes formed by stream erosion and deposition dominate. Terraces seen along the lower part of Co-op Creek could be related to glacial periods when runoff was undoubtedly greater. Some canyons in higher elevations show a definite U-shape, indicating glaciation, and one deposit seen at the mouth of the Currant Creek Feeder

FIGURE 7.—Tertiary conglomerates at Red Ledge.

Canal could be glacial. It is 2 to 3 meters thick and consists of a fine sand, silt, and clay matrix with scattered clasts up to 15 centimeters across. Above it is up to 1 meter of soil and gravel.

In the northeast corner of the area, fan deposits contain volcanic clasts. Volcanic rocks have been mapped by Bissell (1952) north of the Co-op Creek Quadrangle. He called them (p. 619) andesitic and latitic extrusives, with volcanic agglomerate, tuff, tuff breccia, and volcanic conglomerate. He quoted Forrester (1937, p. 642) as saying their age is late Eocene or early Oligocene. The clasts seen here comprise up to 20 or 25 percent of the total. In other northern areas of the quadrangle, volcanic clasts occur in float at the surface, but never in actual outcrops of Tertiary conglomerate. The presence of these clasts probably accounted for Bissell's (1952) first mapping the conglomerates in the northern part of Co-op Creek Quadrangle as Bishop (Miocene), but topographic expression, composition, and lithology indicate the northern and southern conglomerates are the same.

Stream alluvium.—Stream deposits are seen in the valleys of Strawberry River and Co-op Creek and in the other major canyons and valleys. They are easily distinguished from Paleozoic and Mesozoic bedrock, Tertiary conglomerates, and fan deposits by topographic breaks between them. Composition and lithology vary, but the deposits are often composed of clasts from Tertiary conglomerates, which themselves originate in Paleozoic and Mesozoic rocks of the upper thrust plate. Deposits are boulders and cobbles, with abundant sand, silt, and finer material.

STRUCTURE

Thrust faults, high-angle normal faults, and folds are evident in the Co-op Creek Quadrangle. Thrust faults include several slices, rather than one major thrust, which comprise the Strawberry Valley Thrust. Small normal faults are seen in places in the thrust block, and other normal faults of larger displacement involve Cretaceous and Tertiary strata. Folds are common in the upper block, and some folding related to thrusting has occurred in the lower plate. A late Tertiary tilting and gentle folding episode represents the latest structural modification.

Thrust Faults

The presence of a thrust fault southwest of Heber, Utah (the Charleston Thrust), was first noted by Baker (1947) and Baker, Huddle, and Kinney (1949). In the words of Baker (1947), this thrust "may extend eastward into the western part of the Uinta Basin." Baker, Huddle,

FIGURE 8.—Tertiary conglomerates at Red Ledge.

and Kinney (1949, p. 1196) reported that outcrop patterns limit the eastward continuation of this fault "to the vicinity of the headwaters of the Strawberry River where the strata are known to be highly disturbed." Bissell (1952) mapped this extension and called it the Strawberry Valley Thrust.

This thrust, whose leading edge emerges from Tertiary cover to the north and south, is seen in the Co-op Creek Quadrangle. It is characterized by several thrust slices behind the frontal thrust. I have mapped ten separate slices, nine of which are labeled on the geologic map (figs. 1 and 15). Two frontal slices (6 and 9) are major ones, with two smaller ones (7 and 8) between them in the northern part of the quadrangle. To the west, slices 3, 4, and 5 show an interesting relationship. Slice 5 is seen to be a major slice in the Willow Creek vicinity (fig. 1, section A-A'), while 4 is minor and 3 is not present. To the north (section B-B'), slice 5 has died out, 4 is a major slice, and 3 is present, although minor. The three slices form an *en echelon* set, with individual thrusts dying out or merging to the north. Slice 4 appears to merge with slice 3 just north of the quadrangle, and slices 4 and 5 are covered by another thrust block to the south. Slices 1 and 2 are in the western part of the area and run parallel to other slices until they are lost beneath Tertiary and Quaternary cover. As has already been noted, rocks of the upper plate are Pennsylvanian, Permian, Triassic, and Jurassic; those of the lower plate are Cretaceous and older.

Near the middle of the quadrangle, another block of Oquirrh and Kirkman rocks disrupts the trends of contacts and thrust slices mapped to the northwest. Rocks of this block are nearly vertical and strike nearly east-west. Outcrops on the block are poor, and rocks and structural trends are barely distinguishable in the field or on aerial photos. A small thrust slice in the block itself brings Oquirrh and Kirkman rocks over Oquirrh. This block appears to have been transported in from the southwest; a possible explanation for it will be given later.

Deformation Related to Thrusting

Large scale deformation.—The rocks of the upper block are highly deformed. Dips range from below 20° to vertical and overturned. Individual ledge-forming beds are seen to change strike 90° as they run up a hillside a few hundred meters. This is especially noticeable in the Thaynes Formation along Willow Creek (eastern half of section 11, T. 2 S., R. 11 W.; fig. 4). Aerial photographs show many ledges which curve sinuously as they run up hillsides and along crests of hills.

The axis of a large overturned anticline runs approximately parallel to the trend of the thrust slices, but to the north it seems to migrate slightly eastward and is disrupted by thrust slices. Along Strawberry River, near the mouth of Willow Creek, similar outcrops of Pennsylvanian Oquirrh Formation can be seen on both sides of the river. The axis of the fold appears to be between these outcrops. Oquirrh rocks on the west are upright, and the Oquirrh through Woodside rocks on the east are overturned between the fold axis and thrust slice 4 (fig. 1, section A-A'; fig. 15). The axis itself is faulted by slices 1 and 2. Between slices 4 and 5 the bottom of the fold (the synclinal axis) is caught in a slice and pushed up. Section A-A' (fig. 1) shows this relationship, with younger rocks thrust over older on slice 4. This pattern is possible because it occurs on the changing limb of the overturned anticline. East of slice 5 the rocks are upright and moderately folded. The synclinal axis of the overturned fold is, therefore, between slices 4 and 5.

To the north (fig. 1, section B-B'; fig. 15), the synclinal axis shifts to the east and occurs in the Ankareh Formation; the anticlinal axis is obscured by poor outcrops and is probably disrupted by thrusting. Oquirrh through Thaynes rocks are overturned; the Ankareh is in part overturned and in part upright. Farther north the thrust slices converge, and the picture is further complicated. North of the quadrangle boundary the thrust must swing to the west, so the pattern of thrust slices and folds is probably greatly modified there.

Other lesser folds are seen, mostly in the Thaynes Formation (fig. 9). East of the large overturned fold, folding is progressively less intense on each thrust slice. Folds can be seen along Willow Creek and inferred by dip discordances in other areas. A smaller but striking overturned fold is seen near the fork of Co-op Creek (SW corner, section 7, T. 2 S., R. 11 W.). It is directly opposite the anomalous thrust block of Oquirrh and Kirkman previously discussed and may be related to it.

High-angle normal faults of minor displacement (100 meters or less) are also seen, running approximately perpendicular to the structural trends. They offset beds and thrust slices and probably represent minor movement during or after late stages of thrusting.

FIGURE 9.—Small anticline in Thaynes Formation, Willow Creek.

Deformation in the lower plate does not appear to be extensive, although Bissell (1952) mapped a large fold east of the quadrangle, with dips up to 70° eastward. It could easily be related to thrust movement. In the quadrangle, Upper Cretaceous beds dip gently to the south, except near the thrust front, where dips of approximately 60° to the northeast were recorded (fig. 6). These strata were probably pushed up by the advancing thrust mass. Tertiary strata likewise dip gently to the east and north, implying gentle dips in the rocks beneath.

Small scale deformation.—Small scale deformation, while not so spectacular, is evident and interesting. Curious "hump and hollow" structures can be seen on some bedding surfaces in the Thaynes Formation (Figs. 10, 11). They are long, evenly spaced ridges 5 to 10 centimeters high and approximately 10 centimeters wide, with rounded "hollows" between. They could be either depositional features, possibly a type of ripple mark, or features related to thrust deformation. Similar features can also be seen in a vertical ledge of Thaynes forming the southwest wall of the left fork of Co-op Creek (northern half, section 7, T. 2 S., R. 11 W.). This ledge also shows fracture sets along which movement of a few centimeters has taken place (figs. 12, 13). The photos show the view along the dip slope. Fractures give the appearance of a dip slope perpendicular to the true one, dipping approximately 30° to the northwest. Other fractures are perpendicular to these. Beds are slightly squeezed and distorted.

Small folds can be seen in some places, and shale beds of the Ankareh and Thaynes formations are in places highly contorted and crumpled, almost beyond recognition. Movement along thrust planes has also produced brecciation in many areas, on both a large and a small scale. Aerial photos show areas of brecciation and obliteration of structural and bedding trends. On a smaller scale, beds and outcrops show brecciation, slickensides, and rocks which appear to have been badly crushed and fractured, with subsequent calcite veins forming. The intervening crushed material has been eroded out, leaving a well-preserved calcite box work structure. This phenomenon is common in the Park City Formation. Breccias are common in the Park City and Thaynes formations.

Normal Faults

Small normal faults related to thrusting have already been discussed. Two other major normal faults have been mapped. The first is in the southeast part of the area. Through part of its length it involves only Tertiary rocks, but it also involves the Oquirrh-Kirkman thrust block which has already been discussed. This block has been faulted relatively up next to Tertiary strata. The fault then apparently dies out in the Tertiary rocks to the west. The other normal fault is in the northeast corner of the

FIGURE 10.—"Hump and hollow" structures in Thaynes Formation, Willow Creek.

FIGURE 11.—"Hump and hollow" structures in Thaynes Formation, Willow Creek.

quadrangle and juxtaposes Upper Cretaceous Mancos rocks against younger Mesaverde beds. Both these faults probably postdate the thrusting. They also have Quaternary fan deposits related to them. Uplift on the faults has produced these deposits on top of the downthrown block. They can be seen in the northeast and southeast parts of the area.

Other Folds

The lower plate rocks and Tertiary conglomerates show dips which indicate they are gently folded. Mesaverde beds dip gently to the south; conglomerates dip to the east, north, and southwest at 0 to 20°. This dipping may reflect gentle folding during post-thrusting uplift, an irregular topography upon which the rocks were deposited, or both. Gentle folding of lower plate rocks could be after or incident to the thrusting. Exposures are not sufficient to postulate much structure beneath the Tertiary conglomerates.

Sequence of Events Related to Thrusting

The important features related to thrusting are, as shown on the geologic map (fig. 1), several thrust slices running in a generally northwest-southeast direction, folds of varying magnitude whose axes parallel the trend of thrust slices, and high-angle normal faults which offset thrust slices, although with minor displacement. A seemingly anomalous block, mostly of Oquirrh rocks, is present near the center of the quadrangle and obliterates faults and contacts around it. The thrust faults are covered by conglomerate east of Co-op Creek.

This evidence suggests a sequence of events which is summarized in the block diagrams of figure 14. As the allochthonous rocks moved toward the area, a major fold developed, the large overturned anticline in the western part of the quadrangle. As this fold developed, movement began along newly formed thrust planes, probably beginning at depth. A series of thrust slices developed. Some, such as slices 4, 6, and 9, were major; others, such as slices 3, 7, and 8, were minor. A major zone of thrusting developed at the synclinal axis of the overturned fold, involving a complicated set of slices: 3, 4, and 5.

As movement along thrust slices increased, folds developed within individual plates. This deformation resulted in the contortion and folds which are best seen in the Thaynes Formation in Willow Creek canyon (figs. 4 and 9). Small normal faults developed near the end of the sequence, possibly in response to differential movement or slight rotation of the thrust block. As the thrust mass advanced, the rocks in the lower plate were not greatly deformed, except beneath and immediately in front of the thrust block.

The block of Oquirrh near the middle of the quadrangle truncates contacts and faults in one place and itself is truncated in another. This latter relationship is somewhat questionable. The presence of this block can

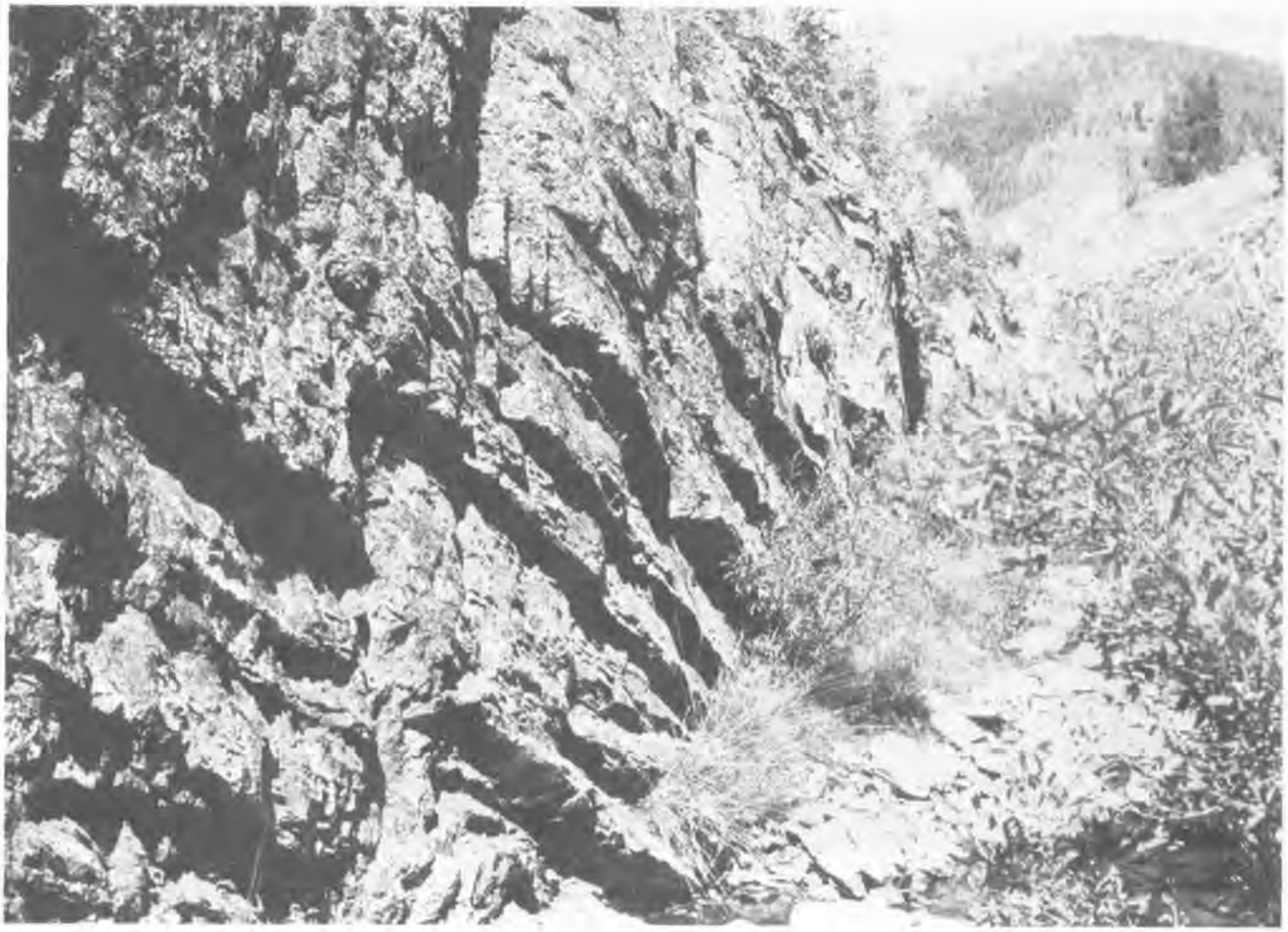

FIGURE 12.—Fracture sets and deformation features in Thaynes Formation at thrust leading edge, left fork of Co-op Creek.

be interpreted in at least two ways, both of which are speculative, because the block is covered by conglomerate to the east and downfaulted by a later normal fault to the south. One interpretation is that this is a major block which has moved forward farther than the exposed Oquirrh-Thaynes sequence. It probably was detached in the southern part of the quadrangle and moved forward in strike-slip fashion. This would mean a block of the entire Permian-Triassic sequence has moved eastward farther than the exposed sequence and either is beneath the conglomerates of the eastern part of the quadrangle or has been eroded away.

A second interpretation is that this is a small block of predominantly Oquirrh rocks which moved forward, probably by gravity movement, and merely covered up the trends of the Permian-Triassic sequence, which would be present beneath it. The relationship is shown in figure 15.

The covering of this area by Tertiary and Quaternary deposits makes it difficult to determine which of these interpretations is correct, or if both are wrong. The rocks of this block are Oquirrh sandstones and quartzites, with some Kirkman present. The southern part of the block contains Oquirrh and Kirkman apparently thrust over Oquirrh that is older. Such a thing would occur in a situation similar to that seen in thrust slices 4 and 5 along Willow Creek. A small slice occurs on the overturned limb of a fold, allowing younger rocks to be thrust over older. The emplacement of this block would have to postdate the formation of thrust slices 4 and 5 but might possibly predate the formation of slice 6 if it is indeed truncated by 6. The actual relationship between this block and slice 6 is, however, uncertain because of poor outcrops. There is, however, a spectacular overturned fold in the Thaynes directly in front of this block which could have formed as the block was emplaced. So deciding whether this is a major feature or a minor one which "slid off" a larger fold is somewhat speculative without subsurface data or better surface outcrops.

THE SEVIER OROGENIC BELT

Thrust faults have long been recognized in a belt stretching from southeast Idaho and southwest Wyoming through Utah, and into southern Nevada. In central and northern Utah the Nebo, Charleston, Willard, and other thrusts (fig. 16) have been studied since the 1930s. Several studies—most notably those by Eardley (1934); Spieker (1936, 1946, 1949); Baker (1947); Baker, Huddle, and Kinney (1949); and Bissell (1952)—confirmed a more or less continuous belt of thrust faults through northern and central Utah.

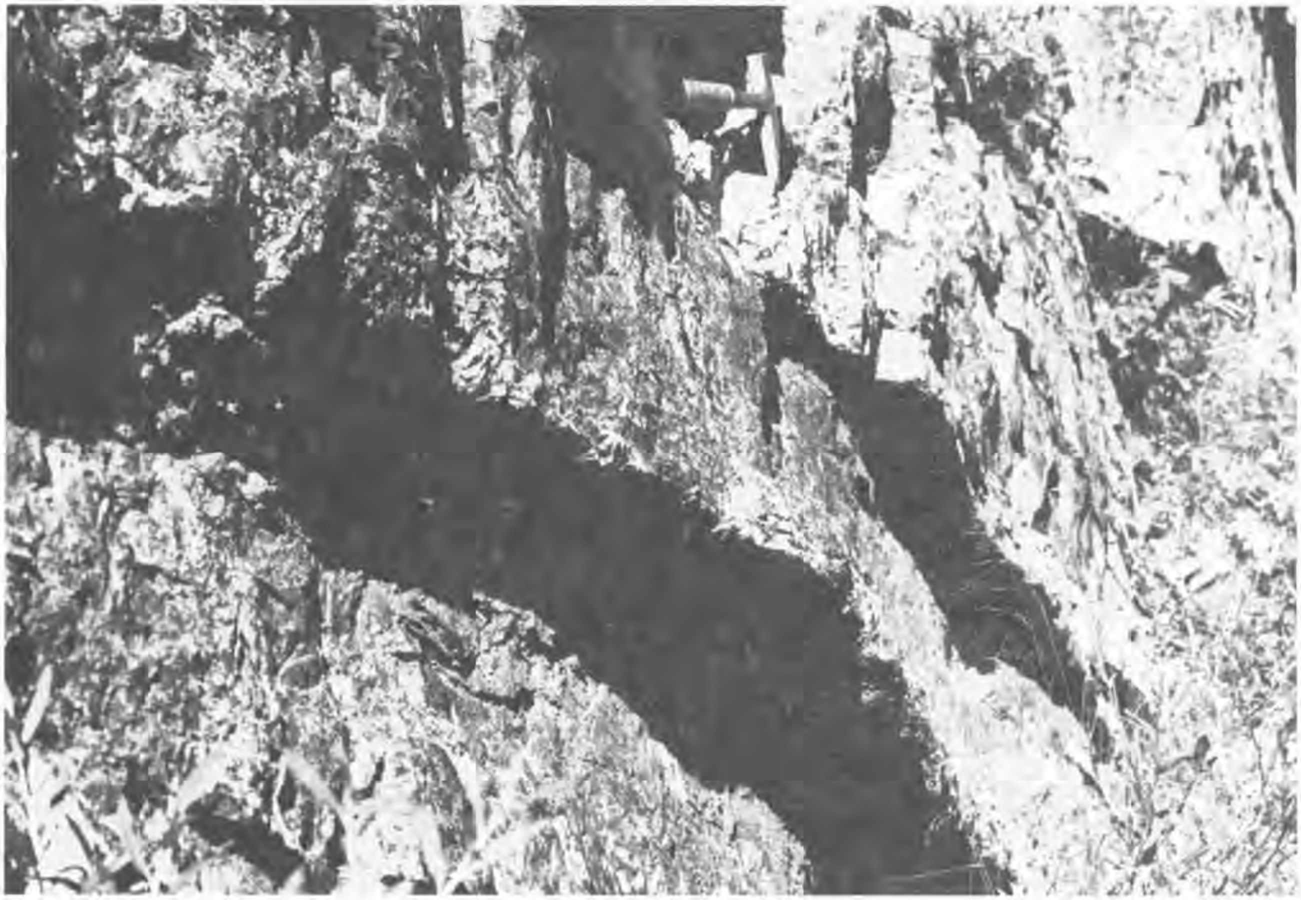

FIGURE 13.—Fractures in Thaynes Formation at leading edge, left fork of Co-op Creek.

This orogenic activity was considered to be a Cretaceous event. Speiker (1946) recognized the two major orogenic pulses in central Utah: the first during mid-Cretaceous, the second in middle to late Montana time. Eardley (1951) named Spieker's mid-Cretaceous disturbance the Cedar Hills Orogeny; the second event was considered Laramide.

Later, Harris (1959) postulated a Cretaceous high area in western Utah, calling it the Sevier Arch. Uplift of this arch culminated in regional thrusting from "southern Nevada northward at least as far as north-central Utah" (p. 2646). He concurred with others who had worked on the thrusts and called this thrusting "early Laramide." Armstrong (1964, 1968a) expanded on the work of Harris and others and proposed the name Sevier orogenic belt for this major zone of folding and thrusting, and coined the term Sevier Orogeny. He confined the Laramide Orogeny to vertical uplifts beginning in late Cretaceous (Maestrichtian) and ending by middle Eocene, and excluded major thrusting from the Laramide. He cited differences in age and characteristics of deformation, putting the age of thrusting in the Sevier belt as early Cretaceous to Montanan (Campanian) p. 451-52). These distinctions have largely been accepted, and today the thrust belt from southern Nevada to southwest Wyoming is generally considered a result of the Sevier Orogeny (Fleck 1970; Burchfiel and Hickox 1972).

The thrusts of the Sevier orogenic belt have been studied from southern Nevada to southeastern Idaho and southwestern Wyoming. Age of thrusting has been dated at Upper Jurassic (Mallory 1956; Crosby 1968, 1969; Armstrong and Oriel 1965) to late Cretaceous-early Tertiary (Hintze 1962, Black 1965; Crittenden 1969, 1974, Eardley 1969a). Estimates of the amount of displacement or shortening on individual thrusts vary from 10 to 20 kilometers (Hintze 1960, Eardley 1934, Black 1965) to 60 or more (Crittenden 1961, Fleck 1970). Armstrong (1968a, p. 441) said crustal shortening of 65 to 100 kilometers is reasonable across the whole belt. Opinions on the mechanism of deformation have also differed; Armstrong (1968a, p. 442), Burchfiel and Hickox (1972), and Fleck (1970) have proposed crustal shortening as the mechanism, whereas Crosby (1968, 1969), Eardley (1969a), and Rubey and Hubbert (1959) have invoked gravity sliding.

NEBO-STRAWBERRY-CHARLESTON ALLOCHTHON

Armstrong (1968a) considered the Nebo-Strawberry-Charleston allochthon as a major section of the Sevier orogenic belt. It is a major structural feature of central Utah, comprising most of the southern and central Wasatch Mountains (fig. 16). It has generally been considered to be a single block and is shown on most maps as such,

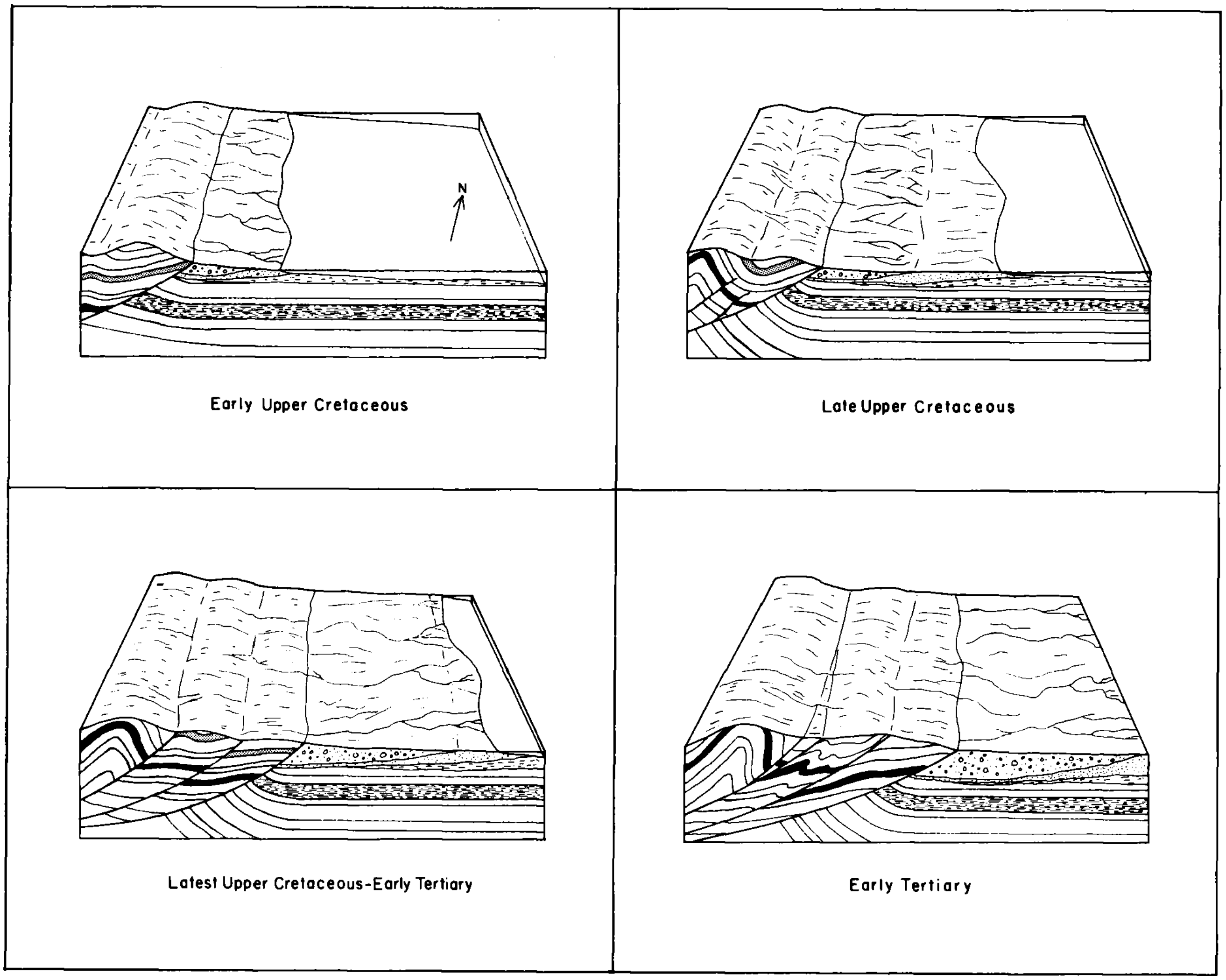

FIGURE 14.—Development of thrusting and sedimentary patterns for Co-op Creek Quadrangle, Upper Cretaceous to early Tertiary.

with the thrust inferred between Nebo and Strawberry Valley and between Strawberry Valley and Charleston. Eardley, however, said (1969b) the Nebo Thrust must die out to the northeast and the Charleston must die out southeast of the Strawberry Valley. This block has been thrust eastward farther than any other part of the Utah thrust belt, a fact which has been attributed to differences in response of the thick Oquirrh Basin sediments (Armstrong 1968a, p. 437).

The character and style of thrusting in the Nebo-Charleston block have been subjects of some disagreement. Bissell (1959, p. 164-165) said the Nebo-Charleston block developed from uparching and upthrusting which were controlled by earlier trends and deflection along the basin-shelf hingeline, with tear faults also contributing to the movement. Morris and Shepherd (1964) also postulated a major east-west tear fault at the southern end of the Nebo-Charleston allochthon. Bissell later (1962, p. 47) interpreted the Nebo-Charleston block as an *ecoulement* structure, transported by gravitational forces off a "geanticlinal welt" to the west; in other words, a gravity sliding mechanism. He stated movement may have been no more than 20 kilometers. Movement of only ten kilometers at Mt. Nebo could have been a result of buttressing in that area. Eardley (1969b) called the Charleston-Strawberry and Nebo thrusts gravitational slide masses.

Burchfiel and Hickox (1972, p. 58) suggested the geosynclinal sequence was detached from the crystalline basement rocks. The deformation produced by the thrusting was "of the type commonly considered as a result of horizontal compression" (p. 62). This compression moved eastward from western Utah, and where the sedimentary rocks were too thin to transmit these stresses, the thrust plates came to the surface and the geosynclinal sequence was carried over the platform sequence. The thicker Oquirrh Basin sequences caused stresses to be transmitted farther eastward, resulting in the increased eastward movement of the northern part of the Nebo-Charleston block. This concept is in agreement with Armstrong (1968a, p. 442), who also considered the major thrusts of the Sevier belt as results of crustal shortening.

Eardley (1934) studied the Nebo Thrust near Nephi, Utah, and postulated 21 kilometers of shortening on the Nebo folds and thrust. Hintze (1960) estimated mini-

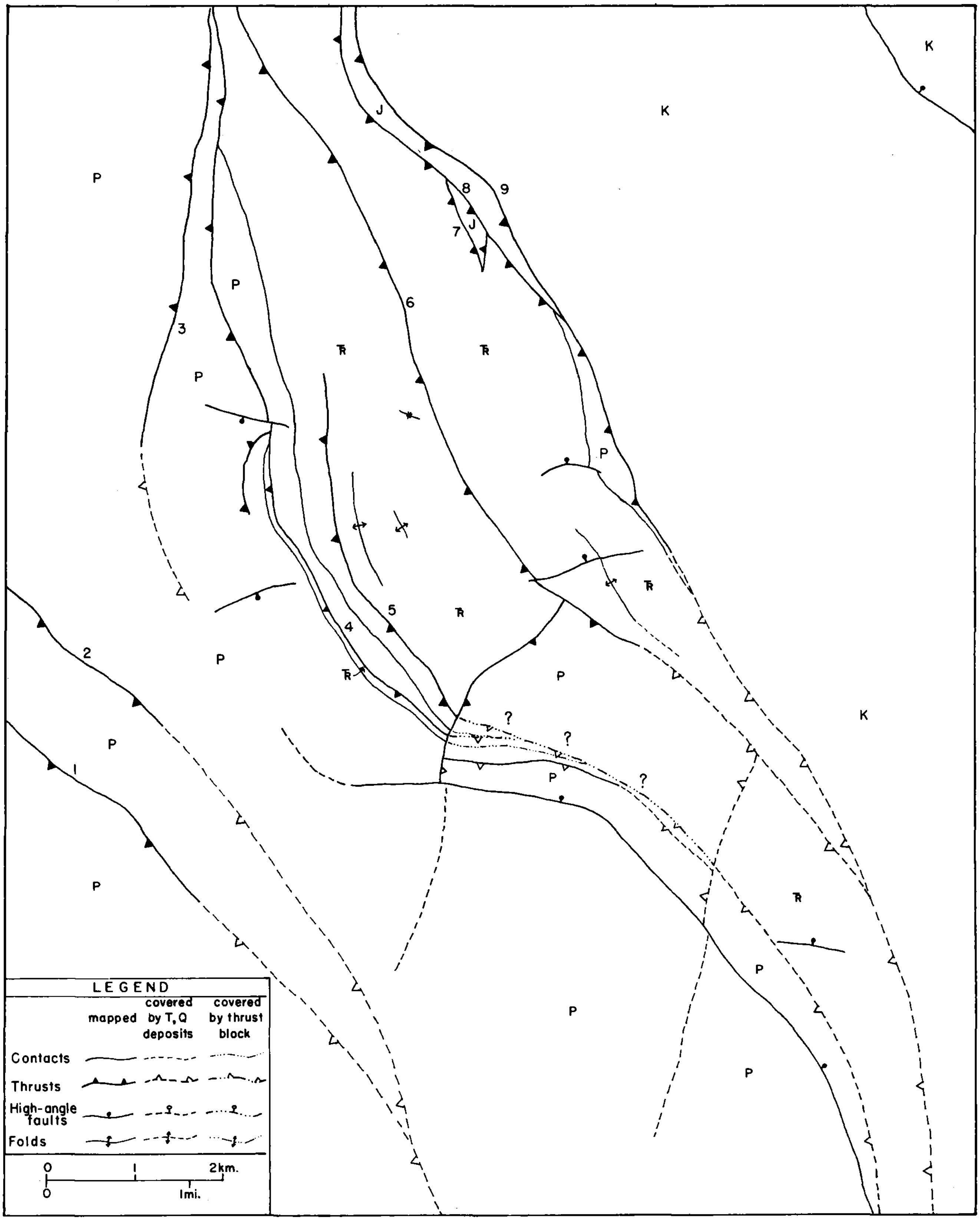

Figure 15.—Inferred structure, with Tertiary and Quaternary deposits removed.

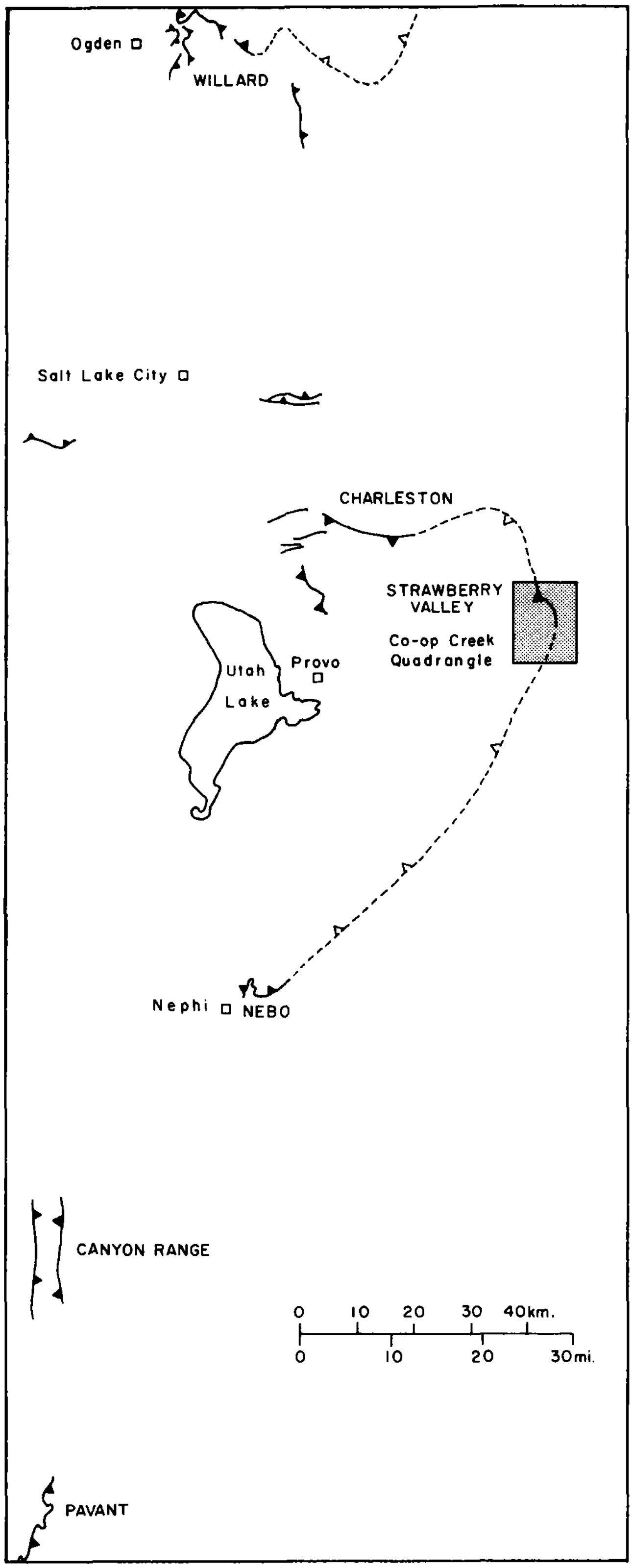

FIGURE 16.—Major thrust faults, central and south central Utah (after Hintze 1975; Bissell 1959).

mum horizontal displacement at 10 kilometers near Nephi, with total displacement possibly as much as 19 kilometers. Black (1965, p. 81) estimated displacement on the Nebo Thrust as 11 to 16 kilometers. Brady (1965) studied the Nebo and other thrusts in the southern Wasatch Mountains and concluded (p. 48) that the folds (and therefore the thrusts) of this area were due to regional compressional forces acting in an easterly direction. He generally discounted the gravity sliding hypothesis. He also postulated two pulses of orogenic activity: the first moving in a direction towards S. 21° E.; the second moving at N. 70° E. He also estimated horizontal movement in the southern Wasatch Mountains was not over 16 kilometers. Pinnell (1972) studied the Thistle, Utah, area, indicated that the continuation of the Nebo Thrust is present in the subsurface there, and estimated thrusting of at least 16 kilometers. Crittenden (1961) noted possible displacement of 65 kilometers on the Charleston-Nebo Thrust.

Fortunately, agreement is better concerning the age of thrusting of the Nebo-Charleston block. Bissell (1959) put development of the Deer Creek-Strawberry Valley and Nebo thrusts in the Cretaceous. Crittenden (1969, 1974) gave the age as Montanan: post-Santonian and possibly as late as Maestrichtian. Black (1965, p. 87) said the age of the Nebo Thrust is middle to late Montanan. Baker and Crittenden (1961) said movement on the Charleston Thrust occurred in late Cretaceous. These dates agree with Armstrong (1968a) and Burchfiel and Hickox (1972), who said major deformation in the Sevier belt ended before the end of the Cretaceous.

In summary, the Nebo-Charleston thrust block has been considered a single block, and more than one block. Proposed mechanisms for the thrusting have included gravity sliding and crustal shortening. Estimates of the amount of movement range from 10 to 65 kilometers, and age of movement is generally thought to be late Cretaceous (Montanan).

My study of the Co-op Creek Quadrangle has revealed information which can help clarify only one of these questions, that of the age of thrusting. Upper Montana Mesaverde beds are deformed by the thrust, indicating the thrust front reached the Co-op Creek Quadrangle in late Montanan, or possibly early Paleocene time. This age is somewhat later than those proposed for the Nebo-Charleston allochthon, but is reasonable because thrusting would be expected to occur later here, in the farthest eastward push of the orogenic front. This age determination, then, does not disagree with those already published.

The other two questions, those of amount of transport and mechanics of thrusting, are somewhat harder to determine. Most published figures for the amount of horizontal transport of the Nebo Thrust range from 15 to 20 kilometers. The fact that the thrust at Strawberry Valley is farther east does not necessarily mean it has traveled farther than the Nebo. The rocks now at the leading edge of the Strawberry Valley Thrust were detached from an area which now either is covered by the western part of the Nebo-Charleston allochthon or is west of the Wasatch fault, in which case it would be downfaulted and covered up. Stratigraphic and structural evidence I have seen in the Co-op Creek area does not help answer the question.

The mechanism of thrusting is equally difficult to resolve. As has been noted, both gravity sliding and crustal shortening have been proposed for the Nebo-Charleston block. The evidence that can be seen in the Co-op Creek area cannot realistically be used to decide one way or the other on this question.

GEOLOGIC HISTORY OF CO-OP CREEK QUADRANGLE

Up to late Cretaceous time, the two suites of rocks now in the Co-op Creek Quadrangle were several kilometers apart. Those of the allochthon were being deposited in the basin to the west; those of the autochthon were being deposited in place on the shelf. Basin rocks are generally thicker up to the Triassic; after that shelf and basin rocks show less variation in thickness. Basin rocks earlier than late Pennsylvanian are not exposed in the Co-op Creek Quadrangle, but are seen farther west on the allochthonous block (Baker 1947; Hintze 1973, p. 140). Autochthonous rocks older than late Cretaceous are exposed to the north and east of Co-op Creek (Bissell 1952; Huddle and McCann 1947).

From late Precambrian to late Jurassic time geosynclinal and shelf sequences developed in central Utah. The rocks now exposed above the thrust in the Co-op Creek Quadrangle and on the allochthon to the west were deposited on the easternmost edge of the Cordilleran geosyncline or in a transition zone between the geosyncline and shelf (Burchfiel and Hickox 1972, p. 55).

The oldest rocks of the Cordilleran miogeosyncline were deposited on a Precambrian basement complex metamorphosed 1.5 to 1.75 billion years ago (Armstrong 1968b, Burchfiel and Hickox 1972). They represent an eastward marine transgression which spread over both the "basin" and the shelf during the Cambrian. From Cambrian to Devonian time similar sequences of rocks were deposited in both geosyncline and shelf, these being marine sandstone, shale, and carbonate (Hintze 1973, p. 140, 144). Elevation of the late Devonian Stansbury uplift eroded away post-Cambrian deposits (Rigby 1959; Hintze 1973, p. 29). The result was the Cambrian-Devonian unconformity in both basin and shelf sequences.

Mississippian through Permian rocks show a great thickness difference between basin and shelf, one of the first evidences seen to indicate the presence of the Charleston Thrust, as thick and thin sequences were seen to be juxtaposed (Baker 1947, Baker 1959, Baker and Crittenden 1961). Both environments were shallow marine, with subsidence in the Oquirrh Basin accounting for the great thickness accumulated there.

Uplift occurred again at the end of the Permian, resulting in an unconformity between the Park City and Woodside formations. Armstrong (1968a, p. 444) proposed that this activity may have been initial uplift on the Sevier arch. Marine regression and transgression resulted in the Woodside, Thaynes, and Ankareh formations.

By late Triassic time, orogenic highlands developed in western Utah and were spreading eastward (Hintze 1973, p. 54, 58). Continental Gartra and Chinle deposits resulted from streams flowing northwest toward western Utah. Actual late Triassic conditions in western Utah are uncertain because of lack of strata preserved. In Jurassic and Cretaceous time, eastward movement of the Sevier orogenic belt probably left synorogenic deposits across western and central Utah, but these strata have also been eroded. A more complete record is seen in the shelf sequence. A great sand blanket covered the shelf and the eastern part of the former geosyncline, resulting in the Nugget Sandstone. The Twin Creek, Entrada, and Curtis formations represent another sequence of marine transgression and regression which followed the Nugget. The seas reached partially into western Utah but were blocked by the Sevier highlands. The marine Curtis Formation shows, according to Stokes (1972, p. 25), the first definite evidence of eastward sediment transport off the orogenic highlands. In late Jurassic and early Cretaceous the highlands moved farther toward the Co-op Creek area, causing erosion to the west and deposition of the Morrison and Cedar Mountain formations to the east (Stokes 1972, p. 23; Armstrong 1968a, p. 445-47).

Another marine transgression, recorded by the Dakota-Mowry-Mancos sequence, spread over the shelf in early Cretaceous. This seaway oscillated, producing shale and sandstone tongues by westward transgression and eastward regression (Hintze 1973, p. 72). By late Cretaceous (fig. 14) the Sevier thrust front was nearing the Co-op Creek area, forcing the sea out as it moved eastward. This regression is recorded by the Mesaverde shales and sandstones.

The thrust front advanced into the Co-op Creek Quadrangle in late Cretaceous or early Paleocene time. Upper Mesaverde beds, which are Upper Montanan (Hale 1972, p. 30), are deformed by the Strawberry Valley Thrust along the right fork of Co-op Creek. Thrusting was probably later in the Co-op Creek area than in other parts of the Nebo-Charleston allochthon, and could have been active into the Paleocene. The clastic debris shed off the highlands first contained much sand, as evidenced by the high proportion of sand in the lower part of the Tertiary conglomerate section. This clastic debris was deposited on the Mesaverde sands and shales; there was probably a great deal of local erosion in the Mesaverde strata. The conglomerates, then, would have begun to form in latest Upper Cretaceous (before and as the thrust sheet moved in) and continued into the Paleocene and possibly the Eocene, by erosion off the highlands after orogenic activity had ceased. Therefore some of the early conglomerates are probably Upper Cretaceous, but the majority are Tertiary. No strata younger than the conglomerates are present in the area, so the time of the end of conglomerate deposition cannot be known. The style of deformation therefore indicates thrusting is related to the Sevier Orogeny and occurred in late Upper Cretaceous and possibly early Tertiary time. Structures from later Laramide uplift were superimposed on the Sevier thrust structures.

Fresh-water lakes covered much of central Utah in the Paleocene and Eocene (Hintze 1973, p. 76, 80). Their apparent failure to reach into the Co-op Creek Quadrangle was due to the large amount of debris shed off the highlands. They were no doubt nearby, however, and the streams flowing off the Sevier highlands probably flowed into them. Oligocene time saw volcanic centers erupt nearby, producing an ash-flow tuff blanket north of the quadrangle (Bissell 1952). The area was uplifted, with the rest of central Utah, in Miocene time (Hintze 1973, p. 82), causing gentle folding of the entire area (as seen by dips on Mesaverde and Tertiary rocks) and normal faulting. The topography as it is today began to form and continues to the present. Glaciation affected the area in the Quaternary, as evidenced by fan deposits, terraces at lower levels, and glacial valley features at higher elevations. Increased precipitation undoubtedly caused an increase in erosion rates and allowed Oligocene ash flows to be eroded and ash flow clasts to be spread over some of the northern parts of the Co-op Creek Quadrangle.

ECONOMIC POTENTIAL OF THE CO-OP CREEK QUADRANGLE

Thrust faults are of interest to petroleum geologists, for hydrocarbon reservoirs are often associated with them. This association has been shown in the Canadian Rocky Mountains and Foothills (Fox 1959) and also in the Utah thrust belt northeast of Salt Lake City (Crittenden 1974).

Evidence gathered in the Co-op Creek Quadrangle indicates that this area has definite hydrocarbon potential. Nearby areas in front of and behind the Strawberry Valley Thrust should also be considered. Several formations of the Co-op Creek Quadrangle contain rocks at the surface that emit a fetid odor when broken or contain dead oil, as seen in thin section. They include the Oquirrh, Kirkman, Park City, Thaynes, Twin Creek, and Mancos formations. In addition, the Diamond Creek and Nugget formations, and possibly some Mesaverde beds, have good reservoir possibilities.

The presence of the thrust may be a good or a bad factor in determining hydrocarbon potential. Fox (1959) found that many traps in the southern Alberta foothills were intimately associated with thrust faults. Crittenden (1974) expressed the idea that thrusts northeast of Salt Lake City may be connected with those in southwestern Wyoming and suggested that structural traps may be present in the covered interval between. He suggested possible reservoirs in the Frontier, Nugget, Weber, and Humbug formations. The rocks of the Strawberry Valley Thrust may contain hydrocarbons at depth, either near the thrust front or in the folded sequences behind. On the other hand, thrusting could have destroyed possibilities for traps on the upper plate by intense folding, brecciation, faulting, or fracturing.

The rocks of the lower plate also have hydrocarbon potential. Many of the formations present in the subsurface have possibilities as source or reservoir rocks. They include the Weber, Park City, Thaynes, Nugget, Twin Creek, Dakota, and Mesaverde formations. Gentle folding at depth, associated with thrusting or later uplift, could provide traps in these rocks in the Co-op Creek Quadrangle or in areas to the west or east. Garvin (1969) suggested increased geophysical exploration in areas east of the Co-op Creek Quadrangle. He suggested the Weber, Dakota, Mesaverde, Wasatch, and Currant Creek formations as possible reservoirs, as well as Jurassic sandstones. Most of these formations are also present in the subsurface of the Co-op Creek Quadrangle (fig. 3).

Another possibility is that the thrust has overridden traps in the lower plate. Baker, Huddle, and Kinney (1949) reported the possibility of traps in the transition area where basin facies change to those of the shelf. This zone is now largely covered by the Nebo-Charleston allochthon. Armstrong and Oriel (1965) made a similar suggestion for the Idaho-Wyoming thrust belt. If present, these traps would be in the shelf rocks in or west of the Co-op Creek Quadrangle.

The covering of structural trends by Tertiary conglomerates in much of the Co-op Creek Quadrangle is a hindrance to interpretation, as has already been noted. This difficulty is evident in figure 15, which shows inferred trends of faults under this cover. This interpretation is based largely on mappable features and regional interpretations rather than subsurface data, so is somewhat speculative. It does, however, give a probable interpretation and could be of help if any subsurface work is done in the area.

To summarize, the Co-op Creek Quadrangle has definite hydrocarbon potential, as do other areas in the vicinity. With the data now available, it cannot be said if oil or gas is actually present, but the possibility is there, and further investigation of this possibility should be undertaken.

SUMMARY AND CONCLUSIONS

The main significance of my research has been to delineate further the structure of the area, provide a detailed geologic map, and investigate the area's potential for hydrocarbons.

From my study, the following conclusions are appropriate:

1. The Strawberry Valley Thrust consists of at least three major thrust slices and several minor ones. A large overturned fold occurs behind the frontal slices, and folding is less intense in slices closer to the frontal slice.
2. Large and small scale deformation in the thrust plate consists of folds, normal faults, brecciation, fracturing, crumpling of shale units, and squeezing of beds. The lower plate rocks are relatively undeformed except near the leading edge of the thrust.
3. The thrusting in the Co-op Creek Quadrangle is related to the Sevier Orogeny. The Sevier thrust front reached the area in late Upper Cretaceous (late Montanan) time and may have been active into the Paleocene. Later Laramide uplift caused normal faulting and gentle folding in the quadrangle.
4. Little evidence has been gained which would clarify problems concerning the mechanism of thrusting and the amount of horizontal displacement of the thrust mass.
5. The blanket of conglomerates shed off the thrust mass is largely an early Tertiary feature. It probably should not be considered part of the Uinta or Currant Creek formations. More extensive investigation of these conglomerates is needed to determine their exact age and stratigraphic relations with other units. They are therefore left unnamed.
6. The Co-op Creek Quadrangle has definite possibilities for hydrocarbon accumulations at depth. The following formations contain rocks which at the surface contain hydrocarbon shows: Oquirrh, Kirkman, Park City, Thaynes, Twin Creek, and Mancos. The Diamond Creek, Nugget, and Mesaverde formations have porosity and permeability favorable for reservoir characteristics. The best hydrocarbon potential in the quadrangle is probably in the rocks of the lower plate, which contain these formations or their equivalents. From the present study it is impossible to say how great those possibilities are, but they are encouraging enough to warrant further study.

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APPENDIX
MEASURED STRATIGRAPHIC SECTIONS

Kirkman Limestone

Complete section of Kirkman Limestone measured in northwest quarter of section 14, T. 2 S., R. 12 W., Uinta Meridian, on the west side of a small canyon north of Willow Creek. Contacts with underlying Oquirrh Formation and overlying Diamond Creek Sandstone are conformable.

Unit	*Description*	*Thickness (meters)*	*Cumulative Thickness*
2	Limestone; some sandy; medium gray to light brownish gray, weathers same or light pinkish gray; bedding thin to medium; forms slope of low, poor outcrops and float; some beds formed of limestone breccia-clasts often laminated; rock gives fetid odor when broken.	91	108
1	Limestone; light brownish gray to medium gray, weathers medium to light gray or grayish white; bedding thin to medium; weathers to angular rubble with blocky lined surface, sometimes mottled; some fractures, calcite veins; gives fetid odor when broken.	17	17
	Total thickness of Kirkman Limestone		108 meters

Diamond Creek Sandstone

Complete section of Diamond Creek Sandstone measured west of center of section 14, T. 2 S., R. 12 W., Uinta Meridian, approximately 300 meters northwest of the mouth of Willow Creek Canyon. Contacts with underlying Kirkman Limestone and overlying Park City Formation conformable.

Unit	*Description*	*Thickness (meters)*	*Cumulative Thickness*
2	Slope covered with vegetation and float; outcrops very poor; contact with Kirkman obscured by vegetation, somewhat uncertain.	38	78
1	Sandstone; buff, tan, white and yellow, weathers slightly darker; bedding thin, some beds silty; forms rounded outcrops with rubble and sand; grains rounded to subrounded and spherical to slightly elongate; good sorting, some clay impurities; porous and friable; some fine cross-bedding, fractures.	40	40
	Total thickness of Diamond Creek Sandstone		78 meters

Park City Formation

Complete section of Park City Formation measured in center of section 14, T. 2 S., R. 12 W., Uinta Meridian, at the mouth of Willow Creek Canyon. Contact with underlying Diamond Creek Sandstone conformable; contact with overlying Woodside Shale unconformable.

Unit	*Description*	*Thickness (meters)*	*Cumulative Thickness*
	Franson Member		
15	Covered slope. Rubble and a few low ledges of gray limestone and gray, cream sandy limestone; contact with Woodside Shale obscure.	70	434
14	Limestone, some sandy; gray, grayish tan; gray, grayish cream if sandy; weathers same; forms low ledges and angular rubble; abundant chert in some beds.	53	364
13	Limestone, siliceous; medium gray, weathers light gray to grayish tan; forms jagged ledges and rubbly slope of angular fragments; medium grained, hard, dense; contains chert nodules, some beds quite cherty.	57	311
	Total thickness of Franson Member		180 meters
	Meade Peak Member		
12	Limestone, shaly; dark gray to black, weathers dark to medium gray, some beds weather cream-colored; weathers to angular fragments with slight conchoidal break; some beds oolitic; gives fetid odor when broken.	56	254
11	Limestone, sandy, medium to light gray, weathers cream-colored; forms low ledges and angular rubble; at approximately 15 meters is prominent ledge containing poorly preserved fossils.	43	198
10	Limestone, medium gray to dark gray, weathers same; forms blocky ledges and low ridges; hard, phosphatic; gives fetid odor when broken; some beds shaly and weather light gray to cream.	38	155
	Total thickness of Meade Peak Member		137 meters
	Grandeur Member		
9	Covered slope containing float of gray, tan, and grayish tan limestone and sandy limestone.	34	117
8	Limestone; pinkish gray, weathers same; forms prominent ledge; surface lined from weathering effects; contains calcite stringers and veins.	2	83
7	Covered slope with rubble of gray limestone.	31	81
6	Limestone, coarse grained; light gray to grayish white; weathers slightly darker gray with brown stain; forms rubbly slope of rough, angular fragments with sugary, pitted surface; contains veins, pods of calcite.	6	50
5	Limestone, coarse grained; grayish white, weathers slightly darker gray with some brown stain; forms low ledges with rough, angular fragments; some lined, weathered surfaces.	12	44
4	Slope of dirt, sand, and small, angular fragments of limestone.	9	32

	Fragments gray and stained white. Sand is pink and pinkish brown. Near top is float of greenish gray shaly limestone.		
3	Limestone; gray, weathers dark gray with brown stain; forms two low ledges with rubbly slope between; numerous calcite veins; somewhat sugary appearance.	6	23
2	Limestone, sandy; white to light gray, weathers same, some brown stain; coarse grained; forms low ledges and rubbly slopes.	12	17
1	Limestone; gray to grayish white, weathers medium gray, brownish gray, light gray, somewhat mottled; bedding not apparent; weathers to low ridges and rubbly slope; weathered fragments angular with lined surfaces; fractures common.	5	5

Total thickness of Grandeur Member 117 meters
Total thickness of Park City Formation 434 meters

Thaynes Limestone

Complete section of Thaynes Limestone measured in eastern half of section 11, T. 2 S., R. 12 W., Uinta Meridian, along Willow Creek. Contacts with underlying Woodside Shale and overlying Ankareh Formation conformable.

Unit	*Description*	*Thickness (meters)*	*Cumulative Thickness*
16	Limestone, sandy; red, cream colored; some beds silty; top is light tan, buff calcareous sandstone.	7	330
15	Limestone, sandy; gray, tan, and brown; interbedded with thin-bedded green, greenish gray shale and gray limestone. Gray limestone weathers to low, blocky ledges and float.	24	323
14	Limestone; light gray, weathers medium gray; thin bedded to laminated at bottom, higher beds are slightly thicker with shell hash; forms prominent ledge; many shells larger than those of Unit 10.	2	299
13	Interbedded gray limestone and tan sandy limestone; forms low ledges and float-covered slope; ledges have some beds of shell hash; some chert stringers and nodules.	23	297
12	Limestone like that of Unit 10.	2	274
11	Limestone, small ledge like that of Unit 10, with sandy and silty limestone above and below; sandy and silty beds light grayish brown, weather grayish tan; laminated to thin bedded; weathers to low ledges and platy float; some fractures.	16	272
10	Limestone; light to medium gray with brown and tan stain, weathers light gray; forms prominent ledge; very fossiliferous, most beds a hash of shells; bedding up to 60 cm; forms high ledge with blocky, angular rubble which is somewhat pitted; some beds hard, somewhat siliceous.	7	256
9	Limestone; light gray, weathers medium gray; medium bedded; contains shell fossils.	9	249
8	Limestone, sandy; dark gray, weathers grayish tan; some fine-bedded green and greenish gray shale and shaly limestone interbedded.	21	240
7	Shale, shaly limestone; light greenish gray, grayish green, and reddish brown; thin bedded; interbedded with thicker-bedded (15-30 cm) gray limestone and brown sandy limestone; many shale beds crumpled, contorted.	7	219
6	Interbedded limestone, sandy limestone, shale, and shaly limestone; limestone light gray, weathers medium gray and contains shell hash; sandy limestone tan, buff, light brown, weathers same; shale and shaly limestone greenish gray, weathers same; shaly beds thinner bedded, crumbly; all beds weather to float, low ledges.	45	212
5	Limestone; medium gray, weathers light gray; ledge of fossiliferous limestone with float of medium gray to grayish tan limestone above; contains small fossils and chert stringers.	31	167
4	Limestone and shaly limestone; medium gray, weathers light gray to brownish gray; shaly beds very fine bedded to laminated.	35	136
3	Limestone; medium gray, weathers light gray to brownish gray, somewhat mottled on weathered surfaces; thin bedded (12 cm or less); some beds shaly-crumbly and have low ripple marks; shale beds more greenish gray; some limestone beds have poorly preserved shells.	40	101
2	Limestone; gray, grayish brown, weathers same; some beds shell hash; also interbedded gray, tan and buff sandy limestone; forms low outcrops and float-covered slopes, float angular, or platy if sandy; some beds have chert stringers, fractures.	52	61
1	Limestone, gray, greenish gray weathers brown; contains some poorly preserved shells; forms low ledges, angular float.	9	9

Total thickness of Thaynes Limestone 330 meters

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