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GEOLOGY OF THE STACKS AND REEFS OFF THE SOUTHERN OREGON COAST*

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Introduction

It is sometimes difficult to relate the results of onshore and offshore geologic studies, partly because of information gaps in nearshore waters where ships cannot operate. Offshore sea stacks and shoal areas with numerous stacks, locally called "reefs" (figure 1), can be useful in bridging the gap between onshore and offshore bedrock geology. This is especially true in areas like southern Oregon, where the geology is complex and structural features trend at low angles to the shore (figure 2). One cannot always assume that stacks are similar to rocks immediately onshore.

The stacks off the southern Oregon coast have been studied very little because of difficulties of access (see, for example, Weissenborn and Snavely, 1968). Work described herein was helicopter-supported; skillful piloting by Earl Lady permitted landings on or close approaches to many stacks. To help delineate the structure, field work was supplemented by high-altitude aerial photographs, which revealed the outlines of kelp beds associated with shallow outcrops on the sea floor.

Study of the geology of the stacks of this coastal area adds to our knowledge of the distribution, character, and structure of Upper Jurassic, Lower Cretaceous, and Upper Cretaceous sedimentary rocks.

Stratigraphy

Otter Point Formation

General character: The Otter Point Formation and probably equivalent rocks crop out along parts of the coast from Whalehead Island north to Blacklock Point and beyond (figure 2). Among the more important offshore occurrences of the Otter Point are Mack Reef, part of Rogue River Reef, Island Rock, Redfish Rocks, Orford Reef, and part of Blanco Reef (figures 2-10). The formation was named for its type section at Otter Point (figure 7) and dated by Koch (1966) as latest Jurassic (late Tithonian or late Portlandian and Purbeckian). It is a eugeosynclinal assemblage of mudstone, sandstone (largely graywacke), volcanic rock, conglomerate, and bedded chert. Medium- to coarse-grained igneous rocks are commonly associated with the volcanic rocks in the stacks and are probably hypabyssal equivalents of the extrusive rocks.

The Otter Point Formation commonly is intensely folded and faulted. Although

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most of the Otter Point Formation in the stacks appears unmetamorphosed in outcrop and has no metamorphic fabric, microscopic and X-ray diffraction studies show that low-grade metamorphism is common. Bodies of ultramafic rock, largely altered to serpentinite, and glaucophane-bearing schist and phyllite are commonly associated with the Otter Point Formation onshore (Koch, 1966; Boggs and Baldwin, 1970; Lent, 1969) but were not found offshore.

Sandstones: Sandstones are widely distributed in the Otter Point Formation of the offshore stacks. Most of the sandstones that form stacks are thick bedded; interbedded mudstone is uncommon. Thin graded sandstone beds separated by mudstone layers are more typical of the Otter Point Formation onshore (Koch, 1966, p. 39) but compose only minor parts of some stacks. Most of the sandstones of the stacks contain a very high proportion, commonly about 75 percent, of rock fragments, the majority of which are volcanic. Quartz, polycrystalline quartz, and chert fragments make up less than 20 percent of the volcanic lithic sandstones of the stacks. Plagioclase is common but the potash feldspar content of the volcanic lithic sandstone is less than 1 percent.

Volcanic lithic sandstones occur in the Otter Point Formation onshore as well as offshore, but onshore they are subordinate or subequal to arkosic and chert-dominated lithic sandstones (Koch, 1966, p. 39-40, and Lent, 1969, p. 111). Sandstones of the types dominant onshore are rare in the stacks except in the Orford Reef, where massive coarse-grained sandstone containing only 50 percent rock fragments is common.

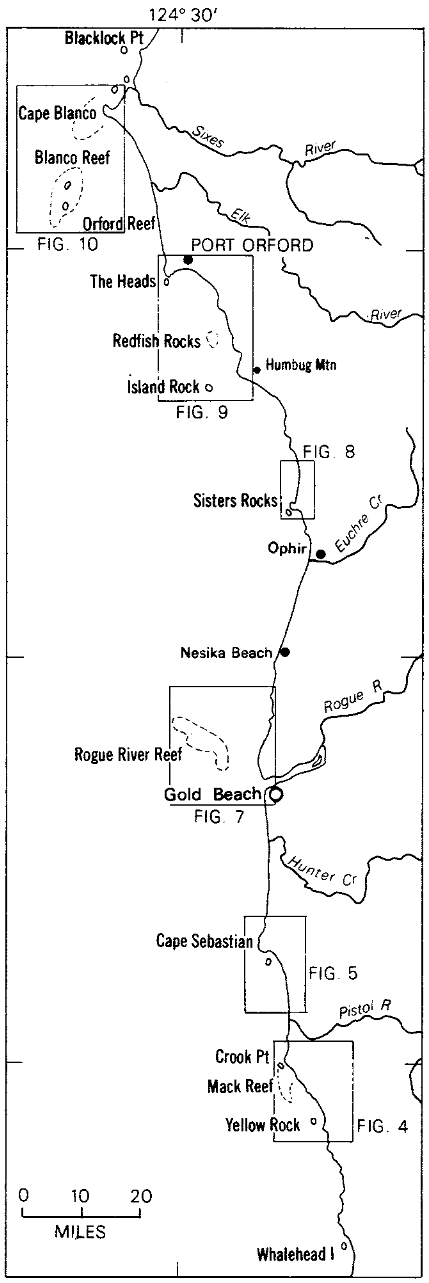
Most of the volcanic lithic sandstones were classified as graywacke in the field. The detrital matrix content is very difficult to estimate in thin section, however, because it is mineralogically similar to the rock fragments, because the rock fragments have been deformed by pressure from the more competent grains, and because textures have undergone incipient modification during metamorphism. Some of the sandstones may have a low matrix content and therefore may be subgraywackes rather than lithic graywackes according to the classification of Pettijohn (1957, p. 290-293).

The assemblage of sedimentary structures in Otter Point sandstones onshore suggests deposition by turbidity currents (Koch, 1966). The Otter Point sandstones in the stacks also probably are turbidites.

Volcanic rocks: Volcanic rocks are subordinate to sedimentary rocks in the Otter Point Formation onshore but are abundant in the stacks (figures 2-10), probably because of their resistance to erosion. Massive flows, pillowed flows, and breccias are the most common types. Yellow Rock (figure 4) is composed at least partly of bedded tuff. Most of the volcanic rocks are andesitic in composition, but some are basaltic. A few contain quartz. Most have been metamorphosed, as described in a following section.

Medium- to coarse-grained rocks of dioritic composition are associated with the extrusive rocks in Mack Reef and on Island Rock. They occur also as clasts in many of the breccias. Some of the breccias containing dioritic clasts have a red hematite-rich matrix. The dioritic rocks probably are hypabyssal, and the breccias containing dioritic clasts may be vent breccias.

Conglomerates: Conglomerates are fairly common in the Otter Point Formation of the offshore stacks. Conglomerate composed largely of pebbles of volcanic



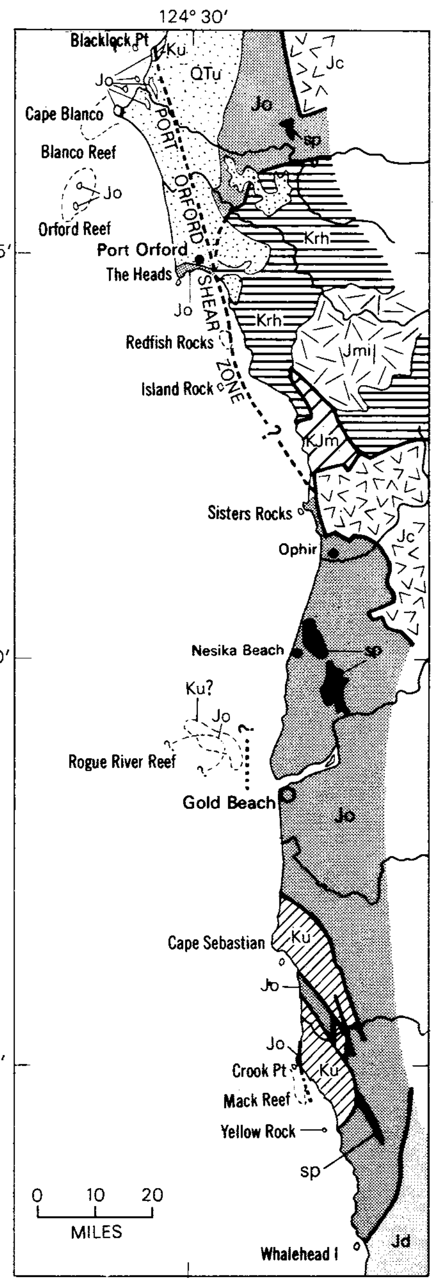


Figure 1. Index map of southern Oregon coast. (Left)

Figure 2. Geology of southern Oregon coastal region. Onland mapping from sources listed in figures 4-10 and from Lent (1969) and Janda (personal communication). (Right)

rocks is a common type. Such volcaniclastic conglomerates are subordinate to conglomerates composed of chert clasts in the Otter Point Formation onshore (Koch, 1966, p. 40) but are common in the Whalehead Formation of Widmier (1963), which crops out along the coast from Yellow Rock to Whalehead Island (figure 2) and is considered to be correlative with the Otter Point Formation (Koch, 1966, p. 36-38).

Bedded cherts: Bedded chert unaccompanied by other rocks forms few stacks in the area studied. However, chert lenses are commonly associated with volcanic rocks in the stacks. Most of the chert is of reddish color. It is veined by quartz and probably is partly recrystallized.

Metamorphism of the Otter Point Formation: Most of the offshore volcanic rocks, sandstones, and conglomerates of the Otter Point Formation have undergone low-grade metamorphism. They are largely unaltered texturally except very near shear surfaces and are thus in textural zone 1 of Blake, Irwin, and Coleman (1967). The degree to which the rocks approached metamorphic equilibrium varies greatly, but only the very sheared rocks have completely recrystallized. The relation between alteration and shearing indicates that the changes are truly metamorphic and occurred during deformation of the rocks.

The most widespread mineralogic change has been the alteration of relatively calcic plagioclase to albite. The altered nature of the plagioclase is indicated by its abundant inclusions of chlorite and colorless to pale-green mica and by the occurrence of relict calcic plagioclase in rocks that were not completely albitized. In the incompletely albitized rocks, grains of clear, commonly zoned plagioclase ranging in composition from oligoclase to labradorite have been partly replaced by cloudy albite along veinlets and in irregular patches.

Of the four offshore clastic sedimentary rocks thin-sectioned, only the massive sandstone from Best Rock in the Orford Reef (figure 10) contained largely unaltered plagioclase. Of the 12 offshore volcanic and dioritic rocks thin-sectioned, only the andesite tuff on Yellow Rock (figure 4) contained largely unaltered plagioclase. Onshore, Koch (1966, p. 40-41) classified half of the andesitic flow rocks as altered; and most of the volcanic rocks examined by Lent (1969, p. 43-55) were altered and contained sodic plagioclase. The albitized volcanic rocks are here classified as keratophyres (andesites with albitized plagioclase) and spilites (basalts with albitized plagioclase).

Most of the albitized igneous rocks contain nearly unaltered hornblende and/or clinopyroxene. In patches or along sheared surfaces, the ferromagnesian minerals of some rocks have been partially or completely altered to chlorite. Chlorite commonly also occurs as patches interstitial to the feldspar and ferromagnesian minerals of the volcanic rocks; the interstitial chlorite may be an alteration product of glass. Chlorite is a common alteration product of the volcanic rock fragments in the sandstones and conglomerates, but some of these rocks contain unaltered detrital grains of pyroxene and hornblende.

Other metamorphic minerals occurring in veinlets and as disseminated grains in the Otter Point Formation offshore include prehnite, found in 7 of the 12 volcanic rocks thin-sectioned, and pumpellyite, found in 3 of the volcanic rocks and in 2 metagraywackes. Optical identifications of the two minerals were checked by X-ray diffraction powder patterns. Actinolite was found on Island Rock and occurs with pumpellyite in the metavolcanic or metadioritic rock forming Sea Rock in the Orford Reef (figure 10); this is the only rock observed in which all the original minerals

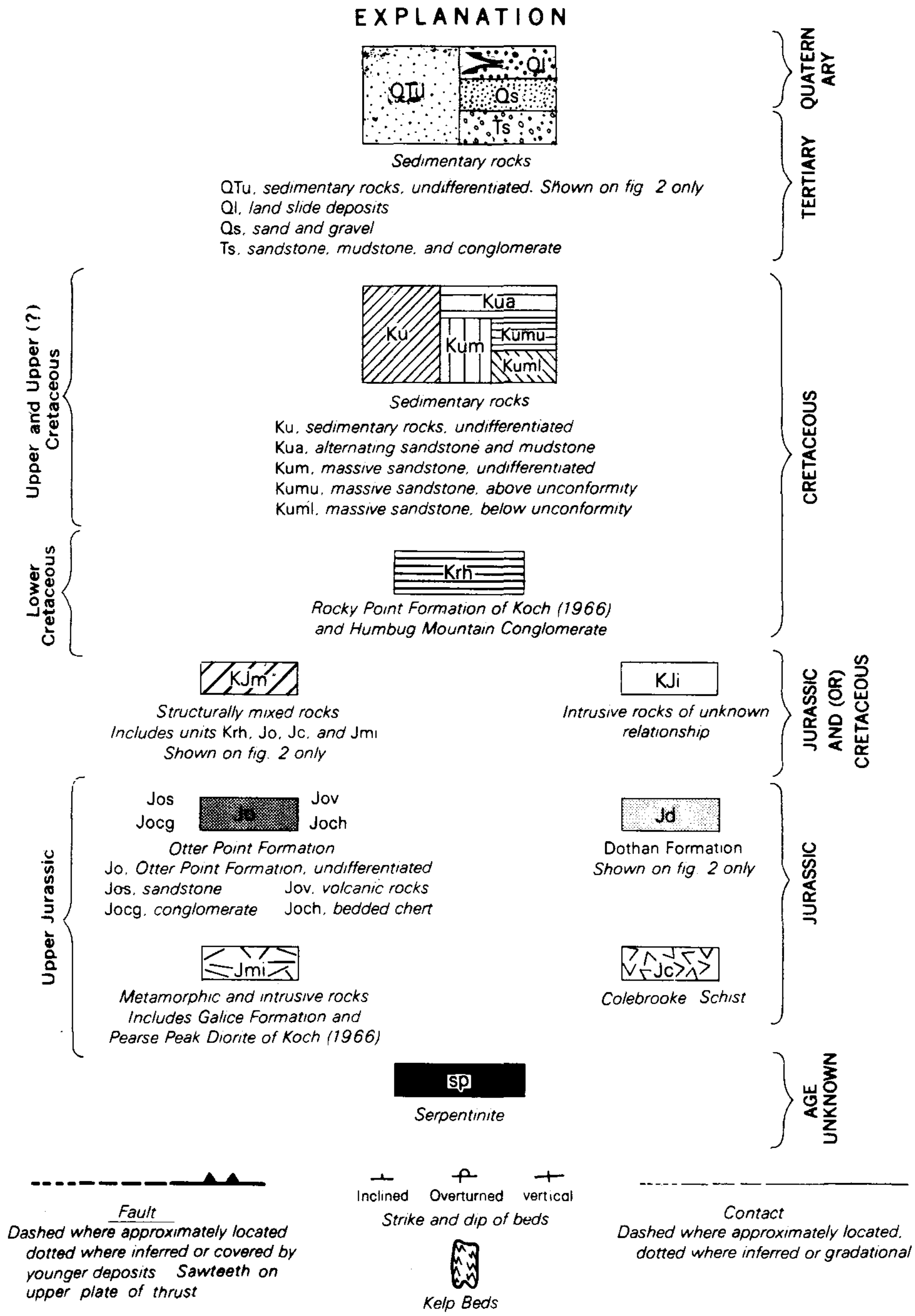


Figure 3. Explanation of figures 2, 4, 5, 7, 8, 9, and 10.

have been destroyed and a metamorphic fabric has been acquired. Calcite is the only carbonate alteration product found in the rocks.

The occurrence of pumpellyite is especially significant in placing the rocks in a metamorphic facies. The assemblage quartz-albite-chlorite-muscovite-pumpellyite in some of the metagraywackes is indicative of the pumpellyite zone of Blake, Irwin, and Coleman (1967) or the prehnite-pumpellyite metagraywacke facies of Coombs (1960, 1961); see also Hawkins, 1967). The albite-chlorite-prehnite and albite-chlorite-pumpellyite assemblages found in the metavolcanic rocks are less definitive but suggest that the metamorphism reached at least the zeolitic facies of Turner and Verhoogen (1960, p. 532) or the equivalent laumontite-prehnite-quartz facies of Winkler (1965, p. 137-141). Lent (1969, p. 52-55) specifically refers certain Otter Point metavolcanic rocks onshore to the laumontite-prehnite-quartz facies, and Coleman (personal communication, 1969) has found laumontite in the Otter Point onshore.

Humbug Mountain Conglomerate and Rocky Point Formation of Koch (1966)

The Humbug Mountain Conglomerate and the conformably overlying Rocky Point Formation of Koch (1966) form most of the coast from Port Orford to near Sisters Rocks (figure 2). Both formations were defined and dated as Early Cretaceous (Valanginian) by Koch (1966). Koch's Rocky Point Formation, whose name unfortunately is preempted for Pennsylvanian rocks in Oklahoma and Tertiary rocks in Oregon, is composed of sandstone, largely of graywacke type and occurring in graded beds, and mudstone. Stacks formed of Lower Cretaceous rocks seem not to occur offshore more than a few tenths of a mile. Although the petrologic differences between some Otter Point and Lower Cretaceous sandstones are subtle (Koch, 1966, and Lent, 1969), the close association of volcanic rocks and sandstones in the reefs excludes the possibility of these rocks being either the Humbug Mountain or Rocky Point rather than the Otter Point Formation.

Upper Cretaceous and probable Upper Cretaceous rocks

Several areas of known and probable Upper Cretaceous rocks are found along the southern coast of Oregon (figure 2). The largest is in the vicinity of Cape Sebastian; the rocks in this area have been described and dated by Howard and Dott (1961) but have not been named. Small areas of probable Upper Cretaceous rocks occur at Blacklock Point (Dott, 1962, p. 130) and near Bandon (Baldwin, 1966, p. 190). During the present study, sandstone and subordinate conglomerate very similar to the Upper Cretaceous rocks at Cape Sebastian were found in the Rogue River Reef (figure 7). Pelecypod molds were found but not collected on Pyramid Rock. Sandstone and subordinate conglomerate similar to rocks at Cape Sebastian were found in part of the Blanco Reef (figure 10) but cannot be as certainly correlated because exposures are too limited for lithologic comparison and fossils have not been found.

Petrographic analyses show that the probable Upper Cretaceous sandstones in the Rogue River and Blanco Reefs are similar in composition to the Upper Cretaceous sandstones in the Cape Sebastian area (table 1). Dott (1965, p. 4692) has shown that Upper Cretaceous sandstones in southwest Oregon are characterized by their higher content of quartz and potash feldspar and lower content of chert fragments, rock fragments, and detrital matrix than other sandstones of southwest Oregon ranging in age from Jurassic to Eocene. Although the petrographic analyses presented here

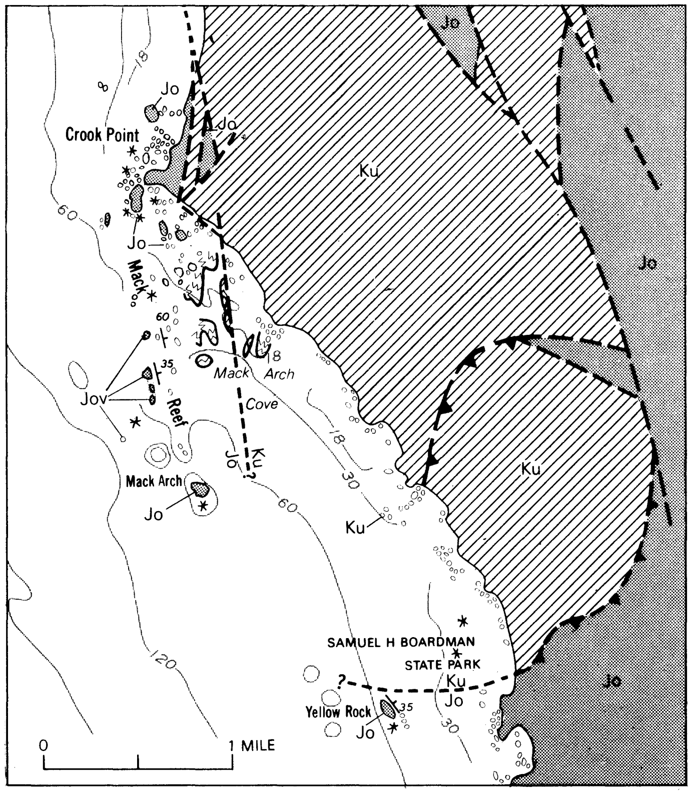


Figure 4. Geology of Mack Reef and vicinity. Onland mapping modified slightly from Howard and Dott (1961) and Widmier (1963).

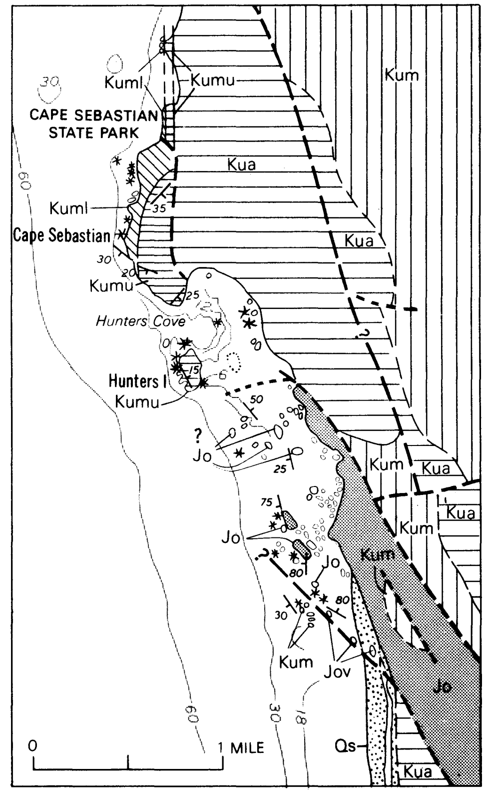


Figure 5. Geology of stacks near Cape Sebastian and vicinity. Onland mapping modified slightly from Howard and Dott (1961).

Table 1. Petrographic compositions of Upper Cretaceous and probable Upper Cretaceous sandstones

Component	Cape Sebastian area (ave. of 2 samples)	Rogue River Reef (ave. of 3 samples)	Blanco Reef 1/ (ave. of 3 samples)
Quartz	25	27	16
Polycrystalline quartz	6	6	5
Chert 2/	2	2	2
Rock fragments	27	26	28
Plagioclase	16	14	21
Potash feldspar	8	7	8
Flaky minerals 3/	3	1	4
Heavy minerals 4/	4		1
Carbonate cement		14	5
Detrital matrix 5/	9	3	10

1/ Pebble fraction excluded from analysis of one sample.
2/ Some silicic volcanic rock fragments may have been misidentified as chert, and some impure chert may have been misidentified as rock fragments.
3/ The flaky minerals include biotite, muscovite, and chlorite; biotite is the most common.
4/ The heavy minerals include, in approximate order of abundance, epidote, black opaque minerals, sphene, and apatite.
5/ Some squeezed rock fragments may have been misidentified as matrix.

differ in detail from those of Dott, the low matrix content and relatively high mineralogic maturity of the Upper Cretaceous sandstones in the Cape Sebastian area and their probable correlatives in the Rogue River and Blanco Reefs are easily recognizable in hand specimen by the light color of the sandstones.

In addition to petrographic similarity, the correlation of the light-colored sandstones in the Rogue River Reef with the Upper Cretaceous sandstones at Cape Sebastian is suggested by the similarity in sedimentary structures and stratigraphic sequence. The Upper Cretaceous rocks in the Cape Sebastian area have been divided into a massive sandstone unit and an overlying sandstone-shale unit (Howard and Dott, 1961). Outcrops in the cliffs at Cape Sebastian, which are nearly inaccessible by land but were visited by helicopter, reveal a further subdivision of the massive sandstone unit. An angular unconformity having a discordance of 16° at one point divides the massive sandstone into two units (figure 5). No fossils have been found in the lower sandstone unit, but its similarity in composition to the upper unit suggests that it is not much older.

Both units are composed largely of sandstone, but a boulder-bearing conglomerate forms the base of the upper sandstone unit, and pebbly sandstone and conglomerate are subordinate rock types throughout the lower sandstone unit and the lower half of the upper sandstone unit. The lower sandstone unit is characterized by common graded bedding; a few beds are made up of unlaminated but graded basal parts, middle parts that have parallel lamination, and upper parts that have current-ripple lamination. This assemblage of sedimentary structures strongly suggests

Figure 6. Aerial photograph of Rogue River Reef.

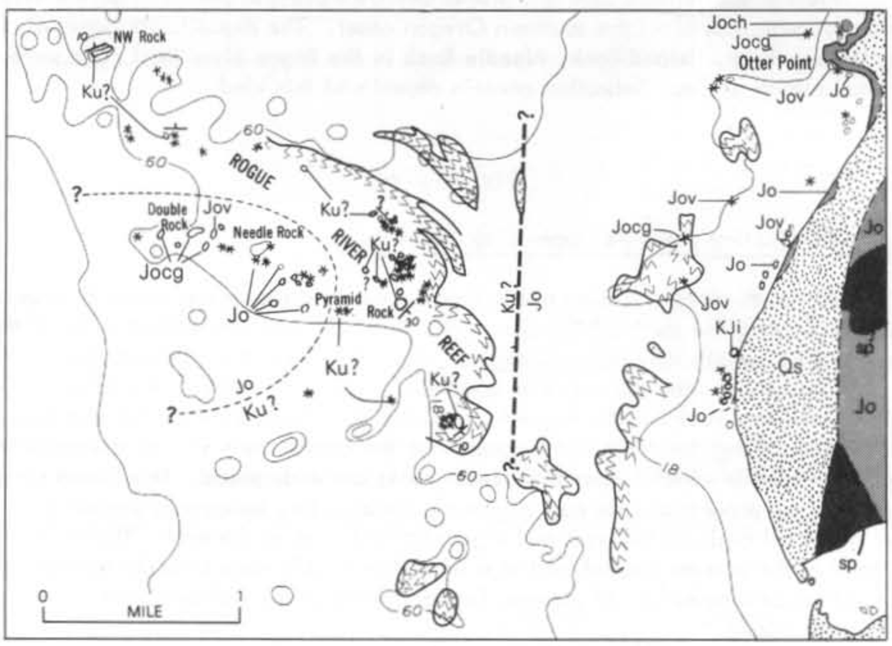


Figure 7. Geology of Rogue River Reef and vicinity. Onland mapping modified slightly from Koch (1966).

deposition by turbidity currents (Bouma, 1962). The upper sandstone unit, on the other hand, is characterized by cross-laminated beds 6 inches to more than 1 foot thick and a few symmetrical ripple marks. A shallow marine origin is probable.

On Pyramid Rock, the best exposure of probable Upper Cretaceous rocks in the Rogue River Reef (figure 7), both the graded, probable turbidite facies and the crossbedded, probable shallow-marine facies are present. The crossbedded facies apparently overlies the graded facies, but the contact itself is inaccessible. Other exposures of probable Upper Cretaceous sandstones in the Rogue River and Blanco Reefs are not large enough for identification of the sedimentary facies.

Tertiary rocks

Eocene rocks crop out along the Oregon coastline south of the Cape Arago area only at Cape Blanco (Dott, 1962), where they are mainly mudstones and do not form stacks. Miocene and Pliocene rocks crop out along portions of the Oregon coast from Coos Bay south to the Port Orford area (Baldwin, 1945, 1966; Dott, 1962; Koch, 1966). They are not present onshore from the Port Orford area south to northern California, where they again occur onshore (Moore and Silver, 1968), but beds of presumed younger Tertiary age are present on much of the continental shelf (Mackay and Kulm, 1968; Moore and Silver, 1968; Bales and Kulm, 1969). Miocene sandstone forms one stack on the beach at Cape Blanco, but Miocene or Pliocene rocks were not recognized on any of the offshore stacks.

Quaternary deposits

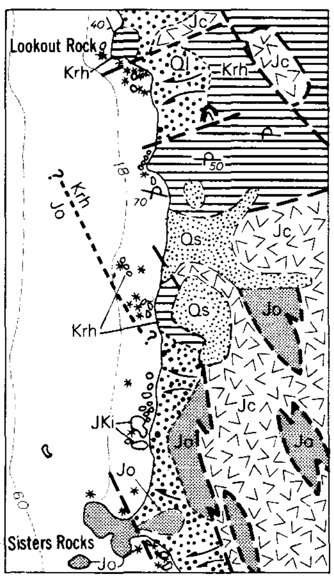
Pleistocene terrace sand and gravel overlie wave-cut platforms on the tops or sides of some stacks off the southern Oregon coast. The deposits are generally less than 10 feet thick. Island Rock, Needle Rock in the Rogue River Reef, and some of the stacks south of Cape Sebastian contain deposits of this kind.

Structure

Structures affecting probable Upper Cretaceous rocks

Although rocks of known and probable Late Cretaceous age occur in several small areas along the southern Oregon coast, they are very rare inland as far as the Medford area, where they occur along the edge of the Tertiary volcanic mass making up the Cascade Mountains (Wells and Peck, 1961). The discovery of probable Upper Cretaceous rocks in the Rogue River and Blanco Reefs extends the distribution of such rocks along the coast and suggests that the coastal belt may be the eastern edge of an area in which Upper Cretaceous rocks are widespread. In a broad sense, therefore, the present coastal belt may mark the boundary between a depositional or later structural basin to the west and a geanticlinal area to the east. The same importance of the present coastal belt at a later date is still more strongly suggested by the widespread distribution of younger Tertiary rocks on the continental shelf and their rarity inland.

The distribution of probable Upper Cretaceous rocks can be extended locally beyond the stacks by the bathymetric pattern and by the pattern of kelp beds rooted on sea-floor outcrops. In the Rogue River Reef, for example, a linear pattern of



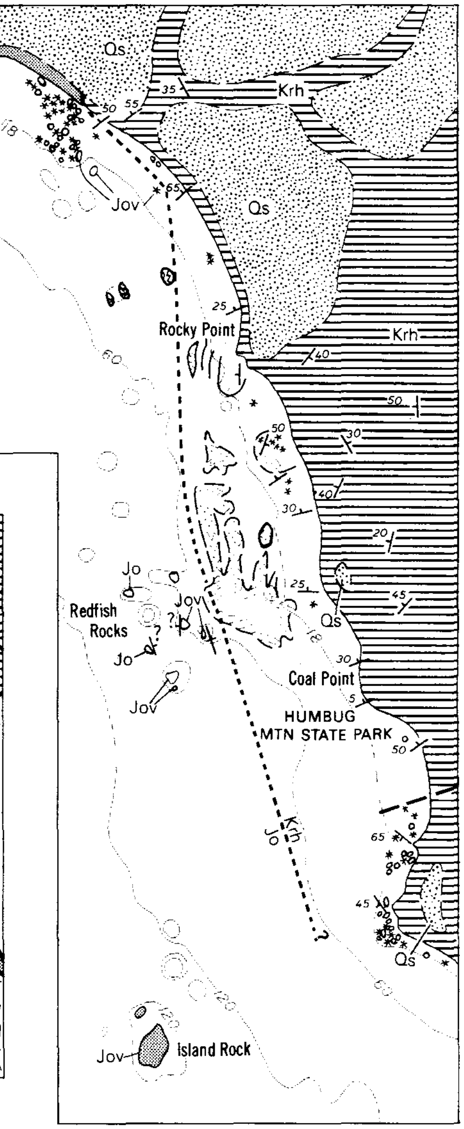


Figure 8. Geology of Sisters Rocks and vicinity. Onland mapping modified slightly from Koch (1966). (Lower left)

Figure 9. Geology of Redfish Rocks, Island Rock, and vicinity. Onland mapping slightly modified from Koch (1966). (Right)

kelp beds northeast of the reef parallels the strike of bedding in the probable Upper Cretaceous sandstones exposed in the stacks and appears to outline resistant sandstone beds that crop out on the sea floor (figures 6 and 7). Similarly, the submarine ridge extending southwest from the southeastern part of the Rogue River Reef is parallel to the strike of bedding in the stacks and is evidently formed by probable Upper Cretaceous rocks. The linear pattern of kelp beds northeast of the reef does not extend past a fairly well-defined north-south line. East of this line, presumably a fault, is an irregular pimple-like pattern of kelp beds typical of areas known to be underlain by the Otter Point Formation. Another linear pattern of kelp beds that may outline Upper Cretaceous rocks occurs south of the Blanco Reef, between the Orford Reef and the shore (figure 10). For these rocks, however, a Tertiary age is perhaps equally possible.

Although Upper Cretaceous rocks may occur widely on the continental shelf, it is doubtful that they underlie any large continuous area, for onshore they are cut by numerous faults. The probable Upper Cretaceous rocks in the Rogue River and Blanco Reefs also are apparently cut by numerous faults (figures 7 and 10). As the major faults cutting Upper Cretaceous rocks in the Cape Sebastian area strike northwest (Howard and Dott, 1961), the probable Upper Cretaceous rocks in the Rogue River Reef probably occur along this same fault system. Most of the faults in the Cape Sebastian area apparently dip at high angles, but at the south end of the area the Otter Point Formation (Whalehead Formation of Widmier, 1963) is mapped as thrust over Upper Cretaceous rocks (Howard and Dott, 1961).

The Upper Cretaceous beds overlie older (Otter Point) rocks with marked angular unconformity in the Cape Sebastian area (Howard and Dott, 1961). The same relation is suggested in the Rogue River Reef, where the probable Upper Cretaceous beds strike in an arc around a core of the highly deformed Otter Point Formation and dip gently away from the core (figure 7).

Although the Upper Cretaceous beds in the Cape Sebastian area are cut by numerous faults, the beds commonly dip less than 30°. The probable Upper Cretaceous rocks in the Rogue River and Blanco Reefs dip almost entirely at angles of 30° or less (figures 7 and 10). The low dips are useful, though not definitive, in distinguishing these rocks from older rocks in the area. Some of the folding took place during the period in which the rocks were deposited, as indicated by the angular unconformity within the massive sandstone at Cape Sebastian.

Structures affecting Jurassic and Lower Cretaceous rocks

The Jurassic and Lower Cretaceous terranes are characterized by numerous differences in general lithology, types of associated rocks, style of deformation, and metamorphism (table 2). Koch's structural interpretation (1966, p. 63-65) offers a possible explanation for these differences. Koch suggests that the eugeosynclinal Otter Point Formation was deformed during the "Diablan orogeny" near the end of Jurassic time, and that when sedimentation resumed during Early Cretaceous time, a miogeosynclinal facies was deposited.

Several problems arise from Koch's interpretation, which implies that both the Jurassic Otter Point and the Lower Cretaceous terranes are autochthonous. Wherever the base of the Lower Cretaceous beds is exposed in the coastal area, the beds unconformably overlie a pre-Otter Point metamorphic-plutonic complex. According to the autochthonous interpretation, this basement complex was a local positive area in which Late Jurassic rocks were never deposited, were deposited as a

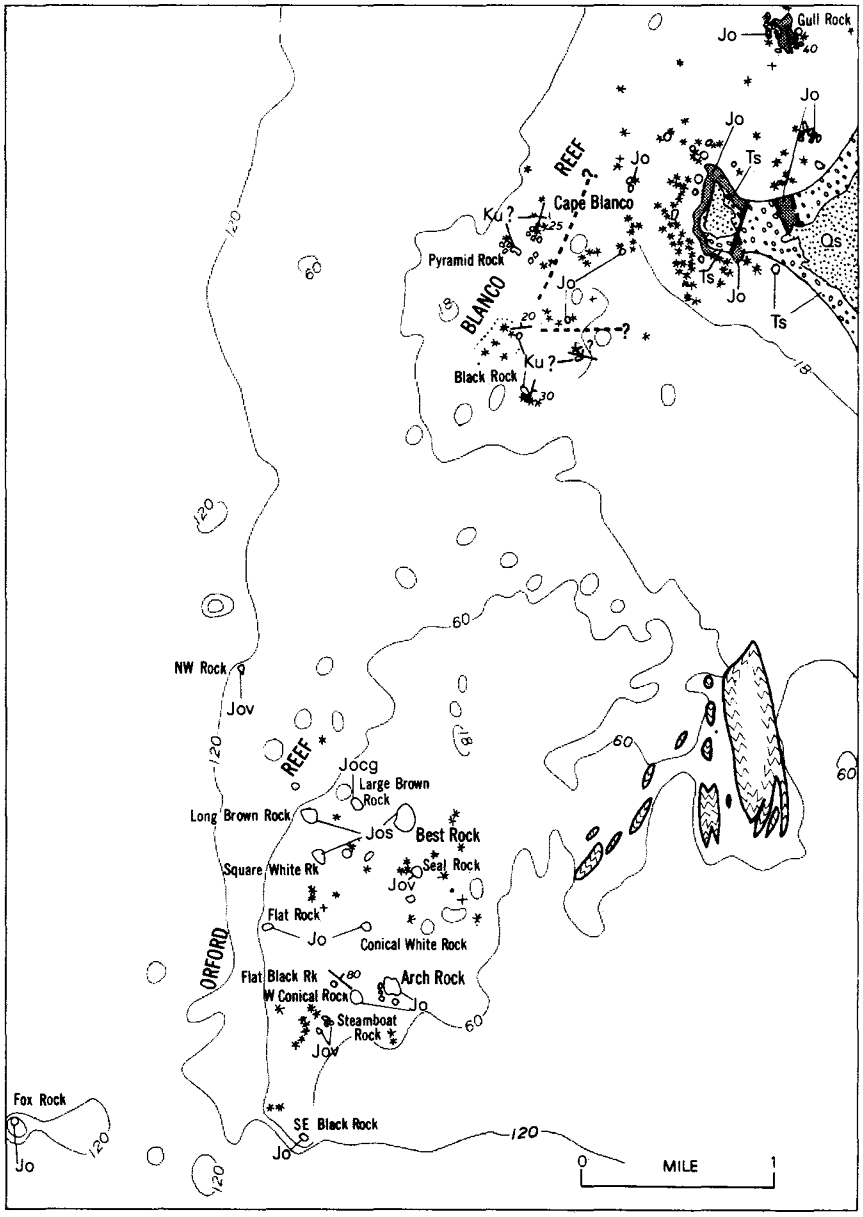


Figure 10. Geology of Orford Reef, Blanco Reef, and vicinity. Onland mapping slightly modified from Dott (1962).

Table 2. Comparison of typical terranes underlain by Jurassic Otter Point Formation and Lower Cretaceous rocks

	Terrane underlain by Jurassic Otter Point Formation	Terrane underlain by Lower Cretaceous rocks [includes Humbug Mountain Conglomerate and Rocky Point Formation of Koch (1966)]
Lithology:	Eugeosynclinal; volcanic rocks and bedded chert present.	Miogeosynclinal; volcanic rocks and bedded chert present.
Associated rocks:		
Underlying rocks	Unknown	Pre-Otter Point plutonic and metamorphic rocks where known.
Serpentinite	Many small to large tectonically emplaced bodies	Typically absent in coastal area
Blueschist and related metamorphic rocks	Many small tectonically emplaced bodies	None known
Colebrooke Schist	Many small to large, tectonically emplaced, superjacent bodies	Few small bodies of uncertain relationship
Style of deformation:	Much faulting and steep folding; parallelism of structures common, producing linear structural grain	Broad folds and domal uplifts; structural grain not pronounced
Metamorphism:	Commonly in the zeolite or prehnite-pumpellyite facies	Not known to be metamorphosed

thin onlapping wedge (Dott, 1966), or were stripped off by erosion during the Diablan orogeny. The existence of such a laterally restricted, but evidently extremely upthrown, area seems somewhat improbable but not impossible. A more perplexing problem is that the Lower Cretaceous beds are preserved on what must have been a profound uplift during Late Jurassic time but have been removed from, or were never deposited on, the surrounding Otter Point terrane, which was a deep basinal area during Late Jurassic time. The implied reversal of positive and negative areas is conceivable but seems unlikely.

Because of the problems associated with an autochthonous interpretation of the Otter Point and Lower Cretaceous terranes, an allochthonous interpretation should be considered. Many of the differences between the two terranes are indeed consistent with, and suggestive of, tectonic transport on a regional scale. Such tectonic transport could have been accomplished by either thrust faulting or strike-slip faulting. In either case, of course, the present contacts of the two terranes may be later faults than those along which the major tectonic transport took place. All these possibilities should be kept in mind.

The contact between the Otter Point Formation and Lower Cretaceous rocks occurs offshore from Port Orford to the vicinity of Sisters Rocks (figures 2, 8, and 9). It must be located between the onshore Lower Cretaceous rocks and the Otter Point Formation on Island Rock and Redfish Rocks, but its precise position is unknown. The contact in the offshore area apparently coincides in a general sense with the Port Orford shear zone.

The Port Orford shear zone is thought to be a wide, north-northwest-trending major fault zone; it is characterized by intensely brecciated, granulated, folded, altered rocks (Koch, 1966, p. 58-59; Dott, 1962, p. 131-132). The shear zone is presumed to extend offshore south-southeast from Port Orford (Koch and others, 1961; Dott, 1965; Koch, 1966) and probably touches shore again in the vicinity of Sisters Rocks (Dott, 1962 and 1965). The Brush Creek shear zone, which is in the coastal area between Humbug Mountain and Sisters Rocks, is probably related to the Port Orford shear zone (Koch, 1966, p. 58). North of Port Orford, faults striking north-northwest to the Cape Blanco area are thought to be part of the Port Orford shear zone (Dott, 1962).

The nature of the faulting in the Port Orford shear zone is poorly known. Koch (1966, p. 58-60) reported several features suggestive of strike slip but did not rule out the possibility of other types of faulting. Even the dips of the dominant faults are not certainly known because exposures are poor and there are many shear surfaces having various attitudes. Some of the faults offsetting Tertiary rocks in the Cape Blanco area are definitely high-angle faults (Dott, 1962), but the relation of these faults to the complex deformation within the Otter Point Formation in the area is unknown.

Evidence suggesting that the Otter Point-Lower Cretaceous contact in the offshore area may be a low-angle thrust fault is the presence of several prominent low-angle faults on both sides of the contact. A low-angle fault is the most prominent discontinuity in the Otter Point volcanic rocks forming Island Rock, just west of the shear zone (figure 9). A nearly horizontal fault was traced by helicopter for a distance of about 3,000 feet along sea cliffs formed by Lower Cretaceous rocks between the Port Orford and Brush Creek shear zones, about 2 miles southeast of Humbug Mountain in the S$\frac{1}{2}$ sec. 6 and N$\frac{1}{2}$ sec. 7, T. 34 S., R. 14 W. Drag along the fault indicates relative westward movement of the upper plate. A recent landslide origin of the fault is unlikely because the fault is offset vertically for distances of a few feet by several steeply dipping faults. The occurrence of calcite veinlets and intense granulation in a zone 1 to 3 feet wide along the fault are further evidence refuting a recent landslide origin. A few other prominent gently dipping faults occur in the sea cliffs between Humbug Mountain and Ophir.

None of the faults mentioned is a major fault separating rocks of greatly differing age, and the inference that these faults are part of a system in which low-angle thrusting was the dominant type of movement must be considered suggestive only. Moreover, the existence of low-angle thrust faults in the Mesozoic rocks does not rule out the possibility of younger faults of different type.

Other features suggestive of a low-angle Otter Point-Lower Cretaceous contact include the apparent bends in the contact in the offshore area (figures 2 and 9) and the occurrence of outliers of the Otter Point Formation in the predominantly Lower Cretaceous terrane between Humbug Mountain and Sisters Rocks (Koch, 1966). These features can be easily explained by original waviness, folding, and vertical offsetting of a low-angle fault contact, but, as noted by Koch (1966, p. 59), a sinuous pattern can also be produced by braided wrench faults. On the other hand, the divergence of the Otter Point-Lower Cretaceous contact from a north-northwest trend in the area north of Port Orford (figure 2) certainly is so extreme that the juxtaposition of the two terranes cannot be explained solely by strike-slip tectonic transport along the Port Orford shear zone as it has been mapped. If a high-angle strike-slip interpretation of the Port Orford shear zone is retained, a complex system of other faults must be inferred to explain fully the juxtaposition of Otter Point and Lower Cretaceous rocks.

The hypothesis that the Lower Cretaceous rocks have been brought into juxtaposition with the Otter Point Formation by low-angle thrust faulting is supported by evidence from the sea stacks and coastal cliffs, but the evidence is far from conclusive. Much additional field work will be required to test this hypothesis against other interpretations.

Regional tectonic transport of Mesozoic rocks in southwestern Oregon and northern California by low-angle thrust faulting has been postulated by many other workers. Irwin (1964) originally suggested that the Upper Jurassic and Lower Cretaceous rocks, later named the Otter Point Formation, Humbug Mountain Conglomerate, and Rocky Point Formation by Koch (1966), formed part of an upper plate above a regional overthrust. This interpretation was followed by Blank (1966) and by Blake, Irwin, and Coleman (1967). However, later detailed studies (Bailey and Jones, 1966; Coleman, 1969; and Lent, 1969) show conclusively that in Oregon the regional thrust occurs above the Otter Point Formation. Moreover, Coleman (1969) and Dott (1966) interpret the thrust as passing over the Rocky Point Formation and the Humbug Mountain Conglomerate. The hypothesis presented here differs from earlier interpretations in suggesting that the Upper Jurassic and Lower Cretaceous rocks are themselves separated by a low-angle thrust fault along which regional tectonic transport has taken place.

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HOW LONG? HOW LONG?

By Richard G. Bowen*

The possibility of developing geothermal power has been delayed again because legislation to allow leasing and production of geothermal resources on Federal lands has not been enacted. The delay was not from a lack of effort by its proponents in Congress, but from a disagreement between the Executive and Legislative branches as to the details of the leasing law. This has been the story of this legislation since the first bill was introduced by Senator Alan Bible of Nevada in 1962.

Two bills allowing the leasing of Federal lands for the development of geothermal resources passed both the Senate and the House of Representatives during this session, but, because of the delay in acting on them, there has not been time for a joint conference of members of the House and Senate to consider and reconcile the differences in the two bills. The chances of performing the necessary conference work for passing the final bill during the special session, to be held in November and December, are rated as slim by Washington observers.

Since its introduction, the geothermal leasing bill has been plagued by controversy which has centered around two points, the so-called "grandfather" clause and the amount of rents and royalties to be charged. The grandfather provision recognizes that the pioneers in the industry who, prior to 1965, had either filed claims or applied for leases on Federal land for geothermal resources and had done a significant amount of work on the claims, should have a preferential right to these lands. The other dispute has centered around the revenue aspects of the bill.

The Senate bills have followed the pattern established for the leasing of oil and gas on Federal lands; that is, competitive bidding for leases on lands known to have geothermal resources and on a first-come-first-served basis for so-called "wildcat" acreage. The royalty payment would be a fixed percentage based on the amount of production. This system has served very well during the development of the oil and gas industry and has helped make the domestic oil industry the strongest in the world and prices in the United States the lowest.

The Interior Department has taken the position that, because geothermal energy was not specifically mentioned as a claimable or leasable mineral in any of the mining laws, it could not be developed on Federal lands and those who were exploring for it under any other type of claim were guilty of trespass and had no valid claim. The Senate committee has repeatedly rejected this thesis and pointed out that the development of the mineral resources in the United States has been by the prospector and the developer who entered the public domain and risked their own capital with the expectation of financial reward for their efforts. In the committee's words: "Pioneers have made enormous contributions to the development of the Nation's natural resources. And the geothermal pioneers are no exception. Through their efforts -- their courage, their initiative, their willingness to risk substantial investment, their foresight -- they have demonstrated the great potential value of this little-known resource."

In Senator Bible's bill a compromise was struck in which this right was recognized, but the amount of acreage that could be claimed under the grandfather clause was limited to a total of two leases in any one state and a maximum nationwide of 10,240 acres. Industry representatives at the hearing felt that this amount was only

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a token of what they had worked on and filed claims for, but that it was satisfactory if it would enable passage of the bill.

Establishment of a rate of return from the production of geothermal resources has been the other source of contention between the Interior Department and the Senate committee. The Interior Department recommended that a royalty of not less than 10 percent be charged and that the rates could be increased by regulation if the Secretary of Interior felt the field could support higher rates. This, of course, is an open escalation clause. The objection to this clause came from industry representatives who pointed out that, in order to develop geothermal power, large capital commitments had to be made to build the electrical power plants on the site where the steam is produced and that these capital commitments could amount to hundreds of millions of dollars. For example, Pacific Gas & Electric Co. has already spent more than ten million dollars and is committed to another fifty million over the next five years at the Geysers area in California.

If the amounts of royalties were not determinable within a limited range, the financing, based on the amortization of the plants, would be impossible to arrange, because lenders have a habit of wanting to know when and how they will be repaid. The committee's recommendation was that royalties would not be readjusted for the first 35 years, but after that would be readjusted every 20 years to a maximum of $22\frac{1}{2}$ percent. This would allow for the initial amortization of the plants. A succinct statement by the Senate Committee gives its philosophy on the matter:

"Further, the committee seriously questions the wisdom of placing undue emphasis at this time on rentals and royalties from geothermal leases as a source of Federal revenue. The emphasis now must be to establish a climate favorable for development of the resource. Looking to the future, the tax revenue return to the Government from a vigorous, prosperous geothermal power industry producing low-cost, pollution-free energy will far exceed any present return from lease rentals and royalties."

Both bills are similar to the one passed by both the Senate and House in 1968, but vetoed by President Johnson on the recommendation of the Interior Department. It appears that even if the bill were approved by Congress during the special session it would again be vetoed because of the objections of the Secretary of Interior, who has the job of implementing the bill. If this is the outcome, geothermal development will again be shelved for at least two more years while the nation is facing a power shortage.

The western United States, with its vast areas of recent volcanism, is believed to contain a large amount of the world's geothermal resources. The abundance of subsurface heat is manifested by more than 1200 hot springs and fumaroles. Oregon alone has nearly 200 hot-spring areas, and drilled wells reveal temperatures as high as 295°F. Thermal manifestations and studies of heat flow indicate that many areas are probably underlain by very hot rocks (temperatures as high as 2000°F. have been measured in lava flows) that are proven in places to be capable of producing dry superheated steam.

Where this source of low-cost power has been developed, capital costs are only two-thirds to three-quarters those of comparable fossil fuel plants and less than half those of a nuclear plant. Not only are costs lower but, perhaps more importantly, the plant produces a minimum of air and water pollution and has no radioactive emissions.

Geothermal energy may not be able to provide all the power that Oregon and the other western states need, but in some regions it could be an equal partner to the nuclear and fossil fuel plants now under development. Geothermal energy is a proven method of power production that, on a world-wide basis, has an installed capacity of nearly 1,000,000 kilowatts. It needs no funds for research. The technology for its utilization has been perfected and industry is ready to start its development, but unless some action is taken to pass the legislation that has been before the Congress for the last eight years, there will be no chance for an appraisal of its potential.

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DEPARTMENT GEOLOGIST ATTENDS GEOTHERMAL CONFERENCE

R. G. Bowen, Economic Geologist for the Department, attended the United Nations Symposium on the Development and Utilization of Geothermal Resources held in Pisa, Italy, from September 22 to October 1. This conference, the first that had been held since 1961, was a review of the progress that had taken place since that time. The sessions included the following:

1. Geothermal Systems; a discussion of the geology and physical characteristics of the known geothermal systems.
2. The Status of Geothermal Development; exploration, development, and production activities in the geothermal fields throughout the world.
3. The Geologic Environment of Geothermal Fields as a Guide to Exploration; the geologic factors to consider on an exploration program.
4. Geophysical Techniques in Geothermal Exploration; methods of detection of the geothermal reservoir based on physical measurements.
5. Geochemistry Applied to the Discovery, Evaluation, and Exploitation of Geothermal Energy Resources; chemical analysis as a tool for predicting location and temperatures in geothermal reservoirs.
6. Drilling Technology; recent improvements in drilling and blow-out prevention techniques.
7. Reservoir Physics and Production Management; methods of extracting a maximum amount of energy to the surface for exploitation.
8. Collection and Transmission of Geothermal Fluids; handling of geothermal fluids with emphasis on corrosion prevention and fluid disposal.
9. Utilization of Steam and High Enthalpy Water; mainly electrical power production.
10. Utilization of Low Enthalpy Water; space heating, industrial, agricultural, and other uses.
11. The Economics of Geothermal Power; costs and cost comparison of geothermal with other forms of energy.

Special sessions were devoted to United Nations programs for utilizing the geothermal resources in the under-developed nations. A one-day tour was made of the Larderello Geothermal Field, the world's oldest and presently the largest.

The participants at the conference represented nearly all the counrries in the world where geothermal studies are taking place. Since the 1961 conference, production had been increased in every geothermal field that was under development at that time, which included Italy, New Zealand, the United States, and Mexico. New countries that have joined the ranks of geothermal electric-power production are Japan, Iceland, and Russia.

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