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August 26, 1987

Memorandum

To: Charlotte Abrams, Project Officer, Geotechnical Branch, Division of Waste Management, U.S. Nuclear Regulatory Commission, Washington, D.C.

From: Program Manager, Division of Minerals Availability

Subject: Letter Report Re NRC Sponsored Columbia Plateau Field Trip, August 3-6, 1987.

Per your request, the Bureau of Mines attended the subject field trip. Six copies (6) of Russ Raney's trip report are enclosed. Seems to have been an interesting and informative assignment.

Please call Russ if there are any questions about the report and trip.

Ransom F. Read

Ransom F. Read

Enclosures

WM Record File 101

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Letter Report of
NRC Stratigraphy and Structural Orientation Field Trip,
Columbia Plateau, Central Washington and Northern Oregon
August 3-6, 1987

by Russell G. Raney

The purpose of the NRC field trip was to familiarize the participants with the stratigraphy and structural geology of the Columbia Plateau in preparation for the upcoming meeting pertaining to the BWIP Site Characterization Plan. Of special interest to the Bureau of Mines is the existence of inter-flow sedimentary units (specifically coal, lignite, and peat deposits) that may represent a potential source of hydrocarbons in and around the BWIP site.

The field trip was organized by Messers. Harold Lefevre and Keith McConnell of the Silver Spring office of the NRC and lead by Dr. Robert Bentley and Mr. Jack Powell, Central Washington University, Dr. Newell Campbell, Yakima State College, and Dr. James Anderson, Pomono College.

Sunday, August 2, 1987

Met with Mr. David Faley of W.E. Mays and Associates at 3:00 p.m. to discuss details of and solicit comments pertaining to the draft copy of the Washington oil and gas map prepared by the Bureau of Mines for the NRC. Attended 7:00 pm orientation briefing by Dr. Robert Bentley at Central Washington University (CWU) accompanied by Messrs. Harold Lefevre, Keith McConnell, and Jim Morrow of the NRC and other field trip participants.

Day 1, Monday, August 3

Participants assembled at 7:00 am in Lind Hall on the CWU campus where Dr. Bentley presented an overview of Yakima Fold stratigraphy and structural geology. Those in attendance include:

Robert Bentley (CWU. Field trip leader)
Jack Powell (CWU. Co-leader)
Newell Campbell (Yakima Valley College. Leader-day 3)
James Anderson (Pomono College. Leader-day 4)
Harold Lefevre (NRC-Silver Spring)
Keith McConnell (NRC-Silver Spring)
Jim Morrow (NRC-Silver Spring)
Robert Cook (NRC-Hanford)
Don West (Yakima Tribal representative)
Steve Armstrong (Nez Perce Tribal representative)
Pat McGee (Yakima /Earth, Water, and Air representative)
Russell Raney (U.S. Bureau of Mines)
Jerry Black (Oregon Div. Geol. and Mineral Industries)
Terry Tolan (BWIP)
Art Lassila (DOE)
Mike West (Consultant)
Darwin Marjaneimi (DOE)
Mike Parsons (Westinghouse)
Don Caldwell
Bill Kul
Dick Galister

Figure 1 presents the route of the field trip.

The first field stop was in a road cut along an abandoned section of the Milwaukee railroad. At this location in the Boylston Mountain structure (Johnson Canyon Fault Zone), rocks of the Rocky Coulee/Hole-in-the-Wall flows have been thrust upon alluvium and gravel that could be as young as late Pleistocene. Bentley feels this may be evidence of neotectonic (1 mybp or less) faulting. The alluvium and gravel have yet to be dated.

A sag pond on a flat area in the crestal area of the Hog Ranch axis (Stop 2) suggests (to Bentley) possible evidence of Quaternary or Holocene faulting.

The greater portion of the day was spent observing various flow units and structural manifestations in numerous roadcuts and canyons between Ellensburg and Vantage. Locations visited include the Schnebly Fault Zone, Kittitas Cribb Linears, Chevoit Linear (there is the possibility of stream offset in these three areas; Bentley feels that if this can be substantiated, then this fault zone may have neotectonic significance); Schnebly Canyon and Hell's Kitchen Faults on the Ryegrass Mountain Anticline; Sentinel Gap flow; Saddle Mountain Fault at Foster Creek, Doris Canyon, and Sunset Run Canyon; and an overlook demonstrating the relationship of the Lynch and Poison Creek linears to changes in geometry of the Saddle Mountains Fault in the Boylston Mountains Structure.

The day's activities concluded with an examination of an excellent exposure of the Vantage Member (interbedded siliciclastic sediments) in the vicinity of the Hog Ranch axis. Apparently, the local presence or absence of this sedimentary unit throughout the CRB aids the investigator in the determination of pre-Vantage topographic highs and lows, particularly in the Columbia Hills and in northern Oregon in the vicinity of John Day dam and the Laurel Fault Zone (see day 4 section).

Day 2, Tuesday, August 4

The day was spent in the general areas of Vantage and Sentinel Gap. At Sentinel Bluffs, the complex relationship of stratigraphy to structural evolution of the Saddle Mountains was observed and discussed at length. At the west side of the Priest Rapids Dam the Umtanum Fault was observed and discussed. According to Bentley, the Umtanum structure is much more complex than reported by Price in his 1980 study (presumably for the Department of Energy through its contractor, Rockwell Hanford Operations). Bentley suggests the "complex geometry of folds in the Yakima structures must also be present in this structure. If so, the simple fold-fault model of Price must be modified. We interpret the faults to be fundamental structures that concentrate and localize strain to form complex interference folds as these structures grew in a two stage history". The apparent significance of Bentley's observations is the two-stage history of the Yakima structures. Ostensibly, this is in contrast to the DOE view that the structures were the result of steady-rate deformation.

Structural relationships between Wanapum and Grande Ronde basalts, main-and side-stream facies of Selah sediments, and the Mabton and Pomona units exposed in the Umtanum fault zone on the north side of Untanum Ridge (Filey Road area) may, according to Bentley, host evidence pertaining to the time of deformation of the ridge. Bentley, Powell, and Campbell maintain Umtanum Ridge deformation (as well as many other major structures in the CRB) took place in Quaternary time.

The balance of the day was spent in the detailed examination of a section of the Cohasset and Rocky Coulee flows north of Sentinel Gap on the margin of the Yakima Firing Range.

Day 3, Wednesday, August 5

Early stops included examination of road cuts in the Umtanum and Manastash structures. Rocks exposed in the cuts demonstrated the complex structural and stratigraphic nature of the ridges but did not provide any apparent evidence of neotectonism.

The latter portion of day 3 was spent on and around Toppenish Ridge on the Yakima Indian Reservation. In 1979, a series of trenches were dug by Dr. Campbell in ridge-top grabens (sag ponds) in an effort to collect evidence of neotectonism. Plant material collected in the lower part of the fill of one pond yielded carbon-14 dates of 505 plus or minus 160 years, and 620 plus or minus 135 years. In the spring of 1987, on the lower northern flank of the ridge, Campbell excavated a series of three trenches for the same purpose. In trench 2 was found evidence of thrusting the upper plate of which rested upon sediments also hosting abundant vegetable matter. Dating of the organic matter may, along with the 1979 samples, provide the neotectonic evidence Campbell has been pursuing. As of August 5, the samples have yet to be dated.

In a paper published by Campbell and Bentley in the November 1981 issue of Geology, the authors present arguments to support their contention that the ridge-top grabens are the result of Quaternary deformation as opposed to ridge-top spreading due to gravity. A copy of the paper is enclosed.

Day 4, Thursday, August 6

Traveled from Yakima to Goldendale accompanied by Messrs. Lefevre, McConnell, and Morrow, to meet Dr. Anderson and the remainder of the participants for a trip to the Columbia Hills and the Laurel Fault Zone. Drs. Bentley and Campbell, Jack Powell, and Richard Galister left the field trip in Goldendale.

The first stop entailed an examination and walk through a complete section of Wanapum Basalt exposed in road cuts in Yakima Canyon.

Stop 2 was on an overlook above John Day Dam where uplift along the Columbia Hills anticline prior to eruption of the Frenchman Springs Member is in evidence. Also in evidence is thinning of the earliest Frenchman Springs flows in the vicinity Columbia Hills fault zone.

According to Anderson (day 4 trip handout), " a plot of the Gingko and Sand Hollow flows indicates that flows closest to the frontal fault zone are the thinnest and overall thinning of the Frenchman Springs Member (exclusive of the Sentinel Gap) is 28 per cent. Further, "A plot of the Sand Hollow only indicates that thinning of the Sand Hollow flow totals a maximum 52 per cent (37 meters) near the Columbia Hills fault." Regarding the collective Gingko flows, "...thinning of the Gingko flows occurred in two areas: closely adjacent to the Goldendale strike-slip fault and near the frontal fault zones of the Columbia Hills fault. Moreover, thinning of the Gingko flows totalled 39 per cent near the Goldendale fault and 36 percent near the Columbia Hills fault. As I understand it, thinning of units across ridges and in proximity to major faults acts to support DOE's contention of steady-rate deformation.

The day and the field trip were concluded at an exposure of the Laurel Fault Zone east of The Dalles, Oregon. The fault zone includes a rotated fault block bounded by splays of the Laurel fault. While present nearby, the Vantage interbeds are missing on the eastern side of the zone. Lines of evidence indicate the Vantage was not deposited in this area as it was probably elevated with respect to the surrounding areas.

Personal observations

An ongoing difference of professional opinion between Drs. Bently and Anderson (aided and abetted by Mr. Tolan) pertaining to everything from the stratigraphic and structural evolution of the Columbia Plateau to the price of tea in China was immensely distracting and introduced more than a modicum of confusion into a subject at best very complex and at worst incomprehensible (at least in my case). While "spirited debate" among members of the scientific community is enevitable, even healthy and necessary, the behaviour of Dr. Anderson and Mr. Tolan toward Dr. Bentley (and by association, Mr. Powell and Dr. Campbell), lacked professionalism and is not in the best interests of communication and understanding. Dr. Anderson strongly objected to Bentley's professional interpretations and went so far to suggest that DOE conduct a similar field trip "to present their side of the story." I get the distinct feeling of political overtones.

Anderson's objections notwithstanding, there does seem to be evidence that would suggest neotectonic activity in the Columbia Plateau. Whether this constitutes problems (in terms of 10CFR60.121 (c) 11) for DOE in regard to siting the HLW repository at Hanford is yet to be seen. It could be argued that Quaternary deformation on and around Toppenish Ridge would not affect operations at the proposed HLW repository, as the sites are more than 35 kilometers apart. However, work currently in progress on Smyrna Bench, immediately north of the Handford works, has produced apparent evidence of neotectonism at that location. The work is being conducted by Michael West and Associates, a consulting firm from Denver, CO (it is my understanding that a report on the Smyrna Bench project is forthcoming). Whereas neotectonism in the vicinity of Toppenish Ridge may have little or no impact on site characterization by virtue of distance, such activity on the northern margin of the site may be highly significant.

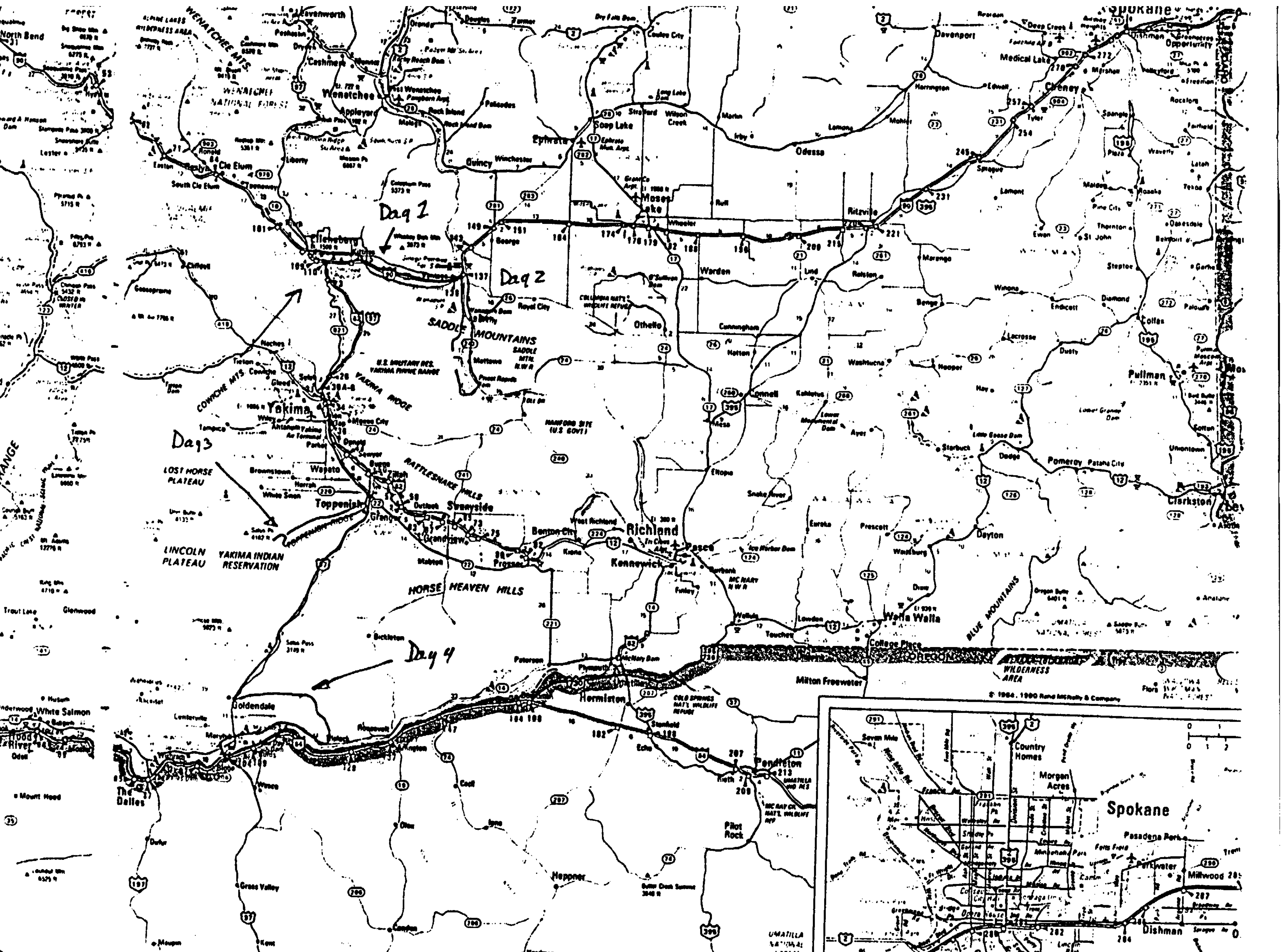
Day 1
Day 2
Day 3
Day 4
Spokane
Ellensburg
Wenatchee
Cle Elum
Ephrata
Soap Lake
Moses Lake
Ritzville
Odessa
Davenport
Medical Lake
Cheney
Quincy
George
Warden
Othello
Connell
Royal City
SADDLE MOUNTAINS
YAKIMA RIDGE
Yakima
Naches
Toppenish
Wapato
Zillah
Sunnyside
Grandview
Prosser
Benton City
West Richland
Richland
Pasco
Kennewick
RATTLESNAKE HILLS
HANFORD SITE (U.S. GOVT)
LOST HORSE PLATEAU
LINCOLN PLATEAU
YAKIMA INDIAN RESERVATION
HORSE HEAVEN HILLS
Goldendale
Hermiston
Pendleton
Pilot Rock
Heppner
Milton Freewater
Walla Walla
College Place
Dayton
Pomeroy
Clarkston
Pullman
Colfax
BLUE MOUNTAINS
OREGON
The Dalles
White Salmon
Hood River
North Bend
© 1984, 1990 Rand McNally & Company
Country Homes
Morgan Acres
Pasadena Park
Millwood
Dishman

Figure 1.

Late Quaternary deformation of the Toppenish Ridge uplift in south-central Washington

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ABSTRACT

Mapping of Quaternary sedimentary rocks and Miocene basalts on Toppenish Ridge, a fold in south-central Washington, reveals a 32-km-long zone of nearly 100 surface ruptures. The ruptures indicate renewed movement on Miocene structures in latest Quaternary time. The ruptures probably formed in response to regional compressive stress, between 500 and 13,000 yr ago. These ruptures are interpreted to represent the most recent surface deformation in central Washington.

INTRODUCTION

The Yakima fold belt is a series of east-trending anticlinal ridges and synclinal valleys located in south-central Washington (Fig. 1). The timing of the Yakima structures has been the subject of extensive investigations recently because of their proximity to radioactive waste storage sites and nuclear reactor facilities at the Hanford site, Washington (located about 75 km east of Toppenish Ridge). Radiometric dating and regional field studies of the extensive Columbia River Basalt (McKee and others, 1977; Bentley, 1977; Swanson and others, 1979a; Myers and Price, 1979; Swanson and others, 1979b; Reidel and others, 1980) have largely substantiated the view of early workers that most of the Yakima structures have grown by north-south regional compression in late Cenozoic time. Although shallow-focus historical seismic events (Rasmussen, 1967; Malone and others, 1975; Washington Public Power Supply System, 1977; Rothe, 1978; Smith and Lindh, 1978) suggest that the region is still undergoing compressional deformation, there has been little evidence of surface faulting. We present evidence that one of the Yakima structures has continued to deform by thrusting, folding, and vertical surface rupture into late Quaternary time.

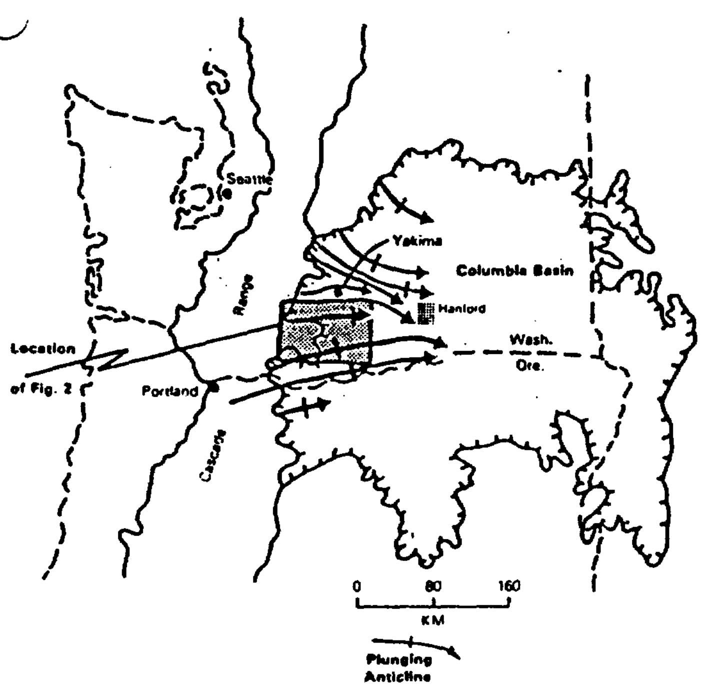

Figure 1. Location map showing Columbia Basin, Yakima fold belt, and Yakima Indian Reservation (stipple).

SCOPE AND GEOLOGIC SETTING

Russell (1893) and Smith (1903) described the regional extent of the Yakima structures and discussed their late Cenozoic evolution. Waters (1955) suggested historic growth of these anticlines on the basis of speculative changes in levels of irrigation canals. Quaternary deformation in the Columbia Basin has been suggested by many workers (Jones and Deacon, 1966; Bingham and others, 1970; Washington Public Power Supply System, 1977; Bond and others, 1978; Myers and Price, 1979; Rigby and Othberg, 1979), but only Waitt (1979) has documented faults cutting Quaternary units.

The Toppenish Ridge structure is one of eleven east-trending anticlines of the Yakima fold belt (Fig. 1). Like most of the Yakima folds, the Toppenish structure is segmented (Fig. 2) by northwest-trending strike-slip faults (Bentley and Anderson, 1979). The Satus Peak anticline, the middle of three segments of the Toppenish Ridge structure, is east plunging and box shaped, with angular hinges. It is similar in structure and topography to more than 50 other segments in the Yakima fold belt. Its bedrock geometry has been delineated by the mapping of many flows of Miocene Yakima Basalt (Bentley and others,

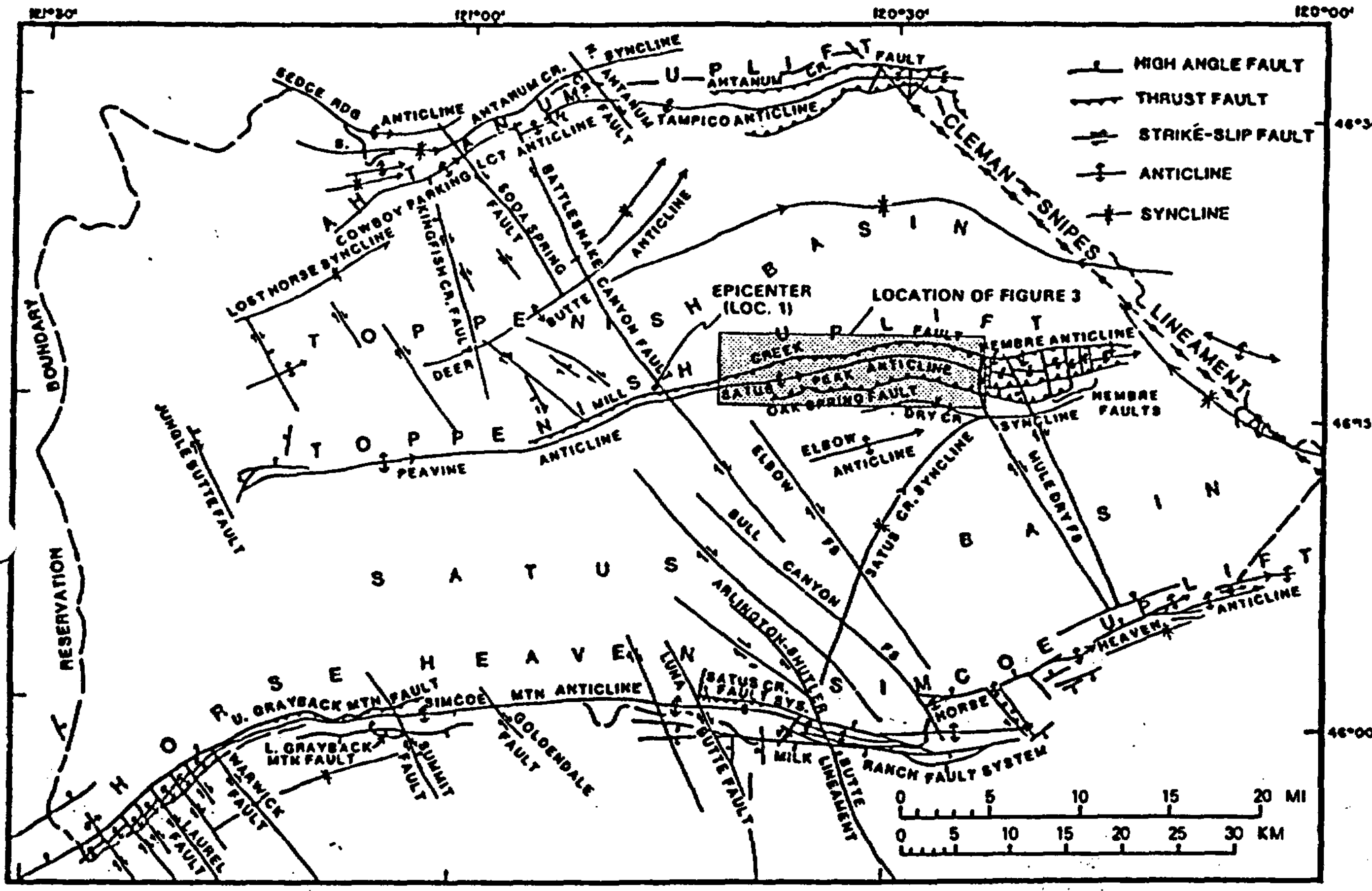

Figure 2. Major tectonic features of Yakima Indian Reservation. Epicenter (loc. 1), marks position of 3.8 intensity seismic event on February 2, 1981. (Modified from Bentley and others, 1980.)

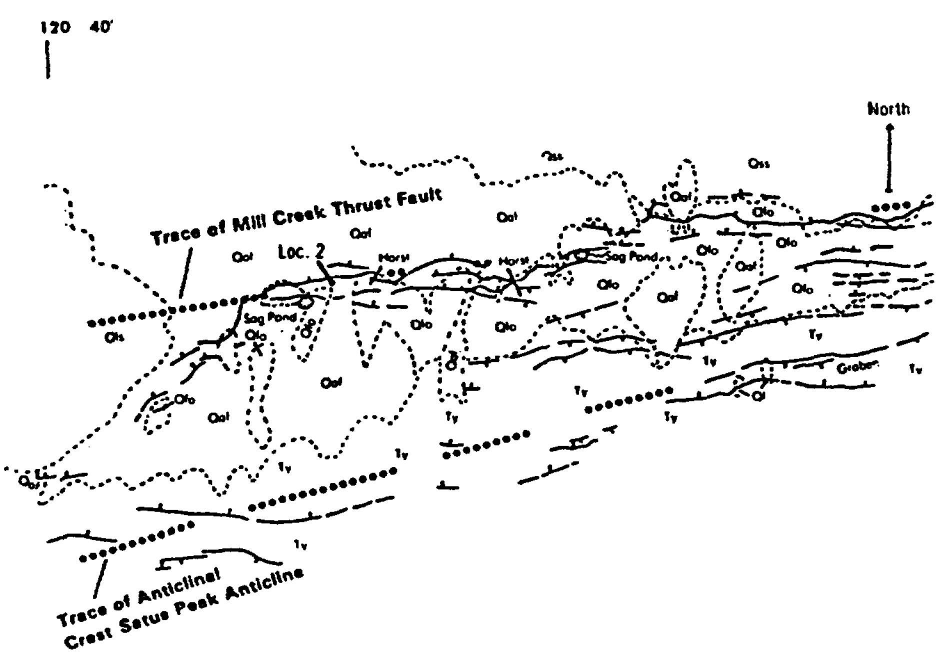

Figure 3. Geologic map of Satus Peak anticline of Toppenish Ridge uplift, showing location of cross section A-A' (Fig. 4). Qaf = alluvial fan and stream gravel; Ql = loess; Qss = Touchet Beds (slack-water sediment related to glacial Lake Missoula flooding); Qls = landslides and debris flows; Qfo = older dissected alluvial fan and pediment gravel; Ty = Miocene Yakima Basalt Subgroup undifferentiated; dashed line shows approximate contact between rock units; bar with ball = surface rupture, with ball on downdropped side; irregular circle with interior tick marks = sag pond.

1980). Thrust faults (Figs. 2, 4) occur along both limbs of the anticline. The fold has 1 to 1.5 km of late Cenozoic horizontal shortening north to south across the fold, as shown in a cross section (see Fig. 4). Virtually all of the bedrock deformation is late Miocene (10 to 7 m.y. B.P.), as indicated by radiometric dating of deformed basalts and overlying sedimentary units in adjacent areas (McKee and others, 1977; Kienle and others, 1978). Although the surface structures described below are important because they deform Quaternary units (Figs. 3, 4), the Satus Peak segment of Toppenish Ridge is distinct from other Yakima folds because it alone contains numerous surface ruptures of late Quaternary age.

GEOLOGIC CHARACTERISTICS OF QUATERNARY STRUCTURES

A zone of late Quaternary ground breakage 0.5 to 2.2 km wide parallels the crest and north limb of the Satus Peak anticline for 32 km (Figs. 2, 3) between long 120°W and 120°45'W. Although field mapping at 1:12,000 shows nearly 100 surface ruptures, numerous smaller unmapped scarps are visible on large-scale (1:12,000) aerial photographs. Individual ruptures are 0.1 to 9 km long; most are less than 1 km long, but at least six exceed 3 km. On average, about seven ruptures occur in profile across the zone. Although dip-slip separations on individual ruptures are no more than 4 m, the net slip across several cross-sectional profiles exceeds 9 m, with the anticline displaced up and to the north. Ruptures with south side down are nearly as numerous as those with south side up (Figs. 3, 4). The net vertical displacement across the zone is estimated between 4 and 9 m, south side up (Figs. 3, 4). Exposed Quaternary fault zones are less than 2 cm wide, and at least one fault can be traced from Quaternary units directly into bedrock. No striae have been observed in any Quaternary fault zone. The surface slopes in the vicinity of the ruptures are variable from gentle (less than 10°) to steep (about 35°), and no relationship of number, length, or amount of displacement exists between slope and surface ruptures.

The 100 surface ruptures form three linear sets according to location relative to the older Satus Peak anticline (Figs. 3, 4). One set is located along the broad crestal area of the anticline, a second set along the north hinge area on the steeply dipping north limb of the anticline, and the third on the distal part of alluvial fans near the projection of the Mill Creek thrust fault (Bentley and others, 1980).

The crestal set of surface ruptures cuts both the Pomona Member of the Yakima Basalt Subgroup and Quaternary loess. These ruptures form dextral en echelon ridge-top grabens (Fig. 3). All ruptures in the crest set dip steeply and form straight map patterns even when crossing stream gullies (Fig. 5, A). Therefore, these scarps are the expression of near-vertical, dip-slip displacements. No open fractures were observed. The scarps lie mainly on the north slope of the ridge but transect the ridge top and cross over diagonally to the south slope near their eastern end. Vertical displacement across the graben varies from 1 to 3 m. Several older (Miocene?) large-displacement ridge-top faults occur along the crest of the anticline just south of the ruptures (Bentley and others, 1980). Disrupted drainage is common where south-side-down ruptures cross north-draining gullies. Several sag ponds containing as much as 1.5 m of silt occur along the interrupted drainages (loc. 1 in Fig. 3; Fig. 5, A). Plant material recovered from the lower part of the fill of one sag pond yielded ^{14}C ages of 505 ± 160 yr and 620 ± 135 yr (Geochron, GX-6588 and GX-6589, 1979).

The hinge set of surface ruptures cuts the Pomona Member and older units of the Yakima Basalt Subgroup (Figs. 3, 4),

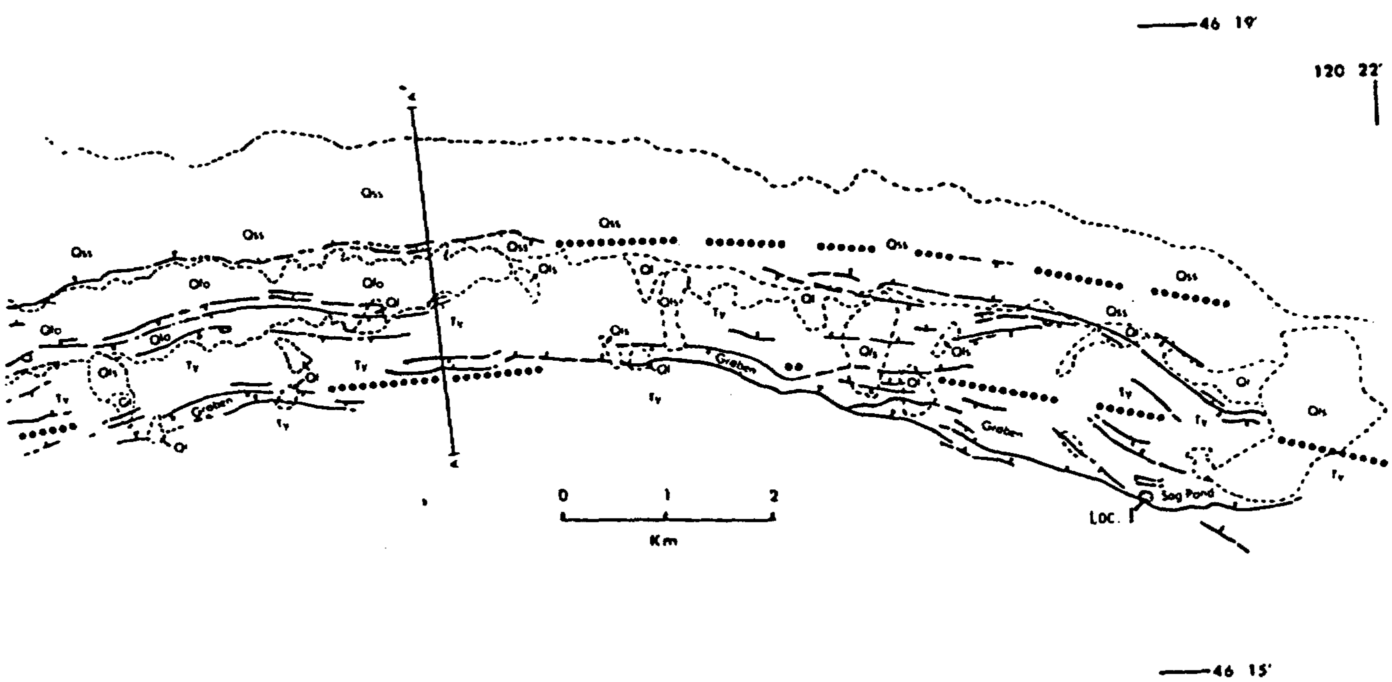

Figure 3. (Continued)

early(?) Quaternary fan gravel, late Quaternary alluvium, and landslide deposits (Fig. 5, C and D). Ruptures in this set have vertical displacements as great as 2 m, generally with south side down. No curvilinear-planar surfaces were observed. Nearly all of these ruptures have straight-line map traces across gullies, consistent with dips greater than 85°. (One exposed rupture dips 81°S.) Drainage is disrupted along several of these surface breaks, and younger landslides may have been localized by the ruptures. This set of ruptures follows approximately the north upper hinge line and steeply dipping limb of the Satus Peak anticline (Fig. 4).

The fan set of ruptures cuts older, partially dissected alluvial gravel (early Quaternary?), glaciofluvial slack-water sediment from glacial Lake Missoula flooding (Waitt, 1980), and late Quaternary alluvium. These ruptures form a broad minor horst parallel to the main anticline for at least 5 km (Fig. 3). This set has a sinuous trace along much of its course consistent with a planar surface dipping less than 20° to the south. It has an apparent average net slip of 4 to 5 m (Fig. 5, B, C, D). This rupture set appears to follow the trace of an older (Mill Creek) thrust fault. One exposure of the Mill Creek fault breccia is within 10 m of the northernmost surface rupture (loc. 2 in Fig. 3). The fan set of ruptures is younger than 13,000 yr, the approximate ^{14}C age of the Mount St. Helens "set S" tephra that is found within nearby slack-water sediments (Mullineaux and others, 1977; Waitt, 1980). The breakage in this fan set is likely to be much younger than 13,000 yr, because ruptures in this set also displace alluvium deposited by streams cutting the glaciofluvial deposits.

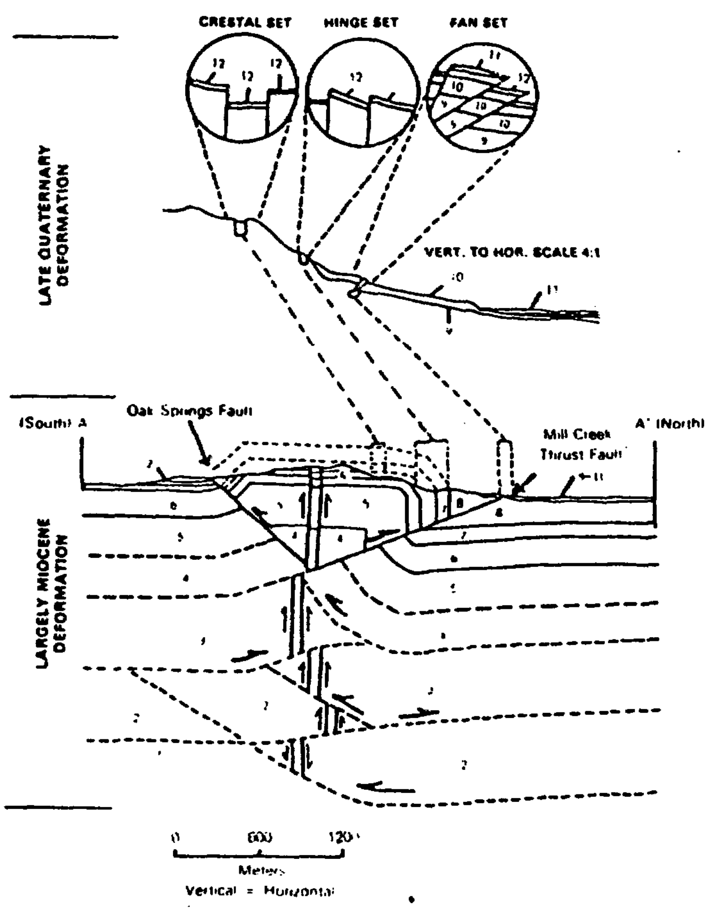

Figure 4. Cross section showing relationship of Miocene bedrock geology to Quaternary units. 1 = Pre-Columbia River basalt rocks (?); 2 = R_1 Grande Ronde Basalt (?); 3 = N_1 Grande Ronde Basalt (?); 4 = R_2 Grande Ronde Basalt (?); 5 = N_2 Grande Ronde Basalt; 6 = Wanapum Basalt; 7 = Saddle Mountains Basalt; 8 = Ellensburg Formation; 9 = Pliocene(?)-Pleistocene gravels; 10 = late Quaternary glaciofluvial slack-water sediments (Touchet Beds); 11 = Holocene alluvium; 12 = Holocene loess. Hinge, crestal, and fan sets of surface ruptures shown diagrammatically in circles at four times scale. See Figure 3 for location of cross section.

INTERPRETATION

On the basis of their geometry and close spatial alignment with the older Satus Peak structure, the surface ruptures are interpreted as faults formed in response to regional compressional stress. The three sets of ruptures are probably related to uplift, folding, and thrusting of the Satus Peak segment of the Toppenish Ridge structure as it moved northward relative to the Toppenish basin. This segment moved northward along northwest-striking fracture systems (Fig. 2, Mule Dry and Elbow fractures). During this period of deformation, extension along the crestal and hinge areas of the anticline formed the crestal and hinge rupture sets. Simultaneously, compression occurring in the lower thrust area caused bulging of the horst and thrust faulting of the fan set. The crestal area was in a dextral extension couple and responded with left-stepping en echelon grabens. The hinge set formed as extension occurred in the main hinge of the fold, probably because of the increased bending moment. This hinge set of surface ruptures dips steeply south and is offset consistently down to the south, indicating their origin as stress release along fractures paralleling the axial surface of the older fold. Localization of the fan-set thrust faults at the line of the older Mill Creek thrust fault suggests that the older fault zone acted as a slip plane for the Quaternary deformation. The general geometry of the deformation is consistent with decollement of the low-angle south-dipping fault plane bounded by tear faults (Fig. 2), similar to other Miocene Yakima folds (Bentley, 1977; Reidel, 1978; Waitt, 1978; Swanson and others, 1979b; Bentley and Anderson, 1979), suggesting that this Quaternary deformation is only the latest episode in a continuing history of regional compression.

Further evidence that Quaternary deformation may be continuing along the Toppenish Ridge structure is documented by the occurrence of a seismic event on February 2, 1981. This shallow event (depth, 0.1 km; magnitude 3.8) occurred along the north limb of the fold about 8 km west of the zone of surface ruptures. This is at the approximate junction of the Mill Creek thrust fault and northwest-trending fracture system (loc. 1 in Fig. 2). Linda Nosom (April 1981, written commun.) has interpreted the seismic event to be from right-lateral strike-slip movement along a N47°W (dip 90°) or N43°E (dip 70°NW) fault plane. This is consistent with the tectonic origin postulated in this paper.

Alternative, nontectonic, explanations for the origin of the ruptures must be considered in view of the nearness to the Hanford reactor and nuclear-waste storage site (Fig. 1). Nontectonic hypotheses are all related to gravitational movement caused by "unusual" effects. Those considered are ground-water withdrawal, ridge spreading, and landslide slope failure.

Ground-water withdrawal is quite limited compared to other parts of the Columbia basin and will not account for ground breakage to the extent seen on Toppenish Ridge.

Another alternative explanation for the origin of the ruptures is that they formed by ridge-top spreading (Radbruch-Hall and others, 1977; Beck, 1968). The Toppenish ruptures are not considered to have formed by this gravitational process because they have very few characteristics in common with recognized spreading ridges. Table 1 compares common characteristics of ridge-top spreading with those of Toppenish Ridge.

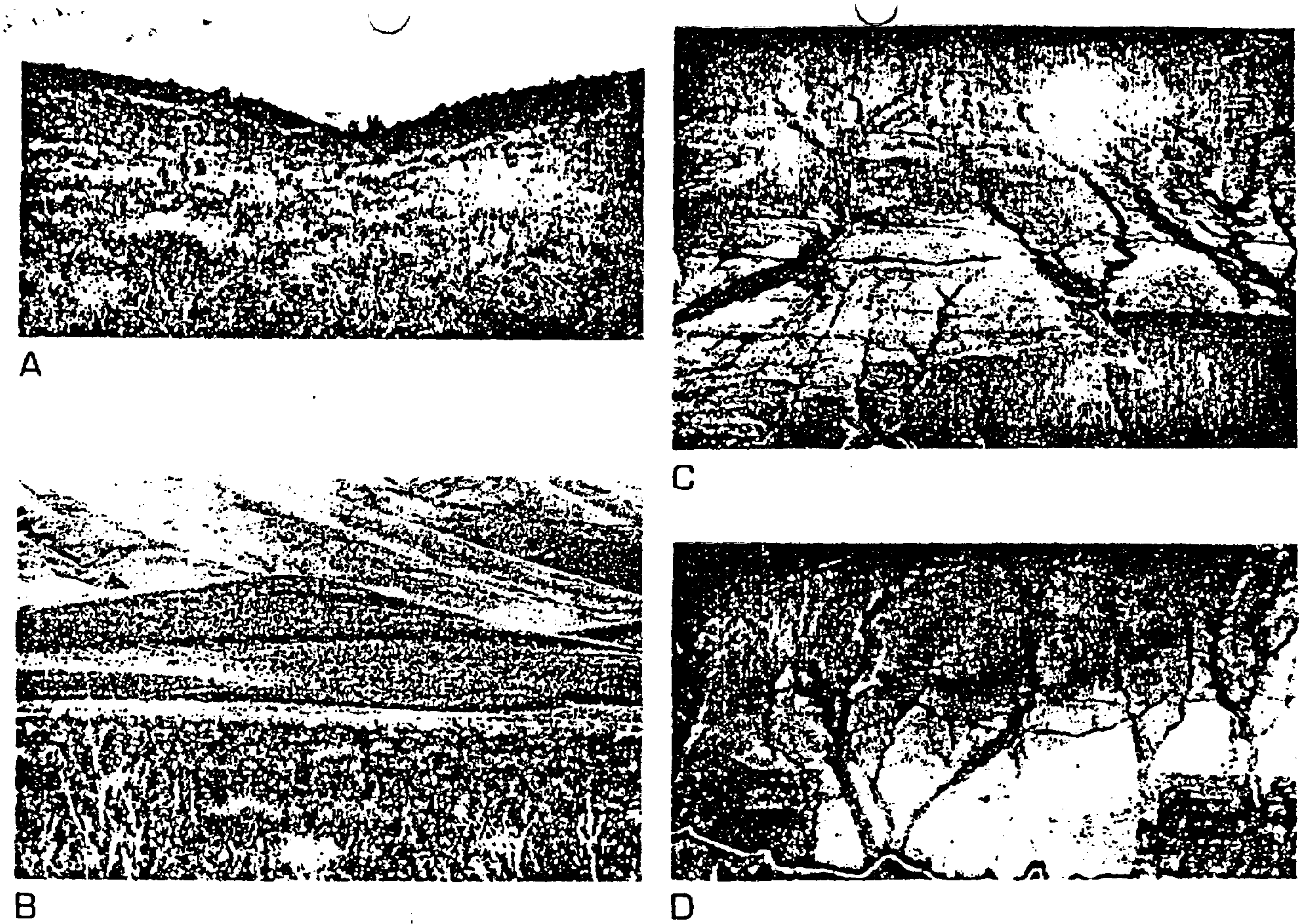

Figure 5. Surface features on Toppenish Ridge uplift. A: Sag pond formed by crestal surface rupture; B: fan set of surface ruptures showing 2 m offset; C: aerial view of fan set of surface ruptures displacing Touchet Beds and late Quaternary alluvium (photo courtesy of John Lillie, Rockwell Corp., Richland, Washington); D: aerial photo of fan and hinge sets of surface ruptures.

TABLE 1. COMPARISON OF RIDGE-TOP SPREADING AND TOPPENISH RIDGE CHARACTERISTICS

Features common to ridge-top spreading	Features on Toppenish Ridge
1. In glaciated terrains	No glaciation
2. Locally oversteepened high, and relief greater than 1,000 m	Relief less than 500 m
3. Short, arcuate, and discontinuous scarps, usually less than 1 km long	Planar, continuous scarps as long as 9 km
4. Scarps invariably facing ridges with dips less than 70°	Scarps face both toward and away from ridges with dips usually exceeding 80°
5. Offsets to 10 m common	Offsets less than 4 m
6. Active talus slopes and commonly on barren terrain	Few talus slopes and normal vegetation cover
7. Slip planes often correspond to bedding, joints, or penetrative structures	Slip planes cut across lithologies but probably follow pre-existing faults
8. Central graben invariably present	Graben discontinuous and en echelon
9. Bulging and shattered rocks common on sides of ridges	No bulging sides or shattered rocks
10. Arcuate trenches on sides of ridges	No arcuate trenches present
11. Often on ridges where rigid rocks overlie ductile units	Basalt only rock type that underlies sediments
12. No net slip across ridge	Net slip exceeds 9 m
13. Scarps parallel to both sides of ridge and in greatest abundance in topographically highest areas	Scarps confined to north side and not on highest part of ridge

A third alternative for the ruptures is that they formed as a result of landslides. Landslides of at least three ages do occur on Toppenish Ridge at random places along the north flank. They form arcuate and discontinuous lobes that are never more than 2 km wide. The landslides, typical of those found on other ridges of the Yakima fold belt, contrast sharply with the long planar scarps on Toppenish Ridge. The planar scarps cut across the landslides in at least two places but usually terminate near the landslide boundary. Many of the comparisons made in Table 1 between ridge-top spreading and the surface ruptures on Toppenish Ridge can be applied to landslides as well.

Although a tectonic origin cannot be conclusively proven without the excavation of some of the scarps (restricted by the Yakima Nation), a tectonic origin is favored primarily because of the unique geometric location of the surface ruptures relative to older Miocene structures. If they are not of tectonic origin, then why do they occur only on the north side of a minor segment of an average Yakima fold? There are more than 50 other anticlinal segments with like stratigraphy, identical topography, and similar structural setting in the Yakima fold belt that do not have surface scarps. The Toppenish scarps have a unique position between two interpreted strike-slip faults, one with historic strike-slip movement.

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