Late Cenozoic Deposits, Landforms, Stratigraphy, and Tectonism in Kittitas Valley, Washington

---

GEOLOGICAL SURVEY PROFESSIONAL PAPER 1127

U.S. DEPARTMENT OF THE INTERIOR
March 3, 1849

1879 · CENTENNIAL · 1979

Late Cenozoic Deposits, Landforms, Stratigraphy, and Tectonism in Kittitas Valley, Washington

By RICHARD B. WAITT, JR.

GEOLOGICAL SURVEY PROFESSIONAL PAPER 1127

U.S. DEPARTMENT OF THE INTERIOR
March 3, 1849

UNITED STATES GOVERNMENT PRINTING OFFICE, WASHINGTON : 1979

UNITED STATES DEPARTMENT OF THE INTERIOR

CECIL D. ANDRUS, *Secretary*

GEOLOGICAL SURVEY

H. William Menard, *Director*

Library of Congress catalog-card No. 79-600011

For sale by the Superintendent of Documents, U.S. Government Printing Office
Washington, D.C. 20402
Stock Number 024-001-03147-7

CONTENTS

Page

Abstract-- 1

Introduction-- 1

Grande Ronde Basalt of Yakima Basalt Subgroup--------------------------- 1

Ellensburg Formation-- 1

Surficial Deposits and landforms-- 3

  Depositional facies--- 3

  Criteria for subdivision-- 7

  Nomenclature-- 7

  Correlation of surfaces and deposits---------------------------------- 9

  Alluvium and drift-- 9

    Thorp Gravel-- 9

    Lookout Mountain Ranch Drift-- 12

    Kittitas Drift-- 13

    Lakedale Drift-- 13

    Holocene alluvium--- 13

  Comparison to glacial sequence and chronology of Sierra Nevada-------- 13

Structure--- 14

  Folds--- 14

  Faults-- 15

    Post-Yakima faults in central Washington---------------------------- 15

    Young faults in Kittitas Valley------------------------------------- 15

  Regional tectonic significance-- 15

Acknowledgment-- 16

Reference cited--- 16

ILLUSTRATIONS

Page

Figure 1. Tectonic map of south-central Washington---------------------- 2

2. Geologic map of Kittitas Valley area---------------------------------- 4

3. Diagram showing nomenclature and age of Yakima Basalt Subgroup------- 7

4. Geologic map of northern Kittitas Valley----------------------------- 8

5. Composit section of Thorp Gravel------------------------------------- 10

TABLES

Page

Table 1. Nomenclature of surficial deposits----------------------------- 9

2. Fission-track ages of Thorp Gravel----------------------------------- 11

3. Correlation of surficial deposits of Kittitas Valley with Sierra Nevada---- 14

LATE CENOZOIC DEPOSITS, LANDFORMS, STRATIGRAPHY, AND TECTONISM IN KITTITAS VALLEY, WASHINGTON

By Richard B. Waitt, Jr.

ABSTRACT.--Kittitas Valley, a structurally determined wide segment of the Yakima River valley, is partly filled with the Pliocene Thorp Gravel and with Pleistocene till, outwash, and related sediment that accumulated during three glaciations. The Thorp Gravel, whose age according to fission-track dating is about 3.7 m.y., forms a conspicuous fill terrace locally as high as 130 m. Bodies of drift, all younger than the Thorp Gravel, form nested fill terraces along the Yakima River. The massive moraines, intermediate morpho-stratigraphic position, and well-developed soil of the Kittitas Drift suggest its correlation with the penultimate northern-hemisphere glaciation of about 0.13 m.y. ago. The Lakedale Drift, which composes a single outwash terrace in Kittitas Valley, evidently correlates with the classical late Wisconsin Glaciation. The newly named Lookout Mountain Ranch Drift, which forms moraines at higher altitudes than and is older than the Kittitas Drift, lacks an attendant valley train.

Three faults disrupt the Thorp Gravel but apparently not the Kittitas Drift, and therefore probably are between 0.13 and 3.7 m.y. old. The eastward trend and up-to-the-basin throw of the faults probably reflect reverse faulting due to a regional north-south compression that uparched several east-trending anticlines in central Washington. The southeast trend of the dextrally echelon arrangement of the faults apparently is due to a right-lateral couple across a zone parallel to the Olympic-Wallowa lineament.

INTRODUCTION

Kittitas Valley, an unusually wide segment of the Yakima River valley near the western edge of the Yakima Basalt Subgroup, is the topographic expression of a broad synclinal basin in the Yakima Basalt Subgroup and the Ellensburg Formation (figs. 1 and 2). Containing the most complete Pliocene and Pleistocene record in the eastern Cascades and lying parallel to and immediately north of the Olympic-Wallowa lineament as defined by Raisz (1945), the valley is a likely area in which to examine Pliocene and Pleistocene tectonism in the region.

Since the early reconnaissance of Russell (1893, 1900) and early mapping by Smith (1901, 1903a, 1904), who dealt with the Quaternary but casually, only Porter (1975, 1976) has scrutinized the Pleistocene record in upper Yakima Valley. The present report augments the investigations of Porter and evaluates Pliocene and Pleistocene tectonism in and beyond Kittitas Valley.

GRANDE RONDE BASALT OF YAKIMA BASALT SUBGROUP

The geochemical, petrographic, and megascopic character of the laterally continuous basalt flows peripheral to Kittitas Valley indicate their stratigraphic position low in the Yakima Basalt Subgroup, below the Vantage Sandstone Member of Mackin (1961) (Rosenmeier, 1968; Tabor and others, 1977; Bentley, 1977; D. A. Swanson, oral and written commun., 1978) (fig. 3). The basalt is thus part of the Grande Ronde Basalt of Swanson and others (1977). The absence of post-Vantage basalt in western Kittitas Valley is consistent with the absence of the younger formations of the Yakima Basalt Subgroup near the western margin of the basalt field farther south (Waters, 1955; Mackin, 1961; Swanson, 1967; Swanson and Wright, 1978).

ELLENSBURG FORMATION

Conformably underlying, interlayered with, and conformably overlying the Grande Ronde Basalt are volcaniclastic sedimentary rocks that range from siltstone to cobble conglomerate, the latter comprising silicic to intermediate volcanic clasts. The lowest of the volcaniclastic strata, which crops out at the base of the Grande Ronde Basalt in the Yakima River canyon south of Lookout Mountain, includes fluvial conglomerate similar to that characteristic of the thick suprabasalt beds, in which some fluvially rounded boulders exceed 35 cm and whose diamictites contain rare clasts as large as 2.3 m. Although most of the sedimentary rocks are moderately sorted plane-bedded and crossbedded alluvium, several massive diamictite units as thick as 6 m in the suprabasalt strata apparently originated as lahars (Schmincke, 1967b). Crossbedding in sandstone and imbrication in conglomerate in western Kittitas Valley indicate variable paleocurrents, mostly toward the northeast, east, and southeast, down the regional eastward paleoslope envisioned by Waters (1955) and Schmincke (1967a).

Russell (1900) noted the volcaniclastic sandstone beds at the base of the basalt on Lookout Mountain, but did not include them within the Ellensburg, which he and Smith (1901, 1903a) defined as strictly overlying the Yakima Basalt Subgroup (then, Yakima Basalt) in the area. The interbasalt and subbasalt sedimentary strata on Lookout Mountain and vicinity, however, apparently are everywhere conformable with the basalt. And in color, mean and maximum grain sizes, sorting, bedding, lithology, and lithification they are similar to the sedimentary beds overlying the basalt, but in all these respects differ from the unconformably underlying Eocene arkosic sedimentary rocks farther

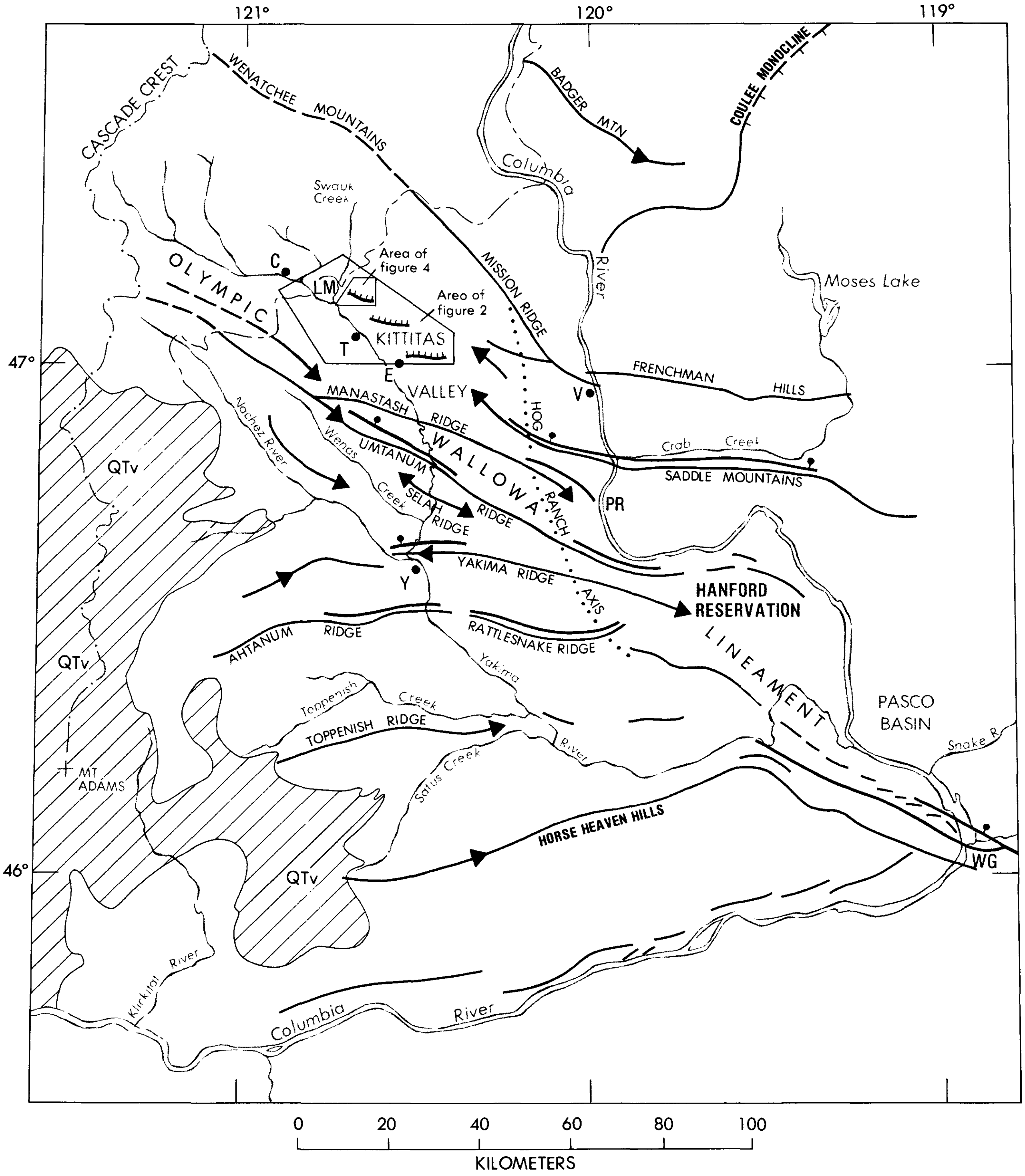
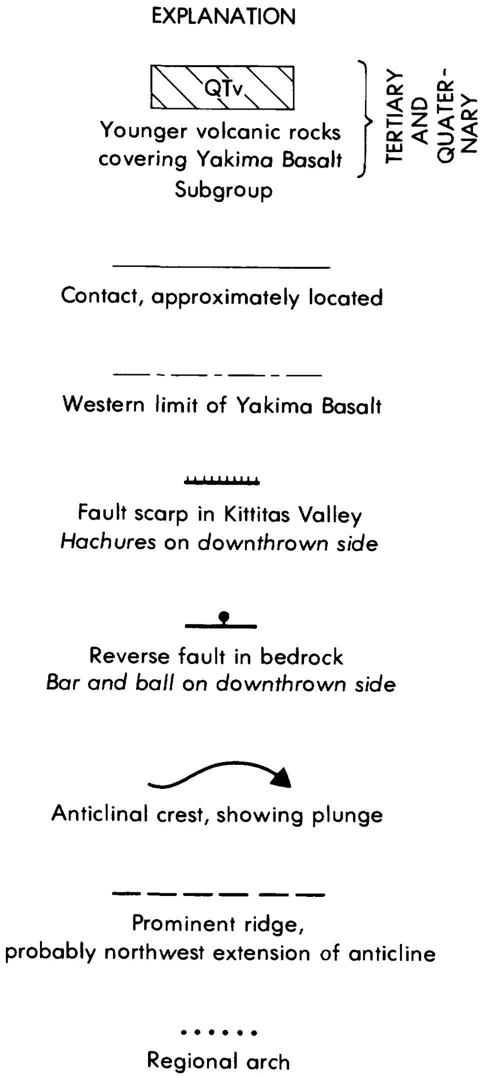


Figure 1. Tectonic map of south-central Washington, showing Olympic-Wallowa lineament, major anticlines and faults in the Yakima Basalt Subgroup, the Hog Ranch axis of Mackin (1961), and western limit of the Yakima Basalt Subgroup. C, Cle Elum; E, Ellensburg; LM, Lookout Mountain; T, Thorp; WG, Wallula Gap; Y, Yakima. Anticlines plunge generally eastward from the Cascades and westward from the Hog Ranch axis; the Yakima River thus crosses the several anticlines south of Ellensburg generally along a cross-structural sag. The Kittitas Valley faults are en echelon to each other and to anticlines and attendant compressional faults to the southeast. Data from Mackin (1955), Newcomb (1970), FUGRO (1974), Tabor and others (1977), Bentley (1977), and R. D. Bentley (oral commun., 1977).



northwest. Evidently all of the volcaniclastic sedimentary beds conformably with the basalt are genetically and temporally related, and they collectively compose a unique, mappable body of rock.

Regionally, the base of the sediment-rich part of the basalt-volcaniclastic section rises in stratigraphic position southeastward. Mackin (1961) defined the base of the Ellensburg in the Vantage-Priest Rapids area fairly high in the section, at the top of the Wanapum Basalt of Swanson and others (1977). Smith (1903a), Waters (1955), and Schmincke (1964), however, included the interbasalt sediment as far down in the section as the base of the Wanapum, in the Ellensburg Formation. Schmincke (1964, 1967a, 1967c) also redefined the Ellensburg as mutually interfingering with the Wanapum and Saddle Mountains Basalts, a practice adopted by Bingham and Grolier (1966) and by more recent workers. In western Kittitas Valley the sedimentary strata intercalated with and underlying the Grande Ronde Basalt show that the mutually interfingering relation of the two lithosomes--westward-tonguing basalt and eastward-tonguing silicic volcaniclastic sedimentary rock--extends to the very base of the Yakima Basalt Subgroup. The interbasalt sedimentary strata are distinguishable from each other and from the suprabasalt Ellensburg strata only because of the intervening basalt members. As indicated by figures 2 and 4, I therefore opine that all of these conformable, sedimentologically related strata in the Kittitas Valley area be included within the Ellensburg Formation, and that the definition of the Ellensburg be extended stratigraphically downward to the base of the basalt-sedimentary sequence. A precedent for this type of definition is Griggs' (1976, p. 6) exclusion of sedimentary interbeds from the Yakima Basalt Subgroup and his assignment of them to the Latah Formation, which he redefined as mutually intertonguing with the Grande Ronde and Wanapum Basalts.

The Ellensburg strata overlying the basalt near the margin of the basalt field are relatively thick because they are not punctuated by the younger basalt members, which, offlapping eastward, failed to gain the western margin of the field. The frequency of basalt eruption, moreover, generally decreased between the earlier (16.5 to 14 m.y.) and later (12 to 6 m.y. ago) periods of the basalt eruption (fig 3; McKee, Swanson, and Wright, 1976). Consequently, the silicic volcaniclastic debris, even if supplied at a constant mean rate throughout Yakima time, should have built fans that were thicker and extended farther eastward in Saddle Mountains time than in Grande Ronde time, thus making the upper part of the basalt-sedimentary suite particularly rich in sediment, especially in the western parts of the basalt field.

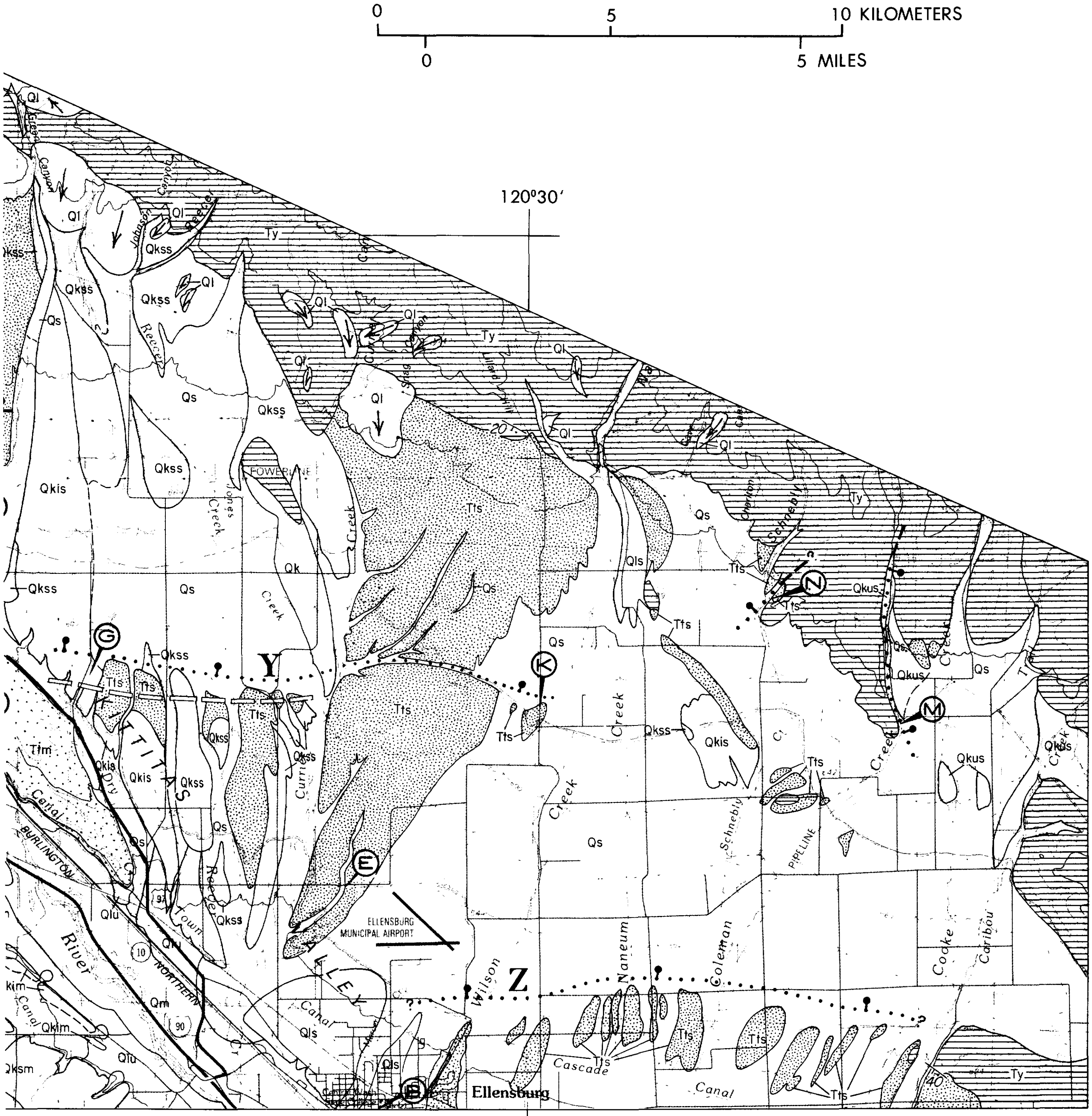
In the western areas the suprabasalt volcaniclastic beds overlie only the Grande Ronde Basalt: there is no guarantee that the top of the Ellensburg in western Kittitas Valley is as young as the base of what Mackin (1961) defined as Ellensburg farther east. From such exposures as on Lookout Mountain and in the areas to the south (Waters, 1955; and Swanson, 1967) it is clear that the shedding of Ellensburg-like silicic volcanic debris eastward from the Cascades was not confined to the latter part of the eruption of the Yakima Basalt Subgroup, but commenced before the earliest basalt flows reached the area.

SURFICIAL DEPOSITS AND LANDFORMS

DEPOSITIONAL FACIES

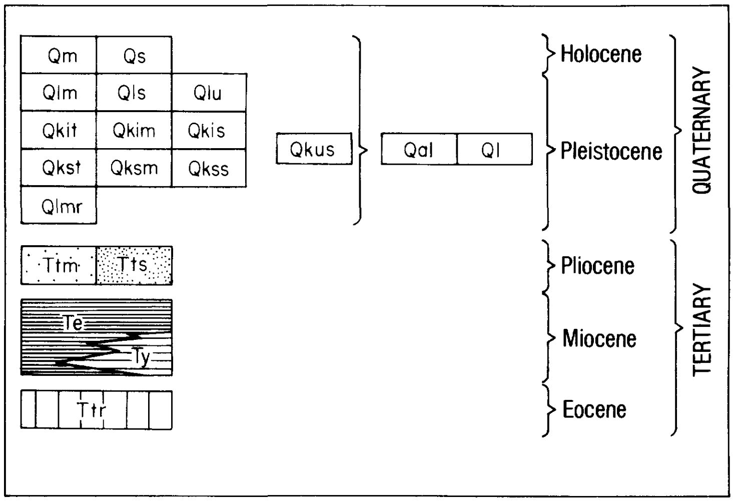
Till, poorly sorted muddy gravel containing stones of diverse lithology, forms moraines in the valleys and a discontinuous blanket in the uplands of westernmost Kittitas Valley. Both the nonglacial mainstream (Yakima River) alluvium and the outwash spread downvalley from moraines consist of moderately to well-sorted sandy gravel comprising rounded stones of diverse volcanic, metamorphic, plutonic, and sedimentary rock types derived mostly upstream of Kittitas Valley. Sidestream alluvium graded to the mainstream deposits is easily distinguished by its monotonous content of subrounded to subangular basaltic gravel. The sidestream fans head along the mountain front at the mouths of canyons, but on interfluves merge upslope with steep fans of angular basaltic colluvium. Sand and silt layers, presumed to be fluvial overbank deposits and loess, occur mainly as minor beds within and atop mainstream deposits. Fine tephra occurs as rare discontinuous beds enclosed by alluvium and colluvium.

Figure 2. Geologic map of Kittitas Valley area. Base from U.S.



Geological Survey Wenatchee quadrangle, Washington, scale 1:100,000.

CORRELATION OF MAP UNITS (figures 2 and 4)



—— - -	Contact—Precisely to approximately located. Dashed where gradational or inferred
—⊥…	Fault—Dashed where approximately located; dotted where concealed. Bar and ball on downthrown side
— ·· —	Crest of moraine
—·····—	Overridden moraine or drumlinoid topography
⟋	Strike and dip of Yakima Basalt
Ⓐ—	Locality referred to in text
X,Y,Z	Faults referred to in text
⟶	Direction of movement of landslide
▭ ▭ ▭	Basement structure from magnetic survey

DESCRIPTION OF MAP UNITS (figures 2 and 4)

Qm	Alluvium, mainstream (Yakima River) facies
Qs	Alluvium, sidestream facies
Qal	Alluvium, undifferentiated
Ql	Landslide deposit-Arrows indicate direction of movement
	Lakedale Drift outwash. Divided into:
Qlm	Mainstream facies
Qls	Sidestream facies
Qlu	Outwash, undifferentiated
	Kittitas Drift. Divided into:
Qkit	Indian John phase, till
Qkim	Indian John phase, mainstream outwash
Qkis	Indian John phase, sidestream facies
Qkst	Swauk Prairie phase, till with discontinuous loess cap
Qksm	Swauk Prairie phase, mainstream outwash
Qkss	Swauk Prairie phase, sidestream facies
Qkus	Undifferentiated sidestream facies
Qlmr	Lookout Mountain Ranch Drift
	Thorp Gravel. Divided into:
Ttm	Mainstream gravel. Locally includes thin discontinuous cap of Tts
Tts	Sidestream gravel
Te	Ellensburg Formation; fluvial cobble gravel, sandstone, and lahars
Ty	Yakima Basalt Subgroup. Grande Ronde Basalt of Swanson and others (1977)
Ttr	Teanaway Basalt and Roslyn Formation, undifferentiated

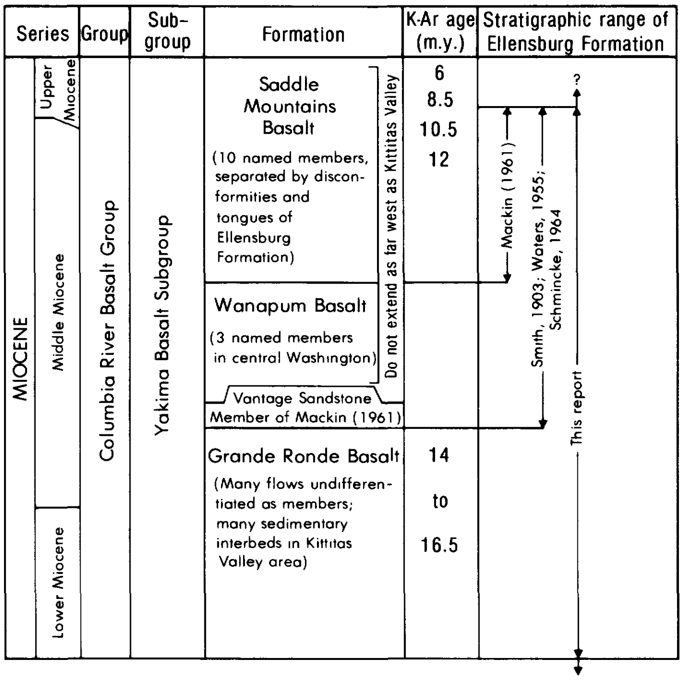


Figure 3.--Nomenclature and K-Ar ages of the Yakima Basalt Subgroup, abridged from Swanson and others (1977), and showing stratigraphic position of Vantage Sandstone Member of Mackin (1961) and stratigraphic range of the Ellensburg Formation as variously defined.

CRITERIA FOR SUBDIVISION

The Pliocene and Pleistocene sequence in Kittitas Valley is subdivided largely on the basis of relative geomorphic position. In the western end of the valley sets of moraines are separated from sets farther upvalley by moraine-free areas. From each of these moraine sets an outwash terrace grades downvalley, such that in central Kittitas Valley the several outwash (mainstream) terraces are nested one inside another, forming four paired terrace levels. In northern Kittitas Valley four levels of sidestream terraces are nested one inside another, each of them graded southward to one of the mainstream (outwash) terraces. Relative altitude and longitudinal position of geomorphic features in the valley are thus the foremost criteria for subdividing the surficial deposits of Kittitas Valley. Each of the despositional surfaces that connects a moraine to a mainstream terrace, and a sidestream terrace to a mainstream terrace, is a geomorphic memento of the conclusion of an episode of aggradation in the valley. All of the lithologically varied deposits underlying such a surface predate the surface; all of the deposits within valleys incised below such a surface postdate the surface. These isochronous depositional surfaces are used to divide the lithologically varied ensemble of surficial deposits into local time-stratigraphic units.

Useful to confirm the geomorphic subdivision and to temporally group the various bodies of drift are time-dependent criteria like soil development (color, thickness, horizonation, clay content), degrees of weathering of surface and subsurface stones, thickness of loess cover, and presence of paleosols (Porter, 1975, 1976; Coleman, 1976).

There is little field evidence with which to evaluate whether any of the terraces are surfaces cut in older alluvium, rather than being, as I perceive them, nested fill terraces. The mainstream terrace-gravel units are so lithologically similar that the deposits of different ages are distinguished only by their relative geomorphic positions and by differences in weathering, soil development, and loess thickness at their surfaces. Because all of the prominent terraces are traceable upvalley to moraines, it is thought that the terraces were formed during aggradational rather than degradational episodes. Most of the alluvium underlying a given terrace therefore is thought to be related to the same episode of aggradation that formed the surface. With the possible exception of the Thorp Gravel, the deposits of Kittitas Valley therefore are thought to represent a series of relatively brief episodes of aggradation and swift incision, each followed by a lengthy episode when the Yakima River and its tributaries flowed at or near their present grades.

NOMENCLATURE

Blackwelder (1915, 1931), dividing alpine-glacial sequences in Wyoming and in the eastern Sierra Nevada on regionally applied time-stratigraphic bases, named the divisions "stages", drawing precedent from that crucible of glacial terminology, the Midcontinent. "Stage," however, has all but disappeared from the glacial literature of the West, having been superseded by descriptive lithologic terms like "drift" and "till", and by reference of deposits to a "glaciation." The terms "drift" and "till", sometimes regarded as rock-stratigraphic units, in fact refer to units that are time-stratigraphic in nature. Blackwelder (1915, 1931), for example, again taking precedent from the Midcontinent, used "Pinedale drift" and "Sherwin till" nearly synonomously with "Pinedale stage" and "Sherwin stage," his contexts leaving no doubt that he intended each of these terms in a time-stratigraphic sense.

The Code of Stratigraphic Nomenclature (American Commission on Stratigraphic Nomenclature, 1970) is an ambiguous guide for time-stratigraphic classification and nomenclature of Quaternary alpine deposits, which in practice are divided on a morphologic or time-stratigraphic basis, and only later, if at all, are further divided on a rock-stratigraphic basis. Richmond (1962) and Porter (1976) divided glacial deposits into "formations" or "drifts", said to be rock-stratigraphic units of formation rank, and divided some of these into "members." While the division of a "formation" or "drift" into "members" conforms to Articles 6 and 7 of the Code, the lithologic character of such drifts and the criteria used in their distinction violate Article 5. A single drift, or a named "member"

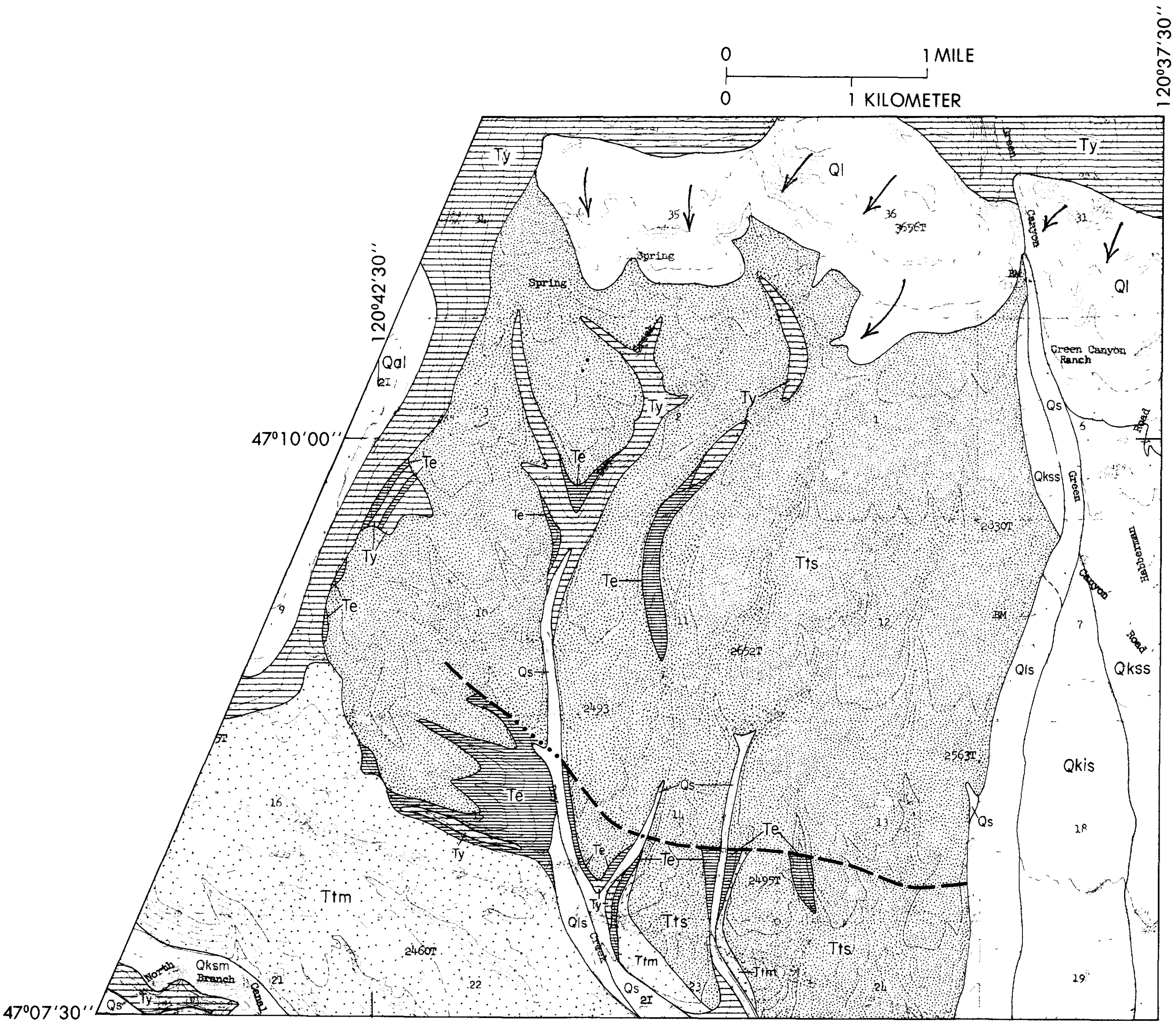


Figure 4. Geologic map of part of northern Kittitas Valley, showing topographic and stratigraphic evidence of westernmost of three faults that offset the Thorp Gravel. Base from U.S. Geological Survey Mount Stuart 4 NW quadrangle, Washington, unedited advance sheet, 1959.

of a drift, comprises sediment as lithologically varied as boulder till and loess; a drift, unlike a bedrock formation or member, is not distinguished by lithology from neighboring lithologically heterogeneous drifts; it is distinguished by its geomorphic position and continuity, and perhaps by its geomorphic character; it is independent neither of time concepts nor of inferred geologic history. Such drifts and so-called "formations" and "members" in fact are more time stratigraphic in nature than rock stratigraphic.

While "formation" and "member" seem to be inappropriate designations for the divisions and subdivisions of glacial deposits in Kittitas Valley, neither does it seem correct to use the accepted time-stratigraphic terms "stage" and "substage" when the units are intended only for local use.

The terminology adopted herein, which is only a temporary expedient until an appropriate terminology is developed for the region, deviates only a little from Porter's (1976) formal names. I retain Porter's term "Kittitas Drift" for the larger unit, though explicitly as a local time-stratigraphic term of stage rank. Porter's Swauk Prairie and Indian John "Members" are informally designated the Swauk Prairie and Indian John phases, both intended as local chronostratigraphic units of substage rank. The Kittitas Drift thus comprises the Indian John phase and the Swauk Prairie phase.

Unlike Porter, I include within each of the drifts and phases substantial volumes of sidestream gravel, which, while not strictly glaciogenic, accumulated pari passu with outwash in the main valley. Otherwise I deviate from Porter's conception of the Kittitas-aged units mostly in name.

CORRELATION OF SURFACES AND DEPOSITS

Table 1 summarizes the Pliocene and Pleistocene morpho- and time-stratigraphic sequence in Kittitas Valley. Terraces along the southern side of Kittitas Valley are distinct and nearly continuous and are readily traced upvalley to moraines. A prominent terrace (fig 2, loc I) on the southern side of the Yakima River, for example, heads at the moraines of the Swauk Prairie Drift that form Thorp Prairie; the next lower terrace is a remnant of the prominent surface that grades downvalley from the Indian John moraine (loc. J). It is by similar geomorphic relations that the deposits are divided into the several time-stratigraphic units and are locally correlated in the map area.

The weathered character of many geomorphic surfaces also is distinct. Stones of Grande Ronde Basalt and of andesite on the lowest terraces have oxidation rinds less than 1 mm thick and are uncemented; volcanic stones on intermediate-level surfaces have oxidation rinds a few millimeters thick but are only slightly cemented; on the highest surfaces these stones are partly rotten and are deeply cemented with hematite and montmorillonite. Porter (1975) noted distinct differences of weathering-rind thickness on clasts of the Eocene Teanaway Basalt between the several geomorphic surfaces; his data have been independently reproduced by S. M. Coleman (1976; oral commun., 1977). High surfaces invariably are more weathered than intermediate surfaces, which in turn are more weathered than low surfaces. Relative heights and degrees of weathering together thus are the means of correlation between the terraces.

Young fans and colluvium that have prograded across older surfaces complicate cartography and time-stratigraphic designations. Holocene fans overlie all terraces; those atop the Kittitas terraces probably accreted throughout the last interglaciation, last glaciation, and the Holocene Epoch. Despite these younger surficial materials, the height of the mainstream gravel above the modern stream and the weathered character of that gravel generally identify a terrace.

ALLUVIUM AND DRIFT

Thorp Gravel

Definition.--A weakly cemented, deeply weathered gravel forming a conspicuous terrace 100 to 220 m above the Yakima River in Kittitas Valley originally was included within the Ellensburg Formation (Smith, 1904). Porter (1976) inferred that the gravel (sediment) which overlies typical Ellensburg Formation (rock) is glacial outwash and named it the Thorp Drift. Because of the apparent Pliocene age of the gravel, its improbable correlation with drift on Lookout Mountain and in Horse Canyon, and the possibility that it is not glaciogenic at all, the accumulation is here renamed the Thorp Gravel.

The Thorp Gravel consists mostly of two facies: mainstream gravel, most of whose stones are rounded to subrounded and comprise durable silicic to intermediate volcanic rocks; and sidestream gravel consisting mostly of subangular clasts of Grande Ronde Basalt. The type locality of the mainstream facies (fig 2, loc A), a landslide scar in the NE¼ sec. 12, T. 18 N., R. 15 E., along the northern side of the Yakima River 1.5 km east of Thorp, Kittitas County, was designated by Porter (1976, p. 66) as the type locality for the outwash facies of his Thorp Drift. The base is not exposed at the type locality, but, in small stream valleys 7 km to the northwest, Thorp mainstream gravel unconformably overlies the Ellensburg Formation. The low-relief upper surface of the Thorp mainstream terrace, which slopes generally about 16 m/km southeastward, roughly parallel to the grade of the modern Yakima River, is incised as deeply as 100 m by small generally southeast-trending creek valleys whose cross profiles are curiously asymmetric, having southwest-facing sides averaging 30° and northeast-facing sides about half as steep. Where not affected by these incised valleys, the upper surface apparently is only a

Table 1.--Nomenclature of surficial deposits in upper Yakima drainage basin

Upper Yakima valley (Porter, 1976)	Kittitas Valley (this report)
Holocene deposits	Holocene
	Alluvial deposits
Pleistocene	Pleistocene
Lakedale Drift	Lakedale Drift
includes four named members	
Kittitas Drift	Kittitas Drift
Indian John Member	Indian John phase
Swauk Prairie Member	Swauk Prairie phase
	Lookout Mountain Ranch Drift
Thorp Drift	
Till and Outwash	Disconformity
	Pliocene
	Thorp Gravel

little modified, and in a roadcut 2 km north-northwest (loc. L) of the type locality displays a brown (7.5 YR 4/3) to yellowish red (5 YR 4/6) soil having a very argillic B horizon as thick as 45 cm within which plutonic stones are rotted. There is no evidence that this surface has ever been overlain by anything other than incidental veneers of loess and fine tephra.

The type locality for the sidestream facies of the Thorp Gravel is a small abandoned gravel pit in NE¼SE¼ sec. 6, T. 18 N., R. 19 E., Kittitas County, Colockum Pass SW 7.5-minute quadrangle (fig 2, loc. K). The pit exposes 6 to 8 m of gravel whose clasts, angular to subrounded, reach 38 cm in intermediate diameter and are entirely of Grande Ronde Basalt derived from the mountain front 6 km to the north. The deposit is thick bedded, comprising beds variously of small pebble to cobble gravel enclosed in a sandy granule basalt-clast matrix ranging from closely packed to meagerly openwork. Within 1 m of the surface the basaltic stones have thick oxidation rinds, vague Liesegang banding, and deep cracks. The sidestream facies is conspicuously cemented at the type locality to a depth of at least 10 m with alternating bands of reddish hematite and, verified by x-ray diffraction, pale-yellow montmorillonite. Similar material can be seen in many localities to the west and south, as at localities B, C, E, F (fig. 2). The type locality does not reveal the base of the sidestream facies, but gullies incised into the western remnant of the Thorp sidestream terrace 17 km northwest of the type locality reveal that the sidestream facies overlies the Ellensburg Formation and the Grande Ronde Basalt with an angular unconformity (figs. 2 and 4).

The upper surface of a prominent Thorp sidestream terrace 3 km west of the type locality slopes about 22 m/km to the south-southwest and evidently is a primary depositional surface, albeit is dissected like the mainstream terrace. A similar Thorp sidestream terrace 14 km farther northwest is smoothly graded to the top of the Thorp mainstream terrace. Like the surface of the mainstream terrace, there is no evidence that the Thorp sidestream terraces have ever been buried by anything but a veneer of loess and tephra.

The surface of the western Thorp sidestream terrace contains several percent of rounded to subrounded pebbles and granules of various resistates not derived from the Grande Ronde Basalt, wherein the headwaters of the modern streams that incise in the terrace originate. These resistates include variously colored chert and opal; variegated chert-granule conglomerate; various porphyritic and nonporphyritic durable felsites; quartzite; vein quartz; fine-grained dense black basalt (Teanaway Basalt); and a characteristic opal popularly known as "Ellensburg blue," whose bedrock source is the Teanaway Basalt. The resistates signify that while the western part of the Thorp sidestream gravel accumulated, the contributing streams headed in the Teanaway Basalt and Swauk Formation, which crop out north of the updip limit of the Grande Ronde Basalt. The beheading of these streams by the Swauk Creek tributary, First Creek, (fig. 2, loc. P), a capture described by Russell (1900, p. 124) and Smith (1904, p. 3), therefore occurred after the accumulation of the Thorp Gravel. The lack of these resistates in sidestream deposits of the Kittitas Drift indicates that the capture took place prior to Kittitas time.

Stratigraphy and sedimentology.--At the type locality of the mainstream facies (fig. 5) five mixed-lithology gravel layers, each 5 to 15 m thick, separate much thinner layers of sand (overbank alluvi-

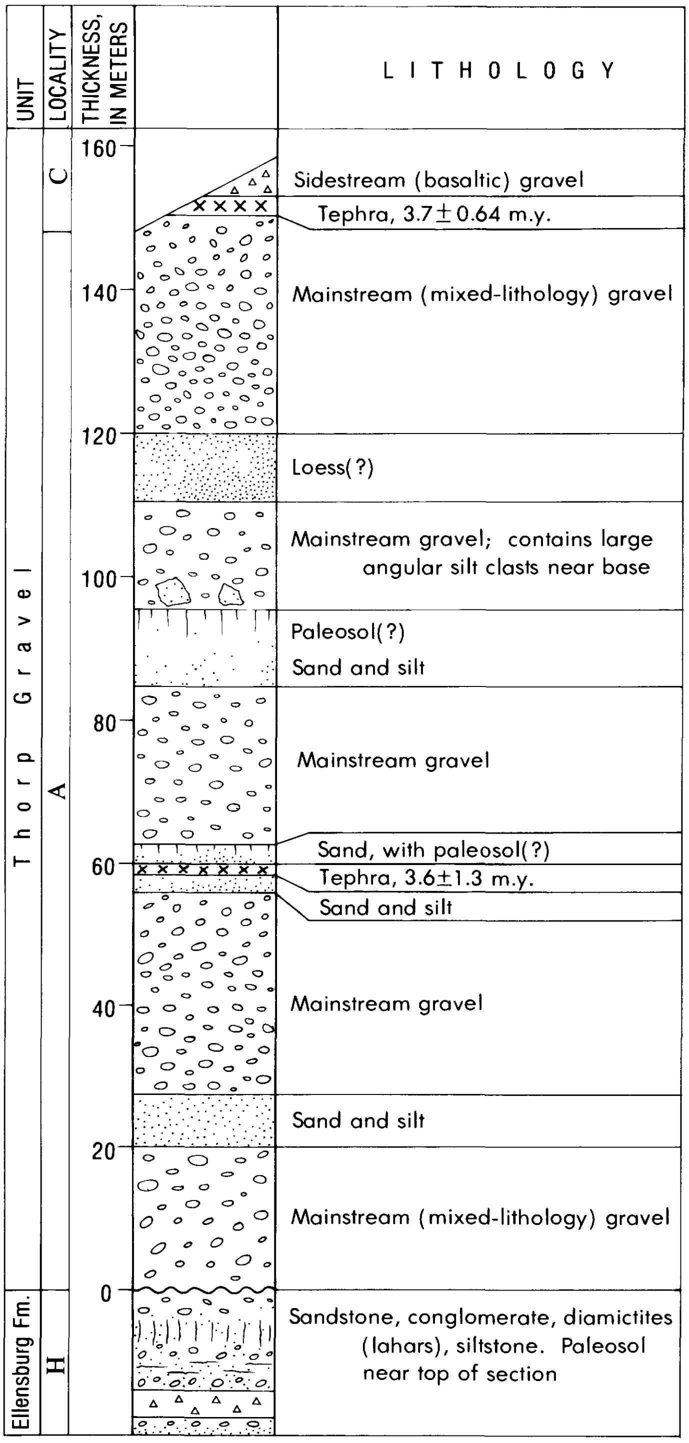


Figure 5.--Composite section of Thorp Gravel at type locality of mainstream facies (fig. 2, loc. A), and nearby locality (fig. 2, loc. C) containing upper tephra and sidestream facies.

um ?), silt (loess?), and rare tephra. While the mean grain size varies within the gravel units, there are no consistent differences in grain size, sorting, bedding character, or lithology of clasts among the gravel units. The fine layers persist for 100 m or more along the exposure, showing the general conformity of the bedding. Several oxidized zones, possible paleosols (fig. 5), are present at the type locality, though ground water seepage, which occurs at several levels, may account for some of the zones. In a roadcut 2 km to the north-northeast (loc. L), a brown (10 YR 5/4) argillic paleosol 60 cm thick is buried 4 m below the upper surface of the deposit. While the paleosols and minor unconformities--gravel, for example, channeled a few decimeters deep into underlying sandy mud--indicate minor hiatuses within the Thorp Gravel, the several gravel layers are so lithologically and sedimentologically similar as to appear related and not of greatly different ages.

In several localities (fig. 2, locs. B, C, D, and E) where the mainstream and sidestream facies occur in the same section, the basaltic gravel overlies the mixed-lithology gravel, indicating progradation by high-gradient sidestreams after the Yakima River abandoned, or migrated to the southwestern margin of, the mainstream surface. At locality F along Dry Creek, basaltic gravel apparently intertongues with mainstream gravel, indicating that sidestream fans occasionally spread over the mainstream surface during aggradation; at locality G, a layer of mixed composition is sandwiched between the dacite-rich basal gravel and a basalt-rich surface gravel, indicating that the mainstream and sidestream facies occasionally intermixed at their margins.

Paleocurrent indicators and changes in grain size and in pebble lithology reflect the direction of transport in both facies. Paleocurrents inferred from pebble imbrication and from crossbedding vary greatly but in the mainstream facies are generally eastward, and in the sidestream facies in northern Kittitas Valley are generally southward, indicating paleocurrents roughly parallel to the modern incised drainage. The intermediate diameter of the largest clast in the mainstream gravel near Thorp (fig. 2, loc. A) is 20 cm, but at Craigs Hill 14 km downvalley (loc. B) is 9 cm; the nonvolcanic fraction near Thorp is about 25 percent, of which one-fifth or more is plutonic stones, whereas at Craigs Hill the nonvolcanic fraction is less than 2 percent and evidently includes no plutonic stones. The maximum size of basaltic stones in the sidestream gravel decreases from 50 cm near the mountain front to 10 cm where the toe of the sidestream fan overlies the mainstream terrace just north of the Yakima River.

Age.--Table 2 shows data on fission-track dates (by C. W. Naeser, U.S. Geological Survey) on zircons from two tephra layers interbedded with the Thorp Gravel (fig. 5). Because the samples bracket the upper half of the thickest section of Thorp Gravel, these dates suggest that all of the Thorp is Pliocene[1]. Geomagnetically reversed layers within the Thorp Gravel therefore must lie within the Gilbert reversed polarity epoch, rather than within the Matuyama epoch as suggested by Porter (1976).

Origin.--Porter (1976) argued that the Thorp Gravel is an outwash facies of a pre-Kittitas drift that he named the Thorp Drift. While many characteristics of the Thorp Gravel are consistent with the outwash hypothesis, several relations suggest that it does not correlate with the till on Lookout Mountain and in Horse Canyon. First, the great lithologic variety of till on Lookout Mountain and in Horse Canyon contrasts with the overwhelming dominance of intermediate volcanic stones in the Thorp mainstream gravel. Second, the heights of the Thorp and the Swauk Prairie terraces are very different, despite the proximity of the downvalley limits of Porter's (1976) Thorp and Swauk Prairie till. Third, whereas the Thorp Gravel is weakly but distinctly cemented, till on Lookout Mountain and in Horse Canyon is uncemented. Fourth, Thorp sidestream gravel caps the narrow divide east of Horse Canyon and perhaps part of the divide west of Horse Canyon, suggesting that it formerly extended over the area now occupied by Horse Canyon. Because drift in Horse Canyon postdates the excavation of the canyon, the "till facies" of Porter's Thorp Drift evidently postdates his "outwash facies".

---

[1] A preliminary K-Ar age by R. W. Tabor and W. C. Gaum (written commun., 1978) on hornblende crystals from a tephra layer in SW¼NE¼ sec. 35, T. 18 N., R. 17 E. and of stratigraphic position intermediate between the two tephra layers yielding the fission-track dates, is $4.40\pm^{0.70}_{0.78}$ m.y. The statistical error overlaps the mean of each of the two fission-track dates.

Table 2.--Fission track ages by C. W. Naeser on zircon from two layers of tephra in Thorp Gravel (C. W. Naeser, written commun, 10/20/76). Discussion of techniques in Naeser (1969) and Izett and Naeser 1976)

Collector, Field No., Lab. No.	Crystals counted	Uranium concen. (ppm)	Spontaneous tracks		Induced tracks		Neutron flux[2]	Age [3] (m.y. ±2σ)
			No. counted	Density[1]	No. counted	Density[1]		
S. C. Porter, 5 Porter U. Wa., DF-743	4	280	32	0.553	482	16.6	1.79	3.64 ± 0.74
R. B. Waitt, RBW 75.410, DF-1047	6	320	147	0.635	1280	11.1	1.05	3.70 ± 0.2

[1] Values x 10^6/cm^2

[2] Values x 10^{15} neutrons/cm^2

[3] $\lambda_F = 6.85 \times 10^{-17}$ yr^{-1}

With the possible exception of the apparent antiquity of the Thorp, its characteristics generally are consistent with an origin as outwash. A striated boulder found on the Thorp mainstream surface 2 km from the head of that surface certainly keeps this possibility open. If it is outwash, however, it must substantially postdate the Lookout Mountain Ranch Drift.

An alternative origin of the Thorp Gravel is aggradation caused by local tectonic activity. Mainstream aggradation can occur as well by interruption of grade downvalley as by increased load (because of glaciers) upvalley. Because the Yakima River is antecedent to the anticlines south of Ellensburg (Smith, 1903), aggradation in Kittitas Valley should have resulted whenever the rate of relative uplift of the anticlines exceeded the rate of stream incision. The structure-transverse segment of the Yakima River south of Ellensburg coincides with a cross-structural sag, toward which prominent east-trending anticlines and intervening synclines plunge eastward from the Cascade Range and westward from the Hog Ranch axis (fig. 1). The coincidence of the Yakima River with a structural sag is either fortuitous or admits that during relative uplift of the ridges, the Yakima River was defeated from an earlier course into its present structurally and topographically favorable course. Such a tectonic diversion should have caused aggradation upstream: an ancient, tectonically caused aggradation in Kittitas Valley is thus deductively logical. Whether the Thorp Gravel represents this aggradation, or instead represents relative upward movement on the anticlines south of Kittitas Valley after the Yakima River acquired is present course, is an open question. That the Thorp apparently is not involved in the regional folding would suggest the latter, as is inferred (Newcomb, 1958; Brown and McConiga, 1960; Newcomb and others, 1972) for the Pliocene Ringold Formation, which is stratigraphically to Pasco Basin what the Thorp is to Kittitas Valley.

Correlation.--The only known deposit in the region with which the Thorp Gravel may be reasonably correlate is the Ringold Formation, which crops out typically on the White Bluffs of the Columbia River in the central part of the Pasco Basin, 120 km southeast of Kittitas Valley (fig. 1). After comprehensive reexaminations of Ringold vertebrate faunas, Gustafson (1973, 1976, 1977, 1978) and Tedford and Gustafson (1977) designated the fauna from the gravel member as Hemphillian; they inferred that the fauna from below and above a prominent tuff higher in the Ringold is very early Blancan.

According to the time scale of Berggren and van Couvering (1974, fig. 11), the Hemphillian-Blancan boundary is at about 3.9 m.y.; and according to comparison by Tedford and Gustafson of the Taunton and White Bluffs Local Faunas with the Hagerman Local Fauna of Idaho, the upper unit of the Ringold is no younger than 3.2 m.y. old. From recent northern hemisphere geochronologic, biochronologic, and geomagnetic data, C. A. Repenning (oral commun., 1978) and Repenning and Fejfar (1977) suggest an approximate age of 4.5 m.y. for the very early Blancan. The 3.7 m.y. Thorp Gravel either correlates with the upper part of the Ringold containing the very early Blancan fauna, or is as much as one million years younger.

Lookout Mountain Ranch Drift

Definition and description.--Till preserved on Lookout Mountain 70 m or more above the well-defined Kittitas (Swauk Prairie) moraines is here designated Lookout Mountain Ranch Drift, named for the ranch that occupies most of the top of Lookout Mountain. The type locality is the exposure at the top of the northwestern scarp of Lookout Mountain, at altitude 1,000 to 1,300 m, in SE¼SW¼ sec. 36, T. 20 N., R. 16 E., Cle Elum 15-minute quadrangle, Kittitas County, where the drift unconformably overlies the Grande Ronde Basalt (fig. 2). One to 3 km beyond the well-defined type Swauk Prairie moraine the drift is also exposed in Horse Canyon, the type locality of the till facies of Porter's (1976, table 4) Thorp Drift.

The Lookout Mountain Ranch Drift consists of a varied lithologic mix including porous dark-gray basalt (Grande Ronde Basalt), fine-grained dense black basalt and diabase with brown rind (Teanaway Basalt), several varieties of felsite and dikerock porphyry, altered porphyritic andesite (Keechelus Andesitic Series of former usage), granodiorite, gneiss, quartzite, gray to black chert-pebble conglomerate (Guye Formation), sandstone and siltstone (Swauk and Rosylin Formation), vein quartz, chert, and opal. As described by Porter (1976), the till forms subdued lateral moraines on the southern slope of Lookout Mountain and on the western side of Horse Canyon. Most rock types are conspicuously weathered, and the till at the type locality has a soil that includes a reddish brown (5 YR 4/4) argillic B horizon at least 50 m thick; but it also locally displays a few surficial clasts of partly weathered granodiorite and contains conspicuously striated cobbles of hornfels and volcanic rocks. The Lookout Mountain Ranch Drift evidently is less weathered than the Thorp Gravel and is uncemented.

Unlike the younger drift sheets in the upper Yakima Valley, the Lookout Mountain Ranch Drift has no recognized outwash facies. The reason for the absence of outwash is unclear, but the pattern is not unlike that 45 km to the north in the Wenatchee Valley. Page's (1939) Peshastin Till and Leavenworth Till, which evidently correlate respectively with the Kittitas and Lakedale Drifts in Yakima Valley, include easily recognized outwash terraces immediately downvalley of the valley-floor moraines. An older drift, conspicuously weathered and forming an eroded lateral moraine well above the outer Peshastin moraine on Boundary Butte, does not include a recognizable valley train in the Wenatchee Valley (Waitt, 1977).

Age and comparison to Thorp Gravel.--As compared to the outer Kittitas moraine on Lookout Mountain, the Lookout Mountain Ranch moraines are at higher altitudes, are broader and flatter, have a redder surficial hue, and display fewer surficial boulders. The Lookout Mountain Ranch Drift thus is distinctly older than the Swauk Prairie Drift. Several lines of evidence suggest, however, that it is not millions of years older. The Lookout Mountain Ranch Drift has been exposed to weathering since its deposition, but nonetheless displays a variety of slightly to moderately weathered stones, including a few coarse-grained plutonic and metamorphic rocks. Although the soil on the Lookout Mountain Ranch Drift is well developed, it does not resemble the deep cementation of the

Thorp Gravel. Moreover, whereas the Thorp Gravel is extensively dissected by tributary canyons as deep as 100 m, the original shape of the moraines on Lookout Mountain and in Horse Canyon is still recognizable. These criteria together with geomorphic evidence that Horse Canyon postdates the Thorp Gravel indicate that the Lookout Mountain Ranch Drift is much younger than the Thorp Gravel, though definitely older than the Swauk Prairie Drift.

Kittitas Drift

The Kittitas Drift, deposited during the penultimate glaciation of Yakima Valley, comprises the Swauk Prairie phase (older) and the Indian John phase. Massive moraines at Swauk and Thorp Prairies define the downvalley limit of glaciers that deposited the Swauk Prairie phase. A well-defined mainstream terrace (fig. 2, loc. I) 60 to 100 m above the modern river descends downvalley from the moraines at Thorp Prairie; a lower, equally prominent terrace 30 to 60 m above the river descends from the Indian John moraine (loc. J) (Indian John phase) farther upvalley. Stratigraphic exposures at Thorp Prairie, Swauk Prairie, and Indian John Hill show that while each of the moraines consists of till, the till is a veneer variously 0 to 10 m thick overlying mainstream gravel, evidently recording the advance of glacier ice over its own proglacial outwash. The Indian John and Swauk Prairie phases show similar degrees of weathering and soil development, suggesting that both accumulated during a single glaciation (Porter, 1975, 1976; Coleman, 1977); hence their grouping under the common name Kittitas Drift.

Several remnants of sidestream terraces in northern Kittitas Valley are roughly graded to the Kittitas mainstream terraces and have weathering characteristics intermediate between those of the Thorp surface and low-level surfaces. Like Thorp sidestream terraces, Kittitas terraces that descend from the northern mountain front consist of basaltic gravel. A well-defined surface that heads 2 km south of Green Canyon and continues 15 km southward unambiguously matches the Indian John mainstream terrace south of the Yakima River (fig. 2). I therefore correlate sidestream terraces in northern Kittitas Valley that are above the Indian John sidestream surface, but well below the Thorp sidestream surface, with the Swauk Prairie mainstream terrace.

Soil on the Kittitas Drift in many places is well developed. On the outer moraine of the Swauk Prairie phase on Lookout Mountain the soil displays a brown (7.5 YR 4/4) textural B horizon at least 60 cm thick, which probably developed during the last major interglaciation. This soil resembles the buried paleosol developed on Kittitas-aged loess and the underlying till of the Swauk Prairie phase at Swauk Prairie (Porter, 1976, Fig. 9. loc. 12). Kittitas Drift therefore apparently represents the penultimate full glaciation of the marine isotope record, of which Stage VI culminated 0.14 to 0.13 m.y. ago (Emiliani and Shackleton, 1974, Time Scale D; Hays and others, 1976). Remarkably similar ages are reported in two continental glacial sequences: Pierce, Obradovich, and Friedman (1976) obtained an age of about 0.14 m.y. for the Bull Lake Drift in West Yellowstone, Mont., and Porter, Stuiver, and Yang (1977) reported an age f 0.130 to 0.136 m.y. for the penultimate glaciation of Mauna Kea, Hawaii.

At Craigs Hill in the town of Ellensburg, the downsection change from normal to reversed polarity (the Brunhes-Matuyama boundary, 0.7 m.y. ago) occurs below the well-developed post-Kittitas soil (S. C. Porter, written commun., 1975). The available paleomagnetic and soil data therefore are internally consistent in the Kittitas Drift.

Lakedale Drift

Outwash of the Lakedale Drift, forming three or more terraces near Cle Elum (Porter, 1976), forms a single well-defined mainstream terrace 5 to 10 m above the Yakima River in Kittitas Valley. The terrace is nearly continuous along the southern bank of the river but is dissected by several tributaries on the northern side. Partly of Holocene alluvium, the floor of Green Canyon Creek also forms a terrace above the floor of Dry Creek distinctly below the Indian John sidestream terrace; it is therefore correlated with the Lakedale mainstream terrace (fig. 4).

Weathering rinds on fine-grained stones in the Lakedale Drift are less than 0.7 mm thick. Soils, the base of whose C horizon is only a meter or so deep, lack a textural B horizon and are no redder than 10 YR. The freshness of depositional landforms and the meagerness of weathering and of soil development identify the Lakedale Drift with the Fraser Glaciation of the Puget Lowland (see Armstrong and others, 1965) and with the late Wisconsin Glaciation of the mid-continent.

Holocene Alluvium

Because Holocene colluvial aprons, tributary fans, and sidestream gravel are graded to and cap all pre-Holocene terraces, they compose the largest area of surficial deposits--more area, in fact, than shown in figure 2. Near the Yakima River Holocene sidestream gravel is smoothly graded to the modern river channel and forms surfaces below the Lakedale terrace.

COMPARISON TO GLACIAL SEQUENCE AND CHRONOLOGY OF SIERRA NEVADA

A brief comparison of the glacial sequence in Kittitas Valley with the dated glacial sequence of the eastern Sierra Nevada, a region of broadly similar climate, is revealing of relative ages of the older surficial deposits in Kittitas Valley. Recent reinterpretation of the Sierra Nevada sequence, moreover, renders the disparity between the glacial sequences in the two regions not so great as it formerly seemed.

From new relative-age criteria on the Sierra Nevadan drifts and from new limiting dates by Bailey, Dalrymple, and Lanphere (1976) on the Casa Diablo Till of Curry (1971), Birkeland, Burke, and Yount (1976) and Burke and Birkeland (1976) tentatively conclude that the Mono Basin and Casa Diablo Tills are temporally related to the Tahoe Drift, and the Tenaya Drift variously to the Tioga and Tahoe Drifts. Personal observations on several relative-age criteria, however, convince me to agree with Sharp and Birman (1963) that the type Mono Basin moraines are distinctly older than the topographically unconformable Tahoe moraines. If most of the conclusions of Birkeland, Burke, and Yount are correct, however, the eastern Sierra Nevada sequence is not dissimilar to Blackwelder's (1931), as is shown on table 3 with suggested correlations to the Yakima Valley sequence. The prominent pre-Tahoe drifts in the Sierra Nevada are the valley-floor Sherwin Drift and the divide-capping McGee Till. Sharp (1968) inferred the age of 0.75 m.y. for the Sherwin Drift, which underlies the 0.7 m.y. Bishop Tuff (Dalrymple and others, 1965; Izett and Naeser, 1976). The highly weathered state of the McGee Till, and the major topographic inversion between the times of deposition of the divide-capping and valley-occupying drifts evince a large hiatus separating the McGee and Sherwin Drifts (Blackwelder, 1931).

In Kittitas Valley the type Lookout Mountain Ranch moraines are higher than but parallel to the outer Kittitas moraine. Because valleys surrounding the mountain harbor both drifts, the configuration of ridges and valleys has not changed greatly since emplacement of the drifts. In weathering, preservation of original morphology, and topographic locale the Lookout Mountain Ranch Drift far more closely resembles Sherwin Drift than it does McGee Drift, despite that weathering and erosion of the type Sherwin was retarded by the accidental carapace of Bishop Tuff. The Lookout Mountain Ranch Drift probably is no older than Sherwin Drift, thus reinforcing the inference that the Lookout Mountain Ranch Drift is much younger than the 3.7 m.y. Thorp Gravel in Kittitas Valley.

STRUCTURE

FOLDS

The erosionally stripped, centripetally dipping surfaces of the Grande Ronde Basalt advertise the synclinal basin of Kittitas Valley. From a zone of steep (10° to 50°) dip along the margins of the basin, the basalt strata flatten near the crests of anticlines that form the Wenatchee Mountains and Manastash Ridge.

Table 3.--Suggested correlation of surficial deposits in Kittitas valley, Washington and in the eastern Sierra Nevada, California

Kittitas Valley, Cascade Range (This report)		Eastern Sierra Nevada (Blackwelder, 1931; Sharp and Birman, 1963; Birkeland and others, 1976)	
Approx. age (m.y.)	Unit	Approx. age (m.y.)	Unit
0.01-0.02	Lakedale Drift		Tioga Drift
0.13-0.14(?)	Kittitas Drift		Tahoe Drift
			Mono Basin Drift
		0.71	Bishop Tuff
	Lookout Mountain Ranch Drift		Sherwin Drift
			McGee Till
		2.7	Basalt
3.7	Thorp Gravel		

Close to the axis of the basin, strata of the conformably overlying Ellensburg Formation generally dip less than 5°. Steeply dipping inliers of basalt trending subparallel to the margins of the basin, however, hint that minor anticlines or fault blocks lie beneath the basin sediments.

West of Ellensburg the Yakima River flows down the plunge of the Kittitas Valley syncline; and its tributaries, heading on the limbs of the syncline, flow generally downdip. Inclined as the underlying structure, the depositional slopes of the Thorp mainstream and sidestream terraces are difficult to distinguish from any effects of post-depositional warping. The slope of the Thorp sidestream terrace adjacent to lower Green Canyon is, in fact, almost identical to the slope of the Lakedale-Holocene valley-floor surface, suggesting that there has been little if any post-Thorp basinward tilting.

The gradual upsection decrease in the centripetal dips in the Ringold Formation in Pasco Basin suggested to Brown and McConiga (1960) that the deformation of the area including Horse Heaven anticline could have continued at least until the conclusion of Ringold deposition. The presence of thick strata of clay and silt in the lower and upper part of the Ringold Formation (Newcomb, 1958; Brown and McConiga, 1960; Newcomb, Strand, and Frank, 1972) indicates growth of the Horse Heaven anticline at Wallula Gap at least as recently as middle Pliocene, the maximum age of the upper Ringold according to Gustafson's (1973, 1976) vertebrate data.

Growth of anticlines south of Kittitas Valley may have influenced the accumulation of the Thorp Gravel in the Kittitas Valley at roughly the same time as the accumulation of the Ringold Formation. Most of the early workers, preoccupied with the notion that the courses of the Columbia and Yakima Rivers were established prior to the rise of anticlines across their courses, inferred or implied that the folds were youthful (Russell, 1900; Smith, 1903a, b; Willis, 1903; Calkins, 1905). Deformation of early Pleistocene pediments (Waters, 1955) and possibly of 19th century flumes(!) (Gilluly and others, 1968, p. 131; Brown, 1968, p. 40; A. C. Waters, written commun., 1976) suggest that some anticlines near Yakima may be still developing. A bulge in the reconstructed profile of Moses Coulee suggested to Hanson (1970) Holocene arching of the Badger Mountain anticline. The near-faithful correspondence of the Columbia and Yakima Rivers to structural lows in central and southern Washington, together with Schmincke's (1967a) stratigraphy indicating that in the Yakima area the accumulation of gravel of Columbia River provenance outlived the accumulation of silicic volcaniclastic sediment, suggest that it was not eastward-accreting fans but rising anticlines that defeated the Columbia and lower Yakima Rivers into downwarping basins during the Pliocene Epoch (Waitt, 1978). Focal mechanisms of earthquakes indicate modern north-south compressive stress in Pasco Basin and across the Saddle Mountains anticline (Malone, Rothe, and Smith, 1975; A. M. Pitt, oral commun., 1976, 1977; Malone, 1978). Several pieces of evidence thus suggest that some structures in central Washington have grown during the Pliocene and younger epochs.

FAULTS

Post-Yakima Faults in Central Washington

Faults cutting the Grande Ronde Basalt and Ellensburg Formation associate with many of the anticlines in central Washington (Mackin, 1955; Waters 1955; Rosenmeier, 1968; Diery and McKee, 1969; Bingham and others, 1970; FUGRO, 1974, App. 2B and 2C; Bentley, 1977). If some of the folds are growing, some of the faults may be at least intermittently active. There is little evidence, however, that Pleistocene sediment in central Washington is either folded or faulted. Brown (1968) and Bingham, Loudquist, and Baltz (1970), for example, reported no positive evidence of Pleistocene faulting in the Hanford area or near Wallula Gap. Bingham, Londquist, and Baltz, however, cite evidence that the reverse fault north of Saddle Mountains offsets the Ringold, from which Tedford and Gustafson (1977) described a vertebrate fauna that closely resembles the early Blancan fauna at White Bluffs.

Faults along lower Coleman and Schnebly Canyons (fig. 2, locs. M and N) bound a horst made apparent by a basinward offset in the mountain front between those canyons. Like faults that disrupt the Grande Ronde Basalt elsewhere in the region, those peripheral to Kittitas Valley evidently do not disrupt modern sidestream fans and thus can be dated only as post-Miocene, pre-late Holocene.

Young Faults in Kittitas Valley

Three east-trending north-facing scarps break the smooth slopes of Thorp sidestream terraces that descend from the northern mountain front. Of two prominent remnants of Thorp sidestream terraces, the eastern one is interrupted 9 km north of Ellensburg by a conspicuous east-trending north-facing scarp 50 m high, whose only reasonable explanation is a fault scarp (fig. 2, fault Y). The alined upstream ends of 12 flat-topped knolls of Thorp Gravel east and west of the prominent Thorp terrace suggest that the fault is at least 10 km long. Four magnetic traverses by Weston Geophysical Research (1977, fig. 2R I-34) show an abrupt southward rise of about 500 gammas across an east-trending bedrock structure about 500 m south of fault Y (fig. 2). Weston's gravity profile (fig. 2R I-36) shows a conspicuous abrupt rise of about 4 milligals southward across the same structure. These geophysical data, probably showing the greater depth to the Grande Ronde Basalt north of the structure than to the south, indicate that fault Y dips to the south and is therefore a reverse fault.

Tributary valleys incised in the western remnant of Thorp sidestream terrace reveal an upward stratigraphic succession of the Grande Ronde Basalt, conglomerate and sandstone of the Ellensburg Formation, mainstream facies of the Thorp Gravel, and sidestream facies of the Thorp Gravel (fig. 4). The unconformity separating the Grande Ronde and Ellensburg from the Thorp passes gradually southward beneath the floor of the canyons, but abruptly reappears in the walls of the canyons approximately where the surface of the terrace is interrupted by an east-trending north-facing scarp 10 to 15 m high. The topography of the surface of the terrace and the stratigraphy in the walls of the incised valleys independently denote an east-trending fault upthrown at least 30 m to the south (fig. 2, fault X).

The alined northern ends of 15 knolls of Thorp sidestream gravel suggest up-to-the-south movement on a third fault (fig. 2, fault z) striking eastward for 11 km from the northern outskirts of Ellensburg. The knolls also merge eastward with a northwest-trending anticline in the Yakima Basalt Subgroup, but the linearity of the dissected scarp and its similar trend and appearance to scarps that manifest faults X and Y suggest the concealed fault Z dotted on figure 2.

The youngest deposit definitely faulted in Kittitas Valley is the Thorp Gravel, whose enclosed tephra layers are dated at about 3.7 m.y. old. Sidestream sediments of Kittitas age (presumed to be 0.14 to 0.13 m.y. old) and of Lakedale age (20,000 to 10,000 years old) are not demonstrably offset. The Thorp Gravel in Kittitas Valley evidently was faulted between 3.7 and 0.13 m.y. ago. It is possible, however, that younger sediments were faulted and the scarps obscured. Were faulting continuous since 3.7 m.y. ago, a 50-m scarp across the Thorp Gravel should be less than 2 m high across Kittitas surfaces and about 20 cm high on Lakedale surfaces. Such small scarps could have been obscured by erosion and deposition prior to incision of the faulted surfaces.

REGIONAL TECTONIC SIGNIFICANCE

Most folds in central Washington trend eastward; those within a 10- to 40-km-wide southeast-trending zone that includes the Olympic-Wallowa lineament of Raisz (1945), trend southeast. That prominent anticlines like Saddle Mountains, Umtanum and Rattlesnake Ridges, and Horse Heaven Hills are kinked abruptly into the trend of the linear zone suggests that whatever caused the east-west structures outside the zone of the lineament also influenced the trends of the same structures within the zone. Wise (1963) inferred an interregional southeast-trending right-lateral wrench system that generated not only regional southeast-trending right-lateral strike-slip faults but also the east-trending compressional folds. Focal mechanisms of earthquakes confirm modern north-south compression in the Saddle Mountains-Pasco Basin area (Malone, Rothe, and Smith, 1975; A. M. Pitt, oral commun., 1977; Malone, 1978). The northern limbs of many anticlines in central Washington are disrupted by high-angle, up-to-the-south reverse faults (Mackin, 1955; Bingham, Londquist, and Baltz, 1970; FUGRO, 1974, App. 2B and 2C; R. D. Bentley, 1977, and oral commun., 1976 and 1977); some of the anticlines and faults are arranged in southeast-trending dextral echelon systems (fig. 1).

The three east-trending faults in Kittitas Valley form an echelon system that trends southeast and is antithetic to the basinward dip of the Grande Ronde Basalt at the northern margin of the valley. The parallelism of the faults to each other and to anticlines farther east, and the similarity of their dextral echelon arrangement to that of the anticlines and their attendant reverse faults farther southeast (fig. 1; Waitt, 1978), suggest a genetic relation to regional structures. An hypothesis consistent with regional relations is that the individual east-trending scarps in Kittitas Valley evince reverse faults caused by north-south compression, and that the southeast trend of the dextral echelon pattern is due to a right-lateral couple across a southeast-trending structural zone that includes, but is not limited to, the topographically defined Olympic-Wallowa lineament of Raisz (1945) about 10 km to the southwest.

Along the segment of the Olympic-Wallowa lineament bordering Pasco Basin, the east-northeast-trending Rattlesnake Ridge anticline is abruptly kinked into the southeast trend of the lineament. Unlike the continuous long Rattlesnake Ridge, however, the southeastern extension is a series of short ridges formed by elongate quaquaversal anticlines in the Saddle Mountains Basalt (Newcomb, 1970; K. R. Fecht, oral commun., 1977). Many of the anticlines trend individually about azimuth 100 and are collectively arranged dextrally en echelon along a 120 azimuthal trend. The echelon arrangement, which has counterparts elsewhere on the globe (Harding, 1973; Wilcox, Harding, and Seely, 1973), requires a right-lateral couple across a roughly southeast trend, and the eastward trend of the individual anticlines evinces an associated north-south compression.

That two separated areas near or along the Olympic-Wallowa lineament independently indicate similar stress fields suggests that a north-south compressional stress has existed in central Washington, and that a right-lateral couple has existed across a substantial length of the Olympic-Wallowa structural zone, from at least the late Miocene to the middle Pliocene.

ACKNOWLEDGMENT

This paper has especially benefited by stimulating discussions between 1975 and 1978 with R. D. Bentley, R. W. Kopf, S. C. Porter, and D. A. Swanson, who of course do not necessarily agree with all of the conclusions herein.

REFERENCES CITED

American Commission on Stratigraphic Nomenclature, 1970, Code of Stratigraphic Nomenclature: Tulsa, Oklahoma, American Association of Petroleum Geologists, 21 p.

Armstrong, J. E., Crandell, D. R., Easterbrook, D. J., and Noble, J. B., 1965, Late Pleistocene stratigraphy and chronology in southwestern British Columbia and northwestern Washington: Geological Society of America Bulletin, v. 76, p. 321-330.

Bailey, R. A., Dalrymple, G. B., and Lanphere, M. A., 1976, Volcanism structure, and geochronology of Long Valley caldera, Mono County, California: Journal of Geophysical Research, v. 81, p. 725-744.

Bentley, R. D., 1977, Stratigraphy of the Yakima Basalts and structural evolution of the Yakima ridges in the western Columbia Plateau: in Brown, E. H. and Ellis, R. C., eds., Geological excursions in the Pacific Northwest: Bellingham, Western Washington University, Department of Geology, p. 339-389.

Berggren, W. A., and Van Couvering, J. A., 1974, The Late Neogene: Paleogeography, Paleoclimatology, Paleoecology, v. 16, p. 1-216.

Bingham, J. W., and Grolier, 1966, The Yakima Basalt and Ellensburg Formation of south-central Washington: U.S. Geological Survey Bulletin 1224-G, p. G1-G15.

Bingham, J. W., Londquist, C. J., and Baltz, E. H., 1970, Geologic investigations of faulting in the Hanford region, Washington: U.S. Geological Survey Open-File Report, 104 p.

Birkeland, P. W., Burke, R. M., and Yount, J. C., 1976, Preliminary comments on Late Cenozoic glaciations in the Sierra Nevada, in Mahaney, W. C., ed., Quaternary Stratigraphy of North America: Stroudsburg, Pennsylvania, Dowden, Hutchinson, p. 283-295.

Blackwelder, Eliot, 1915, Post-Cretaceous history of the mountains of central Wyoming, Part III: Journal of Geology, v. 23, p. 307-340.

_____1931, Pleistocene glaciation in the Sierra Nevada and Basin Ranges: Geological Society of America Bulletin, v. 42, p. 865-922.

Brown, R. E., 1968, A study of reported faulting in the Pasco Basin: Batelle Northwest Laboratory Report BWWL-662, 55 p.

Brown, R. E., and McConiga, M. W., 1960, Some contributions to the stratigraphy and indicated deformation of the Ringold Formation: Northwest Science, v. 34, no. 2, p. 43-54.

Burke, R. M., and Birkeland, P. W., 1976, Re-evaluation of the late Pleistocene glacial sequence along the eastern escarpment of the Sierra Nevada, California [abs.]: Geological Society of America, Abstracts with Program v. 8, p. 818-819.

Calkins, F. C., 1905, Geology and water resources of a portion of eastcentral Washington: U.S. Geological Survey Water-Supply Paper 118, 96 p.

Coleman, S. M., 1976, Weathering rinds as a Quaternary age-dating technique, western United States [abs.]: Geological Society of America, Abstracts with Programs, v. 8, p. 818-819.

Curry, R. R., 1971, Glacial and Pleistocene history of the Mammoth Lakes, Sierra, California, a geologic guidebook: University of Montana Geological Series Publication 11, 49 p.

Dalrymple, G. B., Cox, Allen, and Doell, R. R., 1965, Potassium-argon age and paleomagnetism of the Bishop Tuff, California: Geological Society of America Bulletin, v. 76, p. 665-673.

Diery, H. D., and McKee, Bates, 1969, Stratigraphy of the Yakima Basalt in the type area: Northwest Science, v. 43, p. 47-64.

Emiliani, Cesare, and Shackleton, N. J., 1974, The Brunhes Epoch: isotopic paleotemperatures and geochronology: Science, v. 183, p. 511-514.

FUGRO Inc., 1974, Geologic regional and site investigations for the WPPSS Nuclear Project No 1 (Amendment 9, Aug. 1974): Nuclear Regulatory Commission, Docket No. 50-460/513.

Gilluly, James, Waters, A. C., and Woodford, A. O., 1968, Principles of geology (3d ed.): San Francisco, W. H. Freeman and Co., 687 p.

Griggs, A. B., 1976, The Columbia River Basalt Group in the Spokane quadrangle, Washington, Idaho, and Montana: U.S. Geological Survey Bulletin 1413, 39 p.

Grolier, M. J., and Bingham, J. W., 1971, Geologic map and sections of parts of Grant, Adams, and Franklin Counties, Washington: U.S. Geological Survey Miscellaneous Geologic Investigations Map I-589.

Gustafson, E. P., 1973, The vertebrate fauna of the late Pliocene Ringold Formation, south-central Washington: Seattle, University of Washington, M.S. thesis, 164 p.

______1976, A revised chronology for vertebrate fossil faunas in eastern Washington: Geological Society of America, Abstracts with Program, v. 8, p. 377-378.

______1977, First record of *Teleoceras* (Rhinocerotidae) from the Ringold Formation, Pliocene of Washington: PaleoBios, no. 27, 4 p.

______1978, The vertebrate faunas of the Pliocene Ringold Formation, south-central Washington: University of Oregon, Museum of Natural History, Bulletin 23, 62 p.

Hanson, L. G., 1970, The origin and deformation of Moses Coulee and other scabland features on the Waterville Plateau, Washington: Seattle, University of Washington, Ph.D. thesis, 137 p.

Harding, T. P., 1973, Newport-Inglewood trend, California--an example of wrenching style of deformation: American Association of Petroleum Geologists Bulletin, v. 57, p. 97-116.

Hays, J. D., Imbrie, John, and Shackleton, N. J., 1976, variations in the earth's orbit: pacemaker of the ice ages: Science, v. 194, p. 1121-1132.

Izett, G. A., and Naeser, C. W., 1976, Age of the Bishop Tuff of eastern California as determined by the fission-track method: Geology, v. 4, p. 587 - 590.

Mackin, J. H., 1955, Geology of the Priest Rapids Development, *in* Priest Rapids Hydraulic Development, Columbia River, Washington: Grant Co. Public Utility District no. 2, 43 p.

______1961, A stratigraphic section in the Yakima Basalt and the Ellensburg Formation in south-central Washington: Washington Division of Mines and Geology, Report of Investigations 19, 45 p.

Malone, S. D., 1978, A review of eastern Washington seismicity: Proceedings of Tectonics and Seismicity of the Columbia Plateau Workshop: U.S. Department of Energy, Rockwell Hanford Operations, in press.

Malone, S. D., Rothe, G. H., and Smith, S. W., 1975, Details of microearthquake swarms in the Columbia Basin, Washington: Seismological Society of America Bulletin, v. 65, p. 855-864.

McKee, E. H., Swanson, D. A., and Wright, T. L., 1977, Duration and volume of Columbia River Basalt volcanism, Washington, Oregon, and Idaho: Geological Society of America, Abstracts with Program, v. 9, p. 463-464.

Naeser, C. W., 1969, Etching fission tracks in zircons: Science, v. 165, p. 388.

Newcomb, R. C., 1958, Ringold formation of Pleistocene age in type locality, the White Bluffs, Washington: American Journal of Science, v. 256, p. 328-340.

Newcomb, R. C., Strand, J. R., and Frank, F. J., 1972, Geology and ground-water characteristics of the Hanford Reservation of the U.S. Atomic Energy Commission, Washington: U.S. Geological Survey, Professional Paper 717, 78 p.

Page, B. M., 1939, Multiple glaciation in the Leavenworth area, Washington: Journal of Geology, v. 47, p. 787-815.

Pierce, K. L., Obradovich, J. D., and Friedman, I., 1976, Obsidian hydration dating and correlation of Bull Lake and Pinedale Glaciations near West Yellowstone, Montana: Geological Society of America Bulletin, v. 87, p. 703-710.

Porter, S. C., 1969, Pleistocene geology of the east-central Cascade Range, Washington: Guidebook for Third Pacific Coast Friends of the Pleistocene Field Conference, 54 p.

______1975, Weathering rinds as a relative-age crierion: application to subdivision of glacial deposits in the Cascade Range: Geology, v. 3, p. 101-104.

______1976, Pleistocene glaciation in the southern part of the North Cascade Range, Washington: Geological Society of America Bulletin, v. 87, p. 61-75.

Porter, S. C., Stuiver, M., and Yang, I. C., 1977, Chronology of Hawaiian glaciations: Science, v. 195, p. 61-63.

Raisz, E. J., 1945, The Olympic-Wallowa Lineament: American Journal of Science, v. 243-A, p. 479-485.

Repenning, C. A., and Fejfar, Oldrich, 1977, Holarctic correlations of microtid rodents: Quaternary Glaciations in the Northern Hemisphere, Report 4, p. 234-252.

Richmond, G. M., 1962, Quaternary stratigraphy of the La Sal Mountains, Utah: U.S. Geological Survey, Professional Paper 324, 135 p.

Rosenmeier, F. J., 1968, Stratigraphy and structure of the Table Mountain-Mission Peak area in the Wenatchee Mountains, central Washington: Seattle, University of Washington, M.S. thesis, 44 p.

Russell, I. C., 1893, A geological reconnoissance in central Washington: U.S. Geological Survey Bulletin 108, 108 p.

______1900, A preliminary paper on the geology of the Cascade Mountains in northern Washington: U.S. Geological Survey, 20th Annual Report, pt. II, p. 89-210.

Schmincke, H. U., 1964, Petrology, paleocurrents, and stratigraphy of the Ellensburg Formation and interbedded Yakima Basalt flows, south-central Washington: Baltimore, The John Hopkins University Ph.D. thesis, 426 p.

______1967a, Flow directions in Columbia River Basalt flows and paleocurrents of interbedded sedimentary rocks, south-central Washington: Geologisches Rundschau, v. 56, p. 992-1020.

______1967b, Graded Lahars in the type sections of the Ellensburg Formation, south-central Washington: Journal of Sedimentary Petrology, v. 37, p. 438-448.

______1967c, Stratigraphy and petrography of four upper Yakima Basalt flows in south-central Washington: Geological Society of America Bulletin, v. 78, p. 1385-1422.

Sharp, R. P., 1968, Sherwin Till-Bishop Tuff geological relationships, Sierra Nevada, California: Geological Society of America Bulletin, v. 79 p. 351-364.

Sharp, R. P., and Birman, J. H., 1963, Additions to classical sequence of Pleistocene glaciations, Sierra Nevada, California: Geological Society of America Bulletin, v. 74, p. 1079-1086.

Smith, G. O., 1901, Geology and water resources of a portion of Yakima County, Washington: U.S. Geological Survey, Water-Supply Paper 55, 68 p.

______1903a, Ellensburg Folio: U.S. Geological Survey, Geologic atlas of the United States, Folio 86.

______1903b, Contributions to the geology of Washington: geology and physiography of central Washington: U.S. Geological Survey Professional Paper 19, 39 p.

______1903c, Anticlinal mountain ridges in central Washington: Journal of Geology, v. 11, p. 166-177.

______1904, Mount Stuart Folio: U.S. Geological Survey, Geologic Atlas of the United States, Folio 106.

Swanson, D. A., 1967, Yakima Basalt of the Tieton River area, south-central Washington; Geological Society of America Bulletin, v. 78, p. 1077-1110.

Swanson, D. A., and Wright, T. L., 1978, Some important facts and inferences concerning the Columbia River Basalt Group: Tectonics and Seismicity of the Columbia Plateau Workshop, 14-16 Feb. 1978, meeting volume: Rockwell Hanford Operations, Richland, Washington.

Swanson, D. A., Wright, T. L., Camp, V. E., Gardner, J. N., Heltz, R. T., Price, S. A., and Ross, M. E., 1977. Reconnaissance geologic map of the Columbia River Basalt Group, Pullman and Walla quadrangles, southeast Washington, and adjacent Idaho: U.S. Geological Survey Open-File Report 77-100.

Tabor, R. W., Waitt, Jr., R. B., Frizzell, Jr., V. A., Swanson, D. A., and Byerly, G. R., 1977, Preliminary geologic map of the Wenatchee 1:100,000 quadrangle, Washington: U.S. Geological Survey, Open-File Report 77-531, 40 p.

Tedford, R. H., and Gustafson, E. P., 1977, First North American record of the extinct panda Parailurus: Nature, v. 265, p. 621-623.

Waitt, Jr., R. B., 1977, Guidebook to Quaternary geology of the Columbia, Wenatchee, Peshastin, and upper Yakima valleys, west-central Washington: U.S. Geological Survey Open-File Report 77-753, 25 p.

______1978, Post-Miocene stratigraphy and tectonism of parts of the Great Columbia Plain and adjacent Cascades, Washington: Tectonics and Seismicity of the Columbia Plateau Workshop, 14-16 Feb. 1978, meeting volume: Rockwell Hanford Operations, Richland, Washington.

Waters, A. C., 1955, Geomorphology of south-central Washington, illustrated by the Yakima East quadrangle: Geological Society of America Bulletin, v. 66, p. 663-684.

Watkins, N. D., and Baski, A. K., 1974, Magnetostratigraphy and oroclinal folding of the Columbia River, steens, and Owyhee basalts in Oregon, Washington, and Idaho: American Journal of Science, v. 274, p. 148-189.

Weston Geophysical Research, 1977, Geophysical evaluation of structures in the Columbia Plateau: Washington Public Power Supply System PSAR for WPPSS Nuclear Project 1 & 4, Amend. 23, Appendix 2R I, Nuclear Regulatory Commission, Docket Nos. 50-460, 50-513.

Wilcox, R. E., Harding, T. P., and Seely, D. R., 1973, Basic wrench tectonics: American Association of Petroleum Geologists Bulletin, v. 57, p. 74-96.

Willis, Bailey, 1903, Physiography and deformation of the Wenatchee-Chelan district, Cascade Range: U.S. Geological Survey Professional Paper 19, p. 41-101.

Wise, D. U., 1963, An outrageous hypothesis for the tectonic pattern of the North American Cordillera: Geological Society of America Bulletin, v. 74, p. 357-362.

Wright, T. L., Grolier, M. J., and Swanson, D. A., 1973, Chemical variation related to stratigraphy of the Columbia River Basalt: Geological Society of America Bulletin, v. 84, p. 371-386.

GPO 689-035