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PLATE TECTONIC STRUCTURES IN OREGON

John Eliot Allen[1] and John D. Beaulieu[2]

Introduction

During the past decade the plate tectonics theory has revolutionized geologic thinking on a scale comparable to the impact of nuclear physics or of evolution in biology. The theory is one of the greatest unifying concepts to develop in the science of geology since its beginnings more than 200 years ago. Basically, it proposes that the Earth's crust and upper mantle (lithosphere) are made up of several large, more or less independent, plates. Movements of the plates relative to each other and the resulting interactions at their edges largely control the world distribution of earthquakes, volcanic activity, and mountain building.

On a world-wide basis the theory may be briefly outlined as follows:

1) Intrusion and extrusion of igneous rock along mid-ocean ridges resulting in the creation of new crust and mantle and in the spreading of the sea floor.
2) Major lateral movements of oceanic material away from the ridges with strike-slip displacement along transform faults on the sea floor and more complex patterns of deformation on the continents.
3) Subduction (underthrusting) of the oceanic lithosphere with resultant seismic and volcanic activity at the edges of the plates (particularly around the Pacific Ocean) in areas of collision.

The farther back in geologic time we look, the dimmer the picture becomes. But a fair amount of evidence points to the following sequence of events:

1) The initiation of plate tectonic activity, continental accretion, and island arc activity on a small scale as early as the Archean, 2.5 billion years ago (Engel and others, 1974).

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2) General quiescence in the Paleozoic Era.
3) Break-up of the "world continent" of Pangea beginning in Mesozoic time approximately 200 million years ago, with the Americas, Antarctica, and Australia drifting away from Africa, Europe, and Asia.
4) Continuation of plate movement to the present day.

The theory of plate tectonics provides the geologist with a variety of conceptual tools with which to reinterpret the geology of selected regions. For Oregon, Beaulieu (1972) summarized recent advances from a stratigraphic approach. In the present paper the authors briefly analyze various structural features.

Using LANDSAT imagery with individual frames covering as much as 25,000 square kilometers, one can usually see many major mapped faults and structures, but one can also see more obscure linear features which have not been previously mapped or fully appreciated. Study of these lineaments in the Northwest has provided yet another tool for our understanding of the geology of Oregon. Preliminary broad explanations (megahypotheses) for these large-scale features should be regarded as tentative until verified or rejected on the basis of further work. On the past record, however, one can judge that a significant percentage of the megahypotheses now being proposed will be accepted as valid.

Lineaments

Lineaments are apparent alignments of features on the ground as revealed by remote sensing images. Lineaments may be major faults or fault systems, patterns of vegetation, topographic features or man-made features, or they may be optical illusions. The lineaments discussed here are relatively large and have associated with them sufficient geologic evidence to suggest that they represent major structures of the Earth's surface. Precise interpretations remain to be worked out on the ground. If the linears are of fault origin, they may represent active or inactive crustal deformation and possibly even major boundaries between blocks of crustal material of different ages and origin. [See map (Figure 1) for locations of the features described.]

Northwest trending

The longest lineament in the Northwest is the Brothers fault zone (1)* (Greene and others, 1972), which runs for 300 kilometers on a northwest trend through central Oregon (Lawrence, 1974, 1976) and its possible extensions. It is a zone up to 20 kilometers wide in which multiple, en echelon faulting suggests deep-seated, right-lateral shear movement of two

*Number refers to location on Figure 1.

crustal blocks. It has been extended to the southeast for another 350 kilometers into Nevada by Stewart and others (1975). To the northwest the zone may swing to a more northerly trend to include the Sisters fault zone (13) and possibly even the anomalously straight valley of the Clackamas River, and the Portland Hills fault (Basillie and Benson, 1971; Schmela and Palmer, 1972; Beeson and others, 1975). In crossing the Cascade Range, the lineament may be represented by an extension of several parallel north-trending faults (Hammond, personal communication, 1976). A total length of the combined features is nearly 900 kilometers. If related to plate tectonics, the zone must continue farther to the northwest off the coast of Washington to merge with plate boundaries on the sea floor.

Lawrence (1974, 1976) described two other northwest-trending fault zones to the south in eastern Oregon with the same right-lateral sense of movement. They appear to offset the north-south line of High Cascades volcanoes a distance of 20 kilometers and are called the Eugene-Denio (2) and the Mt. McLoughlin (3) lineaments. He also maps two northwest trending faults or lineaments to the north, the Vale (4) and Grande Ronde (5) lineaments. Still farther north, the northwest trending Olympic-Wallowa lineament (6) is variously interpreted as a surface manifestation of deep-seated crustal dislocations (Skehan, 1965) or as a more or less imaginary feature of little real significance.

Northeast trending

The Yamhill-Bonneville lineament (7) proposed by Hammond (1972) extends for 250 kilometers in a N. 65° E. direction from near the coast at Taft, through the Yamhill valley and the Portland area, up the Columbia River and beyond Bonneville Dam. In the crest of the Cascade Range the lineament merges into a north-trending extension zone bordered by the Indian Heaven and King Mountain fissures (Hammond and others, 1976). Strata north of the lineament are compressed into a series of northwest-trending folds. On the south the strata are more openly folded in a northeastward trend. Apparent displacement is left-lateral. Historic earthquakes cluster along its course (Berg and Baker, 1963). The lineament is colinear with major strike-slip faulting on the sea floor off the coast of Oregon as described by Silver (1971). Evidence for the fault on land is difficult to interpret and, curiously, the fault apparently is not offset by the Portland Hills fault, a feature that requires explanation.

East-west trending

Two major east-west trending fault zones have been mapped in Oregon. The Canyonville zone (10) (Coleman and Lanphere, 1971) consists of a series of strike-slip faults extending through southwest Oregon from the Sixes River on the coast inland to the Cascades, where the base of Little

Butte Volcanics is offset to the east by uplift of the southern side (Hammond, personal communication, 1976), and possibly farther eastward to Crater Lake. The structural setting of the lineament is extremely complex. It marks the north boundary of a thrust plate of superjacent (post-Nevadan) rocks and is buried beneath younger strata in places. After strike-slip faulting ceased some time in the Mesozoic, sympathetic faulting of a vertical nature continued on the zone of weakness well into the Eocene (Perttu, 1976).

The vertical John Day fault (9) has been mapped by Brown and Thayer (1966) along the John Day valley and by Oles and Enlows (1971) in the Mitchell area. If these segments are connected, the zone extends for at least 140 kilometers. Right-lateral movement of at least 6 kilometers has been documented. Vertical movement appears to be up on the south in the John Day area but down in the Mitchell area.

North-south trending

North-south linears connect major volcanic peaks of the Cascades (11) and to a lesser extent subsidiary lines of smaller basaltic cinder cones. Allen (1965) suggested that the High Cascade volcanoes lie in a graben of regional extent outlined by several fault segments not covered with more recent lavas: the Hood River fault (12), the Sisters fault (13), and the Klamath graben faults (14). Elsewhere in the world, many aligned volcanoes lie in similar volcano-tectonic depressions. A single deep-seated Plio-Pleistocene zone of tension may be postulated on the basis of this feature, although the structure of the Cascades at depth remains unclear (Thiruvathukal and others, 1970).

Volcanism

According to the plate tectonic theory, volcanism represents the ascent of material generated along zones of subduction, along zones of rifting, or in areas of local hot spots. Tholeiitic basalts are most commonly associated with rifting, whereas andesites and explosive volcanic rocks are more commonly associated with subduction. In continental areas, crustal contamination, differing rates of ascent, and other influences modify magma generation and make interpretations of deep-seated structures more difficult.

Explosive volcanism of andesitic composition characterized much of Oregon in Oligocene times and is recorded in a variety of marine and nonmarine units throughout the State including the John Day Formation, the Little Butte Volcanics, and the Pike Creek beds. On the basis of widespread explosive andesitic volcanism associated with subduction zones today, active subduction beneath what is now the State of Oregon is inferred for Oligocene times.

McBirney and others (1974) have shown that Cascade volcanism can be subdivided into Miocene (10 to 17 million years), Mio-Pliocene (4 to 5 million years) and Pleistocene (0.1 to 2 million years) episodes. Gaps occur between these groups at 17 to 20, 5 to 9, and 3 million years ago.

Calculations of the original volume of the volcanic rocks of different ages show that the volume during the Miocene was by far the greatest (5 to 10 thousand cubic kilometers), with those of the Mio-Pliocene very small (0.1 to 0.5 thousand cubic kilometers), Pliocene larger (0.1 to 2.0 thousand cubic kilometers), and Pleistocene smaller again (0.1 to 1.3 thousand cubic kilometers). The authors conclude that volcanism in Oregon is declining in a spasmodic fashion, with intervals of 5 million years between the lessening pulses. Areal distribution also shows progressive reduction of activity towards a more narrow belt of the High Cascades. Walker (1970, 1974) and MacLeod and others (1975) show that rhyolitic domes in the Brothers fault zone decrease in age westward towards the High Cascades.

The Columbia River Basalt of Miocene age constitutes one of the largest continental outpourings of lava in the world and was extruded at rates far exceeding those of oceanic ridges or island clusters such as the Hawaiian Islands (Baksi, 1973). The flows were derived from the upper mantle (McDougall, 1976) and represent a short-lived pulse of intense volcanism that is poorly understood.

Until a few years ago, it was believed that the Columbia River Basalt, which originally covered more than 40,000 square kilometers, must have been derived from local vents. Lack of the vents in the field was puzzling until Thayer (1957) and Taubeneck (1967, 1969) mapped two great swarms of dikes, the Monument (22) and Chief Joseph (23) swarms. Swanson and others (1975) describe two northwest-trending linear vent systems tens of kilometers long and a few kilometers wide that fed the Roza and Harbor basalts. Shaw and Swanson (1967) have since shown that the lava could have flowed hundreds of kilometers to its greatest distribution at rates of 10-20 kilometers per hour if rates of extrusion were the controlling factor. A rate of 6 kilometers per hour is possible if flow on a near-horizontal surface is the limiting factor (Shaw and Swanson, 1969).

The great volume and markedly different composition of the Miocene basalts signal a profound and fundamental change in tectonic style in middle Miocene times. The rocks are not the kind commonly associated with subduction, but rather are more closely allied to those associated with rifting and tensional tectonics.

Thrust Faults and Mélanges

One of the newer concepts in America (much older in Europe), now partly revised in light of plate tectonic theory, is that of regional low-angle thrusts along the continental edges. In places, sheets of rock have been moved horizontally for tens of kilometers. Since rock strength is in-sufficient for this movement to have occurred by compression, it was formerly thought that the thrusts formed as thin sheets of strata slid off high mountain ranges elsewhere.

The totally new mechanisms of deformation introduced by plate tectonic theory have greatly revised geologists' interpretations of these features. They are now viewed as slices of lithospheric material (crust and upper mantle) that were sheared from colliding plates in areas of large-scale subduction. Where slivers of the subducting plate are sheared off and thrust over parts of the overriding plate, the term "obduction" is applied. Coleman (1972) interprets this sort of emplacement mechanism for the Colebrooke Schist (17), a sheet of metamorphic rock possibly thrust into coastal Curry County from the west in Cretaceous times. Where shearing completely obscures original structures, as in parts of southwestern Oregon, the rocks are generally called a mélange, a term first used in this country by Hsu (1968).

In the Klamath Mountains of southern Oregon and northern California, Dott (1965) and Irwin (1966) recognize three large pre-Tertiary megathrusts (16) involving Mesozoic rocks of progressively younger ages towards the west. The youngest thrust (the Rogue thrust fault) is coextensive with the large Great Valley thrust fault in California, which separates the ophiolitic Franciscan Formation on the west from the shelf deposits of the Great Valley sequence on the east. In Oregon the fault separates intrusive rocks, Rogue and Galice Formations, and Cretaceous shelf deposits on the east from the Otter Point and Dothan Formations on the west.

Ophiolites

In areas of crustal spreading along oceanic ridges, one can envisage spreading crust with basaltic magma rising to fill the gap. At depth, intrusions of gabbro and residual melts of peridotite are emplaced, and at the surface extensive flows of submarine basalt are extruded. As the crustal material drifts away from the rise, flows of basalt generated by waning volcanism become interbedded with and overlain by deep-sea sediments. This assemblage of rocks eventually may be thrust against the continent and exposed by erosion. Such rocks are termed "ophiolites" to emphasize their deep-sea origin and large-scale displacement.

Masses of peridotite and other ultramafic rock occur as large sheets (Medaris and Dott, 1970) throughout much of the Mesozoic terrain of the Klamath Mountains province and closely resemble ultramafic rocks recovered from parts of ocean ridges today. They are quite different mineralogically from peridotites found in subduction zone tectonic settings, and it is postulated that they have a history something like that outlined above (Medaris and Dott, 1970).

Where entire ophiolite sequences can be mapped in detail the chance of correct interpretation is good, but where only a few key rock types are exposed and structural relationships to surrounding rocks are uncertain, as in parts of Oregon, the chance of error must be considered. Recently Dick (1976) reviewed in detail the rocks of the Josephine Peridotite, long thought to be of simple ophiolitic origin. He showed that the rock had a complex history that included origin beneath a sea floor rise, but which also included considerable subsequent modification associated with igneous activity in a subduction zone. Thus, the Josephine Peridotite may represent a hybrid between sea floor rise and subduction zone peridotite. Rocks of ophiolite origin are found in the Klamath Mountains (18) and in the Canyon Mountain area east of John Day (19), and also in the northern Cascades of Washington.

Columbia Arc

Scattered exposures of pre-Tertiary rocks in Oregon have structural trends towards the northeast from the Klamaths to the Wallowas (20). In the Wallowas this trend swings sharply to the northwest, to reappear in the northern Cascades of Washington. It has been suggested that this trend (King, 1959) be called the Columbia Arc (Taubeneck, 1966). Skehan (1965) and Taubeneck (1966) suggest that most of the western and north-central Oregon and southwestern Oregon lying outside the arc (21) relative to the continental United States should be underlain by thin oceanic basaltic crust rather than thicker continental crust. Gravity measurements by Thiruvathukal and others (1970) suggest that the crustal thickness is less within the triangle in Oregon than in areas to the south and east.

Eardley (1956) and Wise (1963) propose clockwise rotative distortion along a 500-kilometer-wide zone extending northwest from the Colorado Plateau through Oregon and Washington, with several hundreds of kilometers of displacement since the Paleozoic. It accounts for the Columbia Arc and also explains patterns and sense of movements along the lineations and folds of the western United States. Such a theory requires documentation and support from more local studies, however, and it is on the basis of detailed studies in eastern Oregon that Taubeneck (1966) takes exception to the theory. There, dikes aligned in a north-south trend do not appear to be offset or affected by proposed post-Miocene rotation.

Recently Cummings (1976) discusses deformation between the Garlock and the San Andreas faults in the Mojave desert. The region appears very similar in its stress orientations to the Columbia Arc and may represent an upside-down analog of the Columbia Arc.

On an even more regional scale, Burchfiel and Davis (1972) propose that part of the southwestern part of the United States was detached by sea floor spreading in the early Mesozoic. The assorted Permian greenstones and argillites of the detached block possibly drifted north to collide with the then northwestern part of the United States in late Triassic times to form the roots of the Klamath Mountains and possibly even the Blue Mountains

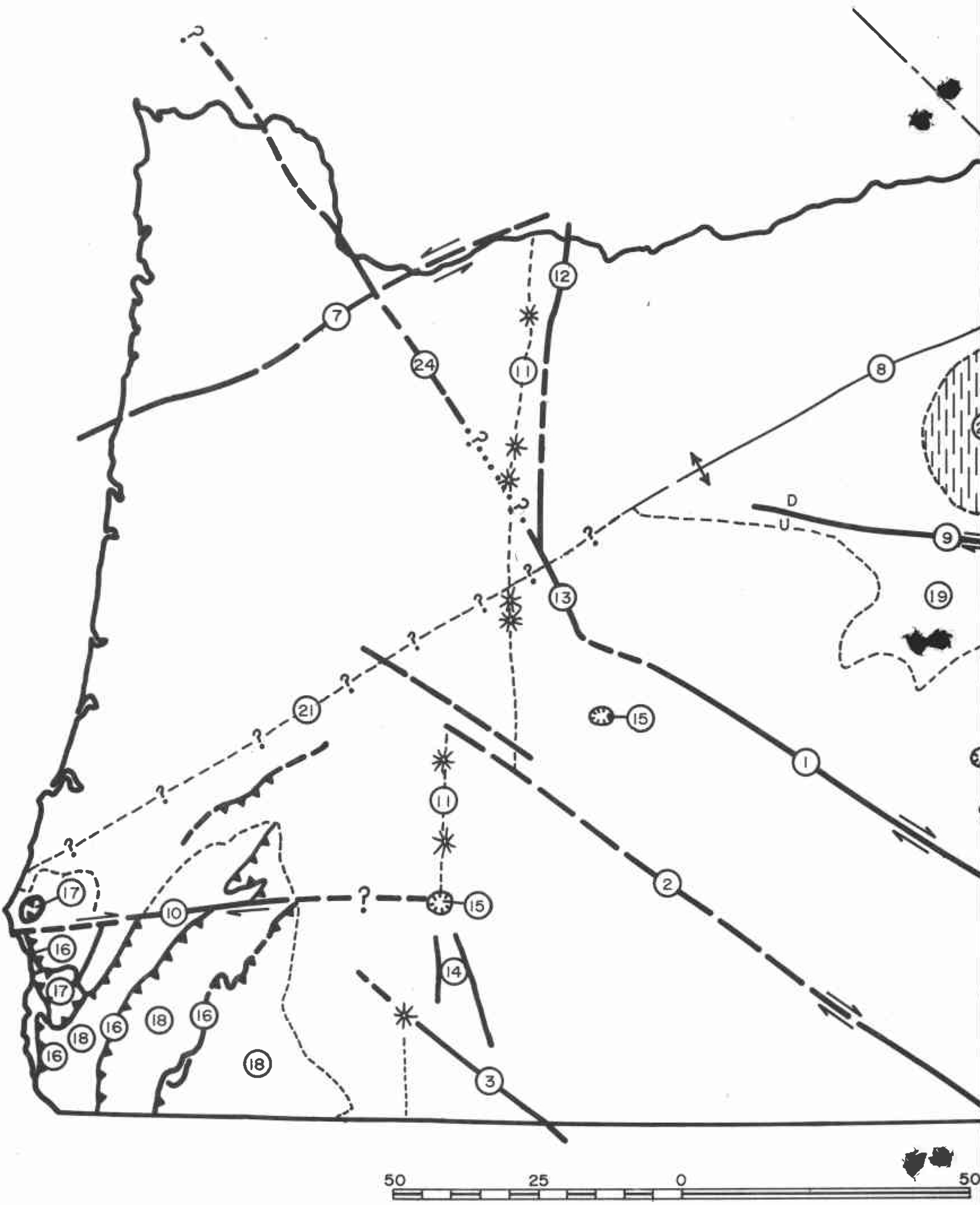
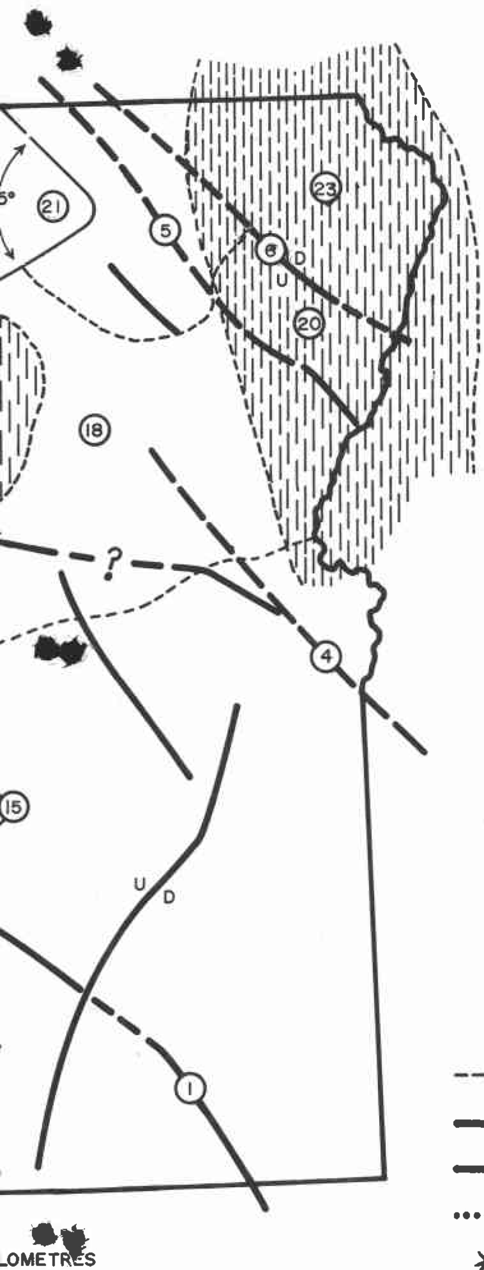


FIGURE 1. MAJOR LINEAMEN



1. BROTHERS FAULT ZONE
2. EUGENE-DENIO LINEAMENT
3. MT. MC LOUGHLIN LINEAMENT
4. VALE LINEAMENT
5. GRANDE RONDE LINEAMENT
6. OLYMPIC-WALLOWA LINEAMENT
7. YAMHILL-BONNEVILLE LINEAMENT
8. BLUE MOUNTAIN ANTICLINE
9. JOHN DAY FAULT
10. CANYONVILLE FAULT ZONE
11. CASCADE VOLCANO ALIGNMENT
12. HOOD RIVER FAULT
13. SISTERS FAULT ZONE
14. KLAMATH GRABEN FAULTS
15. LARGE COLLAPSE CALDERAS
16. PRE-TERTIARY THRUST FAULTS
17. COLEBROOKE SCHIST
18. PRE-TERTIARY ROCKS
19. CANYON MOUNTAIN OPHIOLITE ROCKS
20. WALLOWA MOUNTAINS
21. COLUMBIA ARC
22. MONUMENT DIKE SWARM
23. CHIEF JOSEPH DIKE SWARM
24. PORTLAND HILLS FAULT - CLACKAMAS LINEAMENT

---- CONTACT, APPROXIMATE

DEFINITE FAULT OR LINEAMENT

APPROXIMATE

CONCEALED

* HIGH CASCADE VOLCANOES

S AND STRUCTURES IN OREGON

as we know them today. Schwieckert (1976) proposed this megahypothesis. Possibly the concept of plate tectonics will provide geologists with the tools necessary to properly evaluate the concept of the Columbia Arc and to document it or finally lay it to rest.

Conclusions

The geology of Oregon has become a jigsaw puzzle of moving parts set on a foundation of changing conditions as the crust and mantle undergo successively different manners of deformation through time. As more megahypotheses arise from increasingly sophisticated views of plate tectonics and from more detailed analyses of synoptic images from outer space, it is the task of the geologist to continue to provide sound and reliable ground truth with which to test them. For now it would appear that large overviews from such investigations may include:

1) Possible large-scale bending and dislocation of pre-Mesozoic structures in the subsurface to give an arc-like distribution.
2) Large-scale regional and multiple thrust faulting in the Klamaths through much of the Mesozoic Era.
3) Explosive volcanism in the mid-Tertiary possibly representing subduction.
4) Tensional tectonics represented by Columbia River Basalt eruptions in the mid-Miocene and later block faulting in the Basin and Range province of southeastern Oregon. The Brothers fault zone and its possible extensions may represent the northern boundary of block faulting of the Basin and Range.
5) Possible division of the State into four blocks separated by northwest trending shear zones. A system of north-south compression could account for northeast-trending linears as well.
6) Possible tensional block faulting and graben structures beneath the flows of the Cascades Formation (High Cascades).

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THE FIND - A 98-year-old Dilley resident and an article published in 1914 provided clues in the search for stone needed to repair fire damage at Pacific University's Marsh Hall. Here workmen load the giant block of sandstone, located at the old Boos Quarry, for shipment to Puyallup, Washington, where it was sawed and planed before being sent to the Forest Grove campus.

OLD QUARRY REOPENED

The Doug Remmick NW Stone Company needed matching stone to repair the trimmings of Pacific University's Marsh Hall after the 1975 fire. The Forest Grove building had been constructed between 1893 and 1895, and Remmick did not know where the stone had been quarried.

He turned the question over to Paul Phillips, a young employe who had attended many classes in Marsh Hall and who was vitally interested in the project. Pacific Professor A.C. "Hap" Hingston gave Phillips a long list of long-time residents in the Washington County area. After a number of futile interviews, Phillips found Harold Hansen, a 98-year-old resident of nearby Dilley, who knew of the quarry and had even worked there when he was a young man.

Ralph Mason, of the Oregon Department of Geology and Mineral Industries, found the location and details about the quarry in an article in a 1914 edition of, "The Mineral Resources of Oregon."

The J.G. Boos Quarry is south of Forest Grove, off Highway 47, 2½ miles northwest of Gaston. At one time it was located in Yamhill County, but later redistricting placed it in Washington County. Mrs. Mary M. Wall Baker is the current owner.

The quarry is situated on the ridge which forms the northern boundary of Wapato Lake. The 1914 article describes Boos Quarry stone as "a fine-grained sandstone of a dark bluish-gray color when fresh which becomes a somewhat lighter shade when the stone is seasoned. The grains are chiefly quartz with some feldspar, muscovite and olivine."

Remmick selected a piece of stone weighing about 48 tons, to be trimmed down to 22 tons before it was removed from the quarry. The stone went to Puyallup, Washington to be sawed and planed.

Remmick says that stone from the old Boos Quarry could be marketable today but that it is difficult to mine. He believes that those operating the quarry 50 to 80 years ago must have had many problems in getting the stone out. They used cedar pegs and water to break the stone. Today miners use such equipment as compressors and high-powered drills.

Boos stone was used in Portland's Pioneer Courthouse, for the steps of Mechanical Hall at Oregon State University and all of the older University of Oregon buildings, and as the foundation of the Washington County Court House in Hillsboro. No doubt many homes and businesses in Forest Grove are standing on foundations of Boos Quarry stone.

Remmick says it is unusual to have such an involved search for matching stone but that he believes such efforts will become more common as public interest in restoration of older buildings increases.

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PROSPECTORS BEWARE!

The recent tragic deaths of three miners working in a tunnel on a gold prospect in Linn County points up the need for extreme care in handling explosives and a thorough knowledge of blasting practices. With more and more untrained people poking around in the hills looking for gold the potential for a repitition of this disaster is all too likely.

Apparently the three miners, all brothers in their late sixties and seventies, were caught at the tunnel face where they were lighting a seven-hole round of dynamite. Six of the holes fired, the first hole igniting before the seventh fuse could be lit. The Federal Mining Enforcement and Safety Administration (MESA) team examining the site afterward found that the length of each fuse was critically short, only $2\frac{1}{2}$ feet. Since fuse burns at the rate of 40 seconds per foot, the miners had only 1 minute and 40 seconds to light the seven fuses and retire to a safe place before the first hole exploded. But they never made it; some difficulty in lighting the last fuse caused the fatal delay.

MESA maintains an office at Albany, Oregon and regularly inspects all underground and surface mining operations that it is aware of for compliance with Federal safety regulations. The MESA staff also provides a wealth of on-the-spot information on safe mining practices. Additionally MESA holds training sessions on blasting and the handling of explosives and on other hazards encountered during mining operations. Anyone planning to open an old mine should notify MESA by calling (503) 926-5811 and asking for extension 274 or by writing to P.O. Box 70, Albany, Oregon 97321. Upon request, MESA inspectors will visit a site and check to see if the mine is safe to enter.

Even though it is mandatory that all operators opening or closing a mine must notify MESA, not all of them do. If MESA had been notified of the recent operation in Linn County the tragedy, in all probability, would have been averted.

* * * * *

STAY OUT OF OLD MINES

Once again the summer season has arrived and the annual invasion of the high country begins. Up there in the hills are many old mines, most of them abandoned years ago. Do not give in to the temptation to enter these mysterious holes! The supporting timbers may be rotten, the planking underfoot may conceal deep shafts, and the air may be unfit to breathe.

The Department has a free leaflet which graphically illustrates the many hazards to be found in old mines. Ask for it the next time you visit us, or write to the Oregon Department of Geology and Mineral Industries requesting a copy. It could save your life.

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AVAILABLE PUBLICATIONS

(Please include remittance with order; postage free. All sales are final - no returns. Upon request, a complete list of Department publications, including out-of-print, will be mailed.)

BULLETINS

26.	Soil: Its origin, destruction, preservation, 1944: Twenhofel.	$0.45
33.	Bibliography (1st suppl.) geology and mineral resources of Oregon, 1947: Allen .	1.00
35.	Geology of Dallas and Valsetz quadrangles, Oregon, rev. 1964: Baldwin . . .	3.00
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52.	Chromite in southwestern Oregon, 1961: Ramp	5.00
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88.	Geology and mineral resources of upper Chetco River drainage, 1975: Ramp . .	4.00

GEOLOGIC MAPS

Geologic map of Oregon west of 121st meridian, 1961: Wells and Peck $2.00; mailed -	2.50
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Geologic time chart for Oregon, 1961 10
Postcard - geology of Oregon, in color . . . . 10¢ each; 3 - 25¢; 7 - 50¢; 15 - 1.00
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