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Geology of the Alpine-Type Ultramafic Complex near Mount Stuart, Washington

ABSTRACT

A large alpine-type, mafic-ultramafic complex in the vicinity of Mount Stuart in Chelan County, Washington, consists chiefly of serpentinized harzburgite and uralitized augite gabbro with lesser amounts of pyroxenite and anorthositic gabbro. This complex was tectonically emplaced into metasedimentary and metavolcanic rocks of the Peshastin and Hawkins Formations, probably in Late Jurassic to Early Cretaceous time. The highly magnesian composition of the harzburgite, the high Ca and Al contents of the metagabbro, the tectonite fabric of these rocks, and the virtual absence of contact metamorphism are compatible with an origin at an active oceanic ridge or within a marginal basin. Primary textures and bulk modal compositions of volcanogenic sediments and flows in the Peshastin-Hawkins sequence are interpreted as evidence for an island-arc environment of deposition. Argillite, volcanic-derived epiclastic graywacke, sorted and unsorted breccia and tuff-breccia, and some pyroclastic rocks are associated with flows ranging in composition from basalt to quartz keratophyre. The mafic-ultramafic complex is interpreted as ophiolite that was thrust against older island-arc rocks in an arc-trench system that operated from late Paleozoic through Mesozoic time. The remains of the dismembered ophiolite are now found in intricate tectonic association with rocks of the former arc.

INTRODUCTION

The pre-Tertiary mafic and ultramafic rocks near Mount Stuart, northern Cascade Mountains, Washington, form a typical alpine-type complex (Thayer, 1967) that was tectonically emplaced into highly deformed metavolcanic and metasedimentary terrane. The mafic and ultramafic rocks are cut by the Mount Stuart batholith (Fig. 1) and therefore are older than Late Cretaceous (Engels and Crowder, 1971); a preliminary U-Pb Late Jurassic age from zircon in gabbro pegmatite in the complex (J. Mattinson, 1973, written commun.) probably is a minimum age for the complex as a whole. The age of the Peshastin and Hawkins Formations, both broken by the mafic and ultramafic rocks, is unknown. Early workers thought the Hawkins and Peshastin Formations were late Paleozoic (G. O. Smith, 1904) or early Paleozoic (W. S. Smith, 1915, 1916) in age, on the basis of tenuous long-range correlations with fossiliferous strata, but no firm determination of the age of these rocks has been made yet.

In 1959 I began mapping the geology of part of the alpine complex southeast of Mount Stuart (Fig. 2) on a homemade base map of variable accuracy and reliability (see Southwick, 1962, for results). I intended to improve and extend the mapping and compile the data again on 15′ quadrangle base maps but because of other commitments, the additional field work never was done. The plate-tectonics theory has caused a renewed surge of interest in alpine-type ultramafic complexes (see, for example, Coleman, 1971; Dewey and Bird, 1971), and I have received numerous requests during the past five years for information on the complex near Mount Stuart. Therefore, I decided to describe these rocks on the basis of research now more than a decade old in the hope that this will be of use to geologists currently working in the Cascades and Coast Ranges.

PRE-INTRUSION SUPRACRUSTAL ROCKS

Three named formations have been penetrated by the ultramafic complex southeast of Mount Stuart. The Peshastin Formation, named by Smith (1904) for good exposures along Peshastin Creek, is a thick sequence of argillite and volcanic graywacke with lesser amounts of intercalated pebble conglomerate, thin dacite lava flows,

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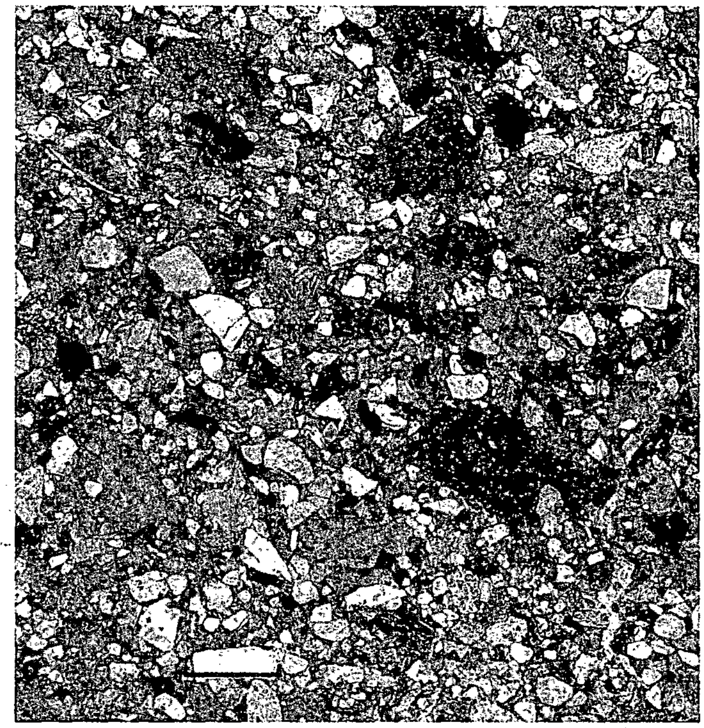

Figure 3. Photomicrograph of virtually unaltered graywacke from Peshastin Formation. Clasts of quartz, plagioclase, several kinds of microporphyritic volcanic rock, and carbonaceous siltstone can be readily identified. Most of formation has not retained original features as clearly as this specimen has. Bar scale = 1 mm.

material to intervening basins, where argillites and graywackes of the Peshastin accumulated.

The grade of metamorphism of the Peshastin and Hawkins Formations is lowest in the southeast part of the map area and increases to the north. Chlorite argillite is raised to biotite slate and phyllite north of Ingalls Creek, and chlorite greenstone is raised to actinolite greenstone and weakly foliated epidote amphibolite. There appears to be a complete gradation from low-grade rocks of the Peshastin-Hawkins sequence to the medium-grade rocks of the Chiwaukum Schist, mapped and named by Page (1939) in the Chiwaukum quadrangle just north of the area of Figure 2. The Chiwaukum Schist is a rather heterogeneous group of pelitic to amphibolitic schist, generally without relict textures; it is the principal pre-ultramafite wall rock from Allen Creek north to Leavenworth and beyond.

LEAST METAMORPHOSED ROCKS IN THE PESHASTIN FORMATION

Although the Peshastin rocks have been battered by metamorphic recrystallization and the development of cleavage over much of the map area, there are many places where original minerals, textures, and structures are preserved. Because the major purpose here is to determine the origin of these rocks, I emphasize the primary features rather than the metamorphic features.

The most common rock in the Peshastin Formation is a tough, hackly argillite that consists of ~ 10 to 30 percent fine sand and silt grains in a recrystallized silt-clay matrix. The sand-silt fraction is very angular and is composed of quartz, plagioclase, and fragments of exceedingly fine-grained carbonaceous shale, in decreasing order of abundance. In some specimens, the coarser material forms thin laminae, but more commonly it is dispersed throughout the muddy matrix. The matrix is a poorly defined fine paste containing quartz, chlorite, montmorillonite, graphite, and iron oxides.

Fine-grained graywacke is the second most abundant rock type in the formation. The sand grains range from 0.2 to 0.5 mm diam, are very angular and consist of lithic fragments, plagioclase, and quartz (Fig. 3). Potassium feldspar is lacking. Several kinds of felsic to intermediate volcanic rocks, fine-grained black shale, and chert are represented in the lithic fragments. In most specimens, the lithic fragments exceed the sum of feldspar plus quartz (Table 1), and therefore the graywackes are lithic, in the terminology of Pettijohn (1957). The matrix is an indistinct paste of chlorite, sericite, carbonate, graphite, and abundant iron oxide, which has recrystallized metamorphically and invaded the margins of adjacent framework grains. The outlines of lithic fragments in particular have been blurred by this process. Small amounts of coarser graywacke and graywackelike pebble conglomerate occur locally; these differ from the common fine-grained graywackes only in grain size.

Flows, breccia, and tuff, all somewhat metamorphosed, constitute a small but significant part of the Peshastin Formation. Several porphyritic flows, and possibly some thin sills on the divide between Ingalls and Nigger Creeks, contain relict-zoned plagioclase phenocrysts and pseudomorphs of former hornblende and clinopyroxene phenocrysts in a partly recrystallized groundmass of plagioclase microlites, actinolite, phlogopitic biotite, quartz, clinozoisite, and minor chlorite. Phenocrysts and phenocryst pseudomorphs make up ~ 10 to 20 percent of the flows. The groundmass is a patchy tangle of relict and neocrystallized minerals within which primary taxitic texture can be made out only locally. Typical specimens contain 50 to 52 percent oligoclase (with dusty clinozoisite inclusions), 20 to 25 percent actinolite, 12 to 20 percent biotite, 5 to 8 percent quartz, 2 to 3 percent granular clinozoisite, and 0 to 1 percent opaques, indicating a composition in the dacite-andesite range.

Breccia and tuff-breccia are interstratified with the flows and form minor beds elsewhere in the formation. Angular fragments of metadacite identical to the flows described above, somewhat more mafic meta-andesite, medium-grained epidote amphibolite, and calcite marble are cemented by a recrystallized matrix of actinolite, epidote, clinozoisite, oligoclase, chlorite, carbonate, and leucoxene. The mineral assemblage in the matrix is the same as that in the metavolcanic fragments, indicating that the matrix probably was comminuted volcanic debris before low-grade metamorphism occurred. The matrix minerals have invaded and intergrown with the metavolcanic fragments but have encroached only a little on the fragments of epidote-amphibolite and marble. The volcanic fragments appear to have been metamorphosed along with the matrix while in the breccia, whereas the epidote-amphibolite and marble were incorporated as metamorphic rocks and were only slightly affected by later low-grade metamorphism of the breccia.

TABLE 1. TYPICAL MODES OF UNMETAMORPHOSED PESHASTIN GRAYWACKES

		K-20		P-11	
Quartz		2.5		2.5	
Plagioclase		8.0		14.7	
Lithic Fragments	Chert	20.5		7.5	
	Volcanic and metavolcanic rocks	16.0		12.2	
	Graphitic shale and slate	5.8		7.3	
TOTAL FRAMEWORK			52.8		44.2
TOTAL MATRIX			44.0		52.0
Opaques		1.9		2.1	
Carbonate		1.1		1.5	
Epidote		0.2		0.2	
TOTAL ACCESSORIES			3.2		3.8
OVERALL TOTAL			100.0		100.0
Number of points		800		600	

Laminated units of siliceous tuff ranging in thickness from 0.3 to 1.5 m are scattered throughout the formation. These rocks are chiefly cryptocrystalline silica and undoubtedly are a large part, if not all, of the "cherts" referred to by Smith (1904). In places they contain faint ghosts of glass shards, partially outlined by a fibrous, birefringent mineral (actinolite?), and scattered angular grains of clastic quartz and plagioclase. Individual centimeter-scale lamellae are graded. The basal part of each lamination contains shards 0.1 to 0.3 mm long, and clastic quartz and plagioclase grains of similar size; the upper part contains shards 0.03 to 0.08 mm long and is free of clastic quartz and feldspar. The shards are preferentially oriented with their long dimensions parallel to bedding planes, but they exhibit no evidence of welding or collapse compaction. The orientation of the shards, lack of compaction, and graded lamination indicate subaqueous deposition, possibly from ashfalls into water.

LEAST METAMORPHOSED ROCKS IN THE HAWKINS FORMATION

All rocks in the Hawkins Formation have experienced lower to upper greenschist-facies metamorphism. In addition, the formation has been severely fractured by complex systems of joints and small faults. The metamorphism and extreme fracturing have made stratigraphic synthesis within the formation all but impossible, but primary textures and structures have survived well locally. The most abundant rocks by far are greenstones derived from basalt lava flows, followed in decreasing abundance by mafic to intermediate breccia and tuff-breccia, metadiabase sills, and highly siliceous metadacite or quartz keratophyre.

The metabasalt flows are porphyritic, generally amygdule, and contain secondary minerals typical of the greenschist facies (Table 2). Original plagioclase typically is limited to large, zoned, partially resorbed phenocrysts (~ An $_{45-65}$) although some groundmass laths have locally survived. Original clinopyroxene is limited to very scarce, small scraps that are deeply invaded by secondary chlorite and (or) actinolite. Most of the groundmass microlites have been converted to albite that is choked with tiny inclusions of clinozoisite, sericite, and chlorite. Most of the original groundmass materials other than plagioclase microlites have wholly recrystallized to a tangled mat of chlorite, epidote, clinozoisite, and carbonate, with varying amounts of actinolite, magnetite, hematite, and leucoxene. Chlorite and calcite are the most common amygdule fillings.

TABLE 2. TYPICAL MODES OF BASALTIC TO ANDESITIC GREENSTONES, HAWKINS FORMATION

	R-10	R-12	K-26	N-3
Plagioclase*	56.4	55.7	26.5	30.3
Clinopyroxene	14.9	18.9	12.5	0.3
Chlorite†	20.4	19.9	11.4	4.8
Actinolite	tr	tr	tr	4.2
Biotite§	-	-	-	1.4
Epidote	4.0	0.4	0.7	0.8
Carbonate	0.2	0.1	14.4	1.0
Opaques	4.1	5.0	3.5	1.0
Groundmass#	-	-	31.0	56.2
TOTAL	100.0	100.0	100.0	100.0

Note: 1250 points counted per specimen.

* *Primary plagioclase plus varying amounts recrystallized albite; choked with dusty clinozoisite.*

† *Includes only large, discrete chlorite flakes. Much fine chlorite is counted with groundmass.*

§ *Occurs intergrown with actinolite as pseudomorphs of clinopyroxene.*

\# *A fine-grained, nearly opaque mat of chlorite, albite, muscovite, and leucoxene.*

R-10 and R-12: Partially altered diabase sills.

K-26: Vesicular greenstone from upper part of flow.

N-3: Andesitic greenstone, glass-rich originally.

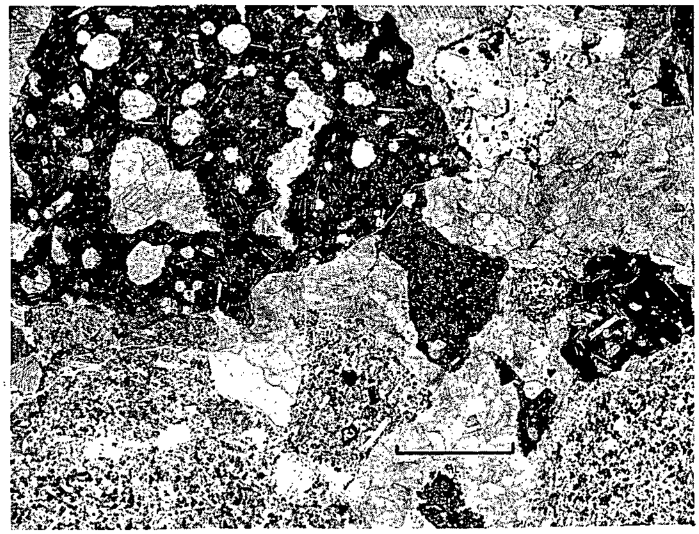

Figure 4. Photomicrograph of calcite-cemented volcanic breccia from Hawkins Formation. Large, dark fragments are opaque-rich, formerly glass-rich(?) andesite; lighter fragments at bottom of photograph are typical chlorite greenstones, comparable to flows with which breccia is interbedded. Bar scale = 1 mm.

Thin diabase sills that crop out on the south flank of Windmill Peak contain well-preserved primary minerals and textures. These hypidiomorphic granular rocks contain remnant scraps of subcalcic augite (2V = 44°), twinned saussuritized andesine (An_{35}), chlorite, iron-rich epidote, sphene, and magnetite, along with varying, small amounts of recrystallized interstitial albite and actinolite. The andesine grains are full of clinozoisite inclusions and clearly are less calcic than the original igneous plagioclase. The composition of these diabases is very similar to that of the metabasalt flows in the Hawkins Formation. Probably the sills and flows were fed from the same magma source, with the sills representing masses of magma that spread laterally between the flows of a growing volcanic pile.

Beds of volcanic breccia and coarse volcanic sandstone compose about 10 to 20 percent of the Hawkins Formation. The total amount of clastic material in the formation is hard to estimate closely because of structural complexities, but it is clearly substantial. Individual clastic beds range from ~2 m to >30 m thick and contain fragments ranging from a few millimeters to >1 m in size. Generally, the thickest beds contain the largest clasts. Some beds are well graded, fairly well sorted, and cemented by crystalline calcite (Fig. 4), whereas others lack grading and sorting and are cemented by a presumably detrital matrix now composed of intergrown chlorite, epidote, calcite, cryptocrystalline silica, and opaque substances. The sorted and graded beds must have been reworked by water currents and may represent deposits offshore from a volcanic island chain; the unsorted deposits may be mud flows.

The volcanic rock fragments in the breccia are of three main kinds; in order of abundance they are:

1. Metamorphosed andesite or keratophyre, commonly amygdular, probably glass rich originally, with zoned, partly resorbed plagioclase microphenocrysts. The groundmass is a brown to black, nearly opaque microcrystalline aggregate containing abundant, very small plagioclase microlites. Some microlites are bifurcated. Commonly, the microlites are randomly oriented, but some fragments have an aligned, felty fabric. Scattered squarish epidote aggregates may represent former mafic phenocrysts.

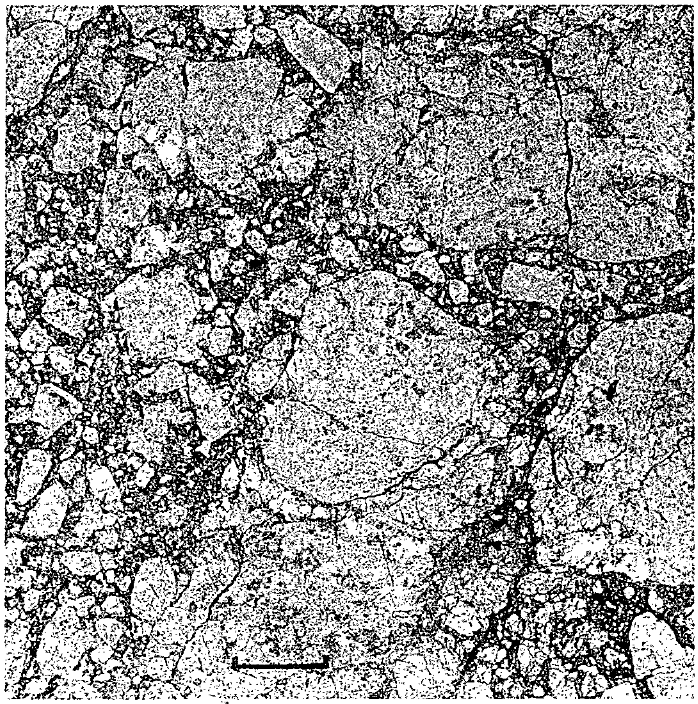

Figure 5. Photomicrograph of extensively brecciated felsite from Hawkins Formation. Most of rock is exceedingly fine-grained mosaic of quartz and sodic plagioclase; dark material in fracture zones is chiefly epidote. Bar scale = 1 mm.

2. Normal Hawkins greenstone, probably basalt originally, commonly amygdular and microporphyritic. The mineralogy and texture of this rock have already been described.

3. Very fine grained greenstone rich in yellowish chlorite and fine opaque dust; possibly derived from glassy basalt or basaltic andesite.

Siliceous dacite and (or) quartz keratophyre form a small percentage of the Hawkins Formation. Megascopically, they are aphanitic, greenish-gray to black rocks with a characteristic greasy luster; because of their hardness they form prominent, clifflike outcrops. Microscopically, they consist of a fine-grained, generally seriate mosaic of untwinned sodic oligoclase and quartz, with minor clinozoisite and chlorite, in which extensively saussuritized, small phenocrysts of andesine are sprinkled. At only one locality, on the north side of Windmill Peak, is the groundmass sufficiently unrecrystallized to reveal relict plagioclase microlites. Crushing seems especially pervasive in this lithology (Fig. 5), with fine epidote, chlorite, opaque minerals, and leucoxene occupying the cracks and crush zones. Although completely convincing evidence is lacking, it appears that the crushing and veining took place during the late stages of low-grade metamorphism rather than during a later hydrothermal event.

These rocks are interpreted as metamorphosed dacite and (or) quartz keratophyre flows on the bases of their high estimated silica content and relict volcanic textures. Mineralogically, they fit the description of propylite (Coats, 1940), but there is no clear evidence that silica metasomatism is necessarily responsible for their high silica content.

TECTONIC INTERPRETATION OF THE PESHASTIN-HAWKINS SEQUENCE

Rock fragments in the Peshastin graywackes clearly indicate a heterogeneous volcanic source terrane. Present in the source area were abundant dacites and andesites, carbonaceous mudstones, at least minor epidote-amphibolite and marble, and possibly some intermediate plutons. Such terrane is found in present-day mature island arcs, such as Japan and the Greater Antilles. The generally fine grain size of the argillite and graywacke is interpreted to indicate deposition in a basin well offshore from the source area. The geosynclincal thickness of the formation and the presence of interstratified flows, tuff, and breccia indicate deposition in a tectonically active environment.

A peculiarity of the Peshastin Formation as a whole is the relative scarcity of graded bedding. Typical immature graywacke is a major lithology, yet most of the graywacke beds are not graded turbidite. Most of the graywacke occurs as poorly stratified subunits as thick as several meters within thick sections of rather uniform silty argillite. The upper and lower contacts of graywacke subunits typically are diffuse and indistinct. This type of bedding is not readily explained by the turbidity current model (Bouma, 1962); nevertheless, it is difficult to understand how angular, ill-sorted, and chemically immature lithic graywackes can be deposited except by some sort of turbulent transporting mechanism.

Hubert (1964) marshalled textural evidence to show that bottom currents were an important mechanism in the deposition of graywacke and graywackelike muddy sand and silt in the western North Atlantic. He also pointed out (1964, p. 779) that constantly fed, rather than suddenly released, turbidity flows tended to produce ungraded beds in the classic tank experiments of Kuenen and Menard (1952). Such ungraded beds became graded in their upper parts only when the sediment supply was shut off. Thus, it appears that mechanisms other than turbidity currents are capable of laying down poorly sorted deposits of sand in the marine setting, and also that turbidity currents need not lay down graded beds if a fairly continuous supply of detritus is available.

Dott (1963, p. 124) emphasized the complexity of the graywacke–turbidity current relation by pointing out the importance of source environment to the character of a sandstone. Sediments in tectonically unstable regions tend to be texturally and mineralogically immature, regardless of the depositional agent, simply because the weathering and transportational segments of the sedimentary cycle are relatively short. Under these circumstances graywackes may be deposited by means other than the classic turbidity current model, and graded deposits not of graywacke composition may occur.

The Peshastin Formation was probably deposited in an environment with more or less steadily supplied fine volcanogenic detritus, gentle basin slope, weak bottom currents, and fairly shallow water. Under these conditions, gentle slumping and downslope movement may have been almost continuous, but of fluctuating intensity, resulting in low-energy mixing and redeposition of ungraded fine sand and mud. Such conditions might prevail in the plexus of submarine valleys and fans offshore from an island arc or a tectonically active continental margin (Shepard and Dill, 1966). The basin of deposition may have been a trough in the arc-trench gap of an arc-trench system (Dickinson, 1971, 1972), an interisland basin along an island chain, or a marginal basin behind the arc (Karig, 1971). Data are too sparse to permit a choice among these related yet distinct tectonic-sedimentary environments.

The volcanic rocks of the Hawkins Formation probably accumulated in an island-arc setting. Basalt, basaltic andesite, and andesite, with smaller amounts of dacite and quartz keratophyre, are interpreted to have been the premetamorphic lithologies, and these are all widely represented in modern-day arcs. Detailed chemical data are lacking, but the abundance of basalt relative to andesite and dacite suggests that these rocks may belong to the tholeiitic series of Jakes and White (1972) and Miyashiro (1972, p. 637); this series typically is found on the ocean side of mature, active island arcs. Further evidence for an arc origin is found in the association of these volcanic rocks with sedimentary rocks whose characteristics suggest deposition in basins near rugged volcanic source areas.

An alternative to the island-arc interpretation is to consider the Hawkins as part of a slab of uplifted ocean floor, genetically related to the intimately associated mafic and ultramafic complex. Variably altered basalt (spilite) and keratophyric rocks similar to those in the Hawkins are typical of the upper parts of many ophiolite complexes, and similar rocks have been dredged from modern oceans (Dickinson, 1972). In this interpretation, the Hawkins Formation becomes the dismembered upper part of an ocean-floor slab in which the gabbro and serpentinite of the alpine complex are the lower parts.

While ocean-floor origin of the Hawkins Formation cannot be ruled out completely on the basis of present evidence, the island-arc interpretation seems preferable for several reasons:

1. Hawkins flows are interbedded with substantial thicknesses of volcanic breccia and tuff-breccia, many of which are polymict, graded, fairly well sorted, and carbonate cemented. Such rocks have not been emphasized in descriptions of ophiolites or ocean-floor dredge hauls but are common in island arcs. They may form from time to time when shallow waters flanking an island chain and supporting carbonate-secreting organisms are deluged by volcanic debris from explosive eruptions, or from landslides, mudflows, and related gravity movements down the island flanks into the sea. This material is then reworked and redeposited by normal current action.

2. Poorly graded and sorted breccia in the formation may be subaqueous slurry floods triggered by seismic activity or large-scale landslides from the flanks of volcanic islands; chaotic polymict breccia with detrital matrix may be the remains of subaerial mudflows.

3. Pillow structure in the flows is scarce, if not lacking altogether. Pillows may have been obscured by shearing and metamorphism, but the preservation of other features such as vesicles and phenocrysts (and clastic textures in associated breccia) suggests that pillows should have survived if they were abundant initially. In the absence of abundant, clearly defined pillows, palagonite horizons, or other direct evidence for subaqueous extrusion, only the indirect evidence of association with probable water-laid breccia suggests submarine emplacement for some of the flows. Other flows may well be subaerial.

4. The kinship of the Hawkins Formation to the Peshastin Formation is suggested by the similarity of intermediate to silicic flows in the Peshastin to flows in the Hawkins, and by a conformable, seemingly unfaulted contact between Peshastin and Hawkins on Sheep Mountain, a short distance south of Windmill Peak (Fig. 2). The characteristics of the Peshastin are more compatible with an island-arc depositional environment than with a deep-ocean environment.

5. The presence of the spilite-keratophyre association in a suite of rocks is far from convincing proof of oceanic origin for the suite. Low-grade metamorphism and at least local metasomatism of lime and alkalis have plainly affected the Hawkins rocks (see, for example, the epidote veinlets in Fig. 5). These processes are capable of modifying more "normal" calc-alkaline rocks of the arc environment to the mineralogy and chemistry of spilite and keratophyre (Hughes, 1973).

DESCRIPTION OF THE MAFIC-ULTRAMAFIC INTRUSIVE COMPLEX

The ultramafic complex that has invaded and disrupted the Peshastin-Hawkins sequence is roughly 65 to 75 percent serpentinized peridotite and 25 to 35 percent uralitized gabbro. Pyroxenite, anorthositic gabbro, and anorthosite are important but much less abundant lithologies. Compositionally and structurally, this complex fits into the alpine category as originally defined by Benson (1926) and further described by Thayer (1967). Its composition and geologic setting permit its inclusion in the "ophiolites" as originally described by Steinmann (1905), although neither pillowed basalt nor radiolarian cherts have been found in close association.

The serpentinite and associated mafic rocks form a broad, arcuate belt bordering the Mount Stuart batholith on the southeast, south, and southwest (Smith, 1904). Discontinuous ultramafic masses interspersed with Chiwaukum Schist also occur north of the batholith (Page, 1939). Altogether, $\sim$320 km^2 of mafic and ultramafic rock are found within the area of this study (Fig. 1).

The ultramafic complex was mechanically emplaced into the Peshastin and Hawkins Formations while solid and relatively cool. Contacts between serpentinite and wall rock invariably are shear zones occupied by slickensided, lensoid slivers of serpentinite or, more rarely, angular serpentinite breccia rehealed by secondary serpentine and carbonate. Locally, wedges of schistose serpentinite have been driven into foliation planes in the wall rocks, showing that the wall rocks were deformed before or during serpentinite emplacement. Tectonism that accompanied serpentinite emplacement has split the Hawkins and Peshastin Formations into a multitude of irregular blocks and pods ranging from a few meters to several kilometers in size. Those blocks are unevenly dispersed throughout the complex, and some smaller ones have been rotated.

Rocks adjacent to the serpentinite have suffered little or no contact metamorphism. Locally, the Hawkins greenstone has been converted to granular epidote-amphibolite near serpentinite contacts, but this is the exception rather than the rule. In most places the older rocks show no evidence whatever of contact metamorphism, apart from cataclastic shearing and granulation.

Irregular masses of uralitized gabbro, ranging in area from a few square meters to several square kilometers, are apparently coeval with the more voluminous serpentinite. This gabbro was mapped by Smith (1904) as "Eocene gabbro" but his age assignment clearly was in error (Southwick, 1966). The gabbro is older than the Mount Stuart batholith (Late Cretaceous) and recently has been dated as Late Jurassic by U-Pb methods (J. M. Mattinson, 1973, written commun.). Contacts between gabbro and serpentinite commonly are hidden by large talus piles shed from the more resistant gabbro, but relations indicating mutual penetration of the two lithologies can be adduced at several spots. Gabbro is chilled against serpentinite along a contact exposed in the north wall of Ingalls Canyon $\sim$5.8 km above the mouth of Ingalls Creek. Near benchmark K 12/1931 in Peshastin Canyon, severely sheared anorthositic metagabbro has been invaded by mildly sheared serpentinite. Small, steeply inclined, tabular bodies of meta-anorthosite and metagabbro lie within serpentinite in the headwaters of King Creek, north of Windmill Peak, and at several places in the Gold Creek Basin. Some of these are inclusions of gabbroic rock in serpentinite, whereas others are plainly dike-like intrusions of gabbro into ultramafite. It appears, therefore, that the serpentinite and gabbro are virtually the same age and are genetically related.

There is no regular stratification or compostional layering within either the ultramafic or gabbroic parts of the complex. Layerlike pods of coarse meta-anorthosite as long as 700 m and as thick as 30 m occur in the Magnet Creek drainage, but no layering was detected in the serpentinite surrounding them. Probably they are sheared out, dike-like intrusions rather than primary layers.

Prior to serpentinization, the ultramafic rocks were mainly harzburgite; minor amounts were wehrlite and pryoxene-free dunite. Serpentinization has been pervasive except for rare local occurrences of relatively unserpentinized harzburgite. Although relict minerals generally comprise <3 percent of the rock, textural features of former olivine, orthopyroxene, and clinopyroxene have survived serpentinization well enough to allow rough estimates of preserpentine modes. Diallage pyroxene composes a small percentage of the total ultramafic mass and generally has not been so severely serpentinized as the olivine-bearing rocks. No enstatite pyroxenite was found in the area studied, although it is reported in abundance from parts of the Chiwaukum quadrangle (Page, 1939, p. 37).

Optic-angle measurements on olivines and orthopyroxenes from the peridotite yield composition ranges of Fo_{81-97} and En_{90-93}, respectively, based on the correlation charts of Poldervaart (1950) and Hess (1960). Clinopyroxenes from the diallage pyroxenite have compositions near $En_{44}Fe_{12}Wo_{44}$ based on refractive index measurements, 2V, and the correlation curve of Muir (1951). These Mg-rich olivine and pyroxene compositions agree with the compositions found in the ultramafic parts of other alpine-type complexes (see, for example, Moores, 1969; Himmelberg and Loney, 1973).

Prior to uralitization, the gabbroic rocks of the complex included all gradations between anorthosite and mafic augite gabbro. Hydrous metamorphism, probably coeval with serpentinization of the ultramafic rocks, has produced a variety of saussurite, uralitized gabbro, and epidote-amphibolite. Some rocks have recrystallized only slightly and retain primary igneous textures, whereas others are thoroughly reconstituted. Modal analyses in Table 3 indicate the variability of the metagabbroic rocks.

Premetamorphic textures range from aphanitic (in chilled zones) to subpegmatitic (in late blebby schlieren throughout the complex). Typical medium-grained gabbro is either ophitic or hypidiomorphic granular. Rapid changes in grain size are characteristic of the gabbro as a whole. Medium ophitic rocks grade abruptly into fine granular rocks and also into coarse, vaguely bounded pegmatoid masses.

Compositional variations in the gabbroic rocks are very irregular. No cumulatelike layering or cryptic mineral zoning was observed anywhere in the complex. Streaks rich in plagioclase or mafic minerals are locally swirled together in marble-cake fashion. Anorthositic patches as long as 1,000 m grade almost imperceptibly into normal augite gabbro on all sides, and normal augite gabbro grades into mafic augite gabbro as the augite content increases.

The main primary igneous minerals in the gabbroic rocks are calcic plagioclase and clinopyroxene. The primary plagioclase ranges in composition from An_{65} to An_{85} (universal stage determinations) with the more calcic varieties in the anorthositic rocks. Zoning is uncommon. The composition of the clinopyroxene could not be determined accurately by optical methods because of extensive interpenetration by uralitic amphibole. Considerable variability in composition is indicated by a 2V range from 46° to 60°, as determined on 37 separate specimens, but detailed work on pyroxene chemistry remains to be done.

The primary minerals have been extensively and variably replaced by secondary andesine, epidote, clinozoisite, and fibrous uralitic hornblende. Small patches of entangled chlorite, serpentine, and fibrous tremolite were noted in a few thin sections and may represent former olivine or orthopyroxene crystals. These patches are uncommon; most of the gabbro is not olivine or orthopyroxene bearing.

A foliated, gneisslike fabric of dimensionally oriented olivine grains is present in harzburgite specimens that contain enough primary olivine to reveal it. Aligned, rudely augen-shaped olivine crystals as long as 0.8 mm are surrounded by a mosaic of equidimensional smaller grains in a manner suggesting cataclastic granulation. Orthopyroxene crystals as large as 1.5 mm across stand out as pseudophenocrysts in the groundmass of foliated olivine. Some orthopyroxene crystals are bent or lightly crushed, showing mosaic extinction. Most are rimmed by a girdle of olivine and pyroxene, 0.3 to 0.5 mm wide, as if they had rolled and brecciated their margins and immediate neighbors.

Foliated fabric is not apparent in thoroughly serpentinized rocks. In the absence of abundant residual grains, it is impossible to distinguish between mesh textures derived from foliated and nonfoliated olivine-rich ancestors.

The diallage pyroxenites are characterized by a xenomorphic mosaic of large and small grains reminiscent of the "two-size" texture common in plutonic anorthosites (Kehlenbeck, 1972). Large diallage crystals are rimmed by girdles of smaller crystals, a relation suggestive of granulation and recrystallization during emplacement.

In places, the gabbro has a steeply inclined, primary flow foliation of aligned plagioclase. This foliation seems to be local, but subsequent uralitization may have obscured it over wide areas.

The orientation of olivine, clinopyroxene, and plagioclase in

TABLE 3: TYPICAL MODES OF URALITIZED GABBRO

	(1)* G-14	(2) N-41	(3) N-54	(4) I-3	(5) I-9	(6) I-25	(7) I-29	(8) N-47	(9) N-45	(10) I-26	(11) I-10	(12) N-51
Plagioclase†	64.4	62.9	52.4	42.2	44.3	47.6	43.5	42.0	58.8	51.0	34.2	38.0
Clinopyroxene	27.7	17.5	31.4	1.6	12.8	10.0	1.2	5.3	0.2	10.0	-	-
Orthopyroxene	-	-	0.1	tr	-	-	-	-	-	-	-	-
Uralitic amphibole	-	10.0	10.3	55.0	42.3	42.2	54.7	52.4	34.9	36.5	63.5	50.0
Epidote and clinozoisite	tr	0.4	0.4	0.3	0.1	tr	0.1	0.1	0.8	0.1	tr	10.4
Chlorite	7.8	8.6	5.5	-	-	-	-	-	5.1	0.4	0.2	tr
Sphene	tr	tr	-	0.3	tr	tr	0.5	-	tr	0.2	-	0.6
Opaques	tr	0.2	tr	0.2	0.1	0.2	0.1	0.2	tr	0.7	2.1	1.0
Carbonate	-	-	tr	0.2	0.1	-	tr	tr	tr	-	-	-
Zoisite	-	-	-	-	-	-	-	-	-	1.0	-	-
Prehnite	-	0.3	-	0.2	0.2	-	-	-	-	-	-	-
Apatite	-	-	-	-	-	-	-	-	0.2	-	-	-
Zircon	-	-	-	-	-	-	-	-	tr	tr	-	-
TOTAL	99.9	99.9	100.1	100.0	99.9	100.0	100.1	100.0	100.0	99.9	100.0	100.0

Note: 1900 points counted per specimen.

**Specimens 1-3 are unusually fresh gabbro, 4-9 are uralitized extensively but retain igneous textures, and 11-12 are wholly recrystallized epidote-amphibolite. Specimen 10 is a coarse pegmatoid veinlet.*

†Primary plagioclase intergrown with variable amounts of recrystallized albite, oligoclase, and dusty clinozoisite; plagioclase of 11 and 12 is entirely recrystallized andesine.

peridotite, pyroxenite, and gabbro clearly preceded serpentinization, uralitization, and the extensive discontinuous shearing that affected all these rocks. The primary foliation is interpreted to have formed during tectonic flowage of essentially solid material at an early stage in the history of the complex.

Schistose shear zones that are clearly younger than the gneissic foliation of primary minerals occur throughout the ultramafic parts of the complex. These zones range from a few centimeters to hundreds of meters wide and are occupied by very platy, slickensided fragments of serpentinite. Lenses of carbonate and rodingite are developed in some. Several sets of shears commonly intersect and mutually offset one another, and an individual shear zone may curve sharply or fade out abruptly. In areas of numerous wall-rock inclusions (such as the old Blewett mining district) the shear zones curve wildly, generally tending to parallel the nearest contact. Shearing is less pervasive in the mechanically stronger gabbroic rocks than in the serpentinite, but it is widespread nevertheless. Shear zones in gabbro are occupied by an aggregate of pulverized plagioclase entangled with secondary actinolite, epidote, and calcite.

Serpentinization and uralitization have produced a number of secondary textures and minerals in the mafic and ultramafic rocks, details of which are discussed elsewhere (Southwick, 1962; B. R. Frost, 1973, oral commun.). Serpentinization and uralitization may have occurred well before final tectonic emplacement of the complex into its present environment (Aumento and Loubat, 1971), and may have been renewed during episodes of intense shearing that accompanied final emplacement.

TECTONIC INTERPRETATION OF THE ALPINE COMPLEX

The problems and controversies surrounding the origin and history of mafic-ultramafic igneous complexes in orogenic belts are well known. Several recent papers provide succinct, well-documented summaries of thought on these problems (Wyllie, 1967, p. 407–415; Coleman, 1971; Dewey and Bird, 1971; McTaggart, 1971; Moores and Raymond, 1972) and show that unanimity of opinion remains to be achieved.

A currently popular hypothesis, based on the larger model of plate tectonics, proposes that rocks of the ophiolite petrogenetic association are oceanic crust originally generated at diverging plate boundaries along oceanic ridge systems or in marginal basins (Karig, 1971). These oceanic rocks are thought to have been "emplaced in orogenic belts, at consuming plate margins either beneath and behind oceanic trenches (subduction zones) or by thrusting onto continental margins (obduction zones) when a continental margin meets a subduction zone" (Dewey and Bird, 1971, p. 3179). Two lines of evidence supporting this notion are (1) The frequently observed ophiolite "stratigraphy" of voluminous peridotite at the base, gabbro and associated quartz dioritic rocks in the upper half, and volcanic rocks (chiefly pillow basalt with some quartz keratophyre) at the top fits with a widely accepted model for the structure of oceanic crust as adduced from seismic evidence (Shor and Raitt, 1969; Coleman, 1971). (2) The bulk chemical compositions of rock types comprising the ophiolite assemblage compare closely with the compositions of oceanic tholeiite, gabbro, and peridotite dredged from ocean ridges.

At and near converging plate margins, fragments of oceanic crust may be emplaced into a variety of petrotectonic associations that have little to do with the origin of the oceanic crust itself. Thus, pieces of oceanic crust (ophiolite) may become (1) parts of mélanges formed within subduction zones, as in the Franciscan terrane of California (Ernst, 1970); (2) parts of structurally complex, regionally metamorphosed volcanic-sedimentary sequences, presumably representing the tectonic emplacement of oceanic crust into the roots of island-arc systems; (3) parts of block-faulted, metamorphosed sequences containing abundant graywacke and volcanogenic detritus, presumably representing small-scale ophiolite generation caused by thermal diapirism and spreading in marginal basins behind island arcs (Karig, 1971; Dewey and Bird, 1971, p. 3187); or (4) more or less continuous allochthons thrust upon continental crust along the edges of continental plates, as in New Caledonia and Papua (Davies, 1968; Lillie and Brothers, 1970), and in Newfoundland (Dewey and Bird, 1971).

The mafic-ultramafic complex near Mount Stuart has many features that are consistent with an ophiolite interpretation, as that term is currently used (Coleman, 1971; Dewey and Bird, 1971; Dickinson, 1972), but it has been tectonically dismembered and is incomplete. As described above, somewhat more than half the complex is (or was) magnesian harzburgite and dunite, the composition of which matches rather closely the composition of the ultramafic parts of better preserved ophiolite at Canyon Mountain, Oregon (Thayer, 1963), Vourinos, Greece (Moores, 1969), and in New Caledonia (Lacroix, 1943; Lillie and Brothers, 1970). Furthermore, the gabbroic part of the complex is, in general, plagioclase rich and calcic, which compares closely to the typical Ca-rich gabbros of ophiolites and with abyssal gabbros from the mid-oceanic ridges (Miyashiro and others, 1970).

Unserpentinized masses of harzburgite in the complex near Mount Stuart have a good gneissic fabric of dimensionally oriented olivine, and some of the gabbro has a primary foliation of oriented plagioclase. Tectonite fabrics are common in ophiolite complexes elsewhere and also in rocks dredged from the sea floor, and they are thought to develop during the complex petrotectonic generation of ocean crust and mantle along mid-ocean ridge crests (see summary in Dewey and Bird, 1971, p. 3184–3186).

In composition and texture, then, the serpentinized harzburgite near Mount Stuart is similar to the ultramafic parts of many other ophiolitic or alpine-type complexes, and may well represent a depleted residue of olivine and orthopyroxene left after primitive lherzolitic mantle has partially melted to yield tholeiitic magma deep within a spreading mid-ocean ridge (Kay and others, 1970). The calcic gabbro, too, is like those in many ophiolite complexes, and may have formed by accumulation and partial differentiation of tholeiitic magma in transitory chambers within the "plumbing" beneath a spreading ridge crest (Kay and others, 1970; Miyashiro and others, 1970).

If indeed the alpine-type complex near Mount Stuart was generated at a spreading ridge crest and is a remnant of oceanic crust mantle, it has suffered much in its transport from the ocean basin to its present continental location. The complex has been so deformed during emplacement that serpentinite and gabbro meet along subvertical sheared contacts and are distributed in a blocky, disorganized pattern. Any layering or regular ophiolite "stratigraphy" that may once have existed has been thoroughly disrupted. Moreover, the upper parts of the ophiolite sequence, namely, the pillow basalt flows and ocean-floor sediments, have been removed from the lower parts. The volcanic and sedimentary materials in the Peshastin and Hawkins Formations are not typical oceanic rocks but, instead, are analogous to rocks found in present-day volcanic island arcs and along tectonically active continental margins.

Further interpretation is considerably hampered by uncertainties about the age and detailed structural setting of the Peshastin and Hawkins Formations. In 1904, Smith postulated correlation of the Peshastin-Hawkins sequence with the upper Paleozoic Cache Creek series in British Columbia and the Calaveras Group in California, correlations that still are plausible on lithologic and regional-tectonic grounds. Equally plausible, however, are lithologic correlations with various early to middle Mesozoic sequences in the Klamaths (Irwin, 1964) and northeastern Oregon (Thayer and Brown, 1964; 1973). In short, because of its broken, jumbled condition, distance from similar rocks, and lack of fossils, the

Peshastin-Hawkins sequence cannot be correlated confidently with any other rocks in the Pacific Northwest. These argillites and greenstones definitely are pre–Late Cretaceous, however, and have been deformed together with ophiolite that crystallized in Late Jurassic time.

I tentatively prefer to consider the Peshastin and Hawkins Formations as late Paleozoic(?) to early Mesozoic(?) in age, reiterating the basic position of Smith (1904). If this age is correct, the rocks near Mount Stuart fit rather well into the plate-tectonics model proposed by Monger and others (1972) for Mississippian to Middle Triassic time in the Canadian Cordillera. The synthesis of Monger and others (1972, p. 584–592, especially Figs. 6 and 7) indicates, for Mississippian through Middle Triassic time, an active oceanic ridge not far west of the present British Columbia coastline, a system of island arcs through central and eastern British Columbia, now corresponding to much of the intermontane tectonic belt, and a broad area of slope and shelf deposits lying east of the arcs on continental crust.

Extending the model of Monger and others (1972) into the Cascades, the rocks of the Peshastin, Hawkins, and perhaps also the Chiwaukum Formations are assigned a syntectonic origin in the late Paleozoic to early Mesozoic arc-trench system. These rocks were deformed during continuing Mesozoic tectonism. Somewhat later, in Jurassic time, ocean floor later to become the alpine ultramafic complex was generated. The peridotite and gabbro may have been formed and partially hydrated within a ridge system in the open Pacific, or they may have originated in a spreading marginal basin behind the arc (Karig, 1971). In either case, the ocean-floor rocks were carried toward the still-operating arc-trench system where, in latest Jurassic or Early Cretaceous time, they were thrust against the highly deformed and variably metamorphosed older roots of the arc. The entire complex moved repeatedly in response to more or less continuous tectonic activity throughout Cretaceous and much of Cenozoic time. Extensive faulting, shearing, and granitic intrusion accompanying this later tectonism have obliterated many original features of the older rocks.

Obvious uncertainties and difficulties exist in the foregoing interpretation. Clearly, in order to extend the model of Monger and others (1972) southward into the Cascades, it is necessary to recognize and trace belts of pre-Cretaceous rocks that can be interpreted logically in terms of a converging margin between oceanic and continental plates. In the geologically complex northern Cascades, such tracing is not easy to do.

The ophiolite assemblage southeast of Mount Stuart is of Late Jurassic age and, on the basis of petrologic and structural criteria already discussed, is believed to have been emplaced within a subduction zone. Hopson and Mattinson (1973 and 1973, personal commun.) reported Late Jurassic ophiolites from Manashtash Ridge and Rimrock Lake, south of the Mount Stuart area (Fig. 1) and concluded that these also were emplaced in a subduction zone. Whether these three isolated areas define the trend of middle to late Mesozoic subduction across central Washington is of course speculative, subject to the findings of future mapping and geochronologic studies.

Of greater importance and equally perplexing are the relations of the Mount Stuart ophiolite and its wall rocks to other rock units in the northern Cascades. What connection, if any, is there between rocks of the Peshastin-Hawkins sequence, here interpreted as arc-trench deposits, and grossly similar rock types in the Shuksan-Darrington-Easton metamorphic belt (Fig. 1)? At present there is no concrete evidence of any sort to suggest correlation. On the other hand, the principal reasons for *not* considering the Easton to be correlative with the Peshastin are the greater metamorphism and deformation of the Easton (Smith, 1904), and the fact that the two units are on opposite sides of a major high-angle fault zone (Fig. 1). Much of the Easton Schist is thoroughly recrystallized, highly crinkled phyllite and pelitic schist composed of quartz, mica, and chlorite. This is essentially the same low-grade mineral assemblage that is found in much of the generally uncrinkled Peshastin. Mafic rocks in the Easton are chiefly well foliated and crinkled actinolite- and epidote-bearing schists, mineralogically not greatly different from less penetratively deformed mafic rocks in the Peshastin-Hawkins sequence. Thus, the most striking physical differences between the Easton Schist and the Peshastin-Hawkins sequence are that the Easton is more thoroughly recrystallized and has a good crenulation cleavage, which the Peshastin-Hawkins lacks. Modern, detailed structural and metamorphic comparisons are needed to determine whether these differences are sufficient to deny correlation unequivocally.

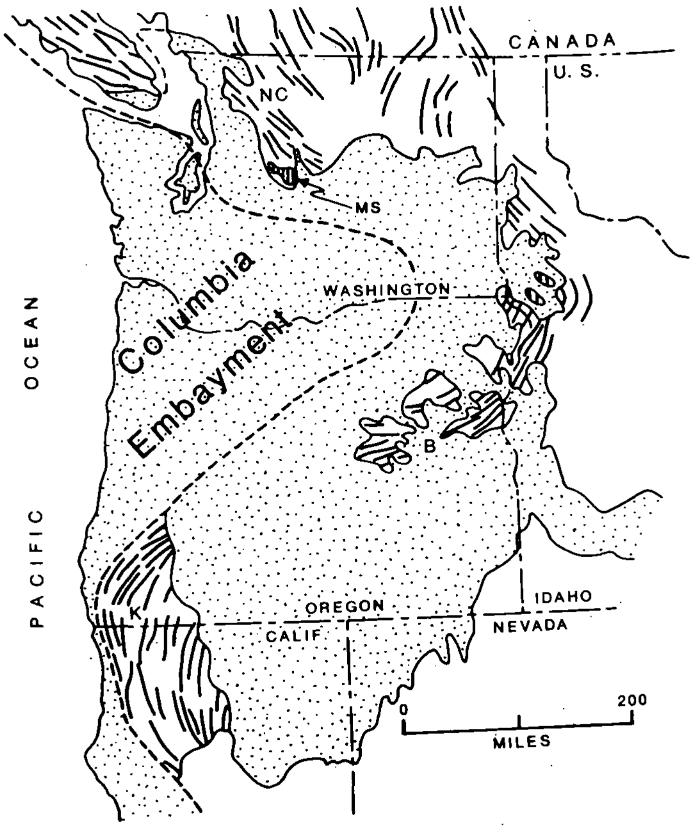

Figure 6. Tectonic sketch map of Columbia embayment, Pacific Northwest. NC = northern Cascade Mountains; B = Blue Mountains of Oregon; K = Klamath Mountains; MS = Mount Stuart batholith. Heavy lines portray major structural trends in Mesozoic and older rocks that frame embayment; heavy dashed line is inferred western margin of Mesozoic and older rocks. Stippled area is covered by Tertiary and younger rocks, chiefly volcanic, of central and southern Cascades, Coast Ranges, Columbia Plateau, and Snake River Plain. Map modified from King (1959, Fig. 89, p. 159).

Glaucophane- and crossite-bearing schists are known to occur at several localities in the Shuksan-Darrington-Easton terrane (Smith, 1904; Misch, 1966, p. 109), and therefore it is tempting to postulate the presence of a former subduction zone, following the arguments of Ernst (1970) and Miyashiro (1972). Can such a zone actually be mapped, and, if so, does it have anything to do with the Mount Stuart ophiolite, which lies east of the main Shuksan-Darrington-Easton trend and is nearly perpendicular to it (Fig. 1)?

Misch, who, with many graduate students, has done more mapping than anyone else in the northern Cascades, clearly is not convinced that subduction ever was involved in northern Cascades tectonics (Misch, 1973). He claims that the autochthonous Paleozoic and Mesozoic rocks below the Shuksan thrust (Fig. 1) are wholly endosialic, and views with skepticism any model that involves oceanic crust. It is accurate to say, therefore, that extensive mapping in the Shuksan-Darrington-Easton terrane by Misch and his associates has *not* turned up proof for a Mesozoic or older subduction zone. Nevertheless, the possibility of one being associated with the blueschist rocks remains intriguing.

If a former subduction zone should ultimately be demonstrated *within Shuksan-Darrington-Easton terrane, a connection between it* and the Mount Sutart ophiolite is plausible (not proved!) on purely geometric grounds. Easterly structural trends in the pre-Tertiary terrane south of Mount Stuart (Figs. 1 and 2) reflect a large-scale bend in pre-Tertiary structural axes (Fig. 6). Approximately at the position of the Mount Stuart batholith, the northwesterly trends typical of the Canadian Cordillera and northern Cascades swing abruptly eastward to form the north limb of the Columbia embayment (Cohee, 1962; King, 1969, p. 70; Monger and others, 1972, p. 591; Fig. 6). Thus, a pre-Tertiary subduction zone, being parallel to the tectonic grain of the Cordillera, should follow this bend and swing eastward in the vicinity of Mount Stuart. It is unfortunate that this major tectonic rotation is largely buried by relatively undeformed rocks of Tertiary and younger age.

These tectonic speculations certainly will require extensive modification as more facts become known about the Mount Stuart area in particular and the northern Cascades in general.

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STATE OF WASHINGTON
DANIEL J. EVANS, Governor

DEPARTMENT OF ECOLOGY
JOHN A. BIGGS, Director

GEOTHERMAL ENERGY POTENTIAL
of
WASHINGTON STATE

By
Robert H. Russell, Geologist
Office of Technical Services

Presented at the
"Third Annual Thermal Power Conference"
October 5 & 6, 1972 Washington State University
Pullman, Washington

CONTENTS

ILLUSTRATIONS

GEOTHERMAL ENERGY POTENTIAL OF WASHINGTON STATE

By Robert H. Russell

-ABSTRACT-

The State of Washington generally, the Southern Cascades principally, and the Northern Cascades and Olympic Mountains, to a lesser degree, do possess geohydrologic parameters, thermal springs and other surface and subsurface manifestations that suggest that the state may have the potential for a moderate to major geothermal energy resource. Further, geologic, hydrologic and geophysical investigations and evaluations will be required, however, before reservoirs can be identified and defined and their energy potential estimated on a quantitative and qualitative basis.

Under the present "state of the art", geothermal energy development presents a number of advantages and disadvantages, principally in the area of "impact on the environment." If, however, the environmental impact problems can be resolved within acceptable limits and we are to exploit and utilize this valuable resource to its optimum potential, and I believe that we should, it then follows that we should proceed with an objective and viable investigation, evaluation and test drilling program. From this preliminary evaluation, one area, North Bonneville, stands out as a preferred site for initial geothermal energy potential testing.

INTRODUCTION

Purpose of Study.

In recent years in the Pacific Northwest and in the State of Washington specifically, people have been warned periodically of possible power shortages due to insufficient developed hydroelectric power generating facilities. This and the fact that most of our hydro sites have been developed requires that other sources of energy be tapped to satisfy the ever increasing demand for additional electric power.

At the present time most makeup power is generated by thermal plants fired by fossil or nuclear fuel; however, both processes possess environmental problems and each consumes a non-renewable, limited resource for fuel. For these reasons, it is only prudent that the State of Washington fully evaluate the potential of all new untapped sources of energy which may provide an important part of the State's ever increasing total energy demand and which may not pose the environmental problems common to fossil fuel and nuclear fired plants.

The purpose of this report is to review existing information, summarize the State's geothermal potential and recommend an objective program designed to keep the Department of Ecology informed on geothermal developments in the State of Washington and elsewhere, provide the Department with accurate information needed to answer the queries that are being raised about geothermal energy and assume its administrative role in the exploration and exploitation of geothermal energy in Washington State.

Previous Investigations.

Although a number of reports and professional papers have been published dealing with various phases of volcanic activity in the State of Washington, none concerned themselves specifically with its geothermal potential. Reports describe in detail one or more of the State's five major volcanoes and the sequence of geologic events that preceeded them. Others deal with thermal anomalies, recent lava flows and other geologic phenomena that relate closely to geothermal power, but it was not until May 21, 1971, when the [1]"First Northwest Conference on Geothermal Power" was held in Olympia that the State's geothermal power potential was discussed even in a general way.

Acknowledgments.

Appreciation is extended to Bert L. Cole, Commissioner of Public Lands and Gerald W. Thorsen, Division of Mines and Geology, for use of the data from the Proceedings of the conference. Data from "Power From the Earth" by David Fenner and Joseph Klarmann is acknowledged. R. G. Bowen's "Electricity from Geothermal, Nucleur, Coal Resources" etc. was very helpful.

1. Geothermal Power, First Northwest Conference

History of Geothermal Power Development.

Geothermal energy, although it is a new field in the State of Washington and the United States generally, it has beeen successfully exploited for many years in other parts of the world. It was in 1904 in Larderello, Italy, that geothermal steam was first used to run a reciprocating engine. The first steam turbine using steam directly was installed at Larderello in 1913. It operated a 250 kilowatt generator.

In the early 1930's, New Zealand utilized naturally occurring steam to heat homes and greenhouses and to evaporate salt water to recover salt and other minerals. In 1940, in the area of Rotoria on New Zealand's North Island, the earth's heat was tapped to heat a number of public buildings and private homes. It was not until 1949 that New Zealand started an exploratory drilling program to develop geothermal energy to generate electricity.

Although geothermal power has been utilized for many years in other parts of the world, it was not until June, 1960, that the first geothermal power was used to generate electricity in the United States. The successful operation of "The Geysers Power Plant", located about 75 miles north of San Francisco, Califormia, demonstrated that under proper geohydrologic conditions geothermal power can become a valuable and renewable source of energy.

Cerro Prieto (Black Mountain), an extinct volcanic cone south of Mexicalli, Mexico, is the site of the most recent geothermal power development in

North America. Here 17 completed wells, averaging 4,500 feet deep, produce enough steam to operate a 75 MW power plant which will start generating electricity later this year. Construction is under way on wells and a plant for a second 75 MW facility at Cerro Prieto.

First Northwest Conference on Geothermal Power.

The first geothermal power conference held in the Northwest and one of the first held anywhere in the United States convened at Olympia, Washington, on May 21, 1971. The conference sponsored by the Washington State Department of Narural Resources was attended by more than 300 persons representing state and federal agencies from Washington, Oregon, California, Idaho, Nevada and other states, as well as representatives from many public and private power groups and institutions of higher learning.

The first national conference on geothermal resources was held February 16 - 18, 1972, at Imperial Valley College and the Imperial Valley Country Club, El Centro, California. The conference sponsored by the "Geothermal Resources Council" was attended by more than 600 individuals and included a trip to the geothermal wells and power plant at Cerro Prieto, Baja California, Mexico.

Enthusiasm shown by representatives of power companies, major oil companies, state and federal agencies, as well as the academic community clearly demonstrated a strong feeling that the "time is ripe" for administrative agencies, who have statuatory responsibility over geothermal development to prepare and adopt regulations and guidelines that will insure that the states' geothermal resources are inventoried and exploited to their optimum potential in a manner that will have a minimum adverse impact on the environment and the geothermal systems.

GEOTHERMAL POWER POTENTIAL

Geothermal Energy.

Before getting involved in an evaluation of the extremely complex field of geothermal power, it is necessary to have a working knowledge of, and appreciation for the geologic parameters which are, when combined, responsible for the complex geohydrologic systems which create geothermal energy.

Heat flows continuously from the earth's interior at a low but constant rate. When distributed equally over the earth's entire surface, it is hardly detectable; however, in certain regions, principally areas of recent volcanic activity, concentrations of heat have accumulated at much shallower depths below land surface. If these concentrations of heat occur in contact with subsurface reservoirs, areas where there is a circulation of ground water confined by an impervious or semi-impervious cap rock layer, the potential for developing naturally occurring steam under high pressure exists. To perpetuate the production of steam, there needs only to be a continued source of water to replace that being consumed tc create the steam and/or hot water.

Sources of Water.

There are two principal sources of water which satisfy the requirement for the many naturally occurring geothermal emissions such as the geysers in Yellowstone and Northern California and the many hot springs throughout the world. They are: (1) juvenile water: that water occurring as an integral part of the magma, and (2) Natural recharge as the result of precipitation falling on the land surface and migrating downward through faults and fractures in the rock materials which overlie the reservoir. It has been estimated that ninety percent of the water consumed by naturally occurring geothermal emissions comes from downward percolating ground water and not more than ten percent is actually juvenile water.[2]

A third source of water, artificial recharge through injection wells, may insure an optimum water supply and in some fields may actually increase the geothermal energy potential and extend the life of the field. This factor is of further interest since it is possible that large geothermal reservoirs exist without water and could become important producers if water were added through injection wells.

Although the geologist may make certain valid generalized statements about geothermal energy, one is reminded that for the most part they are just professional opinions and in reality little detail is known of the complicated and intricate geohydrology of geothermal systems. These unknowns must be identified, defined and resolved before an attempt is made to utilize this potentially valuable resource in the State of Washington.

2. Elder, J. "Heat and Mass Transfer in the Earth; Hydrothermal Systems." New Zealand, 1966.

Existing Geothermal Wells.

Current geothermal wells are relatively shallow, ranging between 500 and 7,000 feet and rarely exceed 6,000 feet and are of a relatively large (12 inch to 24 inch) diameter. Principals involved in drilling geothermal wells are quite similar to drilling oil wells with an added factor of high temperatures (200°C to 300°C) and strong artesian pressures. Refinements in drilling methods have been able to accommodate these problems. One of the greatest problems that geothermal wells present is that minerals collect in the well shaft and eventually plug off the well. The steam under high temperatures and pressures at depth dissolve the minerals but once the water is in the well, the pressure drops causing the water to flash to steam and release the minerals, it may require periodic redrilling of the well bore. A large part of the minerals are ejected from the well by steam and water and must be disposed of at land surface.

Experience has shown that under favorable geohydrologic conditions geothermal power is competitive costwise with other conventional thermo-electric plants. However, there are a number of environmental impact problems associated with geothermal power developments, some are common to conventional thermal plants, but others are unique to geothermal. A Number of misleading statements have been made about this pristine source of energy when in fact such a statement is far from the truth, since there are a number of gases, highly mineralized waters and other debris emitted from some wells. These do pose problems to the local environment and must be recognized, resolved in plant designs and their costs amortized over the expected life of the plant before a project is started.

GEOTHERMAL ENERGY IN WASHINGTON STATE

Areas with Potential.

To date there have been no wells drilled and no extensive studies initiated to test and/or evaluate the geothermal energy potential of the State of Washington although considerable interest was demonstrated at the First Northwest Geothermal Power Conference held in Olympia in 1971. However, the state does possess geohydrologic conditions and structures as well as a number of thermal and mineral springs which, when combined, suggests that the state may have a moderate geothermal energy potential. A further review of surface geology suggests that a large area of recent volcanic activity and lava flows lying between Mt. St. Helens and Satus Pass on the west and east respectively, and Mt. Rainier and the Columbia River in a north-south direction does possess significant geothermal energy indicaters and should be the focal point of additional study and detailed evaluation.

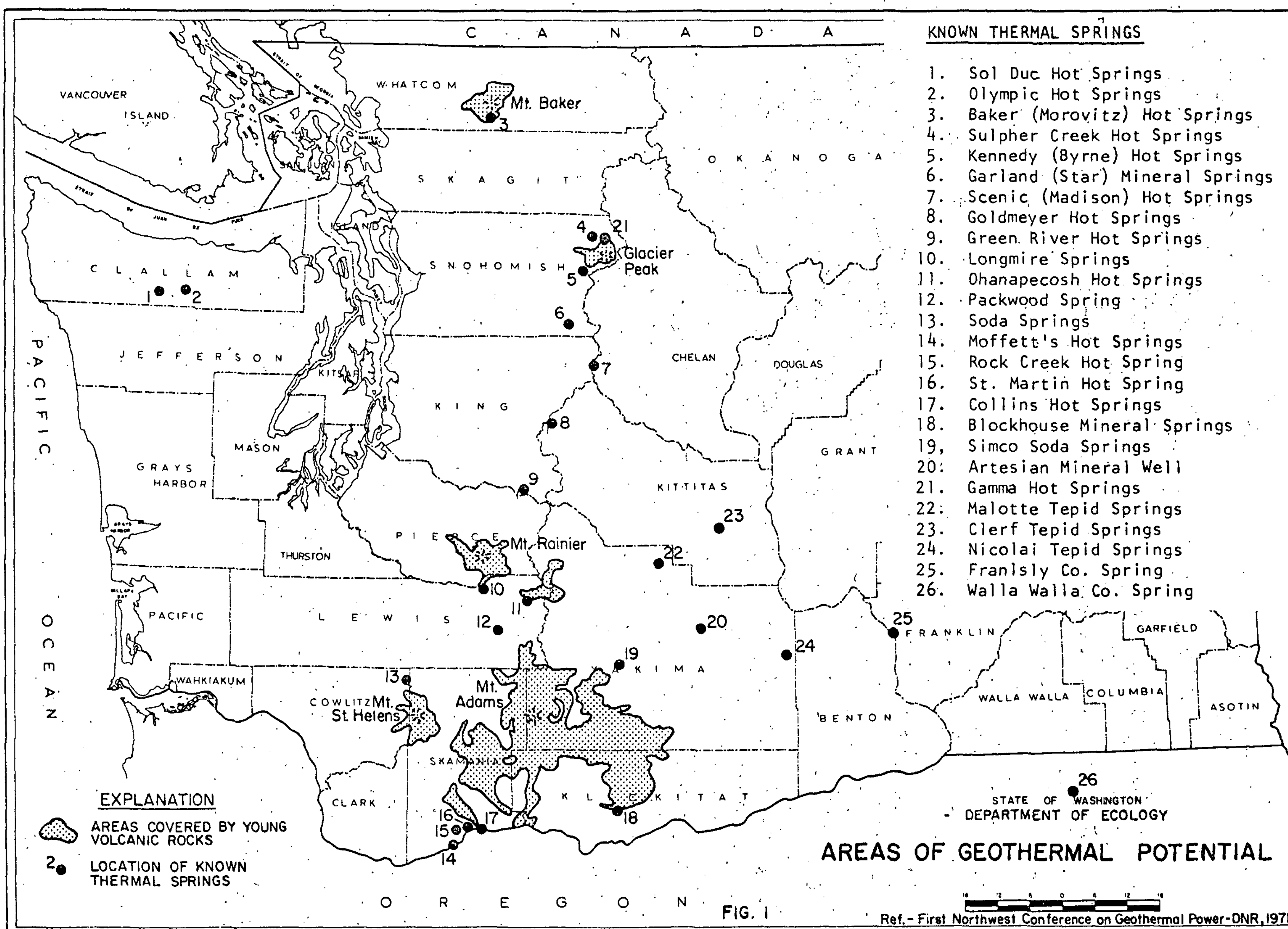
There are other smaller areas in Western Washington which may provide limited geothermal energy potential and they too, are associated with recent volcanic activity in the North Cascades and Olympic Mountains. Figure 1 shows areas of Washington State with favorable geothermal potential and the locations of known thermal springs in Washington.

Geology.

Here, young Quaternary volcanic lava flows associated with Mt. St. Helens and Mt. Adams cover an area of approximately 1,500 square miles. The Cascade lavas are underlain successively by The Dalles Fm., (Troutdale Fm. west of the Cascades), 100 feet more or less in thickness; Columbia River Basalt, up to 2,000 to 3,000 feet thick and the Eagle Creek Fm., an older series of volcanic tuffs and breccias, up to 4,000 feet in thickness. Breccias in the lower section of the Eagle Creek Fm. may serve as reservoirs for super heated water and/or steam production. Anticlines and synclines exposed along the Columbia Gorge appear to be adequate structural barriers to confine the movement of ground water and relatively impervious flows of Columbia River basalt and/or tuffs in the Eagle Creek Fm. may provide the cap layer required to confine the hot water or steam within the structure.

Thermal Springs.

There are 26 known thermal and mineral springs and no spectacular geysers or fumaroles in Washington (Fig. 1). This does not necessarily mean that the geothermal energy potential is poor; rather, it may suggest that most structures are tight and well confined and when tapped by drilling may produce steam under high temperatures and pressures. These questions, as well as environmental impact questions associated with geothermal power development, can only be answered by detailed geologic, hydrologic and geophysical investigations and the actual drilling of one or more test wells under controlled conditions.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DOUGLAS
KING
MASON
GRAYS HARBOR
GRANT
KITTITAS
PIERCE
Mt. Rainier
THURSTON
PACIFIC OCEAN
PACIFIC
LEWIS
FRANKLIN
GARFIELD
YAKIMA
WAHKIAKUM
COWLITZ
Mt. St Helens
Mt. Adams
WALLA WALLA
COLUMBIA
ASOTIN
BENTON
SKAMANIA
CLARK
KLICKITAT
OREGON
KNOWN THERMAL SPRINGS
1. Sol Duc Hot Springs
2. Olympic Hot Springs
3. Baker (Morovitz) Hot Springs
4. Sulpher Creek Hot Springs
5. Kennedy (Byrne) Hot Springs
6. Garland (Star) Mineral Springs
7. Scenic (Madison) Hot Springs
8. Goldmeyer Hot Springs
9. Green River Hot Springs
10. Longmire Springs
11. Ohanapecosh Hot Springs
12. Packwood Spring
13. Soda Springs
14. Moffett's Hot Springs
15. Rock Creek Hot Spring
16. St. Martin Hot Spring
17. Collins Hot Springs
18. Blockhouse Mineral Springs
19. Simco Soda Springs
20. Artesian Mineral Well
21. Gamma Hot Springs
22. Malotte Tepid Springs
23. Clerf Tepid Springs
24. Nicolai Tepid Springs
25. Franlsly Co. Spring
26. Walla Walla Co. Spring
EXPLANATION
AREAS COVERED BY YOUNG VOLCANIC ROCKS
LOCATION OF KNOWN THERMAL SPRINGS
STATE OF WASHINGTON
DEPARTMENT OF ECOLOGY
AREAS OF GEOTHERMAL POTENTIAL
Ref.- First Northwest Conference on Geothermal Power-DNR, 1971

FIG. 1

ENVIRONMENTAL IMPACT PROBLEMS

Geothermal power has been described as a pure, clean source of energy coming from the depths of the earth free of undesirable environmental problems; but this is not entirely true since all power plant developments, including geothermal, do effect a change in the environment in one way or another. In summary one can say that geothermal wells are noisy, they are dirty, and they smell bad. Most of these problems can be accommodated if the operator is willing to pay the price.

Geothermal energy occurs in different forms in many parts of the world based principally on geologic and hydrologic conditions peculiar to each reservoir. The two principal forms, the ones that we are interested in for the development of electrical energy are referred to as wet steam and dry steam reservoirs. Many wells, both wet steam and dry steam, release hydrogen sulfide which imparts a pungent odor to the general area of the well.

Wet Steam Reservoirs.

In the case of wet steam sources, large volumes of water in the reservoir are confined under high temperature and pressure, and under those conditions, dissolves large quantities of minerals from the host rock and when retained under pressure, transports them to the land surface through the well bore. As the superheated, highly mineralizes water enters the heat exchanger at the power plant, the pressure drops and the hot water flashes to steam releasing the dissolved minerals. In some wells, the flash from superheated water to steam occurs in the well bore in which case some of the dissolved minerals are deposited on the wall of the well bore.

In either case, under wet steam conditions, large quantities of highly mineralized water and minerals are brought to the earth's surface and must be disposed of in a manner approved by established environmental impact standards. The mineralized water discharge may create an extremely difficult problem and under the present state of knowledge the price per unit of electricity may make the energy cost excessive and such projects prohibitive.

The large quantities of minerals precipitated from the hot water may be recoverable and sold if a market exists for the types and quantities of minerals produced. These questions can only be answered after completion of a test well and analysis of the mineral content of the brine from the reservoir. If commercial quantities of minerals are recoverable, it could help defray the cost of the project and resolve some of the impact problems.

Dry Steam Reservoir.

Geothermal plants that utilize dry steam, tap sub-surface reservoirs which contain superheated steam created through natural processes and does not involve the large quantities of mineralized water associated with wet steam sources. In this process a heat exchanger is not required since the natural steam passes from the well bore and pipe line directly to the turbine. After passing through the turbine, the steam is condensed and provides water for the cooling towers. Excess water may be returned to the reservoir through recharge wells or discharged to a local steam if the quality is acceptable.

Dry steam plants produce only small amounts of objectionable products. As an example, the Geysers steam has an average of 99.5 percent water. This leaves only 0.5 percent non-condensable gases in the steam, of which about 90 percent is carbon dioxide with lesser amounts of methane, hydrogen sulfide and trace amounts of other gases (R. G. Bowen, 1971). No doubt different gases in different quantities would occur in geothermal reservoirs in Washington State. If geothermal energy does occur in commercial quantities in Washington State, it is not known whether the reservoirs will be wet steam, dry steam or both.

Other Impact Problems.

In addition to the points raised previously, there are other environmental impact questions that must be raised, evaluated, and resolved before approval is given to proceed with development of the first geothermal project in the State of Washington. Such questions as: 1. What effect would the construction and operation of a geothermal steam plant (wells, pipelines and facilities) have upon the aesthetic values of the area? This point is very important since areas with geothermal potential in Washington State are located in popular recreational areas of the Central Cascades and Olympic Mountains; 2. Severe noise problems have been reported when more than one well in a limited area is utilized at the same time; 3. There is a possibility that minor, local earthquakes may be triggered by the reduction of internal pressure as steam and/or superheated water is removed from the structure; and of course, 4. The necessary population and industrial influx that always follows any new industry. All of these points and others must be fully evaluated and at least theoretically resolved before production wells are drilled.

Favorable Impact Points.

In addition to the potential problems associated with geothermal power development, there are a number of favorable points that should be mentioned, such as: 1. Geothermal power would be utilizing a major, renewable source of energy not previously tapped in the State of Washington; 2. There is no combustion or burning as is common with conventional fossil fuel fired plants; 3. There would be no radioactive waste to be disposed of or concerned about; 4. A geothermal plant can be turned off and on quite easily making it extremely flexible for seasonal peaking power purposes; 5. The recovery of minerals in commercial quantities may provide a valuable by-product; and 6. It may be the forerunner to our acquiring the ability to defuse inactive volcanoes such as Rainier, St. Helens and others in the state which may show renewed activity.

FEDERAL GEOTHERMAL LEGISLATION

Three important pieces of federal legislation affecting geothermal power development have been introduced in the U. S. Congress since January, 1969. They are:

1. Senate Bill 368, introduced January 10, 1969 by Senators Bible, Bennett, Church, Hansen, Jorden, McGee and Moss. The

bill was subsequently passed by both houses and signed into law by the President.

SB 368 is known as the "Geothermal Steam Act of 1969" and provides for issuing leases for the development and utilization of geothermal steam and associated goethermal resources on lands administered by the Secretary of the Interior, etc.

2. House Bill 9749, introduced July 13, 1971 by Messrs. Steiger and Rhodes and Senate Bill 1349, by Bible of Nevada March 24, 1971 stress the availability of federal funds for geothermal exploration with the stipulation that 75% of the cost is to be borne by the U. S. Government and 25% by the private developer. Federal funds are to be on a loan basis and repaid from income of the project if it proves economically feasible.

Current Activities.

1. As a result of the First Northwest Conference on Geothermal Power, held in March, 1971 Olympia, the "Geothermal Resources Council" (a new international organization) was created and dedicated to encourage the exploration for geothermal energy and was formally launched at a conference at Imperial Valley College, El Centro, California, February 16 and 17, 1672. The conference included a tour of the Mexican geothermal power facility under development at Cerro Prieto, Baja, California.

2. Professor David D. Blackwell, Southern Methodist University completed a series of temperature gradient probes in a number of wells in the state under a National Science Foundation grant. Work was started during the summer of 1971 and was resumed in 1972.

3. Gerald W. Thorsen of Division of Mines and Geology, Department of Natural Resources, is conducting a number of geothermal probes in existing wells; he has obtained Professor Blackman's geophysical equipment on permanent loan basis.

4. Bob Crossen, University of Washington Geophysics Department, carried out ground noise observations in areas of known thermal springs. The project was sponsored by the Department of Natural Resources and data will be available later in 1972.

5. Division of Mines and Geology has an agreement with Dr. Paul Hammond of Portland State University whereby Dr. Hammond will prepare an open file, detailed geologic map of the Southern Cascades. This is scheduled for completion in 1972.

6. The U. S. Geological Survey plans to conduct an aeromagnetic survey of the State of Washington probably within the next year or two. If the state could provide some funds

while the Survey is doing the work, they no doubt would fly a closer grid pattern over those parts of the Cascades with major geothermal potential.

7. The Department of Ecology and the Department of Natural Resources are working with legislative committees to develop regulations and guidelines for the exploration and exploitation of geothermal energy in the State of Washington.

CONCLUSION AND RECOMMENDATION

Geothermal Test Site, A Proposal.

From this preliminary evaluation of geothermal energy potential of the State of Washington I would recommend what I feel is a preferred area which, if properly evaluated and tested, could go a long way toward answering many of the questions about the state's geothermal energy potential on a quantitative and qualitative basis. Such questions as:

1. Does the state possess exploitable geothermal energy that can be developed on a basis competitive with other available energy sources?

2. What are the average depths and costs of the geothermal wells required?

3. Are the sources of energy wet steam or dry steam reservoirs?

4. What chemicals are contained in the brines and gases; are they treatable and recoverable? What environmental impact problems are anticipated; can they be controlled? And other questions can be answered.

It is true that very little applied research has been done in the past and not much is known about potential geothermal reservoirs in the state. However, there are certain favorable surface indications and environmental limitations which, when combined, strongly recommend one area, North Bonneville, as a preferred area; to evaluate and test geothermal energy potential.

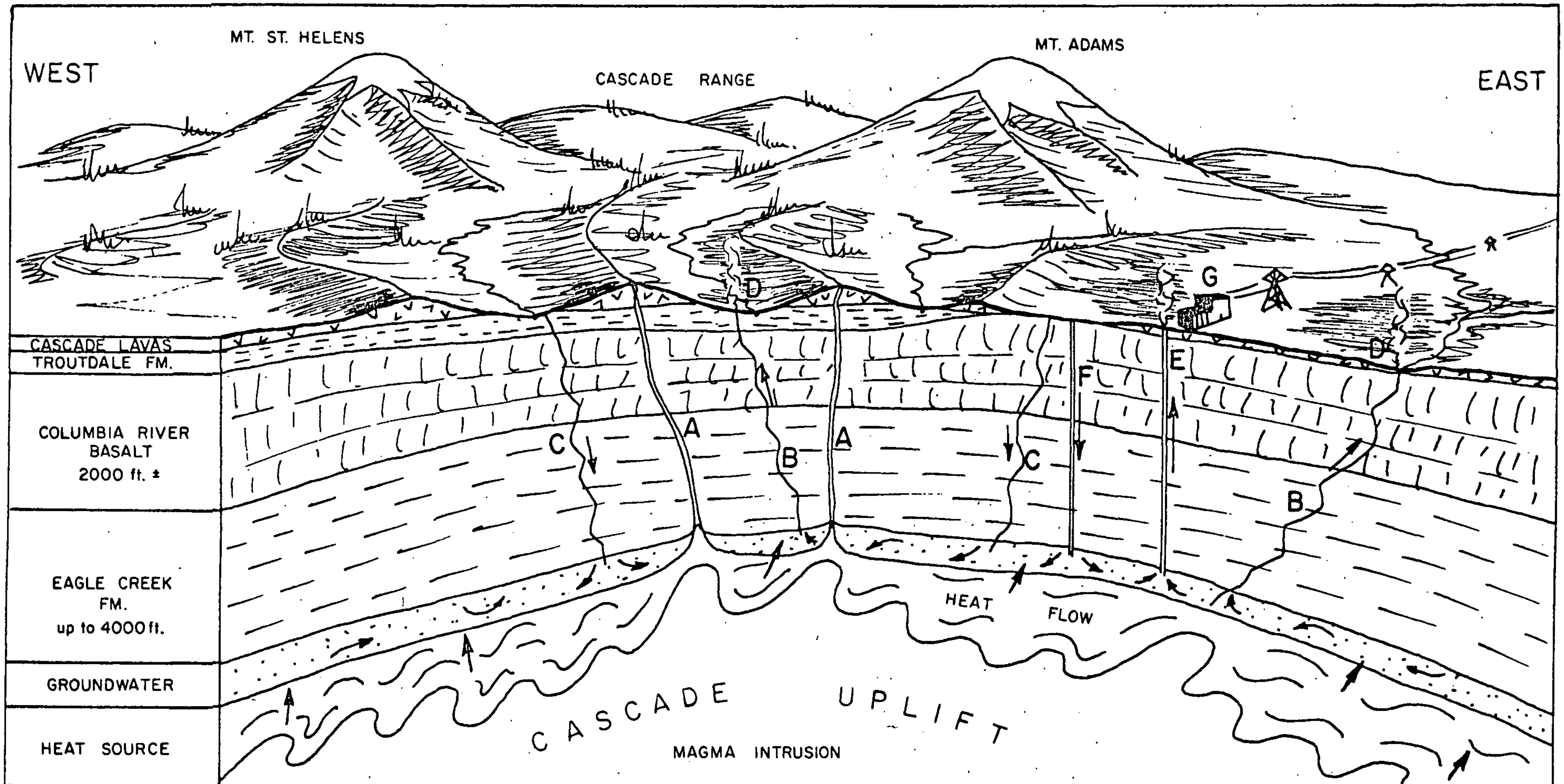
North Bonneville occupies a favorable position on a major anticlinal structure (Cascade Uplift), which brings some of the older deeper rock formations much closer to the land surface (Fig. 2). Here in the central part of the Columbia River Gorge is about the only place where rocks of the Eagle Creek Formation (Upper Triassic) are exposed at land surface within an area with favorable geothermal manifestations.

The advantages of the anticlinal structure plus down-cutting by the Columbia River has greatly reduced the depth and cost of drilling the wells that will be required to test the geothermal potential of the Southern Cascades, one of the prime potential areas in the State of Washington.

North Bonneville has already undergone major man-made physical changes during the construction and operation of Bonneville dam and associated power generating and distribution systems. Rights of way have been cleared. Roads and buildings have been constructed and power lines to convey the electricity are already in. For these reasons and others it follows that geothermal development at North Bonneville would have a much less impact on aesthetic values of the Southern Cascades than any other known area with significant geothermal indications. Some of the anticipated environmental impact problems are now a reality as previously stated and would not need be repeated, while those unique to geothermal such as steam plumes, noise, odors and mineralized waters would have to be dealt with after a reservoir had been identified and tapped and the problems determined. The advantage being that the development would be made in an already exploited area as opposed to the semi-wilderness, forested public lands that occupy much of the Cascades and Olympic Mountains.

If super heated steam or water is encountered in sufficient quantities and a power generating plant developed in North Bonneville, the electricity could be wheeled over existing Bonneville lines. This would reduce the total cost of the project and again reduce the impact on the environment. It is also possible that the Columbia River could absorb waste water from the wells without an adverse effect on the quality of the river water.

Figure 2. Diagrammatic Geothermal Section" across the Cascades through the Columbia River Gorge represents the author's preliminary concept of



EXPLANATION

A - INACTIVE VOLCANIC CHIMMEY

B - GEOTHERMAL DISCHARGE THROUGH A FRACTURE

C - NATURAL RECHARGE - WATER PERCOLATION THROUGH A FRACTURE

D - THERMAL SPRINGS

E - GEOTHERMAL WELL

F - ARTIFICIAL RECHARGE WELL

G - GEOTHERMAL POWER PLANT

FIG. 2

STATE OF WASHINGTON
DEPARTMENT OF ECOLOGY
JOHN A. BIGGS, DIRECTOR

DIAGRAMMATIC GEOTHERMAL SECTION

COLUMBIA RIVER GORGE AREA
SOUTH CASCADES, WASHINGTON

NO SCALE | DATE: JANUARY 1972

BY: ROBERT H. RUSSELL, GEOLOGIST

DRAWN BY: JOHN C. MILHOLLIN, C.E.T., CARTOGRAPHER geothermal conditions that one might expect if a well or wells were drilled in the North Bonneville area. Here, drilling would start near the base of the Columbia River Basalt since the Columbia River, an antecedent stream, was able to keep its down-cutting pace during the Cascade Uplift. This permitted removal by the Columbia of 2,000 feet or more of Cascade Lavas, Troutdale Formation and Columbia River Basalt.

It is possible that geothermal reservoirs occur in breccias and porous sediments of the Eagle Creek Formation or fracture zones near the base of the Columbia River Basalt. To test this concept would require a well or wells about 4,000-5,000 feet deep or about 2,000 feet less drilling than would be required in areas where the younger rocks have not been removed by erosion.

The North Bonneville area generally contains the largest group of thermal springs found in the state. Four springs; one hot 100° F+ "St. Martin's", two warm 81° - 99° F. Rock Creek and Bonneville or (Collins) and Moffetts Hot Spring, temperature not known. This grouping of thermal springs may be significant and tend to support the author's concept as expressed in Figure 2, geothermal section through the Columbia River Gorge. Additional geophysical and geochemical work will be required before a final drilling site is selected and a well started.

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Basalt Waste Isolation Program Annual Report - Fiscal Year 1978

Staff
Basalt Waste Isolation Program

October 1978

see: USGS topo maps, Washington
Yakima East 7.5' quad
Yakima West 7.5' quad
Wiley City 7.5' quad

Prepared for the United States
Department of Energy
Under Contract EY-77-C-06-1030

Rockwell International

Rockwell Hanford Operations
Energy Systems Group
Richland, WA 99352

Structures within the northwest section identified as requiring further evaluation include: (1) the Wilbur Creek fault; (2) the Reecer Creek fault; (3) the Caribou Creek fault; (4) the Zimmerman fault; (5) the Badger Mountain fault; (6) the Beezley Hills anticline; (7) the Orondo fault[7]; and (8) the Winesap lineament[7].

SOUTHWEST QUADRANT

This sector contains the lowest point of the Columbia Basin, the Pasco Basin, where the late Cenozoic sediments reach their maximum thickness. The oldest late Cenozoic sediments within this quadrant include the Columbia River gravels and the Thorp and Ringold formations. The stratigraphic relationship of these sedimentary units to each other and to the Ellensburg sediments interbedded with Columbia River Basalt flows is yet to be established with certainty.

The major late Cenozoic drainage of the quadrant is the Columbia River. As such, the area also contains Lake Missoula flood deposits. Wallula Gap is thought to have ponded south-flowing flood waters, as did Sentinel Gap to the north. Evidence of this impoundment is indicated by the presence of the Touchet beds, a primarily silt unit with some clastic dikes.

Structurally, the southwest quadrant is dominated by the Yakima Fold Belt, a series of anticlinal ridges extending eastward from the Cascade Mountains. Faults recognized within this sector generally occur in association with these east-west anticlinal ridges. Specific structures designated to require more detailed evaluation include: (1) Toppenish Ridge; (2) Smyrna Bench and North Saddle Mountains; (3) Ahtanum and Manashtash ridges; and (4) structures east of Selah and in the western part of the Yakima Firing Center.

SOUTHEAST QUADRANT

Within the southeast quadrant, the Snake River is the dominant late Cenozoic drainage system. Along the course of the Snake River and its tributaries, catastrophic flood waters (older than the Lake Missoula flood event) conveyed sediments into the Columbia Basin. Evidence for such floods includes gravel bars composed of deposits of metavolcanics, quartzites, gneisses, and granitics. The northwestern part of the quadrant contains the southern end of the Cheney - Palouse scabland tract, formed by the younger Lake Missoula flood event. The northeastern part of the quadrant is dominated by extensive Palouse loess hills, reaching a maximum thickness of 250 feet.

The dominant structural feature within the southeast quadrant is the Blue Mountains uplift. At least two faults associated with this uplift, east of Walla Walla (within the Buroker 7.5-minute quadrangle), require further evaluation. Faults located to the south and east of Wallula Gap were also noted to require further evaluation.

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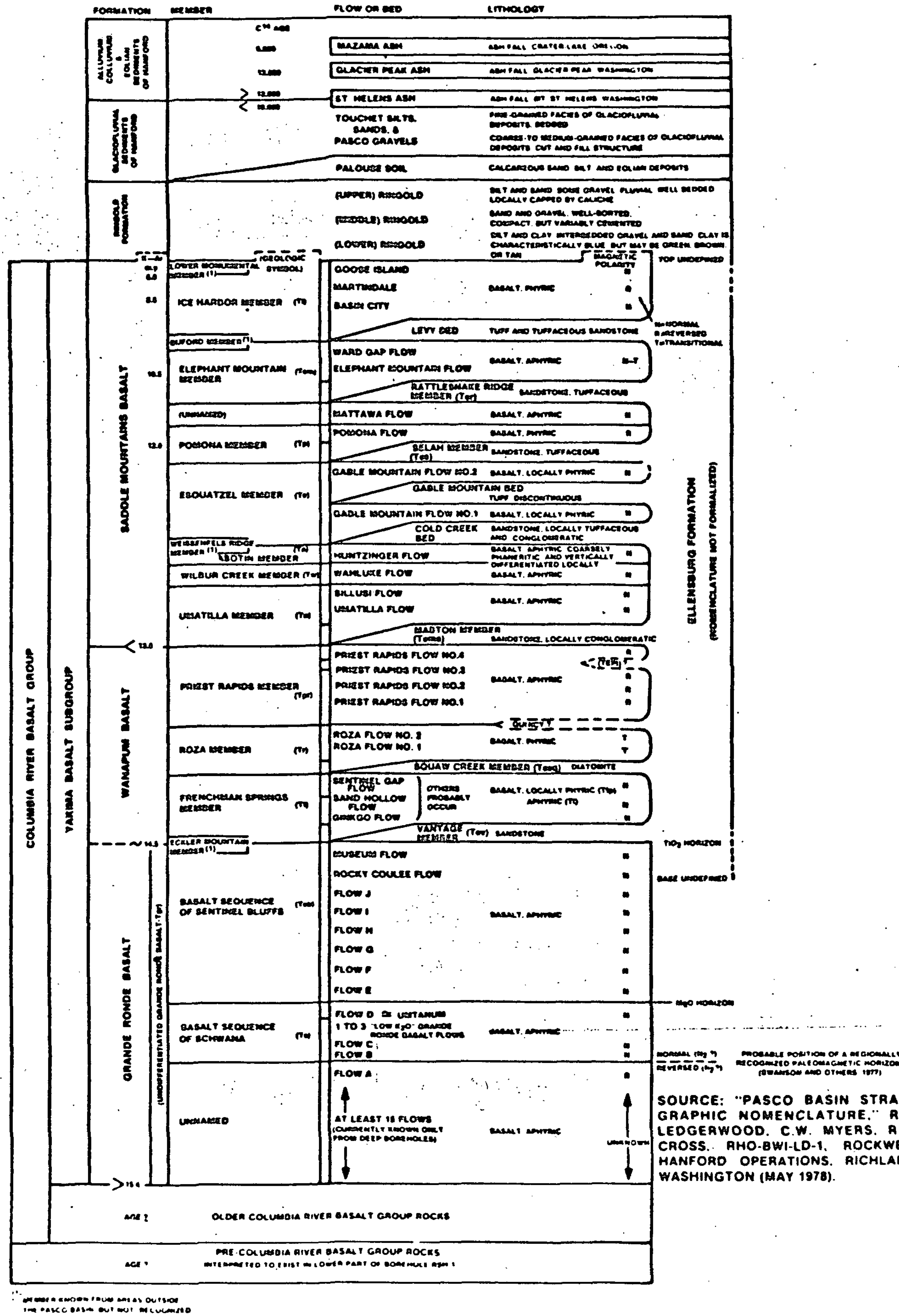

SOURCE: "PASCO BASIN STRATIGRAPHIC NOMENCLATURE," R.K. LEDGERWOOD, C.W. MYERS, R.W. CROSS, RHO-BWI-LD-1, ROCKWELL HANFORD OPERATIONS, RICHLAND, WASHINGTON (MAY 1978).

FIGURE 2

Claron

UNIVERSITY OF UTAH RESEARCH INSTITUTE

UURI

EARTH SCIENCE LABORATORY
420 CHIPETA WAY, SUITE 120
SALT LAKE CITY, UTAH 84108
TELEPHONE 801-581-5283

November 14, 1979

Mr. Fred Rigby
Science Applications, Inc.
P.O. Box 2351
La Jolla, CA 92038

Dear Mr. Rigby:

Enclosed is a rough draft memorandum by C. E. Mackelprang which presents the modeled resistivity distribution and corresponding computed resistivity values for lines A-A' and B-B' from Camas, Washington. Dr. William Sill of the University of Utah Department of Geology and Geophysics also contributed to these model solutions.

Please note the very different models for Line B-B'. Our field and modeling experience suggests that either the high (94.2, 76.6, 104.3 ohm-m) or low (5.5, 37.1 ohm-m) data values at n=4,5 on this line are in error. This problem and the many missing data values on the profile make any inversion of the data quite ambiguous so we have not attempted a closer match to the observed data.

I regret that travel commitments and other factors have delayed our response to your interpretation request. In Duncan Foley's absence I am forwarding this memorandum in a draft form to avoid further delay.

Sincerely,

Howard P. Ross

Howard P. Ross
Senior Geophysicist

HPR/hb

cc: D. Foley

Enclosure

November 14, 1979

MEMORANDUM

TO: Duncan Foley and Howard Ross

FROM: C. E. Mackelprang

SUBJECT: Camas area, Washington - Two-dimensional Resistivity Modeling of Dipole-Dipole Lines A-A' & B-B'

Two-dimensional models for Camas, Washington lines A-A' and B-B' are attached.

Line A-A'

Line A-A' was partitioned into three segments for modeling purposes. A good fit between observed and computed data values was obtained with models having reasonable continuity between segments. Because geologic information is sparse, the model results should only be considered as one resistivity distribution which would give rise to the actual field data, and as a first approximation to the geologic structure.

In general, the model of line A-A' shows a moderately resistive surface layer having a resistivity of about 50 ohm-meters and a thickness of approximately 250 meters extending from stations 0.0 to 3.5. Isolated pods of slightly more resistive (75 ohm-meters) material were necessary to enhance the model/field data comparison. At depth beneath this same station interval lies a thick conductive media which is represented on the model by 10-15 ohm-meters apparent resistivities.

The surface material appears much less uniform between stations 3.5 and 8.0 with apparent resistivities varying between 30 and 150 ohm-meters. It was necessary to significantly thicken this material between stations 3.5 and 7.0. A more conductive media (15 ohm-meters) lies at greater depth.

Finally, from station 8.0 to the end of the line the observed data can be modeled satisfactorily by assuming 50 to 75 ohm-meters material at the surface increasing to about 200 ohm-meters with depth. No conductive media are present over this station interval.

Line B-B'

It appears that several errors may be present in the observed field data for n=4,5 between station 0.0 and 1.0. It is not possible to obtain a single model showning good comparison with all the field data. Adjustments in one area tended to distort values in another.

As a result, two models are shown having equal plausibility which partially match the field data. Major differences in these models are: a very conductive media (1 ohm-meter) extending to great depth beneath and adjacent to very resistive (1000 ohm-meters) material vs. a conductive media (10 ohm-meter) of finite thickness sandwiched between 200 ohm-meter material.

Discussion

Results of the modeling for line A-A' suggest a surface layer of fairly moderate apparent resistivity extending over the entire line. This layer increases in thickness in the central portion of the line. A conductive media is present at a fairly shallow depth on the northwest end of the line but deepens to the southeast and is absent at the southeast end of the line.

Model results of line B-B' are questionable but tend to suggest a layering of resistive - conductive - resistive medias of unknown configuration and thicknesses on the southwest half of the line. To the northeast the models are less complex showing a trend into fairly conductive ground.

The attached models are two-dimensional (i.e. infinite strike length). If the survey lines have been run at some angle other than normal to the geologic structure then the model interpretation will not approximate the true resistivity distribution. The presence of three dimensional resistivity distributions would also detract from the applicability of the model solutions. We understand that line A-A' runs subparallel to a major geologic structure and topographic features. This may reduce the applicability of the resistivity model submitted here.

C E Mackelprang

C. E. Mackelprang
Geophysicist

CEM/hb

September 17, 1979

Dr. Howard Ross,
Senior Geophysicist
Earth Science Laboratory
University of Utah - Research Institute
Research Park
391A Chipeta Way
Salt Lake City, Utah 84108

Dear Howard:

Enclosed are two pseudo sections from the work completed for the State of Washington.

The dipole length used along profile AA' was 500 meters; that used along BB', 250 meters. As you recall, UURI agreed to invert these data using a two-dimensional modeling. When an approximate inversion has been completed, please send a copy to my attention at the address on this letterhead so that it can be included and properly acknowledged in our final report.

Thank you again for your co-operation, and I look forward to seeing you at the GRC meeting in Reno.

Respectfully,

Robert McEuen
by F.A. Rigby

Robert B. McEuen
Consultant to SAI

/jmh

Enc.
cc: J. Eric Schuster

Oct. 17 '79
Call from Fred Rigby
(714)-454-3811

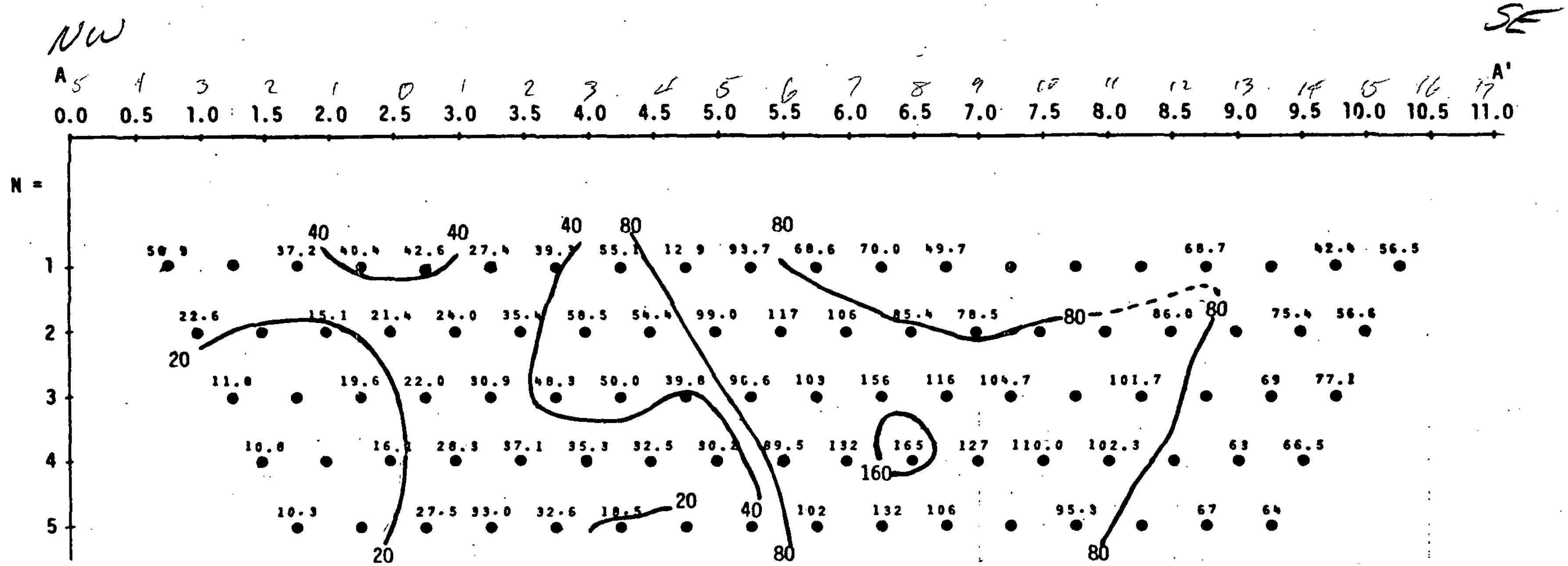

Figure 2. Pseudosection for line AA'. Dipole length was 0.5 km. Resistivities are in ohm-meters. The vertical scale is exaggerated by a factor of two.

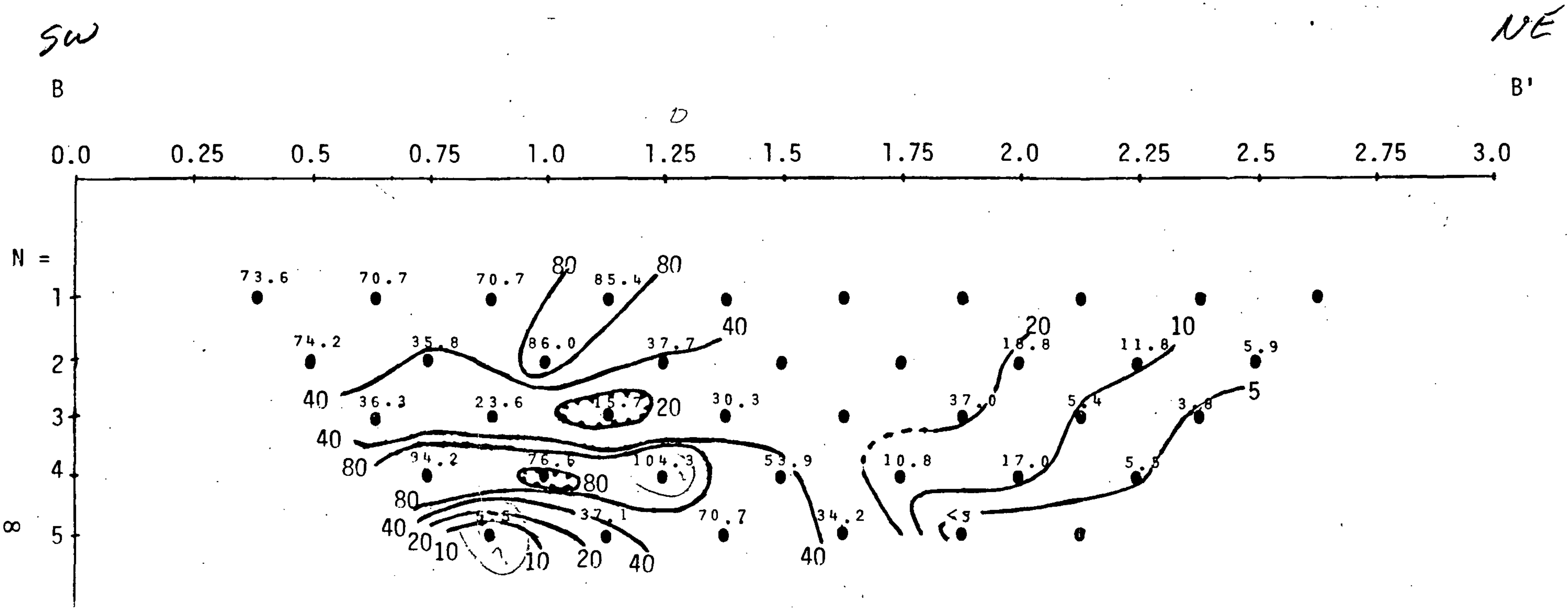

Figure 3. Pseudosection for line BB'. Dipole length was 0.25 km

GEOTHERMAL RESOURCES POTENTIAL OF THE LACAMAS FAULT REGION, CAMAS, WASHINGTON, U.S.A.

Robert B. McEuen — Exploration Geothermics, San Diego, CA

Fred A. Rigby — Science Applications, Inc. La Jolla, CA

Richard G. Bowen — Consulting Geologist, Portland, OR

ABSTRACT

Potential for direct heat applications in southwestern Washington has led to investigation of the possibility of locating geothermal resources in the area. Proximity to geologically recent vulcanism and faulting and the presence of some thermal waters focus attention on Camas, Washington. Previous studies have suggested southern Washington may lie within a zone of crustal weakness which has experienced magmatic intrusion. Existing geophysical data are consistent with the presence of a large intrusive body having an associated geothermal area near Camas.

INTRODUCTION

Interest in the geothermal resources potential of the Lacamas Fault area in southern Washington State has been enhanced by its proximity to the Camas Mill of the Crown Zellerbach Corporation. The Crown Zellerbach Corporation is the largest single industrial energy consumer in the State of Washington. The Camas Mill alone spent 28 million dollars last year for the purchase of energy.

The Lacamas fault can be traced from the Columbia River near Camas, extending northwest from the Camas area. Volcanic outcrops and small cinder cones give evidence of Pleistocene and Holocene activity near Camas. Lying along the southward extension of the strike of the Lacamas Fault across the Columbia River is Corbett Warm Spring (Bowen, et al., 1975). A warm well exists about four miles to the south (Newcomb, 1972). Geochemical data from Corbett Warm Spring suggest a temperature of last equilibrium for this spring of 180 to 195°C.

Available geophysical evidence for the Camas area supports the possibility of geothermal resources. A geophysical program now underway, including gravity, resistivity, and heat-flow studies, by the Washington Department of Natural Resources as part of the State Coupled Program will further aid the geothermal resources evaluation of the area. In the discussion that follows, relevant data from these and earlier studies are integrated with the aim of predicting the nature of the geofluid that could be available in the Camas area for use in process heat applications.

REGIONAL GEOTHERMAL POTENTIAL

Regional geothermal resource potential is associated with major crustal features. Geophysical data greatly aid in determining continuity of major features which may not be well exposed at the earth's surface. Published geophysical data that bear directly on the regional geothermal resources potential of the Cascades, include offshore magnetic data, seismological data, gravity data, heat-flow data, and data derived from the study of large amplitude transients in the earth's magnetic field. These and other regional data were recently reviewed by McEuen and Birkhahn (1975) to determine the geothermal resources potential of the Cascades.

Conclusions drawn from this earlier study that are relevant to the prediction of the resources in the Camas area are:

(1) In the southern Washington region, a mass excess is indicated, the axis of which roughly parallels the present course of the Columbia River. This region is also a region of crustal thinning.

(2) The mass excess may indicate that the Columbia River lies along a rift zone which may have formed about 40 m.y.b.p.

(3) The present pattern of non-steady-state heat-flow had its genesis during active subduction. "Expected" heat-flow values derived from seismic station delays suggest that steady-state values of 2.1 HFU would be characteristic of the lower Columbia Valley.

(4) Low resistivities at depth, found east of Camas suggest that partial rejuvenation of the possible rift may have occurred in the recent geologic past.

While unquestionably controversial, the suggestion that rifting may have occurred along the course of the Columbia is most significant. If the rift or aulocogen exists, it would provide most important components of producible geothermal resources: source of mantle heat, deep fracture permeability to assist heat transfer to the upper level of the crust and allow circulation of groundwater in a hydrothermal system, and crustal stress which would result in increased fracture permeability. The volcanic activity of the Cascade

tures connecting the centers of volcanism.

In the Camas, Washington area, the Lacamas fault represents local surface expression of a major zone of weakness along which intrusion appears to have occurred. This zone is easily

sample because of the lack of a datum for Fe_2O_3. However, the similarity to the Middle Yakima group of McDougall is striking. Temperatures higher than the Curie temperature are, therefore, a possible explanation of the pronounced magnetic low north of Camas. The minimum temperature required

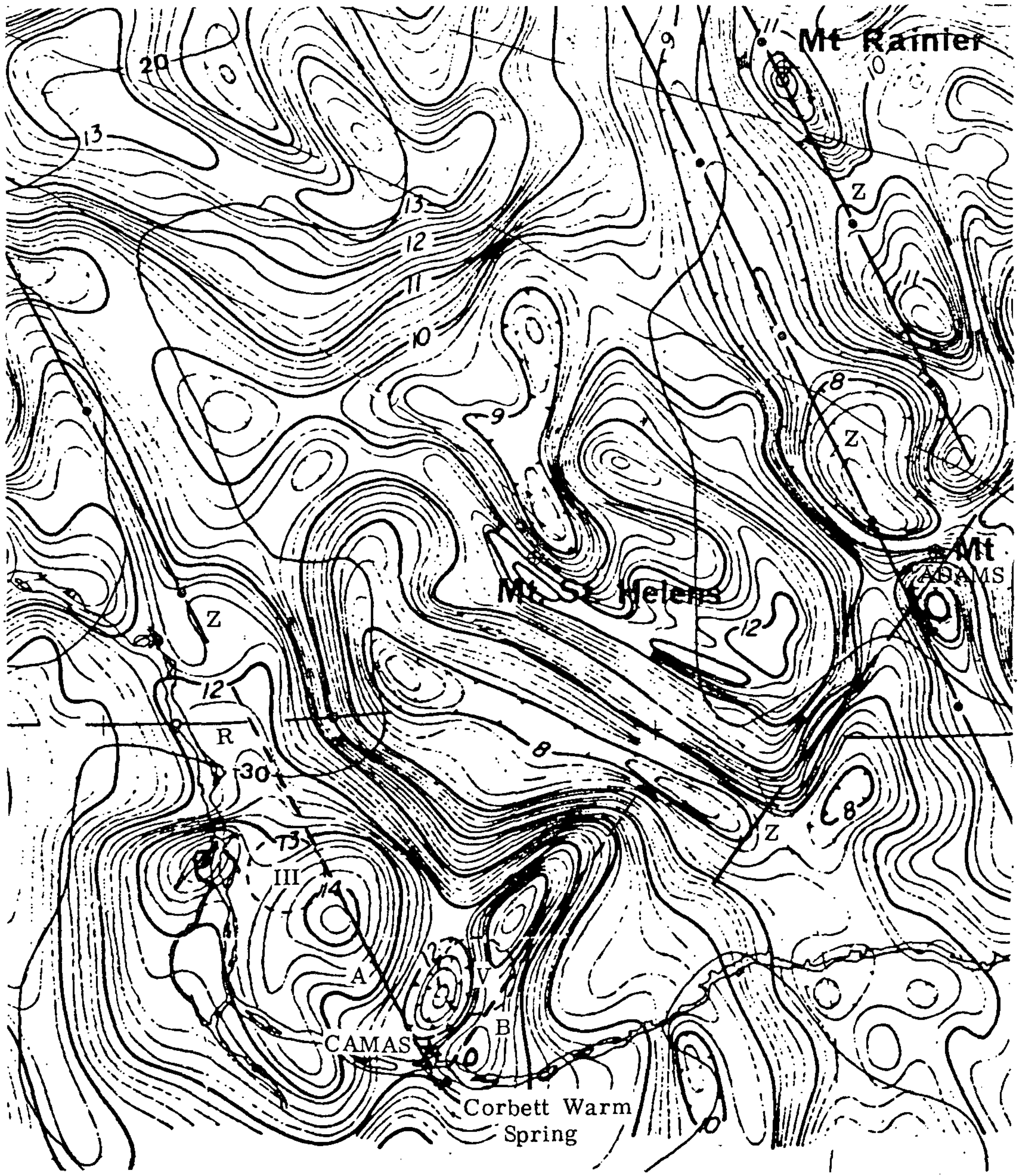

Figure 2. *Aeromagnetic Map of the Camas Area.* Lines marked Z are lineaments identified by Zeitz, et al (1971). Line A is the southern extension of such a lineament and coincides with the trace of the Lacamas Fault. Dashed line B is another lineament identifiable from the magnetics. Dashed circles labeled III and V mark the approximate epicenters of earthquakes of those intensities. East-west line R is the possible northern boundary of the tectonic rift hypothesized by McEuen and Birkhahn (1975). The -30 milligal gravity contour is also shown.

Table 1

	Average Compositions of Yakima Basalt (McDougall)		Mt. Hood Basalt (Wollenberg, et al.)
	Lower	Middle	
SiO_2	53.76	50.12	50.3
Al_2O_3	14.12	13.04	13.1
Fe_2O_3	2.12	3.00	Not Given
Fe O	9.44	11.77	12.9
MgO	4.54	4.39	4.0
CaO	8.18	8.12	7.1
Na_2O	2.98	2.70	2.2
K_2O	1.30	1.27	1.2
TiO_2	1.80	3.21	2.5
Curie Point	165°C	130°C	NA

for such an explanation would be 130 to 170°C, which is reasonable in view of the 180°C or higher temperature indicated by the geochemistry of Corbett Warm Spring.

ACKNOWLEDGEMENTS

This review has been supported in part by the Crown Zellerbach Corporation. The integration of the available data was carried out in preparation for the electrical resistivity program presently being completed in the Camas area by Science Applications, Inc. These new data form part of the State Coupled Program which is being directed by J. Eric Schuster of the Washington State Department of Natural Resources. Mr. Schuster is thanked for his enthusiastic support of our efforts.

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McDougall, I., 1976. Geochemistry and Origin of Basalt of the Columbia River Group, Oregon and Washington. *Geological Society of America Bulletin*, Volume 87, No. 5, pp. 777-792.

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Zeitz, I., B.C. Hearn, Jr., M.W. Higgins, G.D. Robinson, and D.A. Swanson, 1971. Interpretation of an aeromagnetic strip across the northwestern U.S., *Geological Soc. Am. Bull.*, Vol. 82, December 1971, pp. 3347-3372.

4/18/79

TO: DUNCAN
FROM: DEB
RE: CAMAS, WASHINGTON

MOST OF THE SITE-SPECIFIC STUDIES OF THE CAMAS, WA. AREA are ground-water investigations and contain limited and generalized geologic information:

- The structure of the Eocene & Miocene volcanics in the area is largely unknown

- The Troutdale Fm. was deposited in a broad, shallow basin formed during gentle folding in the area

- STRUCTURES of possible interest (SEE MUNDORFF'S MAP; USGS WATER SUPPLY PAPER #160
  a) Intersecting normal faults just north of CAMAS: N45W and N50E
  b) Crosscutting NW & ENE normal faults near YACOLT
  c) NW-trending normal fault near Venersborg

DOMINANT FAULT TREND: N35-45W

THERE ARE NO REPORTS OF THERMAL WATERS IN THE AREA. The ABUNDANCE OF COLD WATER AQUIFERS MAY MASK THE PRESENCE of any GEOTHERMAL RESOURCES. CHEMICAL QUALITY OF the local ground water is very good

NEARBY HOT SPRINGS:

"St. Martins H.S." 49°C

- HOT SPRING E of CARSON, Wa.

"Bonneville H.S." - 32°C / 20gpm

- HOT SPRING near Stevenson, Wa.

see: MOEN - Wa. Energy MAP + Schuster, 1974

both of these are EAST of Camas by at least 20 miles

- THERMAL SPRINGS NEAR Wa-Or. border — see Oregon Spring MAP

a) Corbett - 18° C, 10gpm

b) YMCA Camp Collins - 23°C

- CITY OF VANCOUVER, WA. (Schuster, 1974)

10°C

Generalized Strat Section for Camas, Wa. Area

Age	Formation	Description
[R]ecent	Alluvium	Gravel, Sand, Silt
Pleistocene	Deltaic Deposits of Columbia River	Coarse to fine gravel, sand, silt & clay; coarser phases are excellent aquifers
	Glacial Drift	Till, glaciofluvial outwash, lacustrine deposits
	Boring Lava (Early basaltic volcanics of the High Cascades)	Basaltic vesicular flows, scoria, ash. Extruded from local vents: 1) western end of Prune Hill, west of Camas; 2) Green Mtn, NNW of Camas; 3) Brunner Hill, N of Camas; 4) Battle Ground Lake, NNW of Camas (Moderately Permeable)
	Upper Troutdale Fm	Lightly to Moderately Cemented Quartzite Gravel Originally ≤ 400' Thick. Excellent Aquifer
[Pl]iocene	Lower Troutdale	Clay, Silt, Fine Sand w/ coarser lenses. ≤ 660' thick Poor Aquifer except for coarser phases
[M]. Miocene	Columbia River Basalts	
[..]ene	Goble - Colestin - Clarno - Skamania Volcanics	Intermediate Flows + Pyroclastics

ANNOTATED BIBLIOGRAPHY

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- Camas in zone of normal H.F.

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- Not available in local library

Campbell, K.V., and others, 1970, A survey of thermal springs in Washington state: Northwest Science, v. 44, no. 1, p. 1-11.

- A class project at U of Wa. Contains no info on Camas area, good for a laugh

Griffin, W.C., Watkins, F.A., Jr., and Swenson, H.A., 1956, Water resources of the Portland, Oregon, and Vancouver, Wa., area: USGS Circular 372, ~~p.~~ 45 p.

Contains generalized geologic map (which doesn't show any faults)

Mundorff, M.J., 1964, Geology and Ground-water conditions of Clark County Washington, with a description of a major alluvial aquifer along the Columbia River: USGS Water-Supply Paper 1600, 268 p.

Most detailed geologic reference available. Contains geologic map at 1:48,000. Detailed account of ground-water systems in area.

Schuster, J.E., 1974, Geothermal energy potential of Washington in Energy Resources of Wash: Wash. Div. Geol. and Earth Resources, p. 1-20.

Table 1 & Figure 2 - lists data for nearby thermal systems

Trimble, D.E., 1956, Geologic map of the Camas quadrangle, Oregon-Washington: USGS unpublished map, 1:50,000

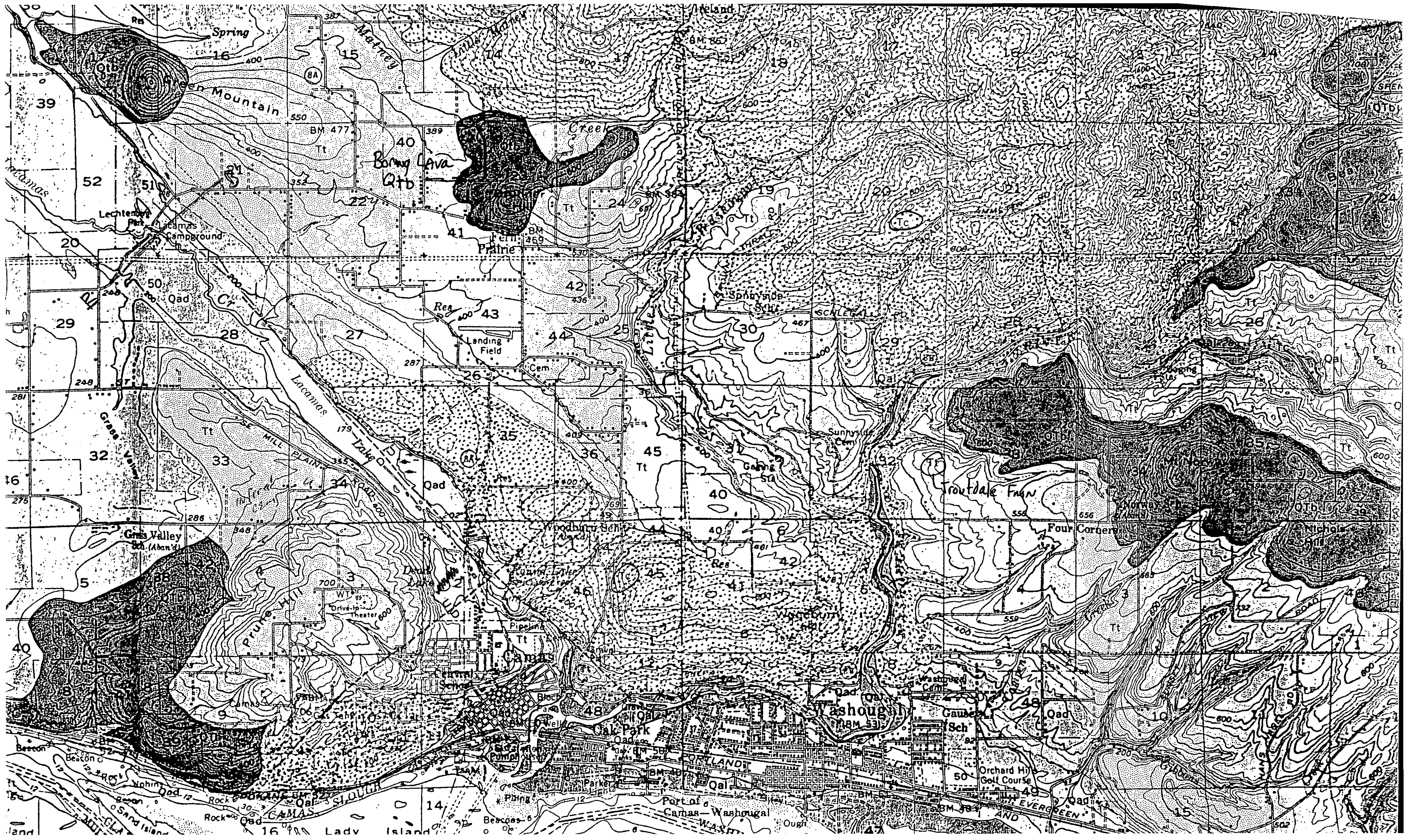
unobtainable

———, 1957, Geology of the Portland quadrangle, Oregon-Washington: USGS Quadrangle Map GQ-104, 1:62,500

missing from library!

USGS, 1975, Aeromag map for part of southwestern Washington: USGS OFR-648, 4 sheets, 1:62,500

not available locally



Spring
Mountain
Boring Lava
Qtb
Lacamas Campground
Fern Prairie
Landing Field
Cem
Creek
Lacamas Lake
SE MILL PLAIN ROAD
Qad
Tt
Qal
Tc
Troutdale Fmn
Sunnyside Cem
Four Corners
Grass Valley Sch. (Aban'd)
Prune Hill
Drive-In Theater
Pipeline
Camas
Oak Park
Washougal
Gause Sch
Orchard Hills Golf Course
Port of Camas—Washougal
EVERGREEN
Beacon
Rock
Sand Island
Lady Island

File 28

Good Enough

CAMUS
LINE A-A' CENTER
MEDIA RESITIVITY (OHM-METERS)

```
        5.00     10.00     15.00     30.00     50.00
       75.00    100.00    150.00    200.00
MEDIA PFE (%)
        0.00      0.00      0.00      0.00      0.00
        0.00      0.00      0.00      0.00
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 8   7   6  5  4  3  8 2 1 5 0 1  2  3  4  5  6  7  8
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APPARENT RESISTIVITY (CALCULATED)

```
 -5     -4     -3     -2     -1      0     +1     +2     +3     +4     +5
  :------:------:------:------:------:------:------:------:------:------:

                    80                  80
        40     39     55    129     94     69     70     50
              48.    64.   110.   103.   100.    66.    55.    66.
            35     59     64     99    117    106     85     79           80
           34.    96.    74.    63.    98.   117.    85.    84.    85.
        31     48     52     40     97    103    153    116    105
       17.    69.    92.    43.    52.   111.   132.   115.    96.    93.
     28     37     35     36     30     90    132    165    127    110    102
    19.    32.    64.    51.    36.    54.   118.   167.   125.    99.    94.
  20    33     33     79                 102    132  160  106            95
       36.    30.    37.    42.    38.    54.   142.   173.   122.    96.
           33.    18.    32.    44.   40   61. 80  142.   164.   117.
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