THE WASATCH FORMATION IN THE CENTRAL BEAR RIVER RANGE, NORTHERN UTAH

by

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ABSTRACT

The study area includes the Naomi Peak, Tony Grove Creek, Mt. Elmer, and Temple Peak 7.5-minute quadrangles and the northern halves of the Logan Peak and Boulder Mtn. quadrangles. It lies in north-central Utah in the midst of the Bear River Range, which forms the north end of the Wasatch Mountains.

The Wasatch Formation in the study area was deposited in NNE-trending paleovalleys, some as much as 500 ft/150 m deep with 10% sideslopes, cut in folded and faulted Paleozoic bedrock. Abrupt onset of deposition of mudflows, debris flows, and openwork gravels followed movement on pre-Basin-and-Range normal faults that had created a lower central area of downfaulted blocks (graben) along an eroded (breached) anticline. The graben controlled locations of the paleovalleys. Algal limestones of the thin, lacustrine Cowley Canyon Member then spread across the filled graben and intervening upfaulted blocks (horsts) through much of the southern part of the study area. Fluvial deposition resumed with decreasing tectonics, shown by only minor offsets of the top of the Cowley Canyon Member and by no further lake deposits.

Locally derived cobbles and boulders dominate the lowest deposits of the Wasatch Formation, whereas clasts in deposits above the Cowley Canyon Member are more cosmopolitan, but still reflect derivation chiefly from bedrock units now exposed in the Bear River Range. Many boulders are quartzite, primarily from the Ordovician Eureka Quartzite, but a few are from the Late Proterozoic to Cambrian Mutual, Geertsen Canyon, and Worm Creek quartzites. Southward pinchout of the Eureka Quartzite near the middle of the study area shows that transport was from north to south.

It is proposed that: (1) Deep erosion and normal faulting of Paleozoic bedrock occurred as the combined Paris-Willard and Laketown-Meade-Woodruff Creek-Crawford thrust sheets were carried "piggyback" through a ramp anticline above a buried stack of thrust-sheet slices (duplex) at a thrust ramp in the Absaroka-Darby-Prospect sole thrust at a site west of the present study area; (2) Initial deposition of the Wasatch Formation, deposition of the Cowley Canyon Member, and minor additional faulting coincided with movement of the upper thrust sheet eastward, down the ramp anticline and onto the adjacent thrust flat; (3) Passive deposition of the main overlying part of the Wasatch Formation occurred while the thrust sheet continued moving eastward above the thrust flat toward its present position; NNE-SSW-trending folds and WNW-ESE-trending sags formed in the Wasatch Formation at this time, probably with local erosion and high-level unconformities; (4) Basin-and-Range normal faulting disrupted whatever drainage existed at the close

of deposition of the Wasatch Formation; (5) Although drainage may have been internal at first, later, westward-draining cross-axial streams (Logan and Blacksmith Fork rivers) formed across the divide formed by the high western part of the Bear River Range; (6) Deep dissection created oversteepened slopes that enhanced remobilization of the mud-rich Wasatch Formation and redeposition, at lower levels, of sediments that are virtually indistinguishable from the original Wasatch Formation; and (7) Much of the present topography of the Bear River Range is paleotopography, now being exhumed, that probably dates from the Paleocene or Early Eocene.

Springs are common along the basal contact, between the Wasatch Formation and underlying Paleozoic rocks, mostly carbonates. However, springs are very scarce within the Wasatch Formation. Although beds of openwork gravels are common, they seldom display lateral persistence, and most of them also are well cemented by $CaCO_3$ and so have little permeability. Mobility of the Wasatch Formation when wet, even on moderate to gentle slopes, suggests that care is needed in the placement of structures and roadcuts. Locally, especially in the northern part of the study area, openwork gravels may be abundant enough for supplies of gravel for roads. Analysis of seismic-reflection data from the bedrock below the Wasatch Formation along the south margin of the study area indicates that petroleum prospects are poor.

INTRODUCTION

Location and Physiographic Setting

The study area lies in the Bear River Range in north-central Utah (Fig. 1). The Bear River Range forms the northernmost part of the Wasatch Mountains (Fig. 2). It is a horst flanked by two graben, Cache Valley, just west, and Bear Lake Valley, just east. The study area occupies four 7.5-minute quadrangles and the northern halves of two more, between 41°41'15" and 42°00'00" N Lat and 111°30'00" and 111°45'00" W Long. (Fig. 1).

The Logan River dominates drainage in the study area (DeGraff 1976). However, tributaries of the Blacksmith Fork River are present in the south part of the study area, and short, west-flowing streams drain the area west of a NNE-SSW divide, along the Logan Peak syncline, north and west of Logan River. The Logan River, including its Right Fork tributary (Plate 4), forms a major cross-axial stream across the NNE-SSW topographic and structural grain of the Bear River Range, and drains west into Cache Valley. A short distance south of the study area, the Blacksmith Fork River forms a second major cross-axial stream that crosses the same topographic ridge.

The horst-and-graben structural style of the study area and of the terrane east to the Bear Lake Plateau (Fig. 2) suggests that it belongs to the Basin-and-Range province. The study area was included in the Middle Rocky Mountain physiographic province by Fenneman (1931) and by Hammond (1965). However, Best and Hamblin (1978) documented normal faulting up to 50 km east of the Fenneman line in central and southern Utah, and both Hunt (1956) and Shuey and others (1973), again in central and southern Utah, provided other geological and geophysical evidence that the transition is considerably east of the Fenneman line.

Purpose and Objectives

This project is the beginning of a major study of the Wasatch and Salt Lake formations in north-central Utah. Cache Valley and the Bear River Range form the starting nucleus for this overall study. The present project establishes the base for the overlying Salt Lake Formation, and documents depositional and tectonic conditions for the Wasatch Formation, which followed Sevier-Laramide thrusting, uplift, and erosion, and preceded major Basin-and-Range faulting.

This project fulfills two of the specified "Topics in Mapping Geology" of the Utah Geological Survey (UGS) for requested proposals to study the geology of Utah, for 1989:

1. Study of a major unconformity (Wasatch Formation over Paleozoic bedrock);

2. Detailed measurement of reference sections (Wasatch Formation);

Because no body fossils were found, a third objective, to establish the age of Wasatch Formation in the Bear River Range, was not successful. However, Dr. Fred E. May is studying palynology of samples of the Cowley Canyon Member in association with bedrock mapping of the Temple Peak quadrangle by R.Q.Oaks, Jr. (RQO) for the UGS, under Contract # 91-1599.

As additional objectives, this study provides geological information with practical application of importance to the State of Utah as follows:

1. Evaluation of petroleum prospectivity, through a Lopatin (1971) time-temperature analysis of the thermal maturity of bedrock underlying the Wasatch Formation, based on industry seismic-reflection data;

2. Characterization of the Wasatch Formation in the study area to assist or improve abilities to predict where this unit may be stable and where it will be unstable and prone to surface failure as slides, slips, and flows;

3. Documentation of places in the study area where failures already have occurred, so that these areas can be avoided; and

4. Determination of relations of springs to the base of the Wasatch Formation and to matrix-free gravels (orthoconglomerates) in the Wasatch Formation for possible local sources of potable water or critical sites of recharge into underlying bedrock aquifers that need protection from contamination.

Previous Work: Geologic Setting

Emplacement of the Paris-Willard thrust sheet (latest Jurassic to earliest Late Cretaceous (Wiltschko and Dorr 1983) was accompanied and followed by deep erosion (Williams 1948) in the study area. During the Early Eocene or Late Paleocene, a change in tectonic and/or climatic regimen in the present area of the Bear River Range converted this erosional terrain to a depositional one dominated by boulder-strewn fluvial and mass-flow deposits and occasional lake deposits that constitute the Wasatch Formation.

Davis (1903) and Hintze (1913) assumed a peneplained surface across the present Wasatch Mountains, covered by Wasatch Formation, and then block faulted to form the present Basin-and-Range. Beeson (1925), Gilluly (1928), and Eardley (1933) marshalled evidence for an erosional surface with at least 3000 ft/915 m of relief, and with "hanging valleys" at the mountain fronts, prior to Basin-and-Range faulting, in the present Oquirrh Range and in the

Wasatch Range south of Ogden Peak. Williams (1948) recognized 500 to 1000 feet/ 150 to 300 m of paleorelief at the base of the Wasatch Formation in the Bear River Range, in the study area. Dover (1985) showed considerable relief at the base of the Wasatch Formation locally in the study area, in his sections. Evanoff (1990) documented the presence of several large Late Eocene paleovalleys filled with Early Oligocene sediments in central and southern Wyoming, and reviewed earlier evidence of other Late Eocene paleovalleys, in Wyoming, Montana, and Colorado. Results of this study do not support the peneplain interpretation.

Wiltschko and Dorr (1983) summarized dating of conglomerates in the Intermountain area. They related several of the conglomerates to deposition in foreland basins formed just east of the advancing margins of successive thrust sheets from the Late Jurassic through the Middle Eocene. Blair and Bilodeau (1988) and Heller and others (1988) have suggested a general two-phase model of foreland sedimentation, based on other areas, wherein relaxation of compression plus erosional removal of the thrust load result in rebound, erosion of sediments in the proximal part of the foreland basin, and redeposition in the distal part of the basin. This model does not appear to fit the Wasatch Formation in the Bear River Range, although it may be applicable eastward for some of the Jurassic and Cretaceous conglomerates.

The Wasatch Formation in north-central Utah may be Early to Middle Eocene in age (Williams 1948; Hintze 1988). If so, its deposition on an erosional surface occurred atop the Paris-Willard thrust sheet, which was riding "piggyback" on lower, younger thrusts (Wiltschko and Dorr 1983). Ori and Friend (1984) originated the concept of a "piggyback" basin, in the Alps. Hurst and Steidtmann (1986) documented a "piggyback" setting for the Early Eocene Tunp Conglomerate Member of the Wasatch Formation just west of the uplifted leading edge of the Absaroka thrust sheet in western Wyoming. Beer and others (1990) used seismic-reflection data from a Late Cenozoic "piggyback" basin in Argentina to determine that at least two kinds of unconformities can result, the first by onlap due to "ponding," caused by thrust uplift, the second due to erosion during episodes of quiescence, caused by re-establishment of thrust-blocked master streams. Results of this study indicate an early episode of ponding. Folding and warping and reworked clasts of Wasatch Formation further suggest the presence of unidentified episodes of internal erosional truncation.

Wells and others (1990) concluded that Late Cretaceous extension took place on low-angle normal faults in northwest Utah (Raft River Range) and southernmost Idaho (Black Pine Mountains) above the sole thrust. Attenuation and elongation of stratigraphic units averaged about 160%, at low-grade temperatures of regional metamorphism (200°-350° C).

Hintze (1988) inferred that Basin-and-Range faulting, with dominance of north-trending normal faults, began about 17 million years ago (Ma) in the present area of Utah (also see Parry and Bruhn 1986). Older rocks are cut by normal faults, whereas younger units are mostly within modern basins (Hintze 1988). However, onset of extension accompanied by extrusive felsic rocks began as early as Late Eocene (39 Ma) and persisted to about 27 Ma near present Salt Lake City (Bryant and others 1989). Rapid regional extension did not begin in the present Salt Lake area until perhaps 21 Ma, based on the earliest known potassic basalts. Deposition of the post-Wasatch Salt Lake Formation in essentially modern basins probably had begun no later than about 11 Ma (Bryant and others 1989). Best and Hamblin (1978) proposed that basaltic igneous activity has shifted northward through time along the Wasatch Front. Brummer and Evans (1989) concluded that major post-Wasatch extension began along the west margin of the Bear River Range no later than Late Eocene or Early Oligocene.

The implication of these varying estimates is that onset of Basin-and-Range faulting may vary from place to place. The present study documents high-angle north-trending normal faults that both pre-date and post-date deposition of the Wasatch Formation and are parallel to Basin-and-Range faults.

Hamblin (1976) concluded that Basin-and-Range faulting has been episodic. His interpretation of successions of triangular faceted spurs along the Wasatch fault, near Brigham City (Fig. 2) and southward, suggests that each episode of rather rapid faulting created about 650 to 985 ft/200 to 300 m of vertical offset, followed by a shorter episode of stability. Hamblin (1965) showed that well-exposed Basin-and-Range faults (east of the Fenneman line) in the western Grand Canyon area curve and flatten westward with depth. Seismic-reflection results in north-central Utah, including those from Cache Valley published by Smith and Bruhn (1984), suggest a similar downward-flattening listric shape of major normal faults. In most cases these faults appear to flatten into west-dipping earlier thrust faults. Evans and Oaks (1989) showed that faults in and adjacent to the study area are very steep at the surface, in contrast to the speculations of Westaway (1989).

Gilbert (1928), Gilluly (1928), and Eardley (1933) concluded that cross-axial (E-W) canyons in the Wasatch and Oquirrh ranges are antecedent, and existed at the time of Basin-and-Range faulting. Hintze (1913) concluded that they are consequent following deposition of the Wasatch Formation, and formed in response to Basin-and-Range faulting. Results of this study suggest that the cross-axial stream valleys draining west across the Bear River Range post-date deposition of the Wasatch Formation. If so, the Logan River may have been subsequent eastward along a structural sag in the Logan Peak syncline, then consequent eastward on the Wasatch Formation along the same sag, and thereafter superposed across structures and paleorelief of the underlying Paleozoic bedrock.

Field Work

Field mapping, 70 days during the summers of 1989, 1990, and 1991, involved walking out the basal contact and contacts of the lacustrine Cowley Canyon Member, which lies near the base of the Wasatch Formation. Bedrock units underlying the Wasatch Formation were identified wherever possible, and faults and bedding attitudes were noted. Three additional field days were used to inspect Late Proterozoic and Paleozoic sandstones and quartzites at High Creek Canyon, Smithfield Canyon, Blacksmith Fork Canyon, and the southeast flank of the Wellsville Range, prior to mapping. Two days were spent laying out and then conducting a field review for the UGS, held on 18 October 1990.

Basic field equipment included: (1) Brunton compass in azimuth; (2) 16-power hand lens; (3) plastic bottle with 10% HCl; (4) grain-size chart; (5) rock hammer; (6) 35-mm Pentax camera and color film; (7) staff 4.9 ft/1.5 m long; (8) Munsell rock-color chart; (9) K & E surveyor's field notebook with percent estimation charts and stereonet pasted in; (10) U.S. Geological Survey 7.5-minute topographic quadrangle maps (scale 1:24,000, contour interval 40 ft/12 m); (11) U.S. Forest Service black-and-white vertical aerial photographs with stereoscopic overlap (1963; scale about 1:17,200); and (12) Thommen temperature-compensated altimeter (interpolated precision 5 feet/1.5 m; USU #5). Color aerial photographs, loaned by the Logan U.S. Forest Service Ranger Station, were used for final photointerpretations.

Mapping included slightly more than 2600 data points. Each observation site was marked on acetate overlays on alternate aerial photographs and on the appropriate topographic quadrangle map.

An altimeter reading was taken at each site. Repeated readings were made about every hour before leaving and after returning to camp, at lunch sites, at the field vehicle, and on return traverses. Additional control was added at stream forks, at road junctions, and at ridge crests, many with marked altitudes. From these control points, correction curves were constructed for observation sites in thick forest, areas clear-cut since the 1963 photos were taken, and other areas of little vegetation or other means of accurate location on the photos or topographic maps. Compass triangulation was added for some points.

For a baseline, prior to field work, RQO took simultaneous readings on a Paulin aneroid-barometer altimeter, which requires temperature corrections, and the Thommen altimeter about hourly in his office and at home, both in Cache Valley, for nearly two weeks in July 1989. The lowest readings occurred between 10 a.m. and 1 p.m. daily, followed by a steady gradual to rapid rise (at the same spot) of 75 to 145 ft/23 to 44 m until about 4 or 5 p.m., then a gradual rise or plateau until between 10 p.m. and 1 a.m., followed by a gradual decline to the lowest reading. In the Bear River Range, although conditions were less ideal, the same pattern prevailed. Rapid and erratic fluctuations in altitude readings resulted from wind gusts, strong winds, fast changes in cloud cover, rain, and low-pressure fronts. After these discoveries, such weather conditions were indicated in the field notes, and readings were made while facing away from the wind and with the altimeter shaded. Diurnal changes in the mountains typically were 100 to 200 ft/30 to 60 m between the low, 9 a.m. to 2 p.m., and the high, usually 7 to 9 p.m. Very rapid declines in altimeter readings occurred when driving to lower altitudes after the sun was shielded by ridges in late afternoon and early evening. Such declines were not noted in camp at similar times on other days. From the repeated altimeter observations, it is clear that parts of several topographic maps are in error by as much as 60 ft/18 m.

Mapping was straightforward except along tree-covered north-facing slopes, where the contacts usually are poorly exposed. Because of greater shade and moisture, the vegetation and surficial plant litter are more dense, soils are thicker, and slopes are steeper. Also, the likelihood of flowage of remobilized Wasatch Formation is greater, but seldom could be confirmed. As a result, the basal contact on many north-facing slopes is poorly constrained. Some places, such as the south side of the Right Fork of Logan River, are mostly photointerpreted.

Mapping Philosophy

Mud-rich portions of the Wasatch Formation often flow, ooze, and creep gradually (and sometimes rapidly) downhill when wet. This obscures other, more resistant lithologies of the unit, and also makes the basal contact of the Wasatch Formation appear more irregular than it really is. Distinct outcrops were noted, where present, whereas loose clasts in a red muddy slope were designated as "float." Remobilized Wasatch Formation considerably lower than its probable original position was mapped as QTw, if it had no headscarp, or as Qms, if it had a distinct scarp at the head (see Symbols, under Stratigraphic Units). Probably most of the area mapped as Wasatch Formation is remobilized, so an argument could be made that all of it should be mapped as QTw and Qms, or else mapped as Qc/Tw (see Berry 1989). However, the desirability of distinguishing original Wasatch Formation from subsequently remobilized deposits along canyons cut after onset of Basin-and-Range faulting made the use of two mapping units desirable.

Undoubtedly we have been conservative in designating areas as QTw, so that some areas mapped as Tw actually may be QTw. This conservative approach is required because there is evidence for considerable relief (Fig. 5) and for major offset on some of the normal faults prior to deposition of the Wasatch Formation (Fig. 4; Tables 1, 2) and some offset during deposition (Fig. 15). Thus, in some areas, especially the canyons that drain west across Temple Ridge (Fig. 3), some low-lying remnants (Fig. 16) could be original Wasatch Formation rather than remobilized. The failure to discover the Cowley Canyon Member above the escarpment of Temple Ridge in the northeast leaves open the possibility that the west-flowing canyons there today could in part be older, pre-Basin-and-Range paleovalleys backfilled with Wasatch Formation but they also may contain later reworked QTw deposited after renewed faulting.

Construction of Contour Maps of the Wasatch Formation

Figure 5 shows the base of the Wasatch Formation. Areas where the base intersects topographic contour lines are shown as solid lines, and other areas, as dashed lines. Where there is continuous cover of Wasatch Formation, the contact must lie below the level of any topographic contour line, so that the same contour line for the base must be uphill. Conversely, where the Wasatch Formation is absent, the contact must have been above the level of any topographic contour, so that the same contour line for the base must be downhill. Figure 3 shows that large areas lie wholly in bedrock and wholly in Wasatch Formation. Therefore, much of Figure 5, especially in the west, is based on interpolation and extrapolation, respectively. Large errors may be present in such areas.

Two other problems bedeviled construction of this map. First is the great number of faults (Fig. 4) and their rapid lateral changes in offsets (Table 1). The importance of this became apparent during analysis of data after the first field season. Thereafter, more attention was given to identifying the Paleozoic bedrock units and their contacts. This permitted independent determination of offsets of the Wasatch Formation and of the underlying Paleozoic bedrock. These offsets commonly are very different (Table 1) and, in some cases, opposed in sense of offset (Plate 7). In places, these conclusions are based in part on tentative identifications of rather similar Cambrian units, and so are subject to modification when more detailed mapping of bedrock in the Temple Peak quadrangle is completed (UGS Contract No. 91-1599). Some changes in Tables 1 and 2, Figures 4 and 16, and Plates 4, 6, and 7 are likely.

Secondly, the Wasatch Formation has been folded locally (Fig. 14), probably during "piggyback" transport. Fold axes trend NNE, and exhibit WNW-trending highs ("crests") and lows ("sags"). The apparent depths of the sags may be accentuated by unrecognized downslope flowage (QTw), especially along the south side of the middle part of the Right Fork of Logan River (Plate 4). As a further complication, there may be a minor unmapped fault along the Right Fork, although its presence is not necessary to explain the linear nature or trend of Right Fork along a WNW sag. The combination of faulting, folding, and renewed faulting made contouring the base of the Wasatch Formation difficult.

Figure 6 shows present thickness of the Wasatch Formation. It was constructed by subtracting values of the contours of the base (Fig. 5) from those of the present surface where the two crossed. Any errors in Figure 5 and in the surface topographic contours will carry over directly to Figure 6. Thicknesses shown are likely to be underestimated somewhat beneath interfluves due to a systematic bias in contouring the base of the Wasatch Formation (Fig. 5) with equally spaced contours in covered areas.

Figure 7 shows contours of the top of the Cowley Canyon Member. Where the top was removed by erosion, especially in the southeast and southwest, 100 ft/30 m was used as a reasonable average thickness added to the altitude of the base. Where absent due to erosion, extrapolations across faults are based on nearby similar offsets of the base of the Wasatch Formation and of Paleozoic bedrock units.

CHARACTER OF THE WASATCH FORMATION

Definition and Limitations

Hayden (1869, p. 90) applied the name Wasatch Group to deposits of the Almy, Fowkes, and Knight formations, exposed in Echo and Weber canyons in the Wasatch Range southeast of Ogden, Utah. Richardson (1941, p. 33) reduced the status of this unit to Wasatch Formation in the Randolph 15-minute quadrangle, which adjoins the east boundary of the present study area. Williams (1948, p. 1144-1145) recognized and named the Cowley Canyon Member, and described a measured section, 83 ft/25 m thick, located 0.9 mile/1.5 km south of Right Fork of Logan River on the east side of Cowley Canyon. His section lies 0.54 mile/0.87 km due south of the base of the Cowley Canyon measured section of this report. Williams (1948) believed the Wasatch Formation is correlative with the basal Almy Formation in the type area, based on the presence of algal limestones in the "Almy" Formation in the Jackson Hole area and the presence of a bed of tuff, similar to those present in the Fowkes Formation, in the Wasatch Formation 8.75 mi/14 km south of the study area.

Characteristics of the Wasatch Formation reported herein are valid only for the lower part of that unit and only in the study area. For example, no tuffs and only scattered granules of volcanic clasts were found in the lower part of Wasatch Formation in the study area. Yet Richardson (1941) found lenses of rhyolite tuff in the Wasatch Formation in the Randolph quadrangle west of the road between Woodruff and Randolph, Utah, and RQO (unpublished observation with L.W. McClurg, 1969) found numerous heavily weathered cobbles of felsic volcanics in the Wasatch Formation in the roadcut just east of Sweetwater resort, between Garden City and Laketown, Utah (Fig. 2). Further search for such volcanics is needed, to establish the time of onset of volcanic activity in the region relative to the time of deposition of the Wasatch Formation.

Criteria for Recognition

The Wasatch Formation is recognized by its:

(1) characteristic red color and muddy cobble- to boulder-bearing conglomerates;

(2) distinctive white-weathering algal-oncolite limestone member near the base (Cowley Canyon Member);

(3) poor degree of lithification overall (except limestones and openwork sands and gravels); and

(4) stratigraphic position above folded, faulted, and deeply eroded Paleozoic bedrock; below white, tuffaceous beds of the Salt Lake Formation

along sides of modern graben valleys; below Quaternary deposits with original depositional topography in the Bear River Range; and intertongued with the Green River Formation in the Bear Lake Plateau just east of Bear Lake.

Distribution, Topographic Expression, Vegetation, and Springs

In the study area the main part of the Wasatch Formation fills paleovalleys, and remnants of it still cover crests of many paleodivides in the downfaulted central part of the Bear River Range. To the east, the Wasatch Formation also covers the eastward-sloping bedrock surface east of the crest of Temple Ridge (Fig. 3), and is present as a small, possibly infaulted remnant where Temple Fork issues from Temple Ridge (Fig. 16). It is generally absent, although probably eroded, from the dissected crests of high ridges and adjacent valleys along the Beirdneau Peak-Naomi Peak divide in the west. Small cemented patches of red sandstone of the Wasatch Formation, less than 3 ft/1 m in diameter, still cling to the Paleozoic bedrock in the uplands just west of Tony Grove Lake (Plate 1) and on the southwest side of Blind Hollow (Plate 3). Such patches commonly are too small to show at the map scale of 1:24,000. Unless reworked and cemented by subglacial processes, the patches west of Tony Grove Lake suggest that the second steep topographic step above the lake existed prior to glaciation.

The Cowley Canyon Member is common in the southern part of the study area. There it thickens locally above some paleovalleys (Fig. 15), and extends across many divides. South of the Right Fork of Logan River, it extends to the westernmost and highest present outcrop of the Wasatch Formation and eastward to the edge of the study area (Plates 5-6, 7: Sections I-J and K-L). Immediately north of the Right Fork, it occupies the downfaulted central area, but fails to crop out in uplands to the west or east (Plates 3-4, 7: Section F-G-H). Farther north, it is known only from one locality, in the downfaulted central area northwest of Spawn Creek (Plate 4). It was not found in the uplands east of Temple Ridge, north and east of Temple Fork. In several places (compare Williams, 1948, p. 1145) it rests on Paleozoic bedrock across paleodivides, but overlies thick fills of typical red Wasatch Formation above some deep paleovalleys. For example, just west of Long Hollow, along the Right Fork, the Cowley Canyon Member overlies at least 300 ft/90 m of Wasatch Formation above Cambrian dolostones, but 3000 ft/915 m west, it rests on the Paleozoic bedrock (Plate 7: Section F-G-H).

The hillslope profiles of the Wasatch Formation usually are convex-up nearly to the base, typical of a dominance of mass wasting rather than running water (Gilbert 1909). Slope-parallel profiles tend to be linear to convex-out, typical of neutral and water-spreading slopes, respectively (Bloom 1991). The drainage texture is moderate to more typically coarse, with tributaries widely spaced. Valley walls usually have moderate to gentle slopes, and valley bottoms commonly are open and flat in cross profile. Infiltration is poor, so that during heavy rains drainage often is rapid as overland runoff. Thus, roads quickly become slick and rutted when wet, but generally dry rapidly except at lows where water collects and in deep shade.

In many places the present drainage (Fig. 8) flows roughly north or south (Fig. 9). Generally the north-south stream segments follow paleovalleys filled with thick Wasatch Formation. The degree to which differential compaction has concentrated the modern streams in older drainage courses is unknown, because the paleovalleys often are bounded by NNE-SSW-trending pre-Wasatch normal faults, many of which were reactivated during Basin-and-Range faulting, and the paleovalleys are just now being exhumed. Thus, structural control probably is more important than compaction in concentrating drainage above the paleovalleys.

On gentle to moderate slopes where the Wasatch Formation thins to a feather edge, the basal deposit commonly is 3 to 10 ft/ 1 to 3 m thick, and consists of red mud with white boulders of Eureka Quartzite. This deposit often has deep shrinkage cracks and a cover of mule ear dock. Just upslope, where the unit thickens, a nearly impenetrable thicket of chokecherry projects downhill due to the weight of winter snows. Somewhat misleading are similar sequences of regolith and of bands of vegetation on shales of the Cambrian Bloomington Formation where quartzite clasts from the Wasatch Formation have worked their way downhill. Where the Wasatch Formation is thicker, aspens with an understory of grasses and black-eyed Susans are abundant on crests and moderate slopes. Aspens are typical of unstable slopes, and may indicate gradual flowage of the surficial material by creep and solifluction. Conifers are abundant on steep north faces and on higher, wetter crests. Sparse maples often mark the Cowley Canyon Member, especially on south- and west-facing slopes. Maples also are present near faults and on some of the Paleozoic bedrock units. Bunchgrass grows along the base of the Wasatch Formation near small springs and seeps. Widely spaced mountain mahogany is common on dolostones, and locally on limestones, in lower, drier settings. These often lie just below the Wasatch Formation, and provide a rather reliable marker for the base.

Springs, present in numerous places, are concentrated along the base of the Wasatch Formation. They commonly lie at small (first-order) drainages where the contact slopes away from paleodivides. Most springs at higher levels are along faults or are related to slumps. Apparent exceptions include Hunsaker, Long Hollow, Sidehill, Trail Hollow, Trigaro, and two unnamed springs, all in the SE quarter of Plate 4. Elsewhere, springs within the Wasatch Formation that are away from known faults or failures are less densely spaced. No extensive aquifer-quality gravels were recognized in the study area, probably because of the lenticular nature of openwork gravels, their cementation by $CaCO_3$, and cover by flowage of mud-rich layers.

Stratigraphic Relations

In the study area, the Wasatch Formation overlies folded, thrust-faulted, normal-faulted, and deeply eroded bedrock. In the southeast, it overlies Late Proterozoic to Early Cambrian Geertsen Canyon Quartzite near Danish Dugway (Plate 6). Westward it overlies successively younger Paleozoic units including the Mississippian Little Flat Formation (Plate 5). West of the study area, the Wasatch Formation overlies the Pennsylvanian-Permian Oquirrh Formation at the north end of the Wellsville Range (Williams, 1948). Southwest of Baxter Pothole in the Mantua 7.5-minute quadrangle, the Wasatch Formation appears to overlie the Oquirrh Formation with angular unconformity and is in turn overlain with angular discordance by the Salt Lake Formation (compare Adamson and others 1955; Williams 1964).

Age

No age dates exist for the Wasatch Formation in the area of study. Three samples from the Cowley Canyon Member submitted by RQO were analyzed for palynology by specialists at Chevron, but no diagnostic materials were found (T.W. Schirmer 1990, written communication). Dr. Fred E. May has collected samples with RQO, and is presently analyzing them in collaboration with UGS Contract #91-1599.

From Wasatch Formation 12 miles/20 km south of the study area, Williams (1948, p. 1146) reported snail and plant fossils that were assigned to the Early or Middle Eocene by F. Stearns MacNeil (written communication to Williams). Based on fossil evidence elsewhere (reviewed by Hintze, 1988) and on intertonguing relations with the Green River Formation just east and south of Bear Lake (McClurg 1970; Coogan in press a,b), the age of the Wasatch Formation in the study area is likely between Late Paleocene and Middle Eocene.

Age assignments of the Salt Lake Formation, which overlies the Wasatch Formation in the Cache Valley area, include:

(1) Middle or Late Pliocene age of plant fossils, along the Little Bear River between Paradise and Hyrum, Utah (Brown 1949);

(2) Pliocene (possibly Late Pliocene) age of 20 species of mollusks (Yen 1947) in the Junction Hills, north of Cutler Dam; and

(3) Potassium(K)-argon(Ar) radiometric age dates of approximately 71 Ma (average of 2 dates; Late Cretaceous! Big Spring Hollow, southern Cache Valley); 58 Ma (average of 2 dates; Late Paleocene! Big Spring Hollow); 19 Ma (Early Miocene; Junction Hills); and 12 Ma (Middle Miocene; Junction Hills)(Williams 1964).

Thirty-one fission-track and K-Ar radiometric age dates from the Salt Lake City region suggest a shift from more basic extrusives, with hornblende and pyroxene, between 27 and 39 Ma (Late Eocene to Late Oligocene), to more felsic volcanics, between 4 and 10 Ma (Late Miocene to Early Pliocene)(Bryant and others 1989). These authors correlated the latter volcanism with the Salt Lake Formation and with onset of rapid extension. They inferred that extrusion of potassium-bearing basalts about 21 Ma (Early Miocene) signalled the beginning of Basin-and-Range faulting in the present area of Salt Lake City, but that the major modern basins did not originate until perhaps about 11 Ma.

If the analysis of Bryant and others (1989) is correct, and if the youngest Wasatch Formation is no younger than Middle Eocene, the period between 40 and 11 Ma lacks a depositional record in the Bear River Range. Furthermore, if major valley formation began about 11 Ma, then the major cross-axial streams may be of that age. Alternatively, if the Logan Peak-Beirdneau Peak-Naomi Peak divide was not breached at that time, the cross-axial Logan and Blacksmith Fork Rivers may have required some time to cut headward through that divide. The persistence of the thin blanket of Wasatch Formation in the downfaulted central part of the study area for the past 40 Ma or so suggests that headward erosion across the divide and integration of each of the two major cross-axial drainages has been rather recent. Thus, internal drainage perhaps was dominant for much of that time.

Texture, Sedimentary Structures, and Color

General Statement

The Wasatch Formation consists of three principal lithologies: (1) mudstones and mud-rich (> 15% mud) diamicton (paraconglomerates) (Pettijohn 1975) with boulders and cobbles common and unlaminated mud matrix; (2) Openwork conglomeratic sandstones to sandy cobble-bearing polymict (multiple types of rock clasts) orthoconglomerates, usually cemented with $CaCO_3$ and containing little mud; and (3) oncolitic (algal) limestones of the Cowley Canyon Member.

In rare roadcuts, gully exposures, and other natural outcrops, the mudstones and paraconglomerates generally appear to be more abundant than orthoconglomerates, at least above the Cowley Canyon Member, but may be slightly less abundant below it. In the section measured above Tony Grove Lake (Fig. 10), where the Cowley Canyon Member is absent, orthoconglomerates constitute 60 to 70% of the exposure. At the section measured along the east wall of Cowley Canyon (Fig. 11), where the Cowley Canyon Member is present, orthoconglomerates constitute 57% below the top of the highest algal limestone, paraconglomerates constitute 30%, and algal limestones, 13%.

In the steep east wall of Ricks Canyon, from near the end of the upland road north from Marie Spring (Plate 6), there are three "packets" of poorly exposed boulder-bearing (ortho?)conglomerates over mud-rich, boulder-poor diamicton in regular succession just below the Cowley Canyon Member, between 7475 ft/2280 m and the fault near 7250 ft/2210 m. The boulder-rich upper parts of each packet are about 20 ft/6 m thick, as are the mud-rich lower parts of the upper two packets, but the mud-rich basal part of the lower packet appears to be more than three times as thick. Clearly, this sequence, some 225 ft/69 m thick, exhibits cyclic deposition. Elsewhere, flowage of the mud-rich lithology downhill generally obscures such evidence.

Each of the different lithologies is discussed separately below. Considerable reliance is placed on the two detailed measured sections (Figs. 10, 11), because they are unusually well exposed. From extensive observations throughout the study area, it appears that lithologic data from these two exposures probably are representative of the lower part of the Wasatch Formation.

Paraconglomerates and Mudstones

Paraconglomerates in the Wasatch Formation range from deposits wherein the clasts form a framework with an infilling ("groundmass") of sand and 15 to 20% mud to a mud-rich deposit in which the clasts are widely separated and appear to "float" in the groundmass. Such deposits probably represent the spectrum from debrisflows to mudflows, respectively. When the gravel falls below 25% and the total of sand plus gravel is exceeded by mud, the deposits grade into conglomeratic mudstone and then to mudstone. Because of poor exposures, it is difficult to determine the relative abundance of the different kinds of paraconglomerates and mudstones.

Although there are exceptions, the average maximum size and the largest clasts usually are in the paraconglomerates. Often the largest clast exceeds 2 ft/0.6 m, and float of Eureka Quartzite on unglaciated ridges locally exceeds 6 ft/2 m. Sorting is poor to very poor, and size grades commonly are bimodal with mud and cobbles or boulders dominant. The larger clasts, even quartzites, are usually subrounded to rounded with a range from angular to well rounded. Cobbles and finer gravel sizes are successively less rounded. Larger clasts are usually equant, subequant, or tabular in shape, whereas pebbles and granules often are also bladed. Graded bedding and alignment of elongate clasts are uncommon. Although calcareous in many places, the paraconglomerates are rarely cemented, and commonly are noncalcareous. The absence of $CaCO_3$ may result from near-surface weathering.

Overall, clasts of both para- and orthoconglomerates are smaller in the north. Possibly this reflects a generally younger part of the Wasatch Formation than deposits exposed in the south. This finer clast size was fortunate, for it facilitated discrimination of glacial till in the downfaulted central area in the north. The till generally has larger clasts, mainly Ordovician through Silurian units, than the Wasatch Formation does.

Sedimentary structures are difficult to observe. At the Tony Grove section, individual beds of paraconglomerates were 1.48 and 9.8 ft/45 cm and 300 cm thick, respectively. At the Cowley Canyon section, individual beds of paraconglomerates cannot exceed 11.5, 13, and 14.75 ft/ 350, 400, and 450 cm, and mudstones are 0.6 ft/20 cm and no more than 3.3 ft/100 cm thick. Local exposures show paraconglomerates filling shallow scours in places and overlying uneroded depositional bedding surfaces elsewhere. The evidence suggests a passive role during deposition, and suggests an origin as mudflows and debrisflows.

Weathered colors are reddish browns to dusky reds to browns, 5R4/2 to 5R3/4 to 10R4/3 to 5YR4/2 (Munsell color solid). Fresh colors are reds, 10R5/6 to 10R4/4 to 5R4/6. Locally mudstones are bleached nearly white, commonly just below organic-rich soils, and thus superficially can resemble the Salt Lake Formation from a distance. Excavation shows that such bleached deposits grade laterally into typical red mudstones of the Wasatch Formation.

Orthoconglomerates and Sandstones

Orthoconglomerates of the lower part of the Wasatch Formation usually have much more sand and less mud and boulders than the paraconglomerates. The content of cobbles is highly variable, and cobbles may be absent. The orthoconglomerates usually have a gradation of sizes, and so are less distinctly bimodal than the paraconglomerates. Boulders rarely reach 3 ft/1 m. Sorting ranges from moderate to very poor, although mud often is lacking or present only in minor amounts. The larger clasts are usually rounded to well rounded, but range to subangular. Broken fragments of rounded clasts are present. Finer clasts are successively less rounded: granules usually range from angular to subrounded, whereas pebbles typically are subangular to

rounded. Larger clasts are usually equant, subequant, or tabular in shape, whereas pebbles and
granules often are also bladed. Perhaps one-fourth of the orthoconglomerates in the measured sections showed normal graded bedding, whereas the others were not graded. Elongate clasts are aligned in many beds, although strong imbrication appears to be rare. Alignment is better developed where clast sizes are finer. The exposed orthoconglomerates and float of orthoconglomerates are cemented by calcite. In the Cowley Canyon section (Fig. 11) three orthoconglomerates, centered near 33, 46, and 82 ft/10, 14, and 25 m above the base, appear to have been deposited in shallow water, for they contain uniform calcite cements, spar in the lower bed, and micrite in the upper two, with colors typical of limestones of the Cowley Canyon Member. Most other orthoconglomerates are only partially cemented with nearly white to red-stained microspar or spar calcite.

Sandstones range from pebbly and granular, and are coarse or medium grained to silty very fine grained. At the coarse end, they grade into orthoconglomerates, and, at the other extreme, into mudstones. The coarser sandstones tend to be more firmly cemented, with calcite, than the finer sandstones.

Sedimentary structures are observed more frequently in sandstones than in paraconglomerates. Better outcrops at the Tony Grove section permitted description of individual beds near the top and base, whereas less complete exposure at the Cowley Canyon section required more lumping of beds into depositional packets. However, individual beds were measured where possible at the Cowley Canyon section, and clasts were taken from the same bed. Seventeen beds of orthoconglomerates in the two measured sections ranged from 0.56 ft/17cm to 4.2 ft/129 cm, and averaged 1.9 ft/60 cm. Bedding surfaces typically are irregular wavy to planar to shallow scours, and beds are wedging (mostly at the Tony Grove section) to parallel (mostly at the Cowley Canyon section). The evidence suggests overall aggradation by sheet-like flows, perhaps braided flows. However, the scarcity of widespread channeling suggests that much of the deposition may have been by sheetfloods. The wide variation in sorting, in sizes of bedload, in composition of clasts, and in thickness of bedding suggest that each bed represents a discrete flood event.

Weathered colors of orthoconglomerates are reds to light reds to pale browns to light gray, 5R7/3 to 10R4/4 to 5YR7/2 to N6. Fresh colors are reds to light browns to pale gray, 5R6/4 to 10R5/6 to 5YR7/3 to 10YR6/4 to N8. The sandstones have similar colors.

Limestones

Limestones have been found only in the Cowley Canyon Member, which is confined to the lower part of the Wasatch Formation (Fig. 7).
Limestones of the Cowley Canyon Member usually form two packets separated by a few meters of typical red deposits containing a distinctive "pink" (5R6/4) pebble to granule orthoconglomerate or conglomeratic sandstone. On hillsides, these limestone packets often form two distinct but discontinuous white-weathering cliffs.

Both limestone packets contain oncolites, algal-laminated beds, and redeposited fragments of similar beds. Oncolites in the lower sequence commonly are smaller, mostly 0.5 to 1 inch/1 to 2 cm in diameter. Those in the upper sequence are often much larger and often less abundant. Some oncolites reach 0.5 ft/16 cm, and have cores of terrigenous detritus that reach the size of small cobbles. Also present in the upper limestones are oncolites shaped like dog bones, bulbous at both ends. Some of these exceed 1 ft/30 cm long and 4 inches/10 cm in diameter at the bulbous ends.

Clasts of algal-laminated limestones are angular to subrounded, and some exceed 1 ft/30 cm long. Distance of transport was probably short. Growth bands in the algal laminae are mostly 1 to 2 mm apart. Bedding is generally wavy parallel and 1 to 4 inches/2.5 to 10 cm thick. Elsewhere, algal-bedded limestones drape over pre-existing low mounds of older algal beds or orthoconglomerates to form curved, wedging beds that pinch out abruptly. Here and there, isolated algal domes are present and have up to 9 inches/24 cm of synoptic relief. Williams (1948) identified "bioherms" up to 4 ft/1.2 m wide just south of the Cowley Canyon section, but none were recognized in that section. However, dips measured in limestones of the Cowley Canyon Member are anomalous, for they typically dip into the outcrop, often opposed to obvious overall dip. Small mesa-like outcrops commonly have concentrically inward dips, and considerable evidence of draping. The draping resembles small bioherms. One possibility is that small bioherms are abundant, and break off preferentially near the middle of their dome-like structures, so that inward-facing dips predominate. Elsewhere, interlayered orthoconglomerates resemble short, steep foresets of small dunes.

In the lower part of Cowley Canyon, the lower limestone packet consists of two to three lenses of limestones. At the Cowley Canyon section, these are centered about 39, 78, and 99 ft/12, 24, and 30 m above the base (Fig. 11). Intervening deposits there are para- and orthoconglomerates and rare mudstones. In the southeast part of the study area, near Saddle Fork (Plate 6), limestones of the Cowley Canyon Member contain numerous cobbles and boulders of varied lithologies. These deposits resemble a transition between typical limestones and the three orthoconglomerates in the lower packet of the Cowley Canyon Member at the Cowley Canyon section, described above, at 33, 46, and 82 ft/10, 14, and 25 m above the base. In the Saddle Creek area, these boulder-bearing limestones probably were deposited in a shallow lake subjected to influx of coarse fluvial sediments during floods.

Weathered colors are pale pink to very light gray, 10YR8/1 to 10R8/2 to 5R7/3 to 5R6/2 to N6 to N8. Fresh colors are pale red to pale brown to light gray, mostly 5R5/2 to 5R7/4, but also 10YR7/2 to N7. From a distance the limestones usually appear white.

Composition of Clasts, Provenance, and Direction of Transport

Immediately above the base in some places, clasts in the Wasatch Formation are angular (to rounded) blocks of the Paleozoic unit immediately below. However, in many places, the basal deposit is a paraconglomerate dominated by rather rounded cobbles and boulders of the Eureka Quartzite. Within a few meters above the base, the clasts usually have a varied but limited and largely local origin.

The Tony Grove section lies on the Laketown Formation, which continues to the crest of the paleodivide to the west. Thus, it is unsurprising that the source rocks (provenance) for the clasts in the Wasatch Formation there consist primarily of the Laketown and underlying Fish Haven, Eureka, Swan Peak, and Garden City formations (Fig. 10), which are exposed northward along the paleodivide (compare Williams 1948, geologic map). Possibly some Cambrian dolostones also are present.

In contrast, the Cowley Canyon section lies on the Garden City Formation, but the paleodivide to the west includes all younger units through the Oquirrh Formation. Most of these Middle to Late Paleozoic units are present as clasts in the lower part of the Wasatch Formation at the Cowley Canyon section (Fig. 11).

East and south of Temple Ridge, the Wasatch Formation overlies Cambrian units, and clasts of these units and of Eureka Quartzite dominate. There is a small but persistent component from the Geertsen Canyon and Worm Creek quartzites and possibly from the Mutual Formation throughout the study area.

The southward pinchout of the Eureka Quartzite, since the Middle Ordovician, lies near and just north of Right Fork of Logan River (Fig. 13). This pinchout trends to the southwest (Oaks and others 1977, Fig. 9) west of the Logan Peak-Beirdneau Peak-Naomi Peak paleodivide. Thus, clasts of the Eureka Quartzite south of Right Fork must have been derived from the north. Such clasts are abundant throughout the lower part of the Wasatch Formation in all parts of the study area. Their persistence to the south margin of the study area and beyond indicates an overall southward direction of transport and, therefore, a southward paleogradient for streams flowing along the fault-controlled paleovalleys. The few paleocurrents that could be determined in scattered and poorly exposed outcrops of the lower part of the Wasatch Formation also support generally southward transport.

The high degree of roundness of boulders of Eureka Quartzite, even in mud-rich paraconglomerates of probable mudflow origin, suggests probable working by fluvial processes prior to incorporation in mudflows. The decrease in roundness of clasts, to angular to subrounded in the granule and pebble sizes, especially in orthoconglomerates, suggests that the distance of transport was moderate to short. The present northward limit of the Eureka Quartzite along the western paleodivide is about 45 miles/75 km from the southern edge of the study area (Oaks and others 1977, Fig. 1). This northward limit formed by erosion immediately prior to and possibly during deposition of the Wasatch Formation, so the distance of transport of boulders of Eureka Quartzite in the study area probably was less than 50 miles/80 km.

Clasts of limestones and of broken and entire individual oncolites are present locally in orthoconglomerates of the Wasatch Formation. Most of these are in deposits a short distance above the Cowley Canyon Member or intertongued with limestones within that member (Fig. 11). However, clasts of the Cowley Canyon Member are present in small amounts through a considerable thickness of Wasatch Formation above the Cowley Canyon Member in many places in the study area. Also, high in the Wasatch Formation, cemented clasts of Wasatch sandstones and finer orthoconglomerates are present in small amounts. These reworked clasts indicate that parts of the Wasatch Formation were cemented, exposed, eroded, and redeposited in younger parts of the Wasatch Formation. Thus, there must exist areas of erosional unconformity within the Wasatch Formation. Because of the poor exposures, it is unknown if such unconformities exist in the study area. Given the continuation of minor normal faulting and folding and warping that probably took place as the Wasatch Formation was carried piggyback eastward above the sole thrust during deposition, it is likely that unconformities exist within the Wasatch Formation in the study area (compare Beer and others 1990).

Thickness, Relief, and Paleovalleys

Thicknesses are difficult to determine because of the considerable relief on the Paleozoic bedrock coupled with its tendency to rise toward paleodivides, beneath the Wasatch cover, at the highest parts of the present topography.

Rapid lateral changes in offsets of faults compounds the problem. Through most of the study area, present thickness of the Wasatch Formation probably is between 100 and 200 ft/30 to 60 m (Fig. 6). Williams (1948, p. 1146) indicated a maximum exposed thickness of the Wasatch Formation in the study area of about 530 ft/160 m just north of the U.S.U. Forestry camp on Little Bear Creek (Plate 2). However, just north, the underlying Paleozoic bedrock crops out and rises eastward. Thus, the maximum there is closer to 300 ft/100 m.

The maximum thickness in the study area probably is slightly more than 800 ft/245 m thick at a site about 1500 ft/450 m WSW of Old Ephraim's grave (Plate 4), near the intersection of a deep N-S paleovalley and the ESE-WNW structural sag along Right Fork of Logan River. In at least four other areas the Wasatch Formation reaches 600 ft/185 m thick (Fig. 6). At the three areas in the south are thick remnants that lie between N-trending ridge crests and the axes of now-dissected former paleovalleys. At the thick area in the north, the Wasatch Formation may occupy a N-trending paleovalley, but streams and glaciers there have carved wide and deep east-flowing valleys that obscure relations. Smaller E-trending valleys southward were "smoothed out" during the contouring to merge numerous small patches of thick Wasatch Formation locally.

The west wall of a major paleovalley exposed along the Right Fork of Logan River east to Cowley Canyon (Fig. 13) has a present relief of about 1200 ft/365 m and an eastward slope of nearly 14°. Removal of the 8° eastward dip of the Wasatch Formation indicates that the original paleorelief there probably was about 500 ft/150 m, with a valley-wall slope of about 6° (10%). This paleovalley is continuous southward, across a saddle (Fig. 5), with the paleovalley along the graben now followed by Herd Hollow (Plate 6), and northward, through another saddle in the area southwest of Chicken Creek (Plate 4). In the north, a paleovalley followed by the present course of the Logan River (Plate 2) probably joined this paleovalley (Fig. 5). Also in the north, a NW-trending tributary formed as a strike paleovalley, on the dipslope at the top of the Eureka Quartzite, then was filled by Wasatch Formation, and now is being exhumed by the stream in Bear Hollow (Plate 3).

The west wall of a paleovalley exposed along the Right Fork of Logan River east of Willow Creek almost to Long Hollow (Plate 4) has a present relief of more than 700 ft/210 m (Fig. 5) through a horizontal distance of 4200 ft/1280 m, with an eastward slope of 9.5° (Plate 7: Section E-F-G). Removal of the 5.5° eastward dip of the Cowley Canyon Member indicates that the original paleorelief there probably was at least 300 ft/90 m, with a valley-wall slope of about 4° (7%). This paleovalley appears to be continuous southward, across a saddle, with a paleovalley now followed by Bear Hollow, although it might have connected instead with another paleovalley now followed by Dip Hollow (Plate 6). High uplift along Temple Ridge has obscured possible connection with paleodrainage northward, although the paleodrainage along Spawn Creek and the lower part of Temple Fork may connect.

A shallow paleovalley follows faults along Card Canyon and Richards Hollow (Plate 5; Plate 7: Sections I-J and K-L). Its reconstructed paleorelief probably is 150 ft/45 m or slightly less. This paleovalley appears to connect northward with a paleovalley that follows or lies just east of a NNW-trending syncline, although not enough remnants of Wasatch Formation persist this far west to exclude the possibility that postdepositional folding has created a pseudovalley there.

The Card Canyon paleovalley is west of the central downfaulted region. The base of the Wasatch Formation and of the Cowley Canyon Member are nearly parallel, and both rise westward from Card Canyon some 2000 ft/600 m to the highest present outcrops along the ridge east of Logan Peak (Plate 5). Restoration of the Cowley Canyon Member to its probable horizontal attitude at the time of deposition suggests that relief just east of the Logan Peak-Beirdneau Peak-Naomi Peak divide was not great during initial deposition of the Wasatch Formation. Scarcity of faults and of deep paleovalleys in this area suggests that the divide, although wide, was gentle, and had low relief.

The major paleodrainages along Cowley Canyon, Long Hollow, Dip Hollow, and Card Canyon appear, from a vantage on Boulder Mountain at the south edge of the study area, to merge southward into a wider, more continuous paleovalley now occupied by Ant Valley (Fig. 2). The Cowley Canyon paleodrainage lies about 500 ft/150 m above the present Right Fork of Logan River (Plate 4) and a similar distance above the present Left Fork of Blacksmith Fork River.

The apparent paleovalley along Saddle Creek (Plate 6) may result entirely from drag folding during major Basin-and-Range faulting. The Cowley Canyon Member here parallels valley sideslopes on at least the west side of the valley of Saddle Creek, and lies near the base of the Wasatch Formation across the upfaulted divide just west (Plate 7: Sections K-L, M-N).

Minor tributaries at a high angle to major paleovalleys were apparent among the extensive exposures of the basal contact in the southwest (Fig. 5). For example, at the present divide south of White Bedground (Plate 5), the Cowley Canyon Member lies directly on Paleozoic bedrock in a small tributary on the west, but overlies 50 ft/15 m of red Wasatch Formation a short distance eastward. Another small tributary enters the Card Canyon paleovalley from the east at a modern saddle (Plate 3).

Origin

Orthoconglomerates and sandstones in the Wasatch Formation represent high energy and turbulence, possible shallow-water and variable-directional flow to explain the scarcity of subaqueous dunes and scours, and both oxidizing conditions and high temperature to reflect the high turbulence and abundant hematite staining. It is unlikely that the completeness of oxidation of the Wasatch Formation could have occurred at the outcrop after re-exposure. The paraconglomerates differ in probably having much lower turbulence, caused by higher amounts of fines that failed to become dispersed and so caused the sediments to flow as-a-unit (Bingham plastic: Blatt, Middleton, and Murray 1980) with the boulders buoyed up within the flow by the buildup of fluid pore pressures. The parallel bedding typical of both types of conglomerates and of the associated sandstones in the Wasatch Formation is common in alluvial-fan settings and fan deltas.

The humidity and pH of the environment are uncertain. Poor exposures hampered the search for paleosols. The lack of abundant plant fossils and the sparse and badly preserved pollen in the Cowley Canyon Member suggest either aridity (few plants) or severe chemical weathering. The sheer volume of mud available might suggest that the source areas were humid and subject to formation of abundant fines, so there may have been abundant vegetation, at least in the uplands. If so, the evidence for proximity of the source areas and for moderate slopes (10%), and the paucity of mudcracks might suggest that the depositional environment was humid.

However, the abundance of carbonate clasts, often angular to subrounded, and the much lesser quantities and finer sizes of chert show that the carbonates were not severely weathered chemically. This suggests arid to semiarid conditions, or cold temperatures. Cold temperatures are refuted by the abundance of hematite. Eugster and Surdam (1973) concluded that the middle part of the partly correlative Green River Formation in Wyoming was deposited under arid conditions, and Ryder and others (1976) reached a similar conclusion for the upper part of the Green River Formation in east-central Utah, but concluded that the main, lower part is open-water lake in origin. Thinness of limestones of the Cowley Canyon Member, the exclusively shallow-water evidence of its oncolites and bedded algae, its sparse fauna, the absence of other lake beds, and the common carbonate cement present in the orthoconglomerates all suggest a semiarid to arid environment. The formation of numerous mudflows and debrisflows is also enhanced under arid to semiarid climatic conditions. Unexplained is the abundant source of mud, although thick shales are present in the Langston, Ute, Bloomington, Swan Peak, and Little Flat formations.

Relation to Sea Level

Williams (1948) concluded that the Wasatch Formation in the Bear River Range was deposited close to sea level under tropical conditions. Evidence of paleovalleys with 500 ft/150m paleorelief in the Bear River Range, and possibly as much as 3000 ft/915 m of paleorelief in the Central Wasatch Range and Oquirrh Mountains (toward which paleovalleys in the study area drained), and evidence of intertonguing eastward with freshwater to nonmarine-saline lake deposits, together suggest that the study area was well above sea level. Deposition of the Wasatch Formation in a piggyback basin within an eastward-moving and eastward-climbing stack of thrust sheets still nearly 45,000 ft/13,715 m thick (Fig. 18) also argues against an origin close to sea level.

Subsequent offsets during Basin-and-Range faulting help constrain the altitude of deposition of the Wasatch Formation. The Wasatch Formation overlies purple quartzite, probably the middle member of the Swan Peak Formation, at -3284 ft/-1001 m in the Amoco #1 Lynn Reese well (Sec 17, T12N, R1E; Brummer 1991). The Wasatch Formation in this well is 358 to 367 ft/109 to 112 m thick, and consists of red quartz sandstone, gray carbonate, and dark red pebble conglomerate (Brummer 1991). The carbonate may be Cowley Canyon Member, and the red sands and conglomerates probably were deposited above sea level. Therefore, Cache Valley must have subsided at least 3284 ft/1001 m relative to sea level since deposition of the Wasatch Formation.

The highest level reached by the base of the Wasatch Formation westward in the Bear River Range is at the west limit of outcrops, very near 9000 feet/2745 m (Plate 7: Sections A-B-C and K-L). In both areas, the base rises between 5° and 10° westward, and lies approximately parallel to the Cowley Canyon Member in the southern section. Therefore, uplift of the Bear River Range relative to Cache Valley probably was no less than 12,284 ft/3744 m. Based on offset of the contact between the Wasatch Formation and the Swan Peak Formation on the west side of Cowley Canyon compared to the same contact in the #1 Lynn Reese well, Brummer (1991) estimated an offset (throw) of at least 9515 ft/2900 m.

The Cowley Canyon Member descends eastward to its lowest level, 6060 ft/1845 m, in the downfaulted central area along the sag followed by Right Fork (Fig. 13). Farther east, its lowest level is near 6400 ft/1951 m along Saddle Creek (Plate 6), 6760 ft/2060 m just west of Ephraims Grave (Plate 4) and 6540 ft/1993 m northwest of Spawn Creek (Plate 4). Its highest level is 9005 ft/2745 m in the ridge east of Providence Lake and Logan Peak (Plate 5), where it lies at the base of the Wasatch Formation. It lies near 5930 ft/1805 m on the southeast side of Bear Lake (Sec 17 T13N R6E), and at or slightly above 7000 ft/2135 m eastward on the Bear Lake Plateau (McClurg 1970).

If the Cowley Canyon Member is present in the Amoco #1 Lynn Reese well, and if all parts of the member are synchronous and initially had their tops at the same level, then both the Bear River Range and Bear Lake Valley have risen relative to Cache Valley. Thus, if the Wasatch Formation were deposited near sea level, then the east side of Bear Lake Valley, at the east margin of the Basin-and-Range province, later had to rise to an altitude near 7000 ft/2135 m prior to downfaulting to its present position near 5930 ft/1805 m. Similarly, the central part of the Bear River Range would have to be uplifted at least 9000 ft/2745 m after thrusting ceased (Fig. 12). It seems more likely that post-depositional (post-thrusting) uplift was minor compared to uplift during thrusting.

There are three other factors to consider: (1) Eastward thrusting probably carried the Wasatch Formation about 10 km eastward on the Darby-Prospect-Tunp thrust complex (Wiltschko and Dorr 1983) during deposition. Because the sole thrust dips about 2.5° to 3° west (Fig. 18), this "piggyback" transport probably raised the Wasatch Formation 1435 to 1720 ft/435 to 525 m above its initial level during deposition; (2) Isostatic uplift due to erosional stripping may have been diminished in the study area by the progressive burial of the topography by deposition of the Wasatch Formation; and (3) Location along the east margin of the Basin-and-Range province probably has led to far less uplift, if any, compared to the central part of the province.

It is significant that Cache Valley probably has subsided since deposition of the Wasatch Formation. We assume that: (1) Basin-and-Range uplift has been neutral along the eastern margin of the province, and (2) Isostatic uplift, after deposition began and prior to Basin-and-Range faulting, was on the order of 2700 ft/825 m, (divided by 0.9: Howell 1959, p. 236), to compensate for removal of an estimated one-third of the average of about 9000 ft/2745 m of bedrock from areas immediately to the west of section K-L, during deposition of the lower part of the Wasatch Formation in the downfaulted central part of the study area. This isostatic adjustment clearly should be a maximum. Subtraction of 2700 ft/825 m (maximum isostatic adjustment) and 1700 ft/520 m (maximum uplift due to thrusting during deposition) from the present maximum level of the Wasatch Formation near 9000 ft/2745 m suggests that the altitude of deposition could have been at 4600 ft/1400 m or higher.

Characteristics of Sites of Failure

Most large sites of failure qualify as slumps (debris slips) that locally evolved into earthflows. Most failures form where the Wasatch Formation has been oversteepened by faulting, undercut by streams (or glaciers in the upper part of Logan Canyon), or both. At the head, a steep tear-away scarp and reversed slopes with local closed depressions and intermittent ponds are typical. The scarp removes support for areas uphill. The main body of failure usually shows an irregular, "lumpy" topography, with local closed depressions and rotated coherent blocks of limestone and cemented orthoconglomerate. The overall gradient is less than adjacent areas that have not failed. The toe commonly protrudes farther and, in doing so, diverts any stream at its base. Failure is most common where lower slopes are rich in paraconglomerates and mudstones. Failure is enhanced by the tendency of the Wasatch Formation to develop convex-up hillslopes with steeper lower segments. There is no obvious relation to aspect. Because most drainages are roughly north-south, most failures face either east or west, but failures also form on slopes with other aspects. There appears to be no inherent advantage to the typically wetter east-facing slopes that collect more drifted snow as cornices and also retain moisture longer because of cooler air temperatures when the sun is on them during mornings.

One of the largest failures is east of the middle part of Herd Hollow (Plate 6). The failure scarp is crossed by two converging major faults. The main body of the failure contains a block of Cowley Canyon Member and another block of orthoconglomerate with a rotated dip of 54°. Another large failure lies just west of the Herd Hollow-Cowley Canyon summit (Plate 6). Box Spring and Pine Spring lie along the head scarp. A fault may be present along the scarp, but this was not proved. Two slumps are present along Little Cottonwood Creek (Plate 4). One is triangular in shape, and has failed southward toward Right Fork. A complex of failures, many with evidence of flowage, is present along Temple Fork and the lower part of Spawn Creek (Plate 4). The area contains one major fault, and has a second near its eastern margin. The toe areas are undercut by the two streams. To the east, two large block slides, consisting of Cambrian bedrock, have slid a short distance to the west, where they cover the major normal fault that removed support from the toes. Still other failures are present northward along the Logan River in areas undercut by glaciers and the Logan River (Plates 2, 4). Probably more failures would be present if the Wasatch Formation contained more paraconglomerates in the study area. No doubt many older failures are present, but their head scarps and "lumpy" topography have been obscured by later creep, solifluction, and other surface flowage. The numerous slumps shown by Dover (1985) in the western part of Plate 2 were not obvious to us on the aerial photographs. Also, much of that area is obscured by moraine.

THRUST FAULTS AND NORMAL FAULTS: OFFSETS AND TIMING

General Statement

Thrust faults (compression) and normal faults (tension) are present in the study area (Fig. 4). Deposition of the Wasatch Formation postdates major movement on at least one thrust fault, possibly two, both with the west side upthrown. Normal faults both pre-date and post-date deposition of the Wasatch Formation. They form a low area with several graben trending roughly north or NNE, mostly through the central part of the study area. At least one normal fault shows modest offset during deposition of the Wasatch Formation. The low central area appears to be the downfaulted crest of a previously unrecognized anticline, here named the Red Banks anticline (Plate 7) for Red Banks, the site of a USFS campground (Plate 2) near the axis of the anticline. Southeast dips along Little Bear Creek, about 8500 ft/2600 m to the southeast, and also on Temple Peak confirm the reversal in dip of Paleozoic bedrock from the westward dip into the Logan Peak syncline.

The maximum present offset on a thrust fault is about 500 ft/150 m some 12,000 ft/3660 m west of point C, where original offset may have been diminished by post-Wasatch listric offset with an opposed offset. The maximum may be as much as 2150 ft/655 m southward where the fault is buried by the Wasatch Formation (Plate 7: Section F-G-H). The maximum pre-Wasatch offset on a normal fault was about 4200 ft/1280 m some 4750 ft/1450 m east of point D. The maximum post-Wasatch offset on a normal fault was between 1000 and 1350 ft/305 and 410 m some 8600 ft/2620 m east of point B (Plate 7).

Cumulative offsets along the four sections that cross the NNE-trending faults at a high angle are summarized in Table 2. These show that the net pre-Wasatch offset was between 1350 and 2725 ft/410 and 830 m, down to the west, and that the post-Wasatch offset has been between 395 and 1225 ft/120 and 375 m, also down to the west. Post-Wasatch offset generally is greater where pre-Wasatch offset also was greater, and vice versa.

Despite the dominance of down-to-the-west offset, the Cowley Canyon Member rises westward (Plate 7). This geometry suggests that the overall post-Wasatch structure is an east-dipping homocline broken by numerous normal faults (Fig. 12). The faults with greatest offsets probably dip west, and may be listric faults that curve into former thrust surfaces or incompetent shales at depth (Fig. 18).

The kinds and ages of faults with offsets of 200 ft/60 m or more are described below. Locations of faults and of sections shown in Plate 7 are

TABLE 1. Changes in offsets of selected faults along strike in study area (see Figure 4 and Plate 7). (+) = West side down; (-) = East side down.

SECTION	LONG HOLLOW THRUST FAULT ft / m	HERD HOLLOW pre-Tw ft / m	HERD HOLLOW post-Tw ft / m	WILLOW CREEK pre-Tw ft / m	WILLOW CREEK post-Tw ft / m
A-B-C	-500/ 150	-200/ 60 (-1000/-300 total to north)	-100/ 30	+4075/1240	+175/ 55
D-E	+800/245 (post-thrust listric)	NO DATA		+4200/1280	<+200/ 60
F-G-H	COVERED (est. -2150/655)	-250/ 75	-50/ 15	+3500/1065	+400/120
K-L	+200/ 60 (post-thrust listric)	-1300/395	-100/ 30	+2250/685	+100/ 30

TABLE 2. Cumulative offsets of faults in study area (see Figure 4 and Plate 7). (+) = West side down; (-) = East side down.

SECTION	TOTAL OFFSET ft / m	POST-WASATCH ft / m	PRE-WASATCH ft / m
A-B-C	+ 3950/1205	+ 1225/ 375	+ 2725/ 830
D-E	>+ 3650/1115	>+ 1040/ 315	>+ 2610/ 795
F-G-H	<+ 2555/ 780	<+ 1205/ 365	<+ 1350/ 410
K-L	+ 2045/ 625	+ 395/ 120	+ 1650/ 505

shown in Figure 4 and in Plates 1-6. In the text, fault offsets that are down on the west are indicated by (+), whereas those that are up on the west are indicated by (-).

Thrust Faults

A thrust splay, apparent in seismic data just south of the study area, rises from the upper segment of the Paris-Willard thrust fault to the present surface near the east end of Section K-L (Fig. 18). Field relations suggest that the thrust joins the western of two N-trending faults in the south (Fig. 4); however, projection of the seismic data due north into Section K-L places the fault at the less likely eastern of the two faults. The eastern fault has post-Wasatch offset about equal to offset of the Paleozoic rocks. However, the western fault also has complications, which require post-Wasatch listric offset of Paleozoic bedrock slightly greater than the original thrust offset, followed by post-Wasatch faulting down to the east. Although irregular, the trace overall is approximately N-S (Fig. 4). This thrust fault appears to continue northward in the west-facing scarp along Temple Ridge. The trace across valleys there indicates a very steep dip at the surface, and a steep dip also is apparent in the seismic data. The maximum present offset is about - 500 ft/- 150 m in Section A-B-C, but may be greater where this fault is covered by the Wasatch Formation farther south (Section F-G-H). Also, later listric offset, down to the west, along this thrust splay may have reduced or reversed the original offset (Table 1). This fault is here named the Long Hollow thrust fault, for Long Hollow (Plate 4).

A possible thrust fault is present along the west side of Herd Hollow (Plate 6). This fault continues north of the Right Fork of Logan River, along the west side of the paleovalley followed by Little Cottonwood Creek (Plate 4). It trends approximately NNE. It is interpreted as a normal fault in Figure 18, based on the down-to-the-west offset in the gap along Cowley Canyon where only one fault appears to be present. However, another fault strand, now covered by the Wasatch Formation, may be present just west of this gap, or post-Wasatch listric offset in the area of the gap may obscure an original down-to-the-east offset. This fault has a maximum present offset of about - 1400 ft/- 425 m in Section K-L. It has an offset of about - 1000 ft/- 305 m near the middle of Plate 2, which decreases to - 200 to 250 ft/- 60 to 75 m in its central part (west part of Plate 2). Both Paleozoic bedrock and Wasatch Formation are folded just east of this fault (Fig. 14: Note that no stream later followed the sag in these folds). The southern part of this fault was named the Herd Hollow fault by Williams (1948), and it is here extended northward past the NE-trending segment with which Williams connected it northward.

The base of the Wasatch Formation and the Cowley Canyon Member show an increased dip toward the west erosional pinchout (Fig. 7; Plate 7: Sections A-B-C, F-G-H, K-L). This suggests increased uplift in the west relative to the rest of the study area, either during the later part of deposition of the Wasatch Formation or afterwards. Uplift on a late thrust splay now exposed along the west face of the Bear River Range (Galloway 1970; Mendenhall 1975; Lowe and Galloway, in press; Evans, in preparation), slightly west of the study area, may be the cause of the increased dip westward. High elevation of the Logan Peak-Beirdneau Peak-Naomi Peak drainage divide may date from this event.

Normal Faults

Pre-Wasatch offset of many of the normal faults is demonstrated by subtracting the offset of the base of the Wasatch Formation from the offset of the underlying Paleozoic rocks. The pre-Wasatch normal faults are classified as minor (less than 200 ft/60 m of offset), intermediate (between 200 and 1000 ft/60 and 300 m of offset), and major (more than 1000 ft/300 m of offset). Most intermediate faults form segments of the major faults, and will be discussed with them. In many places, the offset of the top of the Cowley Canyon Member afforded a check for unrecognized remobilized Wasatch Formation (QTw). Only one post-Wasatch normal fault has major offset, but several others have intermediate offsets. The minor normal faults (Fig. 4) will not be discussed further.

Major pre-Wasatch normal faults include the following:

(a) West part of Plate 2; trend NE; pre-Wasatch offset about + 1800 ft/+ 550 m; places upper St Charles Formation (west) against lower Nounan Formation (east); offset appears to die out rapidly to the SW: not found on divide between Blind Hollow and Cottonwood Canyon (Plate 3). Here named Bunchgrass fault, after Bunchgrass Creek (Plate 2);

(b) Central part of Plate 2; trend NNE; pre-Wasatch offset about -1000 ft/- 300 m; places basal contact of Bloomington Formation (west) against middle to upper part of Bloomington Formation (east); this fault appears to be the northern extension of the possible thrust fault discussed above (Herd Hollow fault);

(c) Central parts of Plates 2 and 4, and west part of Plate 6; beginning in the south, trends NE, then NW, then NNE; pre-Wasatch offset variable, from + 2250 to 4200 ft/+ 685 to 1280 m (Table 1); forms east side of southern part of Herd Hollow; lies west of and converges toward the Long Hollow thrust fault north to Temple Fork, then swings to west and begins to converge again to the north; places Garden City Formation (west) against

Nounan Formation (east) along the east side of Herd Hollow, places Garden City and St Charles formations (west) against Bloomington and Blacksmith formations (east) in the area between Right Fork and Temple Fork, and places Bloomington Formation (west) against Geertsen Canyon, Langston, and Ute formations (east) north of Little Bear Creek. This pre-Wasatch normal fault has the largest offset in the study area; it lies in the hanging wall of the Paris-Willard thrust splay discussed above. However, it may curve downward into shales of the Ute and Langston formations, just above the thick and resistant Geertsen Canyon Quartzite, which shows no apparent offset in the seismic data (Fig. 18). Here named the Willow Creek fault, for Willow Creek (Plate 4). It lies east of the Mud Flat faults of Williams (1948) south of Right Fork, but joins the easternmost of those faults at Right Fork;

(d) East parts of Plates 3 and 5; beginning in the south, trends NNE, then N; pre-Wasatch offset + 950 ft/+ 290 m in south, but decreases rapidly to the north in Plate 5, then may increase again in Plate 3 just south of the anticline-syncline pair that appears to absorb the offset northward; might connect northward with Bunchgrass fault; places upper part of the Hyrum Dolomite (west) against the basal contact of the Water Canyon Formation (east). Here named Card Canyon fault, after Card Canyon (Plate 5);

(e) Easternmost part of Plate 5; trends N; pre-Wasatch offset about - 400 ft/- 120 m; continuation to north obscured by a large landslide; places basal part of Garden City Formation (west) against the main part of the same unit (east). Here named Seep Hollow fault, after Seep Hollow (Plate 5); and

(f) East part of Plate 4, just east of trace of thrust splay; curving U-shaped fault (segments) open to the east; strong "trap-door" configuration with an abrupt increase in present offset to the west, from about - 100 ft/- 30 m in the NE, near the edge of the study area, to about - 1100 ft/- 335 m in the west, near the thrust; control on the south side is less firm, but pre-Wasatch offset there is about - 950 ft/- 335 m close to the south end of section O-P, near the basal contact of the Bloomington Formation. A cover of Wasatch Formation is present only locally across the southern part of this fault and at the head of Temple Fork; in both places the offset of the Wasatch Formation is slight. Here named the Temple Spring fault, after Temple Spring in the headwaters of Temple Fork (Plate 4).

Important post-Wasatch normal faults include the following:

(a) East part of Plate 6; beginning in south, trend curves from N to NE; paired faults form a graben with Langston Formation downfaulted against Geersten Canyon Quartzite (south) and against lower Langston (north); the fault on the east is flatter, whereas that on the west is nearly vertical, so the faults probably merge at depth; post-Wasatch offset is about + 400 ft/+ 120 m on the east and between - 200 and 500 ft/- 60 and 150 m on the west. Here named the West Saddle Creek and East Saddle Creek faults, respectively, after Saddle Creek (Plate 6);

(b) East part of Plates 2 and 4; beginning in south, curves from NW to N to NE trend; places Wasatch Formation against Nounan Formation in south and against Bloomington Formation in middle and north; offset about - 200 ft/- 60 m in the north, may reach - 600 ft/- 180 m in south. Here named the Log Cabin fault, after Log Cabin Hollow (Plate 4);

(c) East parts of Plates 4 and 6; reversed sense of offset on probable listric normal faults associated with Long Hollow thrust fault: north of Temple Fork, normal faults with down-to-the-west offset lie parallel to each side of the northward projection of the thrust; faults so close to the thrust may merge with it in the subsurface; from Temple Fork southward the post-Wasatch offset generally follows the trace of the thrust, except in the area near Long Hollow, where the thrust lies slightly to the west; north of Temple Fork, offset of Paleozoic rocks on the normal fault along the base of Temple Ridge is about + 1650 ft/+ 500 m, whereas that east of the thrust is about + 200 ft/+ 60 m; at the same place, offset of the base of the Wasatch Formation is no greater than + 1550 ft/+ 470 m, and more likely about + 1000 ft/+ 300 m; therefore, part of the down-to-the-west offset probably predates deposition of the Wasatch Formation; at Temple Fork, post-Wasatch offset may be about + 750 ft/+ 230 m, but this value has much latitude for error; south of Temple Fork, post-Wasatch offset is about + 300 ft/+ 90 m east of Long Hollow (Plate 4), and perhaps as much as + 500 ft/+ 150 m east of the upper part of Dip Hollow (Plate 6); offsets in the south near Saddle Creek are complex, as discussed above. The major normal fault along the base of Temple Ridge was named the Temple Ridge fault by Bailey (1927); and

(d) Central parts of Plates 2 and 4, west part of Plate 6; renewed, post-Wasatch offset on Willow Creek normal fault; north of Temple Fork, offset appears to be less than + 200 ft/+ 60 m, although poor exposures, numerous landslides, and the loss of the Cowley Canyon Member northward restricts certainty except just north of Little Bear Creek (Plate 2); offset southward is about + 400 ft/+120 m along Right Fork, and decreases to about + 250 ft/+ 75 m between Steel Hollow and Ricks Canyon and then to about + 100 ft/+ 30 m near the south edge of the study area; low offset north of Temple Fork may result from transfer of most of the offset to faults just east. This distributive transfer of offset could explain the abrupt rise of the topography along Temple Ridge north of the headwaters of Temple Fork.

Offset During Deposition of the Wasatch Formation

Figure 15 documents intermediate to major offset, synchronous with deposition of the Wasatch Formation, on the western fault of a graben exposed on the north wall of Right Fork of Logan River between Maughan Hollow and Willow Creek (Plate 4). Poor exposures west of the graben precluded a firm conclusion about the rapid eastward rise in the top of the Cowley Canyon Member. This rise may be due to an unmapped fault or to a small fold in the Wasatch Formation. No fold is visible in the underlying Garden City Formation along the slopes below, where several attitudes were measured, so a small fault seems likely. Although the Cowley Canyon Member thickens from both sides to a maximum of about 120 ft/35 m in the center of the area west of the graben, the thickness of the Wasatch Formation between the base and the top of the Cowley Canyon Member is fairly constant in the west, and only thins a little in the east (Fig. 15). This suggests that the Cowley Canyon Member fills a small paleochannel, within the Wasatch Formation, that flowed roughly south, and that there was a small rise eastward in the paleorelief on the underlying Garden City Formation.

East of the graben the Cowley Canyon Member appears to retain a fairly constant thickness, so that overall westward thinning of the underlying red muddy deposits suggests that the paleotopography rose gradually westward. Thus, a low divide in the top of the Garden City Formation appears to have been present in the present position of the graben.

In the graben, the base of the Wasatch Formation is offset about 45 ft/15 m more on the west side than on the east. Although drag has reduced the total amount of offset next to the faults, the west side of the graben clearly has subsided more. In the west part, at least 150 ft/45 m, and perhaps as much as 270 ft/85 m, of Cowley Canyon Member accumulated, compared to only about 45 ft/15 m near the east margin. One cliff-forming sequence could be traced across (Fig. 15). Not only did the cliff-forming sequence thicken slightly to the west, but oncolite-bearing limestones crop out locally below it. Deposits of the Wasatch Formation below the top of the cliff-forming sequence are 50 ft/15 m thicker in the west part of the graben than in the east. Above the cliff-forming sequence is another 120 ft/40 m of Cowley Canyon Member in the west that does not continue to the east part of the graben.

We interpret this sequence to result from differential deposition due to ongoing, episodic faulting during deposition (Oaks and others 1989). Initial faulting created a tilted valley with drainage restricted to the west side. Nearly equal thicknesses below the top of the Cowley Canyon Member on both sides of the eastern fault suggest a west-tilted half graben. Faulting also may have blocked the drainage and ponded a lake that deposited oncolitic limestones in the valley and across adjacent interfluves, at least in the lower, southern part of the study area. Renewed faulting followed deposition of the cliff-forming sequence, and led to additional deposition of the Cowley Canyon Member against the west wall of the graben. Faulting there probably ceased shortly after deposition of the Cowley Canyon Member, because about 60 % of the total offset of the base of the Wasatch Formation (160 of 255 ft/50 of 80 m) was completed. Renewed faulting during later Basin-and-Range faulting may have completed the offset along the western fault. The eastern fault may not have existed earlier, and movement on it may have levelled out the originally tilted block in the graben. Uplift and tilting due to thrust faulting along the present west margin of the Bear River Range also may have restored the tilt in part. Thus, faulting here probably was synchronous with deposition.

Remnant of Wasatch Formation in Temple Ridge along Temple Fork

A high-level remnant of Wasatch Formation lies about 600 ft/180 m above Temple Fork at its exit from the Temple Ridge scarp (Fig. 16; Plates 4, 7: Section D-E). The basal contact rises gradually to the north and northeast from an altitude of about 6920 ft/2110 m to about 7080 ft/2160 m. This remnant lies between several faults, the Willow Creek and Temple Ridge normal faults on the west, just south of their convergence, and the Long Hollow thrust fault and later listric normal fault, just east (Fig. 4), at a convergence with a smaller normal fault. The most recent offset on all of these faults was down to the west. Lumpy topography trending northwest through the central part of this remnant suggests failure with flowage, an unrecognized additional normal fault down to the west, or both.

Tonal patterns in aerial photographs suggest that the Wasatch Formation just west of these faults rises toward the east. We interpret this as drag, related to Basin-and-Range normal faulting along Temple Ridge, that brings the basal contact of the Wasatch Formation steeply up to at least 6840 ft/2085 m just west of the fairly level base of the remnant. The contact between the remnant and the western deposits is obscured by aspens, conifers, and heavy underbrush along the northwest face of the remnant.

We interpret the remnant as a downfaulted inlier created during Basin-and-Range faulting. Because deposits just west dip more steeply westward, it is unlikely that the remnant is remobilized Wasatch Formation (QTw) deposited within the canyon of Temple Fork following Basin-and-Range faulting but before Temple Fork had cut below 6920 ft/2110 m.

SYNTHESIS AND TECTONIC HISTORY

Emplacement of the Paris-Willard thrust sheet (latest Jurassic to earliest Late Cretaceous) was accompanied and followed by deep erosion into folded and faulted Paleozoic bedrock. Large offsets on pre-Basin-and-Range normal faults created NNE-trending horsts and graben. To a large degree, paleovalleys followed these graben. Probably from the Paleocene or Early Eocene through the Middle Eocene, the Wasatch Formation was deposited in the Bear River Range in these NNE-trending paleovalleys, some up to 500 ft/150 m deep with sideslopes up to 10%. Onset of deposition was abrupt. It mostly followed, but was partly synchronous with the pre-Basin-and-Range normal faulting. Early deposition of the Wasatch Formation clearly was dominated by overall southward transport, at right angles to eastward thrusting. Fluvial clasts have an overwhelmingly local provenance. Deposits of mudflows and debrisflows (mudstones and paraconglomerates), openwork braided-flow deposits (sandstones and orthoconglomerates), and lacustrine limestones (Cowley Canyon Member) filled the graben and spread thinly across the horsts through much of the area. Fluvial deposition resumed after the early lacustrine episode, and continued across the earlier drainage divides, probably with continued overall southward transport. At some point, perhaps episodically, folding occurred along NNE-trending axes, accompanied by WNW-trending warping. Reworked cemented clasts of the Wasatch Formation, including pieces of the Cowley Canyon Member, indicate that parts of the Wasatch Formation were uplifted and eroded as deposition proceeded. Subsequently, Basin-and-Range normal faulting formed a major offset in the base of the Wasatch Formation along Temple Ridge fault and lesser offsets along many other faults. A high divide probably existed to the west. Eventually the Logan and Blacksmith Fork rivers cut eastward across the divide. Many NNE-trending modern streams flow along paleovalleys filled with Wasatch Formation, so that erosional removal at present is exhuming early Tertiary paleovalleys in the central part of the study area. These modern drainages are discontinuous across the WNW-trending highs, or upwarps, whereas at least one major cross-axial stream, the Right Fork of Logan River, follows a WNW-trending sag.

Any tectonic synthesis must account for the above geologic history. The difficulty is to provide for: (1) major normal faulting (tension), mostly down to the west, within an overall compressional setting of eastward overthrusting; (2) abrupt cessation of the normal faulting about the time of onset of deposition of the Wasatch Formation; (3) later compressional folding and warping of the Wasatch Formation; and (4) renewed normal faulting (tension) that continues today.

Figure 17 shows our diagrammatic model for the tectonic evolution of the

Bear River Range. The illustration is similar to a conveyor belt, in that deposits of the Wasatch Formation now east of the Temple Ridge scarp first enter the diagram on the left side, and proceed through time to the right side. Previous work (see Wiltschko and Dorr 1983) documented that the Paris-Willard thrust had ceased movement before the Wasatch Formation was deposited, so that it must have been carried passively ("piggyback") eastward above the sole thrust.

It is proposed that:

(1) Deep erosion took place as the combined Paris-Willard-Woodruff Creek-Meade-Crawford thrust sheets (compare Wiltschko & Dorr 1983; Dover 1984, 1985) were carried "piggyback" eastward as rising highlands above a west-dipping sole thrust;

(2) Major normal faulting of Paleozoic bedrock occurred as these rocks rode up and over a ramp anticline above a buried thrust ramp (duplex), west of the Bear River Range, beneath the Absaroka-Darby-Prospect sole thrust; this ramp may lie along the present Wasatch fault on the west side of the Wellsville Range (compare Schirmer 1988);

(3) Initial deposition of the Wasatch Formation, deposition of the Cowley Canyon Member, and minor additional normal faulting coincided with movement of the thrust sheets eastward, down the ramp anticline and onto the adjacent thrust "flat;" ponding to form the lakes may have resulted from diminishing but continued offsets of normal faults, from short-lived climatic change, or both;

(4) Passive deposition (compare Tunp Member of Wasatch Formation in Wyoming, Hurst & Steidtmann, 1986) of the main overlying part of the Wasatch Formation occurred while the thrust sheet continued moving eastward above the thrust "flat;" minor NNE-trending folds and WNW-trending highs and sags formed during this cross-country jostling, possibly aided by minor late uplift on thrust splays at the Long Hollow and Herd Hollow faults and by greater uplift on the thrust splay now exposed along the west face of the Bear River Range that formed the high Logan Peak-Beirdneau Peak-Naomi Peak divide along the present west part of the study area; the folds and uplifts produced erosion and high-level unconformities; deposition slowed as distance from the ramp anticline increased, and as eastward thrusting ceased and the uplands were worn down or buried;

(5) Extension replaced compression, and episodic (Hamblin 1976) Basin-and-Range faulting began, perhaps as early as Late Eocene or Early Oligocene (Brummer and Evans 1989), or 21 Ma (Early Miocene), but probably no later than 11 Ma (late Middle Miocene) (Bryant and others 1989); initially the high western divide held, and drainage perhaps was internal; deep west-flowing canyons formed through the uplifted Temple Ridge; west-flowing cross-axial streams then breached the high divide in the

west and captured drainages of streams flowing along the NNE-trending fills in paleovalleys; the cross-axial streams were either consequent (where internal drainage filled the downfaulted central area to a low point on the divide), or superposed (where the streams exited at low areas on a cover of Wasatch Formation and cut down thereafter into Paleozoic bedrock); along steep slopes, Wasatch Formation was remobilized and redeposited at lower levels, a process that continues today;

(6) glaciation in the northern part of the study area oversteepened slopes; the isostatic effects of loading and unloading by glaciers and by Lake Bonneville (Crittenden 1963) renewed uplift, block faulting, and excavation of the pre-Eocene paleotopography.

Thick fanglomerates and thick tuffaceous lacustrine deposits formed in Cache Valley during deposition of the Salt Lake Formation. Probably some of the widespread ashfalls were deposited in the study area, yet these have not been preserved, and the interval since the end of deposition of the Wasatch Formation has left no major depositional record in the study area. The implication is that integration of drainage by the cross-axial streams may have been quite early, if the Wasatch Formation originally was rather thick, or that integration was quite late, and that erosional stripping since deposition of the Salt Lake Formation has been extensive, rapid, and effective in the Bear River Range.

LOPATIN TIME-TEMPERATURE INDEX: IMPLICATIONS FOR PETROLEUM POTENTIAL

Overview

In north-central Utah and southeastern Idaho, the American Quasar #20-1 Hogback Ridge (Fig. 2) is the only well to date to produce significant amounts of complex hydrocarbons (petroleum). It lies in Rich County some 6 miles/10 km east of the south end of Bear Lake and 17 miles/28 km east of the study area. This well produced gas from the Triassic Dinwoody Formation near a depth of 9500 ft/2900 m (-4500 ft/-1370 m)(Clem and Brown 1985). The closest deep wells drilled east of the study area were the Marathon Oil #1-15 South Eden Canyon, which began in Jurassic Twin Creek Limestone in the footwall of the Laketown-Meade thrust fault (LMT), and the Marathon Oil #1-21 Otter Creek, which penetrated a similar sequence below the LMT (Clem and Brown 1985). The first was 2-1/2 miles/4 km east of Bear Lake, whereas the second was 8 miles/13 km south of Bear Lake and 12 miles/20 km east of the area of study (Fig. 2).

Eastward in Wyoming, principal targets for reservoir rocks, based on production or on "shows" of petroleum, are (Blackstone and DeBruin, 1987):

1. Cretaceous Frontier, Kelvin and Aspen formations (Lodgepole South, Aagard Ranch, Sulphur Creek West, Stove Creek, Elkol, Lazeart, Aspen, Spring Valley, and Pineview fields);
2. Jurassic Stump, Twin Creek, and Nugget formations (Lodgepole, Elkhorn Ridge, Pineview, North Pineview, Anshutz Ranch, Anshutz Ranch East, Glasscock Hollow, Bessie Bottom, Painter Reservoir, Cave Creek, Yellow Creek, Chicken Creek, Clear Creek, and Ryckman Creek fields);
3. Triassic Ankareh, Thaynes and Dinwoody formations (Ryckman Creek, Chicken Creek, Shurtleff Creek, and Whitney Canyon fields);
4. Permian Phosphoria Formation (Yellow Creek field);
5. Pennsylvanian Weber Sandstone (Yellow Creek, Red Canyon, and Whitney Canyon fields);
6. Mississippian Amsden and Madison (Lodgepole) formations (Cave Creek, Horse Trap, and Whitney Canyon fields);
7. Devonian Darby Formation (Whitney Canyon field);
8. Ordovician Bighorn Dolomite (Whitney Canyon, Woodruff Narrows, and Road Hollow fields).

The Permian Phosphoria Formation (Maughan 1975; Sando, Sandberg, and Gutschick, 1981; Edman and Surdam 1984) and Mississippian equivalents of the phosphatic Aspen Range Formation (Little Flat and Deseret formations; see Walker 1982, Chidsey 1984) are likely source rocks.

Royse, Warner, and Reese (1975, Plate II) proposed continuation of Jurassic rocks, including the Nugget Sandstone, westward nearly to Ogden Valley, east of Ogden, Utah, based on seismic data. Their inferred westward truncation of this sequence by a ramp of the Paris-Willard thrust fault (PWT) lies about 15 miles/25 km east of the Wasatch normal fault and about 29 miles/48 km due south of the west end of geologic section K-L (Fig. 2) of this report. Schirmer (1988) inferred subsurface continuation of Jurassic rocks even farther west, to the midpart of Ogden Valley. Dover (1985) documented truncation of Mesozoic rocks westward at a ramp of the LMT about 6 miles/3-1/2 km south of Bear Lake, based on the Otter Creek well, drilled through the thrust, and on extensive Paleozoic outcrops just west. If correct, Jurassic strata probably do not extend west beneath the PWT in the study area, but may underlie the LMT far into the northern part of the area of study (Dover 1985, section A-A'). Also, Jurassic rocks could be present beneath the sole thrust.

At Paris Canyon, in southeast Idaho northwest of Bear Lake, the Cambrian-Precambrian Geertsen Canyon Quartzite overlies Permian Phosphoria Formation (Mansfield 1927) at the PWT. Thus, the basal unit in the hanging wall of the PWT rises upsection to the northeast, from the Middle Proterozoic Facer Formation in the area of Ogden Valley (Sorenson and Crittenden 1979, 1985) to basal Cambrian quartzites near Paris, Idaho. In contrast, the highest unit in the footwall of the PWT may decline downsection, from possible Jurassic strata near Ogden Valley to strata of Permian age.

Seismic Section, Geologic Interpretation, and Regional Implications

Seismic data are from the Left Fork of Blacksmith Fork River, immediately south of the study area. The east end of geologic section K-L of this report coincides with the seismic line, whereas the west end lies about 2.5 miles/4 km to the north of the seismic line. Correlation of thrust faults present in the seismic line with regional thrust faults is based on the east-to-west sequence of these faults, mapping of bedrock beneath the Wasatch Formation during this study, and an ongoing joint study, with James P. Evans and R. Daniel Kendrick, of numerous seismic lines in this region. Conversion of two-way travel times to depth for the seismic data utilized both Texaco and Chevron criteria for Paleozoic rocks. The Texaco criteria produce results that plot systematically higher than those determined from the Chevron criteria. An average of results from the two criteria is used in Figure 18. Thicknesses of Late Proterozoic units are from Sorenson and Crittenden (1979, 1985). Measured thicknesses of these and of some younger units that crop out in the study area are given in the section on Stratigraphic Units.

Both results show that the PWT rises steeply, 20° to 25° to the east, to the area of the Saddle Creek thrust fault, a splay, and then steepens to about 40° eastward. The sole thrust lies near -38,000 ft/-11,600 m (at a depth of 46,000 ft/14,000 m) in the west, and rises 2-1/2° to 3° eastward to near -35,000 ft/-10,700 m (42,000 ft/12,800 m depth) at the east end of section K-L.

The interpreted data suggest that thick Proterozoic sedimentary rocks persist northward above the PWT, beneath the central part of the Bear River Range (Fig. 18). Furthermore, a thick sequence of upper Late Proterozoic sedimentary rocks (only the upper part is exposed) continues into southeastern Idaho along the west margin of the Bear River Range. These strata are well exposed at High Creek, Utah, just south of the Utah-Idaho State line. The implication is that the loss of the Proterozoic sedimentary sequence in the hanging wall of the PWT is abrupt and oriented eastward, based on thrust-fault geometry in southernmost Idaho (High Creek to Paris; compare Dover 1985) and in the Ogden area (Royse, Warner, and Reese 1975; Schirmer 1988). This also appears to be the case in the seismic data along section K-L.

Unlike the eastward rise upsection in the hanging wall, the apparent drop downsection in age of rocks at the top of the footwall, northeast from Ogden to Paris, if real, must result from overall northward ramping downsection. This is because ramping in the footwall in the area of southern Idaho must be upsection eastward, to satisfy the observed relations in the hanging wall. It is unknown if this northward transition is abrupt, gradual, if it even exists. A flexure at the north end of the Wellsville Range (Williams 1948) suggests an abrupt subsurface ramp up to the north there (Oviatt 1985, 1986a,b). A north-climbing ramp also may be present through an area of poor results at depth in north-south seismic lines in Cache Valley (Evans in press, Fig. 6), between the Wellsville Range and the Bear River Range. In both cases the direction of ramping is opposed to that required by the assumption of Mesozoic rocks below the PWT in the Ogden Valley area. Eastward, there is no down-to-the-north abrupt flexure mapped in the Bear River Range (Williams 1948, 1958; Galloway 1970; Mendenhall 1975; Mullens and Izett 1963; Dover 1985; Brummer, 1991; this study). If such a ramp is present beneath the area of study, it probably is gradual, not abrupt. We conclude that it is more likely that the rocks below the PWT in the Ogden area are older than inferred by Royse, Warner and Reese (1975) and Schirmer (1988).

Background Considerations for Time-Temperature Models

Edman and Surdam (1984) proposed that thermal models for hanging wall sequences should be cooler, and those for footwall sequences should be warmer, than for unthrusted sequences. They constructed thermally adjusted Lopatin (1971) time-temperature models of thrusted sequences, based on reflectance values of bitumen (not vitrinite) and results of pyrolysis, and compared them with the model of an unthrusted sequence. They concluded that: (1) The paleogradient of temperature for the Utah-Idaho-Wyoming overthrust belt was close to 18° F/1000 ft (32.8° C/km); and (2) frictional heating related to thrusting probably was minor, and could be ignored.

By dating thrust-generated molasse deposits, Wiltscho and Dorr (1983) established that the PWT moved slowly, but at a rate in excess of 0.023 cm/yr (0.01 in./yr), and was active between about 150 and 92 Ma. Thereafter, this thrust sheet rode "piggyback" on younger, lower thrusts. The Crawford thrust (CRT) and LMT moved at a more rapid rate, but less than 0.8 cm/yr (0.3 in./yr), and experienced its main activity between about 91 and 86 Ma. Although minor additional movements may have persisted until about 48 Ma, after 86 Ma rocks above these thrusts primarily rode "piggyback" on younger, lower thrusts. Major eastward thrusting under a compressional regime continued until about 57 Ma (late Early Eocene: Berggren and others 1985).

The preserved thickness of the Wasatch Formation is modest in the study area, probably less than 600 ft/185 m (section M-N). Original thicknesses in some paleovalleys may have exceeded 1000 ft/300 m locally, but the effect on the time-temperature calculations will be less than for the Paleozoic bedrock missing from the canyons. Evidence from other areas also suggests insufficient aggregated thickness of the Wasatch Formation to provide a significant increase to the Lopatin time-temperature index.

Evaluation of Maturation Levels of Hydrocarbons: Models

Because of the great depth to the sole thrust (about 44,000 ft/ 13,400 m, roughly 5000 ft/1500 m deeper than its position 29 miles/ 48 km southward at Ogden Valley), and with the possibility of Nugget Sandstone below it, a best-case scenario was considered. Assumptions are:

(1) Deposition of Jurassic rocks ceased when movement on the PWT began in the west, about 152 Ma, and the area was uplifted as a peripheral bulge (compare Blair and Bilodeau 1988);

(2) Thrust loading just in front of the advancing PWT then depressed the area, and molasse deposits accumulated. These deposits may have been thick. Probably they were bulldozed off and perhaps partly overridden later by the advancing PWT. Because the tenure of these deposits may have been short, and their thickness is unknown, their influence on the time-temperature model cannot be evaluated. Because the present footwall was still shallow, the influence of the molasse deposits was limited, so this factor is ignored;

(3) Erosion downsection to the top of the Nugget Sandstone was linear, and completed by 125 Ma, when molasse deposition began;

(4) Movement ceased on the PWT about 92 Ma when movement began on the LMT. The leading edge of the LMT is about 25 miles/42 km

(Wiltschko and Dorr 1983) east of its splay in section K-L (Fig. 18). The original position of this splay, before 34 miles/56 km (Wiltschko and Dorr 1983) of piggyback transport above the sole thrust, was about 34 miles/56 km west of the present splay, and the leading edge of the LMT was within 6 miles/10 km west of the west end of section K-L. Therefore, thrust loading probably occurred later, after movement on the CRT, during the latter 2/3 of the 17 miles/28 km of displacement on the Absaroka thrust fault (ABT). The ABT covered the 10.3 miles/16.75 km of section K-L in 8.5 Ma at 0.2 cm/yr (0.08 in/yr)(Wiltschko and Dorr 1983). Thrust loading began about 70.5 Ma, and was completed by 62 Ma, when movement on the Darby, Prospect, Tunp thrust complex (DPT) began;

(5) There was no further deposition of regolith or erosion of bedrock, nor any decrease in thickness of the thrust plates overriding the sole thrust, so that the thickness of the overburden was never greater than at present, between 70.5 Ma and onset of deposition of the Wasatch Formation;

(6) An effective net thickness of 500 ft/150 m of Wasatch Formation accumulated between 62 and 45 Ma on eroded Paleozoic bedrock throughout the area, so that the rocks then above the sole thrust in section K-L and those now above it were about the same thickness;

(7) All significant thicknesses of Wasatch Formation were removed by erosion that began at the onset of Basin-and-Range extension, near the end of the Eocene (Brummer and Evans 1989), about 37 Ma (Berggren and others 1985), and finished by the end of the Early Miocene, about 17 Ma;

(8) Mesozoic sediments originally deposited above the Nugget Sandstone in the footwall sequence were sufficiently thin or compacted and cemented so rapidly that no decompaction corrections are needed;

(9) The surface temperature during deposition of the eolian-to-nearshore marine Nugget Sandstone was 80° F/27° C (average present temperature of the Sahara desert), and, thereafter, 38°F/3° C. The present annual temperature at Logan, Utah, is 42° F/6° C. Probably the surface temperature was cooler during deposition of the marine Twin Creek Limestone and while erosion stripped highlands created by the peripheral bulge and later during lacustrine deposition of the Salt Lake Formation and during Pleistocene glacial epochs. Likely the temperature was warmer during deposition of the hematite-stained red Wasatch Formation; and

(10) The geothermal gradient was a modest 18° F/1000 ft (32.8° C/km).

The resulting simplified Lopatin cumulative time-temperature index (TTI), for the shallower east end of section K-L, based on the solid lines in Fig. 19, is astronomical (Table 3): over 10^9 for the interval 70.5 to 62 Ma and over 10^{11} for the last 62 Ma! Even with a modest reduction for temperature equilibration, mostly in the first 20 Ma after loading (Edman and Surdam 1984), it is clear that even with the most optimistic assumptions, petroleum hydrocarbons should not be preserved below the sole thrust.

This conclusion is consistent with the record for production of dry gas from a depth of 26,518 ft/8083 m in the Chevron Oil #1 Ledbetter well in north Texas (North 1985), with a TTI of 65,000 (Waples 1981). Liquid sulfur was encountered at 400° F/240° C at 31,441 ft/9583 m in the Lone Star Production #1 Bertha Rogers well in Oklahoma, with a TTI of 972,000. Hunt (1979) maintained that petroleum is dissociated and eventually destroyed at protracted temperatures above about 337° F/205° C. Rocks below the sole thrust probably have experienced temperatures above 688° F/400° C for more than 40 Ma.

TABLE 3. Cumulative TTI values for models of two reservoir rocks, based on seismic data in Figure 18 and data from Figure 19.

<table>
<tr><th>AGE SEGMENTS IN Ma</th><th>TOP OF NUGGET SANDSTONE</th><th>TOP OF FISH HAVEN DOLOMITE</th></tr>
<tr><td>458-176</td><td>0</td><td>320</td></tr>
<tr><td>176-103</td><td>.249</td><td>2182</td></tr>
<tr><td>103- 92</td><td>.011</td><td>53,400</td></tr>
<tr><td>92-70.5</td><td>.033</td><td rowspan="2">557,349</td></tr>
<tr><td>70.5-62</td><td>3,432,872,508</td></tr>
<tr><td>62- 0</td><td>266,287,972,352</td><td>63,488</td></tr>
<tr><td>TOTAL (TTI) =</td><td>269,720,844,860</td><td>676,739</td></tr>
</table>

For a cumulative TTI of 65,000 or less, the reservoir rock in section K-L would need to be no deeper than about 25,000 ft/7620 m. Given the ideal assumptions made above, the depth probably would be shallower. This depth constraint excludes rocks in the footwall of the Meade thrust fault in section K-L, which lie below depths of 33,000 ft/10,050 m.

The geometry of the thrusts, the presence of Early to Middle Cambrian rocks between the upper and lower splays of the PWT east of section K-L, and the probable truncation of Jurassic and younger rocks beneath the LMT to the east (Dover 1985), together suggest that rocks in the footwall of the PWT in Fig. 18 likely are older than Ordovician. Thus, no reservoir rocks are likely beneath the upper splay of the PWT.

However, a second scenario was constructed for the possibility that the Fish Haven Dolomite (Bighorn equivalent) is present in the footwall beneath the east end of the lower splay of the PWT in section K-L. Whatever the unit present, it would be completely overridden no later than 92 Ma, when movement on the PWT ceased. At the minimum possible rate of displacement of 0.023 cm/yr (0.01 in./yr)(Wiltschko and Dorr 1983) emplacement across the 10.3 miles/16.75 km of section K-L would require nearly 73 Ma. Thus, thrust loading of this area should have begun no earlier than 165 Ma, about the time of onset of deposition of the Preuss and Stump formations, or later.

Assumptions for this second model are:

(1) Displacement was greater than the minimum possible, about 0.2 cm/yr (0.08 in./yr), so that thrust loading at section K-L required about 8.5 Ma, plus about 2.7 Ma for thrusting an additional 3.2 miles/5.4 km east of section K-L (Fig. 18), and began about 103 Ma and ceased by 92 Ma;

(2) Deposition of the Preuss and Stump formations on the footwall sequence ceased about 152 Ma;

(3) Erosional removal from the footwall of all units above the Fish Haven Dolomite was linear and completed by 103 Ma, just as thrust loading began at section K-L; and

(4) Movement on the PWT began about 152 Ma and created a peripheral bulge that terminated marine deposition of the Twin Creek Limestone and initiated erosion of the hanging wall sequence. Vertical erosion was linear in the hanging wall during all subsequent thrusting (238 ft/Ma; 73 m/Ma at the leading, higher eastern end, 102 ft/Ma, 31 m/ Ma at the trailing, lower western end), and lasted until onset of deposition of the Wasatch Formation about 62 Ma. At that time, erosional stripping of the east end of section K-L was stratigraphically 21,000 ft/6400 m total, about 12,000 ft/3650 m more than at the west end (Fig. 18). Assumptions (6) through (10) are the same as before.

The resulting cumulative TTI (Table 3), based on the dashed lines in Fig. 19, exceed 10^5 since the end of thrust loading, about 92 Ma, for the upper part of the footwall sequence below the lower splay of the PWT at the east end of section K-L. The value is so great that the lag time of about 20 Ma for equilibration following thrust loading will not lower the results significantly. Even though the depth of about 14,000 ft/4270 m for the past 92 Ma is well above the predicted maximum possible depth of 25,000 ft/7620 m, the long residence time at that level probably insures that the rocks there have no exploration potential for petroleum.

Exposure of successively older Paleozoic units, beneath the Wasatch Formation, northward from the Right Fork of Logan River and southward from section K-L, suggests that those areas will have lower TTI values for rocks below the lower splay of the PWT than along section K-L. Lower values also should be present eastward beneath the PWT where the PWT rose to the pre-Wasatch surface.

Thus, only rocks beneath the lower splay of the PWT might be prospective, possibly for dry gas, and only in the northernmost part of the study area. It is unlikely that the Nugget Sandstone and other Mesozoic and Late Paleozoic reservoir rocks are present beneath the PWT and other thrust faults above the sole thrust in the study area. Thus, reservoir rocks probably are marginal, if present. No source rocks are known in the Early Paleozoic rocks. In summary, petroleum prospects in the study area are poor.

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STRATIGRAPHIC UNITS

Cenozoic Units

SYMBOL	MAPPED UNIT
Qal	low-level alluvium
Qaf	alluvial-fan deposits
Qat	stream-terrace alluvium
Qc	general areas of fine-grained colluvium
Qcc	colluvium with carbonate cobbles and boulders; in places, north of Spawn Creek, contains huge slabs of limestones of the Bloomington Formation that slid and rotated on underlying Bloomington shales
Qcq_2	younger colluvium with quartzite cobbles and boulders
Qcq_1	older colluvium with quartzite cobbles and boulders
Qgp	periglacial patterned ground; unit involved shown in parentheses
Qgt	glacial till
Qms	landslide block (bedrock) or area of multiple slides and slumps (Wasatch Formation); unit involved shown in parentheses
Qnd	general areas of boulder-bearing colluvium: diamicton
QTw	remobilized Wasatch Formation; most common along walls of west-flowing canyons draining Temple Ridge; contact gradational with Wasatch Formation, with no scarp
Tw	Wasatch Formation; red- to orange-weathering; typically red unweathered; mostly cobble- to boulder diamicton with subordinate lenses of fluvial cobble orthoconglomerate and granular to pebbly lithic arenite; cobbles and boulders in basal part derived locally; higher gravel typically includes white quartzites of the Eureka Quartzite and, locally, brown-weathering pebbly quartzites of the Geertsen Canyon Quartzite
Twl	Cowley Canyon Member of the Wasatch Formation; lacustrine oncolitic (algal) limestone; white weathering; pale brown unweathered; locally with cobbles and minor boulders, especially in southeast near Saddle Creek; typically two resistant units of limestones separated by several meters of red granular to pebbly orthoconglomerate; in south, lies near Wasatch Formation base near margins of paleochannels but lies over 100 meters above Wasatch Formation base above axes of deep paleo-channels (see plate 7 apparently absent north of West Hodges Creek and both east and north of Temple Peak

Paleozoic Units

SYMBOL	FORMATION	SOURCE	APPROXIMATE THICKNESS FEET	METERS
Mlf	Little Flat Formation	Sando and others 1976	801	244
		Laketown Cyn		
Ml	Lodgepole Limestone	Valenti 1982	702	214
		Laketown Cyn		
Dl	Leatham Formation	Sandberg and Poole 1977	0-82	0-25
		Leatham Hollow of Left Hand Fk Blacksmith Fk		
Db	Beirdneau Sandstone	Eliason 1969	805	245
		Logan Cyn; Blacksmith Fk		
Dh	Hyrum Dolomite	Eliason 1969	971	296
		Logan Cyn; Blacksmith Fk		
Dwc	Water Canyon Formation	Williams 1948	393	120
		Green Cyn (Berry, 1989: 1285ft/392m)		
Sl	Laketown Dolomite	Budge 1966	1497	456
		Tony Grove Lk; Rt Hand Fk Logan R; Left Hand Fk Blacksmith Fk		
SOfh	Fish Haven Dolomite	Mecham 1973	138	42
		Smithfield Cyn; Green Cyn; Rt Hand Fk Logan R; Left Hand Fk Blacksmith Fk		
Oeu	Eureka Quartzite (upper part of Swan Peak Formation; removed by pre-Fish Haven erosion south of Right Hand Fork Logan River; thickens to 290 ft/88 m near Idaho State line)			
		VanDorston 1969, 1970	0-290	0-88
Osp	Swan Peak Formation	Oaks and others 1977	205	62
		(lower and middle members) Rt Hand Fk Logan R; E of Wood Camp		
Ogc	Garden City Formation	Morgan 1988	1142	348
		Green Cyn; Blacksmith Fk		
€sc	St Charles Formation	Williams 1948	1015	309
		High Creek (Berry, 1989: 970ft/296 m)		
€n	Nounan Formation	Gardiner 1974	1053	321
		Bear Lk Summit; Spawn Cr; Blacksmith Fk		
€bo	Bloomington Formation	Oaks, unpublished	1438	438
		High Creek		
€bl	Blacksmith Dolomite	Hay 1982	505	154
		Little Bear Cr; Dry Cyn (Smithfield); Left Hand Fk Blacksmith Fk		
€u	Ute Limestone	Williams 1948; Oaks, unpublished		
		Left Hand Fk Blacksmith Fk; High Creek	[illegible]	217
€l	Langston Formation	Buterbaugh 1982	430	131
		High Cr; Dry Cyn (Smithfield); Left Hand Fk Blacksmith Fk		
€pCgc	Geertsen Canyon Quartzite	Dover 1985	4600	1400
		High Creek		
		Crittenden and others 1971, Huntsville, Utah, area	4200	1280
Pz	Paleozoic rocks, undifferentiated			

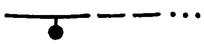
Proterozoic and Archean Units

(present only in subsurface; data from Sorenson and Crittenden 1979, 1985)

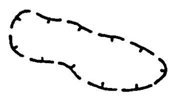
SYMBOL	FORMATION	THICKNESS FEET (Huntsville Quadrangle)	THICKNESS METERS (Huntsville Quadrangle)	THICKNESS FEET (Mantua Quadrangle)	THICKNESS METERS (Mantua Quadrangle)
	Late Proterozoic				
p€b	Browns Hole Formation	400	120	260	80
p€m	Mutual Formation	1200	365	2430	740
p€i	Inkom Formation	400	120	100	30
p€cc	Caddy Canyon Quartzite	1740	530	1310	400
p€pc	Papoose Creek Formation	1970 (Papoose Creek and Kelly Canyon combined)	600 (Papoose Creek and Kelly Canyon combined)	1100	335
p€kc	Kelly Canyon Formation			590	180
p€mc	Maple Canyon Formation	1525	465	1230	375
p€p	Formation of Perry Canyon	1700	520	6235	1900
	Early Proterozoic				
p€f	Facer Formation	>25	>8	2770	845
	Archean				
p€fc	Farmington Canyon Complex			>6000	>1830

EXPLANATION OF MAP SYMBOLS

STRATIGRAPHIC CONTACT - Dashed where approximately located or inferred.

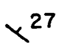


HIGH-ANGLE OR LISTRIC NORMAL FAULT - Dashed where approximately located; dotted where covered; may be covered locally in photointerpreted areas (short dashes); bar and ball on downthrown side; opposed ball-and-bar shown where offsets of bedrock and of Wasatch Formation are different; where listric, normal faults decrease in dip downward and merge with pre-existing thrust faults. In geologic sections, arrows show direction(s) of relative movement; opposing directions of movement exist for bedrock and for the Wasatch Formation on thrust faults that later became listric faults.



LANDSLIDE BOUNDARY - Hachures on side of landslide block (in bedrock) or of multiple landslides with indistinct boundaries (in Wasatch Formation).

STRIKE AND DIP OF BEDDING



Inclined; numeral shows amount of dip.

Dip estimated from distant observation.

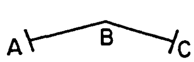
⊗ Horizontal

FOLDS - symbols show approximate surface trace of axial plane, arrow designates direction of plunge.

Anticline

Syncline

Monocline



GEOLOGIC SECTIONS - letters at ends and at bends refer to geologic sections shown on separate sheet.

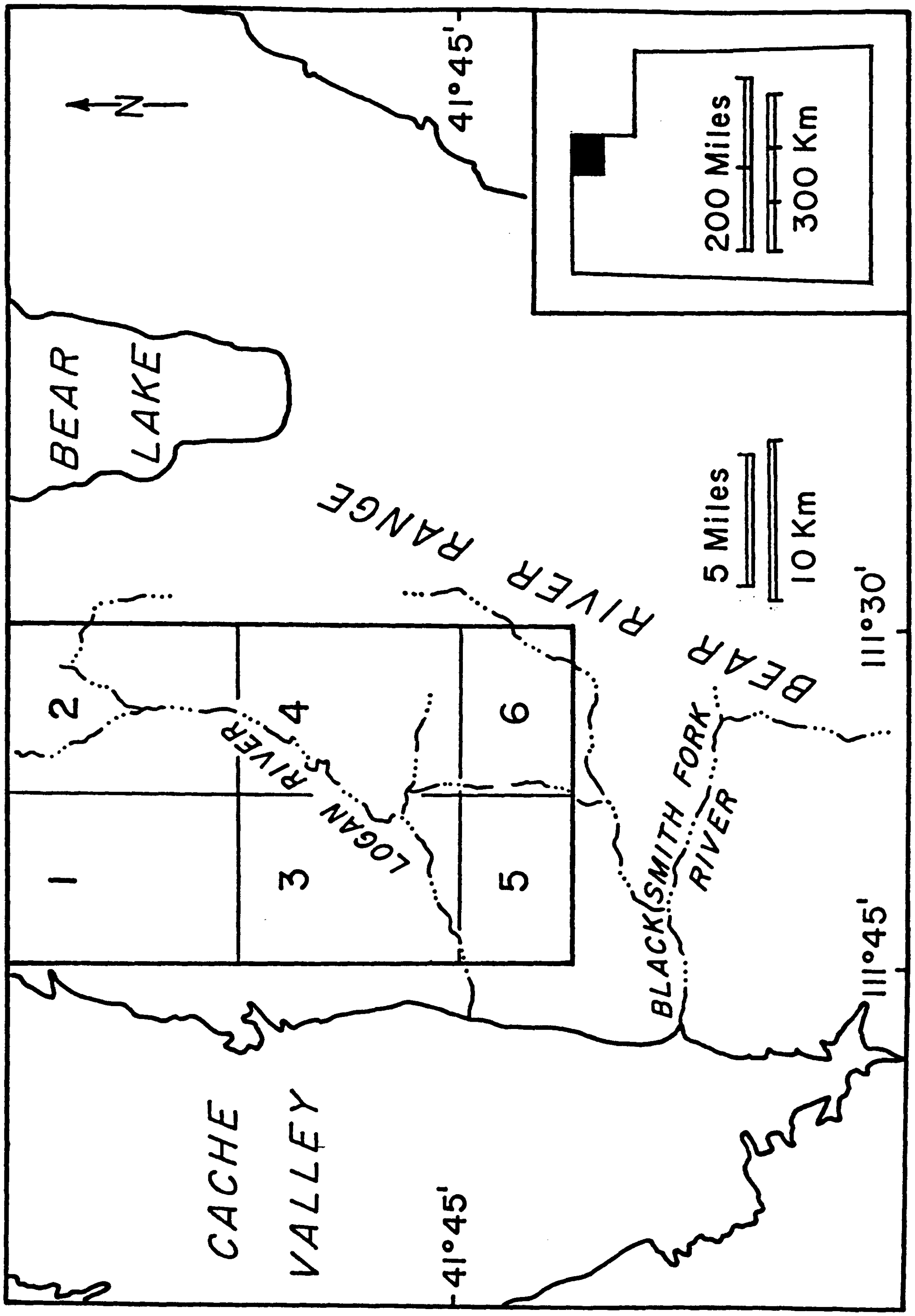


Figure 1. Map showing area studied and locations of geologic maps. Plates 1-6 include the following 7.5-minute quadrangles: 1 = Naomi Peak; 2 = Tony Grove Creek; 3 = Mt. Elmer; 4 = Temple Peak; 5 = Logan Peak; 6 = Boulder Mtn.

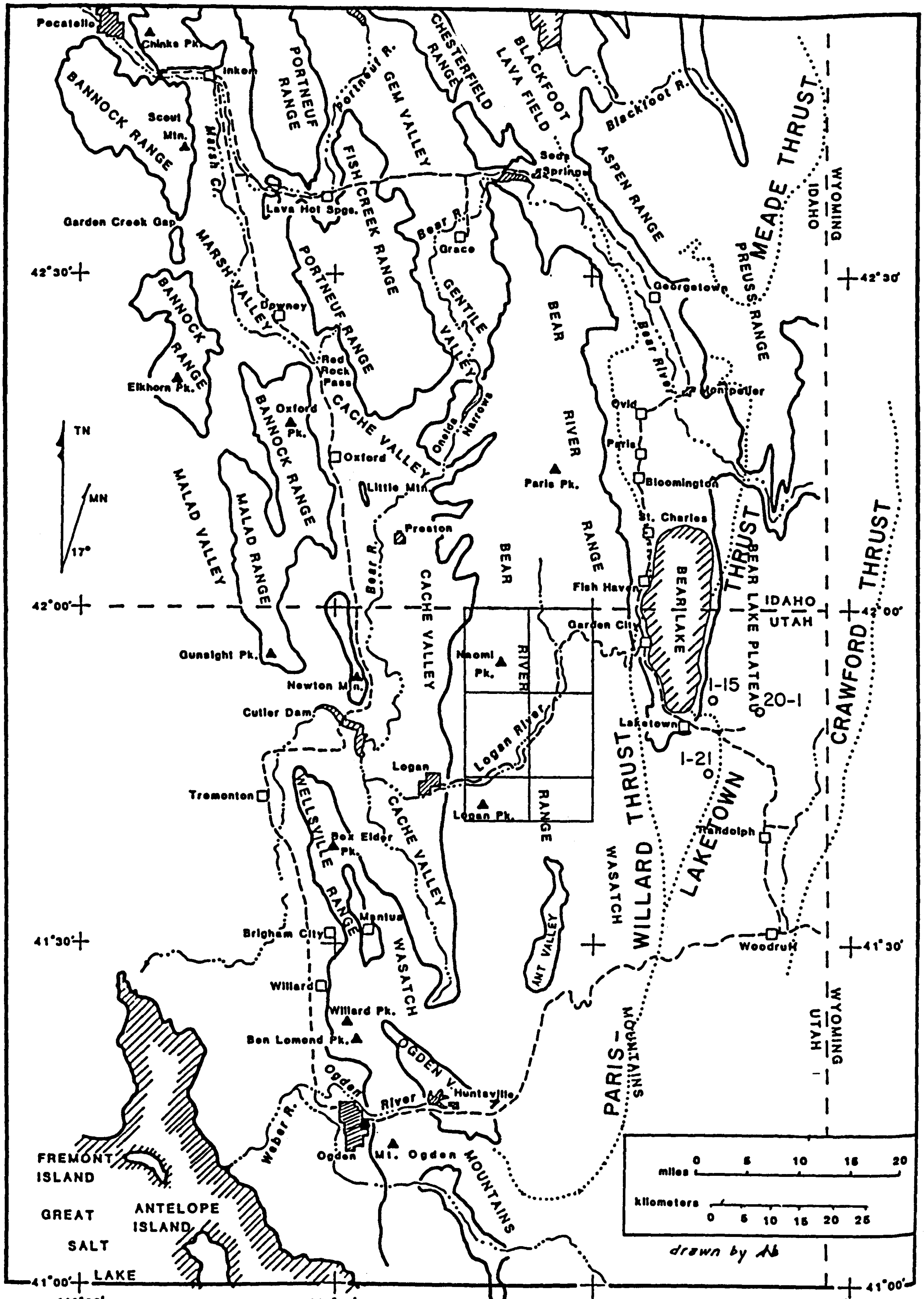


Figure 2. Locations of study area and of thrust faults and deep wells (from Dover 1985; Blackstone and DeBruin 1987). Map base from Chidsey and others (1985, based on Oaks and others 1974).

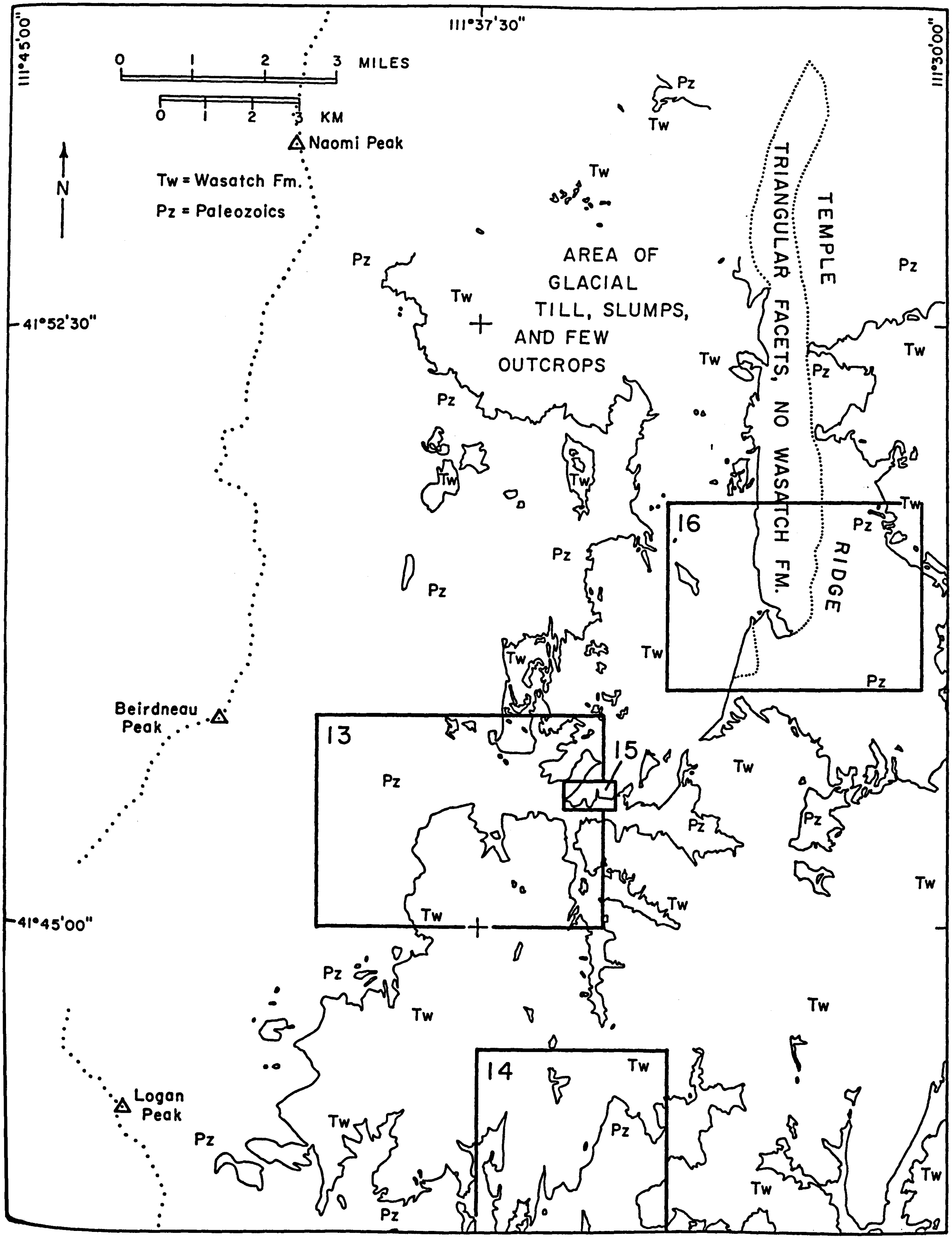


Figure 3. Locations of the base of the Wasatch Formation and of detailed maps shown in Figures 13-16.

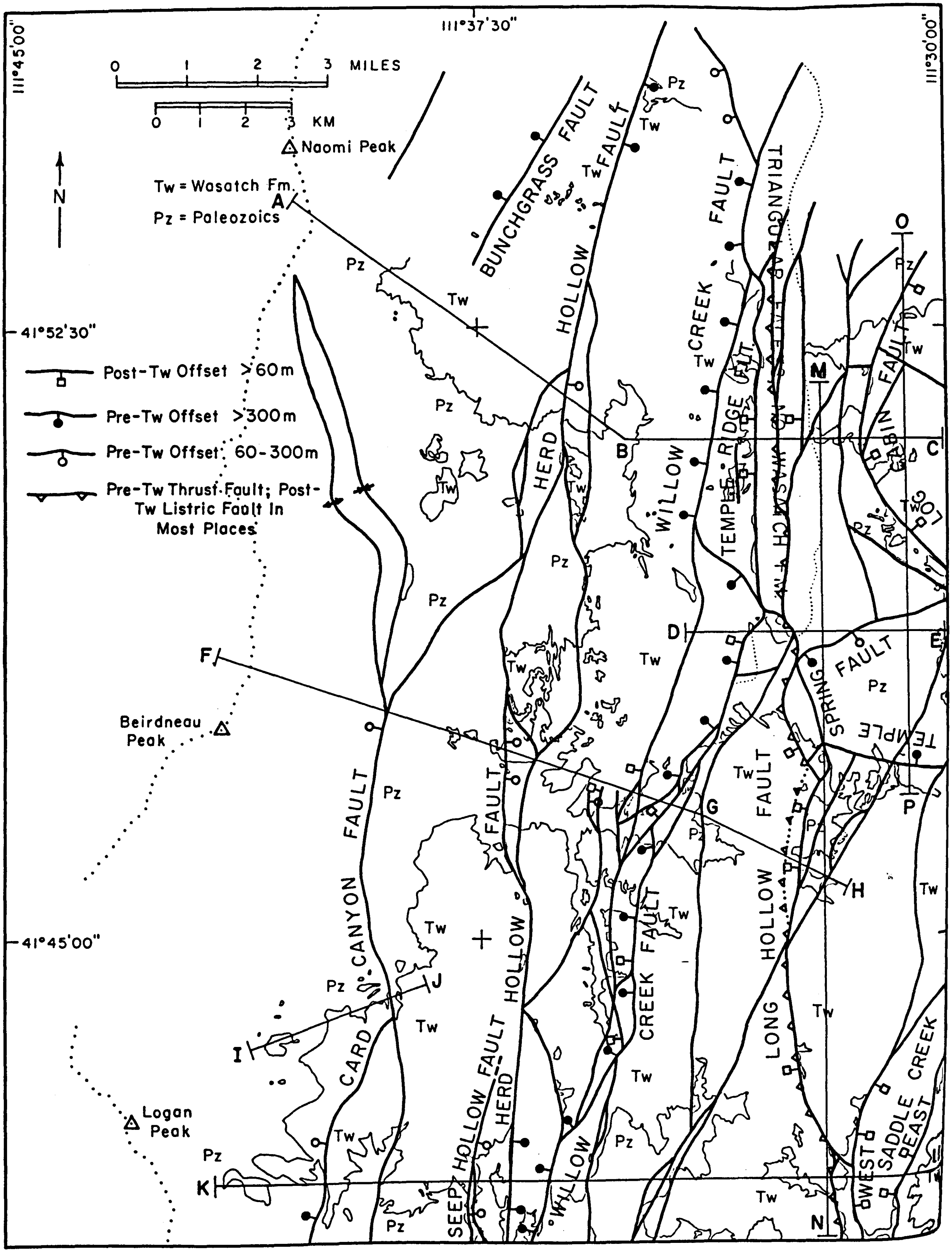


Figure 4. Locations of faults and geologic sections in study area.

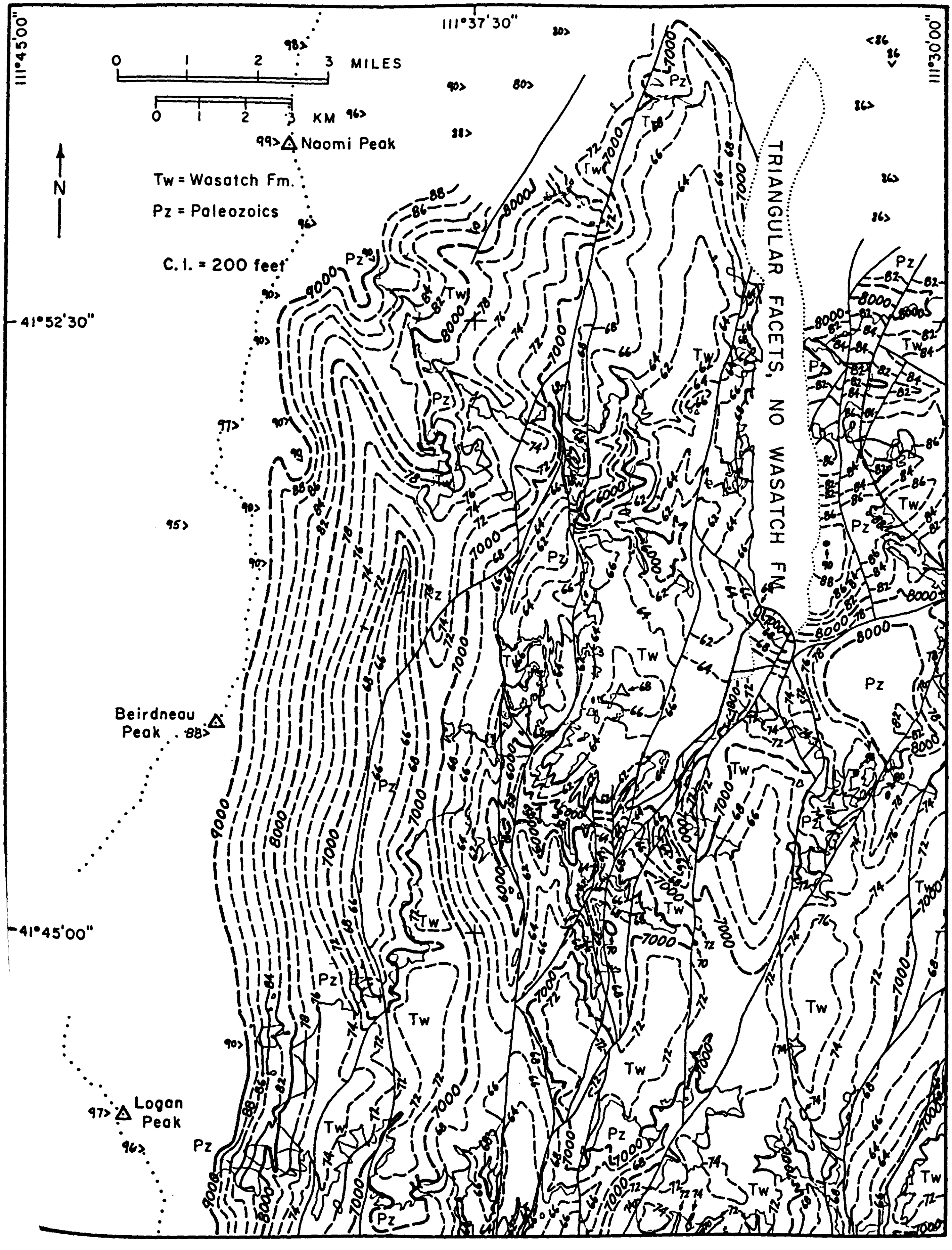


Figure 5. Map showing contours of base of the Wasatch Formation in study area.

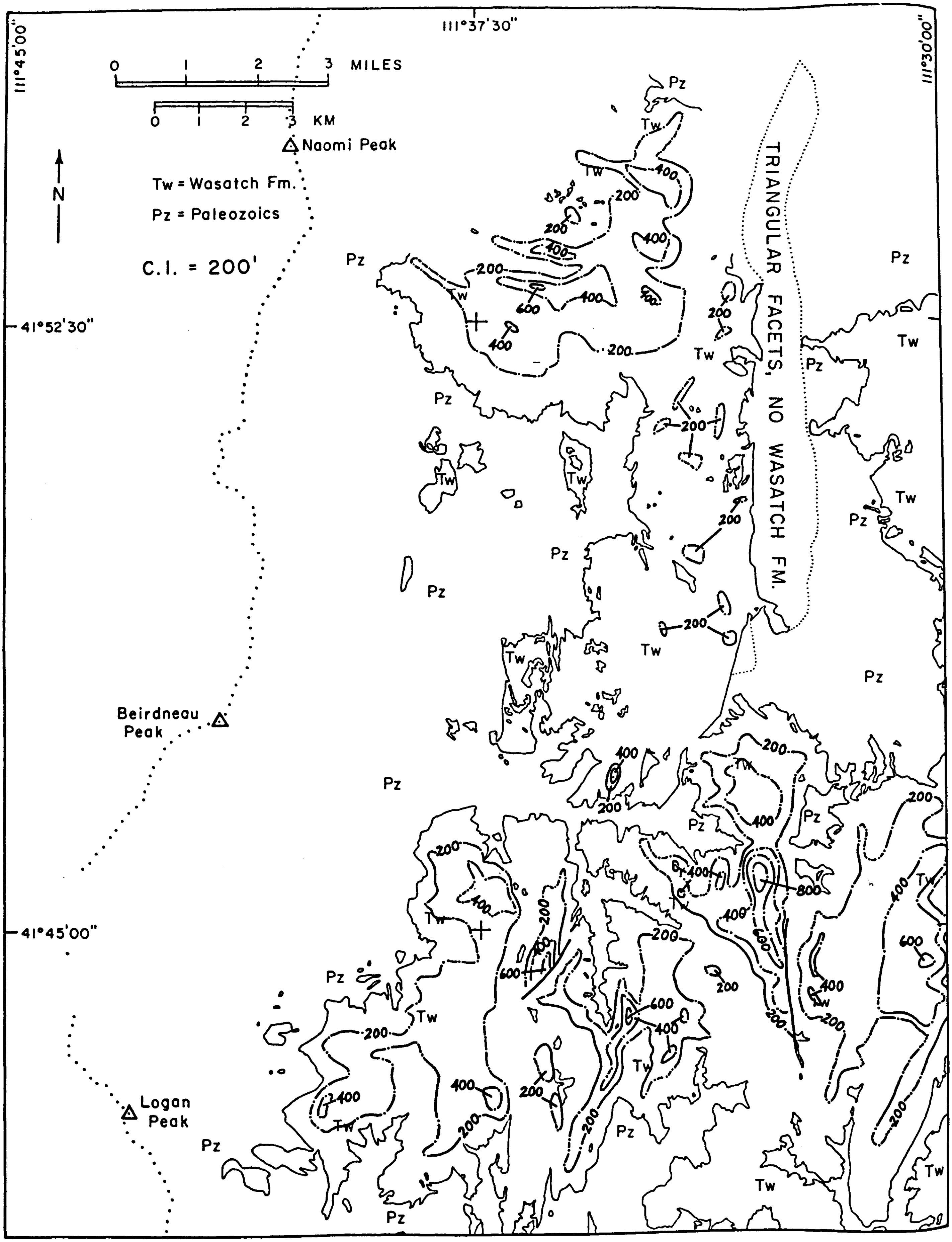


Figure 6. Map showing present thickness of the Wasatch Formation in study area.

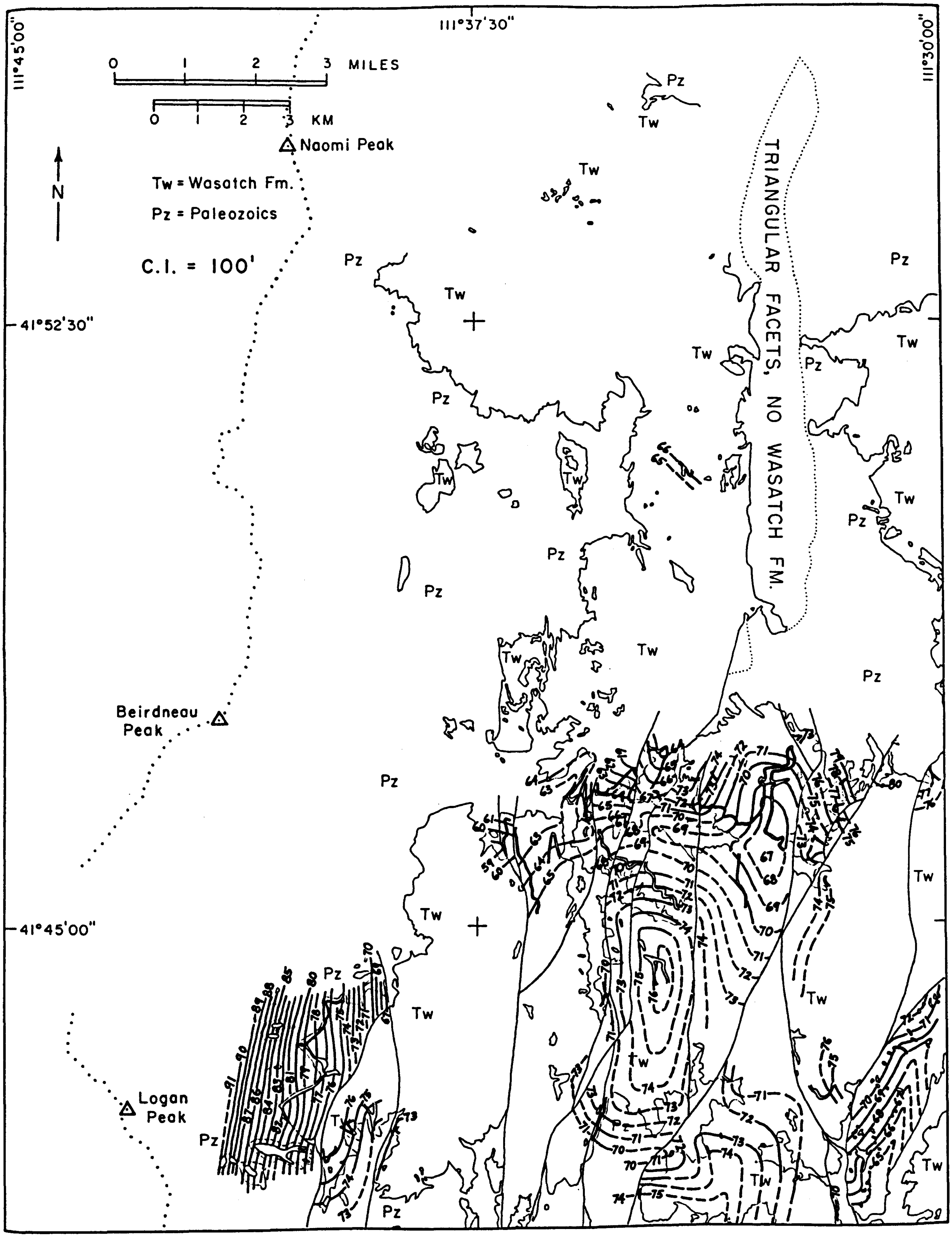


Figure 7. Locations of outcrops of the Cowley Canyon Member of the Wasatch Formation plus contours of its top in the study area.

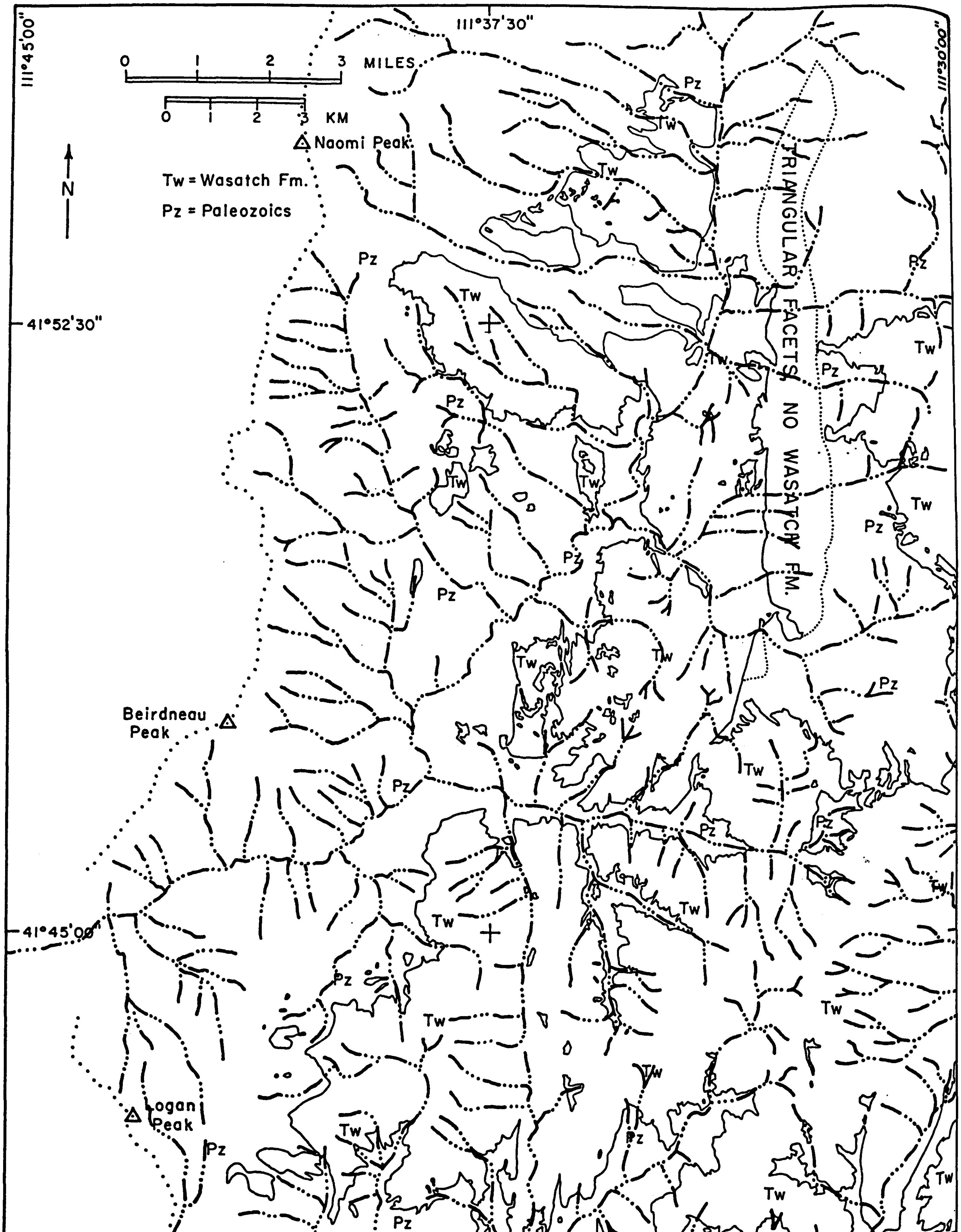


Figure 8. Map showing present drainage and the contact of the Wasatch Formation with the underlying Paleozoic bedrock.

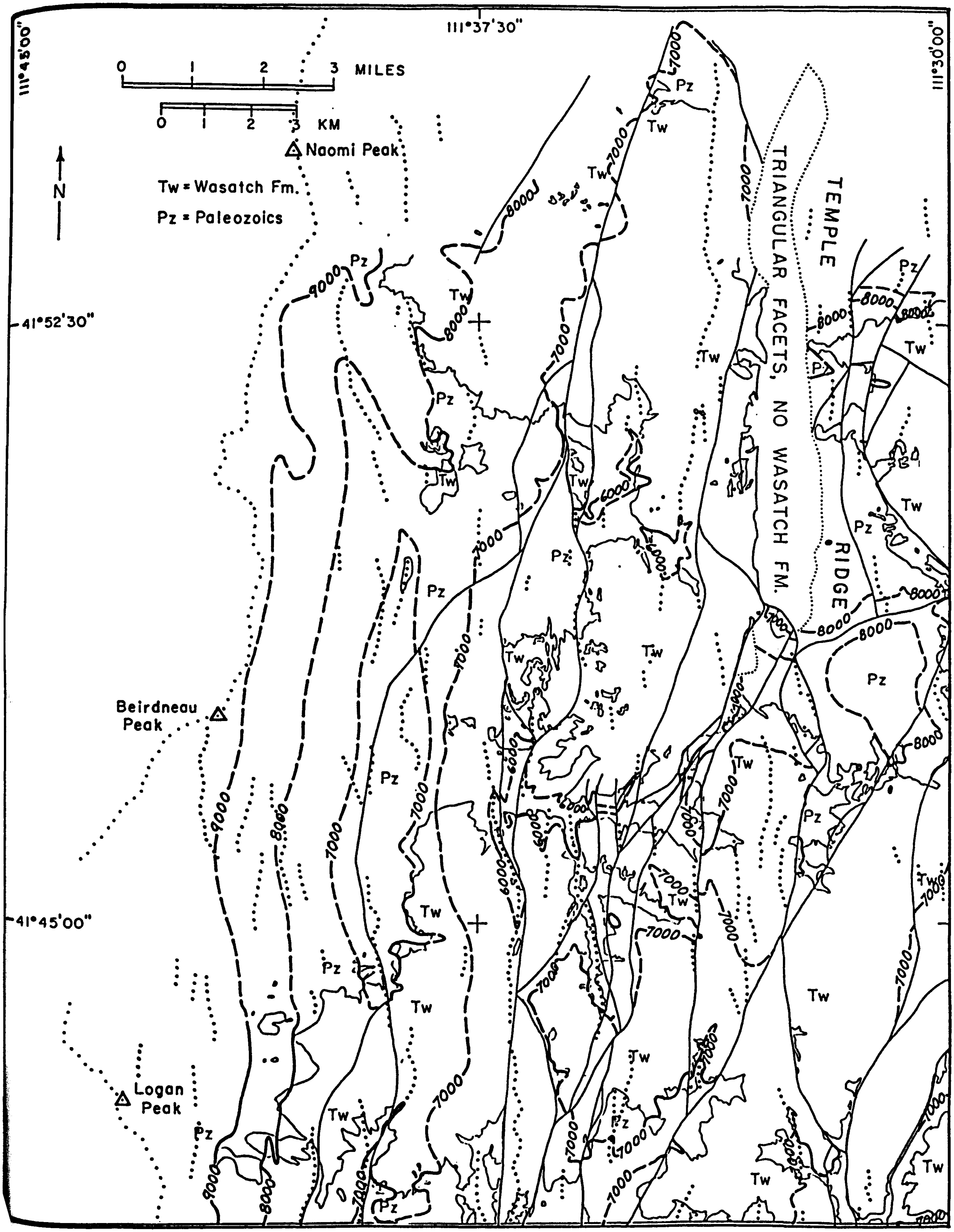


Figure 9. North-south segments of present drainage superimposed on simplified structural contours of the base of the Wasatch Formation (see Figures 5 and 8).

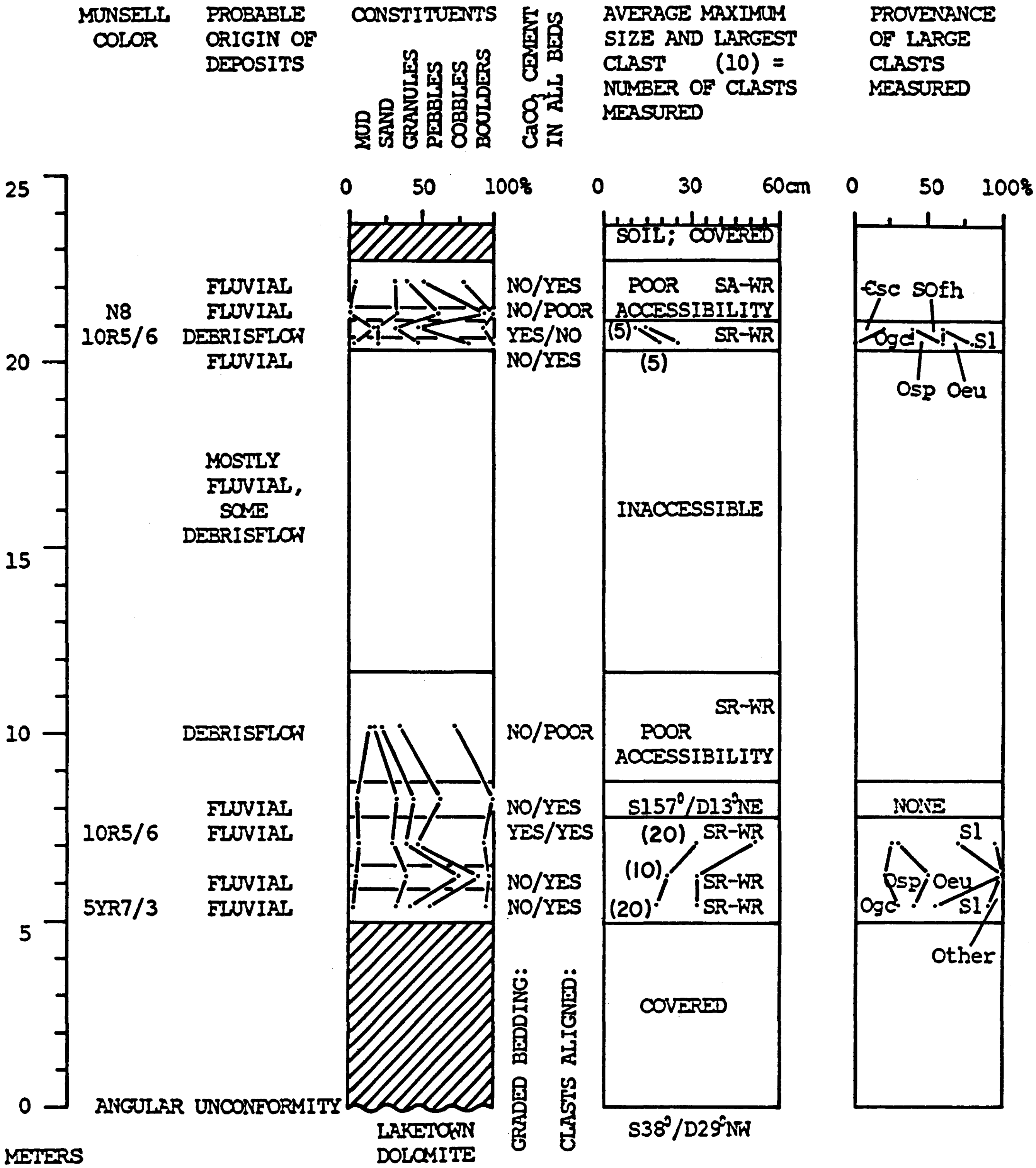


Figure 10. Measured section of base of the Wasatch Formation, exposed in cirque SSW of Tony Grove Lake (Plate 1). Base of section near altitude 8680 ft /2645 m at Lat 41°53'14" N, Long. 111°38'47" E. Measured 9/23/90 by R.Q. Oaks, Jr.

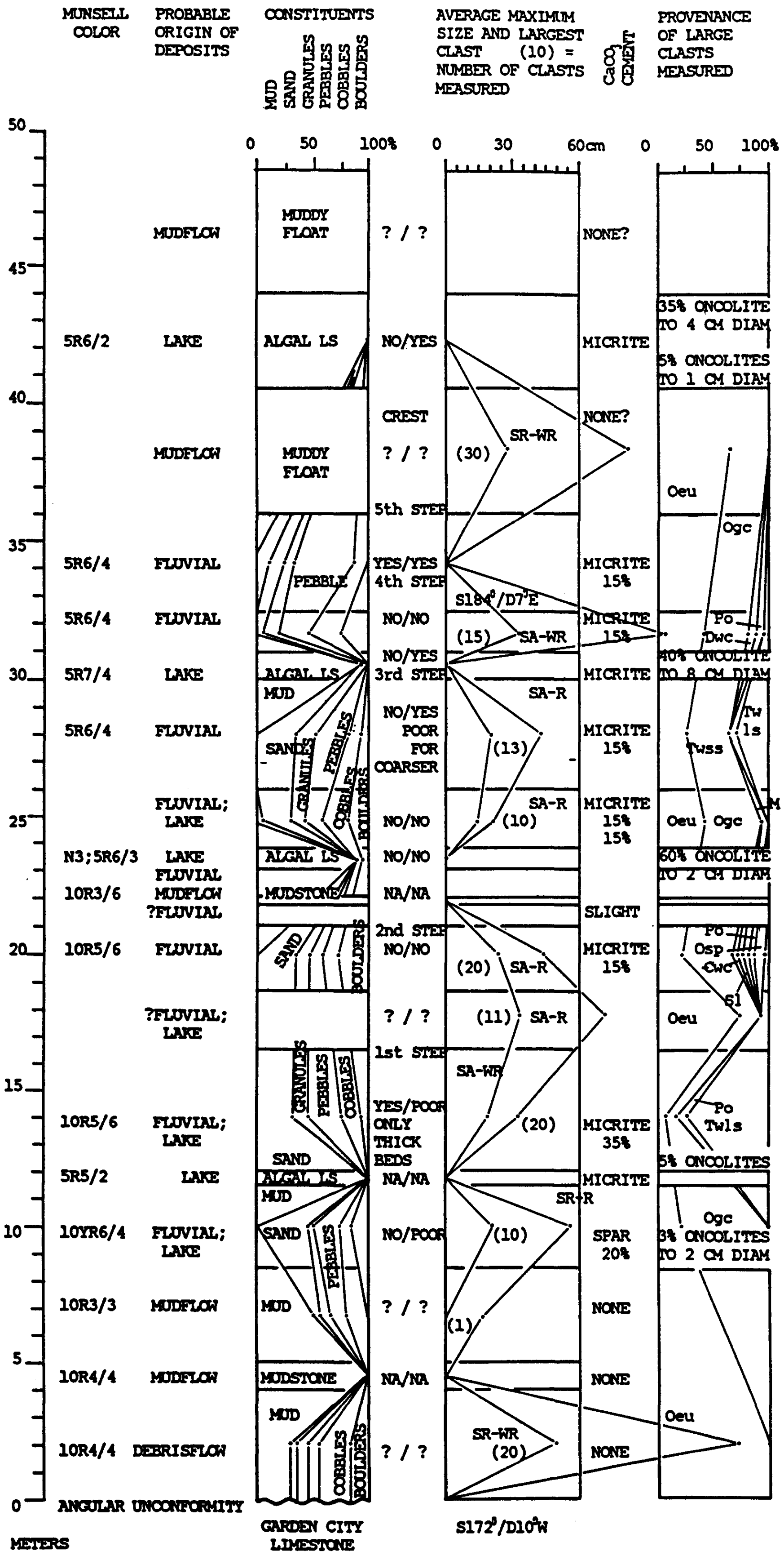


Figure 11. Measured section of base of Wasatch Formation, exposed on ridge along east side of Cowley Canyon (Plate 4). Base of section near altitude 5920 ft/1805 m at Lat 41°43'10" N, Long. 111°37'06" E. Measured 6/16/91 by R.Q. Oaks, Jr.

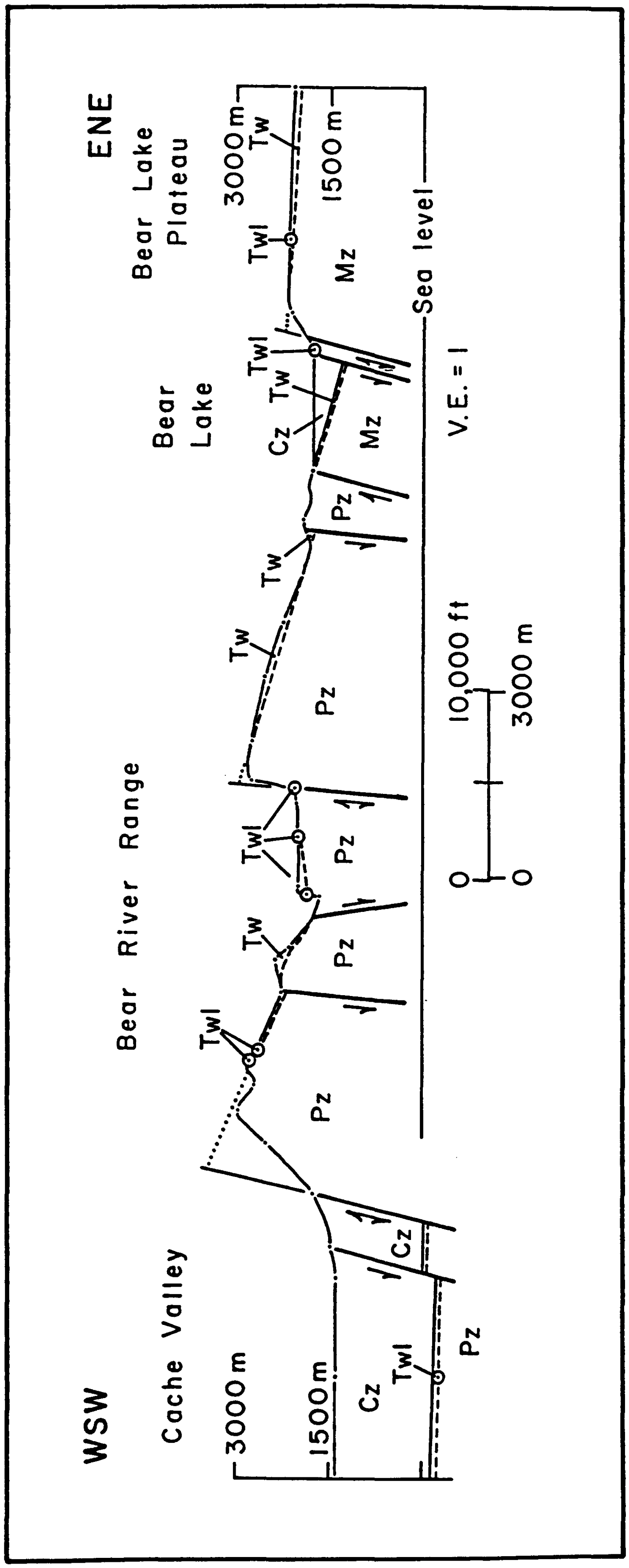


Figure 12. Diagrammatic ENE-WSW section through Bear River Range and Amoco #1 Lynn Reese well in Cache Valley shows lake beds of the Cowley Canyon Member (Twl) of the Wasatch Formation (Tw).

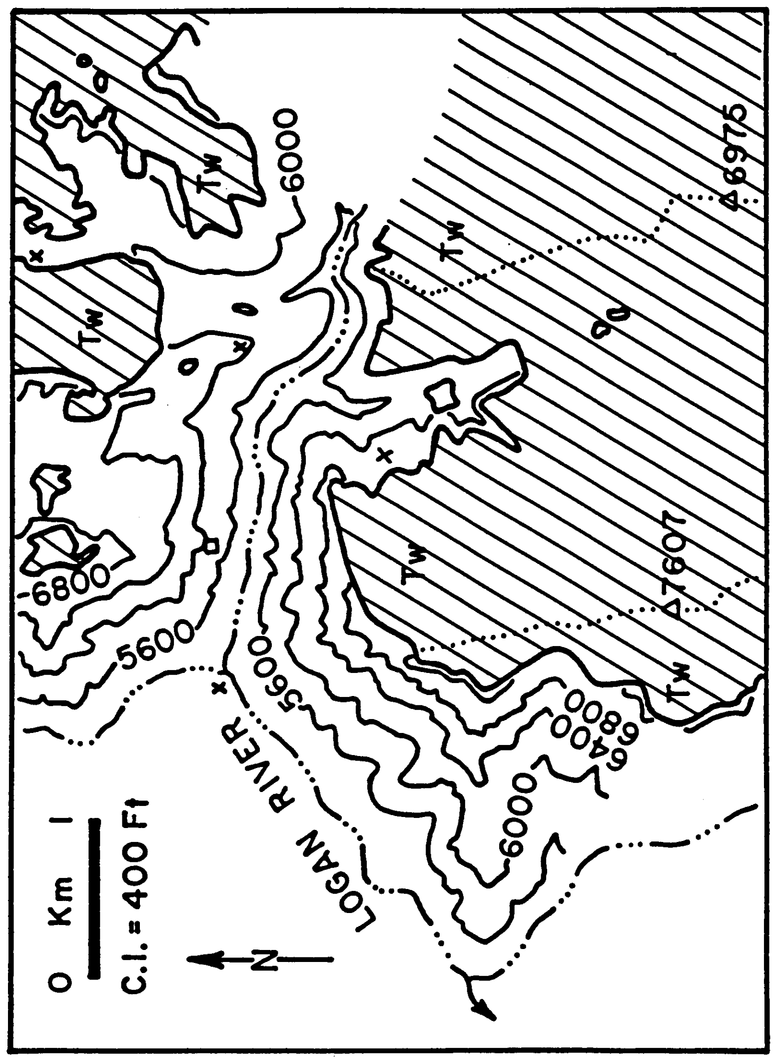


Figure 13. Simplified topographic and geologic map showing major N-S paleovalley filled with Wasatch Formation and later re-excavated by Little Cottonwood Creek (north) and by the stream in Cowley Canyon (south). Faults are omitted for clarity. Small "x" symbols show Ordovician outcrops lacking the Eureka Quartzite. Small box symbol shows outcrop with 2 to 3 m of Eureka Quartzite. See Figure 3 for location.

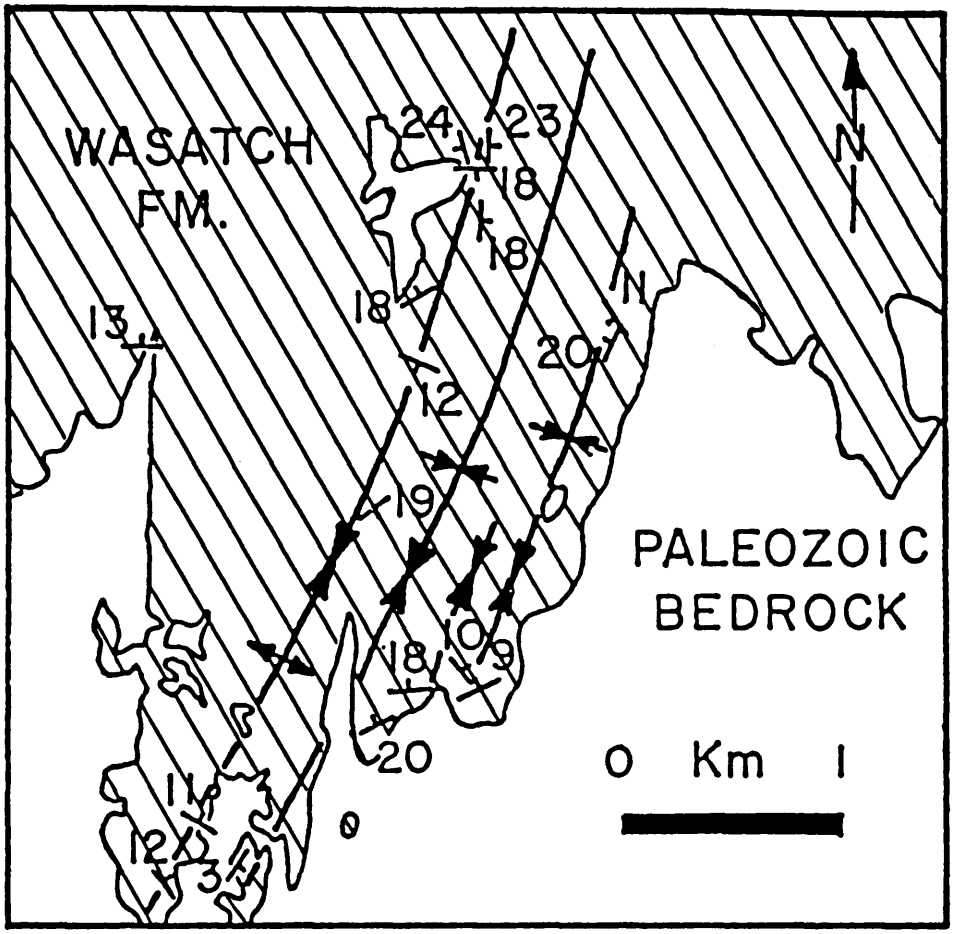
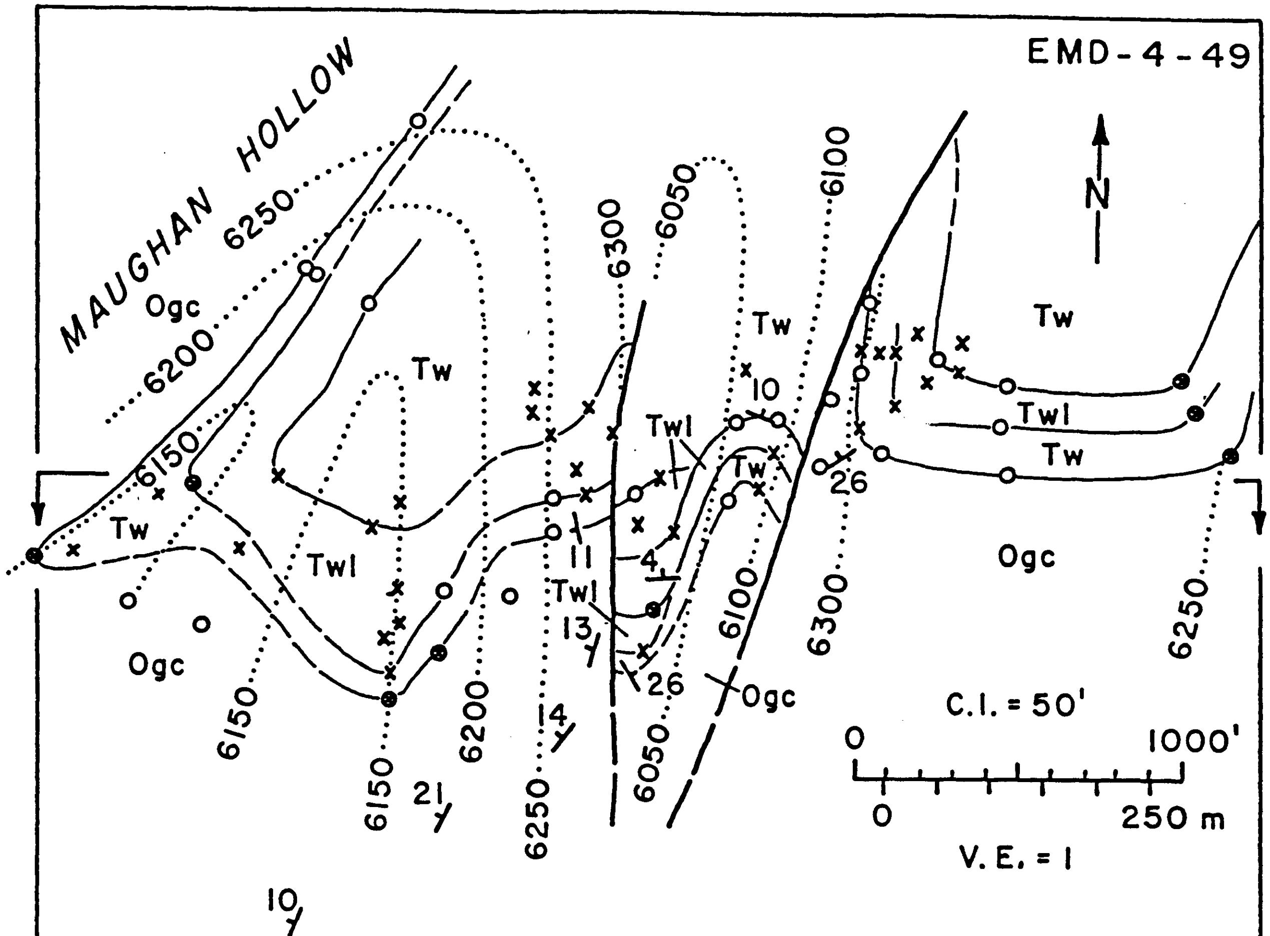
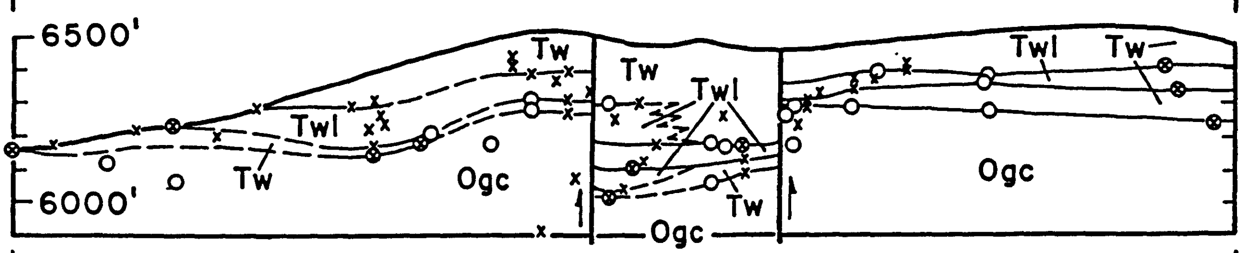


Figure 14. Map showing folds in Wasatch Formation. Fold axes trend NNE-SSW, parallel to the axis of the Logan Peak syncline, and exhibit a sag trending WNW-ESE, parallel to Right Fork of Logan River. See Figure 3 for location.



OFFSET OF TOP, COWLEY CANYON MBR: 95'/30m 210'/65m

OFFSET OF BASE, WASATCH FORMATION: 255'/80m 210'/65m



THICKNESS, BASE OF WASATCH FORMATION TO TOP OF COWLEY CANYON MEMBER

140'	140'	125'	285'	110'	105'	105'	160'
45m	45m	40m	85m	35m	30m	30m	50m

THICKNESS OF COWLEY CANYON MEMBER

55'	120'	80'	270'	45'	60'	20'	65'
15m	35m	25m	85m	15m	20m	6m	20m

Figure 15. Geologic map and section showing paleovalley between normal faults, north side of Right Fork of Logan River. Data in section were collected by C.E. Avery (circles) in 1988 and by R.Q. Oaks, Jr. (crosses) in 1988 and 1991. See Figure 3 for location.

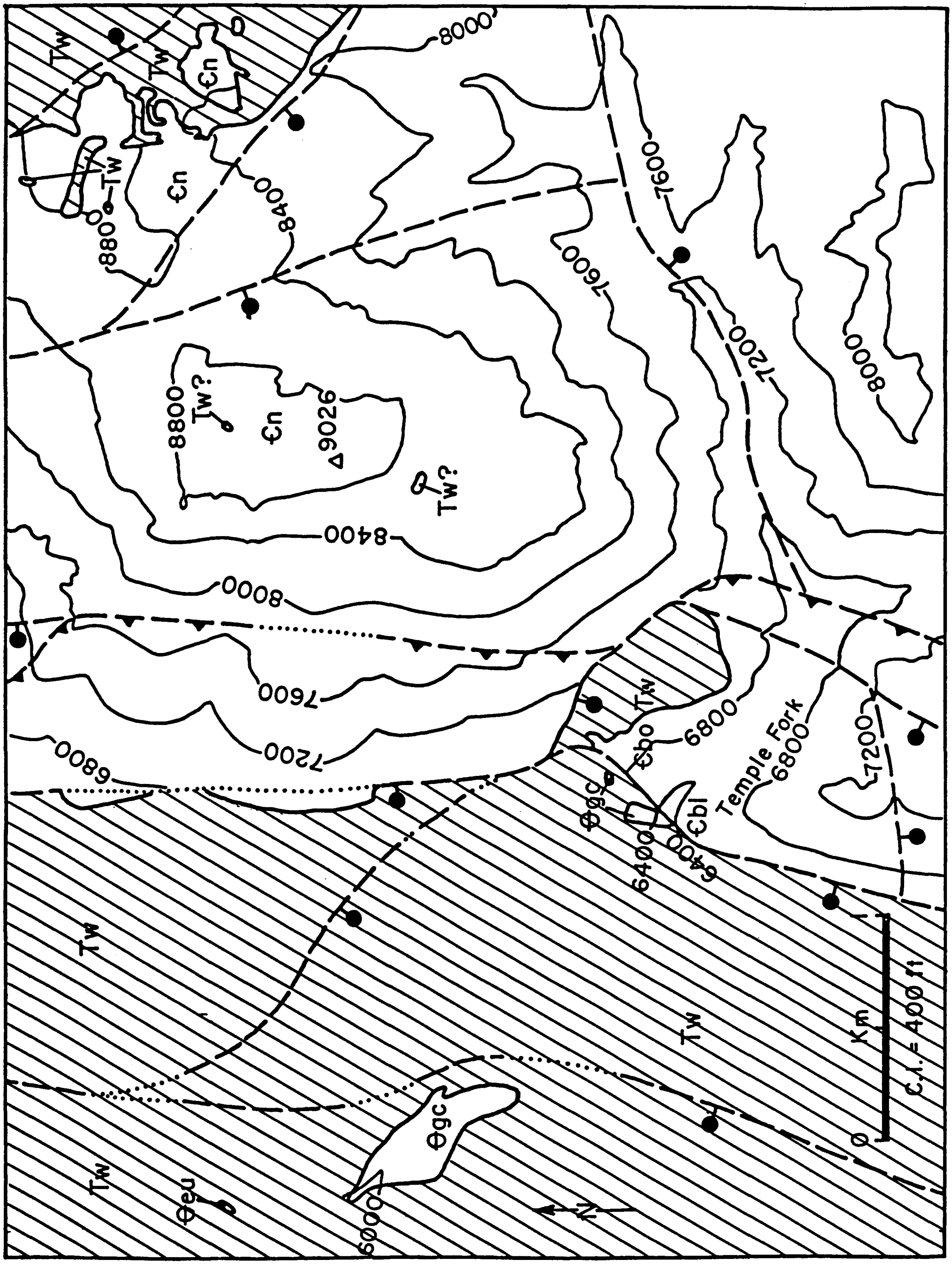


Figure 16. Simplified topographic and geologic map showing terrace-like remnant of Wasatch Formation between major normal faults in the scarp face of Temple Ridge, north side of Temple Fork Canyon. See Figure 3 for location.

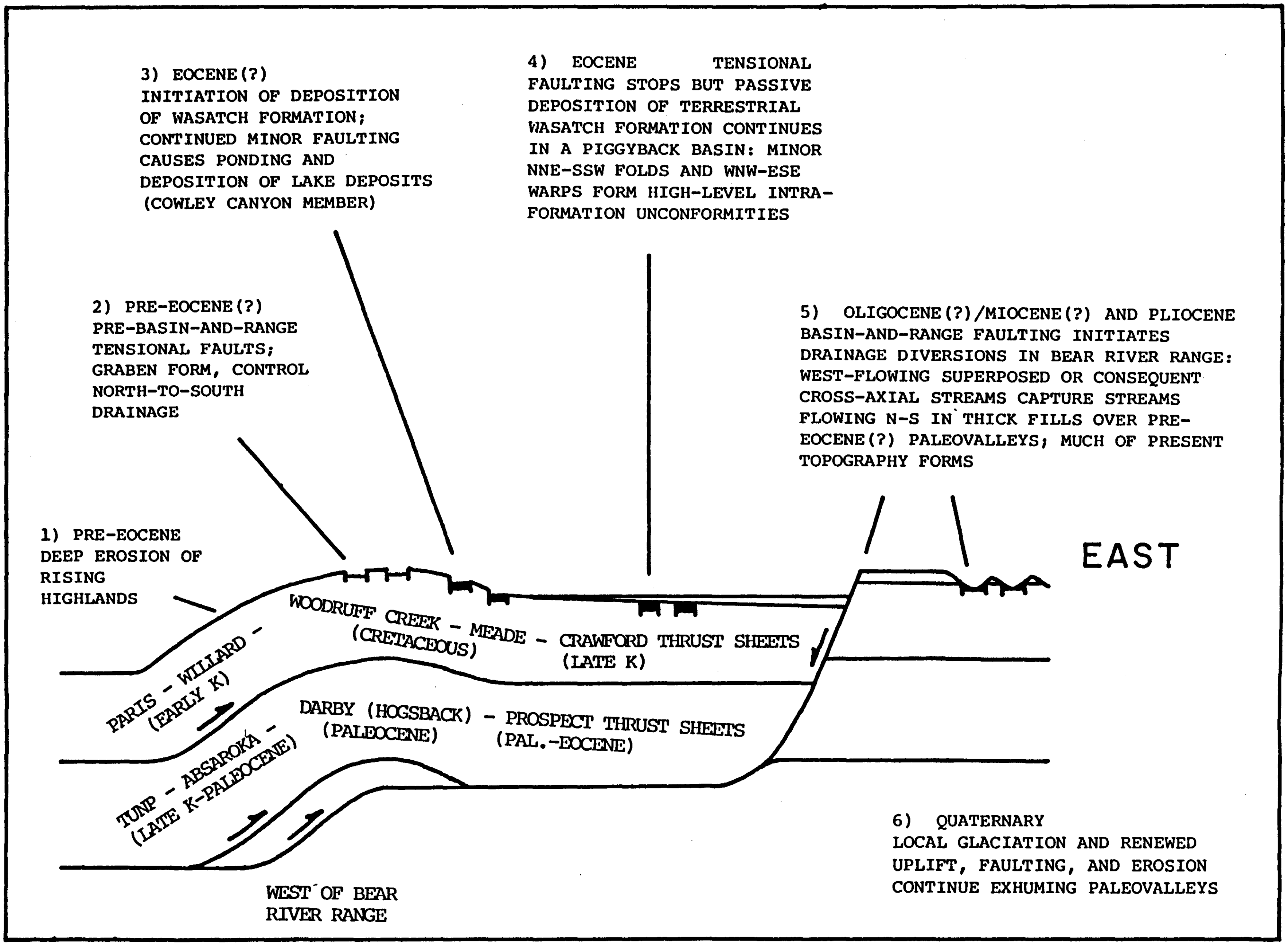


Figure 17. Conveyor-belt diagram showing inferred succession of events as thrust sheets moved eastward, followed by Basin-and-Range faulting and erosion that created the present landscape.

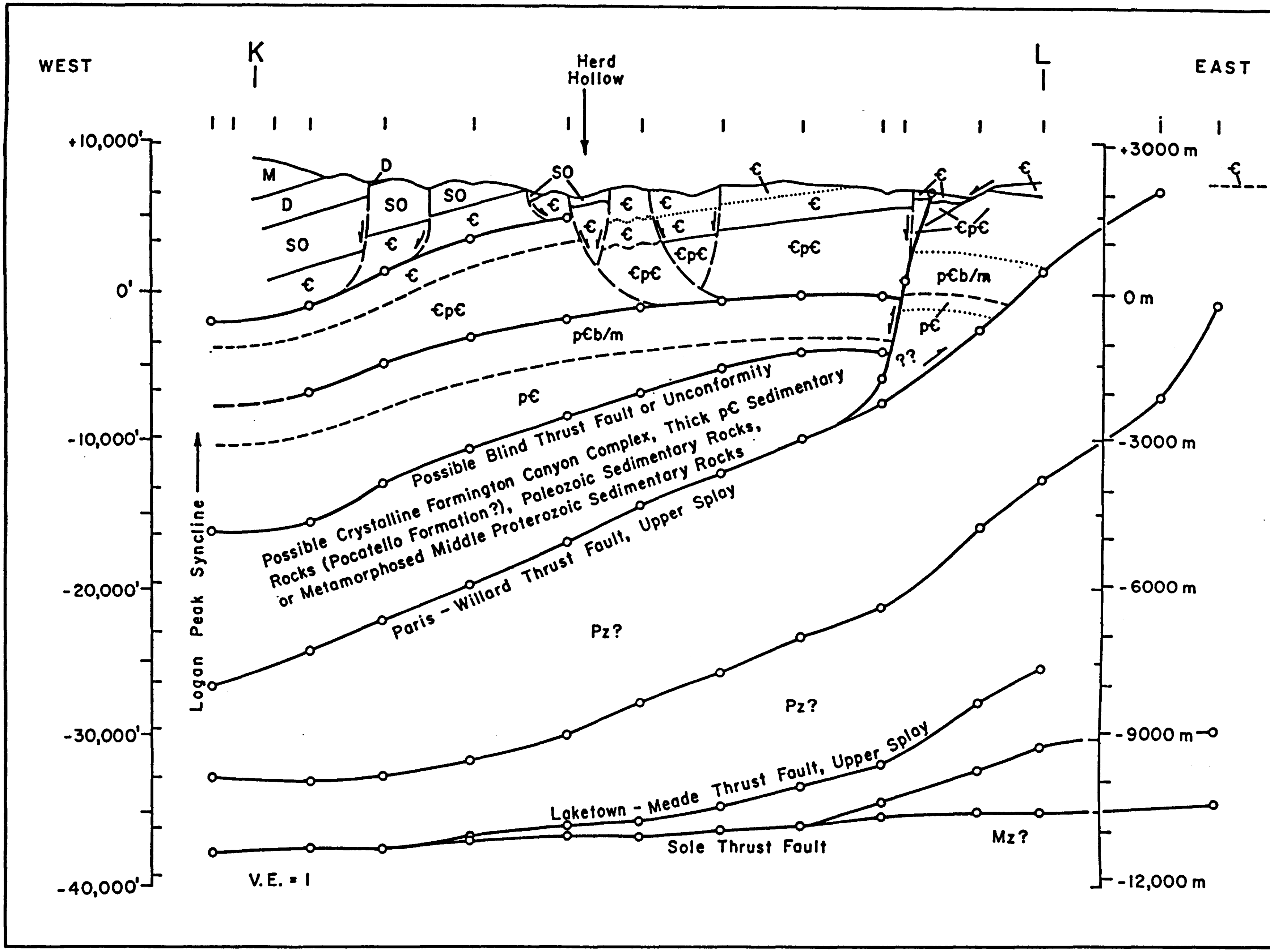


Figure 18. Geologic interpretation of seismic-reflection data projected north into geologic section K-L. Seismic line OT-2A follows Left Fork of Blacksmith Fork River. Seismic datum = +6700 feet/2040 m.

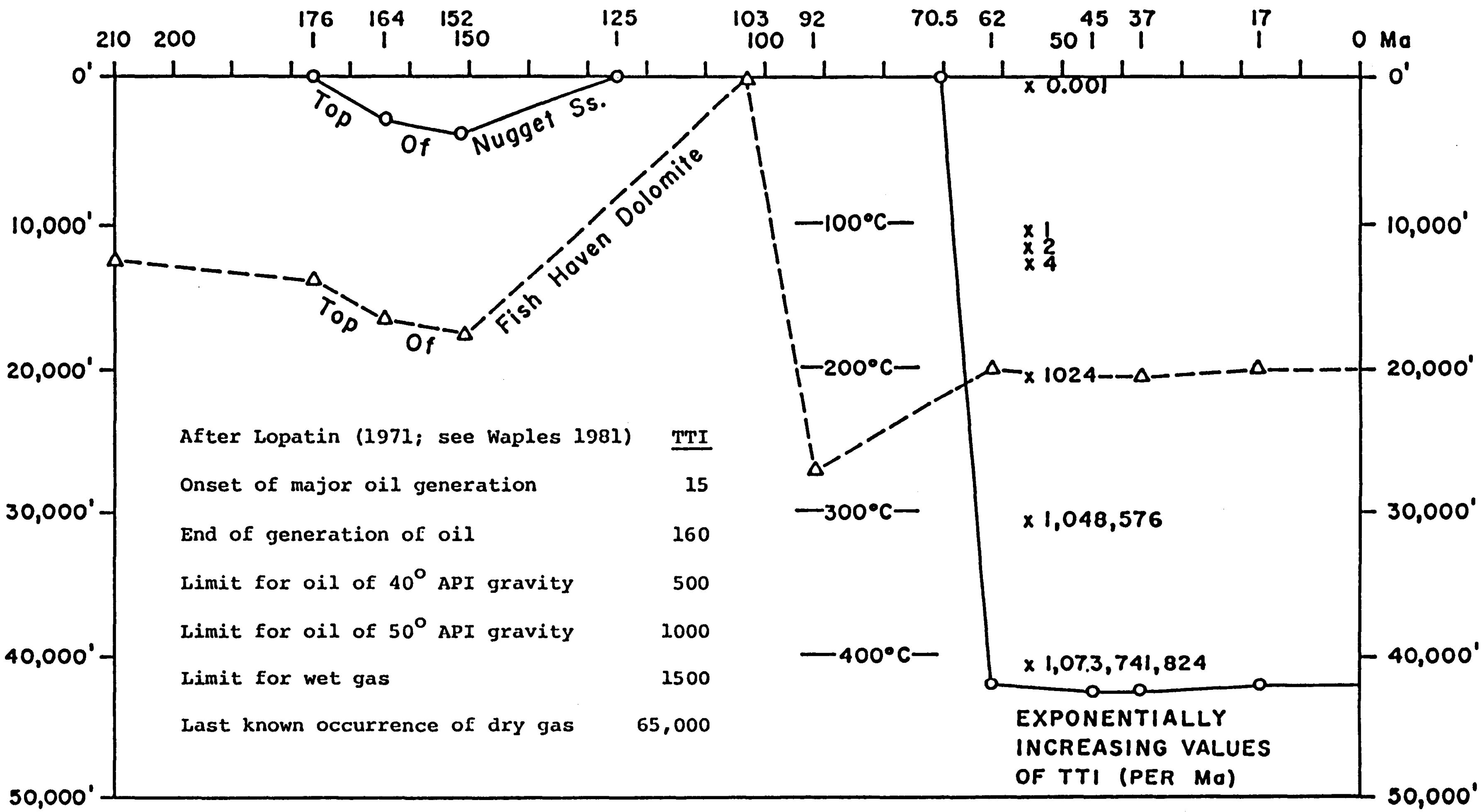


Figure 19. Time-depth diagram (based on Figure 18) and temperature conversion used to determine cumulative time-temperature index (TTI) below the sole thrust and below the lower Paris-Willard thrust splay at the east end of section K-L.

CONTRACT REPORT 92-8 OCTOBER 1992
UTAH GEOLOGICAL SURVEY
a division of
UTAH DEPARTMENT OF NATURAL RESOURCES

PLATE 1

R.Q. Oaks, Jr. and T.R. Runnells 1991

The Wasatch Formation in the Central Bear River Range, Northern Utah

UNITED STATES
DEPARTMENT OF THE INTERIOR
GEOLOGICAL SURVEY

NAOMI PEAK QUADRANGLE
UTAH–IDAHO
7.5 MINUTE SERIES (TOPOGRAPHIC)

Mapped, edited, and published by the Geological Survey

Control by USGS and USC&GS

Topography by photogrammetric methods from aerial photographs taken 1968. Field checked 1969

Polyconic projection. 1927 North American datum
10,000-foot grid based on Utah coordinate system, north zone
1000-meter Universal Transverse Mercator grid ticks, zone 12, shown in blue

Where omitted, land lines have not been established or are not shown because of insufficient data

To place on the predicted North American Datum 1983 move the projection lines 12 meters north and 65 meters east as shown by dashed corner ticks

There may be private inholdings within the boundaries of the National or State reservations shown on this map

UTM GRID AND 1969 MAGNETIC NORTH DECLINATION AT CENTER OF SHEET

GN MN 0°28′ 8 MILS 16½° 293 MILS

SCALE 1:24 000

1 ½ 0 1 MILE

1000 0 1000 2000 3000 4000 5000 6000 7000 FEET

1 .5 0 1 KILOMETER

CONTOUR INTERVAL 40 FEET
NATIONAL GEODETIC VERTICAL DATUM OF 1929

THIS MAP COMPLIES WITH NATIONAL MAP ACCURACY STANDARDS
FOR SALE BY U. S. GEOLOGICAL SURVEY, DENVER, COLORADO 80225, OR RESTON, VIRGINIA 22092
A FOLDER DESCRIBING TOPOGRAPHIC MAPS AND SYMBOLS IS AVAILABLE ON REQUEST

UTAH
QUADRANGLE LOCATION

ROAD CLASSIFICATION

Primary highway, hard surface — Light-duty road, hard or improved surface
Secondary highway, hard surface — Unimproved road
Interstate Route — U. S. Route — State Route

NAOMI PEAK, UTAH–IDAHO
N4152.5—W11137.5/7.5

1969

DMA 3667 I NW—SERIES V897

CONTRACT REPORT 92-8
OCTOBER 1992
UTAH GEOLOGICAL SURVEY
a division of
UTAH DEPARTMENT OF NATURAL RESOURCES

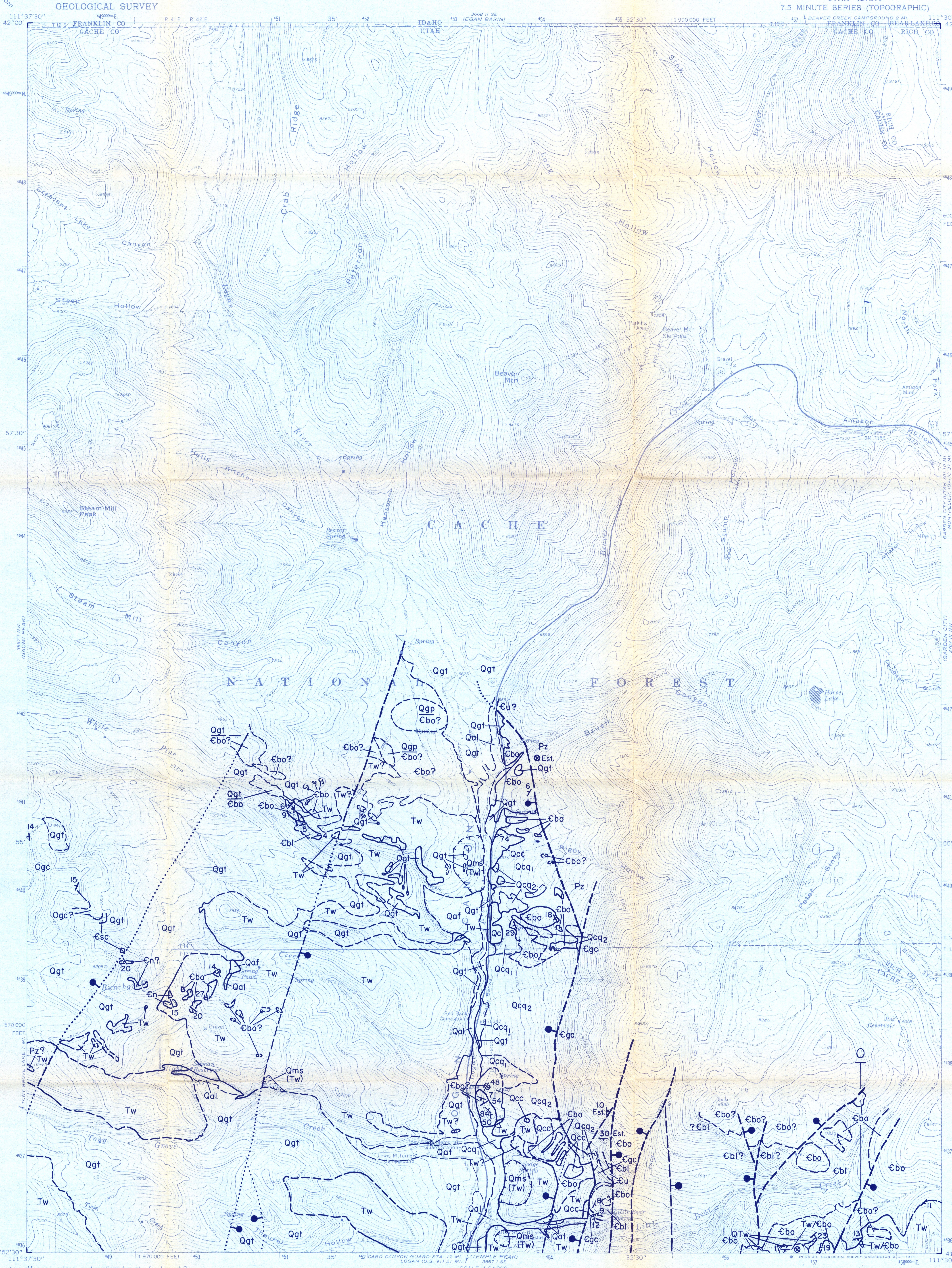
PLATE 2

R.Q. Oaks, Jr. and T.R. Runnells 1991

The Wasatch Formation in the Central Bear River Range, Northern Utah

UNITED STATES
DEPARTMENT OF THE INTERIOR
GEOLOGICAL SURVEY

TONY GROVE CREEK QUADRANGLE
UTAH–IDAHO
7.5 MINUTE SERIES (TOPOGRAPHIC)



Mapped, edited, and published by the Geological Survey
Control by USGS and USC&GS
Topography by photogrammetric methods from aerial photographs taken 1968. Field checked 1969
Polyconic projection. 1927 North American datum
10,000-foot grid based on Utah coordinate system, north zone
1000-meter Universal Transverse Mercator grid ticks, zone 12, shown in blue
Fine red dashed lines indicate selected fence lines
Where omitted, land lines have not been established or are not shown because of insufficient data

SCALE 1:24000

CONTOUR INTERVAL 40 FEET
DATUM IS MEAN SEA LEVEL

THIS MAP COMPLIES WITH NATIONAL MAP ACCURACY STANDARDS
FOR SALE BY U. S. GEOLOGICAL SURVEY, DENVER, COLORADO 80225, OR WASHINGTON, D. C. 20242
A FOLDER DESCRIBING TOPOGRAPHIC MAPS AND SYMBOLS IS AVAILABLE ON REQUEST

QUADRANGLE LOCATION

ROAD CLASSIFICATION
Primary highway, hard surface
Light-duty road, hard or improved surface
Secondary highway, hard surface
Unimproved road
Interstate Route
U. S. Route
State Route

TONY GROVE CREEK, UTAH–IDAHO
N4152.5—W11130/7.5
1969
AMS 3667 I NE–SERIES V897

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a division of
UTAH DEPARTMENT OF NATURAL RESOURCES

PLATE 3

R.Q. Oaks, Jr. and T.R. Runnells 1991

The Wasatch Formation in the Central Bear River Range, Northern Utah

UNITED STATES
DEPARTMENT OF THE INTERIOR
GEOLOGICAL SURVEY

MT. ELMER QUADRANGLE
UTAH–CACHE CO.
7.5 MINUTE SERIES (TOPOGRAPHIC)

Mapped, edited, and published by the Geological Survey
Control by USGS and USC&GS
Topography by photogrammetric methods from aerial photographs taken 1968. Field checked 1969
Polyconic projection. 1927 North American Datum
10,000-foot grid based on Utah coordinate system, north zone
1000-meter Universal Transverse Mercator grid ticks, zone 12, shown in blue
Land lines have not been established or are not shown because of insufficient data
To place on the predicted North American Datum 1983 move the projection lines 11 meters north and 65 meters east as shown by dashed corner ticks
There may be private inholdings within the boundaries of the National or State reservations shown on this map

UTM GRID AND 1969 MAGNETIC NORTH DECLINATION AT CENTER OF SHEET

SCALE 1:24 000

CONTOUR INTERVAL 40 FEET
NATIONAL GEODETIC VERTICAL DATUM OF 1929

THIS MAP COMPLIES WITH NATIONAL MAP ACCURACY STANDARDS
FOR SALE BY U. S. GEOLOGICAL SURVEY, DENVER, COLORADO 80225, OR RESTON, VIRGINIA 22092
A FOLDER DESCRIBING TOPOGRAPHIC MAPS AND SYMBOLS IS AVAILABLE ON REQUEST

QUADRANGLE LOCATION

ROAD CLASSIFICATION
Primary highway, hard surface
Light-duty road, hard or improved surface
Secondary highway, hard surface
Unimproved road
Interstate Route
U. S. Route
State Route

MT. ELMER, UTAH
N4145—W11137.5/7.5
1969
DMA 3667 I SW-SERIES V897

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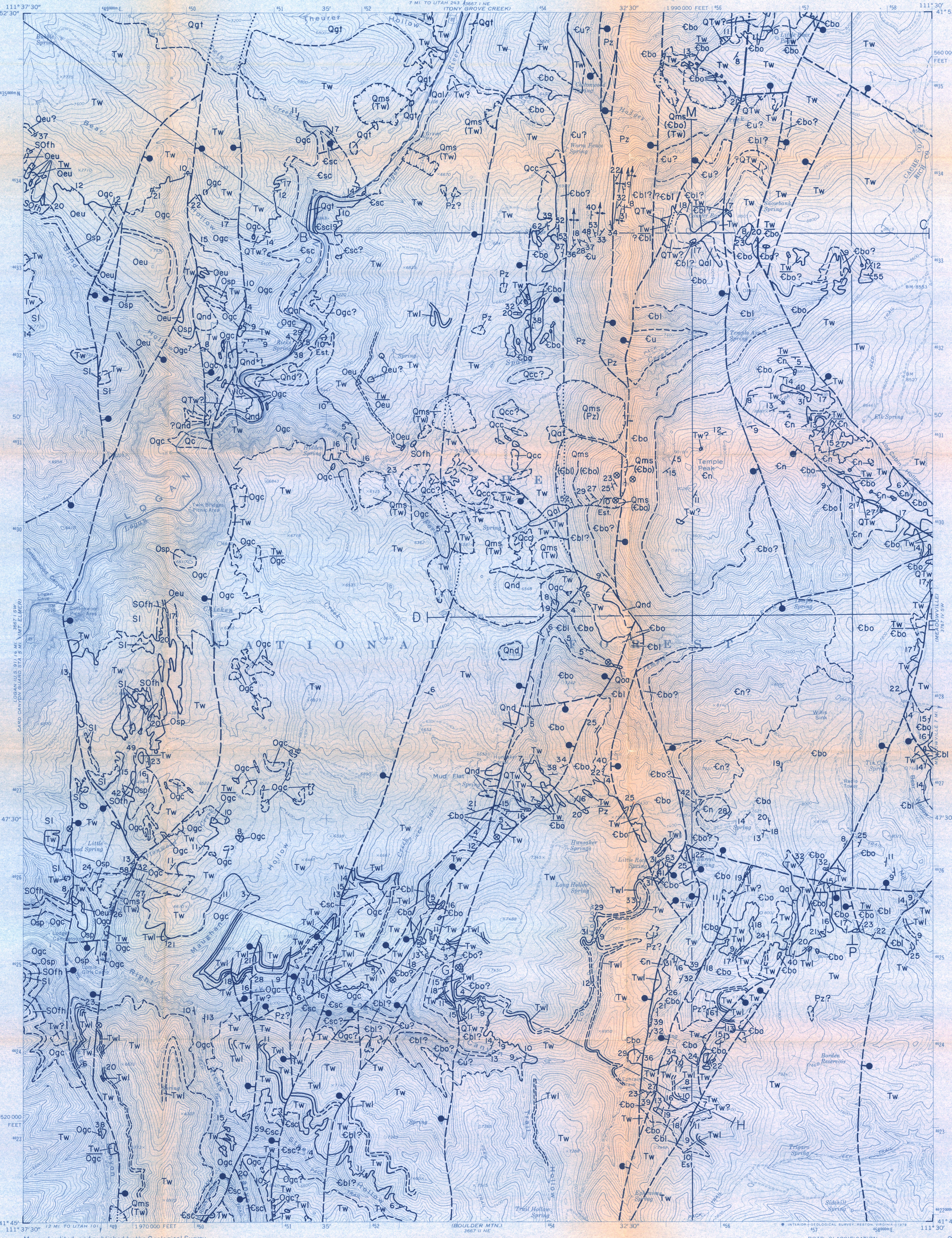
PLATE 4

R.Q. Oaks, Jr. and T.R. Runnells 1991

The Wasatch Formation in the Central Bear River Range, Northern Utah

UNITED STATES
DEPARTMENT OF THE INTERIOR
GEOLOGICAL SURVEY

TEMPLE PEAK QUADRANGLE
UTAH
7.5 MINUTE SERIES (TOPOGRAPHIC)



Mapped, edited, and published by the Geological Survey

Control by USGS and USC&GS

Topography by photogrammetric methods from aerial photographs taken 1968. Field checked 1969

Polyconic projection. 1927 North American datum
10,000-foot grid based on Utah coordinate system, north zone
1000-meter Universal Transverse Mercator grid ticks, zone 12, shown in blue

Fine red dashed lines indicate selected fence lines

Land lines have not been established or are not shown because of insufficient data

There may be private inholdings within the boundaries of the National or State reservations shown on this map

UTM GRID AND 1969 MAGNETIC NORTH DECLINATION AT CENTER OF SHEET

SCALE 1:24 000

CONTOUR INTERVAL 40 FEET
NATIONAL GEODETIC VERTICAL DATUM OF 1929

THIS MAP COMPLIES WITH NATIONAL MAP ACCURACY STANDARDS
FOR SALE BY U. S. GEOLOGICAL SURVEY, DENVER, COLORADO 80225, OR RESTON, VIRGINIA 22092
A FOLDER DESCRIBING TOPOGRAPHIC MAPS AND SYMBOLS IS AVAILABLE ON REQUEST

QUADRANGLE LOCATION

ROAD CLASSIFICATION

Primary highway, hard surface — Light-duty road, hard or improved surface
Secondary highway, hard surface — Unimproved road
Interstate Route — U. S. Route — State Route

TEMPLE PEAK, UTAH
N4145—W11130/7.5
1969
DMA 3667 I SE—SERIES V897

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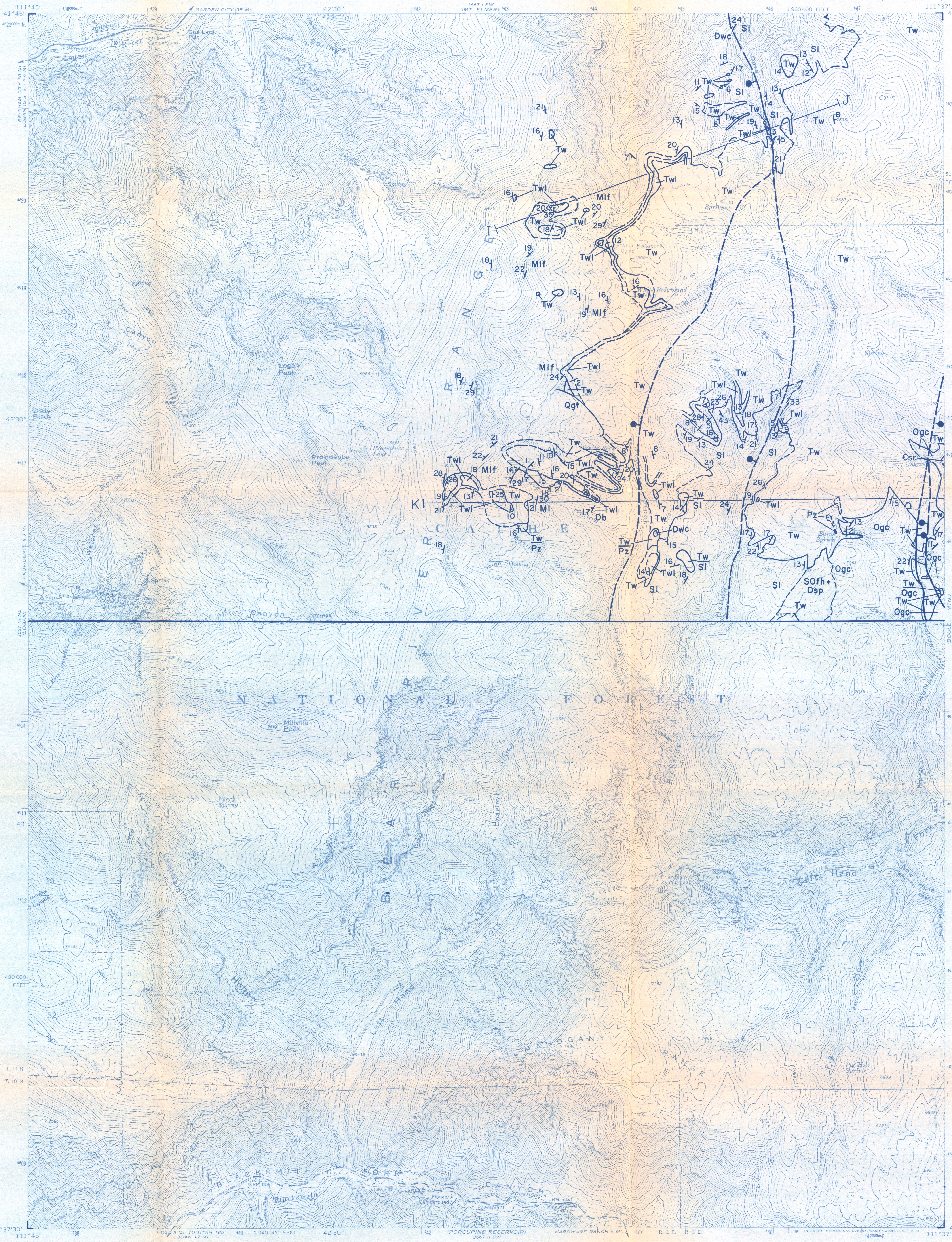
PLATE 5

UNITED STATES
DEPARTMENT OF THE INTERIOR
GEOLOGICAL SURVEY

R.Q. Oaks, Jr. and T.R. Runnells 1991
The Wasatch Formation in the Central Bear River Range, Northern Utah

LOGAN PEAK QUADRANGLE
UTAH–CACHE CO.
7.5 MINUTE SERIES (TOPOGRAPHIC)



Mapped, edited, and published by the Geological Survey
Control by USGS and USC&GS
Topography by photogrammetric methods from aerial photographs taken 1968. Field checked 1969
Polyconic projection. 1927 North American datum
10,000-foot grid based on Utah coordinate system, north zone
1000-meter Universal Transverse Mercator grid ticks, zone 12, shown in blue
Fine red dashed lines indicate selected fence lines
Certain land lines are omitted because of insufficient data

UTM GRID AND 1969 MAGNETIC NORTH DECLINATION AT CENTER OF SHEET

SCALE 1:24 000

CONTOUR INTERVAL 40 FEET
DATUM IS MEAN SEA LEVEL

THIS MAP COMPLIES WITH NATIONAL MAP ACCURACY STANDARDS
FOR SALE BY U. S. GEOLOGICAL SURVEY, DENVER, COLORADO 80225, OR WASHINGTON, D. C. 20242
A FOLDER DESCRIBING TOPOGRAPHIC MAPS AND SYMBOLS IS AVAILABLE ON REQUEST

QUADRANGLE LOCATION

ROAD CLASSIFICATION
Primary highway, hard surface — Light-duty road, hard or improved surface
Secondary highway, hard surface — Unimproved road
Interstate Route — U. S. Route — State Route

LOGAN PEAK, UTAH
N4137.5—W11137.5/7.5
1969
AMS 3667 II NW—SERIES V897

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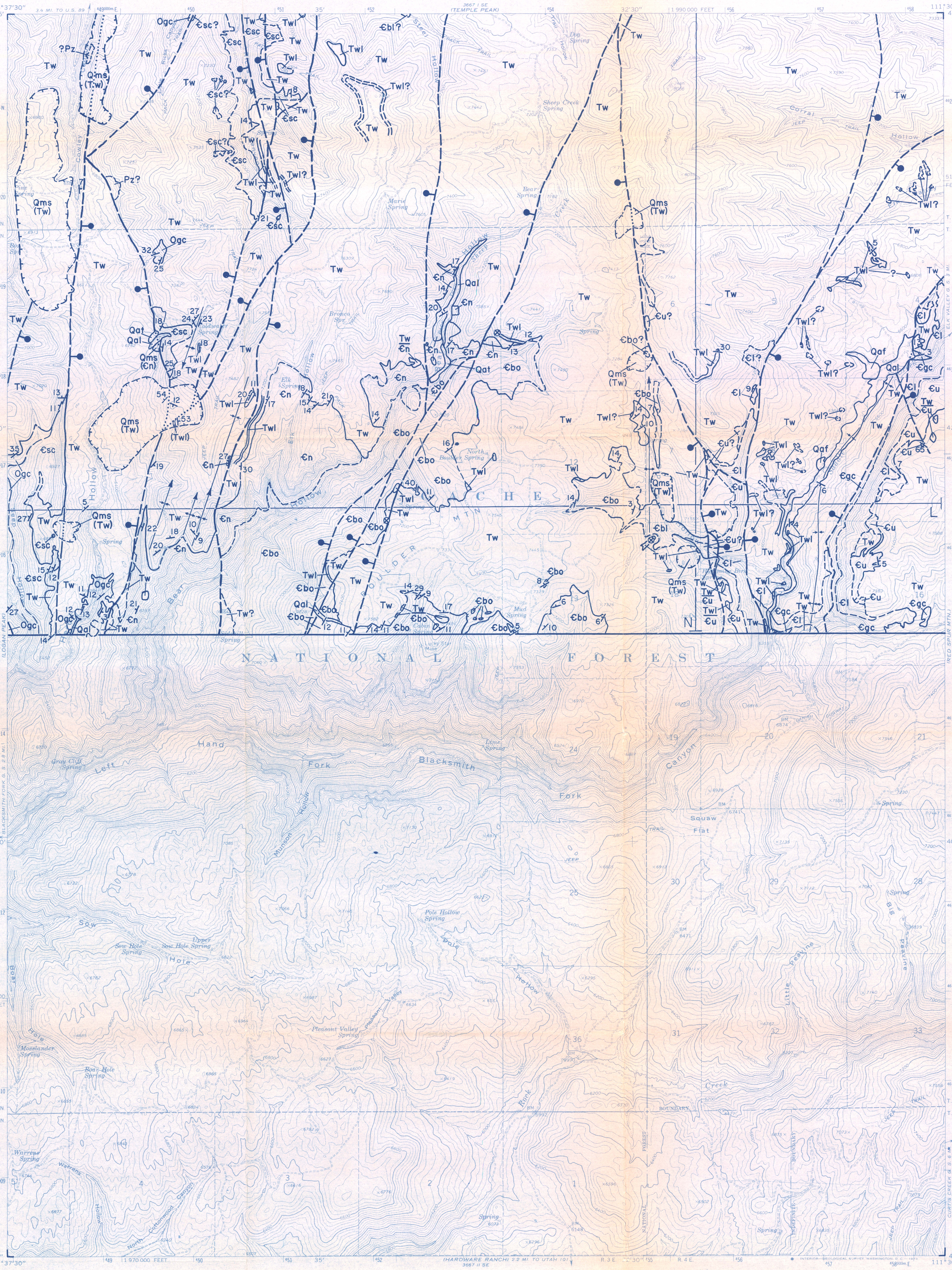
UTAH DEPARTMENT OF NATURAL RESOURCES

PLATE 6

R.Q. Oaks, Jr. and T.R. Runnells 1991

The Wasatch Formation in the Central Bear River Range, Northern U



Boulder Mtn. Quad

R.Q. Oaks, Jr. and T.R. Runnells 1991
The Wasatch Formation in the Central Bear River Range, Northern Utah

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PLATE 7