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Roza Diversion Dam

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PROJECT DESCRIPTION

Roza Dam (Figure 1) is located on the Yakima River approximately 12 mi north of Yakima. The primary purpose of the dam is to divert water to the Roza Canal, which has a capacity of 1,350 cfs, and supplies irrigation water to about 70,000 acres of land north, east, and south of the city of Yakima. The canal also supplies water to the Roza power plant located about 10 mi downstream from the dam.

The dam was built by the U.S. Bureau of Reclamation (USBR) in 1939 (USBR, 1981, 1983). The dam is a concrete gravity ogee-weir-type structure and has a movable crest. It has a structural height of 67 ft and a length of 486 ft. The movable crest consists of two 110-ft x 14-ft roller gates. The canal headworks are located in the right abutment area; the left abutment contains the main fish ladder facility (Figure 2).

In 1985-1986, the USBR replaced the fish passage facilities on the right abutment with a multiple bank of angled, rotating drum screens in the right forebay area of the dam (Figure 2), where there was room to accommodate it. The fish screen structure, the largest fish passage structure on the Yakima River, contains 27 drum screens, each 17 ft in diameter and 12 ft long. Five 30-in.-diameter pipes with capacities of 50 cfs are provided to return the fish that encounter the screens to the river. Associated with the fish screens are the fish bypass structure, the fish return pipe, the fish counting facility, and the canal pumpback scheme (USBR, 1985a). An additional low-level fish ladder was built on the left abutment in 1987.

SITE GEOLOGY

General

Roza Diversion Dam is within the Yakima Fold Belt of the Columbia Plateau province in the central part of Washington. The bedrock is part of the thick pile of lava flows of the Yakima Basalt Subgroup of the Miocene Columbia River Basalt Group. The Yakima Basalt is further divided into the Lower Miocene Grande Ronde Basalt and Middle Miocene Wanapum Basalt (Figure 3).

The Yakima River flows south through the Yakima Fold Belt in a deep, steep-sided canyon. The river is a good example of an antecedent stream; the canyon alignment reflects a strong relict, meandering pattern across the Yakima fold system. Relatively short, steep drainageways enter the master stream from the east and west. Alluvium of various compositions and thicknesses is present in the drainageways and occurs as terraces in some places along the Yakima River. Slopewash from a few to many tens of feet thick is present in many places along the master stream and in lesser quantities along the side drainageways. Landslides, mostly in the overburden materials, are also present in places in the Yakima River canyon (Campbell, 1975; Swanson et al; 1979).

Bedrock

In the area of the dam, the Yakima Fold Belt is expressed as the Selah Butte anticline, a northwest-trending, doubly-plunging, symmetrical anticline about 10 mi long (Figure 3). Exposed in the anticline and forming the foundation of the dam is an unnamed basalt flow (flow no. 5) of the Grande Ronde Basalt (Campbell, 1975). The basalt crops out on the left abutment as a near-vertical bluff of hard, columnar basalt. The basalt in the right abutment area is covered by a large deposit of mixed alluvium and colluvium.

The dam is founded on hard, dense, jointed basalt. The dam site was explored with 11 drill holes prior to construction. Very little is known about the engineering characteristics of the basalt from these old drill holes or from the brief remarks of the construction report (USBR, 1983). One drill hole bored in 1985 for investigation of the juvenile fish counting facility in the right abutment area encountered basalt bedrock at a depth of 36.3 ft. This basalt is lightly weathered, moderately to intensely jointed, dark gray, nonvesicular, and mostly hard (USBR, 1985b).

GEOLOGIC ASPECTS OF SITING AND DESIGN

The dam site is located in a relatively narrow part of the Yakima River canyon where a prominent outcrop of basalt is present on the left riverbank. This siting was also topographically favorable for the elevation of the canal headworks to serve, by gravity, the intended ir-

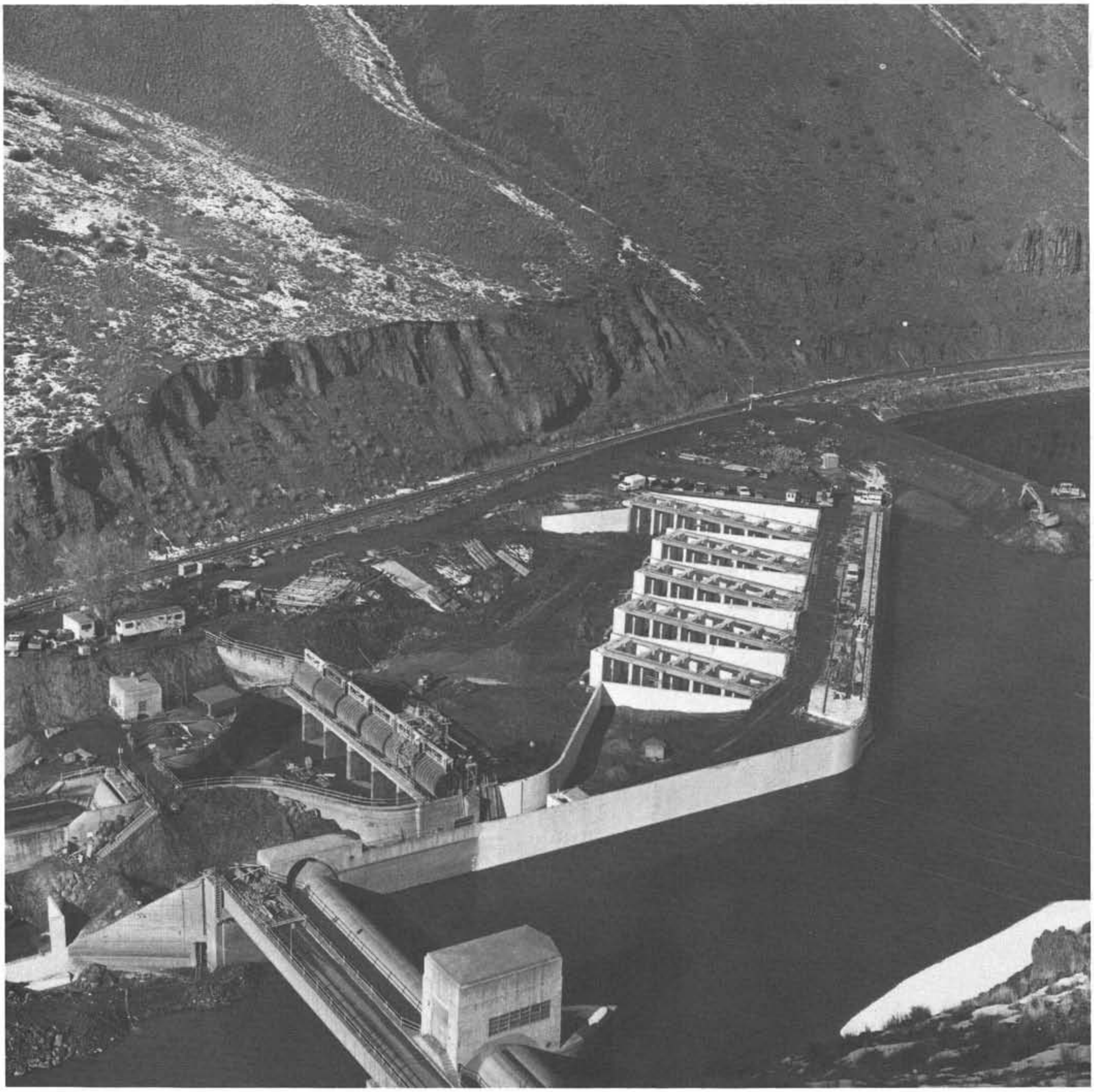


Figure 1. View upstream and into the right abutment area during construction of the new fish passage facilities in 1987. Roza Dam is in the lower left part of the photo; the new multiple-drum screen structure is in the center of the photo. Roza Dam is founded on basalt, and the fish passage facilities on the right abutment area are founded on alluvial-colluvial materials. U.S. Bureau of Reclamation photograph, February 5, 1987.

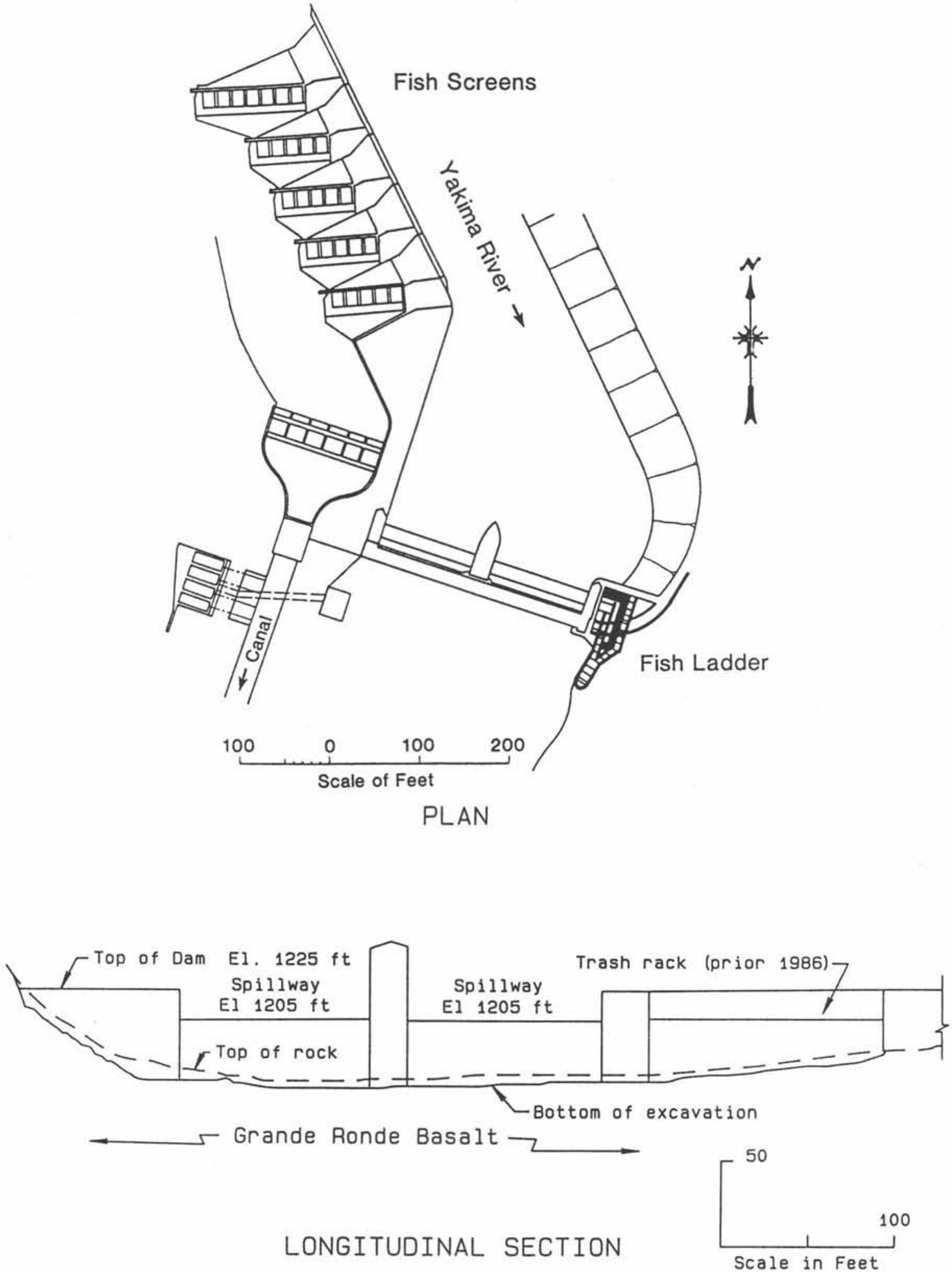


Figure 2. Plan and longitudinal section of Roza Dam. Plan view adapted from U. S. Bureau of Reclamation (1981).

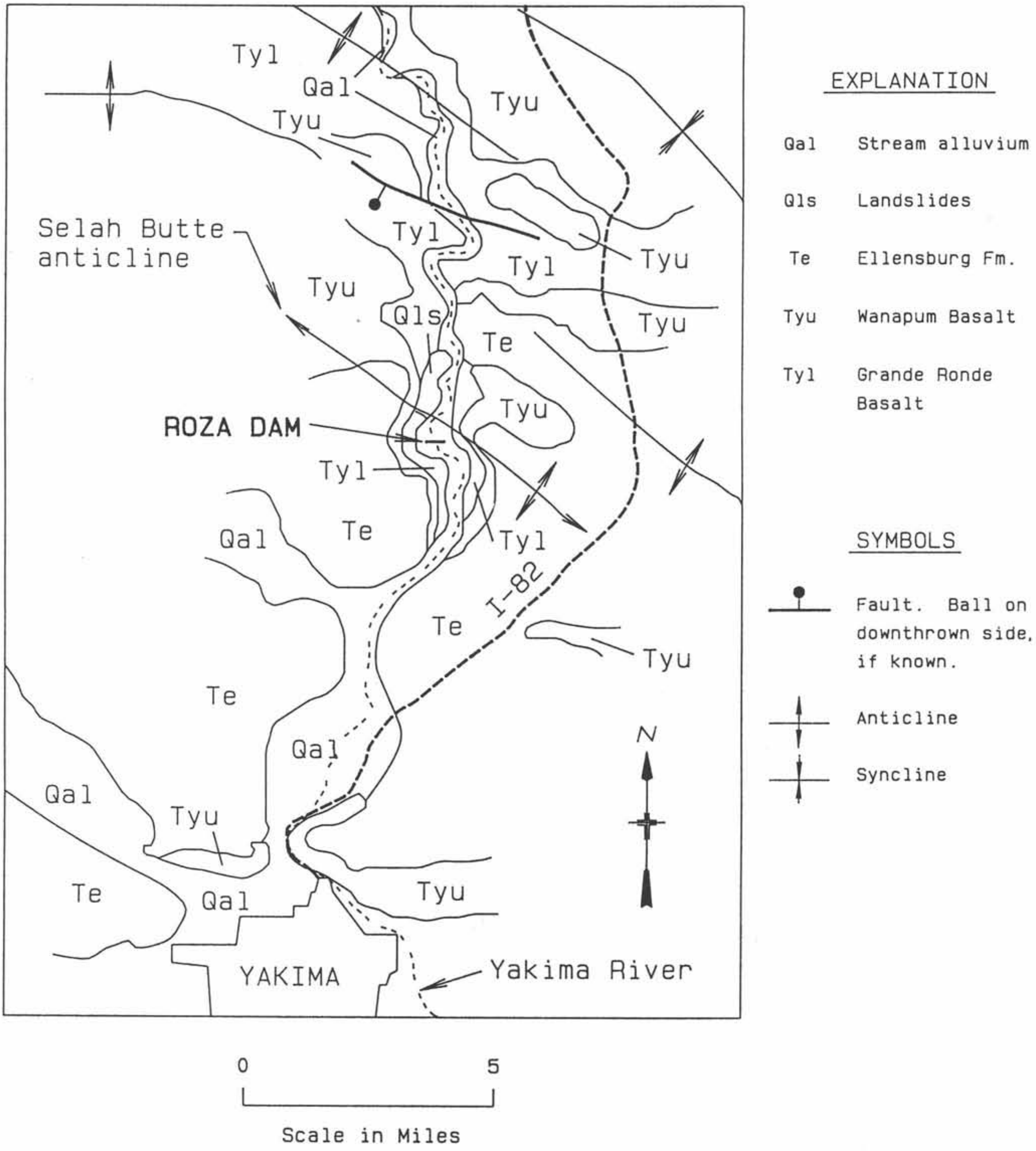


Figure 3. Generalized geologic map of the Roza Dam area. Adapted from Campbell (1975).

rigated land. The exploratory drilling showed favorable rock foundation conditions for a concrete gravity dam.

The old and new fish screen facilities on the right abutment were founded on compact alluvial materials. The new fish screen structure was sited in the forebay area of the right abutment near the canal headworks (Figure 3).

CONSTRUCTION PROBLEMS

Preparation of the dam foundation included removal of alluvial deposits to depths of about 25 ft in the canyon bottom and right abutment area. The lowermost 2 ft of excavation in rock was done using a chipping gun. The foundation was cleaned with water under high pressure prior to placement of concrete. Small gravel-filled drains covered with waterproof paper were placed to control water from several springs in the foundation area. After placing concrete, the drains were grouted shut.

Most of the pressure grouting was done at the heel of the dam. Grouting was done on 5-ft centers in holes 15 ft deep. A total of 2,161 sacks of cement was used in the grouting. Concrete was placed in 5-ft lifts, and vibrators were used to create uniform placement. The water-cement ratio was 0.54-0.58. The concrete had a placement slump of 2 to 4.5 in. and an average unit weight of 154.00 pcf. The average compressive strengths tested at 7 and 28 days were approximately 3,000 and 5,200 psi, respectively (USBR, 1983).

During construction of the recently completed fish screen structure, a large cofferdam was required in the right forebay area. Reservoir leakage into the excavation required considerable grouting in the alluvial materials in the foundation to retard seepage.

OPERATIONAL PROBLEMS

There have been no displacements or major cracking of the concrete structure, nor are there any notable seepage problems at the dam. There has been no undercutting of the basalt formation at the toe of the dam due to spilling flows.

The reservoir area has had a high silt load contributed by the river. Water is discharged through the left roller gate of the dam most of the time to maintain a channel (USBR, 1983). Explorations for the new fish screen site showed this extensive reservoir silt fill to have a maximum thickness of about 10 ft. Part of this large silt deposit was removed from the reservoir prior to construction of the new fish screen structure (USBR, 1985b).

REFERENCES

Campbell, N. P., 1975, *A Geologic Road Log over Chinook, White Pass, and Ellensburg to Yakima Highways*: Washington Division of Geology and Earth Resources Information Circular 54, Olympia, WA, 82 p.

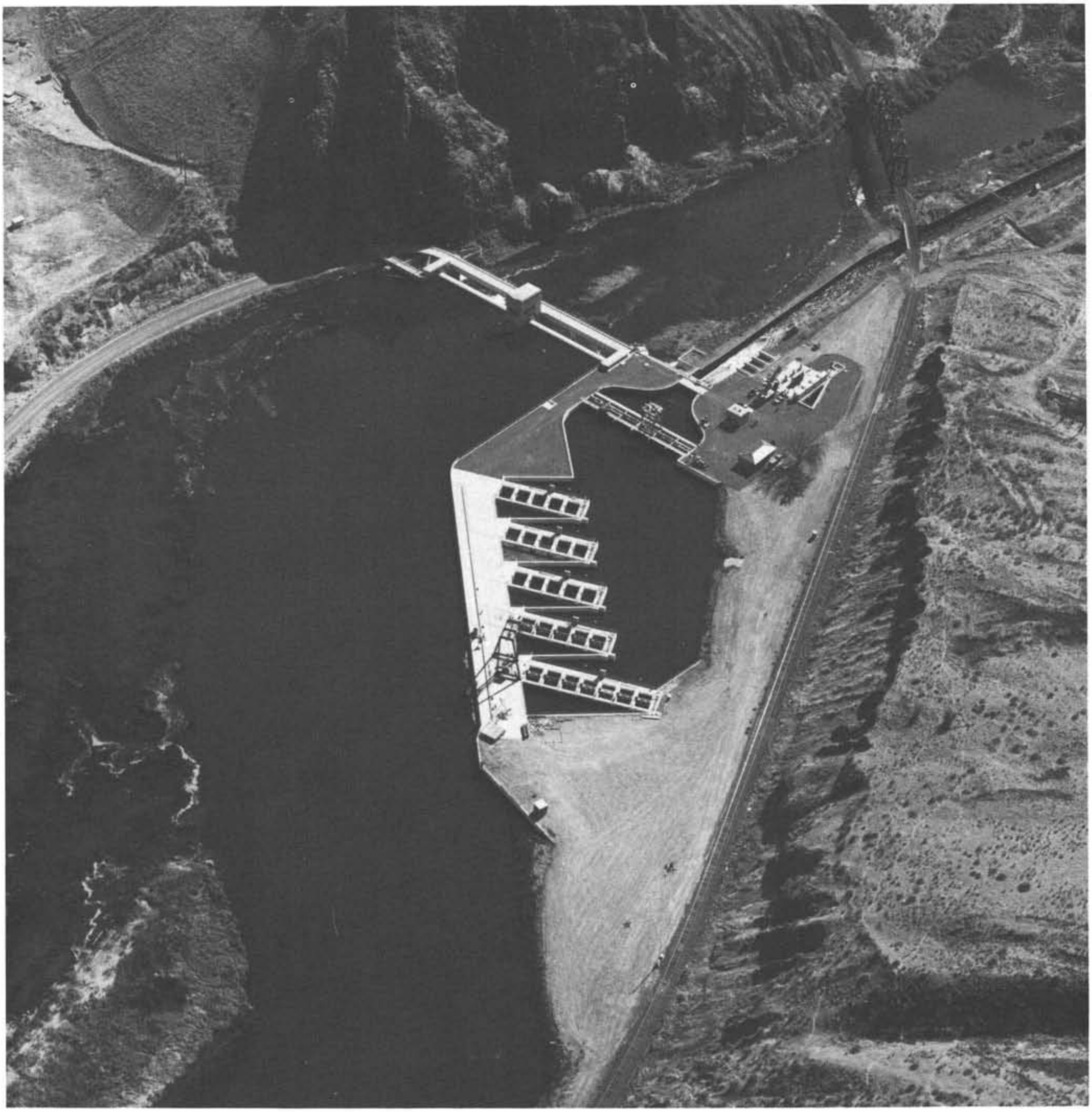
Swanson, D. A.; Bentley, R. D.; Byerly, G. R.; Gardner, J. N.; and Wright, T. L., 1979, *Preliminary Reconnaissance Geologic Maps of the Columbia River Basalt Group in Parts of Eastern Washington*: U.S. Geological Survey Open-File Report 79-534, Sheet 6 of 9, scale 1:250,000.

U.S. Bureau of Reclamation (Water and Power Resources Service), 1981, *Project Data*: U.S. Government Printing Office, pp. 1337-1356.

U.S. Bureau of Reclamation, 1983, *Examination Report of Roza Diversion Dam for Safety Evaluation of Existing Dams Program, Yakima Project, Washington*: U.S. Bureau of Reclamation, E&R Center, Denver, CO, 15 p., photos and drawings.

U.S. Bureau of Reclamation, 1985a, *Roza Diversion Dam, Fishscreen, Pumpback, and Fish Ladders, Specification No. 6-SI10-03480*: U.S. Bureau of Reclamation, Boise, ID, 120 p.

U.S. Bureau of Reclamation, 1985b, *Geologic Report for Design Data Collection, Roza Diversion Dam, Yakima Fish Passage Facilities, Yakima Project, Washington*: U.S. Bureau of Reclamation, Boise, ID, 19 p., illustrations.



Aerial view downstream of the Roza Diversion Dam and fish passage facilities on September 30, 1987. The dam is at the left and the nearly completed fish screens are on the right side of the Yakima River. U.S. Bureau of Reclamation photograph.

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Tieton Dam

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PROJECT DESCRIPTION

Tieton Dam, completed in 1925, is located on the Tieton River about 40 mi northwest of Yakima. The dam is an earthfill structure (Figures 1 and 2) with a structural height of 319 ft, a hydraulic height of 198 ft, and a crest length of 920 ft. Crest elevation at top of the concrete parapet wall is about 2,935 ft. The top width of Tieton Dam is 40 ft, and the maximum base width is 1,100 ft (U.S. Bureau of Reclamation [USBR], 1981). A concrete core wall diaphragm with a maximum thickness of 5 ft near its base and 1.5 ft near the top extends from the crest to about 100 ft below the river bed (USBR, 1925). Three berms are present on the downstream face of the dam, which has a nominal slope of 2H to 1V. The upstream face, which is also bermed, slopes at 3H to 1V (USBR, 1981).

Rimrock Lake, the reservoir behind Tieton Dam, has a capacity of 213,600 acre-ft at elevation 2,928 ft (USBR, 1981). Although primarily intended for irrigation storage, the reservoir is also operated for flood control insofar as irrigation water supplies are not jeopardized. The reservoir is controlled by a spillway and an outlet works tunnel, both located in the left abutment (Figure 2). The spillway is a trapezoidal, concrete-lined chute with a concrete side-channel weir. The spillway weir is controlled by six 65-ft x 6-ft floating drum gates (USBR, 1981). Capacity of the spillway at elevation 2,928 ft is 45,700 cfs. The outlet works consists of a concrete intake tower connected to a partially lined tunnel; flows are controlled by two 60-in. and one 24-in. needle valves (USBR, 1981). An auxiliary intake structure is located below spillway gate number 5. Capacity of the outlet works at elevation 2,926 ft is 2,750 cfs (USBR, 1981).

SITE GEOLOGY

Pre-Tertiary sedimentary and metamorphic rocks and Paleogene intrusive and extrusive rocks are the oldest exposed rocks in the vicinity of the dam (Swanson, 1978; Miller, 1985) (Figure 3). Flows of Miocene Grande Ronde Basalt of the Columbia River Basalt Group lap onto the older rocks north and south of the dam, but are not present at the project site (Swanson, 1978). Tieton volcano, a large andesitic cone within the Miocene Fifes Peak Formation, is exposed in the river canyon about 6 mi downstream of the dam (Swanson, 1966).

The reservoir and part of the dam site are underlain by the pre-Tertiary Russell Ranch Formation, predominantly argillite, feldspathic graywacke and greenstone (Swanson, 1978; Miller, 1985). At the dam site, the Russell Ranch Formation is intruded by the Westfall Rocks and Goose Egg Mountain plutons, which are shallow andesite intrusive bodies (Swanson, 1978). These plutons are separate bodies at their present level of exposure, but they may form a single intrusive body at relatively shallow depth. The andesite and "microdiorite" of both plutons are light gray to purple, dense, and slightly jointed.

Bouldery glacial drift, representing at least two episodes of Pleistocene alpine glaciation, partially fills the Tieton River channel at the dam to depths of about 90 ft (USBR, 1982a) and mantles the slopes around the dam up to about elevation 4,000 ft (Swanson, 1978). Moraines are preserved 3 to 4 mi downstream from Tieton Dam and also about 1 mi downstream of the dam, but the relative ages of these desposits have not been determined.

Several east-west-trending gentle folds are present in the Grande Ronde Basalt a few miles northeast of Tieton Dam, and minor, northwest-trending normal faults are present in the Burnt Mountain area, about 5 mi north of the dam (Swanson, 1978). Several northwest-trending faults cross Rimrock Lake separating segments of the Russell Ranch Formation. The age of these faults is pre-middle Eocene (Miller, 1985).

GEOLOGIC ASPECTS OF SITING AND DESIGN

Tieton Dam is situated in a relatively narrow canyon between Westfall Rocks on the west and Goose Egg Mountain on the east. Available records of exploration and design for Tieton Dam are limited. A site upstream of the present dam site was abandoned when flooding during the winter of 1917-1918 revealed foundation conditions which suggested that a safe and watertight dam would be difficult to construct at that site (USBR, 1983). Investigations were begun at the present site in

Figure 1. Aerial view to the west (upstream) of Tieton Dam. Note spillway on left abutment and stilling basin east of outlet works. State Highway 12 crosses the left abutment through a tunnel. The Westfall Rocks pluton ("microdiorite") forms the right abutment, and the Goose Egg Mountain pluton ("microdiorite"), which is overlain by glacial deposits, forms the left abutment. Glacial deposits are also present above the stilling basin. U.S. Bureau of Reclamation photograph, July 10, 1979.

the spring of 1918, and six combination test pit/drill holes were excavated along the proposed axis (USBR, 1983). Shafts were excavated through the glacial deposits to bedrock, where explorations were continued using core drills. Four additional drill holes were drilled in 1981: two through the maximum section of the embankment downstream from the core wall, and two in the channel near the downstream toe of the dam (USBR 1982a, b). In 1986, two drill holes were drilled above the spillway on State Highway 12 to explore the road foundation (USBR, 1986).

Available records of subsurface explorations and construction show that the channel and right abutment foundations of Tieton Dam consist of 40 to 90 ft of bouldery glacial drift, probably till or reworked till, which is underlain by andesite of the Goose Egg Mountain pluton (USBR, 1925, 1982a) (Figure 4). The till in the channel section is underlain by about 60 ft of shale (USBR, 1925) believed to be part of the Russell Ranch Formation (Figure 4). The left abutment foundation consists of andesite and "microdiorite" of the Westfall Rocks pluton.

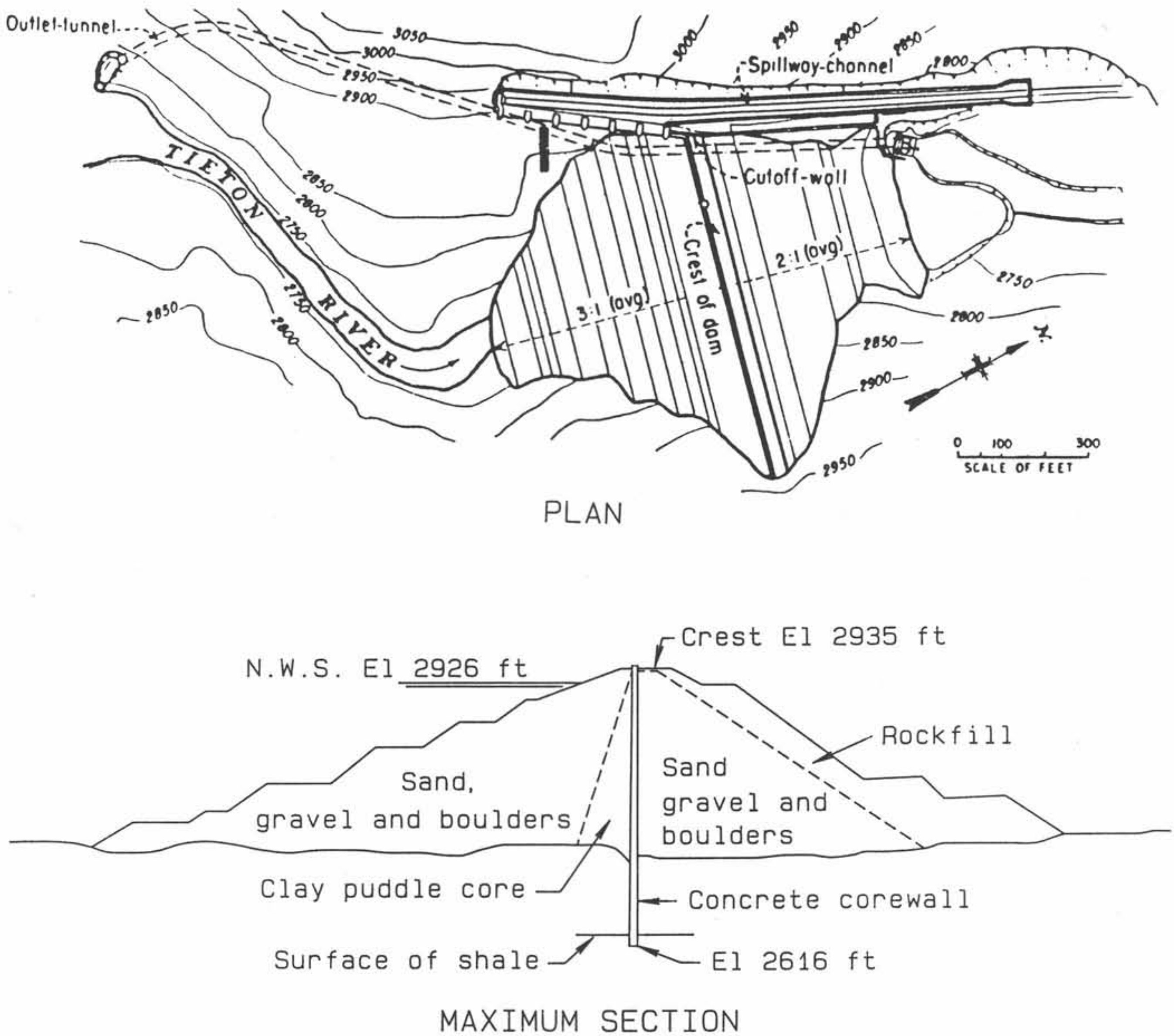

Figure 2. Plan and cross section of Tieton Dam. Adapted from U.S. Bureau of Reclamation (1981).

Tieton Dam was constructed by emplacing glacially derived materials by hydraulic sluicing up against both sides of the concrete diaphragm core wall (Figure 2). Although these methods are no longer used in dam construction, Tieton Dam has performed reasonably well since 1925. Hydraulic sluicing graded the embankment materials from coarser fractions near the outer edges of the embankment to finer fractions near the core wall. The clay-size fraction was retained on the upstream side of the core wall to form a puddled core, but was drained off from the downstream side prior to settlement to insure semipervious material at that location (USBR, 1983).

Limited sampling during the 1981 drilling indicates that the materials forming the embankment immediately downstream of the core wall are relatively coarse, consisting of silty sand with gravel and cobbles (USBR, 1982a). Standard penetration resistance tests in this material averaged about 35 blows per foot (USBR, 1982a). Because of the construction method, it is likely that somewhat finer materials are present in the puddled clay core adjacent to the upstream side of the core wall. The 1981 explorations indicate that the till forming the foundation of Tieton Dam is composed of unconsolidated, mostly subrounded igneous cobbles, gravel, sand, and fines, with some boulders (USBR, 1982a).

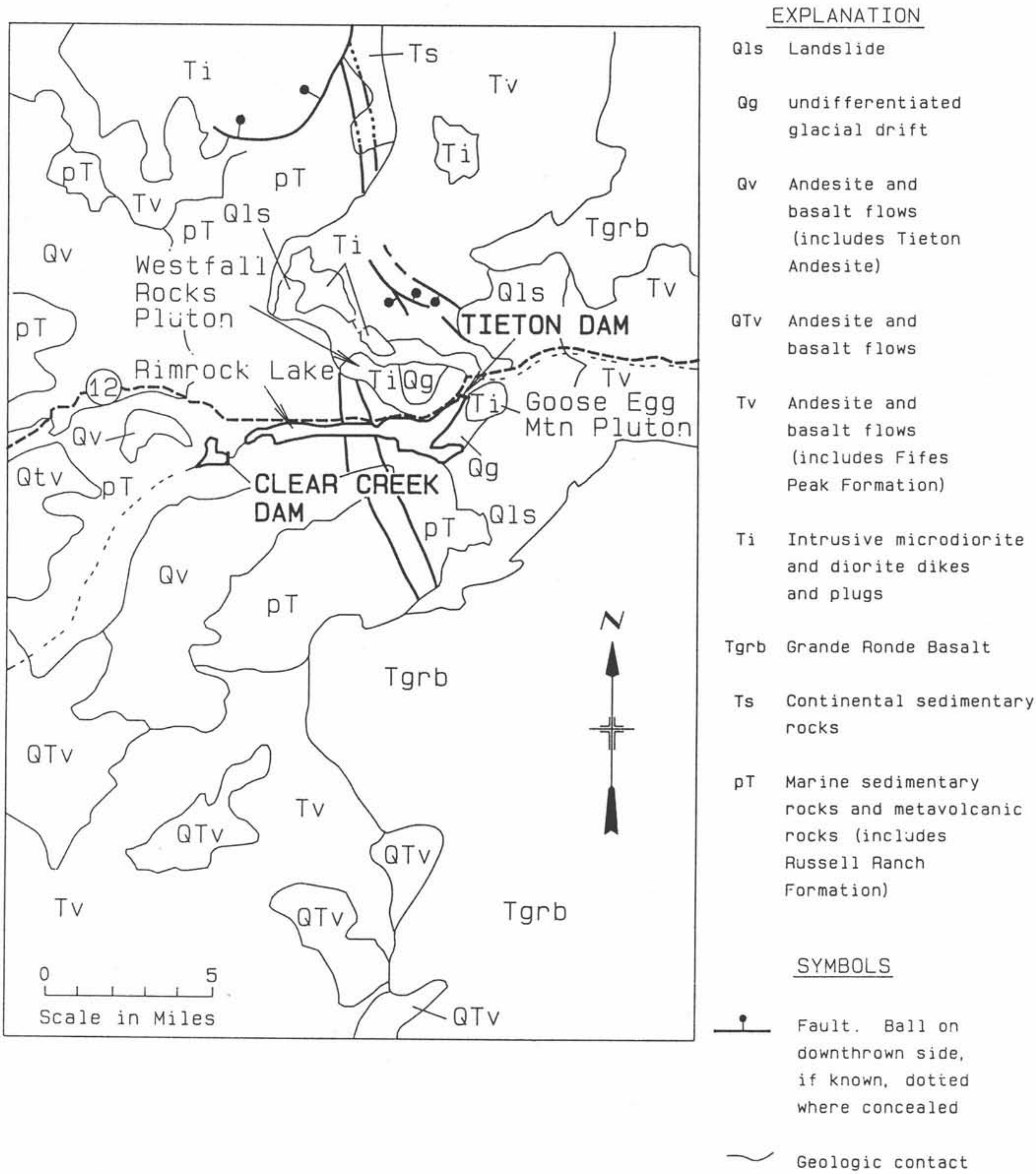

Figure 3. Generalized geologic map of the Tieton Dam area. Adapted from Walsh et al. (1987).

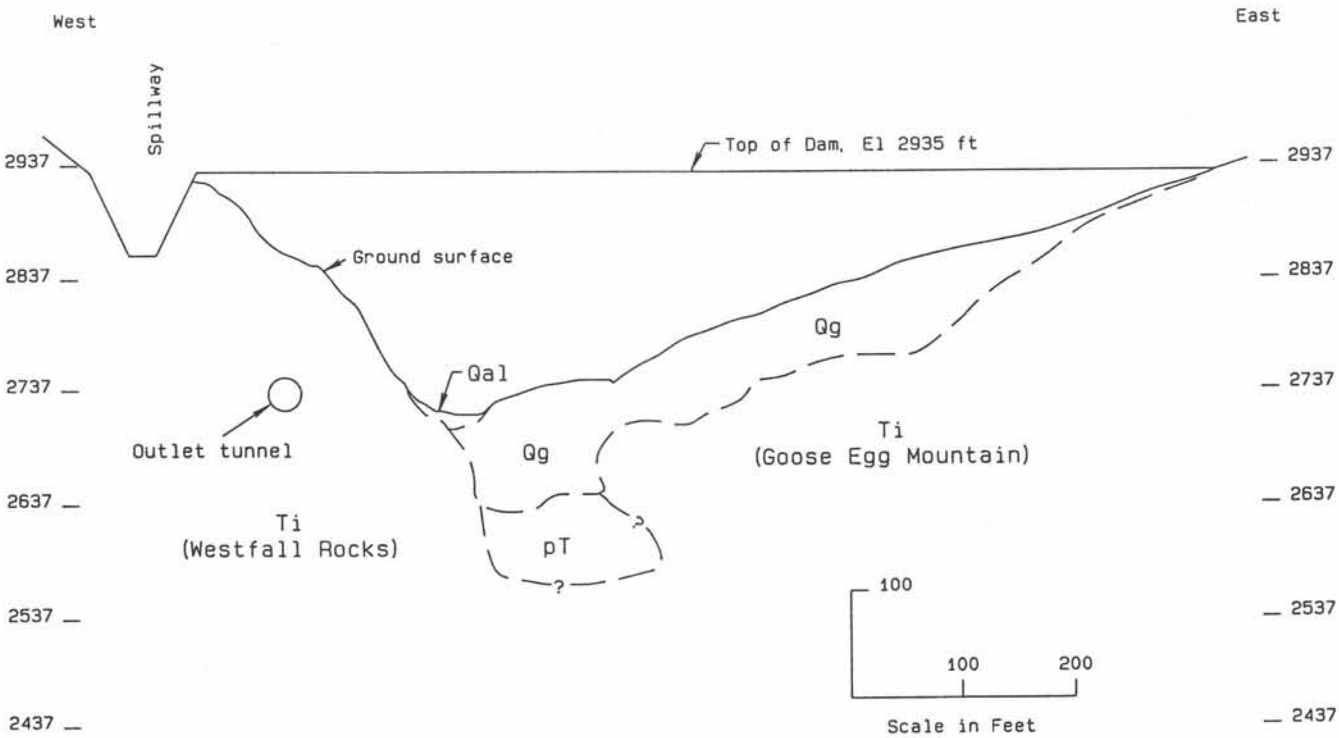

Figure 4. Geologic cross section of Tieton Dam; view downstream. Unit pT is shale believed to be part of the Russell Ranch Formation, unit Ti is andesite and "microdiorite" of the Westfall Rocks and Goose Egg Mountain plutons, unit Qg is bouldery glacial drift, and unit Qal is river alluvium.

CONSTRUCTION

Because of thick deposits of glacial drift in the channel and the lack of suitable impervious fines in the vicinity, a concrete diaphragm core wall was used at Tieton Dam to provide an impervious barrier. The core wall was extended into bedrock a minimum of 10 ft across the axis of the dam except possibly in part of the right abutment (USBR, 1983). (Conflicting construction records suggest that the core wall may not have extended to bedrock in the right abutment but are unclear as to why.) An extensive drain system was constructed in the right abutment location to control seepage through the glacial deposits beneath the core wall. Pressure grouting of the core wall foundation was attempted, but grout take was minimal and additional foundation grouting was not done (USBR, 1983). Grouting also was done in the spillway foundation area.

OPERATIONAL PROBLEMS RELATING TO GEOLOGY

Embankment

Deflections of the concrete core wall at Tieton Dam have been measured since 1927. Deflections measured between 1927 and 1940 were relatively high, occasionally several inches per year. The core wall is currently deflecting downstream at a rate of about 0.015 ft/yr, a rate that has not changed since 1940 (USBR, 1985). To date, maximum deflection of the top of the core wall is 1.68 ft downstream. Settlement of the core wall is less than 0.02 ft (USBR, 1985).

Limited piezometric data show that a high phreatic surface is not present within the embankment downstream of the core wall; seepage through the dam is minimal (USBR, 1985). These data suggest that either there is no major cracking of the core wall, or, if cracking has occurred, the puddled clay core is maintaining an adequate impervious barrier. Additional instrumentation is planned to confirm these conclusions and monitor embankment conditions.

Settlement measurements of the embankment indicate that as much as 6 ft of settlement may have occurred in the maximum section of the dam, with maximum settlement in the area of the puddled clay core. More than 60 percent of this settlement occurred prior to 1939 (USBR, 1985). This settlement does not pose a hazard to the dam.

Spillway

Ravelling of bouldery glacial drift into the spillway stilling basin has been a problem since construction of Tieton Dam. In the early 1960s, the spillway walls were extended and a training wall constructed to keep the glacial deposits from entering the stilling basin (USBR, 1986). These deposits were ravelling out of a buried preglacial ravine eroded in the Westfall Rocks pluton. By the early 1980s, enough ravelled glacial drift had accumulated behind this wall that material was once again entering the stilling basin. The Washington State Department of Transportation became concerned that further ravelling of the area above the stilling basin would threaten the integrity of State Highway 12, a major east-west highway servicing the Yakima area. Several design alternatives considered to correct or mitigate the problem included construction of a bridge over the unstable area and realignment of the highway. However, in a joint effort, the U.S. Bureau of Reclamation and the State of Washington designed a reinforced earth retaining wall structure to stabilize the slope above the stilling basin. Construction of this structure was completed in late 1987.

Rock falls from the spillway cutslopes excavated in the Westfall Rocks pluton have occurred intermittently since construction of Tieton Dam. The spillway cutslopes are in jointed "microdiorite" and range in height from about 50 ft near the north end of the spillway to more than 300 ft at the southern end. The slopes range from about 0.5H to 1V to 1.5H to 1V. Preliminary geologic examination of the spillway cutslopes following a 50-cy rock fall in 1986 showed that well developed joint sets, several of which dip toward the cutslopes, divide the "microdiorite" into blocks of several cubic yards each. Moderate rockfall could significantly reduce spillway capacity. Even relatively minor rock falls damage the spillway concrete and cause scouring of the stilling basin concrete during spillway operation. Geologic mapping of joints and discontinuities in the spillway cutslopes will be completed in 1988, and a slope support system will be designed and installed at a later date.

REFERENCES

Miller, R. B., 1985, *The Pre-Tertiary Rimrock Lake Inlier, Southern Cascades, Washington*: Washington Division of Geology and Earth Resources Open File Report 85-2, Olympia, WA, 16 p., 1 plate.

Swanson, D. A., 1966, Tieton Volcano, a Miocene Eruptive Center in the Southern Cascade Mountains, Washington: *Geological Society of America Bulletin*, Vol. 77, pp. 1293-1314.

Swanson, D. A., 1978, *Geologic Map of the Tieton River Area, Washington*: U.S. Geological Survey Miscellaneous Field Studies Map MF-968, 1 sheet, scale 1:48,000.

U.S. Bureau of Reclamation, 1925, *Tieton Dam, Corewall Details*: U.S. Bureau of Reclamation Construction Drawing No. 32-D-141, Denver, CO, December 17, 1925, 1 sheet.

U.S. Bureau of Reclamation (Water and Power Resources Service), 1981, *Project Data*: U.S. Government Printing Office, pp. 1337-1356.

U.S. Bureau of Reclamation, 1982a, *Safety Evaluation of Existing Dams Geology Report, Tieton Dam, Yakima Project, Washington*: U.S. Bureau of Reclamation, Boise, ID, 13 p.

U.S. Bureau of Reclamation, 1982b, *Geologic Feasibility Report, Tieton Dam Powerplant*: U.S. Bureau of Reclamation, Boise, ID, 9 p.

U.S. Bureau of Reclamation, 1983, *Technical Data Workbook, Tieton Dam–Vols. 1 and 2*: U.S. Bureau of Reclamation, Denver, CO, 100 p.

U.S. Bureau of Reclamation, 1985, *Safety Evaluation of Existing Dams (SEED) Report on Tieton Dam*: U.S. Bureau of Reclamation, Denver, CO, 50 p.

U.S. Bureau of Reclamation, 1986, *Report on Subsurface Investigations of Highway 12 for the State of Washington*: U.S. Bureau of Reclamation Memorandum from J. D. Gilbert to PN Regional Geology Files, Boise, ID, November 20, 1986, 2 p.

Walsh, T. J.; Korosec, M. A.; Phillips, W. M.; Logan, R. L.; and Schasse, H. W., 1987, *Geologic Map of Washington–Southwest Quadrant*: Washington Division of Geology and Earth Resources Geologic Map GM-34, Olympia, WA, 28 p., 2 plates, scale 1:250,000.

The Columbia Basin Project

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Columbia Basin Project

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PROJECT DESCRIPTION

The Columbia Basin Project is located in central Washington and was constructed for the purpose of providing water for agricultural irrigation on a million acres of semiarid land with elevations ranging between 350 and 1,500 ft. Irrigation service is currently available to 557,419 acres (Table 1). To date, there have been no crop failures resulting from a lack of water.

Grand Coulee Dam (discussed elsewhere in this volume) was started in 1933 and serves to impound the Columbia River and provide energy for pumping water from the reservoir (Franklin D. Roosevelt Lake) into the upper Grand Coulee where it is collected to form Banks Lake (Figure 1). The dam was completed in 1941. First water was pumped in 1951.

Banks Lake is the "storage tank" from which water is conveyed through a canal system and delivered to the irrigated land. Construction started on the irrigation facilities in 1945 and reached its present level of development in 1984.

The project occupies three structural basins divided by the east-west-trending Frenchman Hills and Saddle Mountains. The Quincy basin is the northernmost basin. It is bounded on the west by the deeply incised antecedent course of the Columbia River, on the south by the Frenchman Hills, on the east by a gentle upslope, and on the north by prominent structural highlands. The lowest point in the Quincy basin is occupied by the Potholes Reservoir, which collects all surface and subsurface return flow from the irrigated land of the basin. An elongated central basin lies between the Frenchman Hills and the Saddle Mountains. The western part of that basin is drained by Crab Creek, which cuts into a structural slope to discharge into the Columbia River. The eastern part of the basin drains south into the Pasco basin. In the Pasco basin the Columbia River passes through a structural low. Consequently, the Columbia Basin Project, being bounded on the west by the Columbia River, occupies only the portion of the Pasco basin lying north and east of the Columbia River.

The Columbia Basin Project has been constructed by the U.S. Department of the Interior, Bureau of Reclamation, under contracts with: the Quincy Columbia Basin Irrigation District, headquartered in Quincy, Washington; the East Columbia Basin Irrigation District, headquartered in Othello, Washington; and the South Columbia Irrigation District, headquartered in Pasco, Washington. Under the contracts, funding has been provided by the Treasury of the United States with reimbursement required from land owner assessments and from power revenues. Operation and maintenance costs are borne by the districts, which perform most of the work.

GEOLOGICAL SETTING

Bedrock Geology

The north end of the Columbia Basin Project is underlain by an ancient continental rock assemblage formed initially by the deposition of sediments in a shallow sea. After a great thickness of these sediments had accumulated, they were compressed, heated, and uplifted to form the core of a continent made of metamorphic derivatives of these sediments. In addition, during metamorphism, portions of the rock mass became fluidized and mobile, resulting in large areas of granitic rocks. As this continent was eroded away, the granitic rocks became jointed with low-angle lift seams and high-angle sheared joint systems responding to regional stress patterns.

When the Columbia River Basalt Group started to extrude onto the continental erosion surface, the north end of the Project area was mountainous, much as the present Colville Indian Reservation is today. The south end of the Project area was a basin similar to that of the present except that the basin opened westward to the Pacific Ocean through a broad valley and the Cascade Range was not an effective rain barrier. There being no orographic barrier, the moist, temperate climate extended inland to the Rocky Mountains.

As the basaltic lava flows extruded onto the surface from numerous fissures beginning about 16.5 Ma, their characteristic low viscosity caused them to spread rapidly and seek their own level across the floor of the basin. Hence the term *flood basalt* is used to describe the Columbia River flows. Successive accumulations of lava flows progressively lapped onto the erosion surface from south to north so that the thickness is greater in the Tri-Cities area and decreases northward (Figure 2).

Table 1. Major features of the Columbia Basin Project

Irrigable lands with service available	557,419 acres
Dams	
North Dam (earthfill)	
Length	1,450 ft
Height above bedrock	145 ft
Dry Falls Dam	
Length	9,800 ft
Height above bedrock	123 ft
Pinto Dam	
Length	1,900 ft
Height above bedrock	130 ft
O'Sullivan Dam	
Length	3.5 mi
Maximum height above bedrock	200 ft
Reservoirs	
Banks Lake	
Length	27 mi
Active capacity	715,000 acre ft
Billy Clapp Lake	
Length	6.1 mi
Active capacity	21,200 acre ft
Potholes Reservoir	
Active capacity	332,200 acre ft
Scooteney Reservoir	
Active capacity	6,750 acre ft
Feeder Canal	
Length	1.6 mi
Hydraulic capacity	21,000 cfs
Main Canal	
Total length	21 mi
Dry Falls to Bacon Siphon	
Length	1.8 mi
Hydraulic capacity	19,300 cfs
Bacon Siphons and Tunnels	
Length	2.1 mi
Hydraulic capacity	19,300 cfs
Diameter of #1	23 ft
Diameter of #2	28 ft
Bacon Tunnel to Billy Clapp Lake	
Length	4.4 mi
Hydraulic capacity	13,200 cfs
Pinto Dam to Bifurcation Works	
Length	6.6 mi
Hydraulic capacity	9,700 cfs
West Canal	
Length	87.6 mi
Hydraulic capacity at headworks	5,100 cfs
Soap Lake Siphon	
Length	12,883 ft
Hydraulic capacity	5,100 cfs
Diameter	22 ft
Frenchman Hills Tunnel	
Length	9,280 ft
Hydraulic capacity	1,540 cfs
Diameter	14 ft
East Low Canal	
Length	87 mi
Hydraulic capacity at headworks	4,500 cfs
Potholes Canal	
Length	70 mi
Hydraulic capacity at headworks	3,900 cfs
Wahluke Branch Canal	
Length	44 mi
Hydraulic capacity at headworks	2,000 cfs
Wahluke siphon	
Length	3 mi
Diameter	15 ft
Eltopia Branch Canal	
Length	25 mi
Hydraulic capacity at headworks	555 cfs
Secondary distribution system	
Laterals	2,026 mi
Pumping plants	240
Drainage and wasteway systems	
Open channels	1,218 mi
Buried pipe drains	2,467 mi

The oldest basalt exposed in the Project area is called Grande Ronde Basalt. This formation extends throughout the area. The surface it covers was apparently undisturbed during this extrusion (U.S. Department of Energy, 1984).

In the time that passed before the next extrusive event, minor subsidence started, and a widespread layer of water-deposited sediment coated the lava plain, forming the Vantage interbed of the Ellensburg Formation.

The overriding Wanapum Basalt was thick enough to reestablish the level surface. However, a structural basin at the base of the Coulee monocline in the Grand Coulee at Blue Lake contains a thicker section of late Wanapum flows, indicating the monocline was active.

During the time following extrusion of the Wanapum lava flows, the axis of the Frenchman Hills became a hinge line that established a gentle southward dip into the Pasco basin. Consequently, the overlying Saddle Mountains Basalt feathers out on the south flank of the Frenchman Hills and is thicker to the south, except for the central core of the Saddle Mountains uplift. There is no Saddle Mountains Basalt north of the Frenchman Hills.

Water-transported sedimentary materials, called the Ringold Formation, were deposited on top of the lava flows. Stresses contemporaneous with those which uplifted the Cascade Mountains resulted in the uplifting of the Frenchman Hills and Saddle Mountains. After

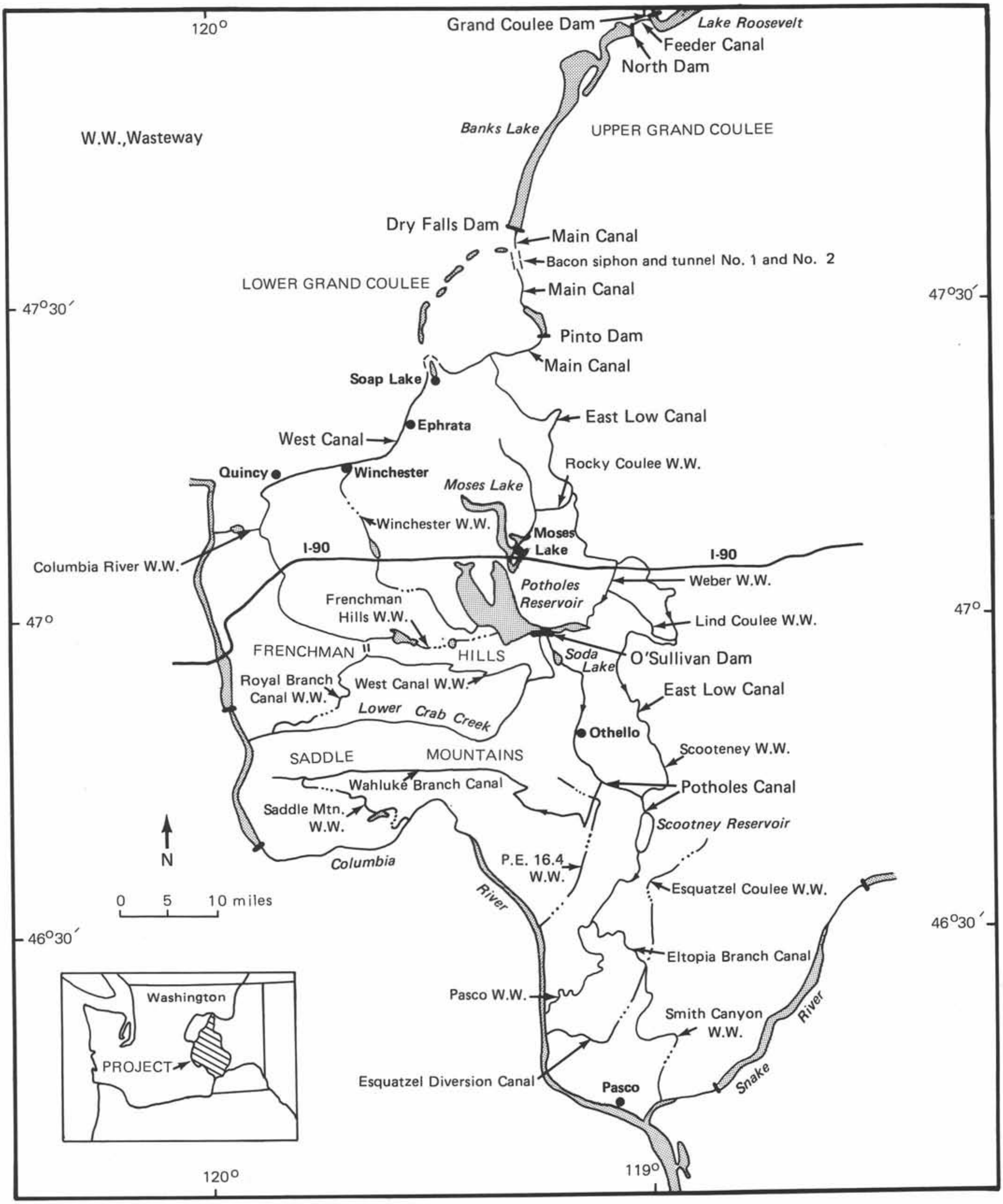


Figure 1. Columbia Basin Project facilities, 1987.

Period	Epoch	Group	Subgroup	Formation	K-Ar Age (Ma)	Member	Sediment Stratigraphy	Unit Symbol (see Figure 6)
QUATERNARY	Pleistocene/Holocene					Surficial units	Glacial Moraine	Qgl
							Flood Deposits (Gravel/	Qgg
							Sand/Silt)	Qgs
							Loess	Ql
TERTIARY	Pliocene			Ringold			Sand, Silt, and Clay of the lower Ringold Fm. (channeled by Missoula flood)	Trls
	Miocene	Columbia River Basalt Group	Yakima Basalt Subgroup	Saddle Mtns. Basalt		Esquatzel Member		Te
						Umatilla Member		Tu
				Wanapum Basalt	13.6	Priest Rapids Member		Tpr
							"Quincy Interbeds" of the Squaw Creek Member, Ellensburg Fm.	
						Roza Member		Tr
						Frenchman Springs Member		Tfs
							Vantage Member of the Ellensburg Fm.	
				Grande Ronde Basalt	15.6	Museum Basalt Member		Tsb
					16.1	Basalt of Sentinel Bluffs		

Figure 2. Geologic column for the Columbia Basin Project area.

this, the Ringold Formation continued to accumulate in the basins south of the Frenchman Hills. The Ringold Formation consists of semiconsolidated bedded silt, clay, and sand. The upper Ringold strata south of the Frenchman Hills contain beds of caliche—petrocalcic horizons which develop below semiarid soils.

On the eastern upslope, the Ringold Formation interfingers the wind-deposited, loessial, Palouse Formation. Soils are predominantly eolian. Residual soils are rare.

Glacial Flood Erosion and Deposition

The continental ice sheets of the Pleistocene Epoch covered most of the land north of the Spokane River and the Columbia River downstream to the Methow River. During the time of maximum advance, ice dammed the Columbia River between Grand Coulee and Pateros. Ice also dammed the Clark Fork River in the Cabinet Gorge near the Idaho-Montana border. This created a "reservoir" in western Montana (glacial Lake Missoula) with a 500-cu-mi capacity. Since there was no alternative spillway, the reservoir level rose until a combination of hydraulic pressure of the lake's water and the buoyancy of the ice was sufficient to release the lake catastrophically (Figure 3). The glacier, being at its maximum advance, would have been at its most active stage, with maximum meltwater rate and maximum rate of southward movement. Consequently, it was capable of repeated flood-release cycles. These floods passed through the Columbia Basin Project area (Bretz et al., 1956; Weis and Newman, 1973), grossly altering the physiography throughout the area presently developed for irrigation. East of the presently developed Project area the pre-flood terrain of basalt is predominantly covered with Palouse soils.

Because the last great catastrophic flood on the Columbia Basin Project (about 18,000 yr B.P.) was the largest, and because this mass of water passed through the area in a few days, the physiographic characteristics below the maximum flood level are predominantly the product of a very fast moving torrent in which hydraulic parameters were constantly changing. The maximum flood level in the Quincy basin was at 1,355 ft elevation, and the maximum flood level south of the Frenchman Hills was about 1,200 ft.

According to Baker (1973), the maximum rate of flow into the Quincy basin was about 470,000,000 cfs. Another 280,000,000 cfs entered the Pasco basin from the Washtucna Coulee-Snake River complex. Two

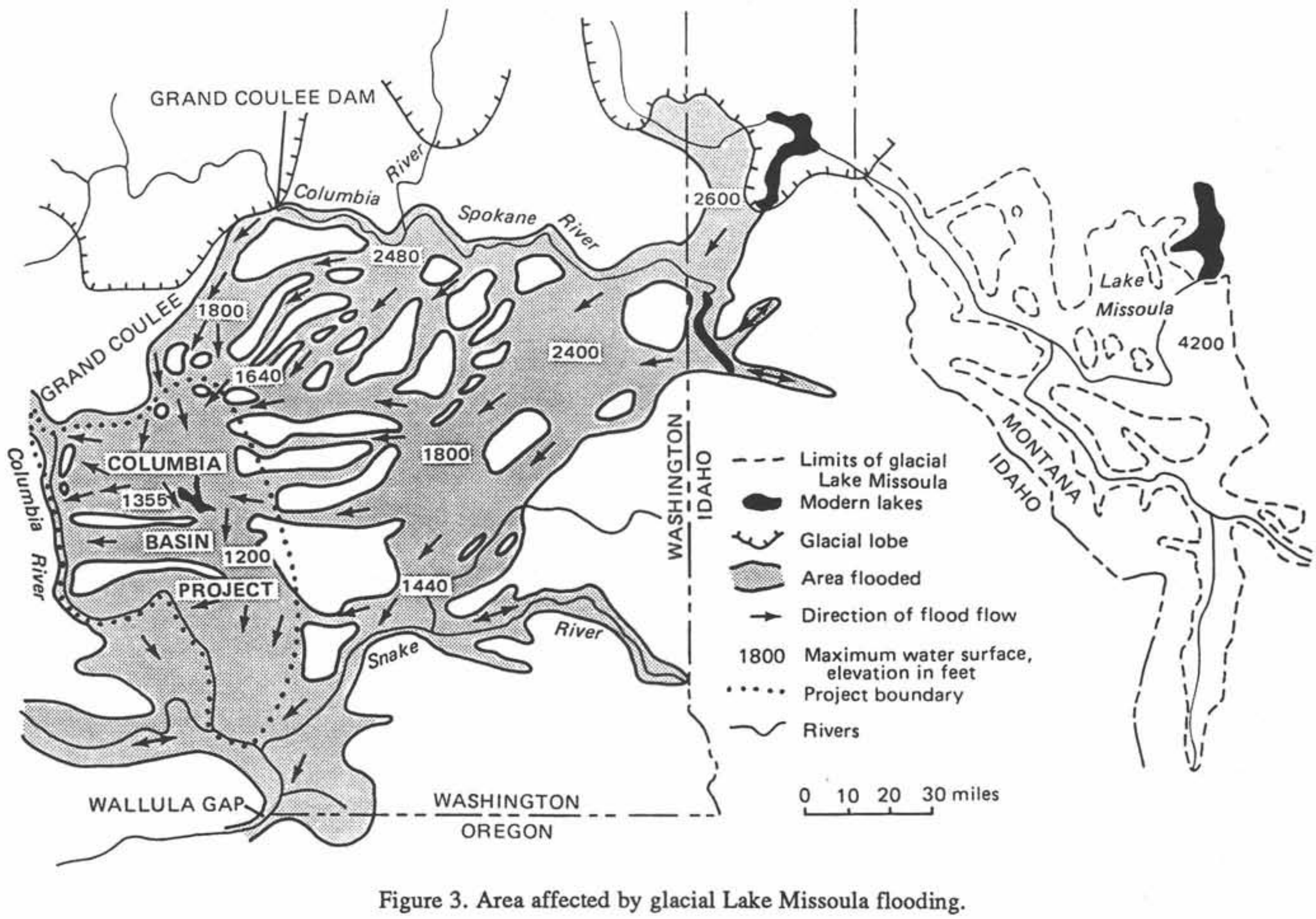


Figure 3. Area affected by glacial Lake Missoula flooding.

hundred and sixty cu mi of water was temporarily stored in the Quincy, Othello, Yakima, and Pasco basins. The outflow through Wallula Gap, south of Pasco, where the flood was hydraulically dammed, peaked at 320,000,000 cfs. Referring to Figures 3, 4, and 5, consider the energy released by 500 cu mi of water dropping from 4,200 ft to 1,200 ft in a distance of 150 mi! With channel velocities as high as 100 ft/sec and water depths as great as 700 ft, the flood water was capable of eroding and transporting all available earth and rock materials including boulders tens of feet in diameter. As velocities decreased, the heaviest suspended materials became part of the bed load, then progressively stablized as channel bottom or terrace deposits.

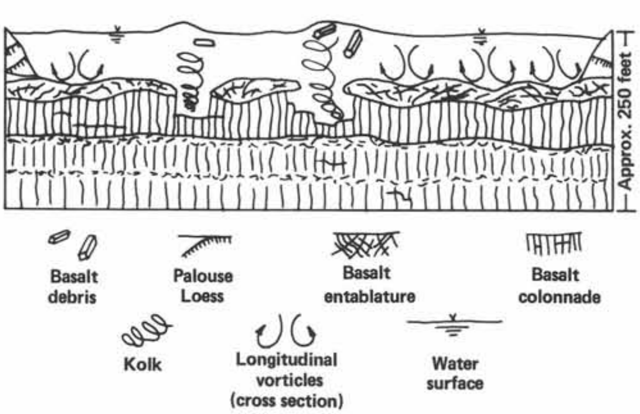


Figure 4. Sketch of the erosion process of a high-veolocity flood passing over Columbia River basalt flows.

The Coulee fan, with its apex at Soap Lake and its toe extending through Moses Lake, reflects velocity-controlled depositional characteristics: a central high-velocity bore maintained mobility of all but the largest boulders. The course of the bore is flanked on either side by bedload terraces of smaller boulders and cobbles. Where the fan widens, the detrital materials are smaller. Twelve miles south of Soap Lake the boulders are sparse, and the bed load is mostly coarse gravel. At the Winchester Wasteway location, 15 mi southwest of Soap Lake, the fan terminates where the flow was diverted southeastward to the Potholes Reservoir site. West of the Winchester Wasteway the flood velocity decreased sharply as an eddy carried the water impounded by the west side of the Quincy basin northward from the Frenchman Hills. This water also spilled over Babcock Ridge into the Columbia River in three separate channels. The flood bedload sediments in the area grade from sandy gravel south of Interstate Highway 90 (Fig. 1) to predominantly silt between Quincy and Winchester. Higher velocities are evident in the erosion of bedrock at the approaches to the west-flowing cataracts that plunged into the Columbia Valley.

Similar bedload clast size distribution characteristics are evident through and south of the channels lying south of O'Sullivan Dam, where the flood flow divided into Crab Creek to the west and into the Othello channels to the southeast. The process of deep erosion and downstream deposition is repeated in the high-velocity channel which cut the Othello channels containing Eagle Lake and Scooteney Reservoir. This stream merged with the flood entering the Pasco basin from Washtucna Coulee.

DAMS

North Dam

General Description

The North Dam is a zoned earth-filled dam with an impervious core; it was completed in 1951. It is 145 ft high with a base width 1,000 ft, a crest length 1,450 ft, and a crest elevation of 1,580 ft; both abutments are grouted (Figure 6).

Site Geology

A basalt monolith, which lies between the north abutment of the North Dam and the Feeder Canal alinement, is a rotated slide block segment of the basal basalt flow resting on the slide-disturbed Latah Formation. Both have been rotated 45 degrees and now dip north (Figure 6). The northern two-thirds of the North Dam extends southward from this monolith and is founded on distorted, slide-transported Latah Formation. The southern third of the foundation rests on an eroded granitic bedrock surface forming the south abutment. South of the abutment, where the highway crosses the dam axis, lies a buried extension of the North Dam named the Delano Saddle cut-off trench. The need for the cut-off was discovered after the south abutment bedrock was exposed and the potential for the existence of a very deeply excavated shear zone with open cobble backfill was hypothesized. A single diamond drill hole verified the presence of a buried, cobble-filled channel. An impervious cut-off wall was placed to seal the gap by excavation and backfill.

The unusual geology of this site is the result of its location near the southern limit of the continental ice sheet that filled the Columbia River valley between Coulee Dam and Pateros. This caused the glacial meltwater to be diverted southwest over a low structural divide. When glacial Lake Missoula breached its ice dam, it, too, was diverted as it overwhelmed the immature Columbia River course. The upper Grand Coulee was formed by the rapid recession—by the headward erosion—of a waterfall which started on a steep structural downslope north of Coulee City.

As the flood water eroded the Upper Grand Coulee, the receding 800-ft-high waterfall eroded headward until it broke through into the much deeper Columbia River valley. At this point, the soft Latah Formation underlying the basalt was exposed to the plunge pool of the waterfall; the resultant rapid undermining and mas-

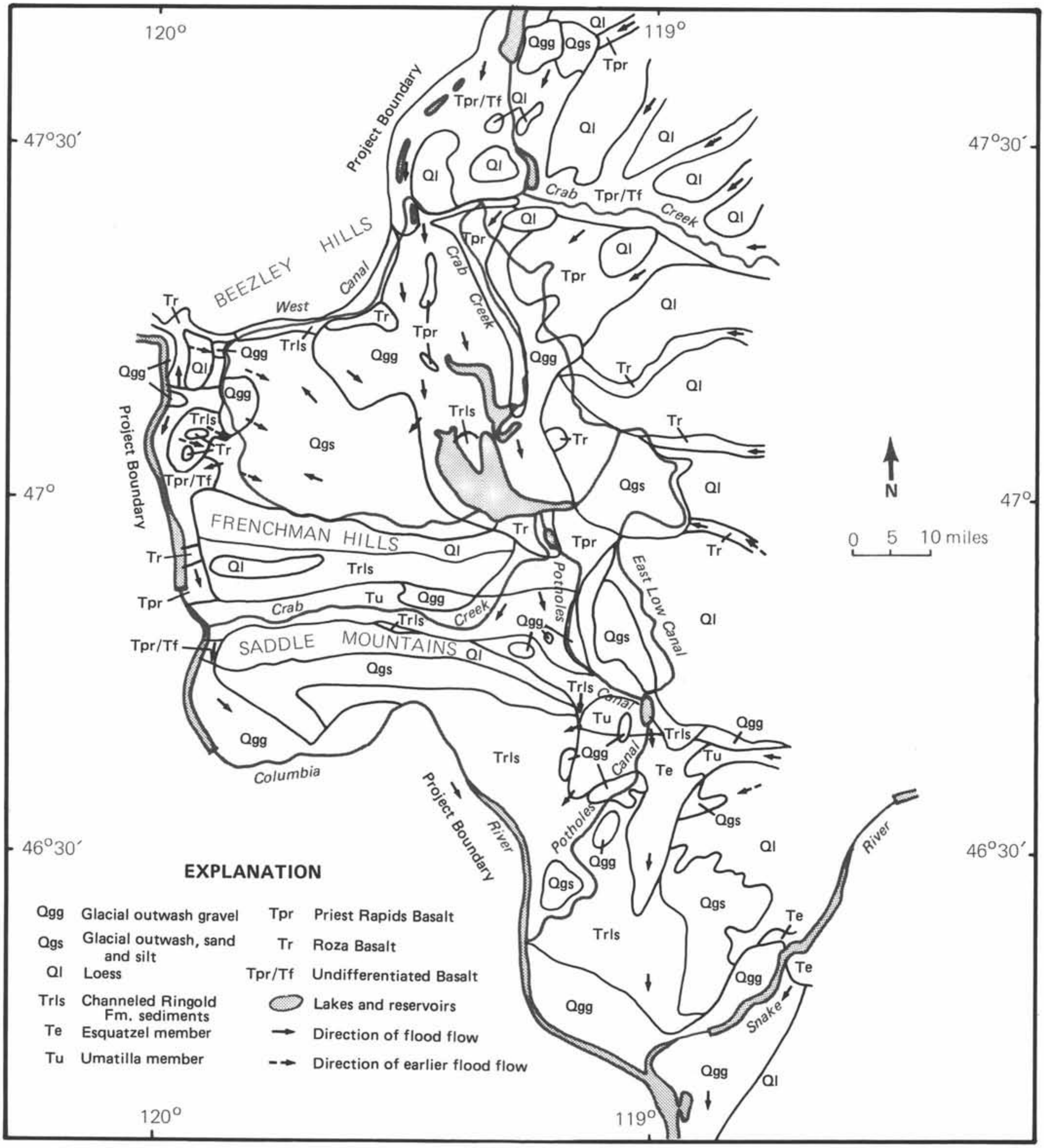


Figure 5. Generalized geologic map of the surficial sediments and bedrock exposed in the area of the Columbia Basin Project.

sive failure of the overlying rock released a wall of water superposed on the flood waters from Lake Missoula. Subsequently, the glacial ice of the Okanogan lobe entered the north end of the Coulee and subjected the exposed surface to ice-thrust stresses. A varved silt and clay, the Nespelem Formation, was deposited in the slack-water areas associated with glacial meltwater around the ice margins and down the Grand Coulee. The

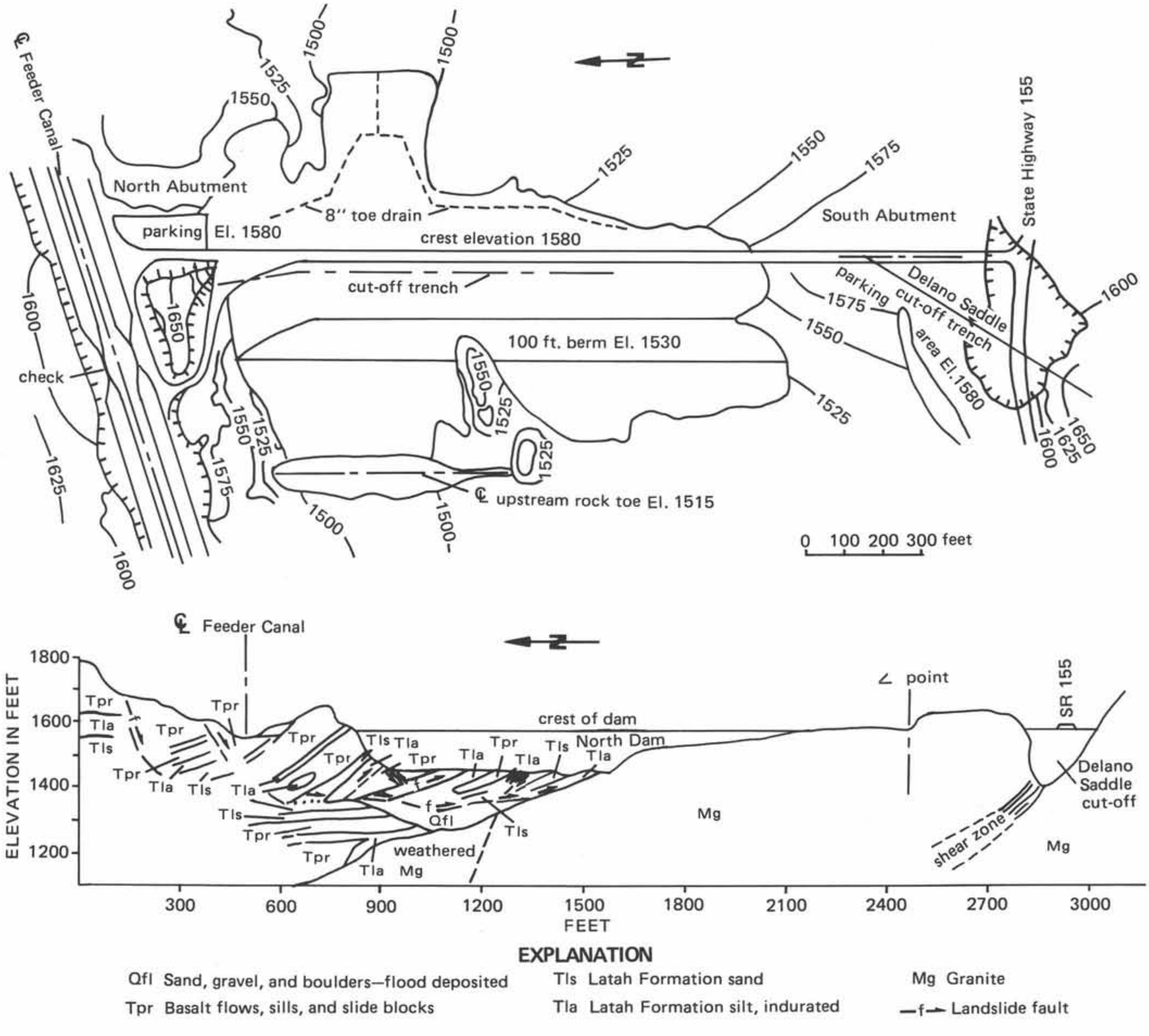


Figure 6. Plan view (above) and geologic section at North Dam, Columbia Basin Project.

Nespelem Formation is exposed in the Feeder Canal and was excavated from the dam site.

Dry Falls Dam

Located at the south end of Banks Lake, Dry Falls Dam has a maximum height of 123 ft, maximum base width of 480 ft, crest length of 9,800 ft, and crest elevation of 1,580 ft. The Dry Falls Dam is a zoned, earth-filled dam with an impervious compacted core and a cut-off trench lying over a grout curtain. It was completed in 1951.

Engineering geology played a key role in the selection of the Dry Falls dam site. Engineering considerations favored a location farther north (Ankeny site) where the length of the dam would be shorter. However, the west abutment contacted the west side of the Grand Coulee where the steeply dipping basalt flows of the Coulee monocline passed from the bed of the coulee into the west side of the coulee. A large number of drill holes, a shaft, and an adit penetrating the monocline revealed shattered rock sealed by parallel, high-angle gouge seams which would release large volumes of ground water when breached. It was concluded that the abutment problems at this site justified the use of the longer site near Coulee City. [Incidentally, it was found that the so-called porphyritic flows (Wanapum Basalt) were 60 ft thicker on the east (downthrown) side of the Coulee monocline than on the west (upthrown) side, suggesting the Coulee monocline was active during Grande Ronde-Wanapum time.]

The Dry Falls Dam was built on top of a shelf of flat-lying basalt bedrock which had been scoured by the glacial flood as it approached Dry Falls and other associated escarpments that drop into the lower Grand Coulee.

Since the bed of the lower Grand Coulee lies more than 400 ft below the Banks Lake reservoir surface, the hydraulic properties of the basalt flows between the dam and the Coulee were thoroughly investigated. Diamond drill holes, with multiple packers at selected depths, provided rock samples, percolation tests, and piezometric data at as many as six levels in the multiple-packer holes.

With the Coulee monocline serving as a ground-water barrier to the west, the up-sloping water table to the east sustained by natural inflow from the Hartline basin (15 mi east of Dry Falls Dam), and piezometric levels in the basalt flows between the dam site and the lower Grand Coulee standing significantly higher than the lakes in the lower Grand Coulee, it was determined that impoundment of the reservoir in the upper Grand Coulee (Banks Lake) would increase the discharge into the lower Coulee by only about 5 cfs. Another 1 cfs of ground-water flow from the east, which previously flowed into the upper Grand Coulee, would be diverted into the lower Grand Coulee.

Experience has substantiated these conclusions. A temporary anomaly was created by the Alaskan earthquake in 1964, which caused a sudden release of ground-water storage from the basalt flows into the lower Grand Coulee. This added discharge tapered off in 3 years.

Surface water standing between the dam and Dry Falls is primarily a result of a spring and effluent discharge from Coulee City being impounded against the south side of the dam. It is interesting to note that the depth to bedrock under the North Dam (upstream end of the Grand Coulee) is 22 ft more than the depth to bedrock under the Dry Falls Dam (downstream end of the upper Grand Coulee). This reversed bedrock gradient of 22 ft over a distance of 27 mi illustrates how catastrophic flood flows respond to hydraulic gradients caused by elevation differences on the surface of the body of water—that is, flood water may move uphill with respect to the ground surface. With a maximum flood surface elevation of 1,800 ft, the water was 300 ft deep at the lip of Dry Falls, which dropped another 350 ft into its plunge pool into the lower Grand Coulee.

The flood flow in the lower Grand Coulee at Soap Lake has been estimated to be 160,000,000 cfs with a velocity of 68 mph (Baker, 1973). Since this is only a major portion of the water that poured out of the upper Grand Coulee, an estimate of 200,000,000 cfs for the flow emerging from the upper Grand Coulee is not unreasonable.

Pinto Dam

A ridge-like alignment of structural domes branches eastward from the Coulee monocline between Lake Lenore and Soap Lake. (See Figures 5 and 11.) The glaciofluvial flood, which poured down the upper Grand Coulee, was briefly impounded behind this ridge until it was breached at three locations to form the lower Grand Coulee, Dry Coulee, and Long Lake Coulee. The Main Canal utilizes Long Lake Coulee to carry water through this structural barrier by impounding Main Canal water behind Pinto Dam to form Billy Clapp Lake.

Pinto Dam (Figure 7) is founded on the two uppermost basaltic lava strata (Sentinel Bluffs unit) of the Grande Ronde Basalt, which dips gently to the southeast. The dam is a zoned earth and rockfill structure. An uncontrolled emergency spillway is provided around the left (east) abutment of the dam in a channel excavated in rock.

A moderately permeable interflow zone was exposed in the excavation. A second interflow zone with high artesian efficiency was exposed in the gravel bed underlying the bottom of the reservoir site. During construction, a fault zone was encountered, which had not been penetrated in the four diamond drill holes on the axis. It trends perpendicular to the dam axis. This required over-excavation and a cut-off wall. The interflow subcrops were grouted.

When the reservoir was filled, small springs were formed in the Crab Creek valley 1 mi southeast of the dam site; also, the static water surface in the City of Soap Lake well #2 rose from a depth of 21 ft to flow at the surface.

O'Sullivan Dam

General Description

O'Sullivan Dam, completed 1949, closes the topographic outlet of the Quincy basin where lower Crab Creek passes through an incised channeled scabland formed by the catastrophic flood of glacial meltwater flowing across the eastern end of the Frenchman Hills uplift (Figure 8). The effectiveness of this dam in retaining water in the Quincy basin is enhanced by a natural ground-water dam at the north toe of the Frenchman Hills uplift where compressive displacement of the interflow aquifers creates a barrier to southward ground-water movement.

The reservoir stores all runoff from the 4,000-sq-mi upper Crab Creek watershed, which extends from Grand Coulee on the north to Ritzville on the east, the Columbia River on the west, and the Frenchman Hills on the

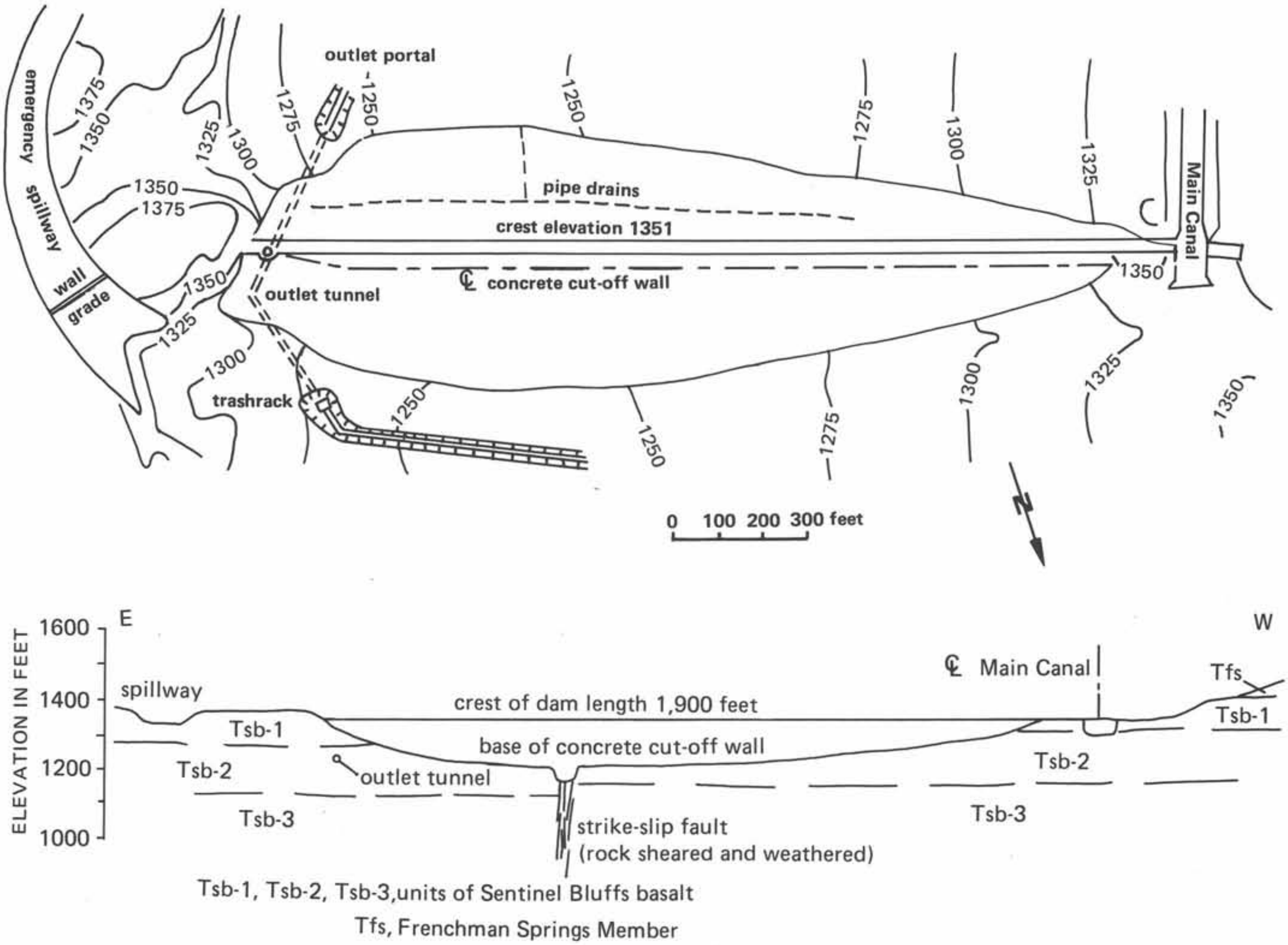


Figure 7. Plan view (above) and geologic section at Pinto Dam, Columbia Basin Project.

south. Surface- and ground-water discharge from all Columbia Basin Project activities within this basin and all dry-land runoff (usually late winter snowmelt) are thus retained as the water supply for most of the Project land in the South Columbia Basin Irrigation District. The Project has the capability for augmenting the reservoir supply by wasting (releasing water) down the Rocky Coulee Wasteway from the East Low Canal, but this has seldom been necessary.

The north end of the reservoir laps onto a very permeable outwash gravel which extends 5 mi north under Mae and Hiawatha valleys and significantly increases the reservoir storage capacity by providing available bank storage.

Site Geology

The dam's axis lies on uplifted basalt bedrock a short distance south of a structural groundwater barrier, leaving a narrow strip of exposed, moderately permeable rock through which reservoir leakage passes, serendipitously sustaining the flow of Crab Creek below the dam. Consequently, the outlet tunnel cut through the bedrock was not needed after the initial years. The dam axis follows the northern edge of the outcropping bedrock stripped and channeled by the ice-melt flood which flowed from north to south forming the Drumheller Channels through the Frenchman Hills. Therefore, the dam is founded on a very irregular rock surface with steep slopes flanking a succession of channels. The lava flows dip gently to the south.

Only one spring emerged in the excavation area during construction. It was on the steep west side of the main Crab Creek channel. The flow was small enough to be controlled as it was covered with compacted earth. Subsequent grouting secured the seal.

Dam description

The dam is a compacted core, zoned earth and rockfill structure containing the headworks of the Potholes Canal and a spillway; all are built on the basalt bedrock throughout (Figure 9). The foundation was grouted to a depth of about 30 ft. The dam, with a crest elevation of 1,061 ft, length of 3.5 mi, and a maximum height of 200 ft, was originally built to impound water to an elevation

Figure 8. Aerial view (to the north) of O'Sullivan Dam, Columbia Basin Project. The headworks of the Potholes Canal is located at the right (east) end of the dam.

of 1,052 ft. An ungated overflow spillway was constructed with a sill at 1,052 ft elevation at a location where the bedrock surface coincides with the crest of the dam.

Subsequently, the operational plan for the Potholes Reservoir was modified to avoid the need for acquiring valuable lakeshore property and improvements around Moses Lake. A new four-gated spillway with a sill elevation of 1,028 ft and a gate top at 1,048 ft replaces the original spillway; it has the capability of spilling flood water and maintaining a maximum operating level of 1,046.5 ft in accordance with an agreement with the Moses Lake Irrigation and Rehabilitation District. Moses Lake is controlled at an operational maximum elevation of 1,047 ft. Potholes Reservoir is not a flood control feature. Therefore, flood water spilling into lower Crab Creek may equal the flow of flood waters entering the reservoir during large flood events. However, reservoir management can normally provide enough late winter storage capacity to minimize downstream flooding.

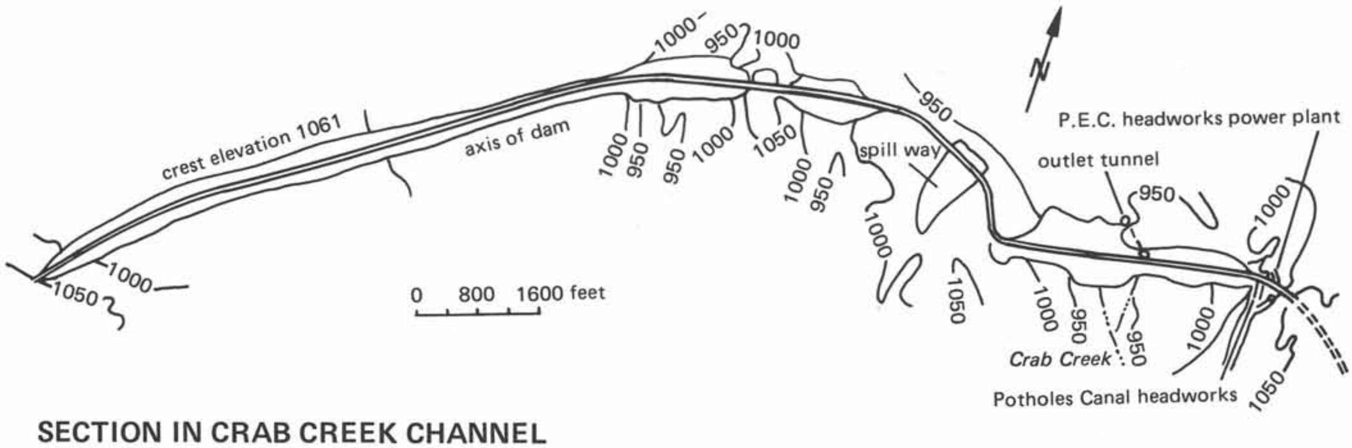
CANALS

Feeder Canal

The outlet tubes of the Grand Coulee Dam Pumping Plant discharge into the Feeder Canal which passes around the north abutment of the North Dam to empty into Banks Lake.

The Feeder Canal is a two-way concrete-lined channel (Figure 10), with a 21,000-cfs capacity, whose water flows into Banks Lake, and a 14,400-cfs return flow capacity from Banks Lake to the pump-generating units.

The Feeder Canal starts in the granitic rock associated with Grand Coulee Dam, then flows onto the Latah Formation, lacustrine siltstone and sandstone un-



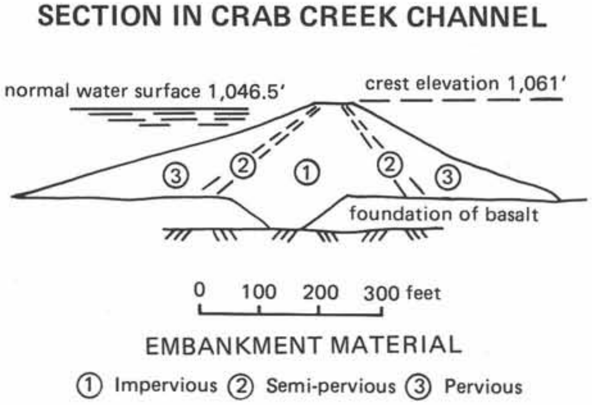


Figure 9. Plan view (above) and section of O'Sullivan Dam, Columbia Basin Project.

derlying the Columbia River basalt. As the Feeder Canal approaches the North Dam axis, it enters an extensive landslide deposit of rotated Latah Formation and Columbia River basalt flows.

During construction of the Feeder Canal, the north side, which was excavated into the Latah Formation lying directly under a series of relatively in-place basalt monoliths, failed on a bedding-plane slip fault in clay at the base of the ice-thrust zone. The slip-plane clay cropped out near the bottom of the canal. The canal was redesigned to provide a cut-and-cover section through the flat-bedded reach of Latah Formation excavation. This cut-and-cover section was converted into an anchor structure when the canal was redesigned as an open canal to accommodate the two-way flow required for utilization of Banks Lake as an off-stream pumped-storage reservoir (described elsewhere in this volume).

Main Canal

Coulee City to Pinto Dam

Initially completed in 1950, the first reach of the main canal extends from the headworks in Dry Falls Dam to the Bacon Siphon. The canal is excavated in the flat-lying uppermost basaltic lava flow with an unlined open cut, except for a lined section 1,000 ft long at the approach to two concrete siphons. The first Bacon siphon and tunnel combination was completed in 1951. The second Bacon siphon and tunnel were completed in 1980. Both the 10,000-ft-long tunnels were constructed by the drill and blast method. The siphons are cast-in-place concrete pipes, 23 and 28 ft diameter. The siphons convey water across a small coulee and into the double-bored Bacon Tunnels. The concrete siphon structures are founded on basalt bedrock.

The Bacon Tunnels penetrate the middle of the massive colonnade of the Frenchman Springs lava flow at its north end and, through its 2-mi length, gradually descends stratigraphically. In the southernmost 1/4 mi, the excavation descends through the light-gray tuffaceous Vantage interbed and into the uppermost Grande Ronde Basalt flow. The interface of the Frenchman Springs Basalt and the Vantage interbed is characterized by fossil trees partially or totally engulfed within the overlying basalt and numerous spiracles resulting from steam rising through the overlying molten lava during crystallization. The soil on top of the Vantage interbed was just a few inches thick, and no woody root structures were observed. The soil appears to have been a bog blanketed with driftwood, which tended to float upward into the overlying lava. At the south end of the tunnels, the contact of the bottom of the Frenchman Springs flow with the sedimentary Vantage interbed is about 3 ft above the top of the tunnel.

The tunnels are steel lined and encased in concrete. Very little ground water was encountered during construction. The southern mile of the tunnel required sup-

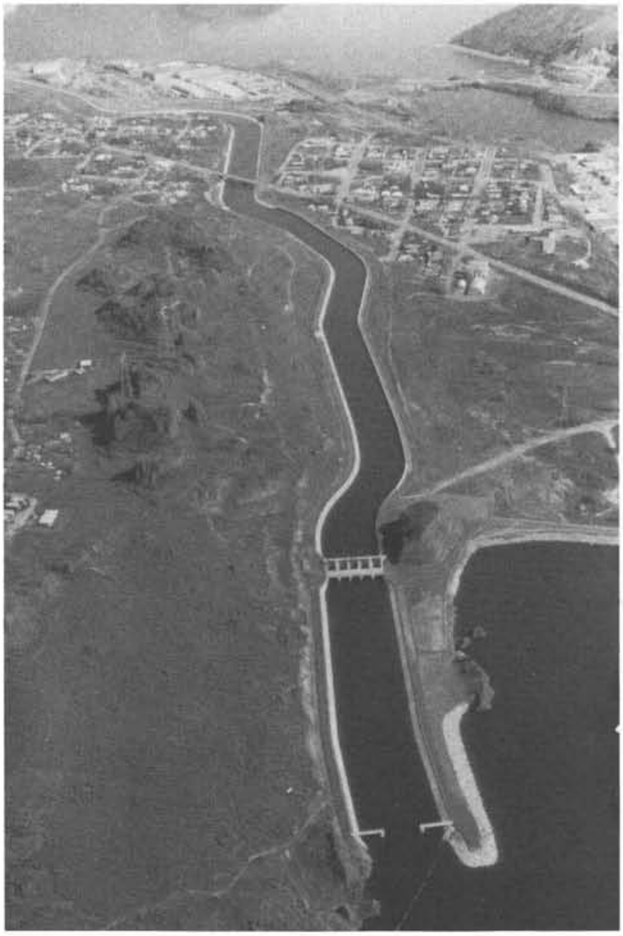


Figure 10. Aerial view (to the east) of the Feeder Canal and North Dam. Lake Roosevelt in background.

port to prevent spalling as the north-dipping basal zone of Frenchman Springs flow rose above the spring line.

South of the tunnel outlet, the Main Canal skirts a feature called the Trail Lake sink. It is a depression located in the bottom of a small coulee where the crest of a south-dipping monocline has been fractured. Historically, surface runoff from the Hartline basin, usually resulting from rapid snowmelt on frozen ground, formed a stream which discharged into the depression, called Trail Lake. The lake basin was plucked out by the torrential glacial meltwater flow. As the seasonal snowmelt runoff dwindled, the accumulated water in the depression would rapidly dissipate into a gravel bed and into the fractured bedrock. A hydrologic study determined that the water which entered the ground did not move southward, but rather followed the crest of the monocline toward Dry Coulee to the southwest. Studies further indicate this water eventually emerged in the lower Grand Coulee. Consequently, the Main Canal was concrete lined through this section to minimize the impact on the hydrology of the lower Grand Coulee.

South of Trail Lake, the Main Canal passes across flat-lying basalt to Summer Falls, where it plunges 165 ft into Billy Clapp Lake. Billy Clapp Lake lies in an elongated depression which was cut through a structural col around the east side of Pinto Ridge, a structural dome. The elongation at Summer Falls trends east-west where the approach velocity of the glacial flood water resulted in a small coulee cut into the overthrusted toe of the north-dipping lava beds. (See section in Figure 14.) The north-south alignment of the coulee cuts into a faulted structural transition of the ridge.

Pinto Dam to Bifurcation

The Main Canal leaves Billy Clapp Lake through the headworks at the right abutment of Pinto Dam. It is concrete lined, excavated in rock near the headworks, then mostly in gravel to the Bifurcation Works, where the water is divided between the 88-mi-long West Canal (5,100 cfs initial capacity) and the 87-mi-long East Low Canal (4,500 cfs initial capacity).

West Canal and Associated Features

General Description

The West Canal (completed by sections, 1949-1954) delivers irrigation water to the western half of the Quincy structural basin and to the Royal Slope on the south flank of the Frenchman Hills. It passes near, or through, the cities of Soap Lake, Ephrata, Quincy, and George. The terminal wasteway enters the Crab Creek drainage area near Goose Lake at the east end of the Royal Slope.

The canal is concrete lined from its source at the Bifurcation Works to the Winchester Wasteway. The remainder of the West Canal was earth lined by supplemental construction wherever experience demonstrated the need. Geological notes of the excavated surfaces were recorded so they could be readily referred to for remedial design and construction. An extreme consequence of this lining procedure occurred in 1951 when the first water ran down the West Canal to the town of George. As much as 500 cfs of flow disappeared in the canal bottom. Nearby depressions, which now contain George and Martha Lakes, began to fill with water. This part of the canal was earth lined before the 1952 irrigation season.

Major West Canal construction features are the Dry Coulee siphons, Soap Lake siphon, and the Frenchman Hills Tunnel. All canal siphons are inverted siphon pipes which carry water across valleys by maintaining a higher water surface at the siphon inlet than the water surface at the outlet.

Siphons

The West Canal crosses the south end of Dry Coulee, an incised divide between Billy Clapp Lake and lower Grand Coulee, with two concrete siphon sections connected by an open canal. Each abutment is cut in bedrock. Otherwise, the structures rest on coarse gravel.

Soap Lake is a body of alkaline water (pH of about 9) which lies in a depression at the lower end of the lower Grand Coulee plucked out of the crest of an east-west-trending anticline. The north limb has a gentle slope, and the south limb dips more steeply. The Soap Lake Siphon, 12,900 ft long, carries water across the south end of the lower Grand Coulee by looping northward around the north end of Soap Lake.

The siphon pipe is poured-in-place concrete with a steel liner in the high-head portion. It is 25 ft in diameter, except in the steel lined portion where it is 22 ft in diameter. The design capacity is 5,100 cfs, and the maximum head is 235 ft. The inlet (east end) of the siphon is located where the West Canal merges with the Vantage interbed between the overlying Frenchman Springs basalt flows (Wanapum Basalt) and the underlying Grande Ronde Basalt. The Vantage interbed and the underlying saprolite were easily eroded by lateral cavitation of the glacial flood flow, resulting in a prominent bedrock terrace on both sides of the coulee. The Soap Lake Siphon lies atop this declining terrace on the north limb of the anticline, crosses the irregularly eroded flat-lying bedrock surface north of Soap Lake, then rises southward up the north limb of the anticline, outletting at the crest of the anticline northwest of Soap Lake.

Soap Lake Protective Works

Soap Lake has a minimum surface elevation of 1,076 ft. Its watershed is bounded on the west and north by the crest of the Beezley Hills uplift, on the northeast by the Dry Falls Dam and the Hartline basin, on the east by the Billy Clapp Lake, and on the south by the divide on which the Burlington Northern Railway travels between Ephrata and Grant Orchards (3 mi south of the road intersection shown in Figure 11). The only surface water flowing directly into Soap Lake enters from two drainages on the Beezley Hills which flow over the Soap Lake Siphon during very infrequent runoff events. There is also infrequent surface runoff from the City of Soap Lake and environs. All other inflow emerges directly from the ground water into the lake by spring discharge. Ground water can be observed entering the lake from the Vantage interbed and from the first two interflow zones below the Vantage interbed.

The bed of Soap Lake lies in a deeply incised depression in the bedrock, partially filled with cobbles and very coarse gravel blanketed with a thick bed of clay. The highly permeable cobble and gravel bed exhibits hydraulic continuity throughout the lake and shoreline area except for the southeast corner, which retains ground water under an artesian head. The clay bed

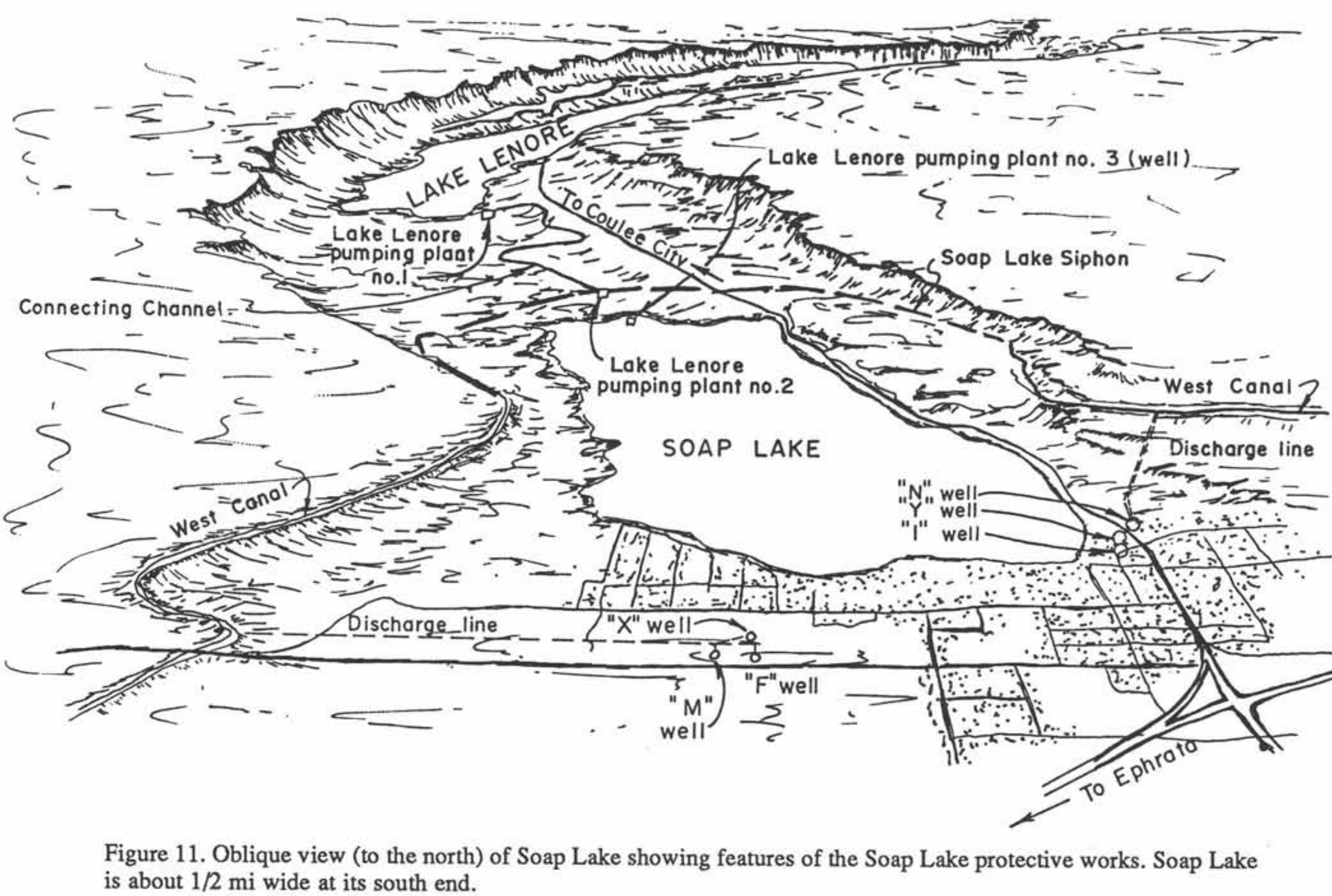


Figure 11. Oblique view (to the north) of Soap Lake showing features of the Soap Lake protective works. Soap Lake is about 1/2 mi wide at its south end.

separates the alkaline lake water from the comparatively fresh water in the gravel. The gravel bed terminates about 1 mi north of the lake and extends southward, filling bedrock channels to the southern limits of the town of Soap Lake beyond the lake's southern end.

The watershed, which discharges into the lower Grand Coulee, maintains the lower Grand Coulee lakes system. Water from Lake Lenore, moderately alkaline, migrates under ground to Soap Lake, which is very alkaline and is the evaporative terminus of the hydrologic system. Under pre-Project conditions, water discharge into this basin was in equilibrium with evaporative discharge and consumptive plant use. The impact of the Columbia Basin Project upon this closed drainage system was studied extensively prior to and during construction of the associated dams and canals.

In 1950 a pumping plant was constructed at the south end of Lake Lenore. Water from Lake Lenore is conveyed in an open ditch to the Soap Lake Siphon where it is injected into the siphon. Initially, this facility was operated during the winter so the water could be diluted and conveyed down the West Canal to the Columbia River Wasteway. By 1959, the salinity of Lake Lenore was low enough to permit discharge into the West Canal during periods of high summer flow. Lake Lenore has now freshened enough to support alkali-resistant fish populations.

Soap Lake is a meromictic alkaline body of water. The upper layer (mixolimnion) historically averaged about 35,000 ppm Na_2CO_3 and Na_2SO_4, and the top of the lower layer (monimolimnion) was at a depth of more than 50 ft. This lower layer had a salt content of more than 100,000 ppm (saturated). The primary salt is Na_2CO_3.

The problem of mitigating the impact of water losses from Project facilities and the irrigation return flow within the drainage basin is complex, and preparations were made to monitor these effects and design corrective measures during the initial years of operation. However, with the onset of a wet climatic cycle, which started in 1940, and the heavy snowfall years of 1948-49 and 1949-50, a natural increase of ground water and surface water flowing into the lower Grand Coulee resulted in Lake Lenore and Soap Lake being near record high levels by 1952. This necessitated direct pumping from Soap Lake into the Soap Lake Siphon where the water was diluted and passed down the West Canal to the Columbia River Wasteway in the 1952-53 winter.

In 1951, the West Canal was tested, and in 1952 water was delivered to the Project farm lands in the Soap Lake basin. Pumping from Soap Lake continued each winter until a system of seven interception wells, three southwest of Soap Lake, three southeast of Soap Lake, and one north of Soap Lake (Lenore pumping plant #3) were brought into operation.

These wells draw fresh water from the coarse gravel aquifer which underlies the lake and discharge it into the West Canal. This well system re-established the balance between inflow and evaporation so that direct pumping from the lake was terminated in 1958. The removal of alkaline water from the lake between 1952 and 1958 resulted in a decline of alkalinity in the mixolimnion to approximately 20,000 ppm, where it has remained to the present.

Winchester Wasteway

The Winchester Wasteway, designed for emergency discharge of the West Canal, flows south from the West Canal midway between Ephrata and Quincy. It drops into a valley which was formed as a bedload feature when the glacial flood was pouring from the Grand Coulee and was impounded in the Quincy basin. The high velocity of the flood discharge was maintained to this location, where the impounded water in the western part of the basin forced the high-velocity water to turn south and east to the channels which are now blocked by O'Sullivan Dam. Consequently, the irrigated land east of the wasteway is underlain with coarse, permeable gravel which is coarser to the northeast. On the west side of the wasteway, the fine-grained sedimentary beds (Ringold?) overlying the basalt lava flows are covered with a lateral bar of medium-grained sand.

The ground-water return flow from irrigated land to the east of the wasteway migrates rapidly through the gravel toward the wasteway, while irrigation return flow from other directions is restricted by relatively lower permeabilities.

The Winchester Wasteway now carries a perennial stream to the Potholes Reservoir. Thirteen miles of the course south of Interstate Highway 90 is unconstructed except for discontinuous channels through dunes.

Frenchman Hills Wasteway

The turnout to the Frenchman Hills Wasteway is located immediately upstream of the north portal of the Frenchman Hills Tunnel. This wasteway joins a major return flow stream a short distance from its turnout and flows eastward through low-lying dune terrain to the Potholes Reservoir along an unconstructed course.

Initially, a 15-mi-long rock-lined channel was proposed to minimize evaporative loss of water. Further consideration of this measure led to the conclusion that maintenance costs would be excessive.

Frenchman Hills Tunnel

Gravity flow of the West Canal is conveyed through the Frenchman Hills by the Frenchman Hills Tunnel, which is 9,280 ft long and 14 ft in diameter. The Frenchman Hills is an asymmetrical anticline that has many variations on the typical anticlinal structure. The initial site for the tunnel, 5 mi west of the final location, was investigated with seven diamond drill holes. These indicated that the favorable topography was the result of severe transverse faulting. The final site was chosen because the topography suggested a flat block uplift. One diamond drill hole indicated relatively normal fracture and joint conditions. Portals were explored with churn drill holes. The construction schedule did not permit further investigation. No firm stratigraphic determination was made.

The north portal encountered a lime-cemented conglomerate conformably lying atop a north-dipping fine-grained sedimentary deposit, the Quincy basin equivalent of the oldest part of the Ringold Formation. Basalt flows dip north conformably with the overlying sediments.

A low-angle thrust fault dipping south was penetrated; beyond it was a normal fault dipping steeply north. A geologic section suggested a wedge had been thrust to the north to relieve compressive stress in the uppermost lava flows at the toe of the north limb of the anticline. This type of feature had been previously identified by the author at the north edge of the Pinto Ridge flexure near Summer Falls.

At the top of the north limb of the anticline, the north dip abruptly changes to horizontal and remains horizontal across the breadth of the uplift. The backwall of the tunnel was near an unstable interflow zone which needed support. As the tunnel excavation approached the south slope of the Frenchman Hills, shattered and altered bedrock was encountered in a massive shear zone. The sheared bedrock gradually merged into a cemented talus; beyond the talus, horizontally bedded sediments were encountered that resembled those at the north end of the tunnel. No water was encountered during construction of the tunnel, which was driven by the drill and blast method.

At the south portal of the Frenchman Hills Tunnel, the West Canal conveys water eastward to the east end of the Royal Slope, and the Royal Branch Canal passes the water southwestward toward Royal City. The terminal wastewater of the West Canal spills down an unconstructed channel to the outlet of Goose Lake, which flows into lower Crab Creek.

West Canal Pumping Plants

Five major relift pumping plants lift water from the West Canal to serve lands that lie above the canal. Foundations were typically placed on basalt bedrock. No construction problems were encountered at any of the sites.

East Low Canal

The East Low Canal (completed by sections, 1949-1954) starts at the Main Canal Bifurcation Works and skirts the east margin of the Quincy basin, passing 4 mi east of the City of Moses Lake. It bends around Warden, passes 6 mi east of Othello, and terminates into the Scooteney Wasteway, which discharges into the Scooteney Reservoir on the Potholes Canal system. The canal is concrete lined to within 8 mi of Moses Lake; the remainder is mostly unlined earth and rock excavation. It is 87 mi long with 4,500 cfs initial capacity.

Ten poured-in-place concrete siphons carry the water across the principal natural ephemeral drainage courses. No pumping plants were built on the East Low Canal because future construction of the East High Canal is intended to provide gravity delivery to the land lying above the East Low Canal.

The Rocky Coulee Wasteway spills from the East Low Canal above the Rocky Coulee Siphon. A concrete-lined channel skirts a depression, then cuts through a flood-deposited sand bar to drop in a concrete chute to the natural Crab Creek channel. Wasteway water then flows into the Parker Horn of Moses Lake.

The Rocky Coulee Wasteway is also used occasionally to augment the water supply stored behind O'Sullivan Dam and to improve the quality of Moses Lake in cooperation with the Moses Lake Irrigation and Rehabilitation District.

The Weber Wasteway turns out of the East Low Canal about 8 mi east of the City of Moses Lake, adjacent to Interstate Highway 90. It was constructed as a concrete-lined trapezoidal channel in a minor drainage course excavated in unconsolidated loessial sandy silt. When the water table rose as a consequence of canal seepage and farm irrigation, uplift pressures threatened the structure. Installed weep holes were ineffective. A concrete tile drain was constructed under the bottom of the concrete floor with great difficulty and limited but adequate success. This wasteway discharges into the Lind Coulee, which flows into the Potholes Reservoir.

The Lind Coulee Wasteway turns water out of the East Low Canal above the Lind Coulee Siphon, 5 mi east of Warden. After the flow is dropped into Lind Coulee, the wasteway uses the previously intermittent course of natural drainage down Lind Coulee to the Potholes Reservoir. An ancient spring, which supported human activity as revealed in the Lind Coulee archeological site, was revitalized by irrigation development.

Moses Lake Outlet Structure

Establishment of the Moses Lake Irrigation District (succeeded by Moses Lake Irrigation and Rehabilitation District) preceded the formation of the Columbia Basin Irrigation Project. Its function was to raise the level of Moses Lake to facilitate irrigation pumping from the lake and to increase percolation losses from Moses Lake to enhance the adjacent ground-water supplies. This was accomplished with a small earth embankment with controlled culvert outlets. Infrequent major late winter flooding bypassed the structure by washing out a separate channel, which subsequently had to be closed.

The Columbia Basin Project's Rocky Coulee Wasteway discharges emergency and operational water through Moses Lake and into Potholes Reservoir. Also, the impoundment of water in the Potholes Reservoir behind O'Sullivan Dam can affect the level of Moses Lake by restricting or eliminating the elevation difference between Moses Lake and Potholes Reservoir.

The Bureau of Reclamation constructed a separate outlet structure to accommodate the Project operational needs while avoiding interference with the objectives of the Moses Lake Irrigation and Rehabilitation District. The outlet site is located atop a natural dam of dune sand behind which Moses Lake is impounded. The structure consists of control gates mounted in a concrete monolith.

Potholes Canal System

Potholes Canal

The Potholes Canal, complete in 1953, is 70 mi long and has a capacity of 3,900 cfs. It passes through a deep rock cut as it flows south from its headworks in O'Sullivan Dam. South of the dam site, the Frenchman Hills structure is a low anticline over which the catastrophic flood of glacial meltwater passed. Extreme differential erosion reflected the joint and fracture patterns of the underlying lava flows. As the Potholes Canal proceeds south, it passes from the gentle northward dip of relatively intact lava strata into a very deep cavitated depression plucked by the flood as it passed over the fractured rock aligned with the axis of the anticline. The deepest parts of this depression penetrate the main water table. Evaporative discharge over the last 18,000 yr resulted in an accumulation of salts, mostly Na_2CO_3 and some sulfate, in these depressions. Part of this salt deposit had been mined, leaving a small body of saturated salt and water called Soda Lake.

As noted, the Potholes Canal utilizes this depression to convey water. The south end of Soda Lake had to be closed by the construction of the Soda Lake Dike. It was determined that the most prudent and economical method to provide assurance that this body of salt would not contaminate the irrigation water was by hydraulic mining of the salts. Water was repeatedly pumped in from Crab Creek, circulated through the salt deposit until the salt concentration reached 30,000 ppm; then water was discharged into a depression south of the dike. This saline solution has been mingling with fresh seepage from the canal and migrating to Crab Creek since 1953.

The Potholes Canal water flows east out of Soda Lake into other depressions associated with the fractured anticlinal axis/crest, then turns southward on the south-dipping south side of the anticline. At one point it crosses a basalt ridge which has been called a dike by the author, but is claimed to be a channel filling lava flow by others. The contact between this lava ridge and the adjacent flow basalt required extensive grouting to restrict water loss from the canal (1,900 sacks of cement).

About 6 mi north of Othello, the Potholes Canal passes from the basalt bedrock onto the overlying sedimentary Ringold Formation, cutting into an erosional scarp and rising stratigraphically as the southward dip of the anticline continues. This reach developed instability as the steep sidehill on the canal's left bank became saturated with discharging ground water emerging as a result of the irrigation on the terrace above. Slope modification, terracing, and sub-surface drainage control restored stability.

As the Potholes Canal route passes from the lower Crab Creek basin into the Pasco basin, the canal encounters the eastward extension of the Saddle Mountains uplift where it intersects a north-south channel cut into the bedrock by the glacial meltwater flood. The north end of the easternmost channel was closed by the North Scooteney Dike to create the Scooteney Reservoir. This dike rests on an alluvial fan of sandy silt, the western portion of which was found to be honeycombed with rodent burrowings or debris cavities. These were sealed with the injection of a silt slurry. The Potholes Canal outlets southward from Scooteney Reservoir in a rock cut on the south-dipping basalt flows. Northwest of the town of Mesa, the canal emerges from the rock into coarse flood-deposited gravel, necessitating supplemental construction of a compacted earth lining. East of Mesa, the canal again enters the sedimentary Ringold Formation, the surface of which has been channeled by glacial outwash flooding and has a discontinuous unconsolidated mantle of flood- and wind-deposited sediments. The Potholes Canal terminates 6 mi north of Richland. From there, the Pasco Wasteway drops terminal waste water to the Columbia River in a concrete box flume.

The Eltopia Branch of the Potholes Canal starts 8 mi northwest of Eltopia, crosses the Esquatzel Coulee south of Eltopia in a siphon, and terminates 7 mi northeast of Pasco into the Smith Coulee Wasteway. This water sinks into the underlying sand and gravel flood deposit before reaching the Snake River.

Ringold Wasteway

The Ringold Wasteway was constructed to carry emergency and operational waste from the Potholes Canal 4 mi east of Ringold. It drops down a 350-ft-high erosional escarpment of the Ringold Formation through a box flume into the Columbia River. The site for this flume was on the south edge of an ancient landslide that became reactivated as soon as seepage from the approach channel and irrigation activity saturated the previously dry sediments. Attempts to control the earth movement by installation of drainage works were unsuccessful, and the slide destroyed the flume. Alternative system improvements permitted carriage of operational waste northward into the PE46A wasteway (a tributary of the PE16.4 wasteway) and into the Mesa Wasteway (which flows into the Esquatzel Coulee). These improvements, together with improved control facilities, have obviated the need for the failed structure.

Wahluke Branch Canal and Saddle Mountain wasteway

The Wahluke Branch Canal turns out of the Potholes Canal near the Adams-Franklin County line, 7 mi southeast of Othello. It begins with the Wahluke Siphon, which crosses a broad valley leading into the main flood-eroded channel through the east end of the Saddle Mountains uplift. This channel contains another example of a deeply plucked depression in the axis/crest of an anticlinal structure; this depression contained a small spring-fed lake. The siphon skirts this depression through a pipe on a series of concrete piers and outlets onto the Ringold Formation sedimentary terrace overlying the basalt on the south limb of the Saddle Mountains anticline. The canal then distributes water to the Project lands throughout the Wahluke Slope between Ringold and Mattawa.

The Saddle Mountains wasteway is the principal discharge facility from the Wahluke Branch Canal. It starts 4 mi east of Mattawa and flows southeasterly to drop onto a flood-gravel bar where it forms Saddle Mountain Lake. Base flow from this lake percolates through the gravel bar; surface discharge flows into the Columbia River during periods of high flow.

PE16.4 Wasteway

The PE16.4 Wasteway starts 3 mi southwest of Othello as the outlet for emergency wasting at the PE16.4 pumping plant which lifts water onto a terrace on the north toe of the Saddle Mountain uplift. After flowing southeast through a ponded area (Linda Lake), it is channeled to Eagle Lake, which is crossed by the Wahluke Siphon. The Eagle Lake depression conveys the flow of water through the lake to its southern end where it flows onto the south-dipping basalt. After a 4-mi reach of scabland terrain, a constructed deep drain conveys the stream to the Columbia River at Ringold after passing over a series of drop structures founded on Ringold Formation sediments.

This stream course had never carried a natural runoff stream, except during the spring of 1910 when record floods were reported throughout the area. It is now a sizeable perennial stream. Its outlet into the Columbia River is a popular fishing site. Design of this system was based on predicted irrigation hydrologic parameters and on outlet requirements for contributory drainage works.

Esquatzel Wasteway and Esquatzel Diversion Canal

The ancient course of the Palouse River (prior to the Pleistocene flooding) flowed westward in the Washtucna Coulee to the town site of Washtucna, past Kahlotus to Connell, where the Washtucna Coulee merges into the Esquatzel Coulee. The Washtucna Coulee is a closed depression with Kahlotus Lake and Sulphur Lake in its bottom. These lakes are not very saline because when floods fill the lakes, there is loss into the ground with resulting dilution of accumulated water.

The Esquatzel Coulee receives infrequent snow-melt or cloudburst runoff from a major drainage area north and northeast of Connell called Providence Coulee, which is not irrigated by the Project.

There is a continuous gradient down Esquatzel Coulee to a depression near the Pasco airport. Physiographic and ground-water evidence suggests that the course of the ancient Palouse River left Esquatzel Coulee at Eltopia and followed Smith Coulee to the Snake River.

The outpouring of at least two catastrophic floods from the outbreak of glacially dammed Lake Missoula occupied the ancient Palouse River valley, overtopped the Palouse-Snake River divide, and permanently diverted the Palouse River into the Snake east of Washtucna. These floods also modified the ancient Palouse valley by scouring its side slopes and plucking deeply into the bottom of the valley wherever the bedrock is weak and/or where a restricted cross-sectional area of the valley resulted in a high-velocity flow. This action also excavated a youthful cut through Ringold Formation sediments southwest of Eltopia to divert the modern stream course southwestward from the southward Smith Coulee location.

Hydrologic changes consequent to the development of irrigation necessitated the construction in 1973 of channel modifications at locations where the predicted perennial streams, augmented by intermittent snow-melt flooding from 480 sq mi and enhanced by the elimination of bed storage, would cause damage to railroad, highway, communities, and farmlands in the coulee bottom. A major modification was required at the south end of Esquatzel Coulee where it empties into a depression north of the Pasco airport. This was accomplished in 1959 by means of the Esquatzel Diversion Canal, a concrete-lined canal excavated into the fine-grained facies of flood deposits and extending from the Esquatzel Diversion Dam westward to its point of discharge into the Columbia River.

Major Canal Failures

In about 1954, the East Low Canal broke through its right bank 8 mi east of Moses Lake, undermined a bridge on a Northern Pacific branch rail line, washed across U.S. Highway 10 (now Interstate Highway 90), and continued down a natural course to flow into Lind Coulee east of the State Route 17 crossing. Cars and a bus on U.S. 10 narrowly missed being engulfed. The canal was emptied by discharging water into Rocky Coulee, Weber, and Lind Coulee Wasteways, and damage was held to a minimum. There were no casualties. Examination of the washout site indicated that a closely fractured caliche bed, which lay conformably a few feet below the original ground surface, was in contact with the transition from fill to cut as the canal alignment crossed a small valley. Water entering the fractured caliche zone broke out of the confining embankment and soil cover at the toe of the embankment, resulting in failure by piping.

In about 1956, with geological conditions very similar to those at the previously described canal failure, the left bank of the East Low Canal washed out into a small valley 5 mi east of Warden, impounding water behind the canal embankment on the up-slope side. A concrete box culvert passing under the canal conveyed 500 cfs down the valley and into the Lind Coulee channel until the canal was emptied by wasting. There were no casualties, although water came close to flooding a house on a farmstead. Property damage was minimal.

In 1956 the right embankment of the West Canal failed at a point 2 mi south of George, discharging canal water westward into a shallow valley which sloped gently upward to a divide between the canal and a surface sloping toward Interstate Highway 90 and the Columbia River. Impounded water was conveyed through a culvert under the West Canal eastward into a deep open drain which runs into the Frenchman Hills Wasteway. The West Canal was emptied by wasting down the Columbia River Wasteway and the Frenchman Hills Wasteway before the water west of the canal overran the divide. A county road was closed for a few hours, but there were no other adverse impacts. This failure coincided with the rise of the water table resulting in the initial saturation of low-density original soil underlying the compacted fill.

LANDSLIDES

The Columbia Basin Project area has experienced major landslides. Ancient slides resulted from the rapid erosion associated with catastrophic flood events. Recent slides were caused by the addition of irrigation water to the lands lying above the oversteepened slopes of the Ringold Formation.

Prehistoric Landslides

The ancient slide that forms the north abutment of the North Dam near Electric City is described elsewhere in this text. A giant ancient slide on the north side of the Saddle Mountains, 12 mi west of Othello, appears to have resulted from the undercutting by the erosive impact of the mass of south-flowing water emerging from the Drumheller Channels south of O'Sullivan Dam; a portion of this flow was deflected westward down the Crab Creek valley. A similar situation is suggested by the physiographic setting of the giant Malaga slide on the Columbia River south of Wenatchee between Stemilt Creek and the Alcoa aluminum plant near Malaga. Several slides on the White Bluffs north and south of Ringold followed the passage of the last great flood down the Columbia, about 10,000 yr ago.

Recent Landslides

Slides involving the Ringold Formation occur on the north slope of the Crab Creek valley between 8 and 15 mi west of Othello; along the Columbia River from 20 mi north of Ringold to 10 mi south of Ringold (described elsewhere in this volume); and west of the PE16.4 wasteway from Hendrix Road to Russell Road. As the Ringold Formation became wetted by the importation of irrigation water on the Columbia Basin Project lands, the wetting of steep slopes left by the channeled scabland flood erosion results in the reactivation of ancient slides and the formation of new ones. The steepest slopes slide suddenly, giving little warning. These slides are large and hazardous. Intermediate slopes fail gradually with movement occurring either on a bedding plane or as characteristic rotational failure. Slopes less than 6 percent are stable.

GROUND-WATER HYDROLOGY

General

There are three distinctive types of earth material involved in the geohydrologic environment of the Columbia Basin Project area: the lava beds of the Columbia River Basalt Group, the Ringold Formation semiconsolidated sediments, and the sand, gravel, and boulder deposits laid down for the most part by the catastrophic glacial flooding.

The basalt flows are flat or gently dipping under most of the area. Characteristically, the central mass of each lava bed has very low permeability, while the permeability of horizontal contact zones between flows varies from low to high. Therefore, percolation of ground water through the basalt generally is low; horizontal ground-water movement is proportionally much greater than vertical. However, the flow contact zones are so thin that total horizontal hydraulic conductivity is low.

Exceptions to these characteristics are found where diastrophic movement has caused the basalt to fracture or where flow contact zones have been cut by faults. Ground-water storage coefficients in the basalt are very low.

The Ringold Formation is made up of alluvial deposits that accumulated in structural basins during the time between the basaltic lava extrusions and the glacial epoch. These deposits were wholly or partially removed wherever they were overridden by glacial flood waters. Within the project area most of these beds were dry before irrigation. They are made up of horizontal layers of clay, silt, and fine micaceous sand. Water tends to perch in sand beds that overlie silt and clay. The formation has a very high porosity, but moderately low permeabilities impede the movement of water. Adhesive forces and wetting resistance are high. Consequently, the Ringold Formation took a long time to saturate (like a very fine sponge), but after it was saturated, it became more of a barrier to ground-water movement than an aquifer.

The flood deposits have very high permeability wherever the smallest grain size exceeds 1/4 in. As grain sizes decrease, permeability decreases to the point where silt in flood backwater locations is infeasible to drain.

Pre-Irrigation Hydrology

Annual precipitation on the Columbia Basin Project varies between 6 and 9 in. per year; December is the wettest month. Natural vegetation is adapted to total utilization of soil moisture. Roots will go as deep as necessary to capture all available moisture. Consequently, the only measurable local contribution to ground water is in active sand dunes or surfaces dominated by bedrock outcroppings having very little soil cover.

Prior to the introduction of irrigation water, main water tables inclined gently from widely scattered discharge locations of low elevation, such as the Potholes Reservoir area, Crab Creek, and the Columbia River. Perched water tables occurred in the confined aquifers associated with zones between lava flows which underlay surface elevations of 1,500 ft or more (Walters and Grolier, 1960). The ground water in the west end of the Quincy basin was prevented from discharging into the deeply incised Columbia River valley by the structural rise of the basalt flows that make up Babcock Ridge. Therefore, all ground water in the west margin of the Quincy basin moved toward lower Crab Creek at the O'Sullivan Dam Site. In general, water-table depths were between 100 and 200 ft under most of the Quincy basin, between 20 and 300 ft under the Othello basin, and between 300 and 600 ft under the Pasco basin (Figure 12).

Irrigation Hydrology

As a broad generalization, out of 6 acre ft of water diverted each year for every acre irrigated, 2 acre ft of diverted water are lost in the distribution system by seepage into the ground and operational waste, 2 acre ft are lost on the irrigated farm lands by deep percolation beyond the root depth of the crop and by surface waste, and 2 acre ft are consumptively used by the crops and associated evaporation and weed growth.

North of O'Sullivan Dam and east of the Potholes Canal, Project land is served by pumping out of Lake Roosevelt behind Grand Coulee Dam. O'Sullivan Dam captures most of the surface- and ground-water loss from irrigation north of the Frenchman Hills. Water is delivered for irrigation in the south part of the Project via the Potholes Canal system. This feature raises the overall efficiency of the Project so that only 4 acre ft of water annually must be pumped out of Roosevelt Lake for every acre irrigated on the entire Project.

During the early years of development, the large quantity of water that percolated into the ground was readily accepted by the permeable facies of the flood outwash deposits, with perched water tables rapidly forming on underlying sediments or bedrock of much lower permeability and subsequent movement toward lower lying outcrops. Less permeable surface soils would transmit water more slowly, with less likelihood of perched water table development.

In the Quincy basin the entire geologic profile had sufficient vertical permeability to permit very rapid rises of the water table within the basalt bedrock which has a very low storage coefficient. In some places the water table rose more than 150 ft in the first year.

South of the Frenchman Hills, much of the land is underlain by thick Ringold Formation sediments having low vertical permeabilities and high storage capacity. In this setting it took several years of irrigation to saturate the sediments. After saturation, perched water bodies developed on horizontal barriers (aquitards), and springs emerged on hillside outcrops. Water-table rises in the bedrock were far less spectacular than those in the Quincy basin (Figure 13).

DRAINS

Design Considerations

The purpose of irrigation drainage is to control the depth of the water table below irrigated land so that the moisture content of soil in the root zone is not excessive and so that a net discharge of ground water into a deep drainage system maintains a level of soil salinity that will not interfere with crop productivity. Natural deep drainage is adequate at many locations. Where it is not, drain systems must be constructed.

Parameters which must be considered for design of drains are: hydraulic conductivity of the soil profile (at least the top 12 ft), depth to a barrier (i.e., major decrease in hydraulic conductivity), amount of irrigation water which infiltrates the soil in excess of the consumptive use, and the water table depth which will be needed to control the moisture content of soil in the root zone. With the use of these parameters and an assumption of a 4-ft minimum water table depth at the midpoint between drains, an effective Project drain system of buried parallel pipe drains can be designed. The spacing between drains varies with the hydraulic conductivity of the soil profile, the depth to barrier, and the efficiency of irrigation. A typical drainage installation would have buried drain pipes at a depth of 8 ft below the surface, laid parallel to other drains about 200 to 500 ft apart. The depth to barrier is the predominant factor is determining drain spacing. A barrier at a depth less than 12 ft will usually result in an uneconomically close spacing.

With only 7 months of irrigation per year, the design can be adjusted to allow for a rise in water table from its low in the spring to the minimum of 4-ft depth in the fall.

Complicating factors that must be accounted for in some drain fields are: sloping land surface, vertical hydraulic conductivity less than horizontal conductivity (anisotropy), downward leakage through the barrier, upward flow from an underlying artesian water source, and high soil capillarity. It is also necessary to determine which areas will be either partially or totally self-draining so that funds for drain construction can be properly timed and distributed to locations of need.

Outlets for the drain systems require the maintenance of a channel whose water surface is low enough to empty the drain pipes. If this is impractical, the drain discharge must be pumped into a shallower waterway.

Investigation and Construction

The first drainage-related construction was the drilling of 50-ft-deep observation wells on a 2-mi grid. Bedrock was penetrated for only 5 ft where encountered. Only 2 of these approximately 250 wells contained water before irrigation was started. All observation wells were measured monthly after the water table rose into them. These data were used to forecast the time when drainage construction would be needed and to observe the hydrologic characteristics of the soil profile.

During the 1950s the primary emphasis of the Project was the establishment of an open discharge system, in many places requiring the enlargement of distribution system wasteways. There were also a few interceptor drains constructed where perched water tables emerged. The 1960s saw an accelerating program of buried concrete drain tile 6 to 15 in. in diameter and in 18-in. lengths with unsealed joints. These were enveloped in a graded gravel filter.

The 1970s saw the increasing use of perforated plastic drain pipe placed in a graded gravel envelope. Concrete pipe usage was limited to large-size buried outlets.

There are now 1,200 mi of open drain and wasteways and about 2,500 mi of buried pipe drains on the Project. The drainage construction is expected to be completed for the presently developed 557,419 acres in the 1990s.

On the average, in the first 5 yr of irrigation, drainage problems are usually associated with excessive distribution-system losses. Losses from laterals or canals can be reduced by lining, or drainage construction may be expedited to relieve the problem.

In the second 5 yr, the water table rises, and drains are needed in low-lying areas. The Project history shows that between 10 and 20 yr after development, the water table becomes stabilized and that the extent to which drain construction is necessary can be finally determined, unless irrigation practices and cropping are significantly changed.

Artesian Drainage Relief Wells

Between Quincy and Winchester, in the northwest part of the Quincy basin, canal seepage combined with deep percolation of irrigation into the ground on land above the West Canal developed a high water table which continues southward through a gently dipping aquifer in the basalt. Below the West Canal, this aquifer is partially confined, resulting in an artisan pressure under land below the canal. The upward percolation of ground water, in response to a hydraulic gradient vertically upward, had the effect of a very shallow barrier. Consequently, an installed drainage system did not work. This problem was solved by the installation of six artesian relief wells, which have effectively reduced artesian head so the drain system can function normally.

USE OF PROJECT GROUND WATER ON NON-PROJECT LAND

When the areas to be served by the Columbia Basin Project were formulated and construction scheduled, certain areas were designated as "deferred and by-passed" where soil, elevation, or slope were such that irrigation technology could not provide an economic return. For example, land west of the Winchester Wasteway and land between Interstate Highway 90 and the Frenchman Hills Wasteway are sandy soils more or less reworked by the wind into dune topography and, therefore, were by-passed. However, after 15 to 20 yr of irrigation on the lands north and west of this area, it became apparent that an enhanced ground-water resource was becoming available and that the sandy soils are ideal for the use of newly developed automated pivot sprinkling systems. These systems not only made it possible to efficiently irrigate sandy soil, but the high infiltration rate was an advantage for this type of irrigation. Consequently, land owners in the sandy areas developed wells capable of utilizing the enhanced ground-water supply which is now sustained by continued movement of ground water from irrigated Project lands.

The regulations governing ground water in the State of Washington (State of Washington, 1984) include a provision for an entity that imports water for irrigation purposes to retain ownership of ground water resulting from its irrigation development, provided that the entity has the facilities to recover the ground water and redistribute it beneficially for the purpose for which it was withdrawn.

In the case of the Quincy basin, the O'Sullivan Dam and the Potholes Canal System which it serves are dependent on the return flow from Project irrigation in the

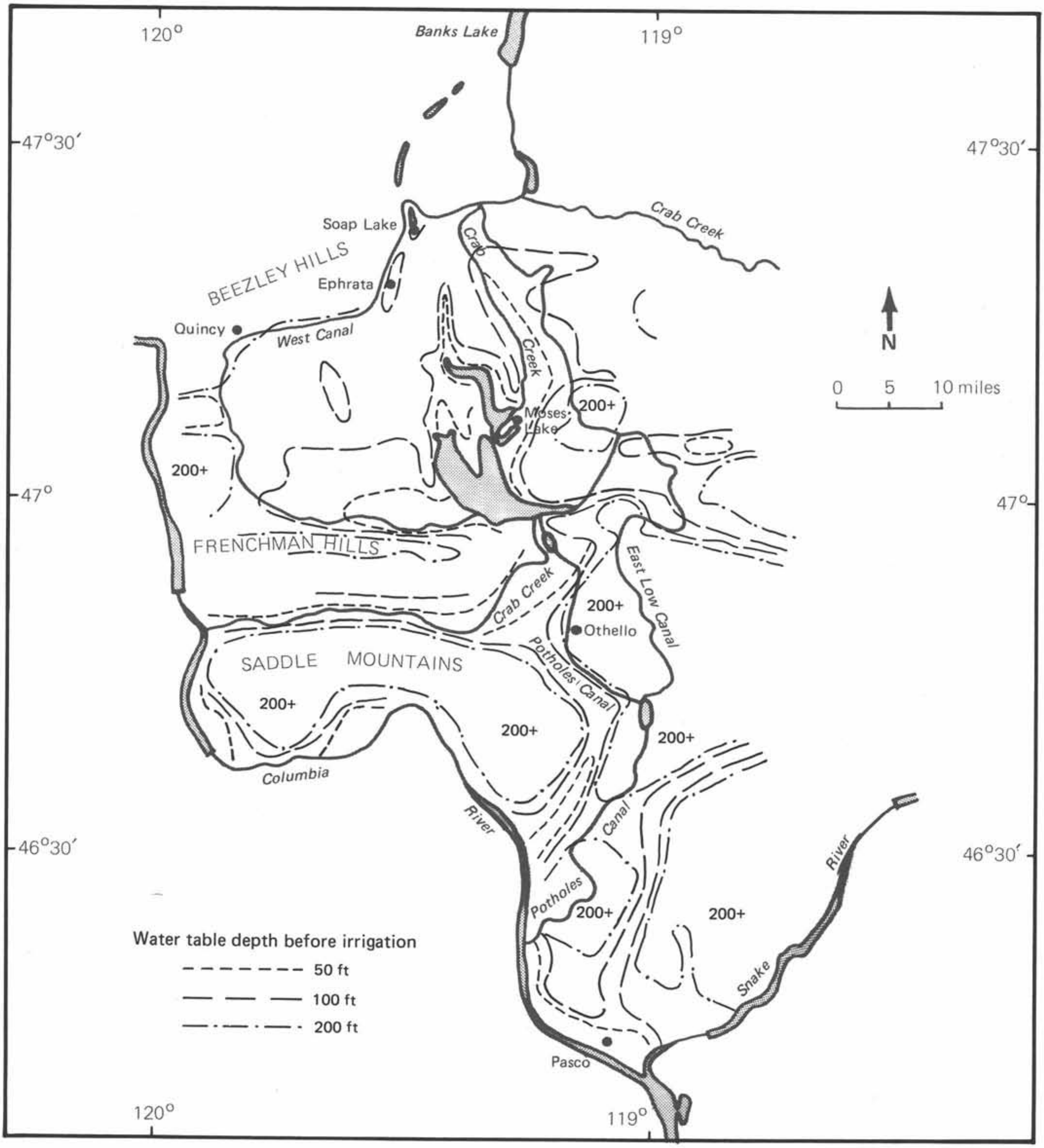


Figure 12. Pre-irrigation water-table depths in the Columbia Basin Project area.

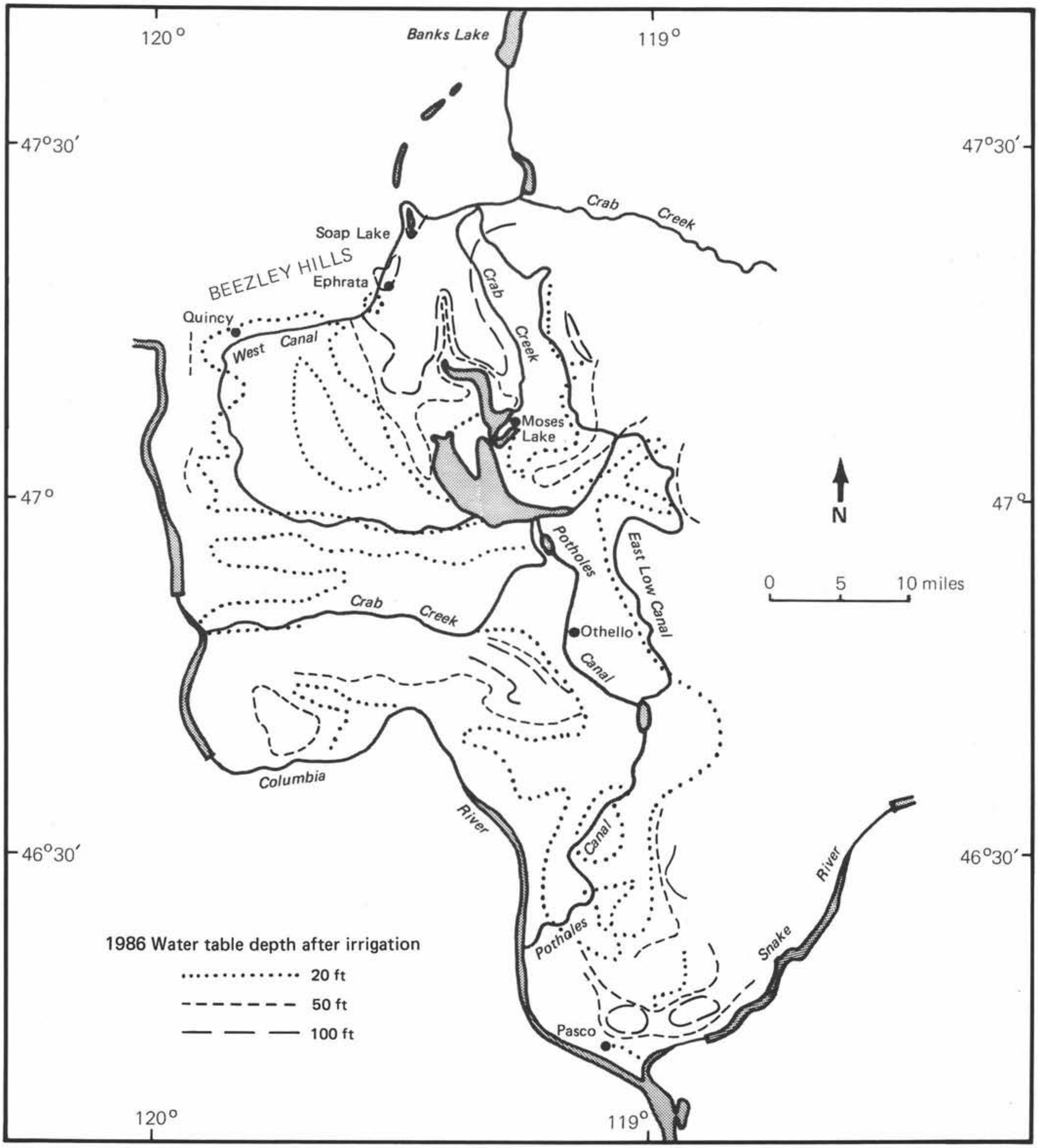


Figure 13. 1986 water-table depths in the Columbia Basin Project area.

Quincy basin to meet the demands of the system. The pumping of return flow water from the ground in the Quincy basin increases the quantity of water that must be pumped from Lake Roosevelt to supplement the Potholes Reservoir water supply.

A cooperative investigatory program among the U.S. Bureau of Reclamation, the Department of Ecology of the State of Washington, and the U.S. Geological Survey utilized ground-water records from 1916 to 1950 to establish the pre-irrigation status. Extensive ground-water measurements made after 1950, which recorded the ground-water elevation response to irrigation development, were assembled to construct a model that duplicates hydraulic changes observed in the field. In addition, test wells were sealed into the underlying basalt to determine the degree of water movement between the basalt and the overburden. A determination was then made as to what portion of the ground-water supply is natural and what part is Project return flow. A licensing arrangement was then implemented whereby non-Project irrigators can buy Project ground water from the U.S. Bureau of Reclamation for a fee determined from the annual irrigation operation and maintenance costs of the Project.

A similar water-purchasing operation is in place on sandy land north of Pasco and south of the Esquatzel Coulee Diversion Dam. The U.S. Army Corps of Engineers' McNary Reservoir is contained behind a dike west of Pasco to protect developed rural residential land. The seepage from the reservoir had to be pumped back over the dike into the reservoir to protect low-lying land behind the dike. When Project return flow raised the water table north of Pasco, the pumping behind the dike could not keep the bottom land dry, so a landward extension of the Corps of Engineer's drainage system was built to intercept the Project return flow. In addition, the emergence of a stream below the Esquatzel Diversion Dam was adding ground water to the problem. To take care of this, the Bureau of Reclamation built a pumping plant to return this flow of water to the Esquatzel Diversion Canal. While this was happening, land owners in the sandy area were developing pivot irrigation systems and drilling wells. They soon experienced rapid declines in their ground water levels, causing them to pursue efforts to regulate pumpage in the area. The problem was resolved with the establishment of a licensing system through the United States Bureau of Reclamation and the Washington State Department of Ecology. The drainage pumps in the residential area of West Pasco are no longer necessary.

OFF-STREAM HYDROPOWER DEVELOPMENT

General

Opportunities for power generation within the distribution and waste system of the Columbia Basin Project were considered during design studies of the primary features. However, with a regional power surplus coinciding with the summer production of power from the irrigation system, off-stream power production was judged to be economically infeasible.

In recent years, the comparatively high cost of thermal power generation, the intertie with California, the increase in summertime load, and the end of large on-stream hydropower development have resulted in a favorable economic basis for hydropower development at selected locations on the Project irrigation system.

The initiative for construction of these power plants is credited to Russell D. Smith, Secretary-Manager of the South Columbia Basin Irrigation District. The end result provides significant benefits for the power consumers, Seattle City Light, Tacoma City Light, and Grant County Public Utility District #2, as well as for the farmer participants of the Quincy Columbia Basin Irrigation District, the East Columbia Basin Irrigation District, and the South Columbia Basin Irrigation District. The South District has operating responsibility for the Main Canal Headworks, Summer Falls, Russell D. Smith, EBC4.6, and PEC66 power plants, which deliver power to Seattle and Tacoma. The Grant County Public District #2 operates the Quincy Chute and PEC Headworks plants.

Main Canal Headworks Power Plant

Located at the Main Canal Headworks in Dry Falls Dam, using a bulb type turbine with a drop of 42 ft, this facility was completed in 1984 (Schuchart/Harza, 1987).

The powerhouse foundation penetrates 109 ft of basalt bedrock at the sump. A 340-ft-long outlet channel, capable of carrying 8,020 cfs when generating a maximum 26.8 MW, discharges into the Main Canal. Three NX boreholes, inclined 30 degrees from vertical, were drilled and pressure tested to supplement investigative data associated with the Dry Falls dam construction. The foundation excavation penetrates 80 ft of Priest Rapids Member and 25-30 ft of the porphyritic Roza Member of the Wanapum Formation. The intervening interflow zone, 2 to 12 ft thick, consists of palagonitic pillows of the overlying Priest Rapids lava flow, which penetrated and mixed with diatomaceous sediments. The scoriaceous crust of the underlying Roza Member is mixed with masses of semiconsolidated diatomaceous earth. The powerhouse excavation bottoms in the entablature of the upper Roza Member.

Design changes resulting from geologic mapping and inspection of excavated rock faces consisted of additional rock excavation at the bridge abutment, intake, and tailrace channels and the placement of a concrete slab across the tailrace to cover weak rock. The entablature of the Priest Rapids Member required extensive rock bolting on 10 ft centers and 10 to 40 ft long to secure the excavation slope at 1 ft horizontal for every 10 ft vertical. A single-row grout curtain extends across the foundation upstream of the intake structure and ties into the pre-existing Dry Falls Dam grout curtain. A ground-water inflow of 150 gpm entered the foundation excavation from the interflow zone and from over-drilled blast holes into the Roza Member. This problem responded satisfactorily to grouting.

Summer Falls Hydropower Development

Project Description

Located on the Main Canal 8 mi south of Dry Falls Dam and power plant, the Summer Falls power plant utilizes a 165-ft drop into Billy Clapp Lake (Schuchart/Harza, 1987).

The development consists of: (1) modification of the Main Canal above the falls, (2) a concrete gravity diversion dam, (3) a 700-ft-long concrete-lined intake channel, (4) a transition intake structure, (5) two 17-ft-diameter vertical drop shafts 130 ft deep, (6) two 17-ft-diameter power tunnels, 700 ft long, (7) a powerhouse with two 42.5-MW Kaplan generators with tailrace, and (8) cofferdam for tailrace, and powerhouse foundation excavation.

Geologic Setting

The site is located at the juncture of the flat-lying lava flows of the Hartline structural basin floor and the faulted toe of the north limb of the Pinto structural dome (Figure 14).

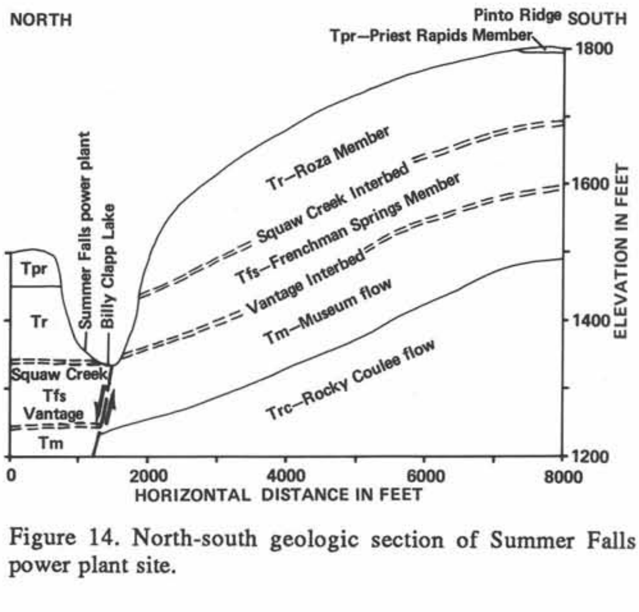


Figure 14. North-south geologic section of Summer Falls power plant site.

The Hartline basin accumulated Pliocene and Pleistocene sediments before the flood waters stripped them away. Flood waters from Lake Missoula filled this basin to a depth of more than 300 ft at this location and discharged southward through three coulees, the Soap Lake section of the Grand Coulee, the Dry Coulee trench, and the Billy Clapp Lake trench. Headward erosion of the Billy Clapp trench extended westward in the fractured bedrock at the north edge of the Pinto dome. The Main Canal drops from the resistent, flat-lying basalt flows of the basin floor into the westward extension of Billy Clapp Coulee (formerly Long Lake Coulee). The basalt profile above the powerhouse foundation consists of three Wanapum flows, the Priest Rapids flow, the Roza flow, and the Frenchman Springs flow. The coulee bottom is blanketed with flood-deposited coarse gravel.

Investigations and Construction

Geological investigations included surface geology mapping, seismic profiling, geophysical refraction surveying, bathymetric profiling, drilling, water testing, auger hole drilling, and digging test pits.

Construction was performed from 1982 to 1984. Grout curtains were installed at the intake structure and the check structure, and contact and consolidation grouting were utilized in the powerhouse tunnels, shaft, and check structure. Shotcrete was used to stabilize the interflow zones in the drop shafts and to stabilize the rock cliff above the tunnel portals and powerhouse excavation. Weep holes were drilled in the shotcrete. Extensive rock bolting was used to prevent rock-falls from the thicker rock units. Portions of the tunnels required support.

Water inflows were minor. Artesian pressure was encountered in the top of the Frenchman Springs basalt below the powerhouse foundation. The overlying interbed sediments (Squaw Creek) were excavated to provide suitable foundation under the upstream side of the powerhouse. Six foundation caissons were drilled into the bedrock under the downstream side of the powerhouse.

The Squaw Creek interbed was exposed on the east side of the tailrace where shotcrete and rock bolting were employed as necessary. A permanent cofferdam forms the west side of the tailrace.

Russell D. Smith Power Plant

The Russell D. Smith power plant is located 7 mi southeast of the City of Othello. Situated below a major concrete drop structure on the Potholes Canal, a diversion feature carries the canal flow into the penstock, which drops the water 52 ft into a 6.1-MW horizontal, air-cooled Leffel-GE turbine-generator assembly which has a maximum discharge capacity of 1,700 cfs. A tailrace returns the water to the Potholes Canal below the canal check structure.

The entire construction area is underlain by lake-bed sediments of the Ringold Formation which pre-date the uplift of the Saddle Mountains and Frenchman Hills. These sediments consist of semiconsolidated light-brown to light-gray, sub-angular particles with a general absence of basalt. It is apparent that the primary source of these deposits was water transportation of detritus from highlands surrounding the basalt basins and eolian transportation of acidic volcanic ejecta from the active Cascade Range.

Construction experiences with this formation indicated that it has adequate bearing strength for structures of this magnitude.

The water table is controlled by the water surface of the Potholes Canal below the drop. Irrigation north of the site maintains a ground water gradient such that drainage construction is required about 1 mi away. No perching of ground-water is observed in this vicinity. Consequently, the excavated surface for the powerhouse is saturated, but the sediments are dry a few ft above the base.

EBC 4.6 Power Plant

Located at mile 4.6 on the Eltopia Branch Canal 6 mi southwest of the town of Mesa, the EBC 4.6 power plant diverts canal water into an intake structure at the top of a pipe drop to a turbine generator which discharges water back into the canal at the bottom of the drop structure. The effective head of 127 ft and discharge capacity of 226 cfs provides a capacity of 2.2 MW.

The geologic setting described for the Russell D. Smith plant applies at this site. However, in this location the powerhouse and tailrace excavation closely approach the contact of the Ringold Formation with the underlying Saddle Mountains Basalt. The uppermost lava flow is moderately permeable as demonstrated by the fact that numerous pothole depressions on adjacent farms do not accumulate irrigation water. Consequently, the water table at the powerhouse conforms with the canal water surface.

PEC 66 Power Plant

The PEC 66 power plant at mile 66 on the Potholes Canal utilizes a canal drop 11 mi northwest of Pasco. The intake structure diverts canal flow into the penstock at the top of the steep hill and drops it 320 ft to the turbine-generator, which discharges into a stilling pool where the canal water is divided. A portion of the canal water enters the Pasco Wasteway, which drops into the Columbia River; the other portion passes into the supply lateral for irrigation farther south.

The geologic setting is similar to that at the two sites previously described.

Quincy Chute Power Plant

Project Description

Located 6 mi south of the town of Quincy on the West Canal, this plant utilizes the 56-ft vertical drop of the Quincy Chute. A gated check structure at the top of the chute is by-passed on the east side by an intake for the penstock pipe. On the west side of the check, a broad-crested spillway stands ready to divert water around the check if the power plant shuts down or slows. At 1,600 ft south of the intake, the penstock drops to the powerhouse which has an installed capacity of 9.4 MW with the passage of 2,200 cfs flow. The tailrace is 3,600 ft long, and it discharges below the end of the Quincy Chute.

Geologic Setting

The Quincy Chute Hydroelectric Project is constructed on a very old, deeply weathered surface. The soil, a saprolite, is residual to the underlying Priest Rapids Member of the Wanapum Basalt and represents a history of slightly elevated, uneroded, residual soil development over the period during which the Ringold Formation was being deposited in the Quincy and Pasco basins. The late Pleistocene cover of wind-deposited soil (loess) was removed by glaciofluvial flood waters associated with the adjacent scabland complex, leaving the slightly scoured older surface exposed.

This soil development took place as the local climate changed from warm-moist temperate to semiarid. A high water table with high evapo-transpiration discharge can be presumed until Pleistocene runoff established major stream courses. Therefore, the soil profile is characterized by a massive accumulation of calcium-carbonate cementation (caliche). Total depth of the soil profile is about 40 ft. As bedrock is approached, the soil is logged as sand, gravel, and cobbles; the cobbles are the result of spheroidal weathering of the unjointed interiors of basalt columns.

Geotechnical investigations (Davis, 1982) consisted of digging 7 test pits, drilling 19 holes, 6 of which were cored in rock, and installing PVC pipe to monitor ground-water fluctuations.

Construction Excavation

The penstock section is excavated into calcareous, gravelly, sandy silt that is as much as 10 ft deep for most of the penstock length. The final 100 ft cuts downward through a 10-ft-thick bed of massive caliche, 20 ft of basaltic gravelly sand (weathered basalt), and into the basalt bedrock of the Wanapum basalt on which the powerhouse is built. The penstock is completely covered with fill.

The powerhouse excavation penetrates the bedrock to a depth of about 30 ft. Bedrock is a dense, closely jointed, non-vesicular basalt; slight weathering is associated with vertical joints, which are typical of columnar structure. Closely spaced horizontal joints are characteristically associated with very large columns. A small flow of ground water enters the powerhouse excavation at the northeast corner above the bedrock. The low permeability of the profile is demonstrated by the widespread perching of surface water in the surrounding area and meager discharge of ground water into the cut.

The tailrace is a concrete box flume continuously excavated into bedrock to its terminus below the end of the Quincy Chute.

PEC Headworks Power Plant

Project Description

Located 12 mi south of the City of Moses Lake on the east side of the headworks of the Potholes Canal in O'Sullivan Dam, the PEC Headworks Hydroelectric power plant will draw water from the Potholes Reservoir at a maximum rate of 2,800 cfs and utilize a drop of 30.6 ft to produce 7 MW (Schuchart/Harza, 1981). This facility is under construction at the time of this writing (1987). The contractor is approaching the end of the excavation phase and the beginning of the construction phase.

An explanation of the name is appropriate. On the original conception of the canal locations outletting the Potholes Reservoir, there were (1) the Potholes East Canal outletting from the east end of what was then Potholes Dam, and (2) the Potholes West Canal outletting the reservoir at the west end of the Potholes Dam. Later, the name of the Potholes Dam was changed to O'Sullivan Dam to honor a promoter of the Columbia Basin Project. The Potholes West Canal location was abandoned in favor of an eastward extension of the West Canal on the Royal Slope. Subsequently, the now meaningless Potholes *East* Canal (PEC) has become the Potholes Canal by popular usage, but the legal designation of rights-of-way continues to use PEC as the feature name.

Geologic Setting

At this location, the O'Sullivan Dam abutment consists of a natural bedrock section in which the canal headworks and the PEC Headworks Power Plant are located. The excavation penetrates the Roza flow of the Wanapum Basalt; this flow is characterized by numerous 3/8-in. feldspar phenocrysts. A water-bearing zone with associated entablatures and colonnades is encountered 35 ft below the crest of the dam. This zone has the appearance of an intraflow vesicular zone which is a characteristic of the Roza flow.

At this location the Frenchman Hills uplift is a gentle anticline whose north flank is flattened and slightly reversed by overthrusting. The north limit of the structure, about 1/4 mi north of the headworks, is a small recumbent overthrust that causes a reversal of dip at the dam site. The diastrophic stresses associated with the formation of the anticline caused secondary shearing and jointing of the rock with increases in permeability and acceleration of weathering processes.

Design and Excavation

Three NX-size core holes, inclined 30 degrees from the vertical, were completed. Each hole was pressure tested to develop representative permeability values for the rock units. An open cut scheme was adopted because of the close-spaced joints found by the drilling.

An approach channel, which is presently a natural-rock cofferdam, leads to the powerhouse, which straddles the centerline of the dam. The tailrace conveys the discharge to the Potholes Canal below the headworks. Ground water is cascading from the east face of the powerhouse excavation north (upstream) of the dam's grout curtain. However, the excavation wall is standing nearly vertical, and the total flow does not appear excessive.

PROJECT PLANS

Proposals to continue construction of the remainder of the Columbia Basin Project have been placed in abeyance. The work now being carried out is that necessary to complete service to the currently irrigated area. Construction of drainage facilities is the present thrust of the project.

ACKNOWLEDGMENTS

I wish to express special appreciation for manuscript review to this centennial volume's editor, Richard Galster, Seattle, Washington, to Merle R. Gibbons, manager of the South Columbia Basin Irrigation District, Pasco, Washington, and to Brent Carter, U.S. Bureau of Reclamation, Boise, Idaho.

REFERENCES

Baker, V. R., 1973, *Paleohydrology and Sedimentology of Lake Missoula Flooding in Eastern Washington*: Geological Society of America Special Paper 144, 79 p.

Bretz, J H.; Smith, H. T. U.; and Neff, G. E., 1956, *Channeled Scabland of Washington—New Data and Interpretations*: Geological Society of America, Vol. 67, pp. 957-1049.

Davis, K. A., 1982, *Geotechnical Investigation, Quincy Chute Hydroelectric Project*: CH$_2$M HILL, Seattle, WA, 14 p.

Schuchart/Harza, 1987, personal communication, Summer Falls field office records.

Schuchart/Harza, 1981, *Geologic/Geotechnical Investigation, Potholes East Canal (P.E.C.) Headworks Hydroelectric Project*: Harza Engineering, Seattle, WA, 8 p.

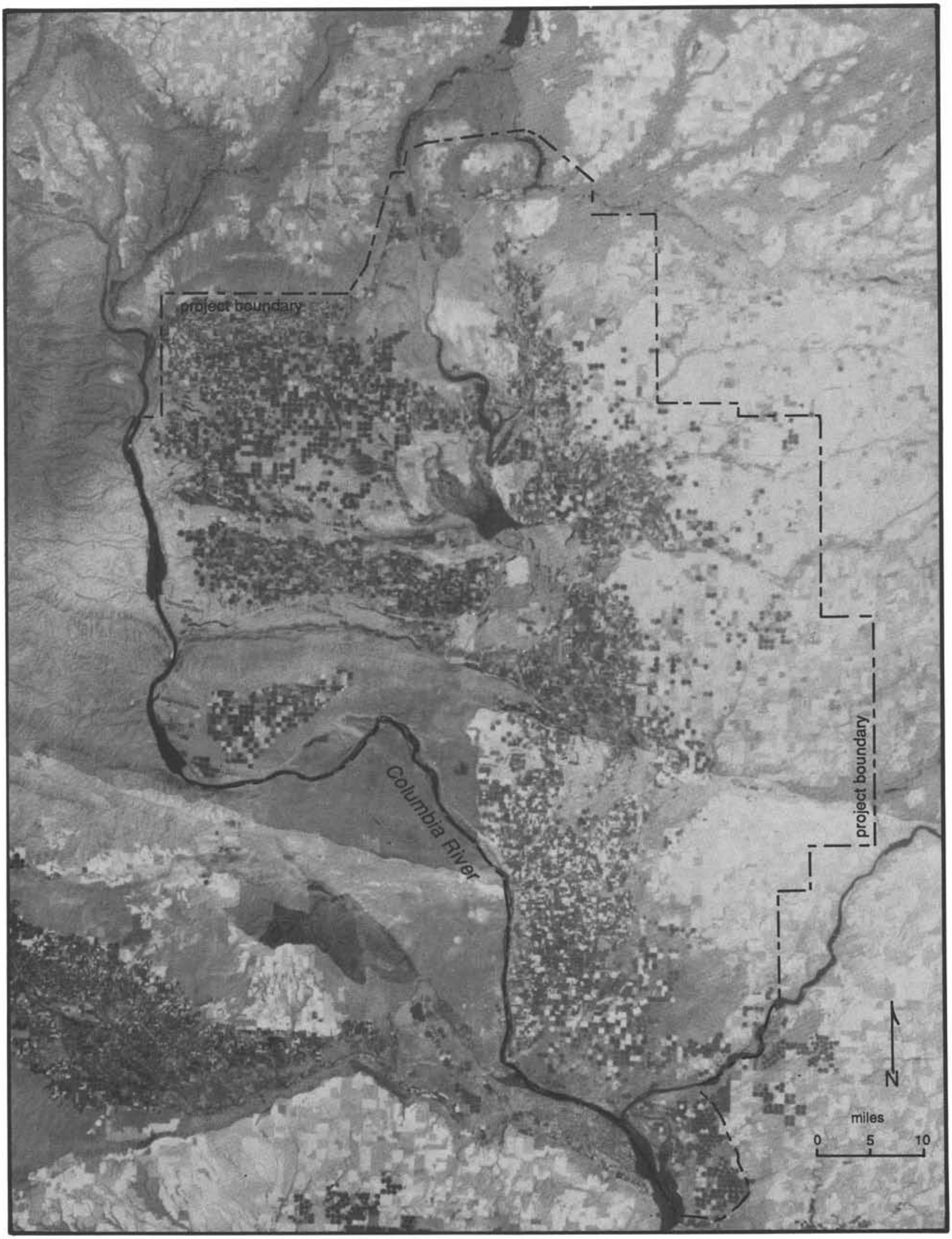
State of Washington, 1984, *Laws and Regulations, Water Resources*, Chapter 173-134A, 5 p.

U.S. Department of Energy, 1984, *Draft Environmental Assessment; Reference Repository Location, Hanford Site, Washington*: Office of Civilian Radioactive Waste Management, Washington, DC, Chapter 3, The Site, 156 p.

U.S. Bureau of Reclamation, 1976, *Final Environmental Impact Statement, Columbia Basin Project, Washington*: Vol. 1, Chap. 1, 150 p.; Chap. 2, 186 p.; Chap. 3, 156 p.; Chap. 8, 55 p.

Walters, K. L. and Grolier, M. J., 1960, *Geology and Ground Water Resources of the Columbia Basin Project Area, Washington*: Washington Division of Water Resources Water Supply Bulletin 8, Vol. 1, Olympia, WA, 542 p.

View to the north of the Soda Lake depression before it was filled by the Potholes Canal in 1952. The crest of the Soda Lake dike crosses the bottom of the photograph. Photograph by George Neff.



Satellite image of the Columbia Basin Project area; courtesy of George Neff.

Nuclear and Coal-Fired Facilities in Washington

Dennis R. McCrumb, Chapter Editor

Nuclear and Coal-Fired Facilities in Washington: Introduction

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INTRODUCTION

During the early 1970s many of the electric utilities in the United States were projecting a severe energy demand for the remainder of the century. In the Pacific Northwest, the utilities were in a unique and potentially precarious position: While the region was endowed with an abundance of hydroelectric power, it did not contain vast amounts of other energy resources that some other areas possessed. In fact, while some feasible dam locations still existed for the expansion of hydroelectric power, the majority of the sites on the Columbia and Snake rivers had been developed. Also, due to growth and increased environmental concern within the area, many of the remaining feasible dam locations were protected in other ways, such as utilization by agriculture and recreation. As a result the utilities began to explore ways in which to maximize and expand the existing power base. This generally resulted in schemes that would increase the base load through development of thermal power plants and thus help compensate for power shortages during dry years or provide for more use of existing hydroelectric capacity as peaking power.

This energy demand was also projected by the U.S. Atomic Energy Commission (AEC) (AEC, 1971, 1973, 1974), and the nuclear option for power generation was favored by many utilities due to the potential benefits provided the utilities. In the United States at that time, 42 nuclear power plants were licensed to operate, 56 nuclear plants were under construction, and 101 nuclear plants were on order (AEC, 1973). In addition, the nuclear power program was receiving wide acceptance throughout the United States and because of the projected energy crises, then President Richard M. Nixon in his November 7, 1973, television address to the nation on the energy crisis, announced that he was requesting the AEC to speed up the licensing of nuclear power plants in order to shorten from 10 yr to 6 yr the time required to bring plants on line. At that time the projected installed electric generating capacity for the United States for the year 2000 was 2 million megawatts with 1.2 million megawatts, or more than half, provided by nuclear power plants (AEC, 1973).

One of the key factors in this licensing process was the safety analysis report, in which engineering geology played a major role. The safety analysis reports required comprehensive geotechnical investigations. These investigations resulted in the integration of information from many disciplines, including those of the earth sciences, environmental sciences, and engineering. The combined factors relating to the electric utility industry in general and the nuclear industry in particular, resulted in many significant engineering geology investigations in the state of Washington.

This chapter deals with investigations at four locations in Washington where investigators have made a significant contribution to the practice of engineering geology and the state of Washington in the areas of geologic site assessment, geologic hazard evaluation, seismicity, tectonics, and engineering geology. The information provided by the papers in this chapter represents only a small portion of the data generated by these and other similar projects. The material generated by investigations from the siting, characterization, and construction of thermal generating facilities and other nuclear projects in the Pacific Northwest is extensive and could not be thoroughly represented in this chapter. Many other investigators involved in these and other projects have made significant contributions to the literature on engineering geology in Washington.

This chapter consists of two papers on nuclear power plant sites, one on the operation of a coal power plant, and a summary of the history of investigations at the Hanford Reservation in eastern Washington. The nuclear power plant projects are the Skagit site north of the Seattle area and the Satsop site west of Olympia. The paper on the major fossil fuel power plant is based on operations at the coal-fired power plant operated by the Washington Irrigation and Development Company (WIDCO) near Centralia. The paper on the Hanford Reservation discusses investigations that occurred from the 1940s through the 1970s. This area has been referred to as a nuclear park and is where the nuclear industry in Washington first began.

The paper on the Skagit site by Adair, Talmage, Crosby, and Testa provides a synopsis of the geologic investigations conducted at a proposed nuclear power plant site northeast of Seattle. The Skagit site paper includes a summary of results from several investigations, including geologic setting, regional seismicity, earthquake design parameters, and volcanic hazards. Investigations began after site selection was completed in 1972 and continued through the 1970s until the project application was withdrawn in late 1980. This report provides insight into the licensing process of critical facilities and how this process may result in significant delays, which may eventually cause the termination of the project.

The paper on the Satsop power plant by McCrumb, West, and Kiel provides a summary of some of the results from the geologic and seismologic investigations at the Washington Public Power Supply Systems (WPPSS) project west of Olympia. Investigations at Satsop began in 1973 and are ongoing for one of the units. Full-scale construction of the dual-unit reactor site began in 1977 and was halted after the utility experienced financial difficulties in the early 1980s. The first unit at the power plant site is currently in a long-term construction delay with the unit at about 76 percent completion. The second reactor unit at the site was canceled in 1985 with the unit about 56 percent complete.

The paper by LaSalata provides a summary of the geologic and geotechnical considerations that are inherent to operations at a coal mine such as that at Centralia. The complexity of issues that an engineering geologist must deal with are discussed in terms of geologic structure, geologic material, and geotechnical considerations which affect mine operations.

The paper by Tillson provides a brief history of the investigations that were conducted at the Hanford Reservation for numerous nuclear facilities that include the Fast Flux Test Facility (FFTF), Department of Defense production reactors, and the WPPSS nuclear projects at that location. Although the investigations began before engineering geology was recognized as an independent profession, the contribution of engineering geologists played a major role in the early investigations and the growth and development of engineering geology.

As the development of the nuclear power industry continued during the 1960s and 1970s, the practice of engineering geology was changed dramatically. This change was due to a great extent by the changing regulatory environment in the nuclear industry during this period. Today, the investigation of most large engineering projects is a multi-disciplinary activity that requires the integration of specialized disciplines with the more traditional practice of engineering, seismology, and geology. The geotechnical investigations that have taken place at the sites covered by the papers in this chapter illustrate the high degree of professionalism in the engineering geologic community in Washington. Even though the period that these investigations span includes a dramatic change in the regulatory environment for nuclear facilities and significant additions to the state of knowledge of Washington's geology, the results continue to stand up and provide a significant resource for investigations in these areas and for future similar projects.

REFERENCES

U.S. Atomic Energy Commission, 1971, Forecast of Growth of Nuclear Power, January 1971: U.S. Atomic Energy Commission, Division of Operations Analysis & Forecasting, Wash-1139 (TID-4500), 187 p.

U.S. Atomic Energy Commission, 1973, The Nuclear Industry 1973: U.S. Atomic Energy Commission, Wash 1174-73 , 101 p.

U.S. Atomic Energy Commission, 1974, Nuclear Power Growth 1974-2000: U.S. Atomic Energy Commission, Office of Planning and Analysis, Wash-1139 (74), 74 p.

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Geology and Seismic Considerations of the Hanford Nuclear Site

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INTRODUCTION

This paper presents a limited historical synopsis of critical facility siting at the U.S. Department of Energy (DOE) Hanford Reservation in southeastern Washington. A summary of the regional and local geologic setting and a summary of the contemporary geologic investigations that were conducted for the Fast Flux Test Facility and Washington Public Power Supply System (WPPSS) nuclear reactors are presented. The investigations described were conducted for the purpose of meeting U.S. Nuclear Regulatory Commission (NRC) requirements for licensing and to provide geotechnical input for facilities design as stipulated in NRC Regulatory Guide 1.132, "Site Investigations for Foundations of Nuclear Power Plants" and Regulatory Guide 4.7, "General Site Suitability for Nuclear Power Stations". The results of these investigations are documented in the Preliminary Safety Analysis Report (PSAR) for WPPSS nuclear power plants WNP-2 (1972) and WNP-1/4 (1974); the Final Safety Analysis Report (FSAR) for WNP-2 (1978, 1981); and in Puget Sound Power and Light (PSP&L) PSAR for nuclear power plant SHNP-1 (1981). Except where otherwise noted, the discussion presented in this paper is derived from those sources. Because of a lack of geologic hazards from surface faulting, landslides, or liquefaction and because of the excellent and fairly uniform geologic conditions at all the Hanford sites investigated, the focus of this paper is on the seismic hazards and the development of the design earthquake. Some specific mapped geologic structures and special studies performed to address these and other issues are also described. There is no discussion of the Basalt Waste Isolation Program, which was terminated in 1988.

GEOGRAPHIC SETTING

The DOE-operated Hanford site occupies approximately 570 sq mi in the Pasco Basin, part of the Columbia Plateau. The Hanford site is roughly 32 mi north to south and 26 mi east to west (Figure 1). The nearest population center to the Hanford site is the City of Richland, which had a population of about 34,000 in 1980. There are more than 285 mi of paved roads connecting Richland with the site's seven major operations areas. Intensive irrigated farming is carried out along the Yakima River valley to the south of Rattlesnake Hills and to the east on the Columbia Basin Irrigation Project area. West of the Hanford site is the U.S. Army Yakima Firing Center, to which access is restricted (DOE, 1987).

The surface elevation of the Hanford site ranges from about 400 ft (msl) near the WPPSS sites to about 650 ft near the 200 Areas. Gable Mountain, a basalt anticlinal structure in the north-central part of the site, rises to an elevation of more than 1,100 ft. At the northernmost boundary the Saddle Mountains rise to an elevation of more than 2,000 ft. Along the southwestern boundary the Rattlesnake Hills reach an elevation of more than 3,100 ft. The Columbia River flows through the east-central part of the Hanford site at elevations of less than 400 ft. Along the east bank of the Columbia River the land surface rises abruptly more than 400 ft forming the White Bluffs. Along the western boundary of the site is a highland area formed by three west-trending anticlinal ridges that gently plunge eastward and terminate at the site boundary (WPPSS, 1981).

The 200-East and 200-West chemical separations areas are located near the center of the Hanford site on what is commonly referred to as the "200 Areas Plateau" (Figure 1). This part of the site contains the irradiated-uranium-fuels-processing and plutonium-separation facilities and the major radioactive waste-storage and waste-disposal facilities. The nine plutonium producing nuclear reactor areas (100-B/C, 100-KE/KW, 100-N, 100-D/DR, 100-H, and 100-F) are located along the south and west bank of the Columbia River where it makes an abrupt swing to the north and then back to the south. The federal government-operated the Fast Flux Test Facility and the WPPSS-operated nuclear power plant facilities (WNP-2, WNP-1/4) are located in the southeastern part of the site about 10 mi north of Richland. Immediately north of Richland are the main site support services (1100 Area), government research

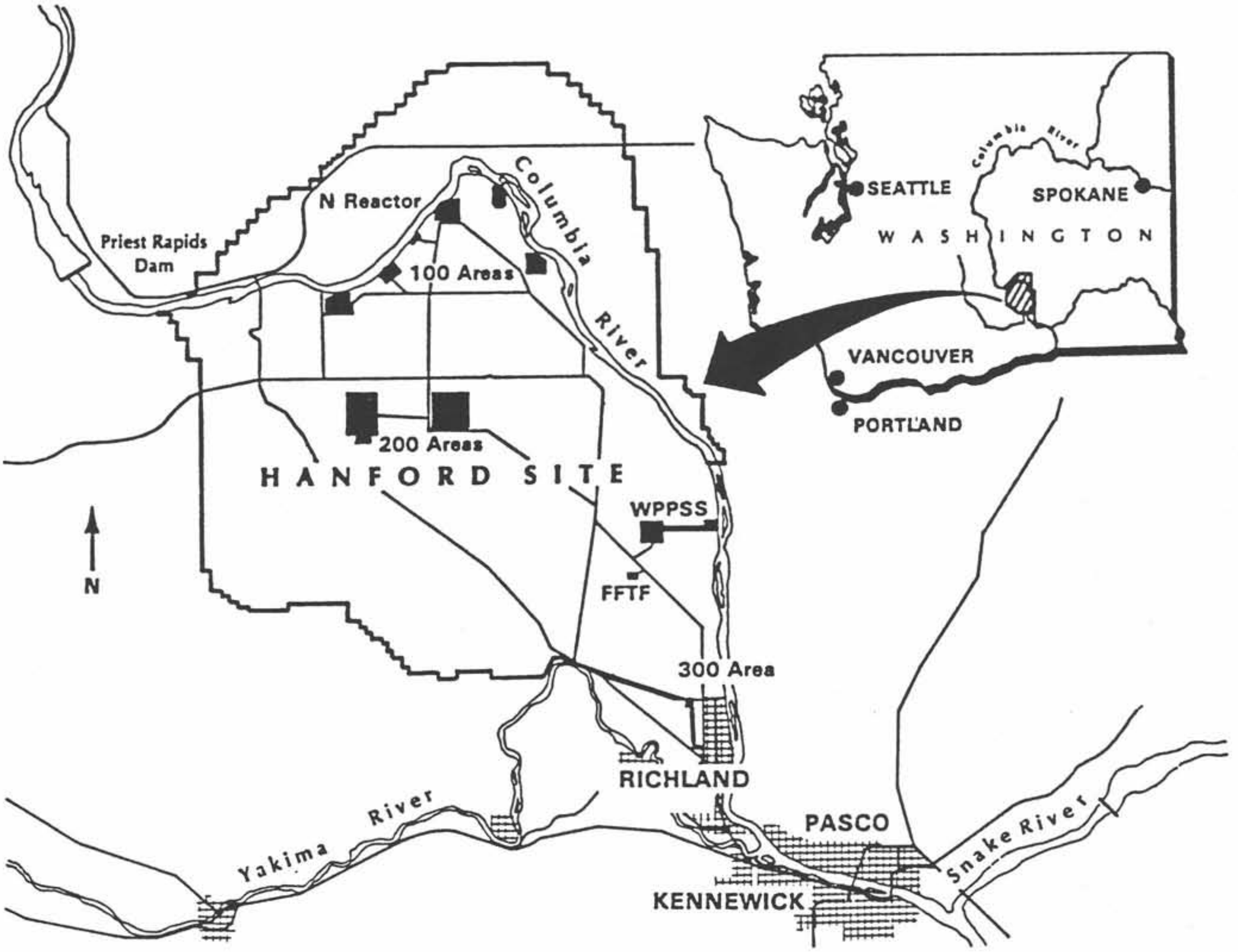


Figure 1. Location of the Hanford Site.

facilities (300 Area), and the private research areas. The 300 Area also houses a nuclear-fuels production facility, a small materials test reactor, and the heavy water Plutonium Recycle Test Reactor.

SITING AND CONSTRUCTION HISTORY

1943 to 1963

In 1943 the U.S. Army Corps of Engineers, in support of the World War II effort known as the Manhattan Project to develop an atomic bomb, selected the Hanford area as the site for the first plutonium production facilities. The area was chosen because of the year-round availability of sufficient water for reactor cooling; electrical power from Grand Coulee dam; a small population to be displaced; and the natural security afforded by the Columbia River and surrounding hills. Eight reactors using a graphite moderated pile with once-through coolant were constructed between 1943 and 1955. The first reactor to begin operation, in 1944, was 100-B. These eight reactors were shut down beginning in 1965; the last to be shut down, in 1971, was 100-B. Also beginning in 1943, companion fuel fabrication plants in the 300 Area and chemical processing plants along with waste-management facilities in the 200 Areas were constructed and operated. The dual-purpose (plutonium production/steam generation) N Reactor began operation in 1963. The N Reactor was also graphite moderated, but instead of once-through cooling, a heat exchanger was used to produce steam. The steam was purchased by WPPSS and used to drive two 425 MWe low-pressure steam turbine generators at their Hanford Generating Project. The N Reactor was placed on standby status in 1988.

Generation of radioactive waste at Hanford began in December 1944 when plutonium from the production reactors was first recovered by processing irradiated uranium in the 200 Area chemical processing plants. The plutonium recovery operations continued through 1972. In 1983, the PUREX Plant (described below) was restarted.

The first chemical processing plants to be constructed were the B and T plants. B Plant was constructed in the 200-East Area between August 1943 and February 1945 and was operated until 1952. T Plant was constructed in the 200-West Area between June 1943 and October 1944 and operated until 1956. These plants separated plutonium from uranium and the bulk of the fission products in irradiated fuel by co-precipitation with bismuth phosphate ($BiPO_4$) from a uranyl nitrate solution. The plutonium was then further separated from fission products by successive precipitation cycles using bismuth phosphate and lanthanum fluoride. The plutonium was isolated as a peroxide and, after being dissolved in nitric acid, was concentrated as plutonium nitrate. Waste containing the uranium from which the plutonium had been separated and the other waste which contained most of the fission products was neutralized and stored in single-shell underground tanks (DOE, 1987).

U Plant in the 200-West Area was originally built as one of three bismuth phosphate process facilities, but it was never used for that purpose. U Plant was extensively modified and used for uranium recovery from the B and T Plant waste. Uranium in waste from the bismuth phosphate process that had been stored in single-shell underground tanks was mined by sluicing, dissolved in nitric acid, and processed through a solvent extraction process using tributyl phosphate in kerosene. The acid waste from the uranium recovery process was made alkaline and returned to the single-shell tanks. The uranium recovery process operated from 1952 to 1958 (DOE, 1987).

The REDOX (S) Plant in the 200-West Area was designed to recover both plutonium and uranium. It used a continuous solvent extraction process to extract these elements from dissolved fuel into a methyl isobutyl ketone solvent. The slightly acidic waste stream contained the fission products and large quantities of aluminum nitrate that were used to promote the extraction of the plutonium from the uranium. The wastes were neutralized and stored in single-shell underground tanks. REDOX was built between May 1950 and August 1951 and operated until July 1967 (DOE, 1987).

The PUREX (A) Plant in the 200-East Area is an advanced solvent extraction process that uses tributyl phosphate in kerosene solvent for recovering uranium and plutonium from nitric acid solutions of irradiated uranium. Nitric acid is used to promote the extraction of uranium and plutonium from an aqueous phase to an organic phase. Most of the nitric acid in the waste is recovered by distillation and re-used. The waste stream containing residual nitric acid is neutralized and stored in double-shell underground tanks. The PUREX Plant was built between April 1953 and October 1955 and operated until 1972. The plant began operation again in 1983 (DOE, 1987) and was still active in 1989.

The Plutonium Recovery and Finishing Operation (Z Plant) was constructed to process plutonium and prepare plutonium products for shipment offsite. Operation began in late 1949. Waste from Z Plant contains minor amounts of fission products, some plutonium, and other transuranic (TRU) elements, and it has high concentrations of metallic nitrates. From 1949 through the late 1960s the waste was discharged directly via cribs to the underlying soil columns which were thought to sorb the TRU elements and therefore retain them close to the point of discharge. Later wastes are being stored in underground tanks (DOE, 1987).

The bulk of the radioactive wastes generated by the chemical processing operations are stored in 149 single-shell tanks and 14 double-shell tanks located in the 200 Areas. Single-shell tanks are carbon-steel lined concrete tanks buried approximately 50 ft below the surface. Single-shell tanks contain various combinations of sludge, salt cake, and nonpumpable liquids. Double-shell tanks have a concrete shell and two carbon-steel liners with an annulus between the liners that provides for secondary containment and leak detection. Double-shell tanks contain residual liquids or slurries that include concentrated salt solutions, soluble organic complexants, and small amounts of sludge. By 1995, existing waste tanks are expected to comprise a volume of about 220,000 cy containing 70,000,000 Curies (Ci) of waste fission products and about 70,000 Ci of TRU, including 0.5 ton of plutonium. Additional wastes from the processing of N Reactor fuel are expected to add a volume of 70,000 cy containing 200,000,000 Ci of fission products and 300,000 Ci of TRU (DOE, 1987).

1963 to 1988

The first major engineered facility not related to the production of plutonium to be built on the Hanford site was the Fast Flux Test Facility (FFTF) reactor. The FFTF is a liquid sodium-cooled reactor that uses an unmoderated neutron source (fast flux). The principal purpose of the FFTF reactor was to test the materials and processes that might be used in developing breeder reactor technology. From late 1968 through 1970 siting studies were conducted by Battelle Pacific Northwest Laboratory and their subcontractors at a location approximately 11 mi northwest of Richland that had been predesignated by the U.S. Atomic Energy Commission (AEC) for security reasons. The scope of the investigations included a review of available literature on geology, soil conditions, and hydrology in the Hanford area; an aerial survey and topographic mapping of the immediate site; a seismic refraction survey; drilling and sampling of exploratory borings; field soil tests from excavation pits; and determination of soil dynamic properties and liquefaction potential. The results of the investigations indicated that, because of the uniform geology, foundation conditions and ground-water depth, there was no preferred facility location. Therefore, selection of the final site was based on optimizing the topography, economy of earthwork for site preparation, and railroad and road access facilities. Responsibility for the project was transferred to Westinghouse Atomic Development Company in 1971 at the start of construction (AEC, 1972). Construction was completed and operation begun in 1980; the plant was still active in 1989.

In 1971-1972, initial siting work for WPPSS nuclear power plant WNP-2 was undertaken at a government-designated site located approximately 2 mi east of the FFTF, then under construction. The principal criteria for siting were optimization of the location relative to the Bonneville Power Administration substations and proximity to the Columbia River for coolant makeup but with sufficient setback to preclude impact from flooding. Except for local site studies to characterize the immediate WNP-2 site foundation conditions, all the recently completed FFTF geologic and seismic studies were essentially accepted by reference in the WNP-2 PSAR. The site is underlain by about 45 ft of Quaternary glaciofluvial sands and approximately 480 ft of dense middle and lower Ringold Formation sediments (Pliocene) resting on even denser flat-lying Yakima Basalt Subgroup flows (WPPSS, 1972). Construction of WNP-2 started in 1972, and the plant went into operation in 1984.

In 1972-1973, preliminary siting work for WPPSS nuclear power plant WNP-1 was initiated next to the 100-N reactor, the site of the Hanford Steam Generation Plant. Subsurface explorations consisted of 2,769 ft of borings, test pit excavations, refraction seismic surveys, and downhole seismic surveys. Regional geologic work included detailed photo analysis, the first detailed geologic mapping of the Saddle Mountains and Wahluke Slope, and a detailed continuity survey of the upper Ringold Formation. The continuity survey results were particularly significant since they provided unequivocal evidence that there had been no tectonic faulting in this part of the Pasco Basin since the end of Ringold time. These results also provided strong support for relocating the 1918 Corfu earthquake epicenter. The PSAR was initially submitted to the NRC in 1973. Before all the site investigations could be completed, a decision was made by the government to extend the 100-N reactor operation. In 1974 a new site was chosen for the WNP-1 power reactor and its twin, the WNP-4 power reactor, approximately one-half mile east of the WNP-2 reactor then under construction. Additional detailed geologic mapping was conducted along the Rattlesnake-Wallula trend and on the Gable Mountain-Gable Butte structures. The continuity survey of the upper Ringold was extended south to the vicinity of the 300 Area with the same results: no evidence of any tectonic faulting. The site investigations included substantial drilling, seismic refraction surveys, test pits, and laboratory analysis. This work is documented in the WNP-1/4 PSAR (WPPSS, 1974). Owing to economic difficulties experienced by the public utility owners that were compounded by a large, near-term power surplus in the Pacific Northwest, construction of the WNP-4 unit was terminated at 24 percent complete in 1982. The WNP-1 unit, at 63 percent complete, was placed on extended construction delay status in 1983.

In 1976, the December 14, 1872, North Cascade earthquake became a major issue in establishing the seismic design for all Hanford facilities then under construction. Because that earthquake could possibly have had a maximum Modified Mercalli (MM) intensity of XI and because the epicenter could possibly have been within the Columbia Plateau tectonic province, the existing seismic design being used at Hanford (MM intensity VIII) would clearly be inadequate. Consequently, a major effort was undertaken by WPPSS between 1977 and 1981 to resolve the issue. This work had three goals: to find the source structure for the 1872 earthquake (unsuccessful); to demonstrate by careful mapping that there was no evidence along the western boundaries of the Columbia Plateau for active faults large enough to sustain an 1872-type earthquake (successful); and to map all structures within 50 mi of the WPPSS sites in sufficient detail to demonstrate that active faults capable of producing an earthquake larger than the Safe Shutdown Earthquake (SSE) were not present (successful). These studies included a 40,000 line-mile aeromagnetic survey centered on the Hanford site; detailed remote sensing studies over all of Washington and northern Oregon; compilation of a single geologic and tectonic map covering the Pacific Northwest region; and compilation of a single gravity map covering the Pacific Northwest region. Results are documented in WPPSS (1977, 1982).

In 1981, PSP&L proposed relocating their Skagit Nuclear Plant to the Hanford site. The site chosen was about 5 mi west-northwest of the WPPSS sites. The geologic and seismic data developed by WPPSS were supplemented with additional detailed geologic mapping of the Umtanum Ridge-Gable Butte-Gable Mountain structures and seismic refraction studies of the area between Gable Mountain and the site. Specific site investigations included 37 soil test borings, 12 menard pressuremeter tests, 10 dutch cone penetration tests, and two 100-ft-long test trenches. The results were documented in PSP&L (1982). The NRC issued a favorable Site Evaluation Report in late 1982. Shortly thereafter, the project was abandoned by PSP&L because of a reduced need for power in the Northwest.

HYDROLOGIC SETTING

Surface Water

The principal surface water bodies, including ephemeral streams on the Hanford site are shown in Figure 2. The Columbia River, which flows through the

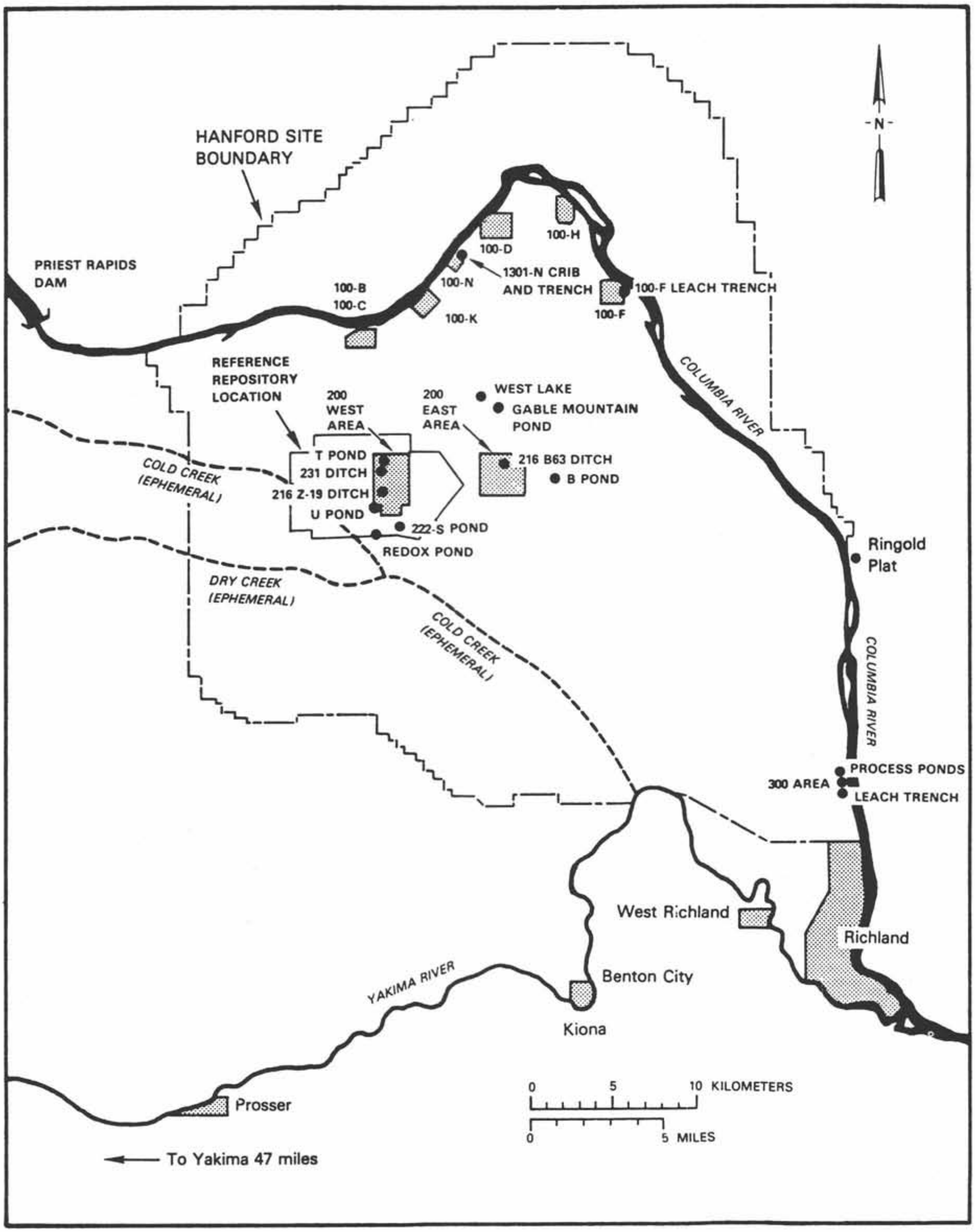


Figure 2. Surface-water bodies near the Hanford site, including ephemeral streams. From U.S. Department of Energy, 1987.

northern part of the site and along the eastern boundary, and the Yakima River, which flows along the southern boundary, are the principal streams in the area. Both rivers are important sources of industrial, agricultural, and domestic water for the regions above and below the site. Normal Columbia River elevations range from 394 ft where the river enters the Hanford site below Priest Rapids Dam near Vernita to 341 ft where the river leaves the site near the 300 Area north of Richland. The average annual Columbia River flow along the Hanford reach, based on the last 65 yr of record, is about 120,000 cfs (U.S. Geological Survey, 1985). The minimum flow recorded for the Columbia River during the same period was 4,100 cfs. The average annual flow of the Yakima River is about 3,700 cfs, maximum monthly flow was about 17,300 cfs, and the minimum monthly flow was 160 cfs. Major Columbia River floods of historical record occurred in 1894 and 1948, with flows of 740,000 cfs and 692,000 cfs, respectively (DOE, 1987). During the 1948 flood, only the 100-F reactor area was significantly impacted. The probable maximum flood calculated on the basis of the most severe combination of meteorologic and hydrologic conditions reasonably possible in the region would produce a flow of 1,400,000 cfs. Flood elevations for this hypothetical flood have been estimated at 423 ft for the 100-N Area, 395 ft at the WNP-2 Reactor site, and 383 ft at the 300 Area. Because the construction of several flood control/water storage dams on the Columbia River upstream of the Hanford site subsequent to the 1948 flood, the recurrence probability and impact from floods of this magnitude has been considerably reduced (DOE, 1987).

As part of the NRC safety analysis requirements for the WPPSS nuclear power plants, estimates were made of the magnitude of flood that would result from a 50 percent instantaneous loss of the center section of Grand Coulee Dam. It was estimated that the resulting flood would create a brief duration maximum flow of about 8,000,000 cfs and reach elevations of 470 to 485 ft in the 100 Areas. The 100-N Reactor at about 450 ft and the WNP-2 Reactor at 440 ft would probably be inundated. The 300 Area and the original Richland town site would also experience extensive flooding. The 200 Areas at elevation 500 ft, where most of the radioactive wastes are now stored, would probably not be affected (NRC, 1982).

Between 1944 and 1971 eight nuclear production reactors using single-pass cooling were in operation along the northern stretch of the Columbia River (Figure 3). During operation, in excess of 200,000 gpm of water from the Columbia River was pumped through each one of the reactors as a coolant/moderator and then discharged at temperatures near boiling back into the river. It is estimated that during the 1960s this type of operation released about 300,000 Ci/yr of radioactive isotopes into the river (DOE, 1987). These mostly short half-life radionuclides were the result of neutron activation of constituents in the cooling water and reactor piping. Some longer half-life fission products that came from ruptured fuel elements within the operating reactors were also released.

Ground Water

Ground water beneath the Hanford site occurs under both unconfined and confined conditions. The unconfined aquifer is contained primarily within the middle member of the Ringold Formation over the interior part of the site and in the glaciofluvial sands and gravels along the main river channels. The bottom of the unconfined aquifer (where known) is either the uppermost buried basalt surface or the clay zones of the lower Ringold Formation. The depth to the top of the unconfined aquifer in the 200 Areas ranges from about 185 to 330 ft. At the WPPSS site, the surface of the unconfined aquifer lies immediately below the foundation of the reactor containment buildings (WPPSS, 1981). The unconfined aquifer is more than 230 ft thick in some areas in the center of the Hanford site and pinches out along the flanks of the major basalt outcrops (DOE, 1987).

Sources of natural recharge to the unconfined aquifer are rainfall and runoff from the higher bordering elevations, infiltration along the ephemeral streams, and river water along influent (losing) reaches of the Columbia and Yakima rivers. The natural recharge from the surrounding highlands is estimated to be on the order of 1.3×10^6 gpd.

The plateau on which the 200 Areas are located has numerous ponds and ditches that have been constructed as wasteways for process and cooling water from the chemical separation facilities (Figure 2). Effluents discharged constitute an artificial source of ground-water recharge, estimated to be about 14×10^6 gpd, ten times the natural recharge rate. Between 1944 and 1982, this recharge produced a ground-water mound of approximately 30 ft between Gable Mountain and the 200-East Area (B Pond) and a rise in the unconfined ground-water surface of approximately 85 ft near the 200-West Area (U Pond). These effluents contain small quantities of radionuclides, both fission products and TRU elements, which have reached the unconfined ground-water system and in some places the confined aquifer (DOE, 1987).

From the recharge areas to the west, the unconfined ground-water flows downgradient to the primary discharge areas along the Columbia River. This general west-to-east flow pattern is interrupted locally by ground-water mounds in the 200 Areas. From the 200 Areas, there is also a component of ground-water flow to the north between Gable Mountain and Gable Butte.

The confined aquifers consist of sedimentary interbeds and/or interflow zones between the Columbia River basalt flows. The main water-bearing portions of the confined aquifers are in the interflow zones and in

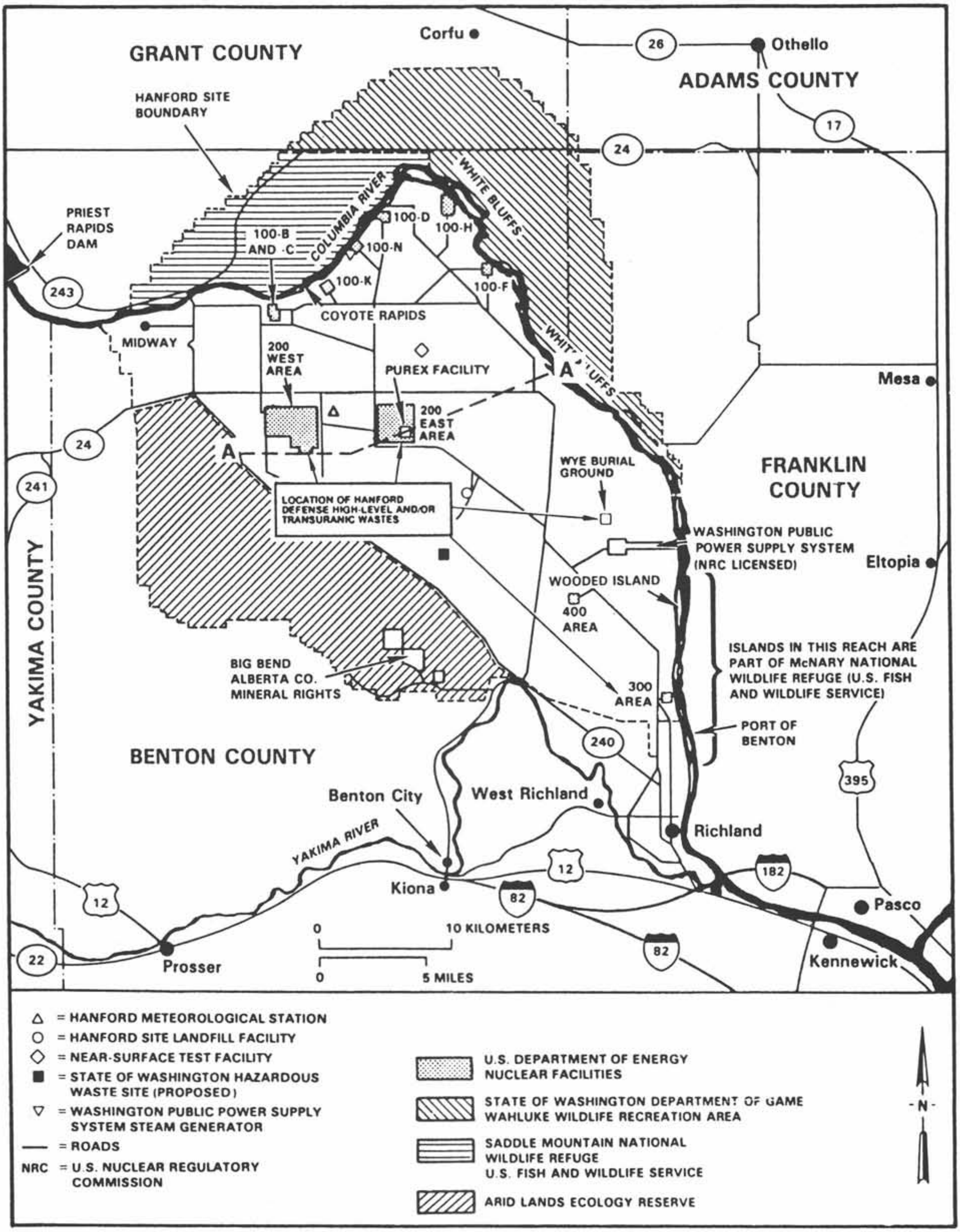


Figure 3. Location of the Hanford Site facilities. From U.S. Department of Energy, 1987.

a network of interconnecting vesicles and fractures of the flow tops or bottoms. Erosional windows through the confining upper basalt flows north of the 200-East Area along the Gable Mountain-Gable Butte trend provide a direct interconnection between the unconfined and the confined aquifers (DOE, 1987).

Contaminated waste waters discharged on the Hanford Site have reached the unconfined aquifer. Some contamination has also reached the confined aquifer south and east of the Gable Mountain Pond. The primary contaminants are tritium, ^{90}Sr, ^{99}Tc, ^{106}Ru, ^{129}I, ^{137}Cs, uranium and nonradioactive nitrates. Most of the nonattenuated radionuclides have moved directly from the underground cribs through the vadose zone to the unconfined aquifer. Some longer lived radionuclides have reached the unconfined aquifer via failed groundwater monitoring well casing and through reverse well injection, a disposal practice now discontinued at Hanford (DOE, 1987). The question of the predominant direction of vapor transport, a major concern with gaseous radionuclides, has not as yet been answered (DOE, 1987).

GEOLOGIC SETTING

General

The Hanford site is located entirely within the Pasco Basin, one of several topographic and structural depressions of the much larger Columbia Plateau province (Figure 4). The adjacent provinces are the Cascade Range on the west, the Blue Mountains on the south, the Northern Rocky Mountains and the Idaho Batholith on the east, and the Okanogan Highland on the north.

The Tertiary rocks of the Columbia Plateau are bordered on the northwest, north, east, and south by pre-Cenozoic rocks. To the west, in the middle Cascades, Puget-Willamette Trough, and Coast Ranges, rock units older than Cenozoic are not in evidence.

Bedrock (Figures 4 and 5) in the Columbia Plateau consists of a thick sequence of Miocene basalt flows with minor amounts of interflow sediments. The bedrock is generally mantled by sediments of Pliocene to Holocene age. The basalts, particularly in the western part of the Columbia Plateau, have been folded into a series of west-trending anticlines. Figure 6 shows a generalized north-south cross-section through the Hanford site.

Tectonic Setting

In the context of present-day plate tectonics, the Columbia Plateau is thought to lie in a back-arc environment to the east of the oceanic Juan de Fuca plate and Cascadia subduction zone (WPPSS, 1981). The Columbia Plateau appears to overlap the pre-Cenozoic continental/oceanic crustal margin.

The Pasco Basin is in the Yakima Fold Belt tectonic subprovince of the Columbia Plateau. The Yakima Fold Belt is bounded on the east by the Palouse subprovince and on the south by the Blue Mountains subprovince. The northern part of the Palouse subprovince is a regional structural slope that dips gently westward with only minor tectonic deformation evident. The southern part of the Palouse (the Clearwater Embayment) consists of several structural basins and uplifted blocks that are tilted and gently folded. The Blue Mountains subprovince is structurally diverse, dominated by the complexly faulted Blue Mountains anticlinorium in its northern portion and a series of structural basins in its central and southern portions (WPPSS, 1981).

The Yakima Fold Belt subprovince contains four major structural elements: the Yakima folds, the Cle Elum-Wallula disturbed zone, Hog Ranch-Naneum Ridge anticline, and the northwest-trending wrench faults.

Stratigraphy

The principal geologic units in the Hanford site vicinity are, from oldest to youngest: the Columbia River Basalt Group with interbedded sediments of the Ellensburg Formation, the Ringold Formation, and the Hanford formation. Figure 7 shows the stratigraphic column for the Pasco Basin. Figure 8 is a generalized east-west cross-section of the suprabasalt sediments beneath the Hanford site.

The bedrock of the Pasco Basin area is considered to be the Yakima Basalt Subgroup of the Columbia River Basalt Group. Within the Yakima Basalt Subgroup are three formations: the Grand Ronde, Wanapum, and Saddle Mountains, each with two or more members that in turn comprise several basalt flows. The maximum thickness of the Yakima Basalt Subgroup is estimated to be in excess of 10,000 ft in the vicinity of Rattlesnake Mountain (Raymond and Tillson, 1967). The Grande Ronde Basalt, extruded between 16.5 and 14.5 Ma, is thought to be the most extensive of the three formations, underlying almost all of the Columbia Plateau and Pasco Basin. The Grand Ronde also appears to be the thickest of the three formations and is estimated to make up about 85 percent of total basalt volume. The Wanapum Basalt, the second most voluminous formation, was extruded between 14.5 and 13.6 Ma. The members of the Wanapum Basalt are most extensively exposed as outcrops in the anticlinal ridges and along the gorges of the Columbia and Yakima rivers. The Wanapum Basalt is estimated to comprise about 10 percent of the total basalt volume. The Saddle Mountains Basalt, the youngest of the basalt formations, ranges in age from 13.5 to 6.0 Ma and makes up about 5 percent of the total basalt volume. Both the Wanapum and Saddle Mountains Basalts are interbedded with and overlain by Miocene-Pliocene epiclastic and volcaniclastic sediments of the Ellensburg Formation. Beneath the Hanford site, the basalts and interbeds form an extensive network of confined aquifers.

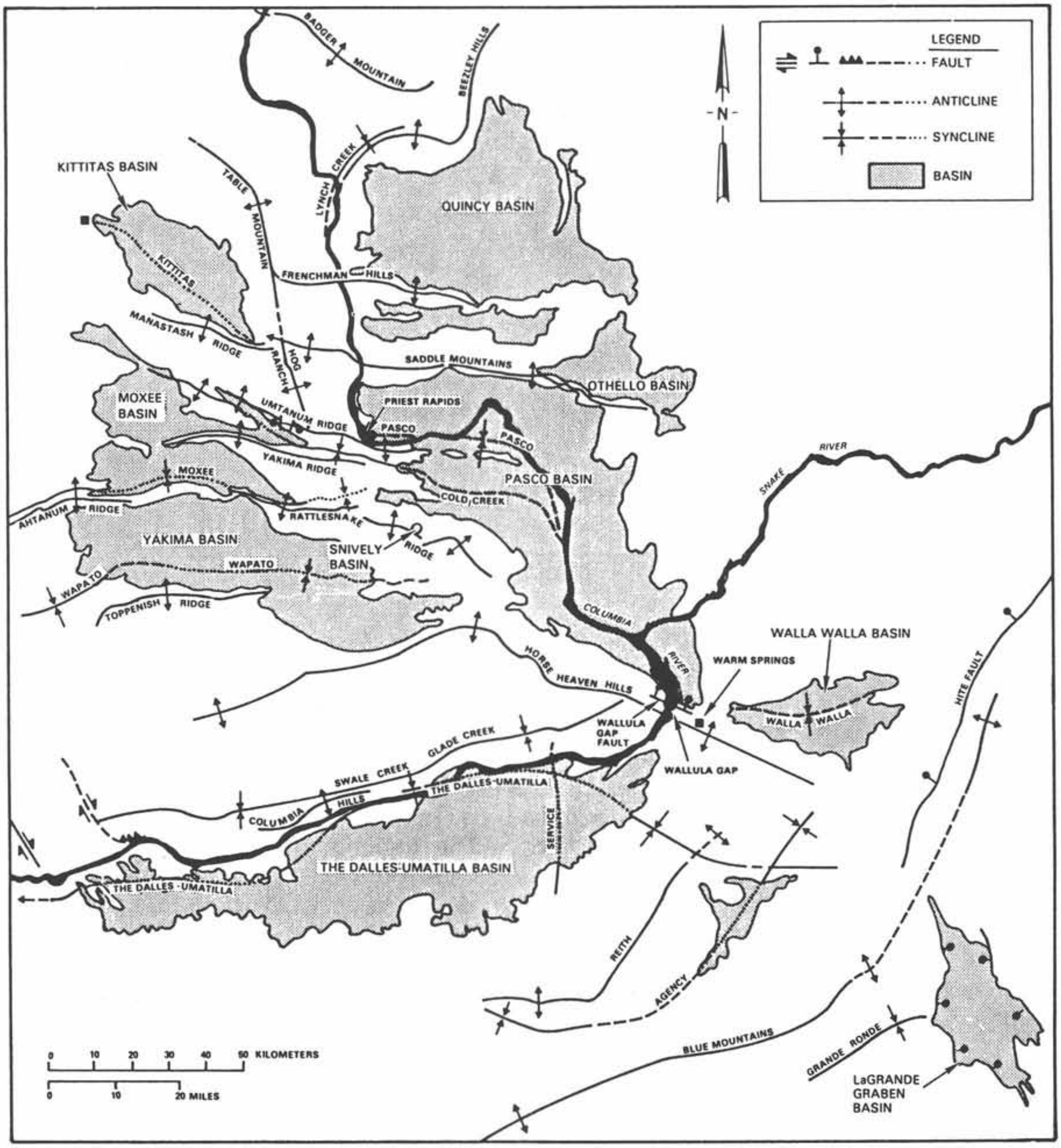


Figure 4. Generalized map of principal geologic structures in the western part of the Columbia Plateau. From Washington Public Power Supply System, 1981.

The Ringold Formation of late Miocene through Pliocene age directly overlies the Yakima basalts on the Hanford site. This fluvial/floodplain deposit is divided into four textural units: a basal sand and gravel which rests conformably on the basalts; the lower sand-silt-clay unit; the middle unit, a well indurated conglomerate cemented with calcium carbonate and silica; and the upper sand-silt-clay unit. The upper Ringold forms the White Bluffs along the eastern and northern banks of the Columbia River but is essentially absent from the Hanford site due to stream erosion. The thickness of the Ringold Formation varies from a maximum of about 1,200 ft in the center of the Pasco Basin to 0 ft on the edges. Within the basin some local variations of thickness are due to thinning over pre-existing subsurface basalt highs that continued to deform. In other places the Ringold shows evidence of channeling and dissection that allowed younger sediments to be deposited directly on the basalts.

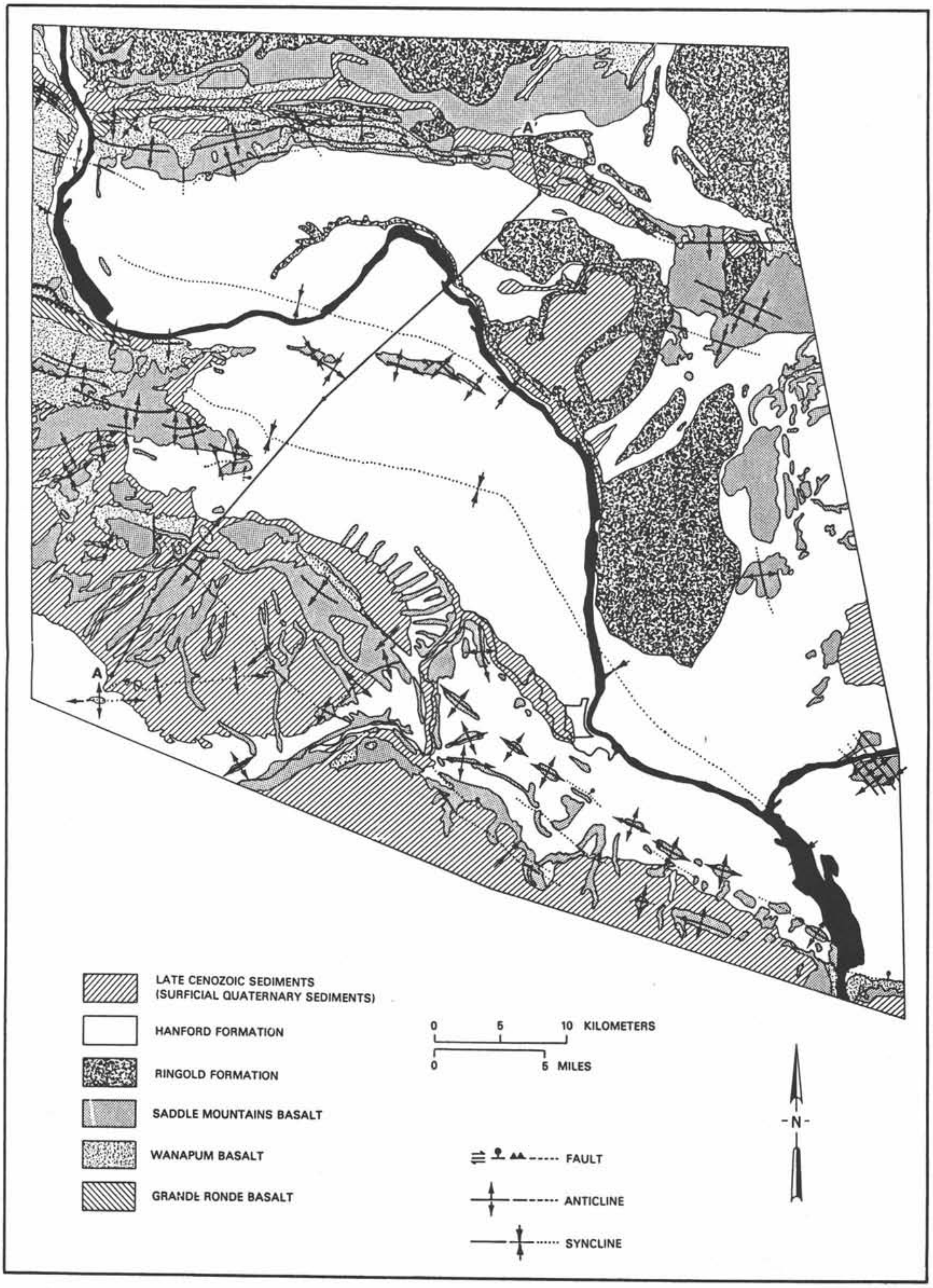


Figure 5. Generalized geologic map of the Pasco Basin. From Washington Public Power Supply System, 1981.

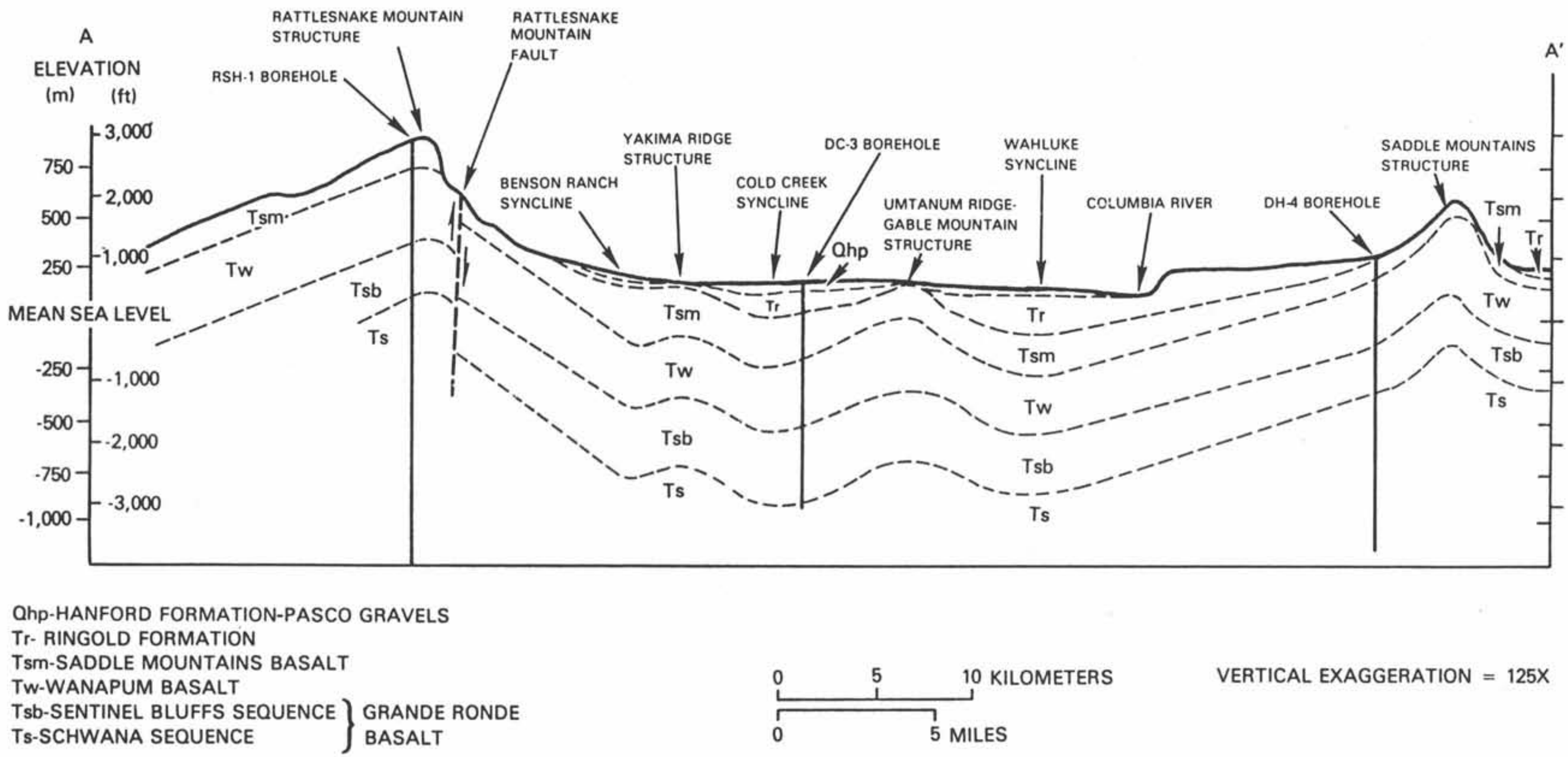


Figure 6. Generalized north-south cross-section through the Pasco Basin showing major structures.

Period	Epoch	Group	Subgroup	Formation	K-Ar Age Years x 10[6]	Member or Sequence	Sediment Stratigraphy or Basalt Flows	
QUATERNARY	Pleistocene/ Holocene					Surficial Units	Loess	
							Sand Dunes	
							Alluvium and Alluvial Fans	
							Landslides	
							Talus	
							Colluvium	
	Pleisto- cene			Hanford		Touchet Beds/ Pasco Gravels		
							Plio-Pleistocene Unit	
TERTIARY	Pliocene			Ringold			Upper Ringold	Fanglomerate
							Middle Ringold	
							Lower Ringold	
							Basal Ringold	
	Miocene	Columbia River Basalt Group	Yakima Basalt Subgroup	Saddle Mountains Basalt	8.5	Ice Harbor Member	Goose Island Flow	Ellensburg Formation Tel
							Martindale Flow	
							Basin City Flow	
							Levey Interbed	
					10.5	Elephant Mountain Member	Upper Elephant Mountain Flow	
							Lower Elephant Mountain Flow	
							Rattlesnake Ridge Interbed	
					12.0	Pomona Member	Upper Pomona Flow	
							Lower Pomona Flow	
							Selah Interbed	
						Esquatzel Member	Upper Gable Mountain Flow	
							Gable Mountain Interbed	
							Gable Mountain Interbed	
							Cold Creek Interbed	
						Asotin Member	Huntzinger Flow	
						Wilbur Creek Member	Wahluke Flow	
						Umatilla Member	Sillusi Flow	
							Umatilla Flow	
					13.6		Mabton Interbed	
				Wanapum Basalt		Priest Rapids Member	Lolo Flow	
							Rosalia Flows	
							Quincy Interbed	
						Roza Member	Upper Roza Flow	
							Lower Roza Flow	
							Squaw Creek Interbed	
						Frenchman Springs Member	Aphyric Flows	
							Phyric Flows	
					15.6		Vantage Interbed	
				Grande Ronde Basalt		Sentinel Bluffs Sequence	Undifferentiated Flows	
							Rocky Coulee Flow	
							Unnamed Flow	
							Cohassett Flow	
							Undifferentiated Flows	
							McCoy Canyon Flow	
							Intermediate-Mg Flow	
						Schwana Sequence	Low-Mg Flow Above Umtanum	
							Umtanum Flow	
							High-Mg Flows Below Umtanum	
							Very High-Mg Flow	
					.16.1		At Least 30 Low-Mg Flows ↓	

Figure 7. Stratigraphic units present in the Pasco Basin. From U.S. Department of Energy, 1987.

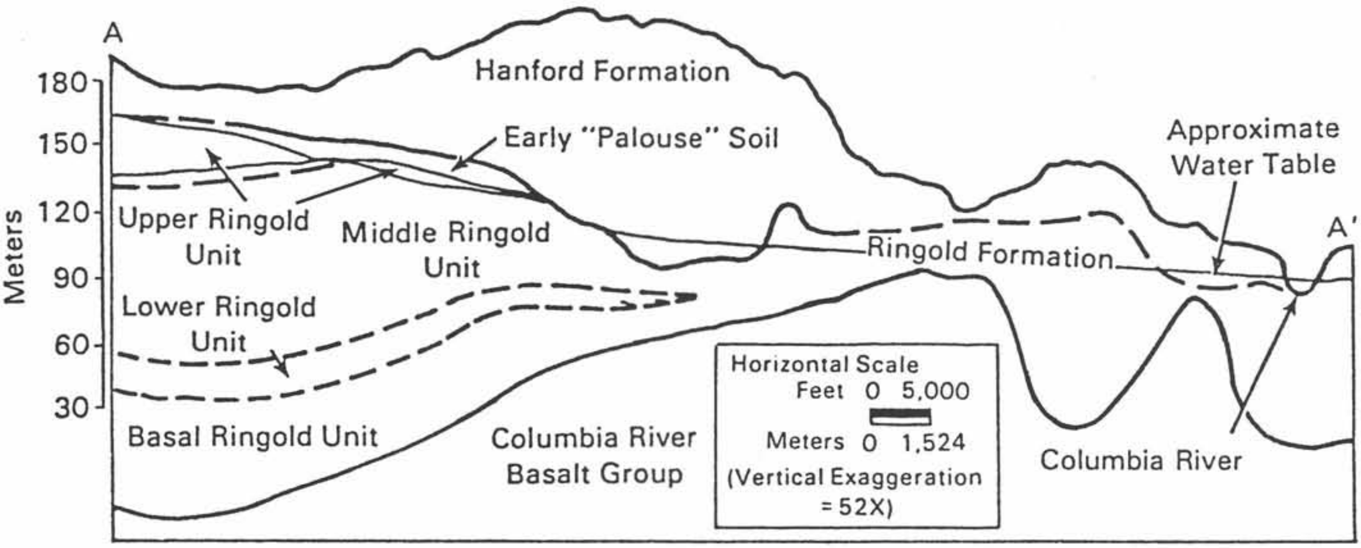


Figure 8. Generalized east-west cross-section of the suprabasalt sediments beneath the Hanford Site. From U.S. Department of Energy, 1987.

The late Pleistocene Hanford formation lies on the eroded surface of the Ringold Formation and the basalt and its interbedded sediments. The Hanford formation was deposited by the catastrophic floods that periodically drained glacial Lake Missoula. The Hanford formation is divided into two main facies: the Pasco gravel facies, composed of poorly sorted clasts deposited in a high-energy environment; and the Touchet beds facies, comprising rhythmically bedded sequences of graded silt, sand, and minor gravel units of a slackwater environment. In many places, the Touchet beds contain clastic dikes that are thought to be the result of hydraulic injection during the catastrophic flooding and subsequent dewatering. The age of the Hanford formation is 13 ka, on the basis of the presence of a layer of Mount St. Helens "S" ash.

Holocene deposits consisting of alluvium, colluvium, and loess, including both active and inactive sand dunes, locally veneer the surface of the Hanford site. While resembling Touchet beds from which most of the sediment was derived, the Holocene alluvium is distinguishable by the lack of rhythmic structure, restriction to present stream valleys, and the absence of clastic dikes.

Structural Geology

The Yakima folds are a series of west-trending asymmetric anticlines that have wavelengths on the order of 3 to 19 mi and amplitudes that are generally less than 3,000 ft (Figures 4 and 9). The anticlines are separated by broad synclines, many of which contain thick sequences of flat-lying post-basalt Neogene to Quaternary sediments. Thrust or high-angle reverse faults that strike roughly parallel to the anticlines are common along both limbs of the folds.

The Cle Elum-Wallula disturbed zone transects the Yakima Fold Belt on a northwest trend. The zone is characterized by an abrupt change in the trend of the Yakima folds along their northwestern to central parts near the Rattlesnake Hills and an aligned belt of doubly plunging anticlines along the southeastern part from Rattlesnake Mountain to the Wallula fault zone.

The Hog Ranch-Naneum Ridge anticline is a broad structural arch that trends north-northwest and forms a portion of the western boundary of the Pasco Basin. The arch extends from near the town of Wenatchee, south to at least Yakima Ridge and possibly as far south as the Horse Heaven Hills. Little is known about the structural geology of this arch.

Numerous northwest-trending, dextral wrench faults occur in the western Columbia Plateau. At least four of these faults are greater than 60 mi in length and cross the trends of several Yakima folds. The wrench faults appear to have developed contemporaneously with the Yakima folds. There is evidence along some of these faults for Holocene deformation. This type of fault decreases in number from west to east and are completely absent from the central portion of the Columbia Plateau and the Pasco Basin.

Deformation that initiated the folding in the Yakima Fold Belt appears to have begun around middle Miocene time, contemporaneously with the main basalt extrusion. Thinning of late Miocene to Pliocene sediments across the folds in the Pasco Basin indicates that deformation continued into the Quaternary. Deformation appears to be the result of north-south-directed compression and is concentrated along the crests of the anticlines; substantially less deformation has occurred in the synclines.

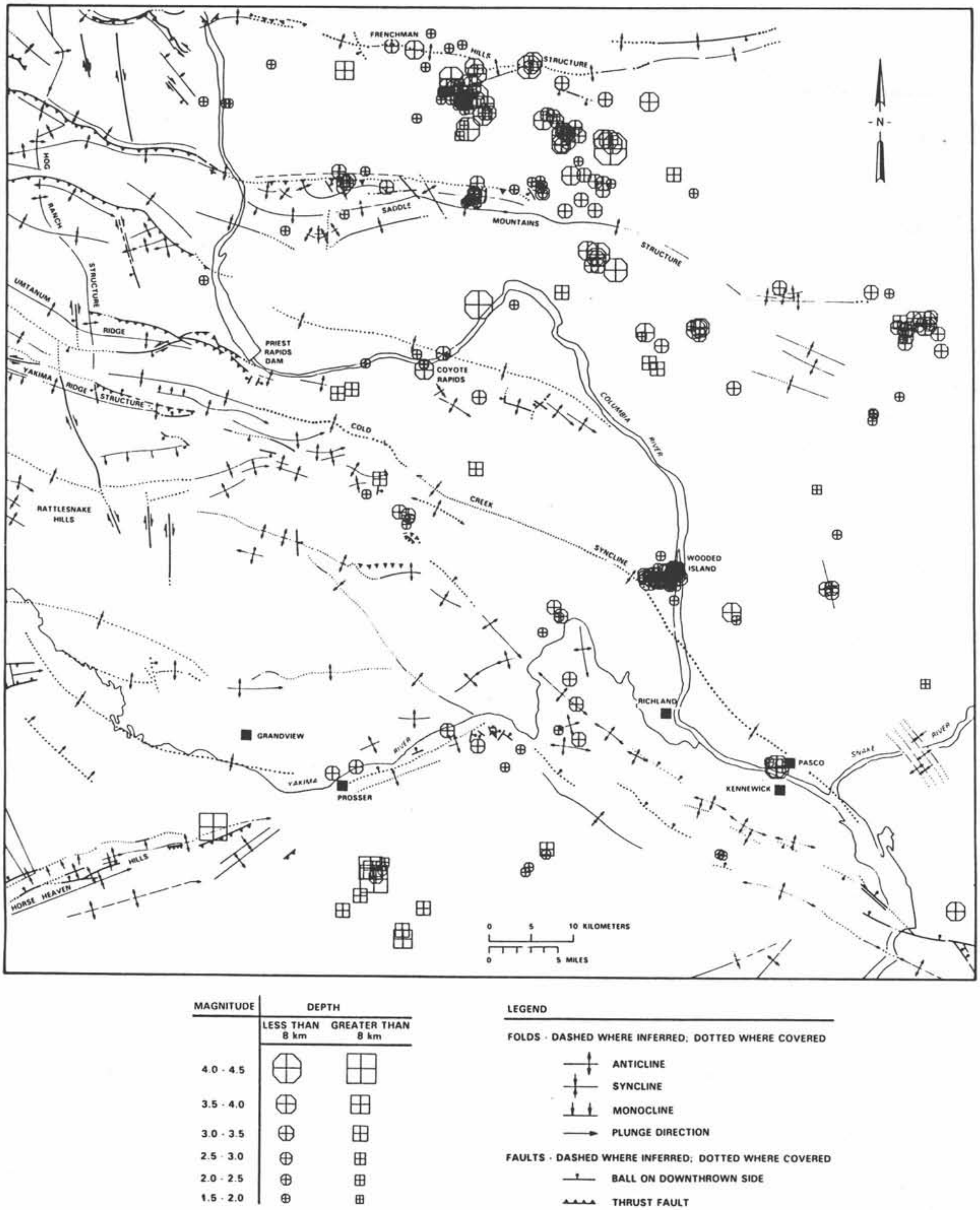


Figure 9. Tectonic and instrumental seismicity map of the Pasco Basin. From U.S. Department of Energy, 1987.

Seismologic evidence, geodetic data, and *in situ* stress measurements all indicate that the Columbia Plateau continues to be in a predominantly north-south compressive stress regime.

SEISMICITY

Historical Summary

The historical record for the Columbia Plateau and for the Pacific Northwest dates from the early 1800s with the establishment of trading posts at Astoria, Oregon; Walla Walla and Okanogan, Washington; and Victoria, British Columbia. Detection of earthquakes having epicentral intensity VII or greater (in the Modified Mercalli Intensity scale, which is used throughout this discussion) is considered complete for the area around the Hanford Site since about 1832 when Fort Walla Walla was permanently established. Detection of epicentral intensity VI or greater events is considered complete for the region from about 1890, with a lower intensity-detection level in the more populated portions of the region.

Instrumental recording of earthquakes in eastern Washington dates from June 1909 when a Wiechert seismograph was installed near Spokane at the Jesuit Seminary, Gonzaga University. This station operated intermittently until 1970. The station did record two of the largest events in the region: the 1918 Corfu M_s 4.4 and the 1936 Milton-Freewater M_L 6.1 earthquakes.

Modern instruments were installed and operated by the U.S. Coast and Geodetic Survey (USCGS) at Newport, Washington, and Baker, Oregon, beginning in 1966. In March 1969, a six-station single-component short-period seismograph network was installed and operated by the U.S. Geological Survey around the Hanford Site as part of the FFTF siting investigations (Bingham et al., 1970). This network was enlarged to 24 stations by October 1971 and subsequently to 29 stations in 1975 when responsibility for operation was turned over to the University of Washington. The University of Washington has since expanded the network further to cover most of eastern Washington and part of northeastern Oregon. Since 1969, the earthquake detection level is estimated to have been M_L1.5 for the immediate Hanford vicinity and M_L 1.5-2.5 for the surrounding portions of the Columbia Plateau.

For the period of 1830 through March 1981, the historical catalog of earthquakes (magnitude > 3.0 and/or intensity III or greater) for the Pacific Northwest developed by WPPSS (1981) lists more than 2,100 events. Most of this activity has occurred in the area of the Cascade Range and west. Historical earthquakes (magnitude > 3.0 and/or intensity IV or greater) within the Columbia Plateau have been generally small and scattered. Relative concentrations of macroseismic activity are evident along the northwest edge of the Columbia Plateau between Wenatchee and Lake Chelan (90 mi from the Hanford site) and trending northeast-southwest from Walla Walla (60 mi from the Hanford site).

Microearthquake swarms are the predominant type of seismic activity presently occurring in the central Columbia Plateau. The principal concentration of swarm activity is between the Saddle Mountains and the Frenchman Hills, roughly parallel to the structural trend and in a more diffuse pattern between Saddle Mountains and Gable Mountain. (See Figure 9). Individual microearthquake swarms have contained from several to as many as 100 events occurring over a few days to several months. The swarms occurred repeatedly in the same general geographic areas. Individual swarms show apparent linear east-west epicentral trends, whereas the entire swarm bodies are roughly oriented northwest-southeast. The microearthquake swarms appear to occur mostly within the basalts and are typically confined to a area of about 40 sq mi at depths of 1 to 3 mi. Individual events range in magnitude (M_L) from 1.0 to 3.5 with the average event size less than 2.0. The largest swarm-related earthquake occurred on December 20, 1973, in the vicinity of Royal Slope to the west of Moses Lake and had a magnitude of M_L 4.4. The Royal Slope event had a focal depth of 1.3 mi (Malone 1979). The maximum intensity of V was felt over an approximately 20-mi radius (WPPSS, 1981).

The closest repetitive swarm areas of interest to the Hanford site are at Coyote Rapids directly west of the 100-N Area and at Wooded Island, approximately 3 mi east of the WPPSS WNP-2 Reactor site. The swarms near Coyote Rapids were at the site of the second largest instrumentally recorded earthquake in the Hanford site area, a M_L 3.8 on October 25, 1971 (WPPSS, 1981). The swarms near Wooded Island have been among the more intense in terms of number of swarms and number of events within each swarm, but all have been of low magnitude (less than 3.0)(WPPSS, 1981).

Focal mechanism solutions for individual earthquakes across the Columbia Plateau commonly show horizontal principal compression axes oriented from west-northwest to north-northeast. The current tectonic stress regime in the Hanford area, as derived from these focal mechanism studies and a few hydrofracturing measurements, indicates a predominance of north-south compression and vertical tension. This suggests that the majority of the deformation from swarm-type earthquakes is occurring on numerous high-angle reverse faults oriented roughly east-west rather than on single planes (WPPSS, 1981).

Description of Important Earthquakes

The December 14, 1872, North Cascades earthquake was one of the largest earthquakes in the recorded history of the Pacific Northwest. The earthquake was reported felt throughout a 500,000-sq mi area extending from the Pacific coast eastward to Montana, northward well into British Columbia, and southward into central Oregon. After extensive studies by WPPSS and its consultants in 1976-1977 as part of their nuclear power plant site investigations, the epicenter for this earthquake was established as having been within a meizoseismal zone that extends from Lake Chelan on the south to southern British Columbia on the north (Coombs et al., 1976; WPPSS, 1977). Although the exact epicentral location of the December 14, 1872, earthquake has not been established, all credible investigators who have studied the event conclude that the epicentral area is in the northern Cascades province, an area that is distinct and different, both geologically and tectonically, from the Columbia Plateau (NRC, 1982).

As discussed in WPPSS (1977), the main earthquake occurred at about 10:00 p.m. on December 14, 1872. Two to four aftershocks of slightly smaller magnitude were felt over a broad area after the main shock during the night of December 14-15, 1872. The large felt area ascribed to the main shock suggests a magnitude near M_s 7-1/4. A maximum intensity of VIII was assigned on the basis of all felt reports that could be related to structural vibration damage (Coombs et al., 1976). An extensive search by WPPSS within the meizoseismal area and along the Columbia Plateau, northern Cascade, and Okanogan Highlands boundaries failed to find any evidence of recent surface rupture that was compatible with an earthquake of this size, thus leading to the conclusion that the event probably occurred at lower crustal or upper mantle depths.

The relevance of this earthquake to the Hanford site lies in the NRC licensing regulations (10 CFR 100, Appendix A) that requires as a minimum a Safe Shutdown Earthquake (SSE) design based on the largest historical earthquake within the province where the site is located. Prior to 1976, the epicenter of the 1872 earthquake was accepted as being at 49°10'N; 121°00'W (in southern British Columbia) as defined by Milne (1956); it had a maximum intensity of VII to VIII (Rassmussen et al., 1974; WPPSS, 1974). Using the same data base, PSP&L (1975) in the PSAR for the proposed Skagit River nuclear power plant concluded that the earthquake epicenter was at Wenatchee and had a maximum intensity of VIII to IX. This relocation presented a serious dilemma for the NRC because the proposed Wenatchee epicenter location could be within the Columbia Plateau province and the postulated intensity (VIII-IX) was larger than the previously accepted FFTF and WPPSS nuclear plant design basis (VIII). On the other hand, if the proposed Wenatchee epicenter location was determined to be within the North Cascade province, the revised estimated intensity (VIII-IX) would exceed the design basis (intensity VIII) that was being proposed by PSP&L for the Skagit River site. Acceptance by the NRC (1982) of the WPPSS position that the 1872 earthquake epicenter was somewhere north of Lake Chelan in the Northern Cascades province at a minimum distance of more than 100 mi from the Hanford site and the abandonment of the Skagit River site by PSP&L rendered the issue academic. (For a complete analysis of the December 14, 1872, earthquake, see WPPSS, 1977, 1981.)

On July 16, 1936, a magnitude M_s 5-3/4; M_L 6.1 earthquake occurred near Milton-Freewater, OR, approximately 55 to 60 mi southeast of the Hanford Site. This earthquake was felt over an area of approximately 105,000 sq mi. This earthquake had a maximum epicentral intensity of VII. The intensity was estimated to be IV near the Hanford site. The earthquake was described in detail by Brown (1937). He states that considerable property damage occurred, but no serious injuries were noted in the area of highest intensity, particularly at Milton-Freewater, State Line, and Umapine in northern Oregon. Brown (1937) reported that, in the Milton-Freewater area, many chimneys were broken or shifted, plaster and windows were broken, several houses were moved off their foundations, a two-story concrete house lost part of the top of its second story, the ornamental railing on top of a cement block office building was greatly damaged, and many capstones in cemeteries were rotated. He also reported numerous changes in springs and water wells and some local ground cracking. The 1936 Milton-Freewater event is considered as the largest historical earthquake to have occurred within the Columbia Plateau province and therefore is used as the principal basis for establishing seismic design.

On November 1, 1918, an intensity V to VI earthquake occurred near Corfu, WA, approximately 25 mi north of the FFTF and WPPSS WNP-2 sites. On the basis of a comparison of the seismograph records from the Jesuit station at Spokane for the 1918 event and the 1936 Milton-Freewater event, it was estimated that the 1918 Corfu earthquake had a magnitude (M_s) of about 4.4 (WPPSS, 1981). The Corfu earthquake and aftershock sequence were reported in the Bulletin of the Seismological Society of America (1918) as follows:

> "The first shock was on November 1st, between 9:15 and 9:30 a.m. This was the most severe and lasted several seconds; it shook goods from the shelves and caused landslides for several miles along the hills. We have had on an average about three shocks every twenty-four hours since, but lighter. The intensity is estimated at IV on the R. F. scale."

The relevance of the 1918 Corfu earthquake lies in the fact that it is the largest felt earthquake in the immediate Hanford site area and because a typographical error in the original catalog placed the epicenter at the site of the 100-N Reactor. A reanalysis of the felt report data by Fifer (1966) and of the seismic records by WPPSS (1981) was able to establish a more probable location for this event near Corfu in the immediate area of the 1973 M_L 4.4 Royal Slope earthquake discussed previously.

Seismic Design

Because of the original classified nature of the Hanford project, the record of any seismic design considerations for facilities constructed prior to 1966 is essentially buried in the government records. The first significant unclassified study of any note was a characterization of the "Geologic and Tectonic History of the Hanford Area" by Jones and Deacon (1966) done at the request of the then reactor operations contractor, Douglas United Nuclear. This report laid the foundation for all subsequent geologic siting studies for the region. Jones and Deacon were the first to publicly recognize the moderate earthquake potential for the area. They recommended that the 1918 Corfu earthquake be investigated in more detail because the historical epicenter was in the immediate vicinity of the 100-N area and because the size (intensity Rossi-Forel IV-V) was large enough that, if another earthquake of that intensity were to occur, it could conceivably cause damage to the nuclear reactor facilities located along the river. Subsequent studies by Fifer (1966) and Jahns (1967) concluded that the 1918 earthquake epicenter was probably near Corfu, had a maximum intensity of V to VI and would not cause any significant damage to existing structures if repeated.

The seismic design basis that is presently used for all Hanford facilities was originally established by the USCGS for the FFTF reactor as part of an informal licensing proceeding (AEC, 1972). A review of all the then available geological information coupled with results from 6 months operation of a microseismic network had failed to identify any active seismic sources in the immediate Hanford vicinity (Bingham et al., 1970). Therefore, it was the recommendation of the USCGS that an earthquake similar in size and character to the 1936 Milton-Freewater (intensity MM VI-VII) earthquake be considered to occur on the Rattlesnake-Wallula structure on the southwest side of the Hanford project that also connected to the 1936 Milton-Freewater earthquake epicentral area. To account for uncertainties in true size of the 1936 Milton-Freewater event and for added conservatism, the hypothetical design earthquake was increased in size to intensity VIII and no allowance made for attenuation. This resulted in imposing a *de facto* ground motion value of 0.25 g (zero period acceleration) for the entire Hanford site.

In 1971-1972, the initial siting work for WPPSS nuclear power plant WNP-2 was undertaken and an application filed with the AEC for a construction permit. Except for local site studies to characterize the WNP-2 foundation conditions, all the recently completed FFTF geologic and seismic studies were essentially accepted by reference. The design earthquake proposed by WPPSS was the same as for the FFTF; an SSE of 0.25 g and an Operating Basis Earthquake (OBE) of 0.125 g. After a safety evaluation was conducted by the AEC and upon completion of formal licensing hearings, a construction permit was issued for WNP-2 in 1973.

In 1972-1973, preliminary siting work for WPPSS nuclear power plant WNP-1 was initiated at the site of the WPPSS Hanford Steam Generating Plant next to the 100-N Reactor. Before all site investigations could be completed, a decision was made by the federal government to extend the 100-N Reactor operation. In 1974 a new site was chosen for the WNP-1 Reactor and its twin, the WNP-4 Reactor, approximately one-half mile east of the WNP-2 Reactor then under construction. Additional detailed field studies along the Rattlesnake-Wallula trend were conducted along with characterization of the WNP-1/4 site. Because no new faults had been identified, the seismic design proposed for the WNP-2 and FFTF reactors was also used for the WNP-1/4 reactors.

In 1973, the NRC was formed out of part of the old Atomic Energy Commission. At the same time a new federal regulation (10 CFR 100, Appendix A, "Seismic and Geologic Siting Criteria for Nuclear Power Plants") required a more deterministic approach in arriving at the earthquake design. Between 1973 and 1981 when the FSAR for WNP-2 was filed, a number of nuclear power plants around the country were licensed using 10 CFR 100, Appendix A, thus further establishing precedence for the deterministic approach.

In 1981, as a result of the evolving regulations and because of the extensive amount of new geologic and seismic information that had been developed by WPPSS for the Hanford site, a major revision was made to the geology chapter for the WNP-2 FSAR. Although the basic SSE and OBE proposed for Hanford remained unchanged, the method for arriving at the design parameters and the number of earthquakes considered were significantly modified.

The earthquakes considered in the WNP-2 FSAR are:

(1) The largest earthquake not associated with a structure within the Columbia Plateau tectonic province was still the 1936 Milton-Freewater (M_s 5-3/4) earthquake, assumed to occur in the site vicinity. A site-specific response spectrum was developed for an M_L 6.1 earthquake occurring within an epicentral distance of 0 to 16 mi. The spectrum was developed by searching the strong motion data base for earthquakes of magnitude M_L 5.7 to 6.4 recorded at distances of less than 16 mi. Strong motion recording stations were chosen to best match the WNP-2 site conditions. Thirty-five sets of strong-motion records were found from which three spectra were developed. All the spectra were considered conservative in comparison with an NRC Regulatory Guide 1.60 spectrum anchored at 0.25 g (WPPSS, 1981; NRC, 1982).

(2) For the Rattlesnake-Wallula alignment, a magnitude M_s 6.5 earthquake is assumed to occur at

the closest approach to the WNP-2 site, a distance of some 12 mi. Peak accelerations and peak velocities were estimated from a number of ground motion attenuation relations. The best estimates for the peak ground acceleration ranged from 0.05 g to 0.17 g at the median level and from 0.11 g to 0.25 g at the 84th percentile level. The best estimates give peak velocities of 17.6 cm/sec at the median level and 31.4 cm/sec at the 84th percentile level. Response spectra were developed using the above peak ground motion values and appropriate spectral amplification factors (Newmark and Hall, 1978). Median spectral amplification factors were used with the 84th percentile peak ground motion values, and 84th percentile spectral amplification factors were used with median peak ground motion values. The resulting response spectrum for an M_s 6.5 earthquake at a distance of 12 mi was found to be less than the design, an NRC Regulatory Guide 1.60 response spectrum anchored at a peak acceleration of 0.25 g (WPPSS, 1981; NRC, 1982).

(3) For the faults on Gable Mountain, a magnitude M_s 5.0 earthquake was assumed to occur 9 mi from the WNP-2 site. Although some uncertainty is attached to the magnitude determination for the Gable Mountain faults, this uncertainty is enveloped by the ground motion assumed for the site specific spectrum derived for the floating 1936 Milton-Freewater earthquake as described in (1) above (WPPSS, 1981).

(4) A swarm-type earthquake of magnitude M_L 4.0 is assumed to occur at a hypocentral distance of 2 to 3 mi from the WNP-2 site. Ground motion was determined using strong motion records from the 1975 Oroville and 1980 Mammoth Lakes earthquake sequences. Thirty-nine sets of ground motion records were tabulated in the magnitude range of M_L 3.8 to 4.2 and the hypocentral distance range of 2.7 to 16.3 mi. Several nonlinear regression techniques were used to predict peak acceleration as a function of distance. The uncorrected results for the 84th percentile ranged from 0.15 g to 0.31 g at a hypocentral distance of 1.9 mi. A corrected value of 0.29 g for the most conservative estimate was used to anchor the response spectrum. The response spectrum shape was also developed from the Oroville and Mammoth data sets by analyzing frequency-dependent spectral acceleration amplification ratios from strong motion records in the 0- to 6.6-mi hypocentral distance range. The resultant swarm earthquake response spectrum was found to exceed the SSE spectrum for frequencies above about 10 Hz. For 5 percent damping, this exceedance is about a factor of 1.5 for frequencies between 15 and 30 Hz (WPPSS, 1981).

SUMMARY

Geologic and seismologic investigations conducted as part of nuclear facility siting on the Hanford Reservation have developed a high level of confidence that the site will not be subjected to any geologic hazard that would pose a problem to the health and safety of the public. Because of a lack of geologic hazards from surface faulting, landslides, or liquefaction, and because of the excellent and fairly uniform geologic conditions, seismic hazard and the development of an appropriate design earthquake has been the major focus of attention. On the basis of the results of studies over the past 20 yr, it has been shown that the Hanford Reservation is in an area of low to moderate seismic risk. Ground motion values of 0.25 g and 0.125 g used as the zero period limit of appropriate response spectrum for the SSE and the OBE are considered to be adequately conservative.

ACKNOWLEDGMENTS

It is not possible in a limited space to suitable acknowledge all the significant individual contributions to the geologic knowledge of the Hanford area represented by the discussion in this paper. However, the author does wish to acknowledge the unmeasureable contributions over the past 25 yr of Howard A. Coombs, Professor Emeritus, University of Washington, as an advisor and consultant to all the earth scientist who worked on Hanford; Greg A. Davis, Professor of Geology, University of Southern California, who made significant contributions to understanding the structural geology of the Columbia Plateau; the late Don Tocher, Woodward-Clyde Consultants, who brought reason to understanding the true seismic risk in the Columbia Plateau; and William A. Kiel, my colleague and successor as Principal Geologist, WPPSS, for his continued support over the years.

REFERENCES

Bingham, J. W.; Londquist, C. J.; and Baltz, E. H., 1970, *Geologic Investigation of Faulting in the Hanford Region, Washington* (with a Section on the Occurrence of Microearthquakes by A. M. Pitts): U.S. Geological Survey Open-File Report 70-27, 104 p., 10 plates.

Brown, B. H., 1937, *The State Line Earthquake at Milton and Walla Walla*: Seismological Society of America Bulletin, Vol. 27, no. 3, pp. 205-209.

Coombs, H. A.; Milne, W. G.; Nuttli, O. W.; and Slemmons, D. B., 1976, *Report of the Review Panel on the December 14, 1872 Earthquake*: Prepared for Washington Public Power Supply System, Richland, WA, 1 v.

Fifer, N. F., 1966, *The 1918 Corfu Earthquakes*: Douglas United Nuclear, Richland, WA, Report DUN-1524.

Jahns, R. H., 1967, *Geologic Factors Relating to Engineering Seismology in the Hanford Area, Washington*: Douglas United Nuclear, Richland, WA, Report, DUN-3100, 35 p.

Jones, F. O. and Deacon, R. J., 1966, *Geology and Tectonic History of the Hanford Area and its Relation to the Geology and Tectonic History of the State of Washington and the Active Seismic Zones of Western Washington and Western Montana*: Report prepared for Douglas United Nuclear, Richland, WA, Report DUN-1410, 44 p.

Malone, S. D. (and others), 1979, *Annual Technical Report on 1979 Earthquake Monitoring of the Hanford Region, Eastern Washington*: University of Washington Geophysics Program, 80 p.

Milne, W. G., 1956, *Seismic Activity in Canada West of the 113th Meridian, 1841-1951*: Canada Dominion Observatory Publication, Vol. 18, no. 7, pp. 119-127.

Newmark, N. M. and Hall, W. J., 1978, *Development of Criteria for Seismic Review of Selected Nuclear Power Plants*: U.S. Nuclear Regulatory Commission Report NUREG/CR-0098.

Puget Sound Power & Light, 1975, *Preliminary Safety Analysis Report for the Skagit Nuclear Project*: Puget Sound Power & Light, Bellevue, WA.

Puget Sound Power & Light, 1981, *Preliminary Safety Analysis Report for the Skagit/Hanford Nuclear Project, Amendment 21*: Puget Sound Power & Light, Bellevue, WA.

Rasmussen, N. H.; Millard, R. C.; and Smith, S. W., 1974, *Earthquake Hazard Evaluation of the Puget Sound Region, Washington State*: University of Washington Geophysics Program, Seattle, WA, 99 p.

Raymond, J. R. and Tillson, D. D., 1968, *Evaluation of a Thick Basalt Sequence in South-Central Washington, Geophysical and Hydrological Exploration of Rattlesnake Hills Deep Stratigraphic Test Well*: Battelle Pacific Northwest Laboratory, Richland, WA, Report BNWL-776, 120 p.

Seismological Society of America Bulletin, 1918, *Seismological Notes*: Seismological Society of America Bulletin, Vol. 18, no. 4, p. 138.

Washington Public Power Supply System, 1972, *WNP-2 Preliminary Safety Analysis Report*: Washington Public Power Supply System, Richland, WA.

Washington Public Power Supply System, 1974, *WNP-1/4 Preliminary Safety Analysis Report*: Washington Public Power Supply System, Richland, WA.

Washington Public Power Supply System, 1977, *WNP-1/4 Preliminary Safety Analysis Report, Amendment 23*: Washington Public Power Supply System, Richland, WA.

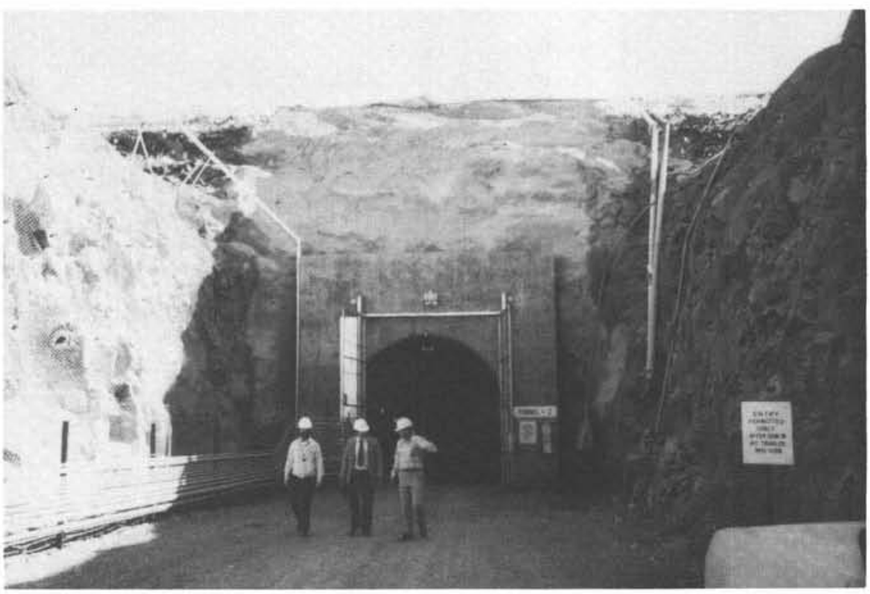
Washington Public Power Supply System, 1981, *WNP-2 Final Safety Analysis Report, Amendment 18*: Washington Public Power Supply System, Richland, WA.

U.S. Atomic Energy Commission, 1972, *Safety Evaluation of the Fast Flux Test Facility:* U. S. Atomic Energy Commission Directorate of Licensing.

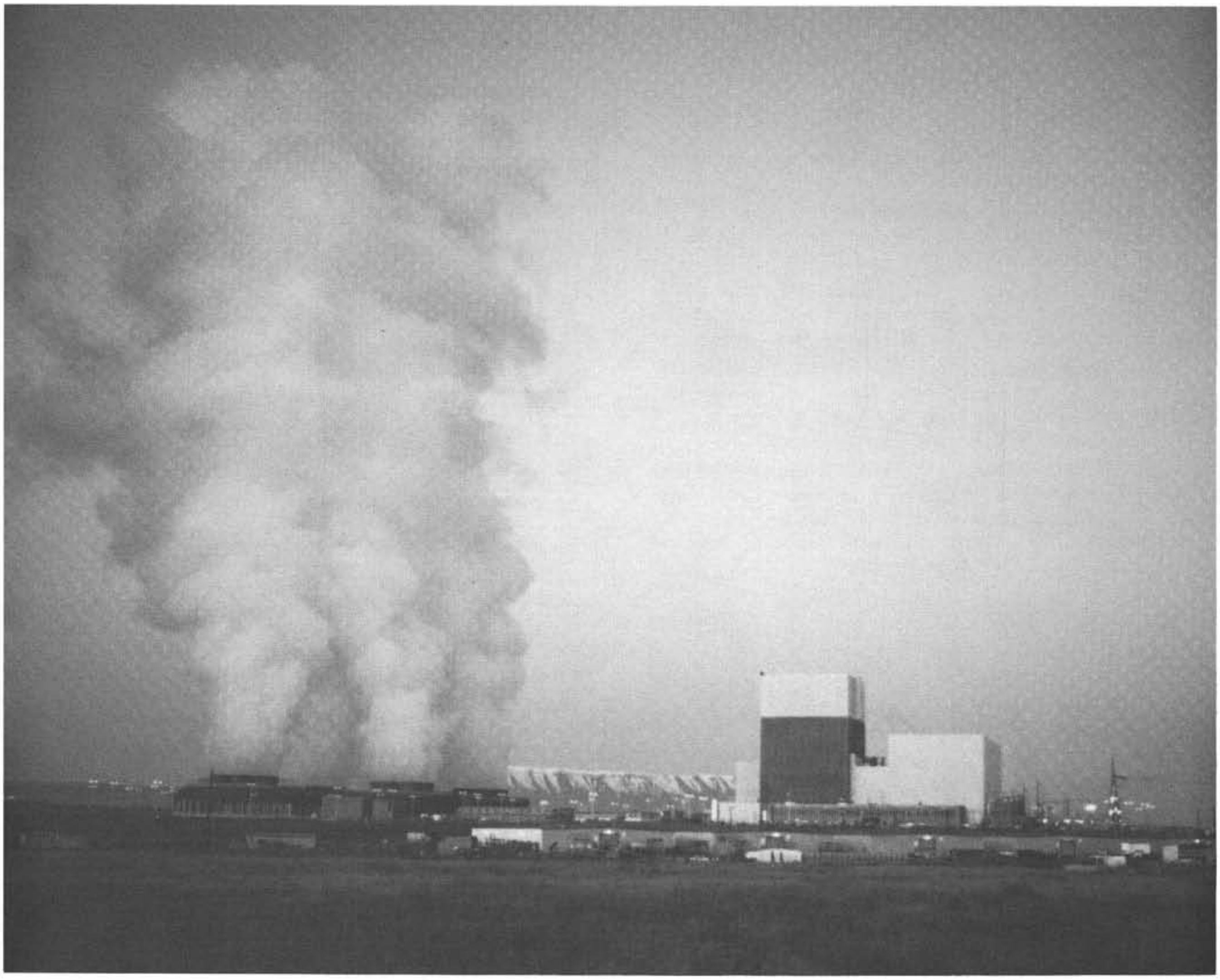
U.S. Department of Energy, 1987, *Disposal of Hanford Defense High-Level, Transuranic and Tank Waste:* U. S. Department of Energy, DOE/EIS-0113, 3 vol.

U.S. Geological Survey, 1985, *Water Resources Data, Washington Water Year 1982*: U.S. Geological Survey, Water Data Report WA-82-1/2, Pacific Northwest District, Tacoma, WA, Vol. 1, 310 p., Vol. 2, 211 p.

U.S. Nuclear Regulatory Commission, 1982, *Safety Evaluation Report Related to the Operation of WPPSS Nuclear Project No. 2*: U.S. Nuclear Regulatory Commission, NUREG-0892, Supplement 1.



Hanford Project. Entrance to the Near-Surface-Test-Facility (NSTF) in Gable Mountain. The facility was part of the investigations for the Basalt Waste Isolation Project (BWIP). Photograph by R. W. Galster, September 1981.



Steam rising from the cooling towers at the Hanford Reservation's Unit 2 nuclear power plant. Photograph courtesy of the Washington Public Power Supply System.

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Geology and Seismic Considerations of the Satsop Nuclear Power Plant Site

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INTRODUCTION

This paper provides a summary of the geologic and seismologic investigations at Washington Public Power Supply System (WPPSS) Satsop nuclear power plant project in western Washington. The investigations began in 1973 for the purpose of meeting the regulatory requirements for licensing and to provide geotechnical input for design of the facility. Construction of the project began under a limited work authorization issued by the federal Nuclear Regulatory Commission (NRC) in 1977.

The Satsop power plant site is located in Grays Harbor County, Washington, about 3 mi south of the town of Satsop and 30 mi west of Olympia (Figure 1). Originally envisioned in the early 1970s during times of projected power deficit, the Satsop plant was designed as a two-unit nuclear-powered electrical generation station. The reactor units were designated the Washington Nuclear Project No. 3 (WNP-3) and No. 5 (WNP-5), each with a designed generating capacity of 1,240 MW. Each reactor was designed to be cooled by a nearly 500-ft-tall natural draft cooling tower adjacent to the reactor building.

Construction was terminated on WNP-5 (16 percent complete) in 1982 owing to economic difficulties experienced by the owners, compounded by a large, near-term power surplus in the Pacific Northwest. Construction continued on the first reactor unit until it, too, was besieged by similar problems. WNP-3 was nearly 76 percent complete by late 1983, when construction was essentially halted. The unit was placed in an extended construction delay to preserve it as an asset for future power planning. Although WNP-3 has remained in a construction delay, geologic and seismologic studies, chiefly concerned with seismic design of the facility, have been ongoing since about 1984.

SITING AND CONSTRUCTION HISTORY

The plant site was selected by the utility company from several locations in western Washington on the basis of technical, practical, and political considerations. One important siting consideration was to minimize transmission costs through line losses by locating the plant between the major electric load centers of the Puget Sound area in Washington and the Willamette Valley in Oregon.

After the location had been selected, a comprehensive site characterization using geologic, geophysical, and geotechnical engineering investigative techniques was initiated in 1973. The site investigations focused on demonstrating the long-term stability of the site. In particular, these studies examined: (1) the engineering properties and stability of the foundation materials to support the plant structures under static and dynamic (earthquake) loading conditions; (2) the static and dynamic stability of natural and manmade slopes; (3) the effects of ground water and long-term foundation rock deformation as they apply to the lateral pressures acting on the foundation exterior walls; (4) the regional and local geology and the geologic structure of the reactor excavations and adjacent cut-slopes; and (5) the seismogenic potential of local and regional faults and lineaments through remote-sensing interpretation, geologic mapping, and trenching.

The results of the site characterization were documented in the Preliminary Safety Analysis Report (PSAR) and submitted for review in 1974 (WPPSS, 1974). A federal construction permit was issued for both units in 1978. Site preparation and excavation at the site culminated in the movement of about 8.5 million cy of rock and soil.

The initial plant site was on a Pleistocene terrace about 300 ft above the Chehalis River. Preliminary geotechnical engineering studies indicated that the underlying glaciofluvial sediments are 100-200 ft thick and would provide for only a marginally adequate foundation with respect to dynamic earthquake loading. As a result, the plant site was relocated to the south onto bedrock material. The final plant location can best be characterized as a forest-covered hill that is approximately 500 ft in elevation and underlain by loess, residual soil, and weathered and fresh sandstone. The location was cleared and stripped of soil materials, such as topsoil, loess, and colluvium. This material was deposited in non-construction areas on the site, either as spoil or stockpiled for use as topsoil.

The plant foundation grade was established by removing more than 100 ft of overburden. The excavation was carried completely through the overlying weathered material so that the foundation of each unit would be in fresh sandstone. Excavation of the sandstone for the reactor buildings was accomplished by ripping and line drilling along the 65-ft vertical walls. Surfaces of the excavations were cleaned by air jetting, then mapped and protected against slaking and weathering by shotcrete over welded wire fabric. The final excavated fresh sandstone foundation bottom also was cleaned by air jetting, then mapped, and covered with a protective concrete mud mat. The placement of structural concrete for the reactor foundations began in 1978.

A two-stage licensing process is required by federal regulations prior to the issuance of the operating license. The construction permit is issued after a review of the PSAR. The next step is application for an operating license, which is issued by the NRC following their further review of the site. The basis for the review is the Final Safety Analysis Report (FSAR) (WPPSS, 1982). At the heart of the review and re-evaluation for the operating permit is the demonstration of an understanding of the site's geologic and tectonic conditions on a local and regional scale, particularly in the context of the regional tectonics and seismicity for analysis of the long-term site stability.

On the basis of a review of the re-evaluation of geologic, tectonic, seismologic and geotechnical engineering data presented in the FSAR, the NRC in 1983 posed a number of questions about the geology and seismicity of the Satsop site. The questions focused on clarifying the nature and mechanism of Cascadia subduction-zone tectonics beneath the site and their impact on the tectonics within the North American plate. In particular, geologic questions focused on the potential capability (activity) of faults near the site in view of their origin in an accretionary complex of a subduction zone that the NRC considers to be active. Questions about seismicity focused on the earthquake potential of the Cascadia subduction-zone interface, source characteristics of the interface and crustal earthquake sources, and the characteristics of design ground motions. Investigations to respond to the NRC questions began in 1984 and continued through 1988. The following sections review some of the geologic and seismologic information developed in support of federal licensing for the Satsop nuclear power plant.

REGIONAL TECTONIC SETTING

The seismotectonics that affect the Satsop site are controlled primarily by the interaction of two convergent crustal plates, the Juan de Fuca and North American (Figure 1). The tectonic processes of concern to this project, such as folding, faulting, and earthquakes, that result from this plate interaction are those that occur within about 200 mi of the site and particularly within about 70 mi.

The oceanic Juan de Fuca plate is converging on the continental North American plate in a northeast direction, oblique to the North American plate motion (Figure 1). The current rate of convergence is estimated to be between 0.8-1.6 in./yr, and this rate appears to have decreased steadily since at least the late Miocene (WPPSS, 1982). The convergence has resulted in the underthrusting of the 6- to 12-mi thick Juan de Fuca plate beneath the North America plate along the Cascadia subduction zone. The subducted Juan de Fuca plate generally dips northeast at about 10°, but its dip steepens to about 20 to 50° beneath Puget Sound. Recent geophysical studies by Crosson and Owens (1987) suggest that the subducted plate is arching beneath western Washington, which complicates this simple geometry.

The North American plate is about 19 to 22 mi thick in western Washington. In the Coast Range and westward to the continental shelf and slope, the plate consists primarily of marine sediments accreted to the continent owing to convergence and subduction since the late Eocene (WPPSS, 1982). This accretionary terrain is characterized by folding and thrusting within sedimentary packets that are scraped off the subducting oceanic plate and plastered against the continental leading edge, or by underplating of sediments beneath the accretionary wedge. Folding and faulting are parallel or subparallel to the trench and active closest to the trench, where the underthrusting and off-scraping is taking place. Accretion off the Washington coast is now active about 113 mi west of the Satsop site.

GEOLOGIC SETTING

General

Physiographic province divisions surrounding the site were defined during the Satsop PSAR investigations from numerous sources and from analyses of Landsat and SLAR imagery (WPPSS, 1974). The Satsop site is situated in the Chehalis lowlands/Willapa Hills of the Pacific Border physiographic province. The area is characterized by low rolling hills and broad stream valleys. The lowlands are bounded by the Olympic Mountains on the north, the Pacific Ocean on the west, the

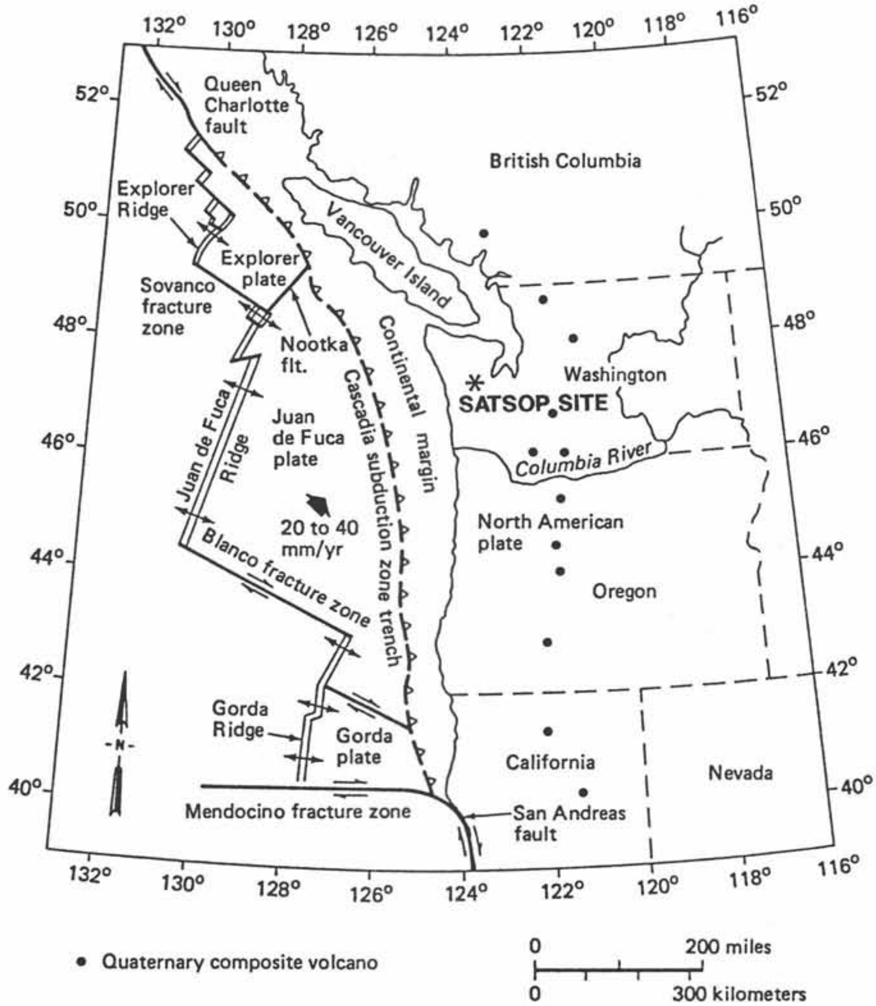


Figure 1. Satsop site location and regional tectonic setting. Modified from WPPSS (1982).

Puget Lowland on the east, and the Oregon Coast Range on the south. The southeastern and southern boundaries are poorly defined. In contrast to conditions in the Puget Lowland and Willamette Valley, bedrock is exposed or lies close to the surface on most of the hills in the Chehalis Lowland. The northern part of the lowland has been modified by glaciation, and many stream valleys are flanked by a series of glaciofluvial terraces that range from about 10,000 to more than 700,000 yr old (WPPSS, 1974, 1982). The largest of the stream valleys and the one nearest the site, the Chehalis River valley, was modified by meltwater of the Puget lobe of the continental ice sheet.

Tectonic Setting

Within the region are five major areas of basement uplift and several minor ones that expose basalts of the Crescent Formation (Huntting et al., 1961). These uplifts occur within a pattern of northwest- and northeast-trending high-angle faults (Figure 2).

These uplifts have probably existed as positive tectonic elements since the early Tertiary (WPPSS, 1974). Faults within approximately 25 mi of the site are concentrated along the crests and margins of the basement uplifts or along the crests of anticlines. The structural highs formed in response to regional east- to northeast-directed compression that affected the area through the late Tertiary (WPPSS, 1982).

Stratigraphy

The Satsop Power Plant site is located on a ridge just south of the confluence of the Satsop and Chehalis rivers (Figure 2). The region is underlain by Tertiary strata, but Quaternary alluvium and glacially derived material are present in the river valleys, and older Holocene and Pleistocene deposits are present on the hillsides and cap some high ridges. The stratigraphic column for the site includes Tertiary bedrock, Quaternary glaciofluvial terrace deposits, colluvium, alluvium, and landslide deposits, and Holocene loess (Figure 3).

Figure 2. Regional geology of the Satsop area. Explanation on facing page. Modified from WPPSS (1982).

Only those formations encountered during plant construction are discussed in the following sections. Detailed information about the geology at the plant is shown in Figures 4 through 6.

Tertiary

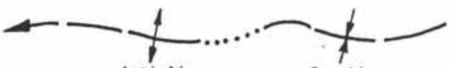
Six Tertiary formations are present near the site (Figure 3). These units are cumulatively more than 15,000 ft thick. The oldest rocks, which make up the basement, are the middle Eocene marine basalts of the Crescent Formation (Rau, 1967; Armentrout, 1977). Descriptions of the formations have been provided by Rau (1967), Carson (1970), and Armentrout (1977).

Sedimentary strata overlying the basement rocks include tuff, siltstone, sandstone, and conglomerate; Miocene basalt is also present. The formations are separated by unconformities. The strata are: the late

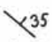
EXPLANATION

Contact, approximately located.

Fault dashed where approximately located; dotted where concealed. U, upthrown side; D, downthrown side.



Folds, approximately located. Showing trace of axial plane and direction of plunge. Dotted where concealed.



Strike and dip of beds

⊕ Horizontal beds

QUATERNARY

Holocene

Qal — Alluvium

Ql — Landslide: slumped masses of bedrock

Pleistocene

Qvt — Vashon Till: undifferentiated drift

Qf — Fraser deposit: glaciofluvial sands and gravels

Qsp — Salmon Springs deposit: glaciofluvial sands and silty sands

Qhc — Helm Creek deposit: glaciofluvial sands and silts

Qwc — Wedekind Creek deposit: glaciofluvial (?) varved clay, silts sands, and gravels.

TERTIARY

Upper Miocene

UNCONFORMITY

Montesano Formation

Tmsl, massive to well-bedded light olive-gray mudstone, siltstone, and very fine-grained silty sandstone

Tmss, friable massive light-gray well-sorted medium-to-coarse-grained sandstone

Tmc, grit, pebble, and small cobble conglomerate composed chiefly of basalt, red limy argillite, and other "Olympic" type rocks

Tm, undifferentiated fine-to-coarse-grained sandstone, pebble and cobble conglomerate, and silty very fine-grained sandstone. Contains basal conglomerate 40 to 150 ft thick

Lower and Middle Miocene

Ta / Tab

Astoria Formation

Ta, Light olive-gray to dark-gray poorly sorted silty very fine-to medium-grained sandstone and sandy siltstone

Tab, dark-gray aphanitic basaltic flows and feeder intrusives. Flow rocks commonly composed of pillow lava and flow breccia

LOCAL UNCONFORMITY

Oligocene

Tl

Lincoln Creek Formation

Light olive-gray to dark greenish-gray tuffaceous siltstone and silty very fine to fine-grained sandstone. Some glauconitic sandstone and siltstone. Contact with the overlying Astoria is gradational and upper 600 to 800 ft of the Lincoln is chiefly soft medium-gray mudstone (Includes some undifferentiated terrace deposits in northeast part of the Malone Quadrangle.)

Eocene

LOCAL UNCONFORMITY

Tms

Skookumchuck - McIntosh Formation

Massive micaceous feldspathic sandstone and siltstone with a few thin coal beds and massive siltstone and bedded tuffaceous sandstone and siltstone and thin lenticular basalt flows

Tc

Crescent Formation

Pillow and massive basalt flows and volcanic breccia

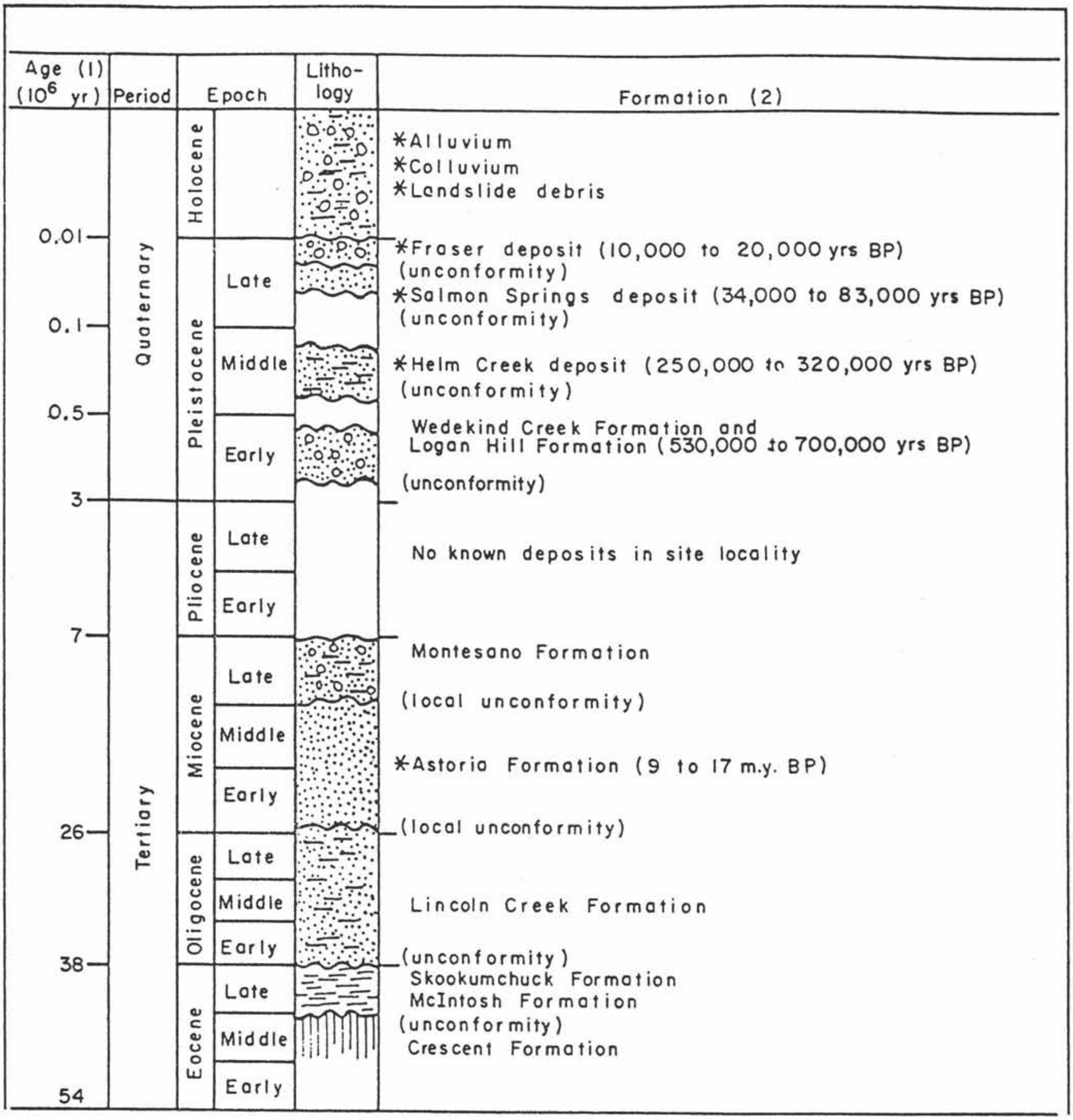


Figure 3. Stratigraphic column for the Satsop study area. Asterisks indicate formations present within 1.5 mi of the power plant site. Modified from WPPSS (1982). (This column does not reflect current usage.)

Eocene Skookumchuck and McIntosh formations, which include as much as 2,500 ft of massive to well-bedded siltstone, tuff, and tuff breccia and massive sandstone (Pease and Hoover, 1957); the Oligocene Lincoln Creek Formation with approximately 3,000 ft of tuffaceous clastic sediments, primarily siltstone (Fowler, 1965; Beikman et al., 1967); the early to middle Miocene Astoria Formation with approximately 3,500 ft of massive sandstone, siltstone, tuff, conglomerate, and basalt (Rau, 1967); and the late Miocene to early Pliocene Montesano Formation with approximately 2,000 ft of siltstone, sandstone, and conglomerate (Gower and Pease, 1965; Rau, 1967; Armentrout, 1977). The Astoria and Montesano formations generally cannot be differentiated in the field. The site is located on the Astoria Formation.

Pease and Hoover (1957) first mapped the site locality and described the sequence of underlying predominantly marine sandstones as part of the Astoria(?) Formation on the basis of its similarity to sandstones near Astoria, Oregon. Fossils collected during PSAR studies are characteristic of the Astoria Formation and confirm that the rock is of equivalent age to the Astoria Formation. Thus the term Astoria Formation was adopted for use throughout the site investigations.

At the site, the Astoria Formation is predominantly a thick-bedded sandstone (Figure 4). The sandstone is composed predominantly of plagioclase, dark volcanic rock fragments, and quartz. Subordinate components include hornblende, pyroxene, muscovite, and magnetite. The Astoria also includes tuff beds composed of glassy, light-gray volcanic rock fragments and plagioclase; siltstone composed predominantly of quartz, feldspar, and mica; and conglomerate, mostly composed of andesitic and dacitic volcanic rocks.

Generally, the lithologic uniformity of the Astoria and the thick vegetation in the region preclude subdividing the formation into smaller map units. However, distinct units can be traced laterally for more than a mile. These units, such as the more tuffaceous sandstones, are generally those more resistant to weathering.

The extensive excavations for the reactor foundations provided a large three-dimensional exposure and an opportunity to conduct detailed mapping. As a result, six laterally continuous and/or lithologically distinct rock units were identified (Figure 5) at the plant location. During the early PSAR investigation phase, these units, particularly unit 3 (Tuff Bed 1), helped investigators predict and confirm the location of faults having vertical separations of less than 10 ft. Within the Astoria Formation the general trend of the bedding is N75°E, the dip 12°N. The outcrop pattern of the individual units in the Astoria Formation at the plant location is shown in Figure 5, and an isometric geologic map of the foundation excavation for WNP-3 is given in Figure 6.

The primary marker bed for the site during the PSAR investigations was unit 3, a fine-grained crystal lithic tuff that ranges in thickness from a trace to 10 ft. The unit's upper contact is marked by a thin, discontinuous, very fine grained sandstone that has a distinctive mottled appearance where weathered. In the WNP-5 excavation, however, a very fine grained sandstone containing concretions marked this upper contact. Seeps were common along the upper contact where the mottled tuff or concretion-bearing sandstone were absent.

Approximately 938,000 sq ft of excavated surfaces were geologically mapped in the two reactor building excavations and surrounding slopes. This included 358,000 sq ft mapped at a scale of 1 in. = 10 ft in the reactor buildings and approximately 580,000 sq ft mapped at a scale of 1 in. = 20 ft in the cut slopes. The geologic mapping was conducted simultaneously with the excavation. In addition, detailed geologic mapping of seven faults exposed in the excavations was performed at a scale of 1 in. = 2 ft along a zone approximately 5 ft wide along the trace of each fault. The results of the mapping efforts are shown in Figures 5 and 6.

Quaternary Sediments

The glaciofluvial Helm Creek deposit is the oldest glacial deposit near the site. Just north of the site (Figure 2) it underlies a terrace whose surface elevation is about 320 ft. The deposit consists primarily of fine- to medium-grained sand, silty sand, silt, and clayey silt. Gravel and gravelly sand are present locally, and peat was encountered in one boring. The deposit is complexly bedded; interfingering and channeling are common. The Helm Creek was deposited on an erosional surface of Astoria sandstone formed by the ancestral Chehalis River. The irregular topography of this erosional surface results in the Helm Creek ranging from 100 to 200 ft thick. The age of the Helm Creek deposit was not directly established. However, it was assigned an age of 320,000 to 250,000 yr on the basis of regional correlation with other glaciofluvial deposits in western Washington (WPPSS, 1974). Although no major plant facilities were founded on Helm Creek deposits, its presence and continuity were used to constrain the age of last movement of faults exposed in the underlying Astoria Formation near the site.

A 5- to 15-ft-thick deposit of loess overlies both the Astoria and glaciofluvial deposits at the site. The loess is genetically related to Pleistocene glaciation. Several closed depressions, caused by piping, were observed in the loess overlying the Helm Creek deposits.

Colluvial material is present throughout the site on the lower ridges and valley slopes. It is the result of creep of loess, weathered Astoria sandstone, and glaciofluvial material. The majority of the colluvium is believed to be Holocene in age, but Pleistocene colluvium was mapped and dated during the site investiga-

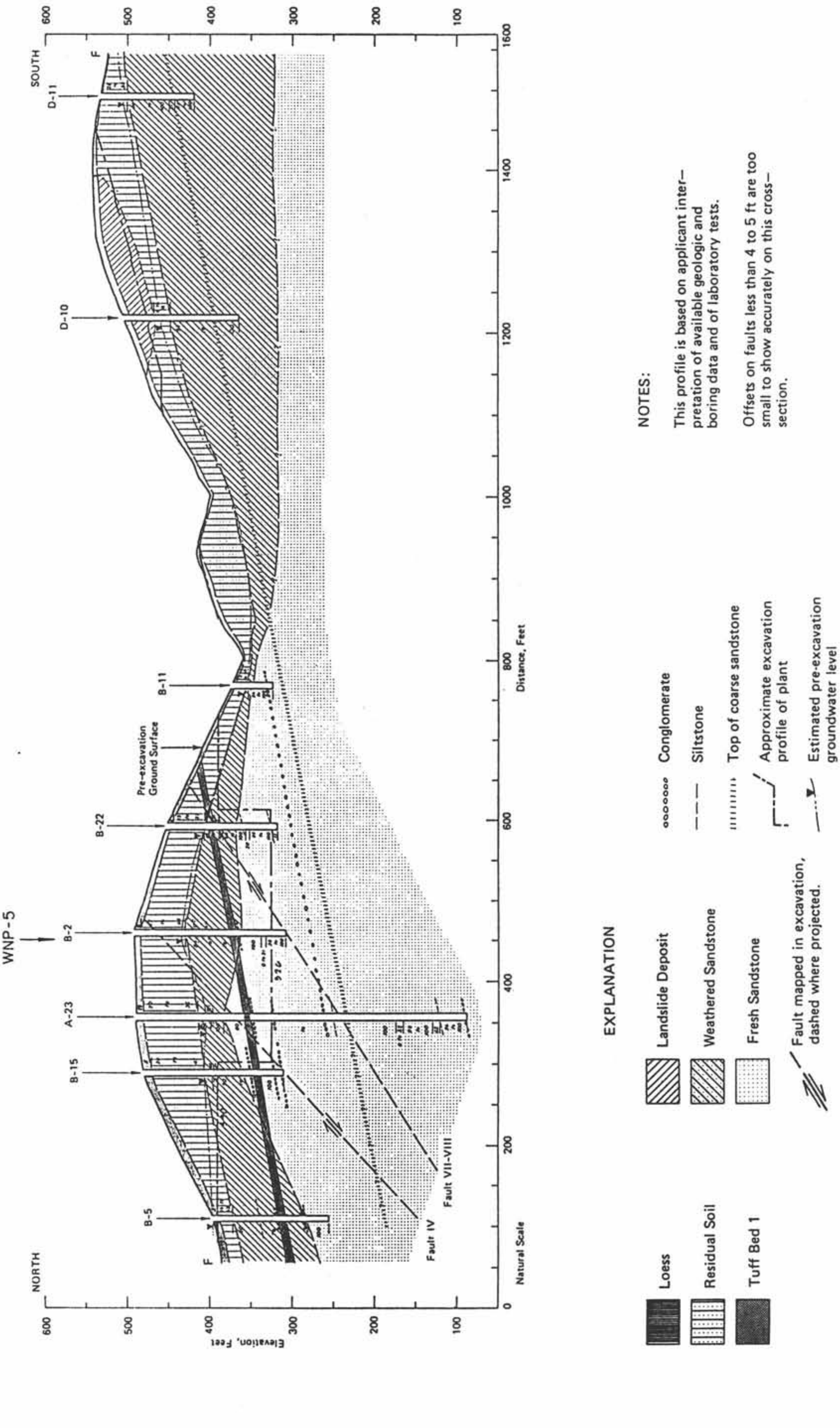


Figure 4. Subsurface profile of the Satsop plant location. Modified from WPPSS (1982).

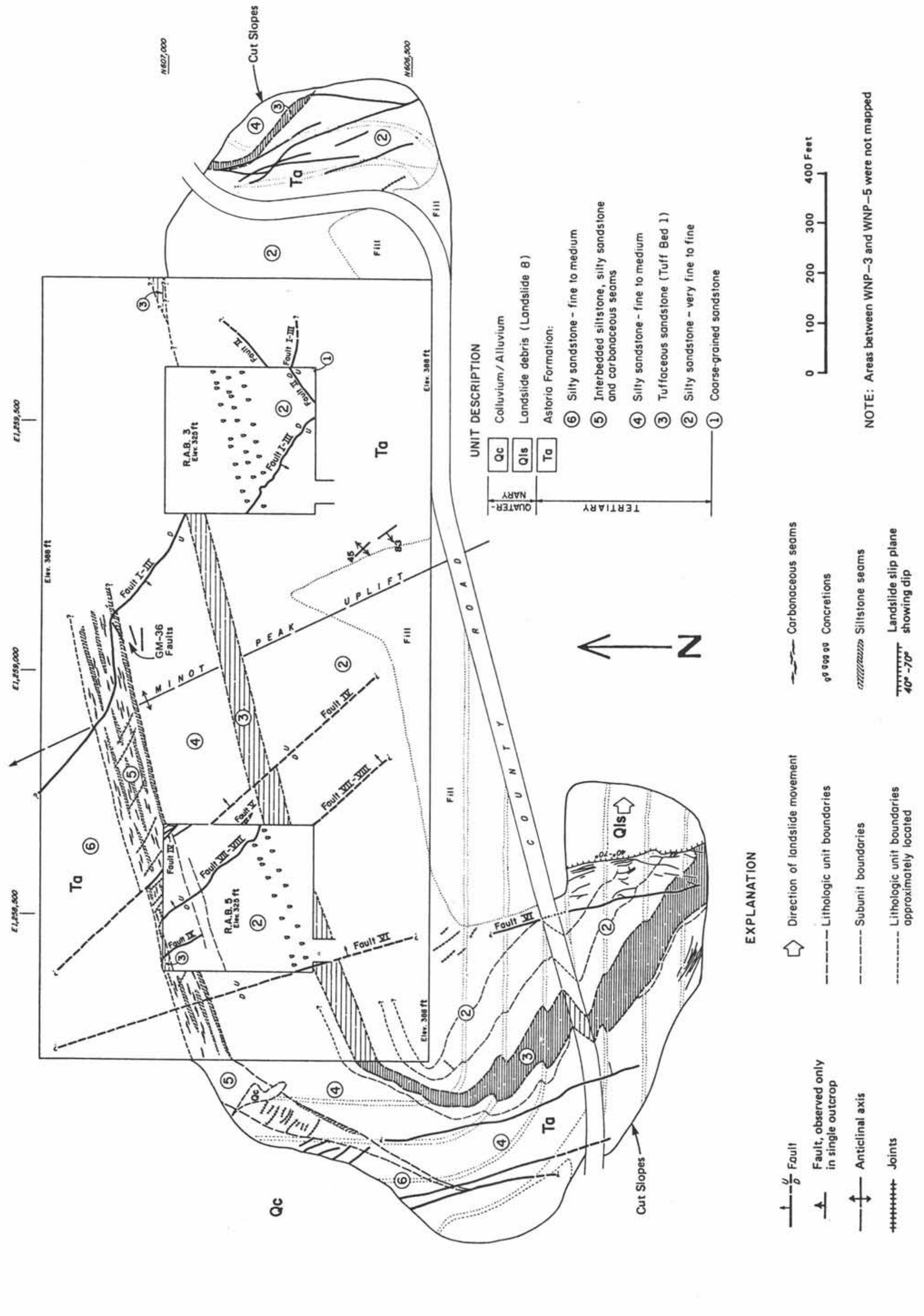


Figure 5. Geologic map of the Satsop plant location. R.A.B., Reactor Auxilliary Building; paired dotted linse, flat bench on the cut slopes. Modified from WPPSS (1982).

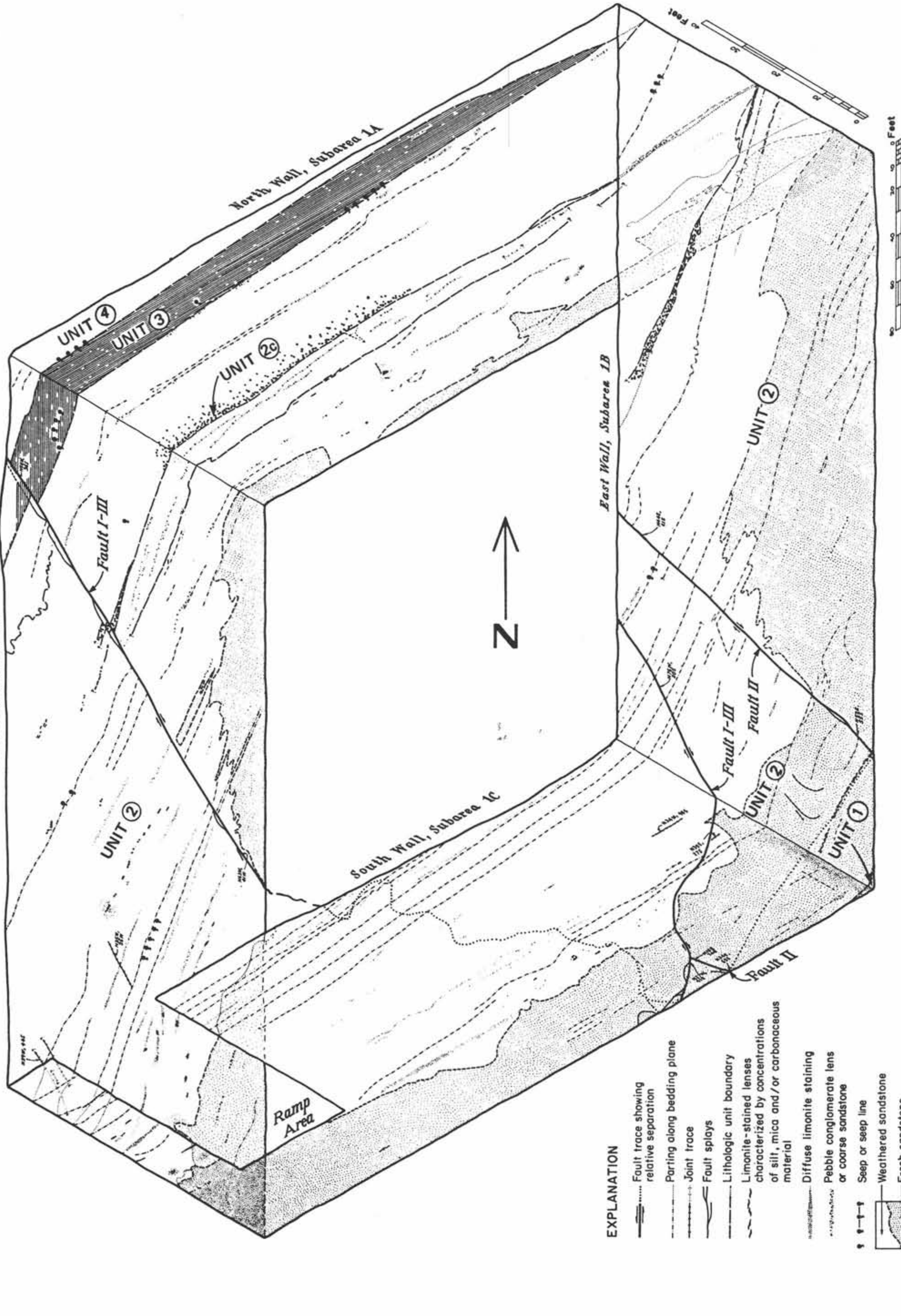


Figure 6. Isometric geologic map of Unit 3 reactor auxiliary building excavation. Modified from WPPSS (1982).

tions. One sample from older colluvium near the site was radiocarbon dated at about 21,000 yr B.P. (WPPSS, 1974).

Small patches of alluvium were mapped in some of the trenches excavated during the fault and landslide investigations at the site. Radiocarbon dates from the older alluvial deposits yielded ages from 17,600 to more than 37,000 yr B.P. (WPPSS, 1982).

Several landslide deposits also were mapped near the plant site. These include both the Astoria Formation and Helm Creek deposits. They consist of broken, fractured, or otherwise disaggregated parent material and range from about 100 acres to less than 1 acre. A small erosional remnant of an old landslide in the Astoria Formation was mapped near a ridge top, just south of WNP-5 (Figure 5). The remnant had no surface expression. The slide is estimated to have occurred >37,000 yr ago, on the basis of radiocarbon dating (WPPSS, 1974). The majority of the deposit was removed during excavation for the reactor buildings. No plant facilities were located on or near any other landslide deposit.

Structural Geology

The geologic structure at the site locality was defined through an extensive field effort that included the interpretation of aerial photographs and topographic maps, site and regional geologic mapping, detailed examination of outcrops within 1-1/2 mi of the plant location, the excavation and mapping of more than 5,000 ft of exposure in 65 bulldozer trenches, the interpretation of geologic logs and cores from 95 boreholes, and the detailed mapping of rock exposed during the excavation.

In general, the structure of the region is characterized by northwest-trending folds and faults. The faults are part of a regional, rectilinear pattern (Figure 7) in which the majority of the northwest-trending features are reverse-slip faults dipping steeply east, and the east-northeast-trending features are high-angle normal or strike-slip faults (WPPSS, 1982). The reverse faults parallel the major folds and are considered to be genetically related to the northeast-directed compression and shortening associated with Tertiary subduction and accretion.

Geologic structures of the Puget Sound region northeast of the site are largely concealed beneath a thick sequence of Pleistocene and Holocene sediments. However, geophysical data suggest that a mosaic of rectilinear fault blocks exists in Tertiary rocks beneath the Quaternary sediments (WPPSS, 1982). The Olympia geophysical lineament, well defined by a linear, northwest-trending steep gravity gradient, forms the southwest boundary of the system (Figure 7). It is closer to the site than the other geophysical lineaments (faults) defining the structural blocks. The elements forming the structural blocks are considered to be active based on their spatial associations to: (1) concentrations of crustal seismicity beneath Puget Sound, (2) prominent linear thickness variations in the overlying Quaternary sediment, and (3) displacements observed in overlying late Quaternary marine sediments (WPPSS, 1982).

Three major uplifts occur within 10 mi of the site: Minot Peak uplift, south of the site; Blue Mountain uplift, southwest of the site; and Black Hills uplift, east of the site. The plant is located on the nose of a broad, poorly defined anticline, which is the northern extension of the Minot Peak uplift. As shown in Figure 2 the majority of the structural features are oriented at approximately right angles to the compression (that is, north-northwest), with secondary structural features aligned with the convergence in an east-northeast direction. Faults that have been mapped within 10 mi of the site are shown in Figure 2 and are associated with these three major uplifts. Typically, these faults have brought basalt of the Eocene Crescent Formation into contact with younger marine sediments of the Lincoln Creek and Astoria formations.

A striking aspect of the structure at the site is the northward decrease of displacement on the faults along the crest of the Minot Peak uplift. The apparent vertical displacement diminishes rapidly. It is more than 1,300 ft at Minot Peak; at a point about 4 mi north, the fault trace can no longer be found (WPPSS, 1974).

Reverse faults having minor displacement were mapped during the excavation of the plant site. These faults, along with bedding, joints and other features, are shown in Figures 4 through 6. These faults generally strike north-northwest to northwest and dip 30° to 80° west or east. The traces of all these faults are marked by a hard, clayey gouge. These faults were probably formed during the middle to late Miocene through early Pliocene while the area was undergoing broad regional uplift.

During the routine geologic mapping of the excavation for WNP-3, two faults were identified and additional displacements were mapped in the adjacent terrace deposits along an approximate projection of one of the faults. This triggered an extensive field mapping program that involved: (1) mapping and trenching of faults in the reactor excavation, along road and railroad cuts, and in the cut slopes adjacent to the plant; (2) trenching, drilling, and mapping three suspected landslide areas in the adjacent Helm Creek terrace; (3) an analysis of aerial photographs and field reconnaissance north of the plant excavation; and (4) an extensive sampling for petrographic analyses and age dating (WPPSS, 1982). The results of these investigations supported previous findings that faults in the Astoria Formation at the site are not capable (WPPSS, 1982). In addition, landslides were found to be unrelated to faulting and were dated at older than 1,030 yr B.P., older than 37,000 yr B.P., and approximately 21,460 yr B.P.

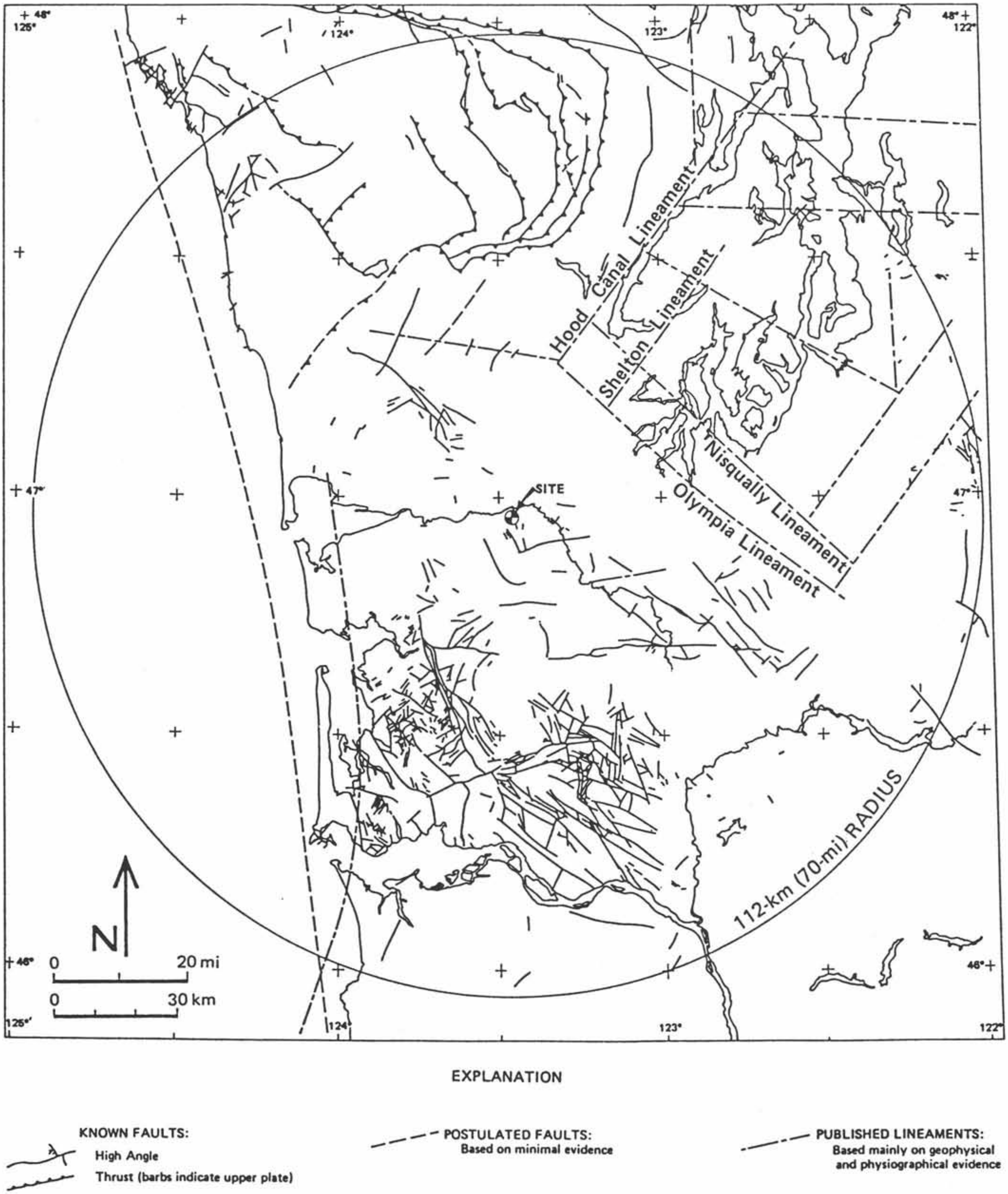


Figure 7. Known and postulated faults and lineaments of the North American plate within 70 mi of the Satsop site. Modified from WPPSS (1982).

Minerals in the Astoria Formation yielded source rock ages of between 59 and 67 Ma.

SEISMICITY

Historical Summary

Earthquake activity, both historic and instrumental, was examined within 200 mi of the site. The focus, however, was on the activity within about 70 mi of the site. For the area within 200 mi of the site, a catalog listing all earthquakes greater than magnitude 3.0 and intensity greater than Modified Mercalli Intensity III included more than 1,600 earthquakes that occurred between 1827 and 1980.

Tectonic Domains

Seismicity within 70 mi of the site can be divided into two main tectonic domains: activity within the North American plate above the Cascadia subduction zone, and activity at depth within the subducted slab of the Juan de Fuca plate.

North American Plate

The shallow seismicity of the North American plate has an uneven spatial distribution (Figure 8). Epicenters of most shallow earthquakes are located in a diffuse pattern in the immediate vicinity of Puget Sound. Another area of activity includes the linear Mount St. Helens seismic zone that extends north-northwest from just south of Mount St. Helens to the southeastern part of Puget Sound. No significant seismic activity in the North American plate has been noted in the Olympic Mountains, the Willapa Hills, or the offshore area (WPPSS, 1982) (Figure 8). The largest recorded earthquake in the North American plate in the Puget Sound region was the magnitude 5.75 earthquake of 1946 near Shelton, Washington (WPPSS, 1982). The epicenter of this event was about 35 mi northeast of the Satsop site. Available focal plane solutions for the events in the North American plate indicate primarily strike-slip faulting (with some dip slip) in a dominant north-south horizontal compressive stress regime.

Juan de Fuca Plate.

Earthquake epicenters at depths greater than about 22 mi in western Washington generally occur along an inclined plane dipping east-northeast. These events are interpreted to be earthquakes within the subducted Juan de Fuca plate (WPPSS, 1982) (Figure 9). The two largest earthquakes to have occurred within the slab are the magnitude 7.1 Olympia earthquake in 1949 and the 1965 magnitude 6.5 Seattle earthquake. These events occurred at depths of 34 mi and 38 mi, and their epicenters were about 38 mi and 58 mi northeast of the site, respectively (Figure 9).

Subduction-Zone Interface

No historical or instrumental record exists of earthquakes occurring anywhere along the Cascadia subduction-zone that could be interpreted to be large-magnitude shallow thrust events of the kind typically associated with underthrusting along an interface zone (WPPSS, 1982; Heaton and Snavely, 1985). In addition, the shallow plate interface lacks the smaller magnitude earthquakes and their associated thrust mechanisms that would be expected to define a typical interface zone (WPPSS, 1982; Taber and Smith, 1985).

Seismic Design

General

Seismic design for nuclear power plants includes the evaluation of regional tectonic features in terms of their potential for producing fault rupture and ground motion. The parameters used to describe the design ground motion are the Safe Shutdown Earthquake (SSE) and the Operating Basis Earthquake (OBE). The SSE represents the maximum probable earthquake expected in the tectonic environment. The plant is designed to be safely shut down following such an event; it may or may not be operable after the event. The OBE represents the earthquake that could reasonably be expected to affect the plant site during the operating life of the plant. The OBE is typically assumed to be one-half of the SSE. Definition of the SSE and OBE requires identification and characterization of potential earthquake sources and estimates of earthquake impact on the site in terms of vibratory ground motion. The design earthquake ground motions for the Satsop plant are currently being investigated and re-evaluated primarily with respect to the potential for a large magnitude thrust earthquake occurring on the Cascadia subduction-zone interface beneath western Washington.

All faults within about 22 mi of Satsop were investigated in detail to evaluate their activity and to identify sources, if any, of instances of vibratory ground motion or fault rupture. None of the mapped faults studied near the site were found to have been active during the Holocene or Pleistocene and hence, in accordance with the regulatory guidelines, did not require further consideration as input to seismic design.

The potential of tectonic features beyond approximately 22 mi of the site for producing significant ground motion at the site (thereby influencing seismic design) also was evaluated and estimated using the following basic approach:

(1) Estimate the peak horizontal acceleration that the site may have experienced from historical earthquakes, including establishing the location (causative fault or tectonic feature) and magnitude of the events. Use this acceleration as an initial reference value for comparing the effects of earthquakes from other potential sources in the region of the site.

(2) Establish the distance from the site beyond which even a very large magnitude crustal earthquake

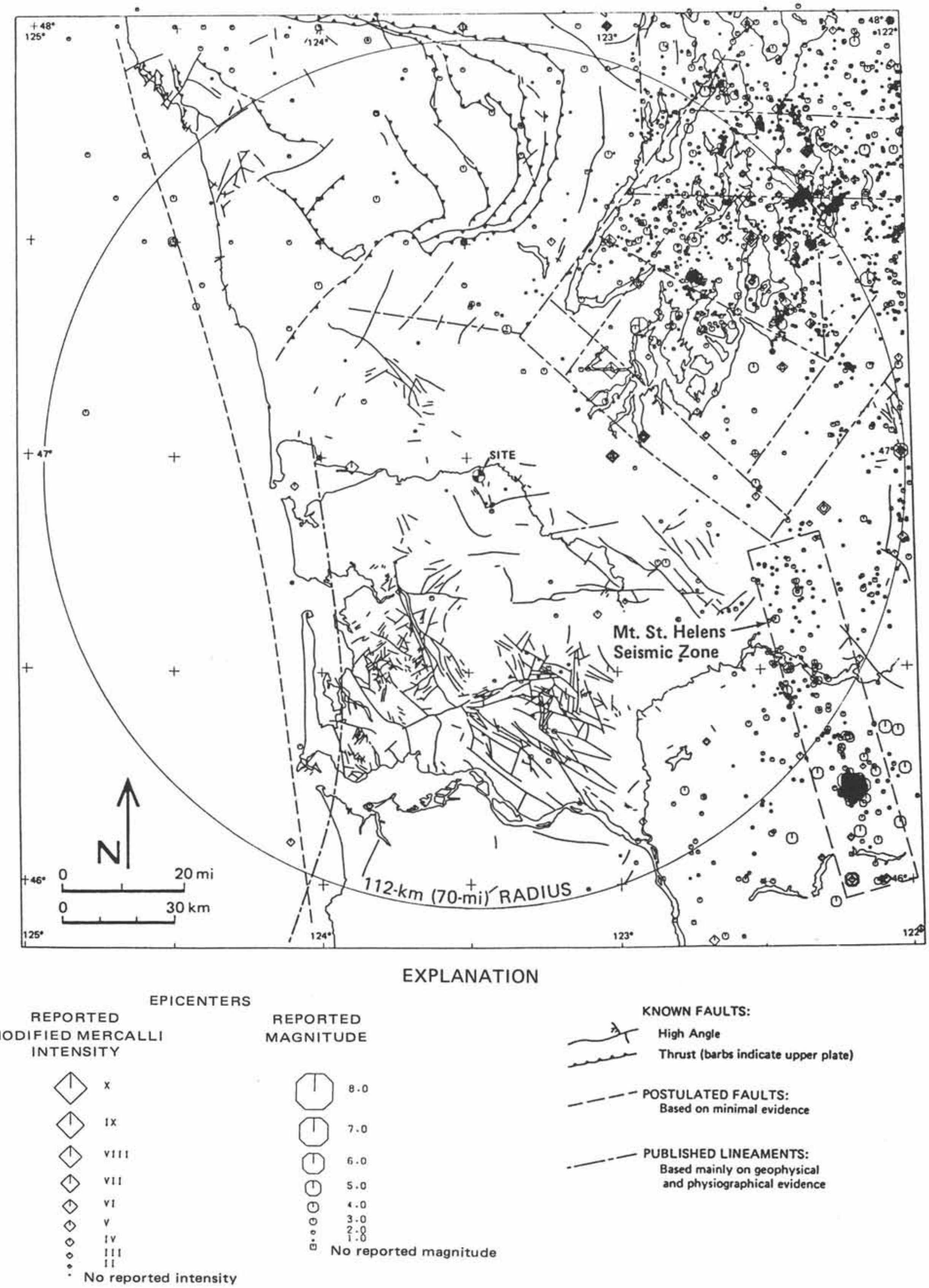


Figure 8. Earthquake epicenters of the North American plate within 70 mi of the Satsop site. Modified from WPPSS (1982).

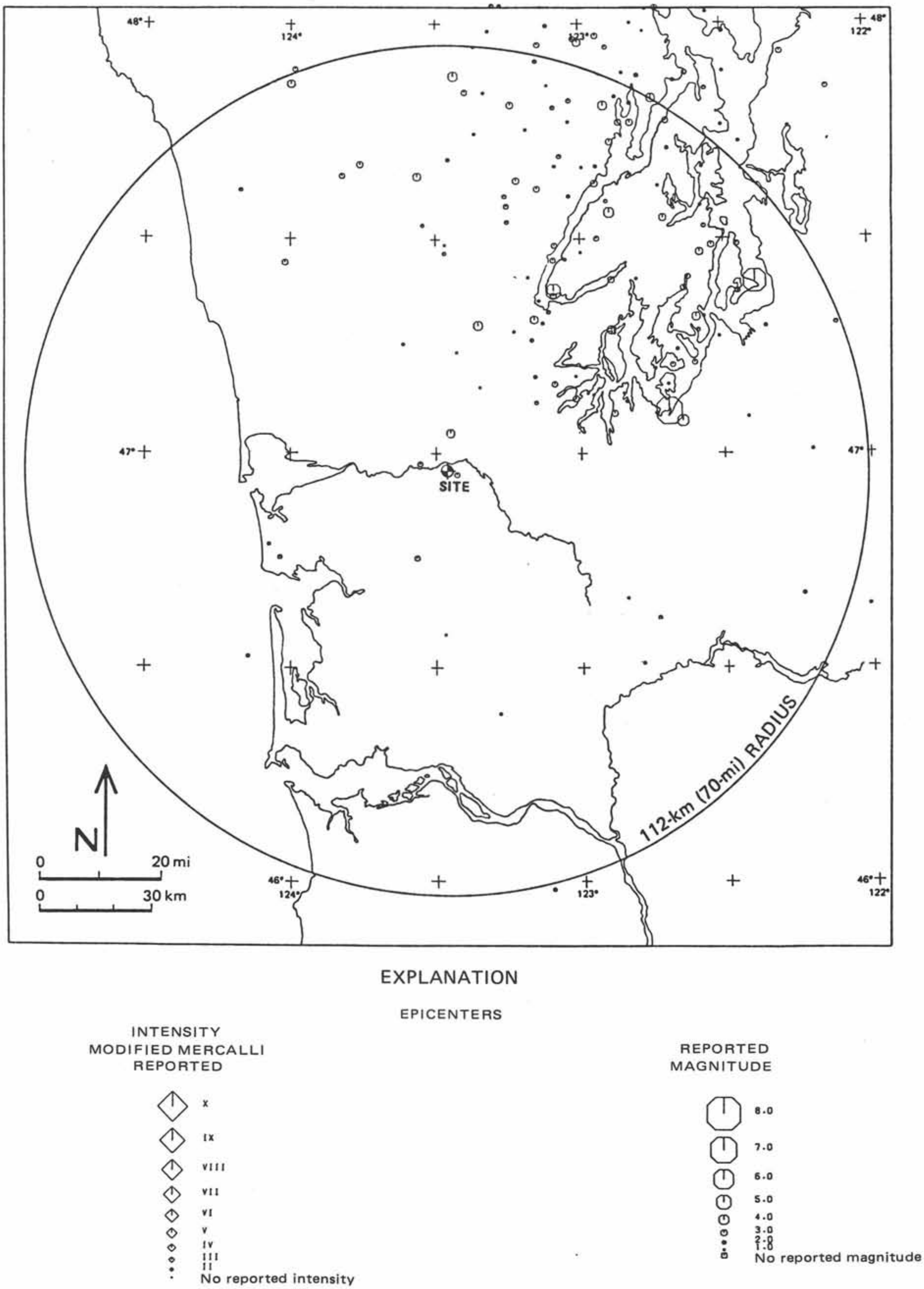


Figure 9. Earthquake epicenters of the subducted Juan de Fuca plate within 70 mi of the Satsop site.

would not induce peak horizontal accelerations greater than the anticipated design earthquake.

(3) Within the distance defined from (2) above, assess the relative significance of the known tectonic features in terms of their potential to induce accelerations at the site comparable to or greater than the estimated historical peak ground acceleration.

This assessment included an evaluation of the activity "capability" of each of the potential earthquake sources, an estimate of the maximum magnitude (based primarily on rupture length), and an evaluation of the resulting ground motion at the plant site.

The above general approach was used during the development of both the PSAR and FSAR. Although there were differences in the implementation of the approach between the two periods, the design ground motion remained essentially unchanged. The differences were related primarily to differing interpretations of the sources of historic earthquakes and of the earthquake attenuation relationships used to derive ground motions at the site.

Identification and Characterization of Earthquake Sources

Evaluations for step 1 above indicated that only seven historical earthquakes had estimated peak horizontal accelerations at the site greater than or equal to 0.03 g (MM VII)(WPPSS, 1982). Thus, this value provided a minimum reference for comparison of the ground motion effects of potential earthquake sources.

Evaluations for step 2 suggested that beyond 70 mi from the site, even a very large magnitude earthquake (for example, magnitude 8.0) in the shallow crust would not result in peak horizontal accelerations at the site greater than the anticipated SSE (that is, approximately 0.30 g). Thus, studies to identify and characterize potential earthquake sources for seismic design were focused on the area within 70 mi of the Satsop site. The studies included the tectonic domains of the North American plate, the subducted Juan de Fuca plate, and the Cascadia subduction-zone interface.

Within the North American plate, 73 tectonic features (known faults, postulated faults, geophysical and topographic lineaments) were examined as potential earthquake sources for seismic design on the basis of their interpreted capability, rupture length (that is, maximum earthquake magnitude), and resulting effect on the site in terms of peak acceleration. Of the 73 features, five were interpreted as being significant to the site in terms of assumed capability, distance to the site, and estimated ground motion. The locations of the five features are indicated on Figures 7 and 8; pertinent characteristics are listed in Table 1.

Table 1. Potential earthquake sources in the North American plate (from WPPSS, 1982)

Structure (type)	Total length (mi)	Distance to site (mi)	Rupture length (mi)	Estimated maximum magnitude (m_s)
Olympia lineament (normal)	55	22	37	7.3
Shelton lineament (normal)	30	22	20	7.0
Hood Canal lineament (normal)	60	28	40	7.4
Nisqually lineament (normal)	50	33	33	7.3
St. Helens seismic zone (strike-slip)	60	58	33	6.2-7.2

Vibratory Ground Motion

Of the potential earthquake sources in the North American plate, the Olympia lineament was considered to be the dominant source for seismic design. For the PSAR studies, the lineament was assigned a maximum magnitude of 7.5, which was attenuated over a distance of 22 mi using attenuation relationships developed specifically for the site. This resulted in a peak horizontal design acceleration of 0.32 g. The OBE was selected to be 0.16 g, horizontal (1/2 SSE).

For the FSAR studies, the Olympia lineament was also assigned a maximum magnitude of M_s 7.5 where it is closest to the site (22 mi). Although the more current, applicable attenuation relationships (Joyner and Boore, 1981; Campbell, 1981) used during the FSAR studies resulted in lower site accelerations, the SSE (0.32 g) and OBE (0.16 g) developed during the PSAR studies were retained for the design ground motions.

Cascadia Subduction Zone

During the studies for the PSAR the Cascadia subduction-zone interface was interpreted to be aseismic with respect to the generation of earthquakes significant to seismic design at the site. This conclusion was consistent with the scientific opinion of that era—that the lack of a well-defined, gently dipping seismic zone and absence of large-magnitude historic seismicity suggested that subduction had ceased and that the subducted slab was now decoupled from the North American plate. The FSAR studies revealed that the Cascadia subduction zone between the converging Juan de Fuca and North American plates is unique among other subduction zones the world over. The Juan de Fuca-North American plate interface is remarkably aseismic, and this seismic quiescence extends along the entire length of the zone. A Benioff zone has been defined only from earthquakes within the subducted plate north of the Columbia River, and the down-dip, seismically defined subducted slab length is among the shortest observed worldwide. Geologic factors that set the Cascadia zone apart from others include the extreme youth of the subducting plate, a relatively slow convergence rate, and the presence at the offshore convergent boundary of the Pacific Rim's most voluminous accumulation of Quaternary trench sediment. However, while there is skepticism that the Cascadia zone is seismogenic in terms of major interplate thrust earthquakes, the possibility cannot be discounted, given the geodetic evidence for low northeast-southwest-directed compressive strain in the North American plate and the geologic evidence for probable coseismic deformation along the Washington and Oregon coast.

At the present time, the case for aseismic versus seismic subduction along the Cascadia zone is not resolved. Recent geologic studies suggesting that the plate interface may be seismogenic (Heaton and Kanamori, 1984; Atwater, 1987; Heaton and Hartzell, 1987) have created sufficient uncertainties that, for purposes of evaluating the earthquake design of the Satsop plant, the plate interface is now considered to be seismogenic. An assessment of the ground motions associated with a hypothetical subduction-zone earthquake will be completed before the operating license is issued.

CONCLUDING REMARKS

The characterization of design ground motions from earthquakes hypothesized to affect critical facilities is a difficult challenge. Engineers and scientists are burdened with major financial and safety decisions that must withstand the test of time. These decisions are subject to a plethora of rapidly changing geologic interpretations, each of which must be addressed. As a result, the subjective assessment of "adequate" protection of public health and safety will remain controversial throughout the lifetime of the facility.

The seismic design for the Satsop power plant is an example of the kinds of problems associated with changing design criteria that accompany prolonged licensing procedures. In 1973, when the original design parameters were established, the consensus was that the subduction of the Juan de Fuca plate had ceased or was not active. As a result, it was not considered as a seismogenic source. Just 15 yr later, however, scientific opinion has swung to the other extreme, and the possibility of earthquakes of great magnitudes occurring along this zone has necessitated a complete re-evaluation of the seismic-design basis of the project. This problem illustrates the need for conservative design practices and maintenance of an active program to sense changes in scientific theory that could result in possible challenges to plant design. Such a dynamic status is unique to critical facilities and is key to maintaining the level of safety required by the regulatory environment.

REFERENCES

Armentrout, J. M., 1977, Cenozoic stratigraphy of southwestern Washington. In Brown, E. H., and Ellis, R. C. (editors): *Geological excursions in the Pacific Northwest*: Western Washington University, Bellingham, WA, pp. 227-264.

Atwater, B. F., 1987, Evidence for great Holocene earthquakes along the outer coast of Washington State: *Science*, Vol. 236, pp. 942-944.

Beikman, H. M.; Rau, W. W.; and Wagner, H. C., 1967, *The Lincoln Creek Formation, Grays Harbor Basin, Western Washington*: U.S. Geological Survey Bulletin 1244-I, 14 p.

Campbell, K. W., 1981, Near-source attenuation of peak horizontal acceleration: *Seismological Society of America Bulletin*, Vol. 71, pp. 2039-2070.

Carson, R. J., III, 1970, *Quaternary Geology of the South-Central Olympic Peninsula, Washington* [Ph.D. thesis]: University of Washington, Seattle, WA, 131 p.

Crosson, R. S., and Owens, T. J., 1987, Structure of the subducted Juan de Fuca plate beneath western Washington: *Geophysical Research Letters*, Vol. 14, pp. 824-827.

Fowler, G. A., 1965, *Stratigraphy, Foraminifera, and Paleoecology of the Montesano Formation, Grays Harbor County, Washington* [Ph.D. thesis]: University of Southern California, Los Angeles, CA, 374 p.

Gower, H. P. and Pease, M. H., Jr., 1965, *Geology of the Montesano Quadrangle, Washington*: U.S. Geological Survey Geologic Quadrangle Map GQ-374, 1 sheet, scale 1:62,500.

Heaton, T. H. and Hartzell, S. H., 1987, Earthquake hazards on the Cascadia subduction zone: *Science*, Vol. 236, pp. 162-168.

Heaton, T. H. and Kanamori, H., 1984, Seismic potential associated with subduction in the northwestern United States: *Bulletin of the Seismological Society of America*, Vol. 74, pp. 933-941.

Heaton, T. H. and Snavely, P. D., Jr., 1985, Possible tsunami along the northwestern coast of the United States inferred from Indian traditions: *Bulletin of the Seismological Society of America*, Vol. 75, No. 5, pp. 1455-1460.

Joyner, W. B. and Boore, D. M., 1981, Peak horizontal acceleration and velocity from strong-motion records including records from the 1979 Imperial Valley, California, earthquake: *Bulletin of the Seismological Society of America*, Vol. 71, pp. 2011-2038.

Huntting, M. T.; Bennett, W. A. G.; Livingston, V. E., Jr.; and Moen, W. S., (compilers) 1961, *Geologic Map of Washington*: Washington Division of Mines and Geology, Olympia, WA, 2 sheets, scale 1:500,000.

Pease, M. H. and Hoover, L., 1957, *Geology of the Doty-Minot Peak Area, Washington*: U.S. Geological Survey, Oil and Gas Investigations Map OM-188, 1 sheet, scale 1:62,500.

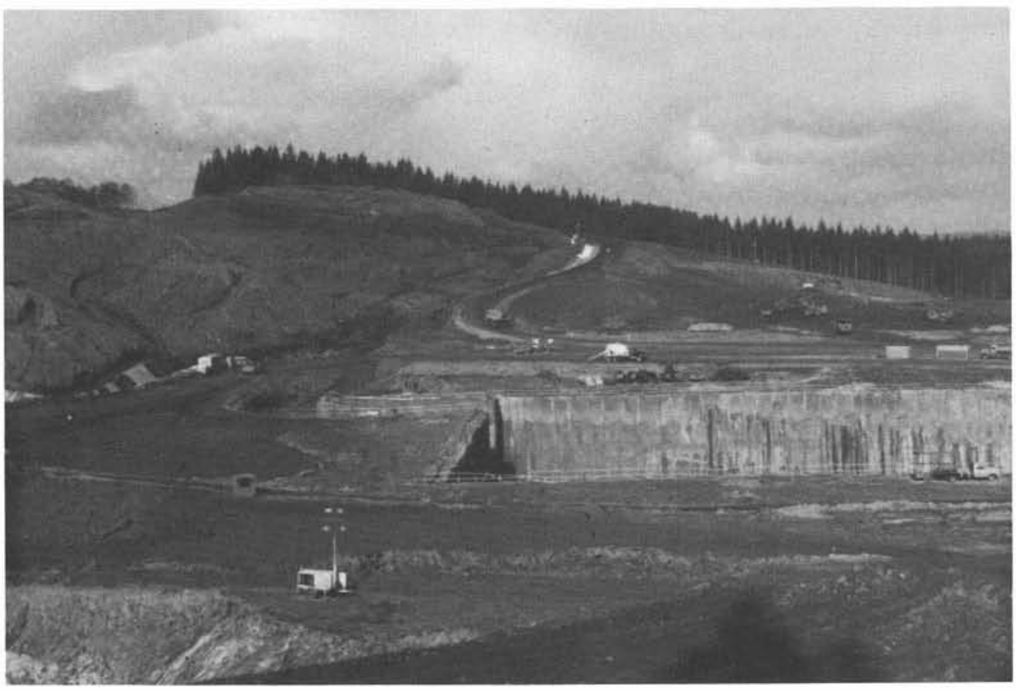
Rau, W. W., 1967, *Geology of the Wynoochee Valley Quadrangle*: Washington Division of Mines and Geology, Olympia, WA, Bulletin 56, 51 p., 1 plate.

Savage, J. D.; Lisowski, M.; and Prescott, W. H., 1981, Geodetic strain measurements in Washington: *Journal of Geophysical Research*, Vol. 86, No. B6, pp. 4929-4940.

Taber, J. J. and Smith, S. W., 1985, Seismicity and focal mechanisms associated with the subduction of the Juan de Fuca plate beneath the Olympic Peninsula, Washington: *Bulletin of the Seismological Society of America*, Vol. 75, pp. 237-249.

Washington Public Power Supply System, 1974, *WPPSS Nuclear Project Nos. 3 and 5, Preliminary Safety Analysis Report, Section 2.5, Geology and Seismology*: Washington Public Power Supply System Docket-STN-50508 and 50509, Richland, WA, 163 p.

Washington Public Power Supply System, 1982, *WPPSS Nuclear Project No. 3, Final Safety Analysis Report, Section 2.5, Geology and Seismology*: Washington Public Power Supply System Docket-STN-50508, Richland, WA, 439 p.



The excavation for the reactor building for WNP-3 near Satsop; view to the west in 1978. Photograph courtesy of the Washington Public Power Supply System.

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Geology and Seismicity of the Skagit Nuclear Power Plant Site

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INTRODUCTION

Site studies for the Skagit Nuclear Power Project were performed by Bechtel, Inc., for Puget Sound Power and Light (PSP&L) in accordance with Regulatory Guide 1.132 and submitted for review under the criteria of Appendix A, "Seismic and Geologic Siting Criteria for Nuclear Power Plants", of U.S. Nuclear Regulatory Commission (NRC) 10 Code of Federal Regulations (CFR), Part 100 (subsequently referred to as Appendix A). The purpose of the investigations was to determine the characteristics of the foundation materials, especially with regard to suitability for supporting plant structures, and to evaluate tectonics, faulting, and seismicity of the area so that the appropriate parameters for seismic design could be selected.

Geophysical surveys, including seismic refraction lines and cross-hole and up-hole velocity measurements, were made on-site by Harding-Lawson Associates, Inc. of Novato, Calif.; they also performed a gravity survey in the lower Skagit River valley. Exploration Data Consultants (EDCON) made extensive aeromagnetic surveys of the region around the site and provided an interpretation of the results. Graduate students, under the direction of Stuart Smith of the University of Washington, measured shallow crustal velocities to better define the epicentral location of a magnitude 3 earthquake that occurred in the Skagit River valley in 1974.

As a result of the investigations performed, it was concluded that the geologic, seismologic, and foundation conditions at the Skagit site were suitable for the construction and operation of a nuclear power plant. The principal structures were to be founded on dense, hard sedimentary rock. The site was located in an area of moderate seismic activity. Maximum historical intensity in the site area was Modified Mercalli Intensity (MM) VI, but the plant was designed to accommodate the maximum historical intensity felt in Puget Sound, MM VIII. The Safe Shutdown Earthquake (SSE) initially was 0.25 g; this was subsequently increased to 0.35 g to accommodate a postulated earthquake on the Devils Mountain fault zone 13 mi southwest of the plant site.

GEOLOGICAL FIELD INVESTIGATIONS

1972 through mid-1978

Upon completion of an extensive site selection process, the Skagit site, located 5 mi east of Sedro Woolley in Skagit County, was chosen in early 1972 for further evaluation of geologic suitability. The site was located on a glaciated bedrock knob about 300 ft above the alluvial plain of the Skagit River. Between May and November of 1972, 23 core holes were completed, several geophysical surveys were made, a trench was excavated across the contact between metamorphic and sedimentary rocks at the site, and geologic mapping on and near the site was performed. Results of these studies indicated that the site was suitable for a nuclear power plant, and a public announcement of the project was made in January 1973.

In February 1973, more detailed geologic studies of the site and the surrounding region were begun. Subsequently, additional investigations were made to answer questions from the NRC and U.S. Geological Survey (USGS) reviewers, to respond to requests by the Atomic Safety and Licensing Board (ASLB), to evaluate new information or hypotheses, and to map new geologic exposures, such as logging road cuts.

Between 1973 and 1977 the following major field investigations were completed for the project:

- Additional geologic mapping, mainly within 5 mi of the site, but in some instances at greater distances;

- Studying all available types of remote sensing data for the site vicinity and for areas 30 mi or more from the site for some geologic features;
- Drilling more than 60 core holes, totaling more than 10,000 linear feet, plus digging 11 on-site trenches, including two exploratory foundation trenches as long as 510 ft and as deep as 30 ft;
- Making on-site cross-hole, up-hole, and surface geophysical surveys;
- Laboratory testing of rock cores;
- Performing two gravity surveys in the Skagit River valley;
- Running 21 seismic lines in the Strait of Georgia and Puget Sound, near the San Juan Islands;
- Collecting and studying data on the 1872 earthquake, which resulted in Bechtel concluding that its epicenter should be relocated from Canada to the Entiat-Lake Chelan area in eastern Washington;
- Mapping, trenching, drilling holes, and making geophysical survey traverses across the Devils Mountain fault zone, and the dating of carbonaceous material.

In November 1977 the Advisory Committee on Reactor Safety (ACRS) issued a letter report stating that they considered the Skagit site to be suitable and that 0.35 g was adequate for the SSE. In March 1978, the NRC and USGS reviewers testified at an ASLB hearing that they considered the Skagit site to be suitable for a nuclear power plant and that 0.35 g, used with the Regulatory Guide 1.60 design spectra, was suitable for defining the SSE for the project site.

However, in June 1978 the NRC and USGS issued a request for additional information regarding an interpretation of the geology of the San Juan Islands and the area south and west of the project site (Whetten, 1978). The response to this request entailed additional studies, which continued into 1979 (Bechtel, Inc., 1979).

Late 1978 through 1979

From 1978 through 1979 the following field studies were conducted:

- Additional geologic mapping at scales of 1:62,500, 1:24,000, and 1:12,000, over about 1,000 sq mi;
- Running more than 6,000 linear miles of aeromagnetic surveys covering 630 sq mi, and measuring magnetic properties on more than 120 rock samples from 25 localities within the survey area;
- Core drilling of 11 holes, totaling more than 8,000 linear feet, and auger drilling and sampling of 26 soil borings in glacial deposits;
- Additional ground magnetic and gravity profiling;
- Making detailed petrographic studies of several hundred samples, plus associated x-ray diffraction analyses; and radiometric age-dating of 39 samples from the study area.

Additional detailed geologic mapping, at greater distances from the project site, continued into 1980, when the application for the site was withdrawn.

GEOLOGIC STUDIES

Regional Geology

The proposed Skagit site was located in the western foothills of the North Cascades, near the eastern edge of the Puget Lowland (Figure 1). The "North" Cascades are defined as that part of the Cascade Range where pre-Tertiary rocks (more than 65 Ma) are far more abundant than younger rocks. Rocks near the Skagit site range in age from about 40 Ma to more than several hundred million years. A regional geologic map is presented in Figure 2.

The region experienced several episodes of strong tectonic activity and deformation prior to about 40 Ma and has experienced much weaker deformation since then. Tertiary fold patterns are shown on Figure 3. According to Misch (1966), two large sheets or plates of rock were thrust westward 30 to 40 mi during the mid-Cretaceous; the Shuksan thrust plate is uppermost, and the Church Mountain plate is below it. Both plates underlie the proposed site (Figure 4). During the thrusting, extensive shearing, crushing, and secondary faulting occurred, particularly in the rocks of the Church Mountain plate, which were dragged along, pushed ahead, and overridden by the Shuksan plate. Some secondary faulting also occurred at this time in the Shuksan plate but not to the extent that it did in the underlying rocks. These thrust faults ceased moving about 100 Ma or before.

In latest Cretaceous and earliest Tertiary time, more than 50 Ma, as much as about 15,000 ft of continental sediments, now the Chuckanut Formation, were deposited on at least part of these thrust plates. These Chuckanut rocks have not been offset by the thrusts, demonstrating that the thrusts have not moved since the Chuckanut sediments were deposited.

In early Eocene time, about 50 Ma, strong tectonic activity again occurred in the region. It produced generally northwest-trending, steep folds in the Chuckanut rocks and in the underlying thrust plates (Figure 3). This tectonic activity diminished greatly by the late Eocene; rocks of that age are much less deformed than are Chuckanut rocks immediately underlying them.

In late Oligocene and early Miocene time, from approximately 15 to 30 Ma, relatively mild deformation caused weak folding and minor local faulting in the region. The Devils Mountain fault zone, 13 mi southwest of the plant site, probably experienced displacement at that time; the fault offsets Oligocene rocks.

The principal tectonic activity in the region since the Miocene has been broad uplift of the Cascade Range and simultaneous downwarping of the Puget Lowland; most of this deformation occurred within the past 3 mil-

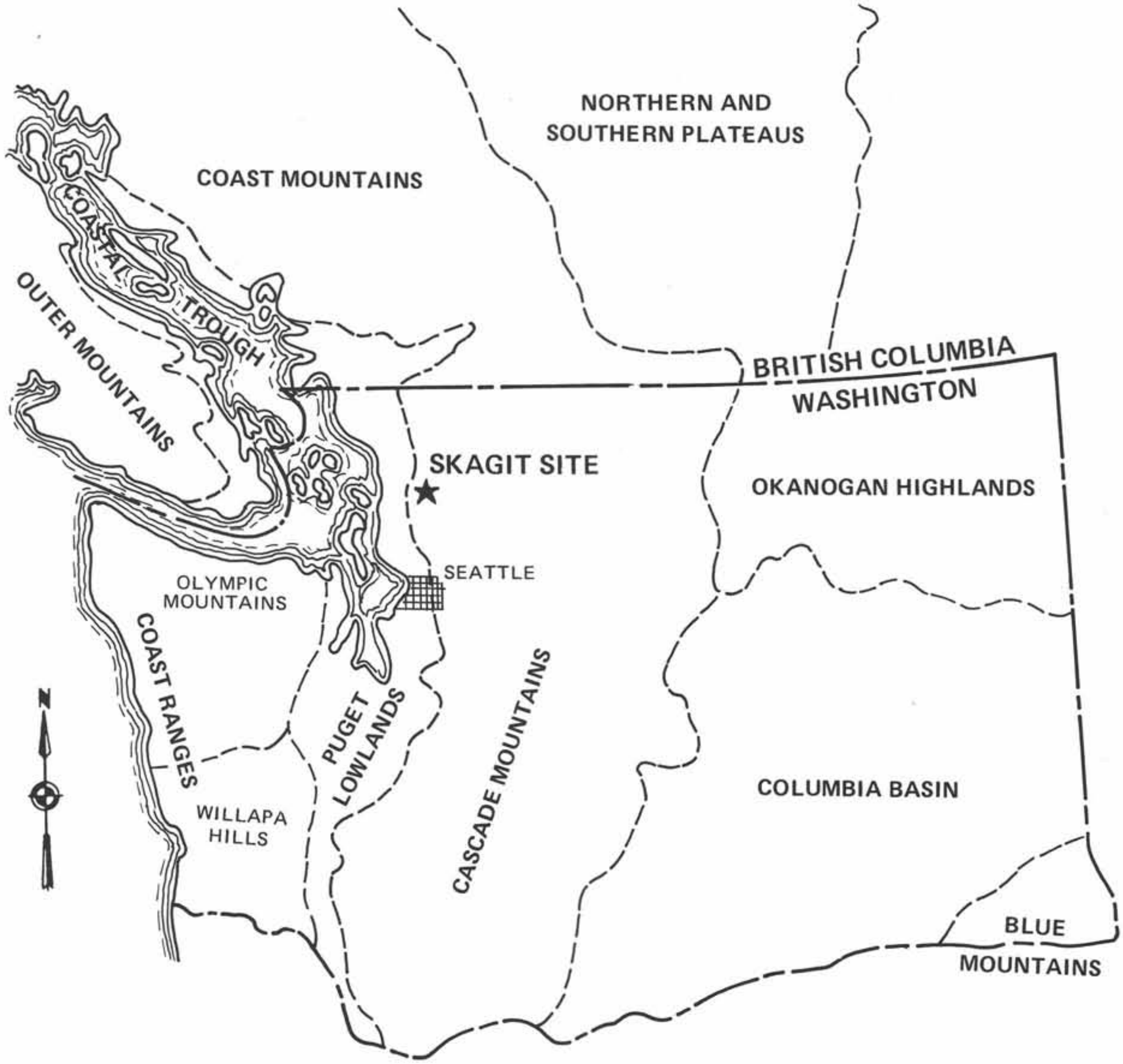


Figure 1. Site location, Skagit Nuclear Power Plant.

lion yr. There is no known faulting near the site that accompanied this uplift. The axis of the North Cascades uplift trends about north-south; consequently, it is discordant to most of the pre-Tertiary rock units and structures, which commonly trend northwest. Figure 5 shows the major tectonic features in the North Cascades.

Thus, it is apparent that the region has experienced several episodes of strong deformation and faulting. The principal tectonic events, which produced the complex geologic and structural conditions in the region around the site, occurred more than about 40 Ma.

Site Exploration

Extensive exploration studies at the Skagit site provided sufficient detail on its geology and seismic stability. These studies included geologic mapping, geophysical surveys, core drilling in rock, soil borings, trenching, and ground-water studies. The feasibility study in 1972 included drilling 23 core holes in sedimentary and metamorphic bedrock and across the sedimentary/metamorphic bedrock contact. Detailed geologic mapping of the site and adjacent areas was carried out at the same time. Geophysical surveys using magnetometer and seismic refraction methods were conducted to evaluate the depth to rock and the position of the buried contact between the metamorphic rocks and the overlying sedimentary rocks. A trench was also excavated across the contact to evaluate the nature and age of the contact and overlying materials. The results of the initial exploration program indicated that the massive

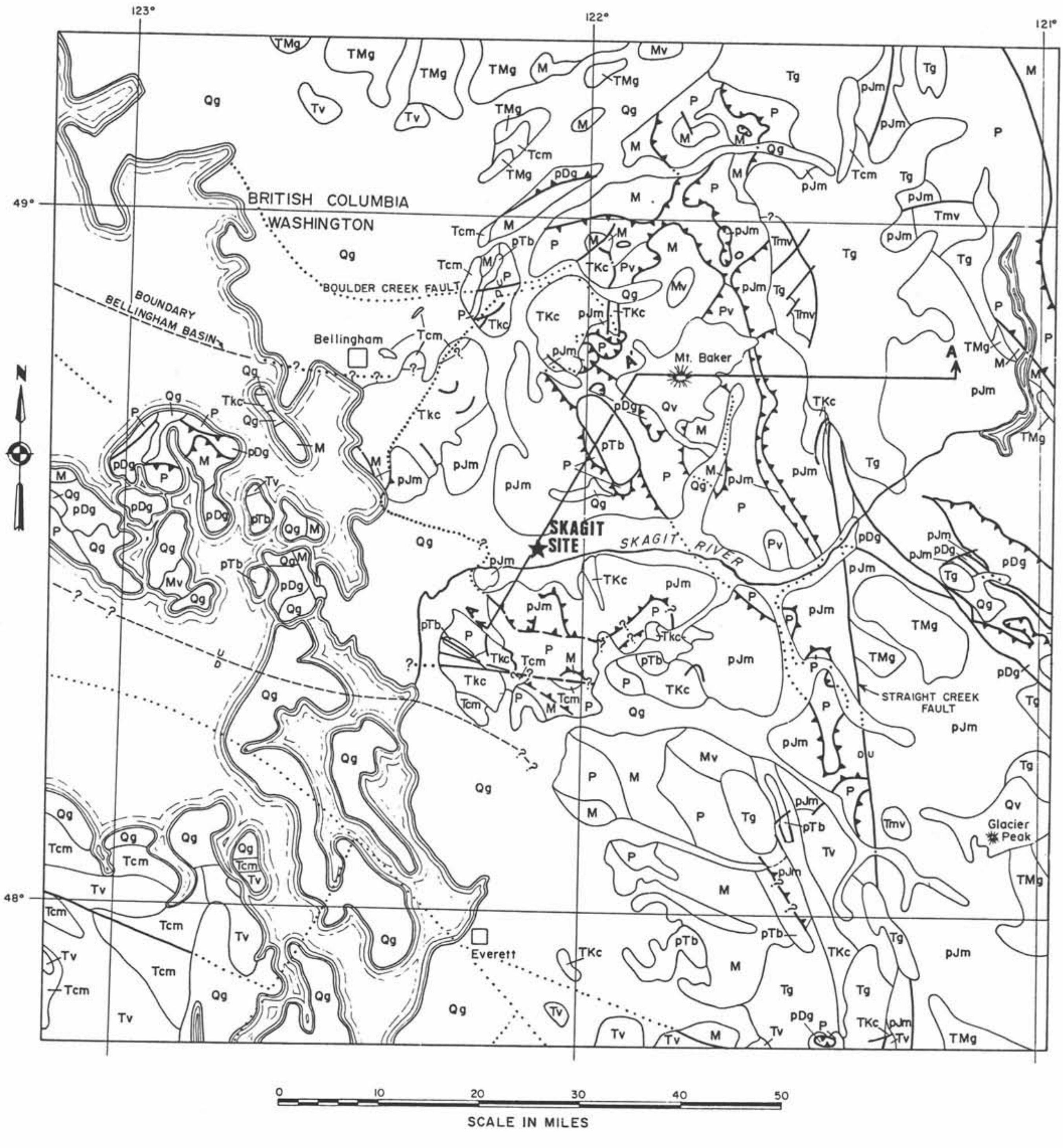
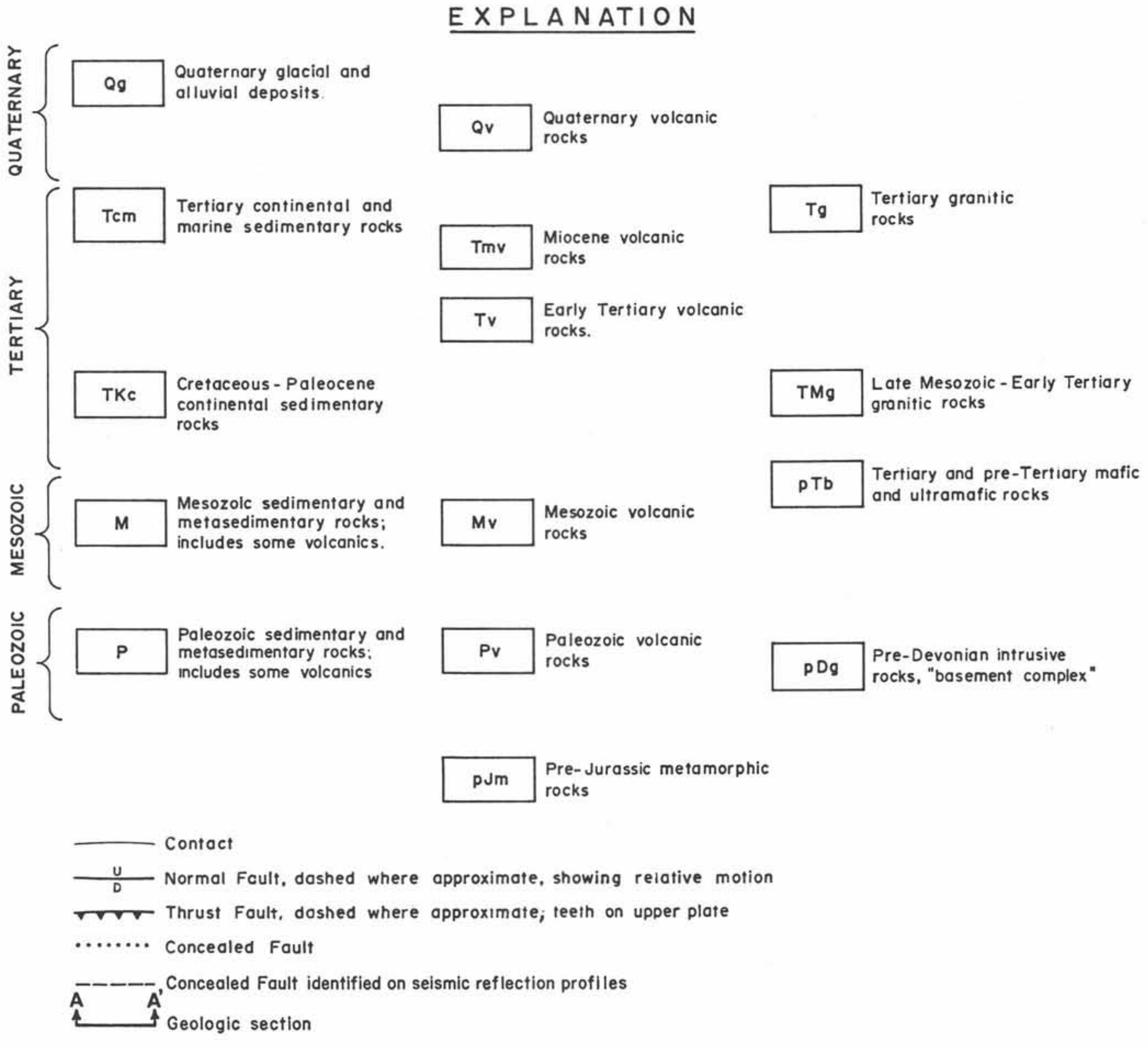


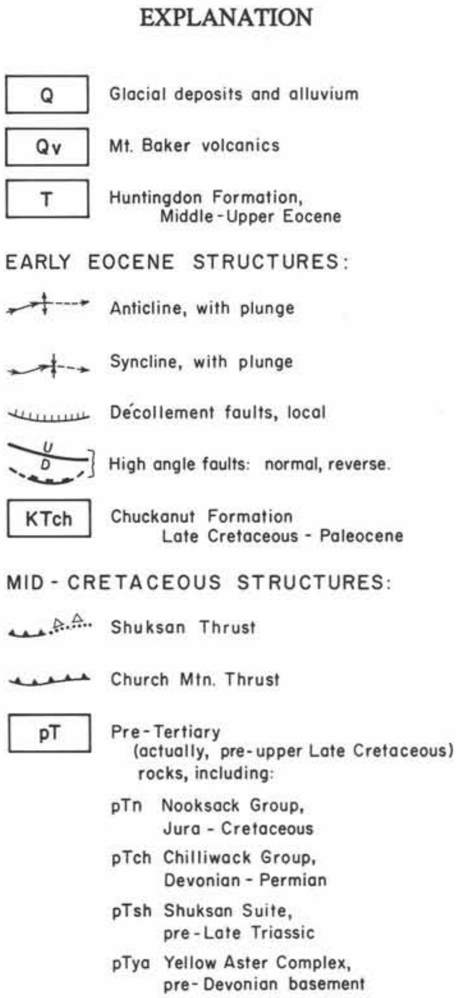
Figure 2. Regional geologic map of the Skagit Nucelar Power Plant area. Explanation is on facing page. For sources of map data, see Puget Sound Power and Light Company (1973).



sandstone and interbedded siltstone units of the Chuckanut Formation were suitable as foundation materials for the proposed nuclear power plant structures.

The detailed (Preliminary Safety Analysis Report or PSAR level) on-site exploration studies were continued during 1973 and 1974 to provide more detailed geologic information on lithology, stratigraphy, and structure over a larger area adjacent to the principal plant structures. In this second phase of site exploration, an additional 64 core holes totaling more than 10,000 linear feet were drilled. Many of the core holes were completed as ground-water monitoring wells. Eight temporary trenches were excavated in the plant structure areas, and three trenches were excavated across the sedimentary/metamorphic rock contact. Two large trenches were excavated perpendicular to bedding in bedrock across each of the two plant containment areas. These exploratory foundation trenches, designated EFT-1 and EFT-2, were 445 and 510 ft long, respectively, and as much as 30 ft wide and 30 ft deep. They allowed a thorough examination of the structure and stratigraphy of foundation bedrock beneath each proposed unit. The trenches were mapped in detail and photographed by Bechtel geologists. Because the trenches were designed to be left open until construction started, they allowed inspection by interested parties, such as NRC staff geologists and advisory board consultants, the USGS geologists, the applicant's consultants, and the intervenor's geologist. Although these trenches were expensive to excavate, they were subsequently considered to be well worth the expense.

Figure 3. Regional geologic structure near the Skagit Nuclear Power Plant site. Prepared from a map by P. Misch (1966); additional details from Miller and Misch (1963) and Bechtel mapping. Explanation on facing page.



Site Geology

The geology at the site consists of folded sedimentary rock of the Chuckanut Formation overlying deformed metamorphic rocks of the Shuksan Metamorphic Suite. Glacial deposits (till, lacustrine sediments, and outwash deposits) locally overlie the bedrock. A geologic map of the site is presented in Figure 6. Site geologic sections are shown on Figure 7.

In the area of the proposed plant structures, the overburden ranges in thickness from less than 1 ft to about 10 ft. To the northwest and east of the proposed reactors, the overburden ranges from 85 to more than 100 ft thick.

The Chuckanut Formation overlies metamorphic rocks of the Darrington Phyllite of the Shuksan Suite. The Chuckanut rocks have been assigned ages ranging from late Cretaceous to the late Eocene. Johnson (1984) assigned the Chuckanut rocks in this area to the Eocene. The Chuckanut-Darrington contact generally trends northwest.

Sandstone predominates within the proposed plant foundation area. Generally, it consists of thick-bedded, well-cemented, hard, stratified, very fine to coarse-grained, cross-bedded arkosic sandstone. Carbonaceous and micaceous laminations are present in varying amounts in all sandstone beds at the site. Most siltstone interbeds in the proposed foundation area are dark gray to black, thin-bedded to massive, and, in places, shaly. The siltstone units are locally carbonaceous, grading from fossiliferous laminations to impure coal beds as much as several feet thick. The siltstone is generally as strong as the sandstones but more brittle and locally weakened by sporadic layers of coal and carbonaceous material. The sandstone and siltstone commonly occur in intervals of thinly interbedded sequences displaying cross-bedding and soft-sediment deformation structures. Extensive core drilling in angle holes perpendicular to bedding showed that the amount of fine-grained rocks and coal beds increases toward the base of the sedimentary sequence at the contact with the phyllite.

The metamorphic rocks of the Shuksan Suite north of the plant site are predominantly graphitic schist and phyllite and minor sericitic phyllite and mica schist. Slate, serpentine, hornfels, and greenstone occur in exposures on Lyman Hill north of the plant site. Rocks of the Shuksan Suite, the oldest formation near the site, were assigned an age of pre-Jurassic by various authors at the time of site investigations. Recent studies (Armstrong, 1980; Brown, 1987) have shown that regional blueschist metamorphism occurred in the Early Cretaceous (120-130 Ma) and that the protolith age is probably Jurassic.

Structural Geology of the Site

The site is on the northeast limb of a northwest-trending syncline (Figure 3), which conforms with regional structural trends. The axis and the southwest limb of the syncline are buried under alluvium and glacial drift in the Skagit River valley. Near the proposed structures, the strike of bedding ranges from N40°W to N75°W and averages about N55°W; the dip ranges from 50° to 75° SW and averages about 60°. The sedimentary rocks rest on an eroded surface; thus the contact is not planar. Southeast of the proposed reactor sites, the trace of the contact was mapped as bending to the south, on the basis of magnetometer survey line data and the eastern limit of exposures of the Chuckanut Formation. The change in orientation of the bedding and contact suggest this is part of the closed end of a syncline plunging to the northwest.

Adjustments to folding are evident in the sedimentary rocks, particularly where soft shale and coal are interbedded with thick, rigid sandstone. Shearing and crushing occurred in and along the softer beds as a result of differential movement during the folding. Drill cores show that the degree of shearing and adjustments to folding increases toward the contact between the

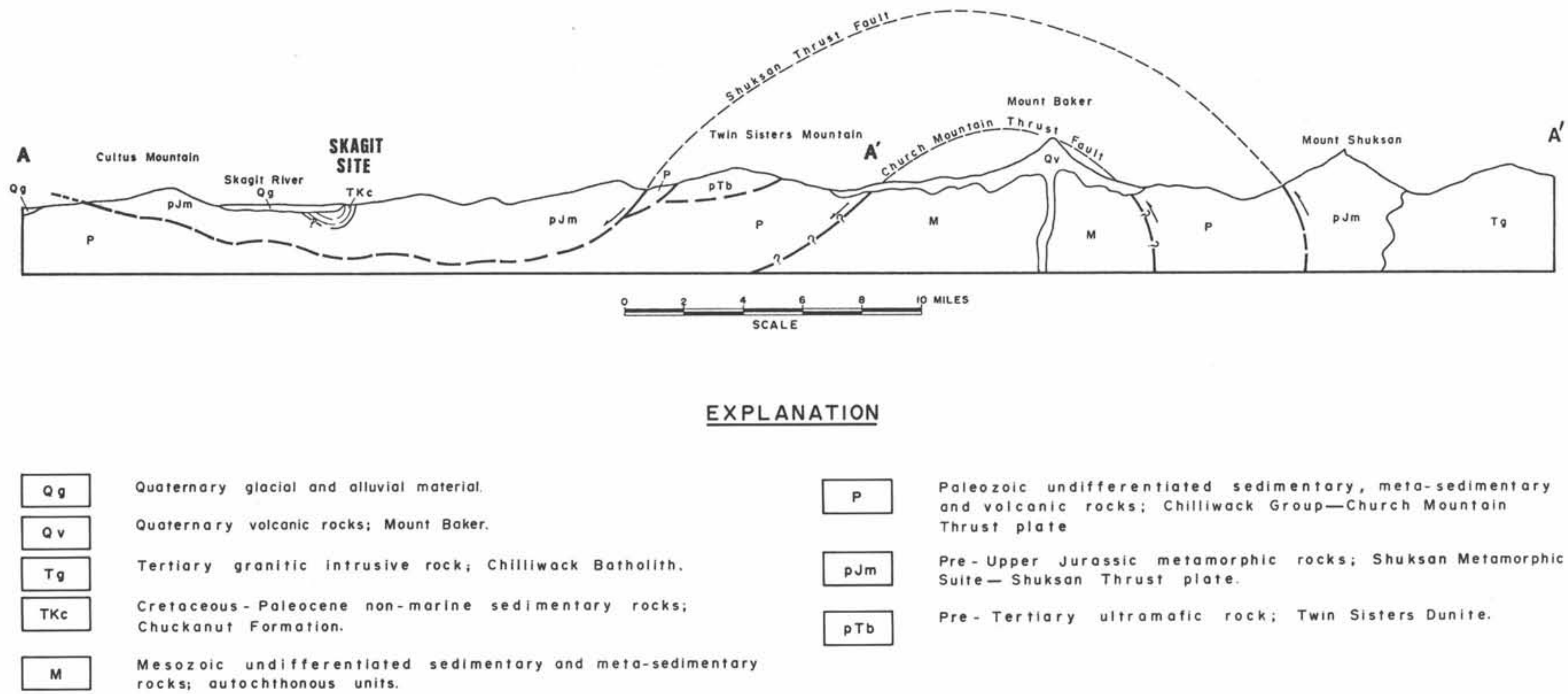


Figure 4. Cross-section of the Shuksan and Church Mountain thrust plates. From Misch (1966), Christenson (1971), McKee (1972), and other sources. See Figure 2 for location of section.

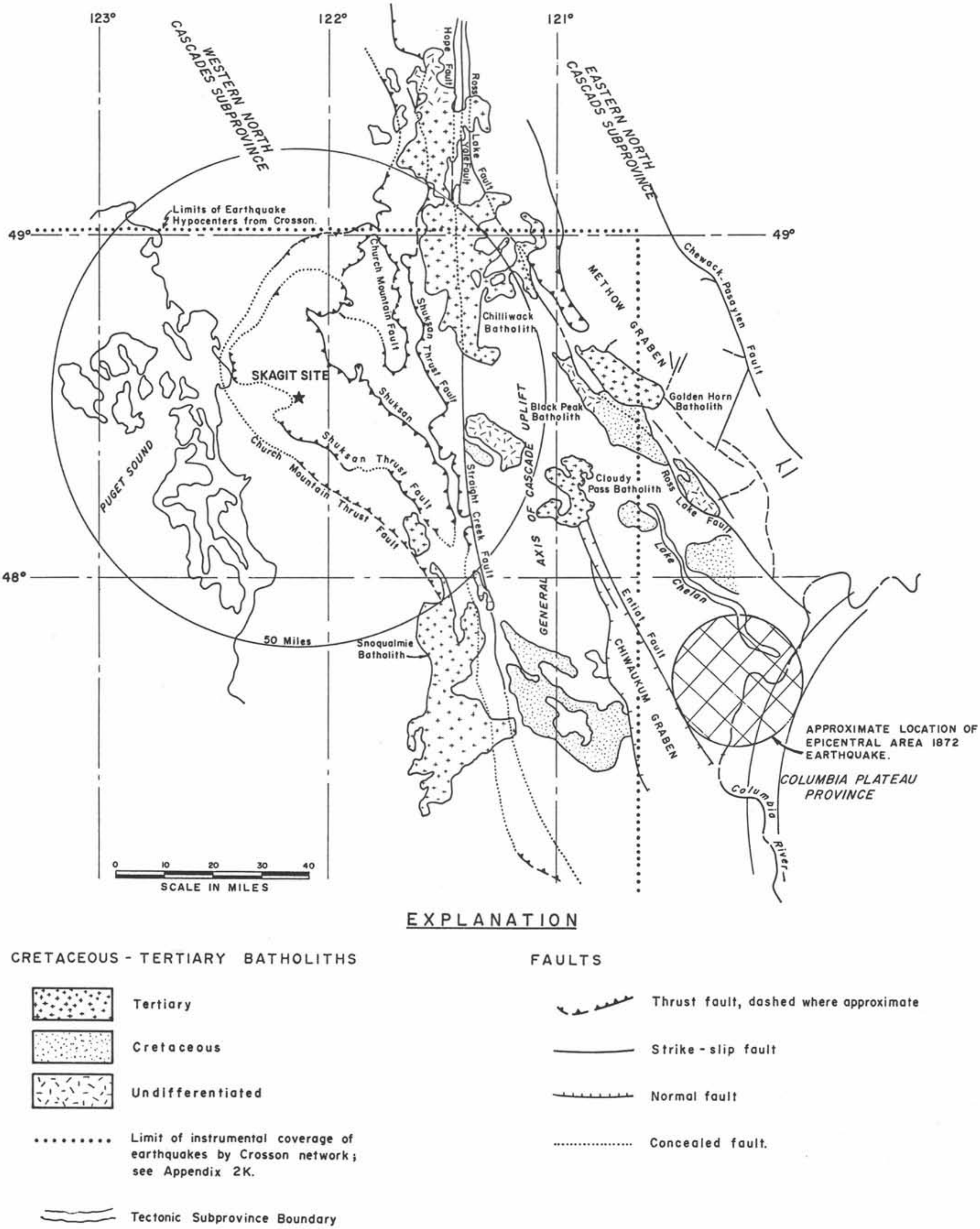


Figure 5. Major tectonic features of the North Cascades. From Peter Misch (unpublished mapping), Huntting et al. (1961), and Bechtel mapping.

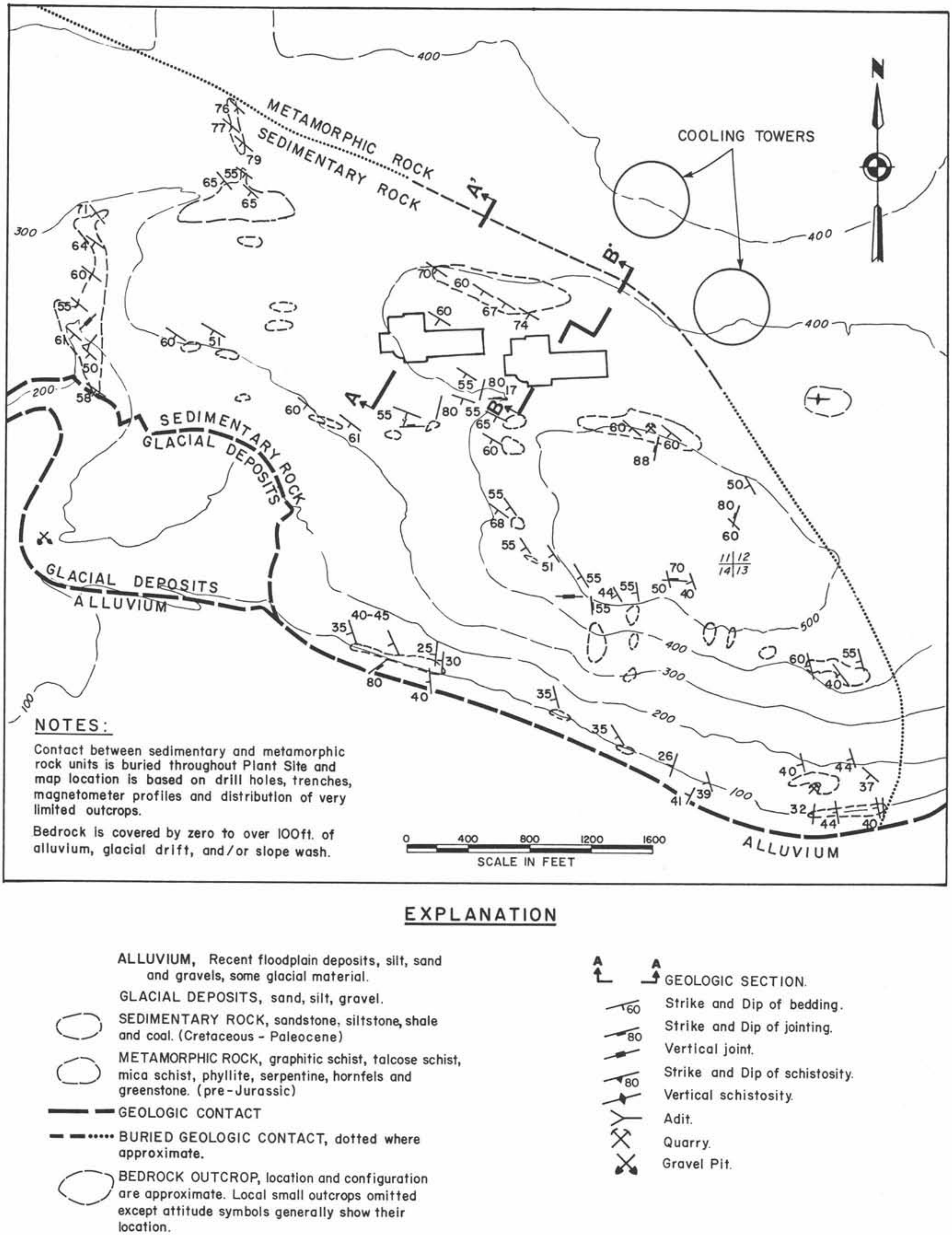


Figure 6. Generalized geologic map of the Skagit Nuclear Power Plant site. From Puget Sound Power and Light (1973).

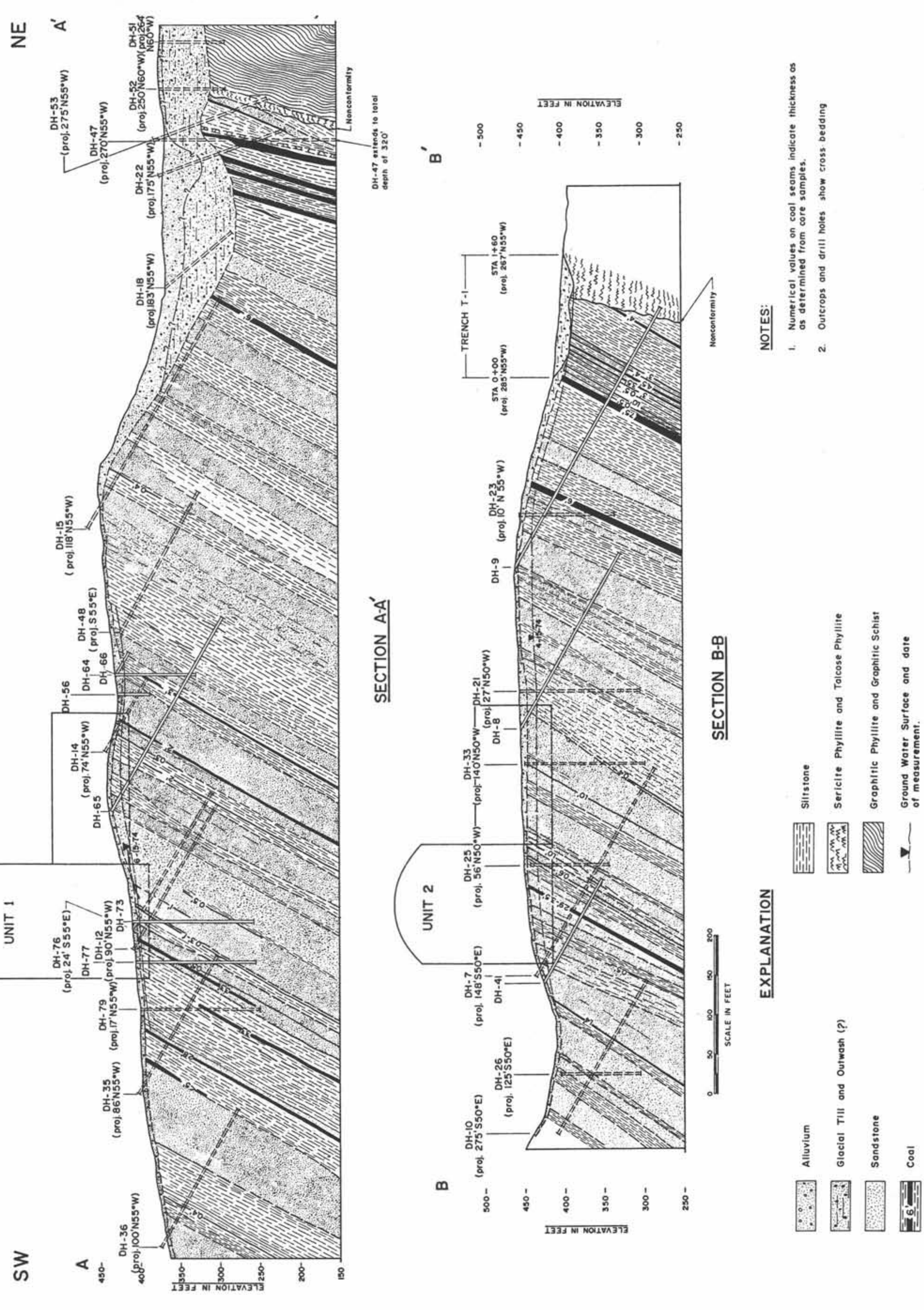


Figure 7. Geologic cross-sections at the Skagit Nuclear Power Plant site. Modified from Puget Sound Power and Light (1973).

sedimentary and metamorphic rocks. This probably results from two conditions: (1) the increase toward the contact of softer, weaker siltstone and coal beds that would absorb most of the necessary adjustments to the flexing of the sedimentary section; and (2) the schists and phyllites at and near the contact are weaker than the sedimentary rocks, owing to their well-developed foliation planes which are lubricated with graphite and sericite. The metamorphic rock absorbed more of the adjustment required during bending and flexing of the adjacent hard, massive sandstone than did the sedimentary rocks. The effect is that of a semi-rigid body folding at a slower rate than the less competent adjacent material, and sliding to a small degree over the curvature of the fold.

The contact was carefully investigated to determine whether it was a fault contact or a depositional feature. Evidence from the drill cores and trenches indicates that it is a depositional contact along which some shearing has taken place. Core from DH-9 and exposures in trenches EFT-1 and EFT-2 showed a tight contact at which carbonaceous siltstone overlies sericitic phyllite. The contact surface exposed in the trenches is locally irregular and uneven. Slickensides resulting from the sliding described previously are present on the rock faces near the contact. Both rock types adjacent to the contact in the trenches were moderately hard to hard and unsheared.

Investigations of Faults

Shuksan-Church Mountain Thrust Fault System

The Shuksan and Church Mountain thrust plates moved 30 to 40 mi westward more than 100 Ma ago (Misch, 1966). The Shuksan was the "master" thrust; it dragged along the underlying Church Mountain plate (Figure 4). The Shuksan thrust plate consists principally of the Darrington Phyllite and the Shuksan Greenschist. The Church Mountain thrust plate contains a variety of rock types.

The Shuksan thrust fault forms the base (or "sole") of the Shuksan thrust plate. The trace of the fault in the site area had been mapped prior to the start of geologic studies for the Skagit Project. In Misch's classic work (1966) on the geology of the North Cascade mountains, his map depicts the edge of the Shuksan thrust plate wrapping around the southern and western flanks of Cultus Mountain and the thrust plate overlying the rocks mapped adjacent to it.

Later, Miller (1969) described the Shuksan plate as having been thrust southwestward over rocks that are now exposed south and west of Cultus Mountain. Subsequently, Miller (1979) conducted additional studies on the western extent of the Shuksan thrust plate and mapped the rocks of the Shuksan plate as structurally overlying the rocks to the south and west, which he identified as rocks of the Church Mountain thrust plate.

The edge of the Shuksan thrust plate was further defined during detailed geologic mapping by Bechtel (PSP&L, 1973). The edge was observed to curve around the southern flank of Cultus Mountain and to form a horseshoe shape to the north around Haystack and Little Haystack mountains between Gilligan Creek and Day Creek. This location of the fault agrees closely with that mapped by Miller (1979). The rocks adjacent to the Shuksan thrust plate have been identified in the PSAR (PSP&L, 1973) as the Church Mountain thrust.

A significant part of the later field studies for the Skagit project was devoted to the investigation of the pre-Late Cretaceous thrust faulting northeast, south, and southwest of the project site. In itself, the mapped thrust system, whatever its tectonic origin, had no significance to plant safety; however, the relative position of mapped units and the interpreted direction of thrusting had a bearing on other interpretations of possible later structures that might have been of significance to the site.

Three interpretations were presented during the project review. The first interpretation, originally proposed by Misch (1966) and presented in the PSAR (PSP&L, 1973), described the Shuksan thrust plate as a continental, alpine-type structure, displaced during the mid-Cretaceous in a westerly to southwesterly direction. The Shuksan plate dragged along, pushed ahead, and overrode the Church Mountain thrust plate, locally creating a broad imbricate zone. Subsequent to thrusting, the entire sequence was folded. The contact between metamorphic units mapped around the southern and western flanks of Cultus, Haystack and Little Haystack Mountains is the trace of the northeast-dipping, folded Shuksan thrust-fault plane.

In the second interpretation, presented by Whetten (1978), the rocks of Table and Haystack mountains are not part of the Church Mountain plate, but are a younger thrust plate (Decatur terrane) that has moved northward and eastward over the rocks of the Shuksan thrust plate as an obducted ophiolite of oceanic origin. Thus, the contact on the southwest flank of Cultus Mountain in this interpretation is the trace of a southwest-dipping fault plane or, in part, a later high-angle fault.

The third interpretation has similarities to both of these models. Vance (1979) considered the rocks on Table and Haystack mountains, as well as those in the eastern San Juan Islands, to be of the same Mesozoic terrane; however, he believed that these units were in place at the time of the mid-Cretaceous thrusting and were overridden by the westward-moving Shuksan plate.

The relative positions of the structural units were investigated by Bechtel by detailed geologic mapping supported by remote sensing, core drilling, ground magnetic profiling, aeromagnetic surveying, and data modeling. Because exposures of bedrock in most of the Cascade foothills are sparse, clear-cut field relationships of any kind are scarce. Study of magnetic susceptibility had indicated that the Church Mountain plate (or "Decatur terrane" of Whetten), including the thrust fault zone, have a distinctive magnetic signature representative of a serpentinite/ultramafic association. Therefore, direct evidence of the rocks present was sought by core drilling supplemented with indirect evidence from analysis of aeromagnetic data.

At several localities, drilling was initiated in the Darrington Phyllite with the intent to determine if, in fact, the phyllite was underlain by the major fault zone and rocks of the Church Mountain plate. Because of the nature of the faulting, not all subsurface data were readily definitive; however, at two key locations, the concurrence of geological and geophysical data provided strong evidence regarding the relative positions of the older metamorphic units. On the southwest flank of Cultus Mountain, data from a series of core holes demonstrated that Darrington Phyllite overlies a fault zone at least 200 ft thick, which, near the ground surface, dips eastward at an angle of 20° or less. Below the fault zone are metavolcanic and metasedimentary rocks, serpentinite, and detached blocks of Shuksan-type rock, all interpreted as part of the Church Mountain plate. The aeromagnetic data from this area were particularly suitable for modeling. From this analysis, it was determined that the model that best fit the measured data was a body of relatively higher magnetic susceptibility dipping northeastward (into Cultus Mountain) at about 15° to 30°. This interpretation conforms well to the dip of the fault zone encountered in the core drilling and to the interpretation of Misch (1966).

A similar interpretation was obtained in an area southeast of the project site, where a similar analysis of drilling and magnetic data was augmented by an exposure of the tectonic contact zone. Here, the phyllite is increasingly sheared near an east-dipping, steep fault zone. Close examination of the zone indicated the phyllite had moved over the fault zone. Below this contact was a tectonic complex of metavolcanic rocks, metachert, and ultramafic rocks in a matrix of pervasively sheared serpentinite. Core-drilling data, plotted with the geologic mapping and surface magnetic data, indicated that the lower limit of the continuous phyllite interval dips about 20° to the east. Analysis of the aeromagnetic data concluded that the high-susceptibility source dips approximately 60° northeast and extends to considerable depth.

It was concluded, therefore, that the rocks on Table and Haystack mountains underlie the Shuksan thrust plate and that the contact between the major map units is the trace of the folded Shuksan thrust fault, as proposed by Misch (1966). The rocks underlying the Shuksan plate are a complex assemblage, which probably includes some Mesozoic rocks similar to those mapped in the eastern San Juan Islands, as well as rocks that are correlative with the Chilliwack Group and Mesozoic rocks that have been mapped in the Church Mountain thrust plate east of the project site. Underlying rocks, which have been dragged along by the Shuksan thrust plate, are, by Misch's (1966) definition, part of the Church Mountain thrust plate, regardless of their previous stratigraphic affinity.

Devils Mountain Fault Zone

The Devils Mountain fault zone (DMFZ) is located approximately 13 mi southwest of the project site. The fault zone is marked by several topographic lineations that coincide with fault splays juxtaposing Oligocene and Paleocene-Eocene sedimentary rocks that include fault-bounded slivers of older metamorphic and ultramafic rocks. The fault investigations for the Skagit project addressed Oligocene/post-Oligocene movement on the DMFZ. In particular, the work focused on determining where faulting was present and the age of movement in two areas: (1) in younger units beneath Puget Sound on a westward projection of the DMFZ; and (2) in the area where the topographic lineations defined the zone's closest approach to the project site.

The westward extension of the DMFZ was postulated partly on the basis of an east-trending aeromagnetic gradient south of the San Juan Islands. The relationship of this gradient to the DMFZ mapped on land was investigated by land and marine magnetic profiling and by marine seismic profiling. The data indicated a deep source for the aeromagnetic anomaly and no associated near-surface expression of faulting west of Whidbey Island. The presence of Late Cretaceous to Eocene and Oligocene rocks in fault blocks on both sides of the major strands of the fault indicated post-Oligocene, down-to-the-south, normal faulting.

A minimum age of movement on the fault zone was investigated by trenching the glacial sediments that overlie and interrupt the longest, most pronounced topographic lineation. Location control over the fault was obtained by core drilling and bedrock exposures in some of the trenches. Several samples of carbonaceous material were recovered from unfaulted glacial deposits, including one dated with 95 percent certainty as exceeding 37 ka. Thus, last movement on the DMFZ is evidently post-Oligocene but pre-late Pleistocene (Crosby et al., 1986). However, because it could not be demonstrated that the fault had not moved more than once in the past 500,000 yr, the fault was assumed to be capable of further motion; this controlled the SSE for the project.

Postulated Gilligan Creek Fault

Field investigations also focused on a number of other postulated faults in the project study area. These faults were proposed on the basis of various interpretations of the topographic occurrence of certain units, photo-lineations, topographic parallelism, and aeromagnetic anomalies.

A fault was postulated by Whetten (1978) to exist along Gilligan Creek, approximately 3 mi south-southwest of the project site. During ASLB hearings and NRC/USGS meetings in 1978, he proposed that the linear trend of Gilligan Creek, and the occurrence of two metamorphic terranes at equal elevations on either side of the creek, were the result of a tear fault displacing the thrust fault to the south.

Because the fault was postulated partly on the basis of a lineation on a photo, remote-sensing imagery was reviewed in great detail with particular attention to cross-referencing of imagery types. From this review it was concluded that a linear trend existed that could be grossly characterized as a photo-lineation; but after detailed examination, it was found to lack continuity, to be irregular, and it apparently be caused by the coincident alignment of unrelated features.

Bedrock and glacial deposits in Gilligan Creek were mapped along projections of the lineation to the north and south. These investigations showed that Gilligan Creek is not fault-controlled, that shearing in the metamorphic rocks of the Gilligan Creek area has random orientation and no preferred alignment or coincidence with the lineation, and that no evidence of offset of the glacial deposits exists along the projections of the lineation.

Finally, the aeromagnetic data showed an excellent magnetic signature for the Shuksan thrust fault, the trace of which was mapped as an irregularly curving feature high on the east side of the Gilligan Creek valley. Gravity surveys in the Skagit River valley north of the postulated Gilligan Creek fault showed no indication of offset of the isogal contours that cross the projection of the postulated fault.

Postulated Day Creek Fault

A fault also was postulated by Whetten (1978) in Day Creek, about 5 mi east of Gilligan Creek, principally because Day Creek is parallel to Gilligan Creek. The lower segment of Day Creek had been examined prior to this postulation because of its linearity, and it was concluded that no evidence of significant faulting existed in this part of the creek. Later, mapping showed that foliation attitudes and fold axes in the Darrington Phyllite continue across lower Day Creek without offset. Likewise, the geophysical data indicated that both magnetic and gravimetric uniformity existed across lower Day Creek. Consequently, there was no basis for inferring a fault along Day Creek.

Volcanic Hazards Study

Because the project site was located at the northern end of the Cascade volcanic chain and 22 mi southwest of Mount Baker, an evaluation was made of possible hazards from volcanic activity. This assessment was based on existing studies of volcanic hazards in the Pacific Northwest and Alaska, consideration of the proximity, relative location, and eruptive history of the northern Cascade volcanoes, and consideration of historical examples of damage associated with volcanic activity.

The study reviewed the five dormant (at the time of the study) volcanoes in Washington: Mounts St. Helens and Adams, approximately 160 mi south of the project site; Mount Rainier, 120 mi to the south; Glacier Peak, 56 mi to the east-southeast; and Mount Baker, 22 mi northeast of the project site. (Volcanoes in British Columbia were not considered to be a potential hazard because of their size, distance, and eruptive pattern.)

Volcanic hazards can occur from one or more of the following events: (1) lava flows; (2) hot ash flows; (3) ash falls; (4) debris flows; (5) flooding resulting from melting snow and ice, or from damage to dams impounding reservoirs; and (6) explosive lateral blasts of the type that occurred at Mount St. Helens in May 1980.

It was concluded from data on eruptive patterns that the hazards analysis for the Skagit site should consider ash fall effects, with Glacier Peak as the most probable source because of the prevailing wind directions, and debris flow/flooding effects originating from a Mount Baker eruption. The risk to the project site from other events and other types of volcanic activity were not deemed to warrant detailed study, but considerations were given to these other types of hazards.

The ash-fall model used was the 1912 Mount Katmai, Alaska, eruption (Wilcox, 1959) superimposed on Glacier Peak, using prevailing wind patterns in the project area. It was concluded that a 6-in.-thick ash fall occurring within a 24-hr period at the site was a conservative assumption. This thickness exceeds the total ash fall of the past 13,000 yr in the Skagit area, as measured in core samples from local peat bogs.

The effects of a mudflow similar in size and properties to the huge Osceola mudflow at Mount Rainier, but originating in the Sherman Peak/Boulder Glacier area on the southeast flank of Mount Baker, also were evaluated; this area on Mount Baker had been the scene of recent solfataric activity and subglacial melting. For simplicity, the model considered the effects of such a mudflow moving into the Baker valley, causing subsequent failure of Upper and Lower Baker dams and resulting in a total mass of more 3 billion cy of debris flowing westward down the Skagit valley. Even with these preposterous conditions, the resulting thickness of a debris flow in the Skagit valley below the site was calculated to be about 85 ft, some 200 ft below project grade.

SEISMIC DESIGN EVALUATION

The pertinent literature regarding the seismology, geology, and seismic history of the region was reviewed and evaluated. A brief description of the earthquake history of the area within 200 mi of the plant site and an evaluation of the seismicity of the site are provided below. Acceleration values selected for design of the plant structures for the SSE and Operating Basis Earthquake (OBE) are also discussed.

The plant site is located in a region of moderate seismic activity that extends from near Portland, Oregon, northward through Puget Sound to the Canadian border and Vancouver Island. The maximum epicentral intensity of any historic earthquake in this region was MM VIII (Wood and Neumann, 1931) during the 1949 Olympia earthquake, the 1965 Seattle-Tacoma earthquake, and the 1946 earthquake in Canada. The maximum intensity experienced in the site area within the last 150 yr is MM VI (Figure 8).

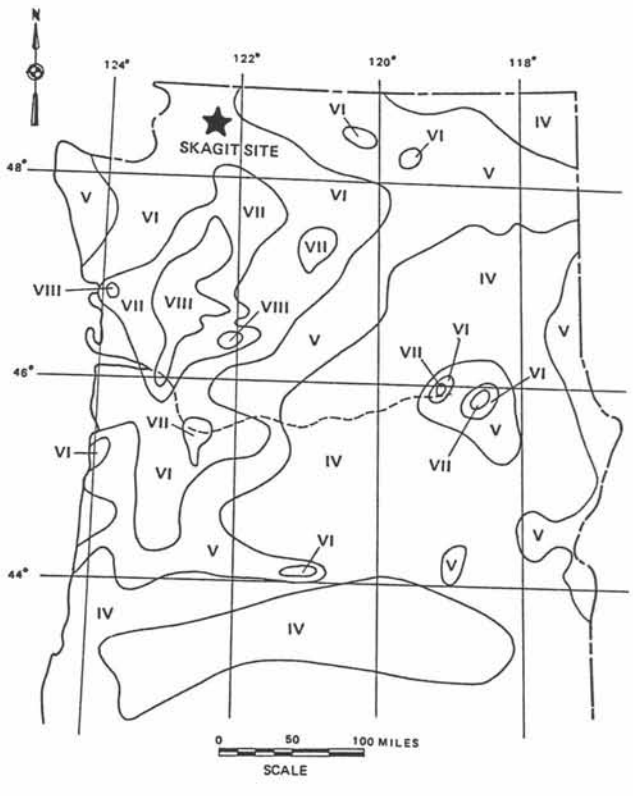


Figure 8. Maximum historic earthquake intensity (Modified Mercalli intensity scale) in Washington and Oregon. From figure 35 of Algermissen et al. (1969).

Earthquake History

Within historic time, 27 earthquakes of epicentral intensity MM V to VI had occurred within 50 mi of the proposed site at the time of PSAR preparation (Figure 9). The largest earthquakes within 50 mi were two MM-VII shocks about 40 mi to the northwest. Within 15 mi of the site, there has been only one reported earthquake of epicentral MM V or higher; this was a MM-VI (on alluvium) shock, which occurred on December 15, 1974, about 4-1/2 mi southeast of the plant site. Only about two dozen shocks have been reported in the literature as having been felt near the site.

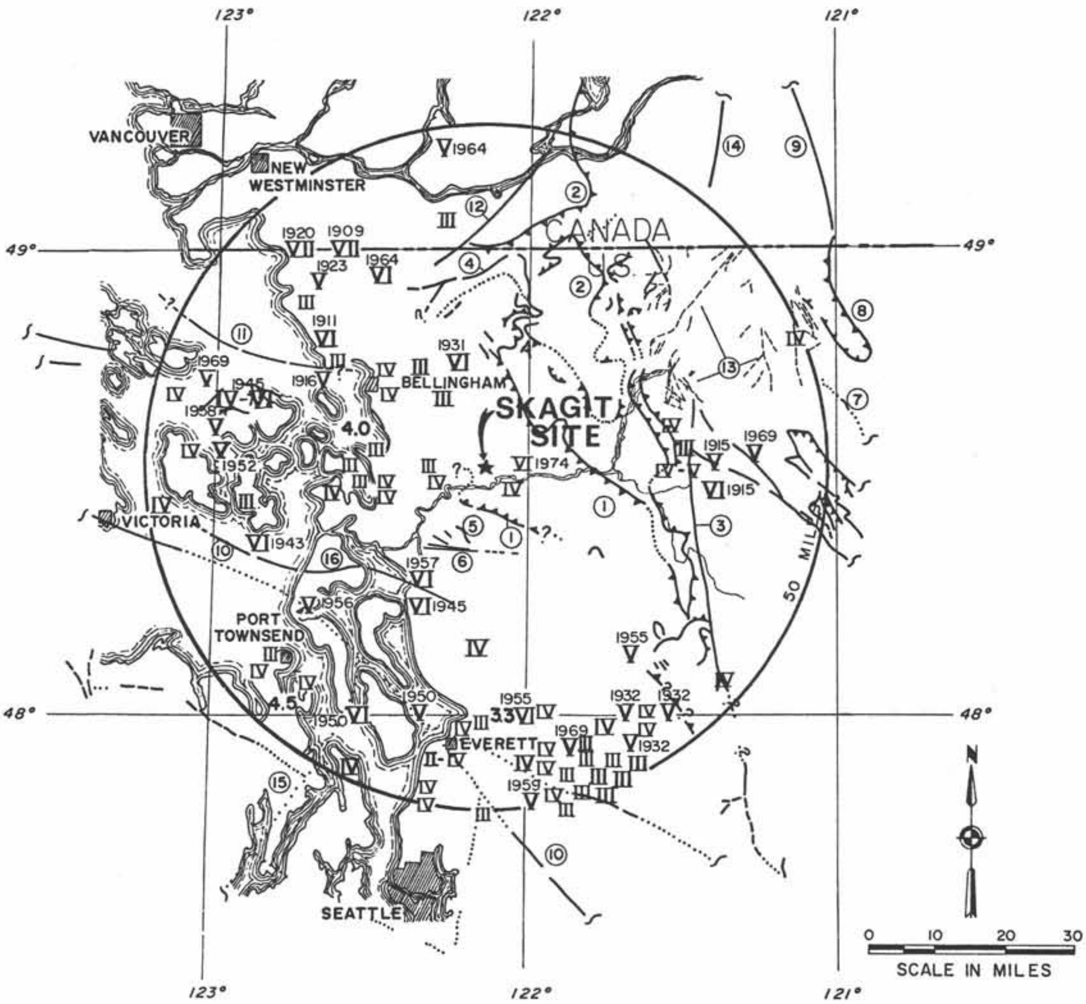
The largest earthquakes that have occurred historically in the Puget Sound-Strait of Georgia region were three epicentral MM-VIII events, all at least 70 mi from the site. Two of these quakes resulted in MM VI near the site, which is the maximum intensity felt in the site vicinity.

The largest historical earthquakes to have occurred within 200 mi of the site were the Olympia earthquake of April 13, 1949 (magnitude 7.1 and MM VIII), and perhaps the December 14, 1872, earthquake (MM VIII+, magnitude unknown). Milne (1956) considered the epicenter of the 1872 earthquake to have been in Canada near Chilliwack. After extensive research for the Skagit Project, Bechtel concluded (PSP&L, 1973) that the epicenter of the 1872 earthquake was in central Washington, near Entiat-Lake Chelan (Figure 5). Other investigators subsequently interpreted the epicenter to have been in the Cascades somewhere between Entiat and Chilliwack. Hooper et al. (1982) reported that they considered the epicenter of the 1872 earthquake to have been in the Entiat-Lake Chelan area.

The maximum intensity, VI, experienced historically in the site vicinity occurred during the June 23, 1946, British Columbia earthquake (epicentral intensity VIII); the April 29, 1965, Seattle earthquake (intensity VIII); and the 1872 earthquake (intensity VIII+). The 1949 Olympia earthquake resulted in intensity V at Sedro Woolley, 5 mi west of the site. Towns near the proposed site that reported intensity VI during these shocks are located on alluvium and glacial deposits. Because the site is founded on bedrock, ground acceleration at the site during these three earthquakes probably did not exceed 0.06 g, on the basis of accepted intensity/acceleration relationships (Trifunac and Brady, 1975). Intensity VI shaking was also experienced at three localities on the Skagit valley alluvium during the magnitude 2.8-3.0 earthquake on December 15, 1974 (discussed above), but the shock was not felt at the plant site; it did not trigger an on-site seismograph.

Safe Shutdown Earthquake

According to Appendix A (PSP&L, 1973), the design basis for vibratory ground motion due to earthquakes shall be determined by associating the historic earthquakes of greatest magnitude or intensity in the region to either tectonic structures or tectonic provinces. Where such earthquakes can be related to tectonic structures, the acceleration at the site shall be determined by assuming that the epicenters or locations of highest intensities are situated at the point on the tectonic structure nearest the site. Where epicenters or locations of highest intensity of historically reported earthquakes in the site tectonic province cannot be reasonably related



FAULTS

NUMBER	FAULT NAME	DISTANCE FROM PLANT SITE (MILES)	REFERENCES (LISTED IN PSAR)
1	Shuksan Thrust	8	Misch, 1966, Ref.5
2	Church Mountain Thrust	20	Misch, 1966, Ref.5
3	Straight Creek	30	Misch, 1966, Ref.5
4	Boulder Creek	25	Miller and Misch, 1963, Ref.17
5	–	11	Jenkins, 1924, Ref.11
6	Devils Mountain	12	Loveseth, 1975, Ref.125
7	Ross Lake	55	Misch, 1966, Ref.5
8	Jack Mountain Thrust	55	Misch, 1966, Ref.5
9	Hozameen	60	McTaggert and Thompson, 1967, Ref.94
10	–	35	King, 1969, Ref.19
11	–	30	Dobrin, 1975, App.2G
12	Vedder Mountain	30	Misch, 1966, Ref.5
13	–	>30	Staatz, et al., 1972, Ref.98
14	Yale	55	McTaggert and Thompson, 1967, Ref.94
15	Hood Canal	35	King, 1969, Ref.19
16	–	20	Dobrin, 1975, App.2G
All other faults shown		-	Ref.5, 10, 19

Figure 9. Faults and earthquakes within 50 miles of the Skagit Nuclear Power Plant site. From Puget Sound Power and Light (1973)

to tectonic structures, the acceleration at the site shall be determined assuming that these earthquakes occur adjacent to the site; epicenters in tectonic provinces that are adjacent to the site tectonic province and can not be related to tectonic structures shall be assumed to occur on the boundary of the tectonic province at its closest approach to the site.

The SSE for the Skagit site was originally selected so that plant structures could withstand the maximum historical intensity (MM VIII) that has occurred in the Puget Sound region. A horizontal acceleration of 0.25 g on rock or firm foundation material is usually correlated with intensity VIII (Trifunac and Brady, 1975), but the plant structures were originally designed for 0.30 g for additional conservatism. When the Devils Mountain fault was assumed to be capable, the SSE was increased to 0.35 g to accommodate the maximum earthquake assumed for that fault.

Consideration was also given to a magnitude 7.1 earthquake (a repeat of the 1949 Olympia earthquake) occurring in the subducted slab under Puget Sound at its closest approach to the plant site, estimated to be 40 to 50 mi. It was concluded that, after attenuation of the ground motion to the site, such an event would be accommodated by design of the structures for 0.35 g.

In ACRS hearings, USGS scientists stated that they thought the SSE should be based on an intensity IX occurring adjacent to the plant site, because they judged the epicentral intensity of the 1872 earthquake to be IX and because they considered the earthquake and the plant site to be in the same tectonic province. However, 0.35 g was accepted by the NRC and ACRS as being adequate for the SSE for the site.

WITHDRAWAL OF PROJECT

In 1980 the USGS studied offshore seismic profiles run by several oil companies in the Strait of Georgia immediately north of the San Juan Islands and interpreted that the records indicate the presence of faults that extend to the "water bottom" (that is, ground surface beneath the water); hence such faults are possibly capable. They postulated that these faults may be part of a "family of faults" that extend from the Strait of Georgia southeastward along the southwest side of Cultus Mountain. The late M. B. Dobrin studied these same offshore records and disagreed with the USGS interpretation (Dobrin, 1980). (The inferred family of faults has not to date been documented to exist onshore.)

However, because of the delays already experienced in licensing the project, the additional delays that would be required to further investigate and respond to the interpretation of the family of faults, plus the lack of assurance that all geologic issues regarding the Skagit site could ever be resolved with the USGS, Puget Sound Power and Light Company decided to withdraw its application for the site near the Skagit River and move the application to a site on the Hanford Reservation in eastern Washington where nuclear facilities already existed.

ACKNOWLEDGMENTS

The extensive studies conducted for the Skagit Project from the early 1970s through the last licensing hearings in 1980 required the talents of numerous geologists, geophysicists, and consultants. The authors thank all of them for their contributions to the effort.

Geologic mapping in the "green hell" of the western Cascade foothills was difficult and challenging at best because of the complex structural and metamorphic setting, extensive glacial cover, and heavy vegetation. The region within 15 mi of the site was largely unmapped prior to these studies. The pioneering studies of the foothills region by the late G. M. Miller (1979) allowed extension to the west of the structural elements mapped previously by the late P. Misch (1966) in the high Cascades. Their critical review of and contributions to structural and tectonic interpretations were of great help during regional investigations. We are greatly indebted to M. B. Dobrin for his many nights of airplane travel to be available for meetings and hearings and for the vast knowledge and judgment he displayed in interpreting geophysical data. We gratefully acknowledge the contributions, reviews, and assistance provided by B. A. Bolt on seismology.

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REFERENCES

Algermissen, S. T; Stepp, J. C.; Rinehart, W. A.; and Arnold, E. P., 1969, *Studies in seismiscity and earthquake damage statistics, 1969, Appendix B*: U.S. Environmental Science Services Administration NOAA-SP-NOS-70112704, 71 p. [Available from National Technical Information Service as COM-71-00054].

Armstrong, R. L., 1980, Geochronology of the Shuksan Metamorphic Suite, North Cascades, Washington: *Geological Society of America Abstracts with Programs*, Vol. 12, No. 3, p. 94.

Bechtel, Inc., 1979, *Report of Geologic Investigations in 1978-1979, Skagit Nuclear Power Project*: Report for Puget Sound Power and Light Company, Bellevue, WA, 2 vol. [Copies of these reports (the PSAR and amendments) and the testimony given at ASLB hearings are in the Public Reading Room at the Nuclear Regulatory Commission offices in Bethesda, MD.]

Brown, E. H., 1987, Structural Geology and Accretionary History of the Northwest Cascades System, Washington and British Columbia: *Geological Society of America Bulletin*, Vol. 99, pp. 201-214.

Christenson, N. I., 1971, Fabric, seismic anisotropy, and tectonic history of the Twin Sisters dunite, Washington: *Geological Society of America Bulletin*, Vol. 82, No. 6, pp. 1681-1694.

Crosby, T. W.; Talmage, R. H.; and Adair, M. J., 1986, *Radiocarbon Dating and Geomorphic Evidence for Dating Movement on the Devils Mountain Fault Zone, Northwestern Washington*: Geological Society of America Abstracts with Programs, Vol. 18, No. 2, p. 97.

Dobrin, M. B., 1980, Oral communication to Nuclear Regulatory Commission and U.S. Geological Survey, and report to Bechtel: Consulting Geophysicist and Professor at University of Houston, Houston, TX.

Hooper, M. G.; Algermissen, S. T.; Perkins, D. M.; Brackman, S. R.; and Arnold, E. P., 1982, *The earthquake of December 14, 1872, in the Pacific Northwest*, presented at 77th annual meeting, Anaheim, CA, Seismological Society of America [typescript].

Huntting, M. T.; Bennett, W. A. G.; Livingston, V. E., Jr.; and Moen, W. S., 1971, Geologic map of Washington: Washington Division of Mines and Geology Geologic Map, 2 sheets, scale 1:500,000.

Johnson, S. Y., 1984, Stratigraphy, Age and Paleogeography of Eocene Chuckanut Formation, Northwest Washington: *Canadian Journal of Earth Sciences*, Vol. 21, No. 1, pp. 92-106.

McKee, Bates, 1972, *Cascadia–The geologic evolution of the Pacific Northwest*: McGraw-Hill Book Company, 394 p.

Miller, G. M., 1969, Western extent of the Shuksan and Church Mountain thrusting in Whatcom and Skagit Counties, Washington [abstract]: *Geological Society of America Abstracts with Programs for 1969*, Pt. 3, p. 42.

Miller, G. M., 1979, Western extent of the Shuksan and Church Mountain thrust plates in Whatcom, Skagit and Snohomish Counties, Washington: *Northwest Science*, Vol. 53, No. 4, pp. 229-240.

Miller, G. M. and Misch, Peter, 1963, Early Eocene angular unconformity at western front of North Cascades, Whatcom County, Washington: *American Association of Petroleum Geologists Bulletin*, Vol. 47, No. 1, pp. 163-174.

Milne, W. G., 1956, *Seismic activity in Canada, west of the 113th meridian, 1841-1951*: Canada Dominion Observatory publication, Ottawa, ON, Vol. 18, No. 7, pp. 126-127.

Misch, Peter, 1966, Tectonic Evaluation of the northern Cascades of Washington State–a west-cordilleran case history. In *A Symposium on the Tectonic History and Mineral Deposits of the Western Cordillera* Vancouver, BC, 1964: Canadian Institute of Mining and Metallurgy Special Volume 8, Montreal, PQ, pp. 101-148.

Nuclear Regulatory Commission, 1982, *Reactor Site Criteria, Appendix A–Seismic and Geologic Siting Criteria for Nuclear Power Plants*: Code of Federal Regulations, 10 CFR, Part 100, Washington, DC, National Archives, Jan. 1, 1982.

Puget Sound Power and Light Company, 1973 and amendments, *Preliminary Safety Analysis Report, Skagit Nuclear Power Project*: Section 2.5 and Appendices. [Copies of these reports (the PSAR and amendments) and the testimony given at ASLB hearings are in the Public Reading Room at the Nuclear Regulatory Commission offices in Bethesda, MD.]

Trifunac, M. D. and Brady, A. G., 1975, On the correlation of seismic intensity scales with the peaks of recorded strong ground motion: *Bulletin of the Seismological Society of America*, Vol. 65, No. 1, pp. 139-162.

Vance, J. A., 1979, Personal communication, Associate Professor at the University of Washington, Seattle, WA.

Whetten, J., 1978, Personal communication to NRC and testimony in ASLB hearing, U.S. Geological Survey, Seattle, WA. [Copies of these reports (the PSAR and amendments) and the testimony given at ASLB hearings are in the Public Reading Room at the Nuclear Regulatory Commission offices in Bethesda, MD.]

Wilcox, R. E., 1959, *Some effects of recent volcanic ashfalls with especial reference to Alaska*: U.S. Geological Survey Bulletin 1028-N, pp. 409-476.

Wood, H. O. and Neumann, F., 1931, Modified Mercalli Intensity Scale of 1931: *Bulletin of the Seismological Society of America*, Vol. 21, pp. 277-283.

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Geology and Geotechnical Considerations of Operations at the Centralia Coal Mine

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INTRODUCTION

To fully understand the geologic and geotechnical considerations inherent to the operation of the Centralia coal mine, a general understanding of its setting is essential. The Centralia coal mine is located between the western foothills of the Cascade Range and a part of the eastern border of the Coast Range in Washington. The mine is approximately 30 mi southeast of Olympia and 8 mi northeast of Centralia. The site is reached by Interstate Highway 5 (I-5) and State Route 503 (the Bucoda Highway).

Topography in the region consists of hills of various angles of repose and gradients. Sedimentary rocks in the district underlie relatively gentle slopes associated with broad meandering river valleys. Erosion of more resistant igneous rocks results in steeper slopes; associated primary drainages have steeper gradients more typical of those in the Cascade Range to the east.

Altitudes in the region range from less than 100 to 1,500 ft above sea level. The average pre-mining elevation at the site was from 200 to 600 ft.

Average rainfall within the district ranges from 40 to 60 in. per year. Much of the rainy season occurs between September and May. The area has a temperate climate, with temperatures ranging from a high of 98° to a low of 20°F. Average annual temperatures are between 50° and 59°F. The heavy rainfall and temperate climate play an important role in the weathering cycle; mass wasting by slump and landslide is common during the wet months.

Vegetation within the area is typical of most coastal regions of Washington and Oregon. The large amount of rainfall and the cool temperate climate create an environment conducive to the growth of conifer forests. As on most of the western slopes of the Cascade Range in Washington, these forests are dense and have heavy understory growth. This condition makes both exploration of the mineral reserves and pre-mining site preparation difficult.

The two primary drainage systems in the area are the Skookumchuck and Newaukum rivers, which are tributaries of the Chehalis River network. Numerous streams dissect the area and feed into the primary drainage systems. Springs are common throughout the area but present no significant difficulties from an operational or geotechnical perspective.

Geologic Setting

Regional Setting

The rocks underlying the district range in age from Tertiary (Eocene) to Quaternary. The cumulated section is approximately 12,000 ft thick. Marine, brackish water, and nonmarine sedimentary rocks with interbedded volcanic rocks and plutonic rocks are present. The rocks have been folded and faulted on megascopic and macroscopic levels. Many places in the region have been buried by poorly consolidated till and outwash from Pleistocene glaciers and by Recent alluvium. Geologic formations in the area are the Northcraft, Skookumchuck, Lincoln Creek, and Logan Hill and are described below.

Most of the formations in the mine area are of early to middle Eocene age. These formations, from the oldest to youngest, are the Northcraft, Skookumchuck, and Lincoln Creek.

The Northcraft Formation, as described by Snavely et al. (1958), consists chiefly of lavas, flow breccias, and pyroclastic rocks in the upper part and basaltic conglomerate, sandstones, and pyroclastic rocks in the lower part. The Northcraft is overlain by the Skookumchuck Formation throughout most of the area. Locally, the contact is an angular unconformity.

The Skookumchuck Formation consists of marine, nonmarine, and brackish-water sedimentary rocks and associated coal beds. Primary lithologies include medium-grained to very fine grained sandstone, siltstone, claystone, and carbonaceous, very fine siltstone intercalated with coal seams that contain numerous partings of volcanic (bentonite) and sedimentary (siltstone) origins. Vertical and lateral variations in lithology over short distances are common throughout the formation (Snavely et al., 1958).

The Lincoln Creek Formation consists of tuffaceous and basaltic marine sandstone and siltstone and associated nonmarine sediments derived from volcanic and pyroclastic rocks (Snavely et al., 1958).

Pleistocene to Recent deposits include the Logan Hill Formation and alluvial, and landslide deposits.

The Logan Hill Formation is composed of partly consolidated, weathered, and iron-stained gravel, sand, silt, and clay that form flat-topped upland surfaces throughout the area. The Logan Hill Formation is early Pleistocene in age and of glaciofluvial origin (Snavely et al., 1958).

Recent deposits consist of landslide, alluvium, and lacustrine sediments that occupy midslope and valley areas throughout the district. Alluvium consists of fine to very fine materials derived from the reworking of Northcraft, Skookumchuck, Lincoln Creek, and Logan Hill formations. Numerous marshlands occupy lowland areas along river and stream systems throughout the region. These wetlands contain sediments which are primarily in the silt to clay size range. Locally, peat horizons are as much as 3 ft thick.

Regionally, the depositional environment is poorly understood. It has been proposed that a major river system flowing from the east to northeast formed a massive deltaic plain during early Eocene time. Swamps formed between the major distributary channels on the delta and along its front. Periodic fluctuations in sea level throughout the early and middle Eocene resulted in transgressive and regressive sequences, which are reflected in the grain-size distribution throughout the section. The swamps were periodically inundated by marine water; marine deposition resulted in some of the thinner coal seam partings and the thicker interburden units between seams in the Skookumchuck Formation. Volcanic activity is indicated by air-fall ejecta, now bentonitic partings throughout the coal beds in the formation.

Geology of the Mine Area

At the Centralia mine three primary geologic deposits are present. Coal seams mined are part of the Skookumchuck Formation. Overburden is chiefly composed of associated sandstone, siltstone, and carbonaceous siltstone. In the northern part of the property, however, Logan Hill Formation materials overlie the Skookumchuck Formation. Logan Hill materials consist of highly varied gravel, sand, silt, and clay characteristic of a glaciofluvial origin. Northcraft and Lincoln Creek rocks are not present in the mine area proper but are observed in the surrounding area within a radius of several miles.

All coal currently being mined is contained in the Skookumchuck Formation. The primary seams being mined are the Big Dirty (Big), Little Dirty (Little), and Smith, all of which occur in the central part of the Skookumchuck section. Coal seams of secondary importance are the Tono 1, Tono 2, Upper Thompson, Lower Thompson, Penitentiary, and Mendota; together, these represent less than 3 percent of the total mine production.

Mining Methods

The Centralia coal mine is a surface coal mine operation. Coal is uncovered in strips, and the overburden material (spoil) is placed in the previously mined void area directly behind the advancing highwall. In this manner the highwall and spoil advance as one, with preliminary reclamation falling out as a result of mine advance (Figure 1).

Mining methods used at the Centralia mine can be broken down into (1) mine site preparation, (2) overburden and coal removal, and (3) final site reclamation. Each of these is summarized below.

Mine Site Preparation

The first phase of the mining operation is preparation of the site. This is a three-step process, the first phase of which is scheduled in conjunction with reclamation when possible.

The first step in the mining operation consists of timber logging, clearing of surface vegetation, and the grubbing of stumps left by the timber harvester. After the clearing and grubbing, scraper operations remove topsoil overlying the coal-bearing strata. When possible, this topsoil is placed over previously mined areas. Then, buffer soil, which consists of the upper 5 to 25 ft of oxidized Skookumchuck Formation sandstone and siltstone, is removed and placed directly over unweathered Skookumchuck spoil in previously mined areas. This practice is part of the intermediate reclamation process.

Overburden Removal

The second phase of the mining operation is overburden removal and is accomplished with various types of equipment (scrapers, electric-powered shovels, draglines, or a bucket wheel excavator). The timing and sequencing of equipment use are important aspects of the mine operation and depend on the material to be excavated.

Pre-stripping of overburden is necessary to prepare the area to be mined for efficient dragline operation, which ultimately uncovers the coal. This first step is accomplished with two primary pieces of electrically powered equipment, a bucket-wheel excavator or a fleet of overburden trucks with an electric shovel (commonly called a truck shovel operation).

A bucket-wheel excavator is used only to remove Logan Hill overburden. The wheel system transports spoil along a 3.5-4-mi conveyor. This spoil is placed over other mine spoil. This mode of handling the Logan Hill material is necessary due to its high percentage of

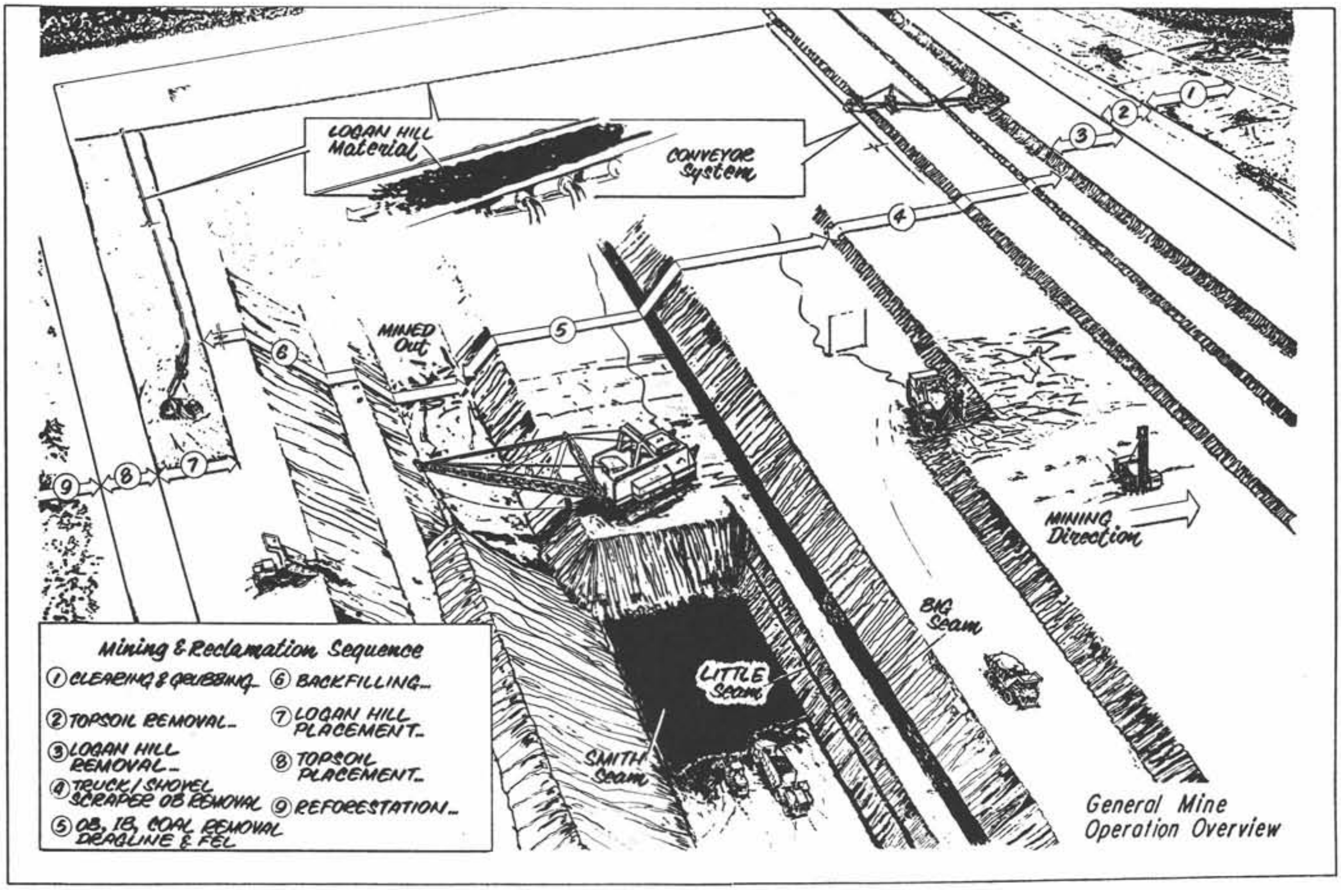

Figure 1. General overview of operations at the Centralia coal mine. OB, overburden, IB, interburden, FEL, front end loader.

clay- and silt-size particles. The Logan Hill spoil material can then be segregated at higher elevations over more competent spoil materials. In this manner the weaker Logan Hill material is placed where it will not be subjected to overloading with resultant spoil instability.

Truck shovel pre-stripping is used to remove the Skookumchuck material that overlies the uppermost primary coal seam (Big). An electric-powered shovel fills five to seven end-dump overburden haul trucks (90- to 130-ton capacity). Truck shovel spoil is hauled from the highwall face to the spoil side of the mine and placed directly over dragline-placed spoil. Current lift thicknesses for spoil dump design are a maximum of 17 ft. This practice results in a reasonable degree of compaction and margin of stability at the truck dump area. The truck shovel operation takes its pre-stripping activities to 50 to 160 ft above the top of Big seam coal. Overburden removal from this elevation down to the bottom of the pit (approximately 170 ft below the top of the Big seam) is accomplished by draglines.

The second step in the overburden removal process is performed by large electric-powered walking draglines. This step involves removal of the 50 to 160 ft of overburden above the seams and exposes the coal. It also is used to excavate interburden material. Draglines currently operating in the mine remove overburden/interburden with a 56-cy bucket. These machines operate around the clock 7 days per week, and each moves an average of 1 million cy of material per month. The overburden material is blasted prior to excavation and is excavated by dragline. The spoil is cast behind and above the given machine location. This process requires that the dragline may move the same material two, three, or four times before the spoil reaches its final resting place. Draglines are sequenced and scheduled through the use of a range diagram which depicts the digging and dumping locations of the machine, bank, and spoil for a given cross-sectional area (Figure 2).

After removal of overburden above (or between) each of the seams, tire-mounted front-end loaders move into the coal face and mine coal. The coal is loaded in 130-ton belly dump coal haulers and trucked up a series of ramps out of the pit to the main haul roads.

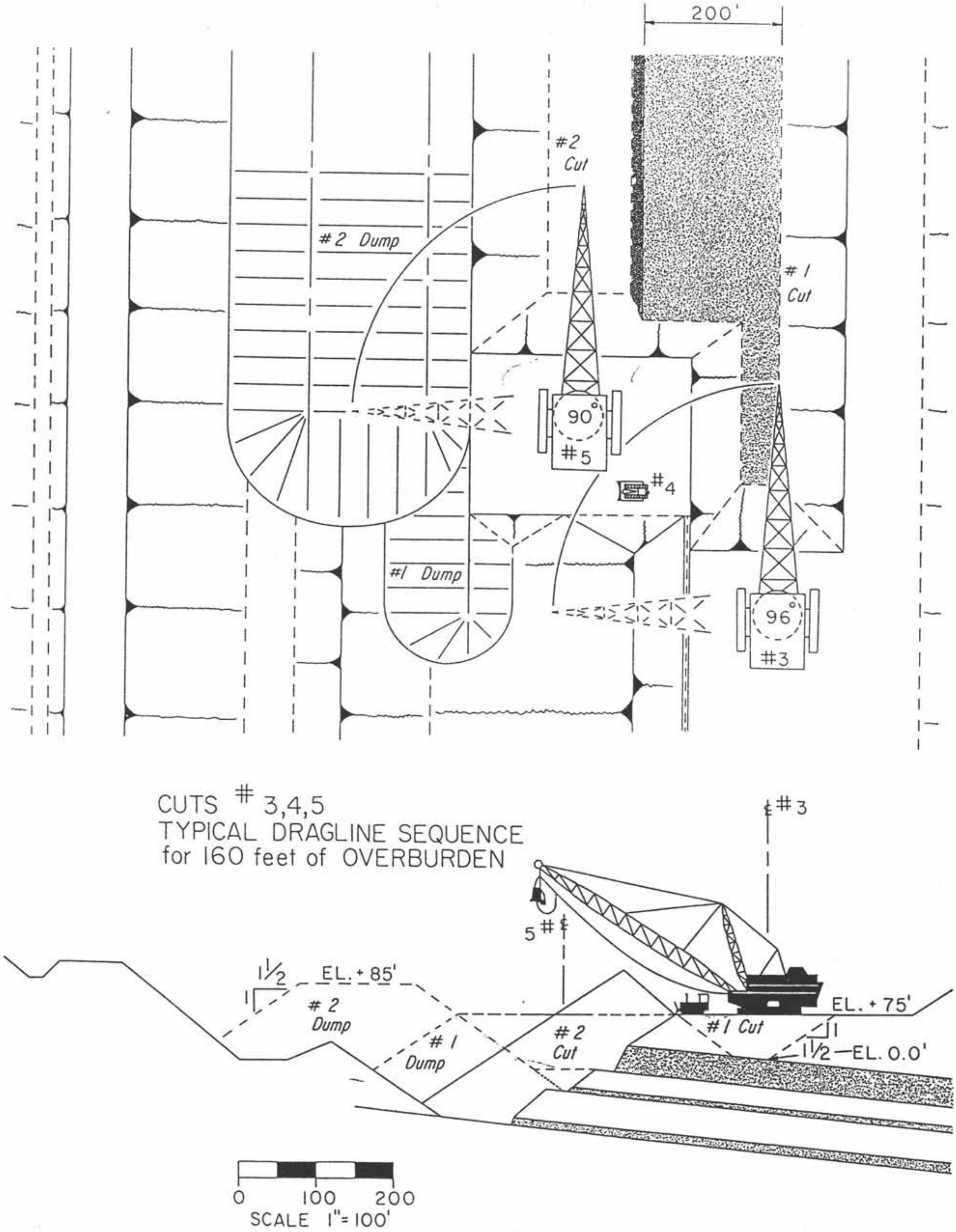

Figure 2. Typical dragline range diagram, Centralia coal mine.

Reclamation

Reclamation is the final phase of the mining operation. This process involves five steps that result in the close resemblance of post-mining and pre-mining topography.

The first step in the reclamation process is the regrading of spoil areas after final placing of spoil (by truck shovel or bucket wheel). This step involves shaping the spoil into gently sloped ridges and valleys. Waterways are established to allow for surface drainage and ground-water discharge. Design of these waterways takes into account surface area, slope, and peak precipitation. The regraded areas are also terraced to allow for intermittent contour ditching so as to decrease the total surface runoff in a given area and allow establishment of vegetation to decrease soil erosion.

Next, buffer soil, which is removed from areas to be mined during the first phase of the mining operation, is placed (when sequencing permits) where the spoil has been regraded. This buffer soil placement is required by permit and is designed to create a "buffered" or weathered root zone for vegetation growth. Buffer soil is placed to an average depth of 5 to 10 ft over regraded spoils.

Topsoil from pre-mining operations is placed over the buffered areas to an average depth of 3 to 5 ft. This topsoil is graded to the topography established during the first step of the reclamation process.

Once topsoiling is completed in a given area, a cover crop of grasses and grains is planted to help prevent surface erosion and to establish a root system within the soils. The grasses include commercial-grade alfalfa and fescue, which are harvested by the company as a cash crop to help offset the cost of final reclamation. Cover crops are allowed to grow in an area for several years prior to reforestation, the final stage of the reclamation process.

In the last step of the reclamation process, once the cover crops have established a well-defined root system over the area and surface erosion has been reduced to a minimum level, native tree species are planted, and the process of reforestation commences. Douglas fir, cedar, and hemlock are managed as a pre-commercial forest plantation. When the trees are deemed to be well established, these areas are regarded as being reclaimed.

GEOLOGIC AND GEOTECHNICAL CONSIDERATIONS

The geological and geotechnical considerations inherent to the Centralia mine operation are complex in nature and involve several major areas of concern. The primary topics discussed here are geologic structure, geologic materials, and the specific geotechnical considerations that affect the mine operation.

Geologic Structures

Numerous faults exist in the active mine area. These faults range from simple dip-slip to major reverse faults. Vertical displacements are from 2 to 100 ft. Strike lengths range from 50 to several thousand feet. Faults create situations in which the coal is shallower or deeper than expected; therefore, operational flexibility is required.

The truck shovel method of overburden removal is flexible. The shovel working along grade in a given lift may encounter coal, or "daylight" the cut within these given lifts. Where coal is uncovered, loaders are brought in to remove the coal. The only significant problem created by faults is the scheduling of equipment that may be in use elsewhere.

The dragline operation, however, is susceptible to problems caused by faults. Faults parallel to a cut are of greatest concern because they influence the size of the area in which the dragline can deposit the waste overburden. Where faults have caused the spoil side to be higher than the highwall side, more bank material is on the highwall, and there is less room on the spoil side (Figure 3).

Geologic Materials

Geologic materials encountered during the mining operation influence the choice of equipment used to excavate the materials and the operating conditions during excavation. The geologic materials at the mine consist of two broad categories: in-place materials and excavated materials.

In-place materials consist of very fine silty sand to sandy, clayey silt. Unified soils classifications performed by Shannon & Wilson, Inc. in the field indicate a range in soil types from ML (inorganic silts and very fine sands, rock flour, silty or clayey fine sands, or clayey silts with slight plasticity) to CH (inorganic clays of high plasticity, fat clays). Pt (peat and other highly organic soils) and OH (organic clays of medium to high plasticity, organic silts) soils are present locally. Results of material testing are summarized in Table 1.

Equipment Constraints

Given the types of materials encountered during the mining operation, certain operational problems arise. These problems are generally those associated with moisture content and plastic properties.

Materials having a high moisture content present "carry back" problems that decrease equipment efficiency and increase operating costs. Carry back is material that sticks to the truck boxes, shovel dippers, and dragline buckets. This material is carried back to the cut instead of being released into the truck or at the dump area. Carry back takes up critical volume in the equipment and decreases both the size of the payload and the unit's efficiency. Within the past 5 yr all primary dirt-

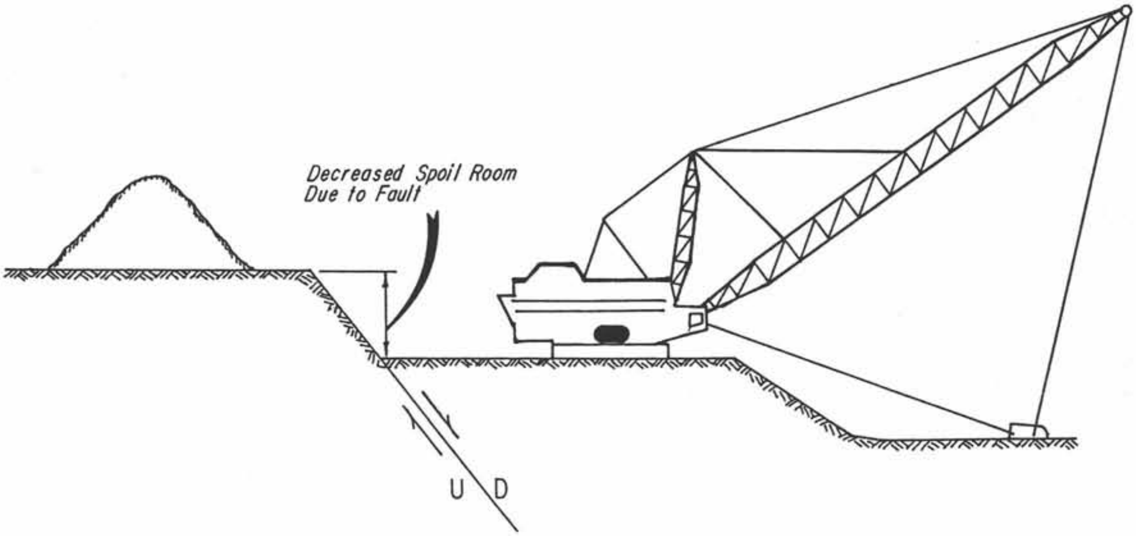

Figure 3. Fault parallel to cut (with spoil side up).

Table 1. Results of material tests

Unweathered Skookumchuck Formation material, calculated average properties (Shannon & Wilson, Inc., written commun., 1968)

Material	Moisture content	Wet Density	Unconfined Compressive Strength
Sandstone	17%	132 pcf	9,600 pcf
Siltstone	17%	135 pcf	31,000 pcf
Claystone	23%	130 pcf	21,200 pcf

Weathered Skookumchuck Formation material (Shannon & Wilson, Inc., written commun., 1968)

Property	Average
Moisture content (%)	25.00
Liquid Limit (%)	40.00
Plastic Limit (%)	30.00
Plasticity Index	10.00
Wet unit weight (pcf)	121.00
Unconfined compressive strength (psf)	2,640.00

Logan Hill Formation material (Golder Associates, written commun., 1987)

Property	Average
Moisture content (%)	38.00
Liquid Limit (%)	39.00
Plastic Limit (%)	22.00
Wet unit weight (pcf)	113.10
Unconfined compressive strength (psf)	281.00

Excavated Materials

(These materials differ from those in place because finer grained sizes have resulted from blasting, excavation, and mechanical and chemical weathering of the reworked material.)

Unweathered Skookumchuck spoil (Skookumchuck dragline spoils) (Golder Associates, written commun., 1987)

Property	Average
Moisture content (%)	35.00
Liquid Limit (%)	46.00
Plastic Limit (%)	20.00
Wet unit weight (pcf)	111.30
Unconfined compressive strength (psf)	116.67

Weathered Skookumchuck Formation spoil (Skookumchuck buffer mud) (Golder Associates, written commun., 1987)

Property	Average
Moisture content (%)	39.20
Liquid Limit (%)	68.00
Plastic Limit (%)	25.00
Wet unit weight (pcf)	106.30
Unconfined compressive strength (psf)	258.00

Excavated Logan Hill Formation material (Logan Hill belt) (Golder Associates, written commun., 1987)

Property	Average
Moisture content (%)	39.70
Liquid Limit (%)	51.00
Plastic Limit (%)	22.00
Wet unit weight (pcf)	107.90
Unconfined compressive strength (psf)	272.00

moving equipment at the Centralia mine has been outfitted with teflon plates in the bucket and truck box areas most susceptible to carry back problems.

Most of the excavated materials at the Centralia mine exhibit some degree of plasticity. Problems associated with this condition are in road and truck dump construction. Truck dumps are areas in the spoils where waste material is dumped in successive 1-ft-high lifts. This requires the trucks to run over a previous dump surface. Highly plastic soils cause high rolling resistances, which in turn increase the time required to load a truck, to move it to the dump site, to dump a load, and to return to the shovel; slower cycles increase operating costs. High plasticity can be partially offset by increased rock placement on major roads and road spur systems; however, the cost of rock soon exceeds the increased operating costs associated with higher rolling resistances. This problem is dealt with on a case-by-case basis. Some roads are more amenable to rock placement because of their low gradient and long-term use. Improving roads having steeper grades and short-term usage is not generally cost effective.

General Operating Constraints

Operations at the mine site are affected by materials, the climate, and the number of times any material must be moved (rehandle).

Moisture content in excavated materials varies as a function of season. A recent study by Golder Associates, Inc. (1987) demonstrates the decrease in shear strength as a function of increasing percent water content (Figure 4). This water content is critical with respect to material excavation and placement during the wet winter operation. During winter higher rainfall results in higher percentages of water being incorporated into the spoil. This, therefore, results in a decrease in material strengths.

Of all equipment currently in use at the mine, the dragline system experiences the highest percentage of rehandle. The draglines are the prime dirt-moving units at the mine; the three units move approximately 40 million bank cubic yards annually. Of this volume, approximately 40 percent is rehandled. The annual total combined yardage is approximately 56 million cy.

This rehandled 16 million cy of material is subject to volume increase as a result of increased exposure to rain; it continues to swell with additional handling. The increase in swell increases the total amount of voids available for water saturation. As noted on Figure 4, the Skookumchuck dragline spoil shows rapid decrease in strength in the range of 25 to 50 percent water content (800 psf to 20 psf respectively). During the winter, moisture content in dragline spoil subjected to two or three rehandle stages can increase by 5 to 15 percent and attain an average water content of between 40 and 50 percent. Because the base of the dragline rehandle is the interface with the more competent truck shovel spoil, and this truck shovel material is dumped over the saturated rehandle, the potential exists for a major stability problem.

Geotechnical Considerations

Geotechnical considerations present at the Centralia mine can be broken down into two types of stability problems: those associated with highwall (in-place material) movement, and those associated with spoil side (excavated material) movement.

Highwall instabilities are generally local in nature and associated with zones of weakness in the in-place material, such as steeply dipping fault and shear zones or highly plastic bentonitic partings that parallel bedding surfaces. Some highwall slides have moved up-dip along these parting surfaces in a classic block glide nature as the mine face advances down-dip into the coal. Slides associated with faults literally peel off the advancing mine face, toppling into the open pit at the excavation site.

Highwall-related slides comprise approximately 10 to 20 percent of the instability problems observed in the mine. This type of instability requires unusual equipment sequencing and scheduling, and it can be associated with destruction of normally minable coal through crushing and pulverization within the slide block. The associated cost of highwall slides is fairly low because in most instances material in the slide block was scheduled to be excavated. The sliding activity simply changes the time at which the material is actually moved. The amount of coal lost due to crushing and contamination by overburden is kept to a minimum through quick action by the operations department.

Spoil-related instability is more common than highwall instability. Spoil slides generally occur where unsuitable materials (for example, weathered and unweathered Skookumchuck Formation spoil having high clay and moisture contents) have been placed low in the spoil pile. Spoil material placed over the wet, clay-rich materials contributes to overloading and can cause failure.

Many spoil slides are the result of dragline operation limitations. The dragline system operates in the lowest part of the pit where surface runoff cannot be ditched out of the pit as it is below the original ground level. Sumps dug in the pit bottom collect runoff, and pumps move the water out of the pit to ditches along the edges of the mined area. Although these pumps do an adequate job of handling some of the silt and clay suspended in the sump water, most of this fine material settles out in the bottom of the sump. When the mine plan calls for the dragline to dump over these sump areas, the fine silt and clay must be dipped up and out of the pit bottom. In the process of dipping this material, the dragline constructs mud cells in the spoils. These mud cells are con-

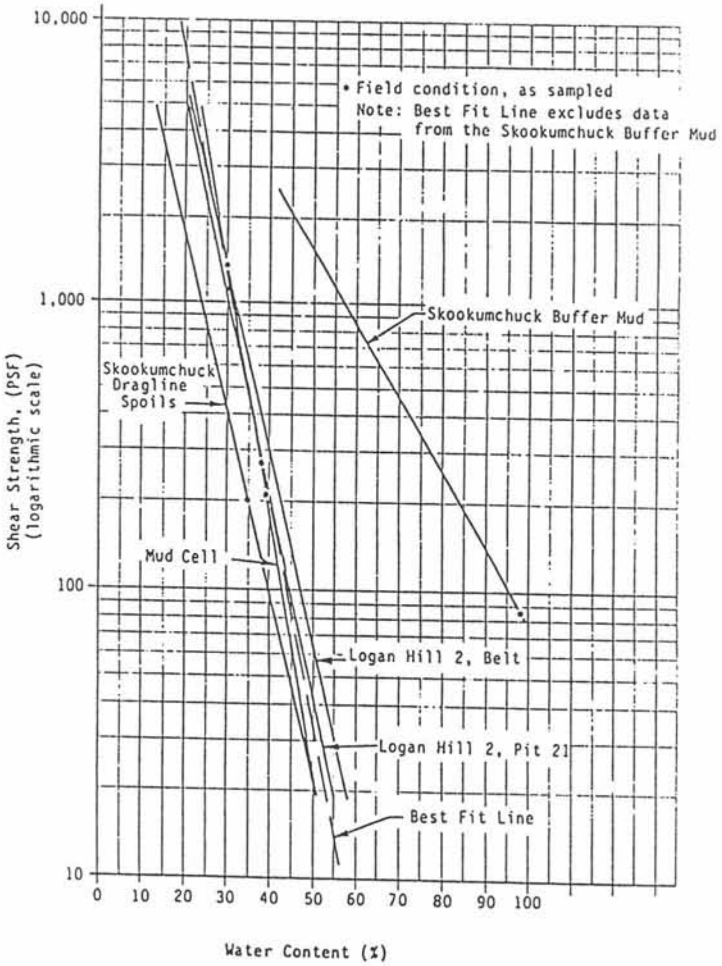

Figure 4. Water content versus shear strength. After Visca and Pitman (1987).

structed by placing spoil as dikes along four sides of a rectangle and filling the center with mud. These mud cells are placed as high in the spoil as practical, and then capped with truck shovel spoil material. If the truck shovel advances faster than the dragline can buttress up the area below the cell, the spoil placed over the cell will fail. Failed material flows into the pit and must be brought back up to the top of the dragline spoil. This type of spoil failure results in some material being rehandled a total of four to six times before it is finally stabilized. This failure is extremely costly to mine operation as it involves the unscheduled movement of material and consumes time scheduled for more productive work. Spoil slides have involved up to 4.5 million cy of spoil material, and they have had a major impact on pit productivity and operation. In one instance, the entire pit mine plan was changed to accommodate the increase in material which slid back into the pit.

An efficient and practical spoil plan is the answer to slide problems. Since 1987 the Centralia mine operation has taken steps to address spoil instabilities. However, given the material types and the seasonal moisture conditions, spoil problems are unlikely to be completely corrected. The goal is to minimize the size and thereby the long-term effects of spoil instabilities.

CONCLUSION

The Centralia mine site presents several complex geologic, geotechnical, and planning problems. The geologic structures create problems for equipment sequencing and scheduling. Stability problems result from both the types of overburden material and climatic conditions. Overall, topography, drainage, and seasonal weather play significant roles in the daily operation and planning aspects of the mine. All of these aspects combine to present a unique opportunity for the study of geology and practice of geotechnical engineering.

REFERENCES

Hilts, D. E.; Miller, R. P.; and Wilson, S. D., 1968, *Mine Slope Stability, Centralia Coal Field*: Prepared for Washington Irrigation and Development Company by Shannon & Wilson, Inc., Seattle, WA, 96 p.

Snavely, P. D., Jr.; Brown, R. D., Jr.; Roberts, A. E.; and Rau, W. W., 1958, *Geology and Coal Resources of the Centralia-Chehalis District, Washington*: U.S. Geological Survey Bulletin 1053, 159 p.

Visca, P. J. and Pitman, K. L., 1987, *Geotechnical Recommendations for Spoil Placement*: Prepared for Washington Irrigation and Development Company by Golder Associates, Inc., Redmond, WA, 36 p.