AN ABSTRACT OF THE THESIS OF

JAMES WARREN CARTER for the degree of MASTER OF SCIENCE in GEOLOGY presented on December 8, 1975

Title: THE ENVIRONMENTAL AND ENGINEERING GEOLOGY OF THE ASTORIA PENINSULA AREA CLATSOP COUNTY, OREGON

Abstract approved: Redacted for privacy

Dr. Robert D. Lawrence

The Astoria peninsula of northwestern Oregon is an east-west trending arm of Tertiary sedimentary and volcanic rocks which juts into the Columbia River. Astoria is the type locality of the Miocene Astoria Formation, a sequence of marine sandstones and mudstones which crops out as far south as Newport, Oregon. Quartzitic river terrace gravels inferred to be equivalent to the Troutdale Formation (Hodge, 1933), Quaternary beach, fluvial, and floodplain deposits and basalts of the Depoe Bay type are also exposed. H. V. Howe (1926) described three "members" of the Astoria Formation, the lower sandstone, the middle shale, and the upper sandstone which are informally referred to herein as the Lower Sandstone, Middle Mudstone, and Upper Sandstone respectively (capitalized for clarity in the text). The Lower Sandstone is a poorly sorted, thinly bedded, subfeldspathic, lithic wacke which is exposed in a narrow east-west trending strip on the north slope of the peninsula. The Lower Sandstone is conformably overlain by the Middle Mudstone which consists of a sequence of
thinly laminated siltstones and claystones with rare sandy and pebbly beds. The Middle Mudstone is intricately interbedded and inter-tongued with the Upper Sandstone, which is a structureless, subfeldspatic, lithic wacke distinct in character from the Lower Sandstone. The Depoe Bay Basalts which intrude the Middle Mudstone are finely crystalline siliceous basalts which correlate petrochemically with Yakima-type basalts of the Columbia River Plateau (Snavely and others, 1973). The basalt occurs as complexes of sills and dikes along the central ridge of the peninsula, and locally as breccias and pepperitic masses. Several outcrops of quartzitic pebble conglomerate thought to correlate with the Troutdale Formation unconformably overly the Middle Mudstone and Depoe Bay Basalt in the western part of the study area.

The strata of the Astoria Formation dip gently to the south in the study area, except where disrupted by basaltic intrusions or by landsliding. The main structural feature of the study area is a normal fault which trends northeast-southwest through the valley of Mill Creek in the eastern part of the study area.

Laboratory and field studies were undertaken of the engineering characteristics of the geological and surficial units. The Middle Mudstone exhibits poor strength and drainage characteristics. The mudstone is nearly impermeable, except along fractures, and weathers rapidly. The clay fraction of the Middle Mudstone is dominated by
expandible clays (montmorillonite) and so the unit is subject to changes in volume and loss of strength upon wetting. Bedding planes and tuffaceous interbeds are common in the Middle Mudstone, representing zones of weakness. The residual soils of the Middle Mudstone exhibit similar strength characteristics and poor drainage as does the matrix of the Troutdale Formation. The Upper and Lower Sandstones of the Astoria Formation have moderately favorable strength and drainage characteristics. The residual soils of these units are also typically well drained and resistant to shear failure. The Depoe Bay Basalt and its residual soil exhibit good strength characteristics and stand in very steep slopes.

Landsliding is the most significant engineering geologic hazard of the Astoria peninsula area. Background factors contributing to slope instability have been quantified, individually mapped, and overlain to construct a composite relative landslide risk map. The background factors selected to best reflect landslide causes in the Astoria area are engineering characteristics of the geological units, engineering characteristics of the bedrock units, structural and stratigraphic features, slope, groundwater and drainage conditions, and historical landslide distribution. The composite of all the factor maps suggests that the Middle Mudstone and its residual soils are the primary high risk units, particularly on the south (dip) slope of the peninsula. While most of the historical landslides of the Astoria area have
occurred on the north slope of the peninsula, it is suggested that the southern portion of the peninsula, due to its structural environment, is a higher risk area. The writer suggests that the reason for this apparent discrepancy is that the much higher incidence of construction activity on the north slope of the peninsula has contributed to over-steepening, undercutting, and alteration of the drainage regime which, in turn, have affected slope stability. It is further suggested that as the city of Astoria expands and further encroaches on the south slope of the peninsula, extreme care must be exercised in excavation and construction because of the adverse slope stability conditions in that area.
Environmental and Engineering Geology
of the Astoria Peninsula Area
Clatsop County, Oregon

by

James Warren Carter

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THE ENVIRONMENTAL AND ENGINEERING GEOLOGY
OF THE ASTORIA PENINSULA AREA
CLATSOP COUNTY, OREGON

INTRODUCTION

Purposes

The City of Astoria has experienced numerous geological disasters since its settlement in the early 1800's. The most persistent and troublesome of these have been landslides. Destructive and disruptive landslides have been recorded in the city engineer's office since at least 1903. During the winter of 1950, 23 houses were destroyed by a landslide in the Coxcomb Hill area of the city (Dole, 1954). In 1954, another slide near the downtown area affected 27 residences. Numerous additional slides have occurred since then, causing extensive damage and loss of property. According to Bruce Clausen (City engineer, City of Astoria, personal communication) continuing landsliding is currently a problem in the city. Several general studies have been made of the landsliding in the Astoria area (Dole, 1954, Schlicker and others, 1972). Although landsliding is characteristic of many of the Tertiary strata of the Oregon Coast Range, no detailed investigations of the mechanisms and background conditions of the slope failures have been made for these materials.

The purpose of this investigation is threefold; 1) To describe the environmental geology of the Astoria peninsula area, 2) To
determine the mechanisms of slope failure, the most significant
geological hazard of the study area, 3) To propose a methodology,
based on factor mapping, for evaluating areal relative landslide risk
in the Astoria peninsula and similar areas.

Location and Access

The Astoria peninsula of northwestern Oregon is bounded on the
South by Young's River, and on the North by the estuarine mouth of the
Columbia River. The area of investigation covers approximately eight
square miles of the peninsula, including all of the City of Astoria and
parts of the adjacent woodlands (Figure 1). The major part of the
study area lies within the city limits of Astoria, and so is accessible
by public streets and roads. Less developed parts of the area are
accessible by logging and utility access roads.

Previous Work

The Astoria Formation in its type locality was first described by
J. D. Dana in 1849 (cited in Niem and VanAtta, 1973). Conrad (1865)
identified Dana's fossil collection and assigned a Miocene age to the
strata at Astoria. Dall and Harris (1892) defined two members of the
Astoria series, the Astoria Shale and the Astoria Sandstone, both
Miocene in age. Dall later reevaluated the faunal evidence and
assigned the shale to the Oligocene and the sandstone to the Miocene
Figure 1. Location map of the Astoria peninsula showing areas of developed and relatively undeveloped terrain.
in 1898. Arnold and Hannibal (1913) first proposed the name Astoria series for the section exposed at Astoria, and assigned an Oligocene age to both the shale and the sandstone. Clark (1918) disagreed with the Oligocene age determination and suggested Miocene as the age of both the shale and sandstone.

In 1926 H. V. Howe conducted the first detailed study of the strata exposed in Astoria and concluded that there were three distinct sedimentary units exposed. He described a fossiliferous, poorly sorted lower sandstone, a well bedded to massive middle shale, and a massive, arkosic upper sandstone. Howe suggests that all three units are Miocene in age, based on faunal evidence and contact relations, and calls all three units parts of the Astoria Formation.

Seitz (1943) in a master's thesis study of the Astoria type locality virtually recapitulates Howe's paper, additionally inferring that the upper sandstone was deposited as an injection phenomenon from sandstones underlying the middle shale. Since that time the strata exposed at Astoria have been variously assigned to the Tertiary Shales of Warren and others (1945) and the Marine Miocene Sedimentary Rocks of Wells and Peck (1961). H. G. Schlicker and others (1972) regrouped the three major sedimentary units at Astoria into two groups based on lithology and engineering characteristics. He calls the lower sandstone and middle shale of Howe (1926) the undifferentiated Oligocene to Miocene sedimentary rocks, and the upper sandstone of Howe, the
Upper Miocene Sandstone. Currently, studies to determine the facies variations, stratigraphic correlations, and paleoenvironments of the Tertiary sedimentary rocks of the Oregon Coast Range are being carried on by graduate students of Dr. A. R. Niem of Oregon State University. In particular, David M. Cooper, a doctoral candidate, is applying his efforts to the description, correlation, mapping, and definition of the Astoria Formation through its outcrop area from Newport to Astoria Oregon.

The landslide history of the Astoria area before 1954 is summarized by Dole (1954). Schlicker and others (1972) briefly mention the landsliding, but map the landslide features on too small a scale to differentiate between individual slides in the city.

Bruce Clausen (personal communication) discussed several recent landslides and indicated that the Astoria city engineer's office has investigated these as they occurred. There have also been several privately financed engineering investigations to determine site suitability for structures.

Methodology

Field work consisted of geologic mapping, soil mapping, rock and soil strength determinations, detailed landslide description, and rock and fossil sampling. Geological and soil mapping was done on U. S. G. S. 7 1/2 minute series Astoria quadrangle maps and enlarged
Rock and soil strength determinations were made using a Torvane (Sibley and Yamane, 1965) and a Pocket Penetrometer (Terzaghi and Peck, 1967). Observations on drainage, slope, foliage, and cultural features were also recorded while field mapping. Several recent landslides were traversed and staked to monitor downslope movement. Representative samples of the major lithologies were collected, as well as samples of minor and local lithologic types for petrographic analysis. Sandstones were collected for sieve analysis and shales for X-ray and microfossil analysis. One hundred pebbles were collected from two conglomerate outcrops for identification using a binocular microscope. Additional shale and soil samples were collected for determinations of Atterberg limits (Means and Parcher, 1963).

Laboratory analyses of samples collected in the field included size analysis, heavy mineral analysis, petrographic study of thin sections and grain mounts, X-ray diffraction analysis of clay minerals, and Atterberg limits determinations.

Size analysis of the sandstones was accomplished by the minimum diameter (sieving) method as described by Royse (1970). Size analysis of the fine grained sediments was accomplished by the settling velocity (hydrometer) method also as described by Royse. Heavy minerals were separated from the 3.0 to 3.5 phi size fraction with the use of
tetrabromoethane and mounted on microscope slides for petrographic study. Petrographic thin sections of selected rock samples were prepared for modal analysis. Atterberg limits determinations were made on shale and soil samples according to the method of A. Casagrande as described by Means and Parcher (1963).

**Factor Mapping**

The use of factor mapping to predict multicausative phenomena (McHarg, 1969) is generally unfamiliar to geologists and so is fully described here. Individual causative factors are identified, quantified and mapped. A composite map is prepared from the individual factor maps which sums the causative impact and predicts the most probable location of the phenomenon. Landsliding is such a phenomenon with numerous, complex causes. Previous landslide studies have dealt with historical occurrence rather than the background factors and trigger mechanisms of slope failure (Cleveland, 1971; Wright and others, 1974). In this study, factor mapping was used. The factors selected for individual mapping are 1) The engineering characteristics of the bedrock units, 2) The engineering characteristics of the surficial units, 3) Structural and stratigraphic features, 4) Slope, 5) Groundwater and drainage conditions, and 6) Historical landslide distribution. Each factor was mapped on a base map constructed from
the U.S.G.S. 7 1/2 minute Astoria quadrangle map and recent (1970) U. S. Soil Conservation Service aerial photographs at a scale of 1:8000. A composite landslide risk map at the same scale was constructed by overlaying the factor maps (Plate 2).
The Astoria peninsula is an approximately 2 1/2 mile by 1 mile arm of land which juts into the Columbia River, separating it from Young's Bay. The area of investigation includes the peninsula itself and the area east of the peninsula to the John Day River (Figure 1). The peninsula is formed by an east-west trending ridge which curves gently to a northeast-southwest orientation in the eastern part of the study area. The 210 m. high ridge is held up by a thick basaltic sill which intruded into the middle Miocene Astoria Formation.

Without the support of the resistant intrusives, the softer sediments probably would have assumed a lower relief through landsliding and other degrading processes. Tongue Point is also an intrusive body, probably the remnant of a basaltic dike. The combination of support of the slope by intrusives and erosion of the toe by the Columbia and Young's Rivers has produced natural slopes as steep as 50% grade in the strate of the Astoria area. The terrain of the study area is dominantly rolling hills which display the concave profile and hummocky appearance characteristic of landslide topography (Figure 2). The more resistant rock types form bluffs and cliffs up to 65 m in height.

Approximately 30% of the study area is urbanized or has been altered by man's activities such as roadbuilding. The undeveloped
portions of the area are covered by a lush growth of Douglas fir, alder, blackberry, and numerous other shrubs and grasses. Commercial logging of the Douglas fir is being carried on by Crown Zellerbach Corporation, so that the natural ground cover of many areas is periodically drastically reduced. This affects the rate and amount of water absorbed into the ground and subsequently the drainage and groundwater regimes. The Astoria area receives 175 to 225 cm of rainfall annually, most of which falls during the winter months. During the winter months, the groundwater table can be considered to be at the surface of the ground for engineering purposes, since the rainfall is sufficient to saturate the slowly permeable ground materials present in the Astoria area. Even during the summer months, the rocks near the surface are at least moist. The year round temperatures are moderate, so that neither frost heaving nor dry shrinkage are common.

The growth of Astoria and the attendant construction activities have altered the morphology and hydrology of the area. Excavation and fills have produced local oversteepening. Drainage and groundwater flow patterns have been affected by the emplacement of impermeable cover such as paving and buildings. In undisturbed terrain, a thick cover of residual soil mantles the bedrock, while cuts and fills within the city limits alternately expose or bury the naturally occurring rock and soil units.
Figure 2. Hummocky landscape looking north from Irving Street in the eastern part of the City of Astoria.

Figure 3. Typical poor exposure of Lower Sandstone of the Astoria Formation near 13th and Harrison Streets.
GEOLOGICAL UNITS

The rock units exposed in the Astoria area form three major groups: Miocene sedimentary rocks of the Astoria Formation, Miocene basaltic intrusives and breccias of the Depoe Bay Basalts, and Pliocene terrace gravels of the Troutdale Formation. Also present are Quaternary beach, fluvial, and floodplain deposits (Plate 1) (Figure 4).

Description and classification of the rock units is after Gilbert (1954) and Shepard (1954) for the sandstone and mudstone units respectively. Petrologic characterizations were made by the techniques of point counting, heavy mineral analysis, and X-ray diffraction analysis. The textural classifications, based on data from settling velocity (hydrometer) and minimum diameter (sieve) size analyses are those defined by Folk and Ward (1957) and Shepard (1954). Macro- and microfossil collections were prepared from disaggregated sediment samples, but failed to yield definitive age determinations. Pebbles (100) from the gravel unit were identified by use of the binocular microscope.

The Astoria Formation

The tripartite division of the Astoria Formation described by Howe (1926) suits the needs of this investigation well. He described
Figure 4. Stratigraphic column of units exposed in the Astoria peninsula area. Scale 1" = 200'.

QUATERNARY

- Alluvium, beach sand, and flood plain deposits.
- Troutdale Formation - Quartzitic river terrace gravels.

Upper Sandstone of the Astoria Formation - Subfeldspathic lithic wacke.

DEPOE BAY BASALTS - Finely crystalline basalts occurring as sills, dikes, and breccias.

Middle Mudstone of the Astoria Formation - Thinly laminated siltstones and claystones.

LOWER SANDSTONE OF THE ASTORIA FORMATION - Poorly sorted, thinly bedded lithic wacke.

Miocene
an arkosic, poorly sorted, fossiliferous Lower Sandstone member, conformably overlain by a Middle Shale. The Middle Shale is better described as a mudstone, due to the variations in texture within the unit, and the lack of fissility in many outcrops. Interbedded with and overlying the Middle Mudstone is an arkosic Upper Sandstone. For the purposes of this report, the names of the units of the Astoria Formation will be capitalized, although they are not formal names.

The Lower Sandstone

The Lower Sandstone described by Howe (1926) is a well laminated, carbonaceous, subfeldspathic, lithic wacke which crops out in roughly 100 meter wide East West trending strip on the north side of the Astoria peninsula (Plate 1). The topographic expression of the Lower Sandstone, although modified by urban development, seems to be characterized by a steeper, more scarp-like slope than the overlying Middle Mudstone. Exposures of the Lower Sandstone are few and poorly preserved due to cover by urbanization any outcrops described by earlier investigators have been built over or buried under fill material as the city of Astoria has grown. The strike of the unit is generally northeast and the bedding planes dip southward, into the slope of the hill at approximately 25°.

Exposures are limited to roadcuts and excavations within the Astoria city limits, and are extremely weathered. In outcrop, the
Lower Sandstone appears as a crumbly, poorly sorted, olive-gray, silty sand with carbonaceous flakes and chips, limy concretions, and numerous pelecypod valves (Figure 3). The sand is locally well cemented with calcium carbonate, probably derived from solution of the calcareous fossils present and possibly the alteration of calcic plagioclase. The fossils occur in all states of preservation and are usually limited to finer grained interbeds near the top of the unit. Previous investigators have assigned a Miocene age to the Lower Sandstone (Dana, 1849; Cope, 1880; Dall and Harris, 1892; Clark, 1918; Howe, 1926; Seitz, 1948; and Moore, 1963). Due to the contact relation of the Lower Sandstone to the Middle Mudstone and to faunal evidence, an early to middle Miocene age is assigned to this unit. Fossil assemblages collected by the writer were not definitive due to their poor state of preservation (Warren Addicott, 1975, written communication).

Petrology

The Lower Sandstone is best described texturally as a poorly sorted fine sand. Applying the statistical size parameters defined by Folk and Ward (1957), median grain diameter is 2.3Ø (fine sand), mean grain diameter 2.3Ø, sorting 0.13Ø (poor sorting), skewness 0.12 (positively skewed, enriched in fines). Sand sized mineral grains of the Lower Sandstone are predominantly subangular while lithic
fragments and the more resistant heavy mineral species such as zircon and tourmaline are subrounded to subangular. The high degree of roundness of the resistant heavy mineral grains suggests recycling of material from sedimentary rocks. Based on Folk's definition of textural maturity, the Lower Sandstone is immature. It is high in matrix (14% 26%), poorly sorted, and angular clasts predominate.

Mineralogically, the framework consists primarily of quartz, basaltic fragments, and feldspars, and subordinate amounts of garnet, ferro-magnesian minerals, opaques, and glauconite (Table 1). Quartz ranges from 26-47% in the Lower Sandstone. Normal and undulatory quartz occur in subequal amounts with smaller amounts of polycrystalline quartz present (4-8%). Plagioclase is the dominant feldspar, ranging from 2-9% of the rock, while potassium feldspars constitute from 2-5%. The plagioclase ranges in composition from oligoclase to labradorite ($\text{An}_{26}$ to $\text{An}_{59}$) with andesine being the most common variety. Most of the feldspar grains are considerably altered although a few grains exhibit sharp euhedral outlines. This could indicate more than one source for the feldspars. The potassic feldspars are dominated by orthoclase with minor amounts of microcline. The potassic feldspars alter to sericite and possibly kaolin, and the plagioclases alter to calcium carbonate.

Mafic igneous clasts, ranging from 9-20% of the sample, dominate the rock fragment fraction of the Lower Sandstone. Most of these
<table>
<thead>
<tr>
<th>Unit</th>
<th>Sample #</th>
<th>Mineral Species (percent of sample)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>The Astoria Formation</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Lower Sandstone</td>
<td>7193</td>
<td>normal quartz 39  polyx. quartz 5  K-spar 4  Plag. 5  micas 4  VRF* 18  MRF* 3  FRF* 2  chert 4</td>
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<tr>
<td></td>
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<td></td>
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<tr>
<td></td>
<td>7194</td>
<td></td>
</tr>
<tr>
<td>Middle Mudstone</td>
<td>7193M</td>
<td></td>
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<tr>
<td></td>
<td>8156</td>
<td></td>
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<td></td>
<td>7266</td>
<td></td>
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<tr>
<td></td>
<td>883 (tuff)</td>
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</tr>
<tr>
<td>Upper Sandstone</td>
<td>7242</td>
<td></td>
</tr>
<tr>
<td></td>
<td>8274 (dike)</td>
<td></td>
</tr>
<tr>
<td><strong>Depoe Bay Basalt</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>7195</td>
<td>plag. 57  clino-85  pyroxenes 18  ortho-85  pyroxenes 3  brown 4  hornblende 4</td>
</tr>
<tr>
<td><strong>Troudostale Formation</strong></td>
<td></td>
<td>vein 32  sedimentary 48  quartzite 8  mudstone 3  chert 3  sandstone 1  pegmatite 3  rhyolite 1  pumice 1  tuff 1</td>
</tr>
</tbody>
</table>

* VRF - Volcanic rock fragments  
MRF - Metamorphic rock fragments  
FRF - Felsic rock fragments
appear to be pilotaxitic basalt fragments in varying stages of decomposition. The primary alteration products are probably celadonite and chlorite. Other rock fragments occurring in smaller concentrations are chert, andesite fragments, quartz-mica schist fragments, granitic fragments, mudstone fragments, and pumice. The presence of granitic and schistose rock fragments in the Lower Sandstone indicates source areas farther inland than the volcanic units of the Coast and Cascade Ranges.

More than half the heavy minerals present are opaques, including magnetite, ilmenite, leucoxene, pyrite, and hematite. Other heavy minerals include garnet, green hornblende, brown hornblende, hypersthene, zircon, tourmaline, augite, and traces of biotite, apatite, and staurolite. Matrix accounts for 14-26% of the Lower Sandstone. Most of the matrix is clay, but sparry calcite and organic materials occur in concentrations up to 10% and 6% of the rock respectively. Most of the matrix appears to be detrital in origin, although alteration of the feldspars and rock fragments may contribute some diagenetic material. Calcium carbonate cementation is evident in two of the samples studied. In these cases, the calcium carbonate concentrations range from 6.17%. Sources of the cement probably include solution and reprecipitation of calcite from the abundant calcareous fossils, and alteration of the calcic plagioclase. A minor amount of iron oxide cement is also present. Glauconite is present in trace
amounts and displays some alteration, possibly to limonite.

Contact Relationships

The Lower Sandstone is the oldest and stratigraphically lowest unit now exposed in the Astoria area. Earlier investigators reported a Miocene mudstone lying beneath the Lower Sandstone (Dall, 1898; Clark, 1918) but the contact has since been covered with cregge material. The upper contact of the Lower Sandstone is a conformable, gradational interbedding with the overlying Middle Mudstone. The sandstone and mudstone units are intricately intertongued and bensed in the vicinity of the contact, indicating a gradual, possibly fluctuating change in the energy level of the flow regime from high to lower. It seems most likely that the Middle Mudstone represents a transition to a deeper water depositional environment, indicating subsidence in this part of the depositional basin.

The Middle Mudstone

The Middle Mudstone (Middle Shale of Howe, 1926) consists of a sequence of massive to thinly laminated, buff to olive-black, silty claystones, siltstones, and sandstones conformably overlying the Lower Sandstone. It crops out as a roughly east-west trending band which covers most of the Astoria peninsula (Plate 1). Most of Astoria is built on the Middle Mudstone, which exhibits the irregular,
hummocky topography characteristic of widespread landsliding. The attitudes of the bedding are extremely variable due to the extensive slumping of the incompetent mudstones and to the intrusion of basaltic sills and dikes along the central ridge of the peninsula. This disorientation makes it difficult to estimate the unit's thickness, but Howe suggests that it is less than 325 m.

The Middle Mudstone varies widely in its outcrop appearance. In most exposures it appears as a massive to thin bedded, moderate yellowish brown (10Y 5/4) to olive black (5Y 2/1), silty claystone to clayey siltstone (Figure 5). Thin tuffaceous and glauconitic interbeds are common locally. In several locations lenses of calcareous concretions occur along the bedding planes. Authigenic pyrite is present in some of the darker, more organic mudstones.

In roadcuts and excavations, the Middle Mudstone is highly fractured along joints and bedding planes, yielding tabular "poker chip" talus. In exposures where the mudstone is water saturated, it displays low strength and little resistance to crushing. In areas of contact with basaltic intrusions, the mudstone is baked to a distance of up to 45 cm. from the igneous body and exhibits considerably higher strength and a lighter color (yellowish gray, 5Y 7/2) (Figure 6).

Clastic dikes of composition similar to the Upper Sandstone up to 75 cm. in thickness and interbeds of Upper Sandstone up to 3m. in
Figure 5. Exposure of deeply weathered Middle Mudstone along Pipeline Road.

Figure 6. Baked, buff colored Middle Mudstone in contact with basalt sill in the vicinity of Coxcomb Hill.
thickness occur almost ubiquitously in the upper portion of the Middle Mudstone (Figure 7).

Seitz (1948) reports megafossils of middle Miocene age from the Middle Mudstone, but fossil localities noted in his report are low in the unit, near the contact with the Lower Sandstone, and have since been covered. Foraminifera collected from several localities within the city limits of the City of Astoria have yielded a Saucesian (early to middle Miocene) age (Moore, 1963, Niem and others, 1973). Microfossil assemblages collected by the writer did not yield distinctive age determinations (Rau, 1975, written communication).

Texturally, the Middle Mudstone ranges from a silty claystone to a clayey siltstone with local interbeds of sandy siltstone and concretionary pebble conglomerate. The silt and sand sized grains are angular to subangular. The matrix proportion ranges from 91% in the finer grained strata to 63% in the coarser interbeds.

The most common mineral of the sand and silt sized fraction is quartz (Table 1). Normal and undulatory varieties are subequal and range from 5% in the claystones to 17% in the siltstones. Polycrystalline quartz occurs in concentrations of from 2% to 3%. Plagioclase is the dominant feldspar at from 1 4% of the sample. Orthoclase constitutes 1% of the composition of the samples examined. Other mineral species noted in occurrences of less than 2% are magnetite, ilmenite, muscovite, tourmaline, garnet, and zircon. Glauconite is
Figure 7. Interbeds of Upper Sandstone in Middle Mudstone along Pipeline Road, south of Astoria. Note soft sediment deformation.
present in trace amounts in a sample from a sandy bed near the top of the unit, probably equivalent to the greensand beds described by Howe (1926) and Seitz (1948). Basaltic rock fragments dominate the lithic constituents at concentrations of from 1-6% of the rock.

X-ray diffraction analyses were made of the clay minerals from 14 of the samples of the Middle Mudstone. Results of the determinations showed that expandible clays, probably montmorillonite, dominate the clay fraction of the Middle Mudstone (Figure 8). Determinations of the composition of mixed clay samples are unreliable, and semi-quantitative at best. Carroll (1970) briefly summarizes the state of the art of quantitative clay mineralogy. She states that peak intensity is not a good quantitative indicator because it is also a function of the degree of crystallinity of the sample, the mass absorption coefficient, grain orientation, and other factors. A very rough estimation of the relative proportions of clay species in a sample can be made by comparing the peak areas of the individual species, and comparing them with the peak areas of the same species mixed in known proportions. A typical clay mineral peak area ratio for the samples from the Middle Mudstone is 45 parts montmorillonite: 3 parts chlorite: 1 part illite: 1 part kaolinite. Weaver (in Royse, 1970) suggested that a sample subequal in kaolinite and illite would produce a 7Å kaolinite peak approximately twice as intense as the 10Å illite peak. Royse also cites Griffen and Goldberg (1963) who indicate that a sample subequal in montmorillonite
Typical X-ray diffraction pattern of clays from the Astoria Formation

Sample 8156, Middle Mudstone of the Astoria Formation
CuK radiation 35KV 35MA
scan from 3°2θ to 13°2θ

Mg saturated, 54% relative humidity
Mg saturated, ethylene glycol atmosphere
Mg saturated, heated to 400° C

Figure 8. X-ray diffraction analysis of typical sample of clay from the Middle Mudstone of the Astoria Formation.
and illite will exhibit a 14-15Å montmorillonite peak which will be as
much as five times as intense as the 10Å illite peak. Readjusting the
average peak area intensities for clay samples from the Middle Mud-
stone by these proportions produces a montmorillonite, chlorite,
illite, kaolinite ratio of 9: 3: 1: 1/2. This very approximate ratio
is representative of most of the samples examined, and indicates that
the primary clay constituents of the Middle Mudstone are the mont-
morillonitic clays. The high proportion of montmorillonite is probably
the result of the alteration of the ferro-magnesian minerals and
volcanic glass which are abundant in the nearby Cascade volcanic
source terrane.

Tuffaceous interbeds up to 5 cm. thick are common in the Middle
Mudstone (Figure 9). In thin section, they reveal abundant relic shard
and bubble wall structures, as well as euhedral biotite, feldspars,
and quartz grains of fine silt and smaller sizes. X-ray examination
of a tuffaceous interbed were inconclusive, due probably to incomplete
devitrification and recrystallization of the ash material.

Calcareous concretions occur locally in nodular interbeds. Many
of the fossils collected by Dana (1849) were in the cores of calcareous
concretions found along the beach at Astoria, at the foot of cliffs of
Middle Mudstone. The concretions collected proved to be barren, but
thin section examination indicated that a calcitic body had, by solution
and subsequent re-precipitation, cemented the mud in which it was cased.
Figure 9. Tuffaceous interbeds in Middle Mudstone near quarry on Navy Pipeline Road.
Aside from the calcium carbonate cement found in the concretionary nodules, no cementation was apparent in the Middle Mudstone.

Contact Relationships

The Middle Mudstone is unconformably overlain in the western section of the study area by a quartzitic gravel inferred to be a Pliocene river terrace deposit. The contact is not sharp, due to considerable weathering, but appears to be undulatory, indicating scour and fill of the mudstone surface at some time after the deposition and lithification of the Middle Mudstone. In the eastern portion of the study area the Middle Mudstone is conformably overlain by and intricately interbedded and intertongued with the Upper Sandstone of the Astoria Formation. It has been suggested (Cooper, 1975, personal communication) that slides of sand from shallower water deposits to the east near Wickiup Mountain periodically covered the deeper water muds, producing vertical interbedding. It is also suggested that these slides were local occurrences, limited to relatively narrow submarine channels, producing lateral intertonguing. Subsequent burial and overburden stress resulted in fracturing of the mudstones and injection of the water charged sands to produce the numerous clastic dikes which are common near the contact of the Middle Mudstone and the Upper Sandstone. Just above the contact in some outcrops, large (up to 2m. in length) undeformed blocks and rip-ups of
Middle Mudstone are incorporated in the Upper Sandstone.

**Upper Sandstone**

The Upper Sandstone described by Howe (1926) is a massive, subfeldspathic, lithic wacke which crops out in the southern part of the study area. In the vicinity of the John Day River and in areas on the south side of the peninsula it crops out in nearly vertical cliffs, overlying the Middle Mudstone (Figure 10). At many locations in the study area, it occurs as pods, dikes and interbeds in the Middle Mudstone. Exposures of the Upper Sandstone are extensively weathered and in outcrop the sand is very friable to a depth of 1 1/2 to 2 meters.

In outcrop, the Upper Sandstone appears as a highly friable, massive sandstone with distinctive Liesegang iron ring staining. Most of the exposures crumble at the touch, although several of the clastic dikes exhibit strong induration, apparently due to iron oxide cementation. Although the Upper Sandstone is unfossiliferous in the study area, Dodds (1970) reports megafossils from the unit in the Astoria reservoir area indicative of a middle Miocene age. Based on the contact relations of the Upper Sandstone in the study area and the faunal evidence reported by Dodds (1970), it seems that a Miocene age is best assigned to the unit.
Petrology

Texturally, the Upper Sandstone is best described as a poorly sorted, fine sandstone. Applying Folk and Ward's statistical size parameters (1957), the median grain diameter for the Upper Sandstone is 2.2\(\phi\) (fine sand), mean grain diameter 2.5\(\phi\) (fine sand), average sorting 1.12\(\phi\) (poor sorting), average skewness 0.43 (positively skewed, enriched in fines), kurtosis 1.33\(\phi\) (leptokurtic, smaller than average distribution about the mean grain size). The sand sized mineral grains of the Upper Sandstone are subangular to subrounded, while the lithic clasts display more rounding. According to Folk's criteria for textural maturity, (1968) the Upper Sandstone is submature to immature, that is, it contains a small to large amount of matrix (4-13\%), is poorly sorted, and is dominated by subrounded to subangular clasts.

The framework grains, which constitute from 87-96\% of the sandstone, are dominated by undulatory and normal quartz, which together account for an average of 38\% of the composition (Table 1). Polycrystalline quartz accounts for an average of 6\% of the mineralogy. Plagioclase and K spar occur in concentrations of from 7-8\%. The plagioclase composition ranges from oligoclase to labradorite (An\textsubscript{14} to An\textsubscript{64}) with andesine being the most common species. Orthoclase dominates the potassium feldspar fraction, with microcline occurring
in trace amounts. Muscovite is very apparent in thin section, and accounts for an average of 4% of the composition. Other minerals noted in lesser quantities include biotite, zircon, garnet, tourmaline, staurolite, magnetite and unidentified opaques. The Upper Sandstone appears to be remarkably free of metastable and other heavy minerals in thin section. As in other sedimentary units in the area, the lithic fraction of the Upper Sandstone is dominated by basaltic rock fragments, ranging from 20-22% in occurrence. These fragments seem to be similar to those found in the Lower Sandstone, and display the same alteration. Other lithic constituents include granitic, sedimentary, schistose, glassy, and pumiceous fragments.

The concentrations of heavy minerals in the Upper Sandstone are lower than in other sandstone units in the area. In thin section point counts, heavy minerals account for only from 1-2% of the sample. The heavy mineral suite is dominated by opaque minerals, the most common of which are magnetite, and ilmenite. Hematite and leucoxene are also noted, while brown hornblende, green hornblende, hypersthene, garnet, and tourmaline are noted only in trace amounts.

The nature of the matrix and cementation of the Upper Sandstone may account for the absence of some of the metastable minerals in the unit. The matrix comprises from 41-13% of the unit and is composed primarily of the chemical weathering products of the minerals and lithics present. Most of the matrix appears to be the diagenetic
products of sericitization of the feldspars, decomposition of the basaltic lithic fragments, and oxidation of metastable minerals. While most of the unit is poorly lithified, some of the less weathered outcrops display moderate iron-oxide cementation.

Contact Relationships

Due to the massive character of the Upper Sandstone, attitudes and stratigraphic relationships are difficult to determine. As previously mentioned, the Upper Sandstone is interbedded with the underlying Middle Mudstone. Lowry and Baldwin (1952) report that the unit unconformably underlies strata of the Troutdale Formation to the east of the study area (in Schlicker and others, 1972). This indicates that even though the Troutdale Formation and the Upper Sandstone are not in contact in the study area, the Troutdale is stratigraphically above the Upper Sandstone.

Depoe Bay Basalt

The basalts cropping out as dikes, sills, and breccias in the Astoria area have been described as Depoe Bay Basalts of middle Miocene age by Snavely and others (1973). The resistant basalts form the "backbone" of the Astoria peninsula, supporting the less resistant sedimentary rocks in such areas as Coxcomb Hill and Smith Point.
The basalts also crop out as local topographic highs and resistant headlands, such as Tongue Point. In outcrop, the basalt generally appears as massive, medium to dark gray, fine crystalline intrusions. In some areas the basalt crops out as brecciated dikes and sills, consisting of angular blocks and cobbles of basalt set in a sandy to muddy, un lithified matrix, formed by the injection of molten basalt into semiconsolidated, water saturated Astoria sediments.

In the Coxcomb Hill area the unit is exposed as a complex of sills with subordinate dikes intruding the Middle Mudstone (Figure 11). The major sills, exposed in quarries on the flanks of the hill, have a visible thickness of 16 m or more. In other areas of the city, smaller dikes, sills, and irregular bodies also intrude the mudstones. At Tongue Point, a sill nearly 65 m in thickness is exposed, displaying rough columnar jointing. In all outcrops noted by the writer, the intact basalt intrusions were in contact with the Middle Mudstone exclusively, as were the breccias.

Commonly, the contact consists only of a thin cap of mudstone overlying a large intrusive body. At other locations, the host mudstone displays disoriented bedding and a thin baked zone adjacent to the contact with the intrusive.

In the Astoria area, the Depoe Bay Basalts intrude strata of middle Miocene age. In the type locality of the Depoe Bay Basalt, the unit unconformably overlies middle Miocene sandstone and siltstone
Figure 10. Outcrop of Upper Sandstone on Pipeline Road showing characteristic Liesegang ring iron staining. Note Middle Mudstone rip-up left of center of photograph.

Figure 11. Thick sill of Depoe Bay Basalt in quarry on south flank of Coxcomb Hill.
of the Astoria Formation (Snavely and others, 1973). Based on contact relations and K/Ar dates determined for basalts of similar age, (Snavely and others, 1973), a middle Miocene age is inferred for the basalts exposed in the study area.

Petrology

Thin section analysis of a sample of Depoe Bay Basalt from the interior of a thick sill in the Coxcomb Hill area reveals the basalt to be equigranular and intergranular in texture. A modal analysis of the same sample shows the following mineralogy:

- Plagioclase 57%
- Clinopyroxene 18%
- Orthopyroxene 3%
- Opaques 7%
- Glass 6%
- Alteration products 9%

In addition there are trace amounts of apatite, biotite, and olivine. The plagioclase ranges in composition from andesine to labradorite (Ca andesine to Na labradorite, according to Snavely and others, 1973). The opaques are magnetite and ilmenite. The alteration products include chlorophaeite (?), alteration of glass, and minor chloritization of the pyroxenes, hornblende, and biotite. The hornblende itself is thought to be an alteration of the pyroxenes. Snavely and others (1973) published chemical analyses of basalt samples from western Washington and Oregon, including a sample from a sill near
Coxcomb Hill. The sample proved to be high in SiO₂ (56.0%) which is characteristic of the Depoe Bay Basalts. According to Snavely, the Depoe Bay Basalts correlate petrochemically with Yakima-type basalts of the Columbia River Plateau.

Contact Relationships

In the study area the Depoe Bay Basalts intrude only the Middle Mudstone. Near Tongue Point, dikes of Upper Sandstone are in close proximity to a basalt dike, but the order of emplacement is uncertain. The mudstone along the contact with the basalt is baked up to a depth of 45 cm. and is fractured and microfaulted in some exposures. Most of the exposures of Depoe Bay Basalt in the study area are capped by Middle Mudstones, indicating that the intrusions did not reach the basin floor in most places. Several outcrops in the eastern section of the study area exhibit a highly fractured, pepperitic contact zone with the surrounding Middle Mudstone, indicating that the mudstone was wet when intruded, or that the intrusive body reached the submerged surface of the Middle Mudstone, causing steam explosions and fracturing.

The Troutdale Formation

The name, Troutdale Formation, was first introduced by Hodge (1933) in reference to deposits of unsorted, quartzose and lithic sands
and gravels which are best exposed near the town of Troutdale, Oregon. Lowry and Baldwin (1952) described the unit in the Portland area as a quartzitic conglomerate with a micaceous sand, marl, and shale matrix. At Troutdale, they described the strata as a massive conglomerate associated with a tuffaceous sandstone. They also suggest that in outcrops of the Troutdale Formation farther down the Columbia River, the prevalence of quartzite pebbles increases.

On the crest and south flank of the Astoria peninsula, exposures of a poorly sorted, semi-consolidated, quartzitic conglomerate exist (Figure 12). Schlicker and others (1972) described the gravel as "...pebbles of quartzitic and acid igneous composition set in a light colored, fine grained matrix." The unit is exposed in several roadcuts near the top of the ridge, where the pebbles weather out of the less resistant matrix, and near the foot of the south slope of the ridge, probably as a result of downslope movement associated with landslide activity. Due to the lack of bedding and very poor exposures, determinations of attitudes and unit thickness are difficult to obtain. A 16m thick exposure at the top of the ridge (T8N R9W S7) is the thickest section exposed in the study area. Schlicker and others (1972) suggest that the gravel unit exposed in Astoria is correlative with the Troutdale Formation, based on lithology and outcrop expression. If this is the case, the gravel is probably Pliocene in age, since
Figure 12. Troutdale Formation pebble conglomerate unconformably overlying the Middle Mudstone of the Astoria Formation in recent roadcut on the south side of the peninsula. This material is inferred to be part of a larger landslide block originating several hundred yards upslope. Note bottle, center photograph, for scale.
a similar age is assigned to the Troutdale Formation in Portland (Trimble, 1963).

Petrology

In the study area, the Troutdale Formation ranges from a quartzitic, gravelly mudstone to a muddy gravel. The matrix content ranges from 26-80%. In some exposures the pebbles are obviously in grain to grain contact, while in others the scattered pebbles are suspended in muddy matrix. In the samples taken, the pebble sizes range from 4-88 mm. in the direction of the longest axis. The pebbles are predominantly well rounded to very well rounded, with the exception of a few mudstone pebbles, which are subangular in shape.

The mineralogy of the pebbles is predominantly quartzitic, with 48% of the pebbles composed of sedimentary quartzite and 32% composed of vein quartz. Mudstones account for 8% of the mineralogy, while rhyolite, granitic rock, chert, sandstone, tuff, and pumice pebbles are present in smaller quantities (Table 1). The matrix is best described as a massive, clayey siltstone. Silt sized grains are predominantly quartz with smaller amounts of plagioclase and basaltic lithic fragments, and traces of biotite, muscovite, glass, orthoclase, magnetite, and zircon. Determinations of clay mineralogy were not made for the Troutdale Gravel matrix, but high plasticity
and observable swelling upon addition of water suggest that montmorillonitic clays are the dominant species.

Contact Relationships

The Troutdale Formation unconformably overlies the Middle Mudstone of the Astoria Formation in the Astoria area. It is inferred to be a fluvial-estuarine deposit of the ancestral Columbia River, emplaced as a terrace gravel on an erosional surface of the mudstone.

Quaternary Deposits

Quartzose sands and fill material skirt the Astoria peninsula. Most of the beach area has been built over and the sands are not readily visible except at the water's edge. Petrologic determinations of the sands were not undertaken, but the sand appears to be rich in dark, probably ferro-magnesian, minerals. The sand is only very slightly indurated, due to compaction and the apparent cohesion imparted by interstitial water. The stream valley of Mill Creek, located in the northeastern corner of the study area, is blanketed in its lower portion by fine grained flood plain deposits. These are primarily silty clays, probably derived from the weathering and erosion of the Middle Mudstone, and are probably similar in composition. Schlicker (1972) indicates that the fine grained surface materials are underlain by as much as 32m of cross-bedded gravel, sand, and silt.
STRUCTURE

Most of the exposures of the strata present in the Astoria area are of poor quality due to extensive weathering and disorientation by intrusion, landsliding, and construction activity. In addition, the rocks are typically highly fractured in outcrop and may be locally microfaulted or tightly folded. Regional structures are difficult to identify because of the lack of reliable attitudes.

Folds

Previous investigators (Howe, 1927, Seitz, 1948) have mapped an east-west trending syncline in the Astoria area with the axis tracing a sinuous course from Smith Point to the John Day River and eastward out of the area. This syncline is based on predominantly southward dips on the north side of the peninsula and several northward dips on the south side of the peninsula. The writer was unable to discern any preferential dip on the south flank of the peninsula, and believes that many of the attitudes are disturbed by landsliding. Southward dips on the north side of the peninsula and in the southern portion of the study area were confirmed. If the dip of the strata throughout the study area were predominantly to the south, it would be reasonable to assume that slope failure, and thus unreliable attitudes would be enhanced on the south, or dip, slope of the peninsula (Figure 13).
Figure 13. Schematic diagram of cross-section of the Astoria peninsula showing disruption of attitudes through base failure slumping on the south side of the peninsula.
Based on field and aerial photo observations, and on construction of stratigraphic cross-sections, the strata exposed in the study area are believed to have a predominantly southward dip. Construction of east-west cross-sections and solution of three point problems to determine the orientation of the Middle Mudstone-Upper Sandstone contact indicate that the dip of the strata in the eastern half of the study area is slightly to the southeast while the strata in the western half dip slightly to the southwest (Plate I). Washburne (1914, in Seitz, 1948) suggested that the axis of a north-south anticline lay in the vicinity of 35th Street. While the east-west cross-section does suggest a very weak anticlinal structure, it is possible that deformation by sagging and landsliding have produced these attitudes, rather than tectonic processes.

Other folding in the study area appears to be limited to local soft sediment deformation and deformation and overturning of strata adjacent to intrusive bodies.

**Faults**

The straight northeast-southwest trend of the Mill Creek in the eastern section of the study area may suggest the presence of a major normal fault along the valley (Plate I). In addition, the writer noted the presence of an abrupt contact between the Upper Sandstone and the Middle Mudstone along the axis of the valley. The Upper Sandstone
is typically topographically and stratigraphically above the Middle Mudstone, but in this instance appeared below or adjacent to it along a roughly 1 1/2 mile long contact. This suggests that the strata on the western side of the contact has been upthrown with respect to the eastern side. This fault has also been mapped by Schlicker and others (1972) based on much the same evidence.

Wells and Peck (1961) have mapped another northeast-southwest trending fault in section 10, T 8 N, R 9 W based on microfaunal evidence. Other smaller faults of similar orientations have been mapped by other investigators (Howe, 1926; Seitz, 1948) and while the writer found no evidence of their movements, it seems likely that other faults of this orientation are present in the area.
GEOLOGICAL HISTORY

According to Snavely and Wagner (1963) the Astoria peninsula was part of a shallow oceanic embayment during early Tertiary time. The basin was the site of a eugeosyncline which was receiving sediment from a volcanic terrane to the east, and basaltic pillow lavas from volcanic centers within the basin. In plate tectonic terms, the basin may have been on the continental shelf behind an active trench. The basalts are similar to oceanic lithosphere. During Miocene time it is suggested that erosion of recently uplifted continental land areas east of the basin provided it with large quantities of arkosic and lithic sand. The ancestral Columbia River, flowing along an east-west trending downwarp, may have been a major source of sediment.

Based on the presence of abundant carbonaceous plant debris and mollusks typical of moderate water depths, it is probable that the Lower Sandstone represents deposition of medium to coarse clastic material in a mid shelf or delta front environment. The gradational contact between the Lower Sandstone and the Middle Mudstone indicates a gradual transition from a higher to a lower energy environment. Microfossils found in the Middle Mudstone indicate deposition at bathyal depths (Niem and others, 1973). As the basin subsided, some dissolution and reprecipitation of calcium carbonate from the calcareous fossils and possibly the plagioclase feldspars occurred in the
buried Lower Sandstone, causing local cementation. Continuing
deposition and deeper burial of the Middle Mudstone subjected the
fine-grained material to vertical compressive stresses, driving out
much of the interstitial water and preferentially orienting the tabular
clay minerals.

The time relationship between the Upper Sandstone and the other
units exposed at Astoria has been uncertain because of the unit's lack
of structure, lack of fossils, and unusual stratigraphic relationships.
Seitz postulated that the Upper Sandstone was deposited as an injec-
tion phenomenon from sand units underlying the Lower Sandstone.
He based his assumption on the existence of apparently upward ter-
minating sandstone dikes. All of the instances of upward terminating
dikes noted by the writer occurred in blocks of Middle Mudstone which
are inferred to have been overturned by landslides. Many bodies of
Upper Sandstone within the Middle Mudstone were previously thought
to be clastic sills, but have been identified as interbeds (Cooper, 1975,
personal communication). Examination of recent roadcuts in the
study area by Dr. A. R. Niem and D. M. Cooper of Oregon State
University reveals that the Middle Mudstone and Upper Sandstone are
intertongued laterally and interbedded vertically. It is suggested that
submarine slides of sand from a shelf-edge bar or spit periodically
spilled clean, moderately well sorted sands onto the surface of the
deeper water mudstones locally. Subsequent rapid deposition and
loading of material exerted compressive stresses on the sediments, fissuring the mudstones and allowing the water charged sands to be forced into them to form clastic dikes. Sandstone interbeds and dikes are present only in the upper portion of the Middle Mudstone, indicating a change in the depositional environment. The Upper Sandstone overlies the Middle Mudstone to the east of the study area and is interpreted to represent deposition in a mid shelf or delta front environment (D. M. Cooper, 1975, personal communication). The Upper Sandstone was never deeply buried, and exhibits only local iron-oxide cementation. While still submerged, the Middle Mudstone and possibly the Upper Sandstone were intruded by basaltic magma. The intrusions fractured and folded the Middle Mudstone and baked it along their contact. It is possible that the intrusion of basalt into the Middle Mudstone provided the fissuring which allowed the formation of the common clastic dikes. In some places, the hot intrusions reached the floor of the basin, forming breccias and pepperitic masses through steam blasting.

Regional uplift late in the Miocene reduced the area of the basin receiving sediment. During the Pliocene, the ancestral Columbia River deposited quartzitic terrace gravels which are inferred to be outcrops of the Troutdale Formation in the Astoria area. Subsequent uplift brought them to their present elevation, nearly 65m above sea
level. The interplay of geologic, atmospheric, fluvial, and estuarine processes during the Pleistocene and Holocene has shaped the Astoria peninsula and continues to modify its morphology.
ENGINEERING CHARACTERISTICS OF THE GEOLOGICAL UNITS

The rock units exposed in the Astoria area have been subjected to intense physical and chemical weathering. These processes have dramatically altered the strength and permeability of the parent rock. Weathering has affected the rocks to depths of 7 meters and deeper. The mantle of regolith which overlies the rock units is as deep as 4 meters in some places. Because of these factors, description of the physical properties of the rock alone is insufficient to understand the engineering behavior of the geological units.

The physical parameters of soil mechanics lend themselves well to the description of characteristics and performance of weathered rock units and their associated regolith. The sedimentary rock units themselves are soils in the engineering sense. According to Terzaghi and Peck (1967) soils are those earth materials which have an unconfined compressive strength of less than 4.0 kg. per square cm. In many locations, the weathered rock units exhibit strengths lower than 4.0 kg./cm.². The regolith, in turn, retains sedimentary and structural features of the parent rock such as jointing and bedding planes. Because of the gradational transition from rock to weathered mantle in the study area, no single set of criteria can characterize a geological unit in all its outcrop area. Herein a simplified
weathering profile classification proposed by Deere and Patton (1971) and based primarily on the engineering characteristics of the weathering zones, and secondarily on the pedologist's soil profile classification will be used.

Their system has three broad categories of earth materials: 1) residual soil, 2) weathered rock, and 3) relatively fresh, unweathered bedrock (Figure 14). Category 1 is subdivided into three zones, 1A, 1B, and 1C, essentially equivalent to the pedologist's A, B, and C horizons. Category 2 is subdivided into zones 2A and 2B. Zone 2A is the transition zone between saprolite and weathered rock, characterized by great variation in the physical properties of its components, which vary from soil like matrix to rock like corestones. Zone 2B is the zone of partially weathered rock, characterized by some discoloration and some alteration along bedding planes and joints. Zone 3 is the unweathered rock zone, typified by little or no alteration. The soil identification method and measurements used are based on a procedure developed by J. R. Bell (Department of Civil Engineering, Oregon State University) and are briefly outlined below. Based on physical properties, three broad groups of earth material types are recognized: granular materials, fine-grained materials, and organic materials.

Granular materials are those in which 50% or more of the particles are larger than .074mm. In general, granular materials
I - Zone 1, residual soil
II - Zone 2, weathered rock
III - Zone 3, relatively unweathered rock

Figure 14. Typical weathering profile in the Middle Mudstone of the Astoria Formation (After Deere and Patton, 1971).
exhibit good load bearing characteristics, are not subject to volume changes with changes in water content, are usually permeable, and exhibit good drainage characteristics. The engineering properties of granular materials are controlled largely by size, shape and gradation of the grains, relative density, and the amount of fines in the material. These criteria may be supplemented by considerations of homogeneity and organic content. Granular materials dominated by large particles will be more stable than those dominated by finer ones. Coarser grained soils also have better drainage characteristics. Gradation, the distribution of particle sizes in a material, is measured by the coefficient of uniformity, which indicates the range of particle sizes, and the coefficient of curvature, which indicates the relative proportion of each of the size classes. Well graded (a wide range of particle sizes) materials generally have better strength characteristics, are less compressible, and are less permeable than uniform sized materials (a small range of particle sizes). The presence of fines in a granular material decreases the permeability. If sufficient fines are present to effectively destroy grain to grain contact, the material may take on the characteristics of a fine-grained material and be susceptible to changes in strength with changes in water content. Density refers to the grain packing arrangement of a material. Dense packing arrangements provide good support characteristics. Loosely packed particles are subject to sudden settlement
caused by rearrangement of the grains when subjected to vibratory loads. In the consideration of granular rock strength, cementation and structures are also important factors.

Fine-grained materials are those containing more than 50% particles smaller than 0.074 mm., the silts and clays. In general, fine-grained materials exhibit greater variation in engineering properties than granular materials, and are more subject to changes in volume and loss of strength with changes in water content. Further classification of fine-grained materials is based on plasticity, the ability of a material to deform rapidly without rupture. Silts do not exhibit plasticity, but clays do. The relative proportions of silt and clay in a material can therefore be estimated from the degree of plasticity of a material. The engineering characteristics of fine-grained materials are grain shape, surface charges on the grains, structural arrangement of the grains, water content, ionic content of the pore water, and stress history of the material. These characteristics are best measured by the degree of plasticity, activity index, natural water content, strength of the undisturbed specimen, loss of strength upon remoulding, organic content, and homogeneity.

Plasticity is an indicator of compressibility and permeability. Higher plasticity indicates higher compressibility, lower permeability, and higher shrink-swell potential. The activity index relates the plasticity of a material to the percentage of clay sized particles, and
is a function of the activity of the clay species present. Two materials with the same plasticity index could contain different amounts of clay if the soil with the lesser amount had a more active clay mineral present. The material with the higher activity index would probably have less favorable strength characteristics. The natural water content of a material influences the undisturbed strength characteristics. Materials in which the natural water content is near the liquid limit (that water content above which the material behaves as a liquid) will be soft and may lose considerable strength upon remoulding. Materials in which the natural water content is near the plastic limit (that water content below which the material will behave as a solid) will exhibit good strength characteristics. If a stiff material is remoulded and shortly thereafter retested for shear strength, the consistency will be much softer. This loss of strength upon remoulding is called sensitivity. A material with high sensitivity loses much of its shear strength with remoulding. Structures of fine-grained materials are especially important. Weathering progresses most rapidly along joints and bedding planes. The strength along such planes is typically much lower than the strength of the intact material. Cementation is also a factor in the consideration of fine-grained rock strength.

Organic materials of all size classes have similar engineering characteristics. They are usually very compressible, have a very
<table>
<thead>
<tr>
<th>Sample</th>
<th>natural water content</th>
<th>plasticity index</th>
<th>liquidity index</th>
<th>sensitivity</th>
<th>activity index</th>
<th>field shear strength weath.</th>
<th>textural class</th>
<th>descriptive class</th>
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<tbody>
<tr>
<td>7246</td>
<td>38.6%</td>
<td>17.4</td>
<td>.80</td>
<td>8-10</td>
<td>.31</td>
<td>3.75TSF</td>
<td>ML</td>
<td>dk. brn. m.s.</td>
</tr>
<tr>
<td>811</td>
<td>44.2</td>
<td>18.5</td>
<td>.73</td>
<td>5-8</td>
<td>-</td>
<td>-</td>
<td>ML</td>
<td>dk. brn. m.s.</td>
</tr>
<tr>
<td>826</td>
<td>48.5</td>
<td>16.2</td>
<td>.46</td>
<td>2-3</td>
<td>.28</td>
<td>3.75TSF</td>
<td>MH</td>
<td>lt. brn. m.s.</td>
</tr>
<tr>
<td>1131</td>
<td>47.7</td>
<td>18.7</td>
<td>.60</td>
<td>3-5</td>
<td>-</td>
<td>-</td>
<td>MH</td>
<td>lt. brn. m.s.</td>
</tr>
<tr>
<td>7269</td>
<td>31.5</td>
<td>3.0</td>
<td>0</td>
<td>0</td>
<td>-</td>
<td>4.5TSF</td>
<td>ML</td>
<td>tan m.s.</td>
</tr>
<tr>
<td>8153</td>
<td>39.3</td>
<td>21.3</td>
<td>.85</td>
<td>8-10</td>
<td>.39</td>
<td>3.5TSF</td>
<td>CL</td>
<td>blk. m.s.</td>
</tr>
<tr>
<td>7244</td>
<td>47.6</td>
<td>27.6</td>
<td>.81</td>
<td>8-10</td>
<td>.50</td>
<td>-</td>
<td>CH</td>
<td>blk. m.s.</td>
</tr>
<tr>
<td>8148</td>
<td>68.3</td>
<td>47.5</td>
<td>.81</td>
<td>8-10</td>
<td>.83</td>
<td>.25-1.75TSF</td>
<td>CH</td>
<td>tuff</td>
</tr>
</tbody>
</table>
Figure 15. Plasticity chart showing classification of Middle Mudstone types (Appendix III)
Table 3. Classification of sedimentary units by the U. S. Soil Conservation Service criteria.

<table>
<thead>
<tr>
<th>Unit</th>
<th>% Gravel</th>
<th>% Sand</th>
<th>% Fines</th>
<th>Plasticity Index</th>
<th>USCS class.</th>
</tr>
</thead>
<tbody>
<tr>
<td>unweathered Tls</td>
<td>0</td>
<td>86</td>
<td>14</td>
<td>0</td>
<td>SM</td>
</tr>
<tr>
<td>weathered Tls</td>
<td>0</td>
<td>74</td>
<td>26</td>
<td>-</td>
<td>SM</td>
</tr>
<tr>
<td>Astoria soils</td>
<td>0</td>
<td>30</td>
<td>70</td>
<td>0</td>
<td>ML</td>
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<tr>
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<td>0</td>
<td>10</td>
<td>90</td>
<td>-</td>
<td>ML</td>
</tr>
<tr>
<td>weathered Tmm</td>
<td>0</td>
<td>10</td>
<td>90</td>
<td>3.0-27.5</td>
<td>ML-CL</td>
</tr>
<tr>
<td>tuff interbeds</td>
<td>0</td>
<td>0</td>
<td>100</td>
<td>47.5</td>
<td>CH</td>
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<tr>
<td>Chitwood soils</td>
<td>0</td>
<td>5</td>
<td>95</td>
<td>78</td>
<td>CH</td>
</tr>
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<td>unweathered Tus</td>
<td>0</td>
<td>96</td>
<td>4</td>
<td>-</td>
<td>SW</td>
</tr>
<tr>
<td>weathered Tus</td>
<td>0</td>
<td>74</td>
<td>26</td>
<td>-</td>
<td>SM</td>
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<tr>
<td>Svensen soils</td>
<td>0</td>
<td>78</td>
<td>22</td>
<td>NP</td>
<td>SM</td>
</tr>
<tr>
<td>weathered Tt</td>
<td>20-74</td>
<td>?</td>
<td>26-80</td>
<td>?</td>
<td>GW</td>
</tr>
</tbody>
</table>
low shearing strength, and are susceptible to large changes in volume with changes in water content. The presence of organic materials lowers the strength of both granular and fine-grained materials.

Index properties of the following units are after the U. S. Soil Conservation Service (1972) and Terzaghi and Peck (1967) (Table 2). Strength and performance characteristics are after descriptions by A. Casagrande in Means and Parcher (1963) (Table 2). Soil classification is by the Unified System, defined by Casagrande (1948) (Figure 15 and Table 3).

The Astoria Formation

The Lower Sandstone

The Lower Sandstone is composed primarily of medium to fine sand with up to 26% fines in weathered samples. By the Unified Soil Classification System, it is a silty sand (SM).

Unweathered Rock

Relatively fresh samples of the Lower Sandstone are dominated by medium to fine sand, indicating fair drainage characteristics except where tightly cemented. The grains are bulky rather than tabular and angular to subangular, providing a high coefficient of friction and enhancing mechanical interlock, enhancing shear strength and
resistance to compression. For the Lower Sandstone, the coefficient of uniformity is 3.43 (uniform) and the coefficient of curvature is 1.3 (well graded). These apparently contradictory determinations indicate that the framework grains are all in the same effective size class, and that the matrix grains are of the correct sizes to fit into the interstices between the framework grains. These characteristics indicate generally higher resistance to deformation than clean sand, but lower permeability. Thin sections confirm that the Lower Sandstone has up to 14% matrix and a dense grain packing arrangement which adversely affect permeability, but enhance resistance to deformation. The strength of the Lower Sandstone is greatly augmented by the presence of calcium carbonate cement in concentrations of up to 20% locally. Cemented samples have an unconfined shear strength far in excess of 4.0 kg./cm.2, the strength division between soil and rock.

The inelasticity of the Lower Sandstone produces little rebound or swelling upon unloading, and so jointing is infrequent. Near the top of the unit, fine-grained interbeds decrease the vertical permeability of the unit. Organic material occurs as partings along bedding planes in most outcrops. The significance of the organic material is that its low shear strength and presence along bedding planes, favors movement along bedding planes.
Weathered Rock

In the Lower Sandstone, weathering produces the dissolution of soluble cement and an increase in the amount of matrix. The grain sizes and shapes are virtually unchanged by weathering, although some of the angular lithic fragments and feldspars are more rounded in weathered samples. The increase in the amount of matrix through the alteration of less stable grains changes the classification from uniform to poorly graded by both coefficient of uniformity and coefficient of curvature criteria. Matrix concentrations in weathered rock samples are as high as 26%. The higher matrix content reduces grain to grain contact, decreases permeability, and increases the susceptibility of the Lower Sandstone to changes in volume with changes in water content. The most significant result of weathering is the dissolution and removal of calcium carbonate cement. This reduces the unconfined compressive strength of the Lower Sandstone to between 1.5 and 4.0 kg./cm.\(^2\). Weathering produces a friable, semi-consolidated sand from the resistant sandstone. Early weathering occurs along joints and bedding planes allowing small blocks (up to 1 meter in length) of still coherent sandstone to fall from steep exposures. Further weathering results in grain plucking, expansion of organic material, and eventual disintegration of the unit.
Weathered bodies of covered sandstone exhibit relic bedding, but crumble to individual grains at the touch.

Residual Soils

Undisturbed exposures of residual soil produced by the weathering of the Lower Sandstone are rare. Since the outcrop area of the unit lies completely within the city limits of Astoria, excavations and fills have removed or covered the natural soils in most areas. A soil profile is difficult to discern, but is probably similar to that of the Astoria series soils. According to the U. S. Soil Conservation Service, these soils are moderately permeable silt loams with a low to moderate shrink-swell potential. The profile in the study area consists of approximately 60 cm of slightly plastic to non-plastic silt loam (ML) overlying up to 2 1/2 m of moderately to highly plastic silty clay (MH). These zones correspond with engineering soil zones 1A and 1B. Zone 1A has better strength and drainage characteristics than zone 1B which is less permeable and less stable.

The Middle Mudstone

The Middle Mudstone is composed of primarily silt and clay sized particles, and therefore exhibits the characteristics of the fine-grained materials. The Middle Mudstone falls into a group of materials known to engineers as overconsolidated clay shales but
are more properly referred to as overconsolidated mudstones.  Overconsolidated materials are those which have in the past been subjected to greater overburden pressures than the present overburden supplies. Overconsolidated mudstone is one of the most troublesome of engineering materials. Scott and Brooker (1968) state:

In spite of the proven validity of theories based on statics combined with physical soil properties as obtained by modern laboratory testing techniques we have not yet been able to predict with reasonable confidence the performance, on either a short term or long term basis, of highly overconsolidated clays or, more particularly, clay shales.

Unweathered Rock

Outcrops of unweathered Middle Mudstone are rare, occurring only in deep, very recent excavations and quarries. Samples of unweathered mudstone exhibit high dry strength, indicating moderate to high plasticity. Because of the high dry strength, attempts at disaggregation for size and index analyses were unsuccessful. The natural water content in two cases noted was below the plastic limit and the field shear strength greater than 4.5 kg./cm.$^2$ (very hard). Bedding planes are not evident in most of the unweathered mudstone. Locally, tuffaceous interbeds occur which exhibit a field shear strength as low as 3.0 kg./cm.$^2$. Jointing is rare in unweathered Middle Mudstone, but fresh exposures rapidly develop fissures along bedding planes and joint sets due to unloading and air slaking upon
repeated wetting and drying.

Weathered Rock

As overburden is removed from intact overconsolidated Middle Mudstone, rebound or stress relief produces an increase in volume, accompanied by the opening of fissures and joints (Terzaghi and Peck, 1967). This fissuring imparts a fracture permeability to an otherwise impermeable material and facilitates groundwater percolation and accelerated weathering along the fissures, producing "clay seams." This phenomenon has been noted in the mudstones of the Astoria area to depths of up to 5m. Weathering then proceeds along the opening fissures, isolating coherent blocks of mudstone from their parent rock. Further fissuring and fracturing produces smaller and smaller blocks, finally producing the characteristic "poker chip" talus of the Middle Mudstone.

Based on physical appearance and engineering characteristics, weathered samples of the Middle Mudstone can be assigned to one of four categories (Figure 15). The first is a massive, olive-black (5Y 2/1), organic mudstone. The plasticity index ranges from 21.3 to 27.6, and the liquid limit from 47.2% to 52.8%. In the Unified System it is classified either as a low plasticity clay (CL) or a high plasticity clay (CH). It has a moderate shrink-swell potential, and moderate compressibility. The activity index is from .39 to .50
The natural water content during the spring ranges from 39.3% to 47.6% which is near the liquid limit, indicating that a small increase in water content will greatly decrease the shear strength of the material. In weathered exposures, the black mudstone has an unconfined compressive strength of 3.5 kg/cm² (very stiff). It has an average liquidity index of .85 and an average sensitivity of about 5 (sensitive). This means that the residual or remoulded strength is only about 1/5th of the undisturbed strength.

The second mudstone type is a moderate yellowish brown (10YR 5/4) clayey siltstone. Its plasticity index ranges from 16.2 to 18.7 and the liquid limit from 55.2% to 57.2%. It is classified as a high plasticity silt (MH). It has a low shrink-swell potential and low compressibility. The activity index averages .28 (inactive) and the natural water content (spring) is near the plastic limit (41%). Field unconfined compressive strength tests average 3.75 kg/cm² (very stiff). The liquidity index is from .46 to .60, and sensitivity from 2 to 4, indicating a normal loss of strength upon remoulding.

The third type of mudstone is a yellowish gray (5Y 7/2) well indurated siltstone found primarily in the baked zones adjacent to igneous intrusions. It has a plasticity index of 3.0 and a liquid limit of 34.5, placing it in the low plasticity silt (ML) category. It has a very low shrink-swell potential, the activity index is nearly zero (inactive), and the liquidity index and sensitivity are very low,
indicating that the shear strength is affected very little by remoulding.

The fourth type of mudstone occurs as thin, off-white, tuffaceous interbeds in the darker Middle Mudstones. These units have a plasticity index of up to 47.5 and a liquid limit of up to 75%. This places it in the highly plastic clay (CH) category. It has high compressibility and a high shrink-swell potential. The activity index is 0.83 (normal) and the natural water content averages 68.3%, which is near the liquid limit, indicating that even in an undisturbed state it will be very soft. In weathered outcrop, the tuffaceous interbeds exhibit a markedly lower shear strength than the surrounding mudstones (0.25 to 0.75 kg/cm², soft to very soft). The liquidity index is 0.88 and the sensitivity about 7, indicating that only 1/7th of the original strength will remain after remoulding.

With the exception of the tuffaceous interbeds, the color of the mudstone is a good indicator of its plasticity and relative strength. The darker mudstones tend to have higher plasticity, higher activity indexes, and lower shear strengths. This is most probably the effect of higher organic content in the darker mudstones, but may also be because fine-grained materials (i.e. clays) tend to be dark.

Residual Soil

The residual soils produced by the weathering of the Middle Mudstone are clays and silty clays which range from 1/2 to 3 1/2 m
in thickness. It is difficult to establish the boundary between weathered rock and residual soil in the Middle Mudstone because it is a gradual transition from fissured rock through blocks of mudstone in a soil matrix to residual soil. As soon as fissures develop in the unit the strength characteristics of the mudstones are governed more by sliding resistance along the fissures than by the physical characteristics of the intact rock. The soils overlying the Middle Mudstone have profiles similar to the U. S. Soil Conservation Service Astoria and Chitwood series. The S.C.S. lists typical liquid limits of from 30% to 60% and plasticity indexes of from 5 to 20. Soil samples collected by Schlicker and others (1972) yielded liquid limits up to 79% and plasticity indexes as high as 78. These characteristics indicate that the engineering characteristics of the material are dominated by the clay fraction. Plastic soils have high dry strength, but lose most of their shear strength upon saturation. In addition, the shrink-swell potential is high, indicating further loss of strength upon wetting, and the drainage is poor, which may allow high pore water pressures to build up when high water contents develop.

The Upper Sandstone

The Upper Sandstone is composed primarily of fine to medium sand with up to 26% matrix and local iron oxide cementation. It is
classified as a silty sand (SM).

Unweathered Rock

Outcrops of fresh Upper Sandstone are rare, occurring only in recent cuts and excavations. The sands are dominated by subangular to subrounded particles which display good strength characteristics through grain interlock and frictional resistance to sliding. Thin section examination reveals as little as 4% matrix, and the coefficient of uniformity is above 4 (poorly graded), indicating that the Upper Sandstone possesses good drainage characteristics where not tightly cemented. Iron oxide cementation lends considerable strength to the Upper Sandstone. The unit is free of jointing and bedding planes, which represent potential planes of weakness. Dikes of Upper Sandstone found in the Middle Mudstone are also locally well cemented with iron oxide and free of any structural features. Where not well cemented, the unit is exposed as a friable sandstone with good drainage and moderate strength characteristics. The Upper Sandstone is resistant to compaction, but because of its local lack of cementation and loose structure, it may be subject to sudden settlement on hills when subjected to vibratory loads.

Weathered Rock

The primary result of weathering of the Upper Sandstone is the
leaching of iron oxide and other cements. Outcrops of weathered Upper Sandstone are extremely friable and crumble at a touch. Weathering occurs rapidly and extends to considerable depths (up to 3m.). Another result of weathering is the production of diagenetic matrix from metastable mineral grains. Matrix may account for up to 26% of weathered samples. This lowers the permeability of the unit and reduces grain to grain contact. The unconfined compressive strength of weathered Upper Sandstone is generally less than 1.0 kg./cm.². Despite low shear strength, outcrops of weathered Upper Sandstone commonly stand in almost vertical cliffs up to 12 meters high. The components of strength are frictional sliding resistance, grain interlock, the cohesion of the matrix, and apparent cohesion due to the surface tension of interstitial water. The unit is subject to grain plucking upon drying and limited slab failure along root paths and weathering horizons. Again, the unit may be subject to local settlement upon vibratory loading.

Residual Soil

The residual soil overlying the Upper Sandstone is primarily a loam similar to the soils of the Svensen series. They are well drained, friable loams and loamy sands up to 2 1/2 m. thick. The soils are permeable with low shrink-swell potential and low to moderate erosion hazard. The plasticity is low to zero indicating little
change in strength upon wetting. The soils, like the weathered rock, will stand in very steep slopes but have little cohesive strength, and so are subject to ravelling and local settlement with vibratory stress.

The Troutdale Formation

Outcrops of the Troutdale Formation in the Astoria area are fluvial terrace gravels consisting of rounded to well rounded pebbles and cobbles set in a massive fine-grained matrix. None of the exposures observed displayed any cementation or consolidation. Although one exposure exhibited framework support, in most cases the engineering properties are governed by the abundant matrix (up to 80% of the composition). The matrix may be described as a massive, clayey silt. It is only slightly permeable, indicating poor drainage characteristics. It exhibits high plasticity when wet and high dry strength. Although no strength determinations were made, it seems that much of the shearing resistance is lost upon wetting.

The Troutdale Formation crops out at the top of the hill overlooking Smith Point, and occurs as landslide debris on the south flank of the hill. It may be that the slope failure producing some of these deposits occurred in the underlying Middle Mudstone, but the Troutdale Formation is suspect in most cases.
**Depoe Bay Basalt**

The Depoe Bay Basalt occurs as resistant highs in the Astoria area. The rock is a hard, fine-grained basalt which is massive to roughly jointed.

**Unweathered Rock**

Most unweathered outcrops of Depoe Bay Basalt are extremely hard, free of structures, and resistant to any kind of deformation. The basalt cropping out at Tongue Point displays rough columnar jointing, which may allow large blocks to come loose and fall, but this is an infrequent occurrence. In some outcrops, the basalt occurs as a breccia with a fine-grained matrix. In these cases, the strength of the rock is governed by the characteristics of the matrix.

**Weathered Rock**

The primary effects of weathering on the Depoe Bay Basalt are fracturing and fissuring along joints and alteration of the feldspars and ferro-magnesian minerals. Seams of alteration products may develop along the widened joints, permitting separation or sliding of intact blocks of basalt, producing rock slides and falls. Advanced weathering produces softening and eventual disintegration of the basalt colluvium. In breccia outcrops, the less resistant matrix is often washed away, allowing pieces of basalt to come loose.
Residual Soil

The soils which develop over the basalt of the Astoria area are similar to soils of the Hembre series. The profile consists of about 30 cm. of silt loam overlying up to 1 m. of silty clay loam. They are well drained and occur on slopes of up to 90%. They have moderate plasticity indexes (5 to 15) and low shrink-swell potential, indicating good strength characteristics. The only adverse characteristic is the high erosion hazard on steep slopes.

Quaternary Deposits

The beach sands of the Astoria area are un lithified and exhibit engineering characteristics such as high compression resistance, good drainage, low dry shear strength, and susceptibility to settlement with vibratory loads. In general, the sands, although loose, are not subject to shifting or erosion, due to the emplacement of basalt rip-rap around the perimeter of the peninsula.

The alluvial and flood plain deposits are similar in physical appearance and properties to soils of the Walluski series (USCS, 73). The Walluski profile is characterized by up to 30 cm. of silt loam overlying up to 65 cm. of silty clay loam which in turn overlies up to 25 cm. of clay. These materials are non-plastic to moderately plastic (0 to 15 plasticity indexes), with a moderate to high
shrink-swell potential. Drainage is good in the upper horizons, but is poor in the clay strata. The deposits are un lithified, and so are dependent on the cohesion and particle interactions of the materials present for their shear strength. Generally, the compressive strength is lower than that of the beach sands, but the low relief of the flood plain and alluvial deposits make slope failure unlikely. Schlicker and others (1972) suggest that a gravelly substratum may occur with a thickness of up to 160 meters under the finer grained flood plain deposits.
GEOLOGICAL HAZARDS

The major geological hazards that pose a potential problem in the Astoria area are earthquakes, floods, and landslides. Of these, landslides are the most common and troublesome, and so are most thoroughly discussed.

Earthquakes

Although noticeable earthquakes are not common in Astoria, the study area is adjacent to an active tectonic belt which roughly parallels the west coast of North America. The National Oceanic and Atmospheric Administration includes the north coast of Oregon in the moderate earthquake risk category (#2) (Coffman and von Hake, 1973) (Figure 16). While seismic activity is more prevalent in the coastal areas of California and Washington, the occurrence of earthquakes in the study area warrants their consideration as a potential geologic hazard.

The threats posed by earthquakes are many. The most obvious consequences of earthquake energy release are shaking and possible damage of structures through vibratory ground motions, and the damage to structures and disruption of underground water and power lines along the fault, if movement occurs at the surface. Earthquake vibration may also cause the sudden settlement of loose granular
Figure 16. Earthquake risk map for the western United States and map of Oregon showing earthquake epicenters from 1841 to 1970. (Coffman and vonHake, 1973, Couch and Lowell, 1971)
materials such as sands and gravels. Terzaghi (1950) describes the effect of lateral ground acceleration on potential landslide wedges and calls seismic activity a significant external cause of landslides. In addition, vibration may cause the collapse of the grain structure of sensitive materials, producing suddenly increased pore water pressure and subsequent loss of shear strength and flow, even on very slight slopes. Schlicker and others (1972) describe the formation and effects of tsunami, or seismic waves which may be generated by earthquakes at sea.

The faults mapped in the study area show no evidence of historical movement, but several earthquake epicenters have been recorded in the area. The first occurred on June 27, 1869 and was reported as felt by Astoria residents, probably of intensity III or IV (Modified Mercalli scale, 1931, Couch and others, 1974). Another occurred on July 23, 1938 with an intensity of IV (Modified Mercalli scale), and was reported as a moderate shock by Astoria residents (Coffman and vonHake, 1973). Other earthquakes with epicenters outside the Astoria area but reported by Astoria residents occurred on February 3, 1892 (houses shook), February 15, 1946 (IV MM scale), June 23, 1946 (V MM scale), and on April 29, 1967 (VI MM scale) (Couch and others, 1974).

Earthquakes with epicenters outside the study area may have a considerable effect on slope stability, even though not noticed by
residents of the area affected. Seed and Idriss (1969) and Seed and others (1969) discuss the characteristics of rock and soil behavior during earthquakes and demonstrate that even minor shocks, or shocks from great distances may trigger landslides given certain rock and soil conditions. Comparison of the occurrences of major earthquakes in the northwest with the occurrences of major landslides in the Astoria area yields no evidence of a causal relationship between them. This does not preclude, however, the possibility of earthquake triggered landslides in the future.

The prediction of earthquake probability is difficult. Couch and Lowell (1971) suggest that the seismic energy release in the Coast Range for the last 100 years \(6.4 \times 10^{16}\) ergs per year is equivalent to 1 magnitude V (MM scale) earthquake every 10 years. Of course this energy release could be gradual, consisting of many smaller earthquakes during that time period, but the calculations suggest that the potential for damaging earthquakes in the Astoria area is moderate but real.

**Flooding**

In discussing the flooding problems of Clatsop and Tillamook counties, Schlicker (1972) describes two types of flooding, stream flooding and ocean flooding. Stream flooding in the north coast area of Oregon is a fairly common occurrence caused by the combination
of heavy rainfall and adverse drainage conditions. The Astoria peninsula area, although bounded by river channels, is not particularly susceptible to stream flooding itself. Most of the streams of the mapping area drain relatively small areas so that the likelihood of flooding due to excessive rainfall alone is low. The John Day River in the eastern part of the study area is an exception. Very recent deposits of flood-plain materials along its banks attest to recent flooding, if only in a limited area (Figure 17).

A much more significant threat in the Astoria area is ocean flooding, or more properly, the combination of ocean and stream flooding. Although Astoria is not strictly a coastal city, the Columbia River estuary and Young's Bay are large enough and have sufficient exposure to the ocean to be subject to flooding due to storm waves and high tides, often augmented by increased runoff in the Columbia and Young's Rivers. Schlicker and others (1972) report that during early December 1967, storm waves, augmented by 10 foot tides caused some flooding in the western part of the city. Most of the Astoria peninsula is fronted by basalt rip-rap and structures are at least 5 m above mean sea level. Exceptions to this rule are the area between Tongue Point and 36th street and the floodplain of the John Day River (Plate 2). Astoria is well protected from storm waves by Clatsop Spit, but the combination of high tides, high runoff and extreme storm
Figure 17. Flood hazard map of the Astoria peninsula area. "Cross-hatching" shows areas of historical flooding. (After Schlicker and others, 1972)
waves could produce flooding in areas lower than 20 feet above mean sea level.

Tsunamis, or seismic waves, have proved to be little threat to Astoria although other coastal cities have experienced heavy damage (Schlicker and others, 1972). This is probably because the river mouth bar of the Columbia River is shallow enough to force large waves to break, dissipating much of their energy before reaching Astoria.

**Landslides**

Landslides are a common phenomenon in the Astoria area. Schlicker and others, (1972) in a report on the environmental geology of the northern coast of Oregon, mapped landslides and landslide topography in the Astoria area, but on too small a scale to differentiate between individual slides. Investigations of the mechanisms of slope failure in the area have been limited to slope stability calculations and post-failure calculations to determine what steps are necessary to repair damage and prevent further movement. To fully understand specific instances of slope failure, one must analyze the causes, types and mechanisms of landslides and relate them to the background factors of the slide area. The writer has attempted to determine the topographic, geologic, hydrologic, and other background factors affecting slope stability in the Astoria area, and to quantify
and rank them in order to understand the occurrence and distribution of landslides there.

**Causes of Landslides**

The causes of landslides are many and varied. Although a single event may trigger a landslide, in most cases a combination of factors is responsible for the failure. Progressive changes over a long period of time may induce a slide in an area of long-standing stability. The accumulation of effects of cyclic seasonal changes and progressive deterioration must be taken into account, as well as the readily apparent effects of earthquakes or heavy rainstorms, in slope stability assessment. Terzaghi (1950) categorizes landslide causes as either external (those due to increases in shear stress along the failure plane) or internal (those due to decreases in shearing resistance along the failure plane). Usually, external causes are blamed for slope failure, but less spectacular internal causes may be responsible.

Landslides occur when the forces tending to move material downhill exceed the forces tending to hold it in place. A numerical expression of the ratio of these forces is the factor of safety (F. S.) given by:

\[
F. S. = \frac{\text{resisting forces}}{\text{driving forces}}
\]
The driving forces acting on a potential landslide wedge are its weight and any external forces acting on it such as a fill or structure. The resisting forces acting on the wedge are the shear strength of the material along the potential failure plane and any external forces such as a retaining wall at its toe. The following discussion summarizes those causes and factors found most important in producing landslides in the Astoria area.

External Causes

1. Addition of weight. In the Astoria area, the weight added by seasonal rainfall is a significant factor in slope stability. Emplacement of buildings or fill on a slope may be important in specific cases.

2. Removal of lateral support. Erosion by wave or stream activity at the foot of a slope will oversteepen it and remove lateral support. The slopes of the Astoria peninsula reflect geologically recent downcutting and sidecutting by the Columbia and Young's Rivers which have removed large amounts of material and produced oversteepened slopes in the area. Rip rap fronting along river fronts and flood control measures have reduced active downcutting to a relatively minor local phenomenon. Excavations are the most significant mechanisms currently producing oversteepening and removal of lateral support. Excavation of material from the toe of old landslide
blocks very commonly results in reactivation of the block. Landsliding may remove material from the toe of a slope, setting the stage for a larger slide, leading to progressive landsliding (Terzaghi and Peck, 1948) wherein a landslide creates a headscarp which then fails, creating a new headscarp prone to failure. This process is primarily responsible for the hummocky topography common in the study area.

3. Seismic activity. Although the Astoria area has experienced some seismic activity, studies of the time relationships between earthquakes recorded in the area and the occurrence of major landslides produced no evidence of seismic involvement.

4. Lateral earth pressure. As elastic materials are unloaded, rebound will produce vertical and lateral stresses in the unloaded material. The Middle Mudstone of the Astoria Formation is an overconsolidated mudstone, that is, it has been subjected to greater overburden stress than the present overburden supplies. As a result it will expand plastically when possible so that small lateral stresses favoring landsliding are intrinsic to the unit. Other sources of lateral pressure in the Astoria area are the stresses generated by water in cracks and fissures and the swelling pressures of clay minerals upon hydration. The dominant clay mineral of the Middle Mudstone is montmorillonite, which can develop considerable swelling pressures when saturated (Warrentin and others, 1957).
5. Seepage pressures. Due to the attraction between water molecules and soil particles, water moving through a sediment will exert a drag or seepage pressure on the surrounding particles. Where the gradient is steep, seepage pressures may be large enough to trigger a landslide (Erskine, 1973). According to Erskine (1973) and Terzaghi (1950), seepage pressures are most effective in silty and fine sand materials, such as the Upper and Lower Sandstones of the study area and the loamy soils. The permeability of fine-grained sediments is so low that velocity and, therefore, seepage pressures are small. The effect of seepage pressures in the study area is not major, except during torrential rains when the sandstone units are unable to drain as fast as precipitation is introduced, causing a hydrostatic head differential in sandy slopes.

Internal Causes

1. Composition. The fine grained units exposed in the Astoria area are composed primarily of clays, which exhibit marked decrease in strength upon saturation. In particular, the Middle Mudstone has a high proportion of montmorillonitic clays, which are particularly susceptible to swelling and loss of shear strength with hydration. Bentonitic interbeds in the Middle Mudstone have a low initial strength when wet. The Lower Sandstone has interbeds of organic material, which are also characterized by low shear strength.
2. Texture. Materials composed primarily of tabular particles exhibit less strength than those composed of bulky grains due to the tabular grain's tendency to readily slide over one another rather than interlock with each other. Loose granular poorly graded materials such as weathered Upper and Lower Sandstone and the beach sands may be susceptible to settlement or shifting with vibratory loads where interstitial material or cements have been removed, leaving the framework grains in a low density packing arrangement. This phenomenon has been noted particularly in the case of weathered Lower Sandstone where cements and fines have been removed by weathering, leaving the sand grains "perched" on one another rather than densely packed.

3. Structure. Joints and bedding planes, which are common in the Middle Mudstone, represent potential planes of low shearing resistance. In addition, such features provide avenues for accelerated weathering and the progressive development of failure planes (Bjerrum, 1967; Skempton, 1948). The southward dip of the strata in the southern part of the study area promotes bedding plane failure in the Middle Mudstone. Stratigraphic relationships such as the occurrence of the massive Upper Sandstone overlying the Middle Mudstone may also produce slope instability.

4. Weathering. The hydration of clay minerals during the weathering of all the units in the Astoria area results in swelling and
substantial reduction of the strength of the parent material. Also, addition of fresh water to fine-grained sediments, particularly the Middle Mudstone, alters the exchangeable ion content of the pore water. Yong and Warkentin (1967) demonstrate the reduction of attractive forces between grains in a marine sediment such as the Middle Mudstone with the reduction of soluble salt concentration of the pore water, resulting in reduction of shear strength. Percoating water will tend to dissolve and remove soluble cements such as calcite, greatly reducing the rock's strength. This process is evident in the weathering of well cemented units such as the Upper and Lower Sandstones of the Astoria area.

5. Hydrostatic pressure. The effects of hydrostatic pressure are probably some of the most significant causes of landsliding in the Astoria area. The high annual rainfall and low permeability of some of the units allow large quantities of water to be trapped in the soils and rock units. Due to the low permeability of the Middle Mudstone, increases in hydraulic head caused by winter precipitation greatly decrease the shearing strength of many slopes. The highly fractured nature of the Middle Mudstone allows water to percolate down to depths of less fracturing. This traps the water and allows the hydrostatic head to build up. Also, water ponding at the head of old landslide blocks may increase the hydraulic pressure along the failure surface and reactivate the block.
At low water contents, fine-grained strata like the Astoria Formation may have a negative pore water pressure value due to capillarity. At very low water contents, adsorbed water is still bound in the structure of the clay minerals and the shearing resistance of this water approaches that of the solid grains. As additional water is introduced during the rainy months, the negative pore water pressure drops, and the apparent cohesion imparted by the surface tension of the interstitial water is decreased. Studies in the vicinity of Mary's Peak Oregon by Larry M. Hansen (Dept. of Civil Engineering, Oregon State University, personal communication) suggest that this effect alone may be responsible for many slope failures in units of the Oregon Coast Range, such as the Astoria Formation.

**Types of Landslides**

Several types of landslide classifications exist based on various combinations of types of materials involved, types of movement, amount of material, and triggering mechanisms. The Highway Research Board (Varnes, 1958) classification, based on types of material involved and types of movement, is best suited for this investigation (Figure 18). The landslide types most common in the Astoria area are rockfalls, rock and soil slumps, rock and soil
Landslide types common in the Astoria area (after Varnes, 1958).

a. Rockfall, typical of basalts in steep exposures.

b. Rock slump, typical in mudstones on dip slopes.

c. Soil slump, typical in fills and very thick soils. (Note flow at toe of slide)

d. Rock glide, typical in sandstones overlying mudstones.

e. Soil glide and associated earth-flow, typical in weathered mudstones.

Figure 18.
glides, and mudflows or combinations of these types of failure.

Examples discussed below are shown in Figure 19.

Rockfalls

Rockfalls in the Astoria area occur primarily in the Depoe Bay Basalt in quarries and nearly vertical natural outcrops. Weathering along joints and fissures causes blocks of the basalt to loosen and fall. In outcrops of basalt breccia, weathering of the less resistant muddy matrix causes basalt fragments to loosen and fall (Figure 20). Quarrying activities tend to accelerate this process, and may even initiate some falls through vibration. An associated phenomenon is the occurrence of rockfalls of the overlying Middle Mudstone into quarries due to shear failure within the unit. The hazard presented by rockfall in the study area is minimal, provided normal precautions are taken in quarry operations and quarry faces are benched according to regulations.

Rock and Soil Slumps

Slumping is a major mode of failure in the Astoria area. The hummocky landslide terrain of the area is mainly the result of slump-type failure. Slump morphology is characterized by tension cracks, a back-tilted head, a steep headscarp, and a bulging toe. Terzaghi (1948) describes two basic types of slump failure. The slope failure,
1. Rockfalls in quarry at Coxcomb Hill
2. Slump in weathered rock at Florence and Agate Streets
3. Slump in fill and soil on Niagara Street
4. Slump on Marine Drive
5. Slump at Bristol and Erie Streets
6. Rock glide of sandstone over mudstone
7. Soil glide at 6th and Exchange Streets

Figure 19. Location map showing location of landslide examples.
Figure 20. Blocks of basalt which have loosened and fallen from the sheer quarry walls.

Figure 21. Head of the slump failure at Florence and Agate Streets showing displacement of approximately twelve feet. Note fracturing and backtilting of head of slide.
in which the failure plane intersects the slope at or above the toe of
the slope, is the predominant mode in rock slumps in the study area.
The base failure, in which the plane of failure intersects a firm base
and exits at some distance beneath the toe of the slope, is character-
istic of the soil slumps in the area.

Rotational movement is dominant in slump failures, but the
failure surface is usually composite. The shear surface will tend to
follow any planes of weakness that it intersects, such as tuff beds,
bedding planes, and joints and so may not describe a perfect arc.
A slump usually starts with the failure of a block of material along a
curved plane. As the slide continues, the block usually disintegrates
beginning at the toe and becomes a mud or soil flow. This combina-
tion failure is common in the Astoria area because the abundant water
present mixes with the material as it fractures and further decreases
the shear strength. The material will continue to move downhill
until it reaches a stable position. Removal of material at the toe or
saturation of the failure plane may reactivate the slump. In addition,
the nearly vertical headscarsps produced by such sliding usually
cannot stand unsupported for very long, and so may fail, producing
progressive landsliding.

A good example of a slump-type failure is an active landslide
about 50 feet west of the intersection of Florence and Agate Streets
in the city of Astoria (Figure 21). The slide covers an area of
approximately 0.25 acres. Dense undergrowth makes it difficult to
determine the exact size of the slide block, but it appears to be about
125 feet long by 90 feet wide (Figure 22). The top of the slide is
delineated by an almost vertical headscarp 12 feet in height. The
flanks of the slide are mostly concealed, but close examination
reveals fractures roughly parallel to the dip of the slope and the
scarps of smaller slumps. The toe of the slide shows signs of dis-
integration and flow such as tension cracking and the destruction of
geological structures such as bedding (Figure 23). The movement
of the slide appears to have been primarily rotational as evidenced
by backtilting at the head of the slide of about 5°. The surface of
the slide block is hummocky, with numerous fractures and fissures.

The slide occurred on a slope of about 35° in the Middle Mud-
stone. Attitudes taken at the headscarp indicate a northeast dip
which is into the slope.

The slip surface extends through approximately 3 meters of
overlying residual soil into the zone of weathered rock. The deepest
exposed mudstones are highly fractured along bedding planes and
joint sets and exhibit a shear strength of 0.5 kg./cm.² at water
content present in the field. This value is substantially below that of
relatively unweathered mudstone, indicating an advanced degree of
disintegration. No tuffaceous interbeds were noted, although some
may exist in the strata beneath the slide. The material at the toe of
Figure 22. Schematic cross section of slump at Florence and Agate Streets involving weathered Middle Mudstone. Dip of bedding is into slope locally, but other structural features such as jointing may control slip surface.

Scale: 1" = 30'
Figure 23. Schematic map of slump in weathered Middle Mudstone at Florence and Agate Streets. Characteristic features include steep headscarp, backtilted head, bulging toe, and hummocky surface.
the slide consists of small (up to 0.25 inch) chips of light brown Middle Mudstone set in a reddish brown, highly plastic matrix. It appears that as the slide progressed, the material at the toe lost most of its strength and flowed plastically. The failure surface enters the mudstone at the head of the slide almost vertically and exits at the toe almost horizontally.

Water is locally abundant at the slide site. Seeps at the toe of the slide indicate that there is water flowing along the slip surface. During a winter visit, ponding was noted at the head of the slide block. In addition to the hydrostatic pressure exerted by the water present, erosion and piping along the failure surface may be further reducing the shearing resistance along it.

The sliding has affected two structures. Most of the rear parking of an apartment building at the top of the slope has dropped 4 meters. The toe of the slide has been encroaching on the corner of a private residence, burying it to a depth of 2 meters and threatening to push it off its foundation (Figure 24).

The background factors leading to this failure are dominated by the advanced weathering and low shear strength of the Middle Mudstone in this section of the city, and by the steepness of the slope. Excavation for the foundation of the house at the toe of the slope caused oversteepening and removed lateral support. The slope was also loaded at the top by the fill from construction of the parking lot.
Figure 24. Toe of slump at Florence and Agate Streets encroaching on residence.
This overloading and undercutting of an already steep slope in highly weathered Middle Mudstone set the stage for the failure.

The triggering cause of the slump at Florence and Agate Streets was most likely an occurrence of high hydrostatic pressure and addition of water weight during the rainy winter season, but the progressive loss of shear strength through weathering and/or the progressive development of a failure surface through unloading are as important. During the course of the winter of 74 75 (Oct 74 - May 75) the slide moved approximately 45 cm. downhill. The markers set by the writer for measurement purposes were repeatedly removed, so measurements were only approximate.

Other examples of slump-type failures occurring within the Middle Mudstone which show signs of continuing movement may be observed at Marine Drive, north of Florence Street (Figure 25) and at the intersection of Bristol and Erie Streets (Figure 26a and 26b). The slide on Marine Drive is buckling the pavement at the toe. The slide at Erie and Bristol is moving into the lot of the county highway garage at the rate of 15 to 25 cm. per year. This slide is being drained by horizontal drains, but continues to move, necessitating the removal of several yards of material from the yard each spring.

Slump failures are also common in soil embankments. Many of the roads in the Astoria area display the semicircular scars of fill slumps. Much of the fill used in the Astoria area has been
Figure 25. Looking north along Marine Drive. Slide block at right is encroaching on the sidewalk and buckling sidewalk and street.
Figure 26a. Head of slump at Bristol and Erie Streets showing approximately six feet of displacement.

Figure 26b. Toe of slump at Bristol and Erie Streets which is encroaching on County Highway yard.
constructed from the debris removed from adjacent cuts. Since most of the roads in the area rest on Middle Mudstone, many fills have been constructed from the Middle Mudstone and its weathering products. Schlicker and others (1972) report:

The high clay and silt content of this unit generally makes it unsatisfactory for fills unless there is rigid moisture control. In order to obtain 95% compaction the material must be near the optimum moisture. Only slight deviation from this will appreciably decrease the degree of compaction which can be obtained. Improperly compacted embankments are slowly permeable yet nearly impossible to drain due to capillarity, and erosion of fill slopes could be excessive.

Particularly good examples of slumps involving fill material may be observed at Niagara and 15th Streets and at many locations along Alameda Street and Irving Avenue (Figure 27). The slide at Niagara covers approximately 1.4 acres and appears to be a combination slump-earthflow of the fill supporting Niagara Street and the nearby residual soils (Figure 28). The headscarp appears to be nearly vertical, but is not readily accessible because it is obscured by more fill placed to bring the road base back up to grade. The scarp is concave in the direction of movement of the slide, which is typical of slumps. In general, the failure surface resembles the surface of a spoon-shaped failure as described by Varnes (1958) (Figure 29). The toe of the slide seems to have lost its coherence and spread out like a flow. The slide has damaged the sidewalk and
Figure 27. Slump in fill material on Alameda Street which has been repaired, but continues to move.

Figure 28. Head of slump on Niagara Street involving fill and soil materials. Note basalt fill used to bring the roadbase back up to grade.
Figure 29. Schematic map of fill and soil slump on Niagara Street. Characteristic slump features include multiple headscarps, closed depressions, en echelon fissures along flanks, hummocky surface, and bulging and flow at toe. Stippling denotes basalt fill emplaced to bring roadbed up to grade.
street, and has undermined and cracked the porch and foundation of a nearby house. The background conditions leading to the Niagara Street slope failure are the relative impermeability of the fill material, the low strength of the fill material and residual soils involved, and the load imposed by the roadway and traffic at the head of the fill. The triggering mechanism was probably the occurrence of high hydrostatic pressure coupled with the weight of water added to the fill by winter rainfall.

Rock and Soil Glides

A glide is the shear failure of a coherent block of earth materials along a predominantly planar failure surface. The most common glide phenomenon in the study area involves failure of thick residual soils along their basal contact with weathered rock. Another common glide is failure along bedding planes which dip in the same direction as the slope. As with slump failures, the failure surface is most likely to follow planes of weakness such as bedding planes or tuff interbeds. The characteristic features of a glide failure include a steep headscarp, tension cracks, and warping or disintegration at the toe. In the case of glide failures, the areal extent of the failure block will usually be very large in comparison to its thickness or depth.
Most of the landslides that have occurred on the north slope of the Astoria peninsula have probably been glide failures. Photographs of the large landslides of 1952, 1954, and 1955 show that the failure blocks covered as much as 25 acres but the failure surfaces were as shallow as six to eight feet. Local slumping is evident within the glide blocks, but the major mode of failure in these cases was shallow glide of the residual soils over weathered bedrock.

The landslide on the corner of 6th and Exchange Streets is a good example of glide failure in residual soils. The slide occurred in the residual soil of the Middle Mudstone on a slope of about $40^\circ$. The slide block is roughly planar, covers approximately .1 acre, and is about one meter thick. The headscarp is nearly vertical, as are the lateral fractures, and the toe is buckled and fissured. The slip surface is along the contact between the residual soil and the weathered Middle Mudstone. A mat of residual soil has broken loose on the hillside, pushing a frame house from its foundations at the base of the hill (Figure 30). The primary agent holding the block together seems to be the intergrown tangle of roots of the abundant underbrush (Figure 31). During construction of the house, a shallow cut was made in the hillside to a depth of about 1 meter, decreasing the lateral support of the rock and soil mat. The triggering mechanism seems to have been high hydrostatic pressure. The soil materials have a greater permeability than the underlying weathered Middle Mudstone,
Figure 30. Soil glide at 6th and Exchange Streets. Toe of slide pushed house from its foundations. Slide block is approximately outlined by dashed line.
Figure 31. Schematic cross section of landslide at 6th and Exchange Streets involving gliding of soil materials on weathered bedrock.

Scale: 1" = 8'
allowing downward percolation of precipitation to the contact between
them. The slowdown of percolation at the contact allows hydrostatic
pressure to build, eventually reducing the shear strength enough to
produce failure.

Shallow glide failure is the primary mode of failure on the north
side of the Astoria peninsula, and is common throughout the study
area. The dominant background factor responsible for these slides
is the character of the Middle Mudstone. In its outcrop area it is
characteristically mantled by a thick cover of highly plastic residual
soils. Even when the unstable material is stripped away before
construction, the slope may later fail either by progressive weathering
of the newly exposed material, or by the progressive development of
a failure surface through unloading. In all cases, the triggering
mechanism is probably elevated hydrostatic pressure.

Large blocks of Upper Sandstone have apparently moved down-
slope primarily by gliding on the underlying Middle Mudstone (Figure
32). On the south side of the Astoria peninsula large, isolated out-
crops of Upper Sandstone occur in several locations at elevations
below the underlying Middle Mudstone. Study of aerial photographs
reveals sharp, scarp-like cliffs above these outcrops and other land-
slide features such as fissuring of the rock still in place and disinte-
gration and disorientation of the material at the toe. The attitudes
of the bedding planes of the Middle Mudstone are generally disrupted,
Figure 32. Schematic cross section of landslide involving gliding of Upper Sandstone on bedding planes of underlying Middle Mudstone.
although fairly reliable attitudes are available in the faces of the head-scarps. The dip of the bedding in these locations is generally downslope, suggesting that failure in the Middle Mudstones was along bedding planes. In addition, tuffaceous interbeds are present in some outcrops and provide planes of reduced shear strength.

The background conditions affecting the Upper Sandstone block glides are the weight of the Upper Sandstone, the low strength of the Middle Mudstone, particularly the tuffaceous interbeds, and the downslope dip of the Middle Mudstone. Fissuring and jointing of the Upper Sandstone may also have played a part in background instability, but these features are rarely exposed in outcrop. The triggering mechanism was probably high hydrostatic head. The relatively impermeable Middle Mudstone inhibited the downward flow of water and forced most of it to seek other paths. This slowdown probably allowed considerable head to build up during periods of high precipitation, finally destroying the frictional resistance of the upper Middle Mudstone and allowing movement.

Mud and Soil Flows

Flow failures result from the loss of shear strength or liquefaction of an earth mass, and consequent downslope movement. The incidence of pure flow failure in Astoria is restricted, but flow occurring in conjunction with other failure types is extremely common.
As a slide progresses downslope fracturing and crumbling of the material usually occurs. In the case of sensitive materials, most of the shear strength is lost upon remoulding. In the case of non-sensitive materials, the abundant water available may mix with the fragments, further reducing their strength.

Most of the previously mentioned landslides involved some flow movement. In many cases, slumps in fill materials deteriorate rapidly into flows due to their low degree of consolidation and high water content. The writer observed no cases of current landsliding which were purely flow phenomena.
EVALUATION OF THE LANDSLIDE PROBLEM IN THE ASTORIA AREA

The occurrence of landsliding in the Astoria area is not random. Slope instability is controlled by a number of quantifiable and map-able background factors. When the mechanisms of various slides observed in the study area are related to these background factors, a pattern of failure types can be discerned. The mode of slope failure in the Astoria area is largely controlled by the geological setting. As would be expected, the Middle Mudstone of the Astoria Formation is the major problem unit. While the sandstone, basalt, and gravel units exhibit various kinds of slope failure, the most troublesome and costly of the Astoria landslides have occurred in the Middle Mudstone and its weathering products.

Structural Control

During the course of field and photographic study of past and present landslides in the Astoria area, a pattern of failure types was noted. In photographs of landslides occurring on the north side of the Astoria peninsula, the slide blocks appear to be roughly planar. The failure planes seem to be quite shallow in respect to the lateral dimensions of the slide blocks. A recent slide in the area is a glide failure, with the failure surface occurring at roughly the contact between the residual soil and the underlying weathered bedrock.
Based on photographic evidence supplied by the Astoria city engineer's office and on field examination of old and recent slide sites, the writer suggests that the landslides on the north side of the Astoria peninsula are primarily shallow glide failures, involving the movement of soil materials over the weathered Middle Mudstone. Exceptions to this rule are the numerous local slump failures occurring primarily in fill materials. The dip of the strata on the north side of the peninsula is predominantly to the south, or into the slope of the hill. This structural environment presents no inherent planes of weakness such as bedding planes or tuffaceous interbeds subparallel to the slope. The primary plane of weakness in this area is the contact between the residual soils and weathered rock. The moderately permeable soils allow downward percolation of precipitation, but the only slightly permeable weathered rock presents a hydrological barrier. During heavy rainstorms, high hydrostatic pressure may occur along this plane, which coupled with the extra weight of the water added to the slope, may trigger failure.

On the south side of the peninsula, the primary mode of slope failure is different. In current and recent slides in this portion of the study area, the dominant mode of failure appears to be slump or rotational failure along deep seated, curved failure surfaces. In this part of the study area the strata dip predominantly to the south, subparallel to the dip of the slope. It is assumed that the reason for the
higher occurrence of deep seated slump failures in the southern half of the study area is structural control of the failure surface. Bedding planes and tuffaceous interbeds represent planes of low shear strength. The progressive development of a failure surface will tend to intersect and follow these planes, possibly only for short distances, producing what Terzaghi (1948) calls base failures.

**Development of the Failure Plane**

In the case of shallow, glide type failure, the development of the failure plane is probably rather rapid, preceding the actual slide by days or even hours. The stage is set by the progressive weathering of the Middle Mudstone and the aeration and mixing of the residual soils by plant root growth. As water percolates downward, it encounters progressively less permeable material and its velocity is reduced. Continued rainwater infiltration causes a backup to occur, and the hydrostatic pressure throughout the system begins to rise. As soon as the pressure reaches the magnitude required to effectively reduce grain to grain contact, a failure surface will develop, perhaps only locally at first, and will spread rapidly throughout the eventual slide area. In addition, the water content of the residual soil during the dry months may be low enough that the pore water pressure is negative. In this case, much of the shear strength of the soil is produced by the surface tension of the interstitial water. As the
water content increases, the negative pore water pressure is dissipated, reducing the shear strength enough to allow failure.

In the case of slump failures, it was assumed that the mode of development of the failure surface in overconsolidated materials was similar to that of failures in soil materials, that is, that the development of the failure surface was very rapid and could be simulated in the laboratory through the use of triaxial deformation devices. It became evident, however, that strength determinations on intact samples of overconsolidated clay shales and mudstones bear little resemblance to the shearing resistances calculated from slides in the field (Skempton, 1964). It has since been suggested that slope failures in these types of materials occur along pre-existing planes which display much lower shearing resistance than the intact material (Bjerrum, 1967). Bjerrum describes the slow, progressive development of such planes, prior to the actual failure. He states that overconsolidated clay shales and mudstones possess great latent strain energy due to their consolidation by pressure, and that upon unloading by erosion and uplift or by artificial means, this energy is released in the form of rebound. He also suggests that through rebound, a continuous and complete failure surface will develop before sliding occurs. After development of the failure surface, other stresses such as hydrostatic pressure or external loading will initiate movement along the surface.
Thus the type and extent of slope failures in the Astoria area are governed by the characteristics of the materials in which the slide occurs and by the structural environment. Landslides in the northern half of the study area are primarily shallow glide failures occurring in the residual soils, while landslides in the southern half of the study area are primarily slump failures, involving weathered rock.
RELATIVE LANDSLIDE RISK IN THE ASTORIA AREA

The topography of most of the Astoria peninsula reflects the extensive history of landsliding in the area. Slope failure is a major factor in the process of degradation in the Oregon Coast Range. Schlicker and others, in a series of reports (1972, 1973), has described the landslide problem in the western Coast Range and has mapped problem areas. In Astoria, most of the outcrop area of the Middle Mudstone is mapped as landslide terrain. Yet within Astoria there are areas of higher and lower landslide risk. Obviously, a major stability factor is the inclination of slopes, but other factors also play important parts. If the factors that control slope instability in the Astoria area are identified, they can be roughly quantified and areally mapped. Mapping each of the factors individually facilitates their comparison from location to location within the study area. In addition, if each factor is quantified or ranked as to its significance in slope instability, mapped areally, and superimposed on the other factor maps similarly prepared, areas of multiple adverse factors can be delineated. Since slope failure is usually the result of the interaction of several factors, it is suggested that these areas are more prone to slope failure than other areas with fewer adverse background factors.
Factor Selection

The factors to be mapped must be specific enough to be subdivided and ranked with respect to landslide risk, but must also be general enough to be descriptive and meaningful in slope stability prediction. Highly specific parameters such as clay mineralogy or porosity must be considered within the framework of more descriptive classes such as engineering characteristics of the geological units, or groundwater and drainage conditions. The quantification and ranking of the factors must necessarily be judgemental in order to be descriptive. In addition no provision has been made for ranking the factor classes themselves. McHarg (1969) points out that in factor mapping there is no possibility of comparing the factors, that they must be considered individually and then as a compilation. Although some factors may be more significant in producing landslides than others, they all must be considered as having an equal value for this technique. The factors and their subdivisions have been selected based on opinions developed by the writer during the course of this study. The factors selected for mapping to best reflect the background conditions affecting slope stability in the Astoria area are:

1. Engineering characteristics of the bedrock units
2. Engineering characteristics of the surficial units
3. Structural and stratigraphic features
4. Slope
5. Groundwater and drainage conditions
6. Historical landslide distribution

Copies of individual factor maps at a scale of 1:8000 prepared by the writer are shown at reduced size below.

Engineering Characteristics of the Bedrock Units

No single factor of the bedrock geology can be identified as the one controlling slope stability. Shear strength, for instance, may not adequately convey the expected behavior of a rock unit in a slope. Features such as plasticity, cementation, and mineralogy all play a part in slope stability. On the basis of laboratory testing and field observation of the units exposed in the study area, four categories of bedrock stability have been delineated (Figure 33). They are, in order of decreasing stability: 1. igneous crystalline rocks; 2. high strength, low plasticity units; 3. moderate strength, moderate plasticity units; and 4. low strength, high plasticity units.

Engineering Characteristics of the Surficial Units

In many cases, it is the materials that overly the bedrock geology that fail on slopes. The surficial units, classified from high to low relative stability, are: 1. low plasticity materials, 2. moderate plasticity materials, and 3. high plasticity materials. Fill material, although commonly unstable in the study area, is not
- Igneous crystalline rocks
- High strength, low plasticity sedimentary rocks
- Mod. strength, mod. plasticity sedimentary rocks
- Low strength, high plasticity sedimentary rocks

Scale: 1: 64000

1 mile

Figure 33. Factor map of the engineering characteristics of the geological units of the Astoria peninsula area.
considered here since unknown variables such as source materials used and the degree of compaction govern its stability (Figure 34).

**Structural and Stratigraphic Features**

In the Astoria area, structural features of the bedrock are a major factor in the type and severity of slope failure. Features such as joints and bedding planes represent planes of lower shear strength, and may be the controlling factors in the location of the failure surface in many slides. Four classifications of structural and stratigraphic features are used. They are, in order of decreasing resistance to slope failure; 1. few or no structural features; 2. strong units overlying weaker units; 3. numerous structures, not parallel to slope; 4. numerous structures sub-parallel to slope (Figure 35).

**Slope**

The slope map of the Astoria peninsula was prepared from aerial photographs, topographic maps, and field observations. The slope groups, after Schlicker and others (1972) are: 1. 0-9%, 2. 10-24%, 3. 25-49%, 4. over 49% (Figure 36).
Figure 34. Factor map of the engineering characteristics of the surficial units of the Astoria peninsula area.
- Few or no structural features
- Strong units overlying weaker units
- Numerous structures, not parallel to slope
- Numerous structures sub-parallel to slope

Scale: 1:64000

Figure 35. Factor map of the stratigraphic and structural features of the Astoria peninsula area.
Figure 36. Factor map of the slope of the Astoria peninsula area.
Groundwater and Drainage Conditions

Water is probably the most important single triggering mechanism active in landsliding in the Astoria area. A standard groundwater map of the average piezometric surface may be misleading because it is the fluctuation in the amount and location of water which is most significant in triggering slides. In addition, it is suggested that due to the generally low permeability of the earth materials in the area, the piezometric surface is effectively at the ground surface over most of the area during much of the rainy season. More significant features in producing landslides in the study area are the flow patterns and drainage of the ample precipitation that the area receives annually. The primary consideration of this factor is the drainage characteristics of the rock units exposed. Highly plastic materials are typically slowly permeable. An almost universal condition in the study area is the presence of permeable soils overlying less permeable weathered rock. The groundwater and drainage conditions mapped are, in order of increasing landslide risk: 1. good internal drainage; 2. permeable units overlying impermeable units in slopes; 3. undercutting and toe erosion; 4. poor internal drainage (Figure 37).
- Good internal drainage
- Permeable units overlying impermeable units in slopes, or fair internal drainage
- Poor internal drainage
- Undercutting and toe erosion

Scale: 1:64000

1 mile

Figure 37. Factor map of drainage conditions of the Astoria peninsula area.
Historical Landslide Distribution

The recognition and location of old landslides is important in ascertaining landslide risk in that excavation or construction activity may reactivate old landslide blocks. The categories of relative landslide activity from most stable to least stable are: 1. no indications of landsliding; 2. landslide topography; 3. ancient landslides; 4. recent landslides (Figure 38).

Figure 39 is a tabulation of the mapping factors and their relative effect on the slope stability of the geological and surficial units of the Astoria area. The adverse background conditions present are plotted opposite the mapping units and their effectiveness in producing landslides in each unit is rated from 0, not effective, to 3, highly effective. Averaging the effectiveness of all the adverse factors for each unit horizontally, it can be seen that the Middle Mudstone and its associated Chitwood soils have the most adverse conditions, followed closely by the Troutdale Formation. This rough quantification of background conditions supports the supposition that the Middle Mudstone is the major problem unit, and that its low shearing strength, steep slope and poor drainage are the main reasons for its instability.
Figure 38. Factor map of historical landslide activity in the Astoria peninsula area.
### Effectiveness in producing slope failures:

- 0 - not effective
- 1 - low effectiveness
- 2 - moderate effectiveness
- 3 - high effectiveness

### Adverse background factors

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<th>Low Shearing Strength</th>
<th>Potential for Sudden Settlement</th>
<th>Shrink-swell Potential</th>
<th>Numerous Bedding Planes</th>
<th>Numerous Joints and Fractures</th>
<th>Steep Slope</th>
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Figure 39. Relative effectiveness of adverse background factors in producing slope failure in the Astoria area.
CONCLUSIONS

The strata of the Astoria peninsula area are dominated by the Miocene Astoria Formation, a sequence of interbedded marine sandstones and mudstones. Also present are Miocene basalts of the Depoe Bay type and Pliocene quartzitic gravels inferred to be equivalent to the Troutdale Formation (Hodge, 1933). Three members of the Astoria Formation are informally referred to in this report. The oldest is the Lower Sandstone, a poorly sorted, thinly bedded, lithic wacke inferred to have been deposited in a mid-shelf or delta front environment. Unconformably overlying the Lower Sandstone is the Middle Mudstone, a sequence of thinly laminated siltstones and claystones inferred to have been deposited at bathyal depths. Intricately interbedded and intertongued with the Middle Mudstone is the Upper Sandstone, a structureless, subfeldspathic, lithic wacke, probably spilled onto the deep water surface of the muds from shallower water deposits. The Depoe Bay Basalt occurs as sill and dike complexes along the central ridge of the peninsula and locally as breccia and pepperitic masses. Quartzitic gravels thought to correlate with the Troutdale Formation unconformably overly the Middle Mudstone in the western part of the study area.

Previous investigators (Howe, 1926, Seitz, 1948) have mapped an eastwest trending syncline with the axis on the south slope of the
This syncline was mapped based on the occurrence of apparently northward dipping strata on the south slope of the peninsula. The writer suggests that these attitudes are the result of disruption of the strata by landslides. It is also suggested that the strata of the Astoria Formation dip generally to the south at an inclination of approximately 25° in the Astoria peninsula area. Topographic and contact relationship evidence in the eastern part of the study area suggest the presence of a northeast-southwest trending normal fault along the axis of the stream valley of Mill Creek.

In order to consider the effects of weathering on the engineering characteristics of the geological units present in the Astoria peninsula area, each unit was subdivided into 3 weathering categories for description; 1) unweathered rock, 2) weathered rock, 3) residual soils. The Lower and Upper Sandstones and their weathering products display relatively high strength and good drainage characteristics. Neither of the sandstone units are well cemented, so that ravelling and sudden settlement of the materials may present potential problems. The Middle Mudstone and its weathering products display much lower strength and very poor drainage characteristics. The Middle Mudstone has been lithified by compaction rather than cementation so that it possesses the engineering characteristics of overconsolidated clay shale. It is nearly impermeable, except along fractures, and weathers rapidly. The clay fraction of the mudstone is dominated by
montmorillonite making the unit susceptible to changes in volume and shear strength upon addition of water. Bedding planes and tuffaceous interbeds are common in the Middle Mudstone, representing planes of weakness. The residual soils of the Middle Mudstone exhibit similar strength characteristics and poor drainage, as does the matrix of the Troudale Formation. The Depoe Bay Basalt and its weathering products exhibit good strength and drainage characteristics and stand in very steep slopes.

As can be seen from Figure 39, the main problem units in slope stability are the Middle Mudstone of the Astoria Formation and its residual soils. In all the recently active landslides observed by the writer, weathered Middle Mudstone or fill material from the Middle Mudstone were the materials in which the shear failure occurred. The resistant Depoe Bay Basalts hold the mudstones in slopes steeper than those which it assumes elsewhere. The high proportion of expandible clays, the unit's impermeability, and its low degree of lithification make the Middle Mudstone especially prone to slope failure.

The primary geologic hazard of the Astoria peninsula area is landsliding. Factor maps of the background conditions contributing to slope instability were used to construct an areal landslide risk map for the Astoria peninsula area (Plate 2). The compilation of the factor maps suggests that the south slope of the Astoria peninsula is generally
a higher landslide risk area than the north slope, although most of the recorded landslides in the city have occurred on the peninsula’s north slope. Two reasons are suggested to explain this apparent discrepancy: 1. That landslides on the southern, less populated slope of the peninsula often go unreported and are rapidly overgrown and obscured, and/or 2. That the higher density of urbanization on the north slope of the peninsula has precipitated many of the reported slope failures. The writer suggests that the south slope of the Astoria peninsula is a higher landslide risk area than the north slope due to its structural environment and that urbanization may present more severe slope stability problems than the north slope.


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