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VOLCANIC GEOLOGY OF
CRATERS OF THE MOON NATIONAL MONUMENT
AND RELATED AREAS

BACKGROUND INFORMATION

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I. REGIONAL SETTING/PACIFIC NORTHWEST

A. Cascade Range

Bingham--Ref#4--Mount St. Helen's is just one of 15 majestic volcanic peaks capping the rugged coastal Cascade Range from southern British Columbia to northern California. The chain of volcanoes is the surface manifestation of an ongoing collision between two crustal plates--the North American Plâte and the tiny Gorda plate that lies offshore. At the boundary between the Gorda and Pacific plates, the Juan de Fuca rift zone adds about one inch of new crust each year to both plates. The growing Pacific plate moves away in a northwest direction, but the new sea floor added to the little Gorda plate moves on a collision course toward the coast of Washington and Oregon where it plunges beneath the westward marching North American plate. It then bends downward into the earth's mantle beneath the Cascade volcanic chain. The friction between these 60-mile-thick slabs sliding past each other supplies the heat necessary to melt the crust and generate molten rock, or magma. Mount St. Helens, as well as the other volcanoes in the Cascade chain, are localized spots where this magma pokes through and spills onto the surface.....

The Pacific Northwest has a long history of volcanic activity, indicating that the area has long been a plate boundary. The earliest volcanism in the Cascades occurred some 250 million years ago, though the bulk of the volcanic rocks are about 50 million years old. The range is punctuated by the eroded roots of old volcanoes.

Findley--Ref #5--Mount St. Helens and other towering young volcanoes of the Cascade Range have been built up by the submergence of the Juan de Fuca plate beneath North America. Creeping under the coast at more than an inch a year, the small oceanic plate melts rock into pockets of magma that work their way up some 60 miles to the surface.

Redfern--Ref #38--When the Farallon Plate had been consumed beneath california and the San Andreas Fault was established, only the northern part of the Farallon Plate remained east of the spreading ridge, and this continued to subduct beneath the Pacific coast in the region of the states of Oregon and Washington. This fragment of the original Farallon Plate (the Juan de Fuca Plate) caused the formation of a magmatic arc (the Cascade Range) and the volcanic flood plains of the Pacific Northwest.

Stern, Carol, and Clark--Ref#37--The Cascade Range of Washington, Oregon and northern California includes a group of volcanoes built on the western side of the Columbia lava plateau in Pleistocene time. The major peaks such as Shasta, Rainier, Hood and Baker combine massive symmetry and graceful beauty with altitudes approaching the highest in the Cordillera.

The lavas in the belt are as old as Eocene, but the major cones accumulated during Pleistocene time by the extrusion of andesite flows.

B. Columbia Plateau

Christiansen--Ref#27--Columbia Plateau...largest Cenozoic basalt field in North America. The basaltic flows are relatively thick (20 m or more) and very widespread, some occurring tens or even hundreds of kilometers from their linear fissure vents.

McKee--Ref#7--Columbia River Plateau (CRP)...first great outpourings of basalt lava built one of the world's most impressive piles. Later, gigantic floods of water raced across the plateau and produced one of the world's most intricately channeled surfaces. Nowhere today can we see flooding of either water or lava on this scale.

A "typical" flow of the Columbia River basalt was approximately 100 feet thick, although some flows were more than 200 feet thick, and others had a thickness of just a few feet. The eruptions were not from a single vent but from very long cracks or fissures, each of which was many miles long. An individual eruption was probably fed by many fissures erupting simultaneously.

The flows spread out almost like water for great distances. One member has been traced...over an area of approximately 20,000 square miles.

Bullard--Ref#6--Columbia Plateau...here, covering most of Oregon and parts of Washington and Idaho with an area of 200,000 square miles, are basaltic lavas reaching a thickness of 3,000 feet and representing hundreds of flows superimposed one upon another.

Greely--Ref#16--Flood basalts form extensive, often thick flows erupted at very high rates from fissure vents and produce vast basalt plateaus.

Kuntz--Ref#8--Columbia Plateau...age between 14 and 16 million years ago. It looks like the Western Snake River

Plain (SRP) has in it basalt that is Columbia River in age. Columbia River basalts are found in the deeper parts of the western plain and are also exposed at various points around its edges. So it appears that it was an extension of the CR basaltic province back 14 to 16 million years ago. In fact, some of the faults that occur along the edges of the WSRP, look as if they may actually be extensions of the same kind of system (deep crust cracks) that formed the CRP. But the CRP basalts ended 14 million years ago and that was it. The SRP has these same basalts, but continued to erupt into more recent geologic times.

Stern, Carroll and Clark--Ref#37--The combined Columbia and Snake River Plateaus represent one of the largest accumulations of lava in the world. One hundred thousand cubic kilometers of lava covered large areas of Washington, Oregon and southern Idaho to form the Columbia Plateau (written before geologist split the CRP and SRP). The basaltic lava must have been a rapidly moving liquid of low viscosity when it emerged from the conduits which are believed to have been fissures in the crust rather than volcanoes, because single flows a hundred meters thick spread for over 150 km before they cooled enough to solidify. The first lava flowed out over a mountainous countryside with a relief of over 750 m. Flow after flow of the molten basalt filled the valleys until they were entirely buried in lava. More lava welled up, ultimately covering an area of 500,000 square km.

Maley--Ref#39--The Columbia River Basalt Group covers an area approximately 77,000 square miles in Oregon, Washington and western Idaho...it has an estimated total volume of approximately 90,000 cubic miles. Radiometric age determinations indicate that the group was extruded during a period form 17 to 6 million years ago. About 99 percent of the volume was erupted during a 3.5 million year period from 17 to 13.5 million years ago.

Columbia River Basalt flows were erupted from north-northwest-trending fissures...These fissures were fed by dikes tens of miles long. Some individual flows are thought to have exceeded 140 cubic miles in volume although most had volumes of 2 to 7 cubic miles. The duration of the eruptive period of each flow probably lasted from several days to as long as several weeks.

An average flow of the CRB was approximately 100 feet thick, although some were more than 200 feet thick. The eruptions were not from a single vent, but from long cracks or fissures many miles long. Each individual eruption was fed by many fissures simultaneously. The basaltic magma was so fluid that it spread like water without change in thickness over tens of miles. Single flows covered as much as 20,000 square miles. The average spreading velocity is estimated to have been 25 to 30 miles per hour.

The first flows of the CRB were erupted over a landscape of rolling hills. Each successive flow filled in the low areas until a flat-surfaced plateau was formed.

Three lobes of CRB extended eastward into Idaho...: the Weiser, the Clearwater and the St. Mary embayments.

...The average thickness of the flows ranges from 50 to 100 feet but some are more than 400 feet thick in basins. The maximum thickness of the group in any one place is about 5,000 feet.

C. Snake River Plain

a. General

Bullard--Ref#6--The SRP is commonly described as an eastward extension of the Columbia River Plateau..., But structurally it is different from the SRP and, in addition to being younger (mainly Quaternary), the lavas are chemically distinct.

Greeley--Ref#16--SRP...(has differentiated SRP as a "Basaltic Plain.") different from the CRP because of average flow thickness of only 10 m, and the presence of lava tubes, channels and shield volcanoes. The SRP contains characteristics of both the flood basalts and shield volcanoes. Lava flows erupted from both central vents that produced low shields and short fissures that formed thin sheet flows; combined flows in the SRP locally exceeds 1,500 m. As with shield volcanoes, flow features such as lava tubes and lava flow channels are relatively common and are important in emplacing lava flows in the low-lying areas between the low shields)..the SRP represents a style of volcanism between flood basalt volcanism and Hawaiian volcanism. Basaltic plans volcanism combines both elements of shields and flood basalt plateaus; the plains commonly aligned along fissures.

Mabey--Ref#3--The SRP, which extends in a 600 km arc across southern Idaho, is the most prominent Cenozoic feature in the state.

Although the regional surface geology of the SRP in Idaho is well known and many shallow and a few deep holes have been drilled on the plain, major uncertainties remain concerning the structure of the plain. Seismic refraction profiles have revealed that under the plain a thin upper crust overlies a lower crust which is thicker than that under the Basin and Range province to the south.

The eastern SRP is more likely a downwarp containing a complex calderas with a great thickness of silicic volcanic rocks overlain by interbeddeded basalt flows and sediments. Fissures, along which the younger basalts have been erupted parallel trends of the basin and range structures to the north and south of the eastern plain and may be extensions of these structures. Although typical upper crustal rocks may underlie the eastern plain, the geological structure in these rocks appears to be different from adjoining regions. The evolution of the eastern SRP appears to have consisted of a northeastward-moving center of volcanism that is now at Yellowstone National Park and of an increase in the density of the crust by a corresponding thinning of the upper crust and the resulting subsidence. Current deformation of the eastern plain is a southwest extension, parallel to the plain.

Smith--Ref#27--A close association of rhyolitic and basaltic magma has characterized the development of Yellowstone and the SRP. Many explanations have been put forward to explain the origin of the two kinds of magma, the most promising hypothesis being that two different source materials melted partially to form two distinct liquids, one rhyolitic and the other basaltic. (This explanation may seem trivial, but it is not. The two kinds of magma could conceivably have formed not out of two materials, but out of a single material with two immiscible ingredients.) The basaltic magma is quite similar to the basaltic magma that forms under oceanic islands; in both settings the basaltic magmas are partial melts of the earth's upper mantle. The origin of the rhyolitic magma is probably the partial melting of the metamorphic rocks of the earth's lower crust.

Mabey--Ref#3--The eastern SRP is basically a downwarp containing numerous calderas. Extension normal to the plain is a possible explanation for the thinned upper crust under the plain and the high thermal anomaly now centered under Yellowstone NP that moved northeastward across southern Idaho producing a complex of calderas that are now largely obscured by the younger basalt flows on the SRP. Such a thermal event can be used to explain the formation of the eastern SRP only if some mechanism for the development of a large positive mass anomaly under the plain is also involved. The current tectonics of the eastern plain appear to be extension parallel to the axis of the plain.

Kuntz--Ref#8--The SRP went through its own very unique geologic history and the style of volcanism was very different from the CRP. There were intermittent eruptions from very short lengths of fissures. Instead of fissures being measured in tens of miles like occurred on the CRP, the fissures were only a few kilometers in length. Large broad shield volcanoes were common in this area. Last eruptions in the WSRP were probably from 500,000 to a few million years old, but there are no verified dates at this time.

If you could view the SRP from above, it would appear as if a whole bunch of pancakes had been flicked out on the surface of the earth. Because this is what a lava flow resembles--a pancake. Some of the pancakes are thin, others thick--some are circular, some are elongated--and they are rather randomly stacked on top of each other.

If you assume that there is an infinite supply of basalt magma at depth beneath the SRP and it extends from Twin Falls to Yellowstone, "Its there and its just like the blood in your arm, if you want to see it, all you have to do is scratch your skin and you will see blood." In other words, all you have to do is break the surface of the SRP and you are going to see basalt.

(Evidence that this very hot magma does exist beneath the plain is demonstrated by the fact that) if you look at a map of Idaho and look at the location of the epicenters of all of the earthquakes that have occurred, you will find that only the SRP is totally blank. This indicates that the area, instead of being composed of rock that is fairly cool and deformed by fracture (faulting) when seismic energy is released, is an area where the rocks are hot and plastic and deform by flow. When these rocks are subjected to stress, they tend to flow rather than fracture. So the best explanation of why there are no earthquakes beneath the SRP is that the crust here is still very hot...

The Columbia Plateau was formed above oceanic crusts where basalt has little difficulty reaching the surface. The Western SRP, however, is located partly above the continental crust. The continental crust acts as a barrier in allowing basalt magma to the surface because it represents a density barrier to the rise of dense basalt magma. so what happens is that only small volumes are erupted. This is very sporadic because evidently the magma is continuously wedging its way upward, but most of it is being blocked by the density barrier and is congealing deep in the continental crust.

Eastern SRP--Theories on the origin of the SRP are involved and currently a combination of the plume theory and the flow theory has the best acceptance. To start with, around the margins of the ESRP, rhyolitic rock has been located in several areas where it extends from under the basaltic lavas on the surface. These rhyolites have been dated and the corresponding ages have been recorded. Twin Falls 15-18 ma, Pocatello 10-12 ma, Arco and Idaho Falls 4-6 ma and Yellowstone .6-2 ma. There is a progression to the northeast from young to old. (Recent research has indicated that it is not this simple--the progression may be young-old-young-old-etc., but general the progression is form youngest to oldest to the northeast).

Thinking now is that these rhyolitic sheets come from massive calderas. The calderas are formed when a large amount of rhyolitic magma in chambers in the crust that are 20 to 40 miles across rises to the surface. The cap on these chambers may collapse or explode due to the tremendous amount of gas in the rhyolite magma that expands once it is no longer under pressure. Some of the material is blown into the air, but much of it moves out laterally in its own unique type of lava flow--it rides along on a cushion of heated air and flows for great distances. The material deposited is known as welded tuff.

Why do these calderas form? Well, calderas form when large masses of melted, crustal material (rhyolite magma) forms and then rises gravitationally (buoyantly) towards the surface. Rhyolite magma forms at the base of the crust where the mantle is so ho that it is melting the crust. This is where the mantle plume theory comes in.

Kuntz--Ref#24--One of the best sites to observe the eruptive sequence of the lavas of the SRP is in the walls of the Snake River Canyon. As the river eroded away the lava deposits, it exposed lava flows that date back millions of years. Upon examining these flows, a definite pattern is found. The pattern is one of small initial eruptions of basalt lava, followed by huge flows of rhyolite and finally more small basaltic flows.

An analysis of this pattern would indicate that hot magma is rising buoyantly through the mantle towards the earth's surface. Upon reaching the earth's crust some of the magma erupts directly onto the surface as basaltic lava, but most of it is trapped within the crust. As the magma begins to collect, a magma chamber develops. As more and more magma gathers, temperatures become great enough that some of the surrounding crustal rock melts and mixes with the magma. The large amount of silica in the crust contaminates the magma and produces a very thick rhyolitic magma. The amount of magma in the magma chamber continues to grow until its buoyancy overcomes the resistant force of the earth's crust and the rhyolite rises to the surface and erupts. Because of the very viscous nature of the lava, these eruptions are usually immense and often explosive eruptions.

Even after this massive eruption, the residual heat that remains is enough to insure a continuing supply of magma is generated. It again will rise towards the surface, but initially it usually cannot overcome the resistance of the earth's crust and is contained beneath the surface. The magma once more begins to accumulate in a magma chamber. This time, however, very little of the crustal rock surrounding the chamber melts. This is because most of the material that would melt at the normal temperature of the magma had previously melted during the formation of the first magma chamber. The minerals that remain in the crust now have a melting temperature that is higher than the temperature generated by the magma.

The magma continues to build in the magma chamber and eventually rises to the surface and an eruption occurs. Since the lava is not contaminated by crustal material, it contains relatively low levels of silica and the eruption is one of basalt lava. These eruptions of basalt can occur periodically for millions of years after the initial eruptions.

When geologist state that they can trace the ages of lava flows across the SRP and these demonstrate a pattern of older to younger as one goes from west to east, they are talking about the age of the rhyolite flows and not the basalt flows. Because the basaltic flows occur at a much more frequent rate and can be considered as still potentially active, basalt flows do not show the same age distribution as the rhyolitic lavas.

Maley--Ref#39--The SRP is a prominent depression across southern idaho extending 400 miles in an east-west direction. The width ranges from 500 to 125 miles with the widest part in the east.

Western SRP--..is 30 to 43 miles wide and trends northwest. It is a fault-bounded basin with both the land surface and the rock layers dipping towards the axis of the plain. The basin is filled by interbedded volcanic rocks and lakebed sediments of Tertiary and Quaternary age.

...The western plain originated as a rift about 17 ma and continued development to the present. About 17 ma major tension in the upper crust thinned or pulled apart the upper crust along the axis of the SRP. The new elongate depression was filled with volcanic flows and sedimentary material derived from the uplands.

Central SRP--...much of the central plain is covered by volcanics....The western and central plain appear to have formed from regional tension normal to the trend of the western SRP.

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Central SRP--...much of the central plain is covered by volcanics....The western and central plain appear to have formed from regional tension normal to the trend of the western SRP.

.....The western and central plain may be a downfaulted block something like a rift or graben. The downfaulting may have been caused by regional extension or possible clockwise rotation of a block south of the plain which thinned or parted the upper crust....The western and central plains are continuing to subside because of cooling, tension, loading of sediment and isostatic adjustment caused by the dense layer beneath the plain.

The central SRP has features common to the eastern and western plains. Downwarping is the most significant structural activity in the eastern SRP.

Eastern SRP--The eastern SRP trends northeasterly and is underlain by mostly silicic and basaltic volcanic with very little sediments. There is no significant fault control on the margins. The plain rises at the extreme east probably due to the proposed hot spot and associated volcanism recently moving from the Island Park Caldera to Yellowstone.

The land surface is higher at the margins than at the center, similar to the western plain. Both north and south of the eastern plain is the basin and range province....is generally covered by Quaternary basalt flows with sources from fissures parallel to the plain, normal to the plain and along extensions of the basin and range faults.

General--The central and eastern plain is apparently a structural downwarp because strata along the flanks dip towards the center; also there is little evidence for boundary faults. By contrast, the area in the vicinity of Yellowstone appears to be experiencing uplift. This eastern propagation of vulcanism may be caused by the migration westward of the continent at a steady rate over a deep mantle plume or hot spot rooted more than 100 miles below the surface. Several hypotheses exist to explain the origin of the SRP:

1. Extension to the north coupled with crustal thinning.

2. Migration of the continent or the NA plate over a stationary hot spot which now exists at Yellowstone NP. The hot spot has a northeastward migration of silicic volcanic centers moving at a rate of 1 to 2 inches per year. Uplift is associated with volcanism and silicic volcanism is followed by basaltic volcanism. The lower crust is thickened and made more dense by injection of basaltic magma. After passing over the hotspot, the crust settles due to contraction from cooling and the density of the basalt. This hypothesis is favored.

3. Propagation of crustal fracture from west to east.

4. Passive deformation.

Geologic Model for SRP Volcanism.....Basalt magma formed in the mantle moves upward because it is less dense than surrounding mafic mantle rocks. However basaltic rock is denser than crustal rock so the basaltic magma column must extend deep enough into the mantle to allow hydrostatic pressure to force it up through the lighter crust. The basaltic magma probably originated at a depth of approximately 40 miles. The original basaltic magmas probably stagnated in the deep crust; however, repeated injection of more magma led to a large magma chamber and a thicker lower crust. During the accumulation of basaltic layers, heat transfer to the crustal wall rocks would cause partial melting (anatexis) of the more silicic crust.

The zone of partially-fused wall rocks continues to enlarge as basalt is added. Because partial melts of silicic magmas are less dense than the basaltic magmas, they would tend to coalesce and move higher in the crust to form magma chambers at about 6 miles deep. Intermediate to silicic magmas would continue to differentiate and interact with wall rocks as well as hydrothermal fluids. These magmas would raise the temperature of the crust and the heat would cause the crust to expand and result in regional uplift. Numerous eruptions of ash-flow tuffs occur during caldera collapse; after collapse, resurgent doming takes place and the cycle is repeated many times. Small rhyolite domes extrude after the main rhyolitic phase represent the residual components of the original silicic bodies. As long as the silicic magma bodies existed as fluids, fissures could not propagate to allow the basaltic magmas to pass. Rhyolitic volcanism ceases with solidification of the silicic magma.

Malde--Ref#33--The SRP is a major late Cenozoic tectonic feature in the North American crust. The plain consists of two distinctive parts, which differ in structural trend and geology: a NW-trending sedimentary basin in the western part, and a NE-trending volcanic plain in the eastern part....

Despite information obtained from geologic, chronologic and geophysical studies, the origin of the SRP is inadequately understood. No unified explanation of why the plain exists has been proposed. For many years, perhaps because of Physiographic continuity, and perhaps because so much of the SRP is covered by distinctive olivine basalt, the plain has been referred to as a single geologic province--as if to imply that its structure and geology reflect one set of forces and processes from end to end. In the last decade, however, a concept has emerged that the western and eastern parts of the SRP represent different entities, structurally and geologically. The two parts of the plain also are now thought to differ appreciably in age.

The western SRP is a structural basin, bounded by high-angle faults and filled with sedimentary deposits as much as 1.7 km deep. The sediments are underlain by a thick slab of basalt and by still deeper silicic volcanic rocks. The basalt slab was probably emplaced at a time of rifting contemporaneous with eruption of basalts of the Columbia River Basalt Group (17-14 Ma). Judging from the distribution of certain ash-flow tuffs, parts of the western plain also may have been sources of silicic eruptions at about 11 MA. The sedimentary deposits began to accumulate soon after these volcanic rocks erupted, decreasing in age to the SE as the rift continued to grow headward. The basin-filling sediments culminate in deposits that have ages of about 3 Ma, where the head of the western SRP is overlapped by basalt of the eastern plain, although such sediments continued to be deposited farther west until about 2 Ma....The Snake River in the western SRP is incised to depths of 150-300 m, forming steep-walled canyons in the basaltic rocks and strongly gullied badlands in the sediments.

The eastern SRP, in contrast, is a bimodal volcanic province, characterized by rhyolitic volcanics nearly completely covered by basaltic lava flows. the rhyolite extends to depths of at least 3 km, and the overlying basalt is about 1 km thick. No evidence for deeply buried basalt, as recognized in the western SRP, has been found. Furthermore, unlike the western plain, the eastern SRP had no identified faults along its margins. The rhyolite and basalt are thought to be products of a migrating thermal anomaly, which progressed from southeast Oregon and adjacent Nevada to the Yellowstone Plateau between 17.5 and 0.6 Ma, reaching the eastern SRP about 10 Ma. In SW Idaho, the path followed by the thermal anomaly is a broad swatch of rhyolite thinly veneered with basalt, which together form an upland called the Owyhee Plateau. At the upper end of the western SRP, downfaulted volcanic rocks of the Owyhee Plateau are overlapped by deposits of the western sedimentary basin....

Rhyolite of the eastern SRP trend in southwestern Idaho ranges in age from 13.8 Ma at the SW to 9.6 Ma at the NE. The age of the basalt is about 9.4 Ma, or older, but the basalt becomes younger to the NE and ultimately is buried by still younger basalt of the eastern SRP....The youthful age of the basalt of the eastern plain reflects widespread eruptions along volcanic rift zones, which are aligned with high-angle faults at the fronts of mountain ranges to the north and south....

Western SRP--The most distinctive feature of the western SRP is its group of sedimentary deposits, locally interbedded with basalt, which together fill a structural basin bounded by older rocks.....

The geologic features reviewed above indicate that the western SRP is a structural basin older than 16 Ma, which grew headward (SE) until 3 Ma, thereby accumulating a thick sequence of lacustrine and fluviatile sedimentary deposits. Geophysical findings outlined below, although still limited in scope, imply that the structural basin is an area of crustal extension and that its present low altitude relative to uplands and mountains to the north and south reflects isostatic compensation for a large underlying mass of basalt and an unusually thick lower crust....

Mabey (1982) sums up the geophysical findings by concluding that the western SRP formed as a rift at about 17 Ma, which was filled with upwelling basalt and with sedimentary debris...Mabey's conclusion that the western SRP formed by rifting is modified here only by suggesting that the rift continued to grow headward until 3 Ma, thus overlapping rhyolite and basalt associated with the thermal anomaly that ultimately produced the eastern SRP....

Eastern SRP--The eastern SRP is a bimodal volcanic province, covered by undissected lava flows of basalt throughout most of its length and underlain by rhyolitic volcanics....the eastern SRP has a fairly uniform width of 90-100 km and a length of 350 km....

The rhyolitic volcanics that underlie the eastern SRP generally are accepted as representing the products of a migrating thermal anomaly, but eruptions produced by the anomaly did not necessarily progress at a uniform rate, and the cause of the anomaly is uncertain. Rhyolitic volcanism began at the McDermitt volcanic center in SE Oregon at 17.5 Ma and progressed NEward along the eastern SRP trend, last being represented by an explosive eruption in Yellowstone Park at 0.6 Ma. In this distance, 580 km, centers of volcanic activity migrated NEward at an average rate of 3.5 cm/yr...

The rhyolitic volcanics are primarily ash-flow tuffs. In the eastern SRP most (or all) of the tuffs are associated with calderas that are concealed by overlying basalt. Tuffs related to calderas range in age from 11.3 Ma at the Bruneau-Jarbidge eruptive center on the Owyhee Plateau to ages ranging from 6.5 to 4.3 Ma near the eastern end of the plain. Farther NE, ash flows associated with calderas in and near Yellowstone Park range in age from 2.0 to 0.6 Ma.

The basalt that overlies the rhyolite began to erupt soon after the migrating thermal anomaly had passed any given point....

Vents for basalt of the eastern SRP are relatively numerous near the axis of the plain. As a consequence, the basalt forms a subdued medial ridge, which is recognizable along most of the length of the eastern plain. Because of the ridge of basalt, streams north of the plain end in playas near the northern margin or, in the case of the Wood River, turn westward...

The basalt vents also is influenced by volcanic rift zones, which cross the eastern SRP approximately at right angle to it axis. The longest and best known of these is the Great Rift, 85 km long, reaching from mountains just north of the plain SEward through CRMO to the Wapi lava field west of American Falls....At least seven other volcanic rift zones were sources of basalt of Holocene and latest Pleistocene age....

The presence of high temperatures at shallow depth under the eastern plain also is implied by magnetotelluric soundings, which provide information about the electrical structure of the crust to a depth of 25 km....

...the presence of volcanic rift zones and widely distributed Quaternary basalt implies that deep-seated fractures are present. As sources of basalt, the volcanic rift zones must extend deeply beneath the eastern SRP. and they presumably are signs of tension in the crust. Because identified volcanic rift zones are extensions of range-front faults to the north, they possibly are further evidence of the regional extension expressed by basin-and-range structures to the north and south, which have the same trend. Whether the range-front faults are linked with volcanism along the rifts cannot be determined from available dates, but recurrent late Pleistocene movements on the faults are reported. On the other hand, the volcanic rift zones simply may be express thermal contraction and, hence, may be features of the thermal history of the eastern SRP....

At each volcanic center [along the path of the thermal anomaly of the eastern SRP], volcanism was preceded by intrusion of basaltic magma into the granitic crust. for this reason, the "fundamental character" of the volcanism has been described as being basaltic. Intrusion of basaltic magma increased the regional heat flow, caused crustal thinning, lowered seismic velocities, produced rhyolitic magmas by local melting of the granitic crust, and caused regional uplift by thermal expansion. In this way, granitic batholiths were formed that became sources for explosive pyroclastic eruptions of rhyolite, usually followed by collapse of associated calderas. Occasionally, basaltic lava erupted concurrently with the rhyolite. After a batholith cooled and solidified, basalt could erupt through the rhyolite, thus producing bimodal complexes of rhyolite and basalt, as at Island Park. With further cooling, thermal contraction caused former areas of silicic volcanism to subside and produced inward dips toward the path followed by the thermal anomaly. The rhyolite eventually became completely covered by basalt, as now found throughout the eastern SRP, but not yet developed in Yellowstone Park. However, basaltic volcanism in the eastern SRP is not just the final volcanic stage at a given volcanic center. Rather, basalt has erupted widely from fractures that have formed perpendicular to the trend of the eastern plain. The widespread basaltic eruptions include lavas of Holocene age, which suggest that the eastern SRP still may be underlain by widely scattered sources of basaltic magma. Such magma may account for local melting of the granitic crust, or for remelting of silicic volcanic rocks, as expressed by Quaternary rhyolite domes NW of Blackfoot and at Juniper Buttes.

b. Mantle Plume

Maranto--Ref#25--For awhile, scientists were at a loss to explain how a chain of volcanoes (Hawaiian Islands) with such an orderly chronology could have been formed. More ever, they had no idea why it would have appeared in the middle of the vast Pacific Ocean.

In 1971, the geologist Jason Morgon of Princeton suggested a bold solution. Isolated in the middle of a vast plate, the Hawaiian volcanoes must have been created by a stationary heat source beneath them in the mantle. Morgan proposed that this source might take the form of a rising column of exceptionally hot, light material, called a plume, that periodically breaks through weak places in the crust. Such a source would account for the pattern of westward ageing. Magma welling up from a single hot spot over the centuries would have broken through the surface many times, as the Pacific plate slowly moved west. In this way, a trail of volcanoes would have been created.

Many geologists believe that this theory best accounts for Hawaii and at least a dozen similar areas throughout the world, including Iceland and Yellowstone....but several large, unanswered questions still puzzle geologists. For example: How do the plumes form? How do they move through the mantle? Why do they form chains of distinct islands rather than continuous ridges? Currently, there are two main views about precisely where plumes originate. The first has them starting about 420 miles down, at the supposed boundary between the upper and lower mantle. The second theory, proposed by Peter Olson, a geophysicists at Johns Hopkins, and more in favor with researchers, argues that the plume begins 1,400 miles deeper, in the region between the mantle and the earth's molten iron core.

Seismographic studies show that this deep layer of the earth is highly irregular in both shape and composition, a hodgepodge of rock heated by conduction from the liquid core....Olsen suggests that the uneven boundary between core and mantle is an ideal place for the creation of plumes. "You have a fairly mobile bottom layer beneath the main body of the mantle," he says. "Because this layer isn't uniform, you are going to get localized upwellings of heat and material." These upwellings heat some pockets of material in the lower mantle more than the rest of it. Made more buoyant by that heat, they begin to flow upward, stringing out into a long column. Once begun, Olsen says, plumes tend to stay in place for as much as a hundred million years...

(In an experiment) Olsen simulated the movement within the mantle by releasing thinned corn syrup (into a tank of undiluted corn syrup that is being moved along a mere fraction of an inch each second). (He expected a continuous plume to form, but instead the plume broke apart). When the bulb atop the stem reached a certain size and distance from the source, it broke off and moved upward independently.

Over time, this process produced an "assembly line of blobs," says Olson, which helps explain how hot spots could produce volcanoes at regularly spaced intervals..Eruptions would occur as new magma gathered in chambers three or four miles beneath the surface. As the moving crustal plate slid old volcanoes off the hot spot new ones would form.

Gore--Ref#28--...the architect of Hawaii is one of the Earth's 30 or more hot spots. Like blowtorches beneath the drifting plates, hot spots continuously pump heat from unknown sources perhaps several thousand kilometers beneath the surface. Hot spots also underlie Tahiti, Samoa, Iceland, the Azores and Reunion Island. New Hampshire's White Mountains and Bermuda may be remnants of the North American Plates's passage over a now extinct hot spot...

Caldera eruptions like La Garta do not necessarily belong to the remote past. With University of Utah geophysicists Bob Smith, I fly over Yellowstone National Park. "Once there was a mountain range as big as the Grand Tetons here." says Smith. "It all went in one colossal eruption of the Yellowstone caldera. That eruption equaled a thousand Mount St. Helenses."

Like Hawaii, Yellowstone is generated by a hot spot. That hot spot 65 ma was probably off the Oregon coast, making islands that now underlie the Coast Ranges. As the continent passed over it, the hot spot has left a trail of volcanic rock across the West. "There was a Yellowstone at Boise, a Yellowstone at Twin Falls and at Pocatello," says Smith. "If you wait a few million years, there may be one at Billings."

Yellowstone has erupted catastrophically about every 600,000 years. Thus we are about due. Recently the caldera floor has begun rising at an increased rate.

Davis--Ref#36--....A hot spot is regarded as a thermal plume of uncertain origin that sears the overriding lithosphere. The path of movement is thus recorded in the form of a linear scar of volcanoes and/or igneous intrusions in the lithosphere....One image that comes to mind in visualizing hot spots is one of slowly passing a 78-rpm record over a blowtorch, thus steadily melting and blistering the record along the line of movement.

Middlemost--Ref#35--Some volcanic activity occurs in discrete areas within lithospheric plates and such areas (e.g. Hawaii and Yellowstone in the USA) have been called hot spots....Morgan proposed that these hot spots are "manifestations of convection in the lower mantle" and that the heat is brought up to the base of the lithosphere by "deep mantle plumes." It has been suggested that these deep mantle plumes originate in, or near, the boundary layer between the liquid outer core and the lower mantle.

Sullivan--Ref#26--The thesis of Smith and others is that the SRP marks the path along which volcanic activity now at Yellowstone has migrated at a rate of one or two inches per year. In 1983, Smith proposed that it is still moving towards Montana. Probably the most popular explanation is that of a hot spot or plume rooted deep in the depths of the earth beneath the moving North American Plate....Yellowstone's eastward migration sees roughly the reverse of North America's drift to the west.....

What is the likelihood of further eruptions at Yellowstone or along the path of its migration? Surveying of the caldera in recent years has shown that the two domes within it are rising at least a half inch per year, "about the growth rate of a human fingernail," according to Smith. This was "extraordinarily high." The rate is comparable to those sometimes measured on the active volcanoes of Hawaii and Iceland and could mean either that magma is moving up beneath the domes, or that gas is being released from a deeper magma body. Not one of the magnetic, seismic, gravity, electric, heat flow, or survey observations "unambiguously proves that any magma still occupies Yellowstone's shallow chamber", wrote the geologist, "but all are consistent with such an inference, "suggesting " a reasonable possibility of further volcanism."

Kuntz--Ref#8--A mantle plume is still not fully understood, but the general idea is that the plume is a very hot spot that is fixed, does not move. Then as a plate (in the case of the SRP, the North American plate that is rotating on the earth in a southwestern direction at a rate of about 3 cm per year), slides over the plume, its base is melted, creating rhyolitic magma. This would produce tracks across the earth's surface and the theory is that this is seen on the SRP. If the ages of the rhyolite flows are compared with the distances between source vents on the SRP, the movement of the NA plate from Twin Falls to Yellowstone figures to be 3 cm. Coincidence? There is nothing wrong with this theory except that it is really very simple. There are other theories being developed.

Redfern--Ref#38--...the (Hawaiian) oceanic islands and the (SR) continental plain were formed by hot spots, or mantle plumes, beneath the upper crust. As the Earth's lithosphere moves over hot spots in the mantle, magmatic vents are burned through the crust. These magmatic holes leave a trail of volcanoes on the surface of the moving lithosphere.

c. Basin and Range

Kuntz--Ref#8--Another theory that explains the formation of the SRP relates to Basin and Range extension where hear is produced not through a plume but rather friction. Since the NA plate has overidden the East Pacific Rise (EPR), several different forces are at work in the western US. The EPR is spreading out in a more or less west and east direction as the continent moves to the southwest thus there must be a tremendous amount of friction at the base of the crust. This friction causes heat.

These are the same forces that are creating the Basin and Range (BR) structure in the western US. The SRP is located at a boundary between a stable part of the continent (Idaho Batholith--a granitic intrusion) and a spreading part of the BR. It becomes a frictional boundary and heating may be occurring at this particular location. We know that the eastern boundary of the BR is moving off to the east as more and more country is being affected by BR extension. This may explain the progression of calderas at this frictional boundary between a non-extending and extending crust. The progression of calderas simply follows the northeast trend of BR expansion.

Mabey--Ref#3--Active volcanism, open fissures and evidence of continued subsidence show that the SRP is an active structure that continues to develop. A suggestion exists in the magnetic data that the eastern plain may be part of a northeast trend reflected in Precambrian rocks to the northeast, but no evidence has been reported to suggest that the plain existed before Miocene time. Several lines of evidence do suggest that the development of the plain may coincide with the large-scale extension of the BR province to the south, which began about 17 million years ago.

The apparent relationship between the rifts on the eastern SRP and the BR faults to the north and south suggests that they represent different responses to extension of the crust approximately parallel to the axis of the plain. Normal faults south of the plain, and presumable those north of the plain, appear to be controlled by old structures, many related to overthrusting; many of the normal faults flatten at depth to merge with major thrust faults. Although the belt of overthrusting probably initially extended across the area of the SRP, subsequent igneous activity along the plain and perhaps extension normal to the plain have disrupted the thrust faults.

The BR structures north and south of the eastern SRP either terminated at the margin of the plain or extended only a few kilometers onto the plain. However, the pattern of volcanic rifts on the plain suggests that they may be related to the BR structure.

MacMahon--Ref#29--The Intermountain West is composed of 150 basins and approximately 160 discrete mountain ranges. This landscape of alternating mountain ranges and their adjacent basins is the physiographic zone know as the BR Province.

The Province has valley floors at high elevations, often more than 4,000 feet. Protruding from the basins are mountain ranges, which were raised through the process of faulting. Most of the ranges have a north-south orientation, and many have peaks higher than 10,000 feet; several exceed 12,000 feet. This means that in some areas mountain peaks rise 5,000 to 6,000 feet above the surrounding basins.

Sullivan--Ref#26--Between 10 and 20 mya, the ridge that was the parent to the Farallon Plate came in contact with more and more of the coast from California north. As the edge of the continent became subject to northwest drag by the newly arrived Pacific Plate, stretching of the landscape began. The consequent alteration o the BRP now extends from Mexico north to southern Washington and Idaho, bounded on the west by the Sierras and on the east by the Rockies and Colorado Plateau. It is most prominent in Nevada and Utah, and an air traveler can count a dozen parallel, uniformly spaced north-south ranges on a flight across these states...

Several explanations have been proposed for the spreading that has produced this extraordinary landscape. One theory is the presence beneath it of the spreading center that, beginning thirty mya, was overridden by NA. Probably the most popular explanation, however, is also used to account for the opening of the enclosed seas that lie behind such arches of volcanic islands as Japan. This process of "back-arc spreading" is believed to have gradually carried Japan away from Asia, forming the Sea of Japan. It is proposed that lava from the plates that has pushed under the islands and beyond them, rises and spreads under the crust, pulling it apart. Some believe spreading in the BRP may have widened the distance between the Colorado Plateau and the Sierras by a hundred miles or more and that, had the process continued, the earth's crust might have been torn completely open, forming a sea like that between Japan and the Asia mainland.

Gore--REf#28--"Fifteen mya, Salt Lake City and Reno were 200 to 300 miles closer together," says Utah's Bob Smith.

The two cities are pulling apart because the Great Basin is being heated from below. The crust is thinning and stretching. Just what causes that heating is controversial. It may be the melting of the old subducted Farallon plate below. Whatever the cause, as the crust stretches, large blocks of land subside. Where they drop, they create valleys next to mountain ranges. The entire region from the Wasatch Range that overlooks the Great Salt Lake to Death Valley and the Sierra escarpment is a series of deepening basins interspersed about every 25 kilometers or so with mountains. The valleys of this so-called BR region do not subside gently (earthquakes).
Geologists debate whether the BR will rift enough to open a new ocean. If it does, the West Coast would become a free-floating continent.

Press-- Ref#13--West of the Rocky Mountains is the BRP, a region of many smaller chains of mountains alternating with elongated basins. This is the area that some see as a potential huge rift valley that may someday separate the continent into two parts.

One might have expected the structurally high BRP, with its average elevation of about one KM, to have a slightly thickened crust to go along with its negative anomaly. Actually, many geophysicists thought this to be the case until experiments with seismic waves revealed the thin crust....The low density mantle (in this area) seems to go with a tectonic setting that includes recent volcanism, high heat flow, and low seismic velocities--which implies, perhaps a partially molten mantle directly below the Moho. Some geologists suggest that these features, as they occur in the

BRP, indicate that tension-producing forces, perhaps due to a spreading or divergence zone, are active within a continent.

Fiero--Ref#34--The big change began about 17 mya. The BR topography that characterizes virtually all the present-day Great Basin (GB) began to form. The crust was stretched and uplifted over an area one thousand miles long and from 300 to 600 miles wide. The amount of stretching, or extension, is estimated to be between 10 and 50 percent of the original width. In some local areas, the GB may be extended as much as 100 percent. Like stretch taffy, the crust thinned as it was pulled apart.

The almost featureless volcanic plain, modified by a few domes of the metamorphic core complexes and the vast subsidence pits of the calderas, arched upward thousands of feet. Uplift was accompanied by extension. This stretching was accompanied by a cracking of the crust. Large blocks slide down and others tilted in response to being pulled apart. Large cracks extended north-northeast along the flanks of the rising mountains and downdropping valleys. These great faults still shudder the land today as adjustments continue in the crust. The GB had a new look--Basin and Range.

...Virtually all geologists are in agreement that the thinning of the crust beneath the BR is directly related to the fault-controlled uplift of mountains and downdropping of basins. We know the crust is thin. We know the valleys and mountains are bounded by faults. But below the valley gravels we can no longer easily trace the faults. Consequently, there are several different ideas to explain their subsurface appearance....

The uplifted mountains now had great relief relative to the downdropped valley floors. Erosion again attacked mountains in the GB, and the age old story of uplift and erosion was repeated. It still continues. Sediments have flooded into the valleys. Some basins contain as much as ten thousand feet of late Cenozoic sediment. If the sediments were suddenly removed, the true relief of BR faulting would stand revealed. Some mountains in the GB would tower from fifteen to twenty thousand feet above their adjacent bedrock floor.

Kuntz--Ref#15--Many volcanic rift zones in the central and eastern SRP appear to be extensions onto the plain of northwest-trending range-front faults that bound basin-range, block-fault mountains along the margins of the plain. In contrast, the Great Rift does not lie on an extension of a range-front fault, but it may be a southeastward extension of a basement structure in older rocks that extends northwest from the margin of the plain.

When the relative position of the Beaverhead, Lemhi and Lost River Ranges and their associated fault systems are charted, a regular pattern of spacing between these structural features become apparent. If an extension is made to the west to include the Great Rift, the regular pattern of spacing is still apparent, but there are no BR mountains to the north of the Great Rift to complete a perfect match up. Between each range and its boundary fault is a separation of approximately 25 to 30 miles. In several areas, the boundary faults for these ranges can be followed onto the SRP and the extensions coincide with volcanic rift zones.

But this may be because the area north of the Great Rift is structurally different because of the presence of the Idaho Batholith (The Idaho Batholith is a series of intrusions ranging from 120 my to about 50-70 my) that spans most of central Idaho. Since the Idaho Batholith is a granitic intrusion, while the typical BR landform consists of sedimentary rock, extentional forces at work in this area may have been expressed differently.

Within the Idaho Batholith, directly north of the Great Rift, is another series of much smaller intrusions or plutons that trend NW-SE, parallel to BR mountains and to their boundary faults. The alignment of the plutons would indicate the presence of a basement structure that would be a flaw in the earth's crust that allowed for their emplacement. From this information, it could be extrapolated that this basement fault represents the effect of BR extension into the batholith.

In summary, at the present time, there is no definite evidence that the Great Rift is a typical BR fault, but the location of the Great Rift and the intrusions directly north of the Rift may indicate that extensional forces related to BR formation may indeed have been responsible for the original formation and location of the Great Rift.

Smith--Ref#27--However, not all areas of continental intraplate volcanism fit into either the rift or uplift category. Such an area is the Cenozoic volcanic province of the western US which, although studied in great detail, is not fully understood. Volcanism in this area falls into two episodes. An earlier phase ranging over a period of from about 70 to 20 mya was characterized by dominating calc-alkaline volcanism of intermediate to silica-rich composition. This was probably related to subduction along the Pacific margin to the west. After only a brief interlude between 20 and 17 mya most of the area was subjected to pronounced regional extension. For example, cumulative tectonic extension exceeded 100 km in the GB. Except in the extreme west, volcanism now changed to either basaltic or alternations of basaltic and rhyolitic in composition. The entire igneous province which extends for about 2,000 km north to south and about 1,000 km east and west encompasses several major and distinct areas, including the block-faulted BRP, the Rio Grande Rift, the Colorado Plateau and, to the north the SRP, the Yellowstone Plateau and the Columbia River flood basalt plateau.

d. Flaw

Kuntz--Ref#8--Another theory is called the "flaw theory." The flow theory states that there is a basic southwest, northeast trending structure in the crust that is being used by the magma to get to the surface. This flaw would be seen only if we could strip off all of the thin, superficial cover of igneous rock to get down to Precambrian rock. Where nearby Precambrian rocks are exposed (Grand Tetons) there is found what is called a structural grain. That grain trends SW-NE. This would mean that in Precambrian time, uniform structural trend was imposed on the Precambrian rocks at that time and with subsequent movement of the continental plate, this particular trend is orientated parallel to the SRP. What may be happening is that whatever process is producing magma seems to be taking advantage of the structural trend and the flaw in the crust to allow magma to move to the surface. Activity may take place along the entire length of the flaw, but magma is only produced on the surface in areas where there is still crustal rock that can be melted. As the continental plate moves over the hot spot, more rock can be subjected to melting and this may result in the progression of young to old lava flows on the SRP.

Geophysical evidence indicates that the structural trend is very extensive. It covers all of the Eastern SRP and goes into Nevada where it is known as the Humboldt Trend. Its placement has all been determined through the analysis of aeromagnetic data.

Tomorrow there will be another theory and then another. the truth may be a combination of these theories of something totally different. All we can do is say, "Here is a theory" and its test for the present is whether it is consistent with the current data available concerning geology, history, geophysics, petrology and other related geological sciences.

E. Craters of the Moon/The Great Rift

Lefebvre--Ref#9--In the CRMO area the interpretable history is very short because the rock ages are younger than 20,000 years in age---less than an instant of geologic time... A lack of erosion to have exposed the deeper, older layers...means that deciphering the exact sequence of eruptions along the Great Rift (GR) is difficult and the story may remain incomplete.

Since the GR is parallel to the basin-and-range structures in southern Idaho, this theory for the origin of the rifting that produced the CRMO lavas is strongly supported. On the other hand, the hotspot theory for the formation of the entire line of successively younger volcanoes that extend southwest of Yellowstone is still a favorite of many geologists. The theory proposes that a plate moving over a hot spot--the source of which is unknown--leaves a trail of successively older volcanoes in positions the hot spot once occupied.

Since lava tends to rise along rifts, it follows that, on the surface, volcanic eruptions occur in alignment with the trace of the rift. In fact, it is often true, that only by connecting eruption centers (vents, cones) with straight lines, can geologists locate the position of the rift.

Rift systems, one of the most common geological processes on the surface of the earth, occur in areas of extension producing vent features along the rift and lava fields off to each side of the rift. The GR, because of its youth, magnitude and large vent systems in the lava fields is probably the best example of a rift system in the conterminous US. Others do occur: there are many in the SRP of southern Idaho and they can be found throughout the western US.

Kuntz--Ref#15--The GR consists of volcanic vents, eruptive fissures, and non-eruptive fissures that extend approximately 85 km from the southern Pioneer Mountains southeastward through CRMO to Pillar Butte in the Wapi lava field, located about 30 km northwest of American Falls, Idaho.

The CRMO lava field is a composite of more than 40 lava flows erupted from more than 25 cinder cones and eruptive fissures, most of which are located in ÇRMONM....The field covers an area of 1,6000 km2, contains more than 30 km3 of lava, and is the largest basaltic lava field of dominantly Holocene age in the conterminous US.

II. History of Eruptions at CRMO

A. Past Volcanic History/Eruptive Sequence

Kuntz--Ref#15--The CRMO lava field formed during at least eight periods of eruptive activity, each of which was about

1,000 years or less duration and separated by intervals of quiescence lasting from a few hundred years to more than two thousand years.

Lava flows and groups of flows that are believed to have similar ages, base on field, radiometric and paleomagenetic data, can be grouped into what we term "eruptive periods." Eight eruptive periods are presently recognized in the CRMO lava field. The duration of each eruptive period is uncertain, but paleomagnetic studies shoe that the durations of most of the younger eruptive periods were probably less than a few hundred years. The intervals between eruptive periods may have been times of volcanic quiescence or sporadic volcanic activity.

The oldest lava flows of the CRMO lava field flowed away from the general location of the GR. This relationship suggests that the GR was a locus of source vents for even the earliest of flows, and that these early flows are covered by younger flows.

The definition, components and extent of each eruptive period is contained in " The Great Rift and the Evolution of the Craters of the Moon Lava Field"--Kuntz.

Malde--Ref#33--By radiocarbon dating 20 of the 60 lava flows at CRMO on the GR, ranging from 15,000 to 2,000 years B.P., the lava flows are assigned to eight eruptive periods. From further studies of the erupted basalts, the "magma output rate" is determined to have been 1.5 km3/1,000yr between 15,000 and 7,000 years BP, and 2.8 km3/1,000 yr from 7,000 to 2,000 years BP. The period of repose between eruptions ranged between 500 years and 3,000 years, averaging about 2,000 years--this being the time evidently needed for local driving forces to produce an eruption. For comparison, Kuntz and others point out that output rates at CRMO were about 10 times less than those for Hawaiian volcanoes, about 20 times less than the rate for Iceland, and 40 times less than the rate inferred for the Columbia Plateau.

These data indicate that volcanism at CRMO took place at a fairly uniform rate during the last 15,000 years...

B. Fissure Eruptions

Kuntz--Ref#15--Basaltic volcanism has occurred as fissure eruptions within volcanic rift zones in many parts of the world, including Hawaii, Iceland and the eastern SRP, especially along the GR. Based on well-documented Hawaiian eruptions, we believe that the typical eruption along the GR consisted of distinct, though gradational, stages. The stages described below represent a generalized gradational sequence during a prolonged basaltic eruptive cycle--individual eruptions may have been included only some of the phases described.

Eruptions generally began with a long line of lava fountains that extended for hundreds of meters and locally for a few kilometers along a single fissure or a series of en echelon fissures. Voluminous outwelling of fluid lava long nearly the entire fissure accompanied fountaining. The basaltic lava in the early eruptive stages was extremely fluid and heavily charged with dissolved gasses. The early stages of such eruptions led to the development of spatter ramparts and downwind blankets of fine-grained tephra.

After several hours or days, the eruptions generally diminished and lava fountains became localized along short segments of fissures. Spatter ramparts were succeeded by spatter or cinder cones which built up around the lava fountains.

After several hours, days or weeks, a decrease in magma pressure and in the amount of dissolved gas in the magma produced a corresponding decrease in the height of lava fountains and thus a change in the types of volcanic processes and landforms. During historic, long-lived Hawaiian activity and, by inference, during prehistoric activity along the GR, fountaining diminished and was followed by quiet but voluminous outpourings of lava over or through the existing spatter or cinder cones. A prolonged period of overflow of lava in most places produced a lava cone composed largely of sheets of pahoehoe lava that mantled the older cone structure. Lava-cone summits are typically indented by an elongated crater. The elongation of the crater is generally parallel to the underlying fissure or rift, which served as a channelway for magma to the vent. Larger craters were formed by collapse of the crater walls, accompanied by repeated crater filling and draining.

Where eruption of fluid basaltic lava extended over periods of months and possibly years at a single vent, large cones or shield volcanoes were produced (shield volcanoes have been identified outside of the monument and the Blue Dragon flow may also qualify as a shield volcano if further research verifies this). These broad, low, rounded, shield-shaped landforms grew by the continued buildup of thin, far-spreading pahoehoe and, to a lesser extent, aa lava flows. Little explosive activity was involved in the shield-building stage.

The fiery-curtain eruptions do not continue indefinitely because they tend to "freeze" themselves shut. There is so much heat lost to the walls of the cracks as the magma moves across these surfaces that the flowing magma tends to congeal. But the magma is still under tremendous pressure so that in the wider areas of the crack (places where two cracks join, etc.) the magma actually erodes the opening to enlarge the pipe. So the eruption will begin to limit itself to pushing up through a few of the wider spots of the fissure. These spots of eruption will continue to diminish as gas is dissipated and more will begin to "freeze" shut. Finally, only one vent may remain active and eventually this will also seal itself off.

Kuntz--Ref#8--Big Craters is probably the best example at CRMO of how an eruptive fissure will finally center down to erupting from one pipe-like conduit. The eruptive fissure that produced the Big Craters and Blue Dragon flow, probably extended from the spatter cones on the south to the northwest corner of North Crater. Along this fissure, eruptions would occur at one end and then at the other end. Each eruption successively starting up and then dying down. Each pulse of a fountain ends up with a circular accumulation of cinders and ash around it. Very powerful eruptions would tend to blow out materials laid down in previous eruptions. It would go on like this with the eruptions switching back and forth until it centered on just one point of eruption. Continued eruptions from the single spot or from a short length of fissure would form a cinder cone or elongated complex, respectively.

The eruptions of CRMO are very similar to the eruptions occurring in Hawaii. In fact the only real difference lies in the plumbing systems. In Hawaii a shallow (2-5 km in depth) magma chamber has developed that is continually being filled by magma from a depth of 100 to 150 km. periodic eruptions or the emplacement of dikes regularly drains the chamber and this occurs in a time span of every few weeks to every few years. At CRMO, magma accumulates at a much slower rate with probable storage deep in the crust (40-60 km) with periodic release every 2,000 +/- 1,000 years. So the intervals between eruptions is very long at CRMO, but very short in Hawaii. Also volumes (long term) are small at CRMO and large at Hawaii.

III. Formations, Features and Characteristics

A. Cinder Cone

LeFebvre--Ref#9--Lava which is richer in silica will be more viscous and therefore more explosive....the higher the silica content, the larger the cone will form....the presence of ground water and the resulting steam can also cause an explosive eruption and produce rather large cones.

A cinder cone hundreds of feet high can be deposited in a matter of hours or days. Big Cinder Butte, the tallest cone at CRMO, stands about 700 feet above the land surface and could have been built in as little as a few days or weeks.

If the wind is strong during the formation of a cinder cone, the cone will not develop the normal circular shape, but will elongate in the direction the wind is blowing. Dominant winds in this area are from the west to east and many cones such as Grassy, Sunset, Paisley and Inferno Cone are elongated to the east.

Kuntz--Ref#15--Cinder cones are widely scattered throughout the eastern SRP, but they are best developed in size, shape and number along the GR. The cinder cones are composed of agglutinated and non-agglutinated tephra layers interbedded with thin lava flows. Composite cones such as Sunset and Big Craters were formed by overlapping accumulations of ejecta from several contemporaneous or nearly contemporaneous lava fountains. The composite cones may have elongated crater walls aligned along the eruptive fissure. Many of the cones are breached on the NW and/or the SE flanks. The breaches probably formed by a number of mechanisms; by burrowing of lava flows erupted along a feeder fissure beneath the cones after they formed, by burrowing of lava flows through, and erosion of, the walls of the cinder cone, or by removal of ejecta by a lava stream that flowed from the feeder fissure during the formation of the cones. Some cinder cones have a multi-stage history. Younger lava erupted from vents in North Crater, the Watchman and Sheep Trail Butte cinder cones as volcanic activity in and near them was rejuvenated.

There are basically two reasons why there is a great predominance of cinder cones on the northern most section of the GR. One is that there has simply been more eruptions on this end of the Rift than there has been on the middle or southern part. The other concerns the composition of the lavas--the lavas from the northern end of the Rift tend to have a higher silica level and the thicker lavas produce more explosive eruptions where the formation of cinder cones is more likely.Cinder cones can form in very short periods of time. Any cinder cone at CRMO could have formed in a matter of a few days or a few weeks. In fact the only cones that appear to have been formed by more than one eruptive event are the Watchman and Sheeptrail Butte.

MacDonald--Ref#10--One of the most familiar of all volcanic structures is the cinder cone--a cone-shaped hill or small mountain nearly always with a truncated top in which is a bowl-shaped crater. It results from the heaping up around a more or less circular vent of cinder thrown into the air during moderately explosive eruptions. The conical form of the hill results from the fact that the largest fragments and the largest proportion of fragments of all sizes fall closest to the vent, so the hill is highest close to the vent and decreases in height away from it. The angle of the slope is close to the angle of rest for piled-up loose irregular fragments and is generally about 30 degrees.

The Crater at the top of the cone is most typically rather smoothly bowl shaped or funnel shaped. The sides are the result of loose fragments rolling and sliding down toward the vent until they obtain equilibrium. The crater may consist of a single depression, indicating a single vent active at the end of the eruption, or it may be multiple with several depressions, each surrounding a former vent. Most typically, multiple craters are aligned, as a result of the arrangement of vents along a fissure. Where multiple craters are present during early stages of the eruption, they may be buried and replaced during later stages by a single crater as all but one of the vents becomes inactive...Sometimes later collapse is very extensive due to the lowering of the magma level in the conduit removing some support and allowing the overlying material to sink in and the loose material of the crater walls to slide to a new position of rest.

Rarely, a diminution in strength of ejections toward the end of the eruption results in filling of the crater and formation of a round-topped craterless cone. Most commonly, however, craterless cones are the result of later erosion that has destroyed the crater rim.

B. Shield Volcanoes

MacDonald--Ref#10--Predominantly effusive eruptions of Hawaiian or Strombolian type build around their vents broad flat cones composed very largely of lava flows. Typically, these have a broadly rounded profile, resembling the upper one eighth or less of a sphere cut off and laid flat side down on a flat surface. Because of a fancied resemblance in profile to the round shields of early germanic warriors, these have been named "shield volcanoes."...The sides of shield volcanoes generally slope at an angle between 2 and 10 degrees, rarely as much as 15 degrees, and at the base the slope merges imperceptibly with the surroundings.

Maley--Ref#39--Low shields are characterized by a small size and low profile. They have slope angles of 0.5 degrees and average 10 miles across and less than 1.6 cubic miles of lava. An excellent example is the Wapi lava field [just south of the CRMO lava field]. this field covers 116 square miles with compound lava flows of pahoehoe. It is characterized by features such as lava toes, collapse depressions, flow ridges and pressure ridges, but lacks lava tubes. The Wapi lavas have a carbon 14 date of 2,270 years. Many of the low shields have pit craters at the summit and many craters show evidence of collapse. Shields tend to be aligned along rifts or fissures.

C. Domes

MacDonald--Ref#10--Lava that is very viscous flows with such difficulty that it tends to pile up, forming a steep-sided hill directly over and around the vent. Such hills are known as "domes", or "tholoids."...Some domes form by extrusion of viscous lava through an opening near their crust , the growth taking place by the piling up of one short flow over another. More commonly, however, new lava being squeezed up through the vent simply distends the mass above it so that the growth is somewhat like that of an expanding balloon [As in the case of Big Southern Butte, Mel Kuntz, January 1987].

D. Spatter Cones

MacDonald--Ref#10--With a decrease in the explosiveness of eruption, or an increase in the fluidity of the magma, or both, cinder cones grade into spatter cones. Sometimes layers that are wholly spatter alternate with others that are largely or wholly cinders.

A still further decrease in the proportion of cinder leads to the formation of purely spatter cones. Typically, they are smaller than cinder cones, rarely reaching a height as great as 100 feet, and most of them less than 50 feet. Their slopes tend to be steeper than those of cinder cones, because the fragments stick together and the slopes are no longer dependent on the angle of rest of the loose material. Welded spatter can stand in a bank that is essentially vertical...Occasionally a pipe-like or fissure-like conduit may remain open to a depth of several tens of feet below the bottom of the crater [this occurs at CRMO]. Where the eruptive vent was a fissure [main spatter cone chain at CRMO], the spatter cones may be very elongate [at CRMO--Vermillion Chasm], or a series of partly coalescing [merge together of parts into a whole] spatter cones may be formed.

"Rootless" spatter cones, also called "hornitoes" [also found at CRMO] commonly form on the surface of lava flows, particularly pahoehoe flows, by the escape of still-fluid gas-charged lava from the central part of the flow upward through breaks in the crust. They are generally small from less than a foot to 10 or 15 feet high, and are sometimes referred to as "driblet cones." Very steep sided ones have been called "driblet spires." They are types of hornitoes.

MacDonald--Ref#19--Because Hawaiian-type eruptions commonly occur along extensive fissures, the heap of ejected material often is very long and narrow, and is called a "spatter rampart."

E. Pahoehoe Lava

LeFebvre--Ref#9-- Of the three major types of lava flows--pahoehoe, aa, and block lava--pahoehoe is the most common in the CRMO lava field.

An example of a large volume eruption at CRMO is the 2100 year old event which produced the Big Craters and the Blue Dragon lava flows. These flows covered an area of almost 300 km2.

Kuntz--Ref#15--Most flows of the CRMO lava field are pahoehoe; they have hummocky, billowy, ropy and wrinkled surfaces that reflect the fluid nature of the lava. The upper centimeter of many fresh, unweathered flows consists of vesicular to dense glass that has a striking blue to green iridescence [eg. Blue Dragon lavas]. The pahoehoe flows were typically fed through lava tubes and tube systems. Pressure ridges and pressure plateaus are common large-scale features of the surfaces of the pahoehoe flows.

Decker--Ref#12--Pahoehoe has a smooth, billowy surface, often wrinkled or ropy appearance where a "skin" has started to form and has been dragged along by the more fluid lava underneath. These are rapidly moving flows, which sometimes divide to surround an obstruction leaving an island--or kipuka--of vegetation in the middle of a flow.

Most flows emerge from the vent as pahoehoe and somewhere downslope change to aa. Change in the other direction doesn't happen, though sometimes pahoehoe will flow through a tunnel under an aa flow and emerge looking like a continuation of the aa flow. The chemical composition of both kinds of lava may be the same; the change occurs when a pahoehoe flow starts to cool and loses some of its gas content. The number of internal crystals increases and the flow starts to break up into jagged blocks in much the same way that a batch of fudge will start to sugar and quickly become chunky.

MacDonald--Ref#19--The great fluidity of Hawaiian lava results in rapid movement of the flows. In the main feeding channels, speeds as great as 55 kilometers an hour have been observed, but the flow as a whole advances much more slowly because the narrow feeding river, seldom more than 15 meters wide, must supply an advancing flow front that may be a km or more across. Common rates in Hawaiian eruptions are a few tens to a few hundreds of meters per hour.

The ropy surface of pahoehoe is the result of dragging and wrinkling of the solidifying but still plastic crust by moving liquid beneath. Because the moving of the liquid stream is fastest in the center, the ropy-looking wrinkles are curved with their convexity pointing in the direction of the flow.

Kuntz--Ref#8--Whether lava flows are of the aa or pahoehoe type can be determined initially by silica content--high silica results in thick flows leaning towards aa in character and vice versa for pahoehoe flows. But after eruption, a pahoehoe flow can turn into an aa flow if it becomes thicker because of a lowering of its temperature or loss of gases.

Temperature loss occurs with the exposure of the lava to the atmosphere. A pahoehoe flow, as long as it is being fed lava for a sufficient period of time, will gradually loose enough heat to become thicker or more viscous and change into an aa type flow. The spreading out of the flow or travel down a steep slope can also increase the surface of the flow and increase the rate of temperature drop. Pahoehoe lavas are usually erupted at a temperature of about 2000 F and a drop of less than 300 degrees can be enough to change it to aa.

As pahoehoe is erupted, gases are constantly rising through the lava to be dissipated into the atmosphere. As a crust develops over the surface of the flow, gases may be trapped until the surface of the flow is broken, but the action of flowing over a cliff or down a steep slope may be enough to break up this crust and again allow the gas to escape. As the gas escapes, the billowy and fluid crust becomes thicker and stiffer until it becomes aa.

Since these procedures cannot be reversed, it would be correct to say that aa can never turn into pahoehoe. It would not be correct, however, to say that aa can never produce pahoehoe because pahoehoe is sometimes dispelled from the interior core of an aa flow when it slow or stops.

MacDonald--Ref#19-- Most flows emerge from the vent as pahoehoe, changing to aa as they advance downslope. The reverse change, from aa to pahoehoe, does not occur, although rarely pahoehoe will burrow under an aa flow and emerge at its lower margin giving the false appearance of a flow changing from aa to pahoehoe.

Chemical analysis of congealed fragments of both types of lava show that there is no consistent difference in composition between them. Whether one or the other forms depends on the physical state of the liquid lava and on the amount of stirring it undergoes. The more viscous the lava, the greater is the tendency for this change. The later is illustrated by the fact that part of the same pahoehoe flow continuing down a smooth slope in one area and tumbling over a cliff in another remains pahoehoe on the smooth slope but changes immediately to aa where it goes down the cliff. In some instances aa issues directly from the vent, apparently as the result of vigorous stirring of the liquid by unusually violent lava fountaining.

F. AA Lava

Kuntz--Ref#15--Other CRMO lava field flows are of aa lava that has a rough, jagged, clinkery surface. Large areas of the surface of aa flows consist of irregular blocks of broken lava, some of which are broken slabs of pahoehoe.

Decker--Ref#12 --An aa flow advances in a different way. commonly there is a central river of molten rock five to ten meters across, flowing at speeds of 5 to 50 km per hour depending on the slope. The flow then oozes out on all sides from this central system and forms slowly-advancing dark lobes of cooling lava rubble riding on a molten but unseen core.

The lava blocks tumble down the steep front of the advancing flow, sometimes giving a glimpse of the glowing interior, and are slowly overridden.

The growing edges and fronts of the flow look like giant slow-motion bulldozer treads moving out, down, and under as the mass spreads forward. As a result the surface is a layer of angular jagged fragments, each covered with tiny sharp spines.

G. Blocky Lava

Kuntz--Ref#15--A few flows, such as the Highway Flow, consist of block lava that is characterized by irregular blocks of dense, glassy lava with smooth surfaces.

Kuntz--Ref#8--Block lava is a variety of aa lava. Instead of having spiny projections of aa, the block lava consists of irregular blocks. This is extremely thick lava because of a very high silica content. The highest silica lava at CRMO are the block lavas at 64 to 66% levels. The Highway Flow is the best example of a blocky lava flow at CRMO.

If we further increased the amount of silica to 75 to 77%, we would have an incredibly viscous lava. This is what produces obsidian--a material that is so thick it is not a liquid and will not allow crystals to grow in it. Thus, glassy material is formed. No deposits of obsidian occur at CRMO, but it is found around Big Southern Butte, but in association with rhyolite lavas.

MacDonald--Ref#10--Block lava flows may be basaltic in composition, but typically they are more siliceous. The greater richness in silica correlates with the greater viscosity.

MacDonald--Ref#19--AA flows grade into another type known as block lava flows, which have much the same structure as that of aa flows., but the upper and lower fragmental parts of the flow, instead of consisting of very irregular jagged pieces of clinker, are made up of blocks with relatively smooth sides. Block lava is formed by more viscous magma than that which forms aa, and consequently the flow tends to be thicker and to move more slowly.

G. Lava Tubes

LeFebvre--Ref#9--Large eruptions that produce lava flows also produce complex plumbing systems in order to move this great volume of lava from the vent past earlier formed products. The lava tube systems in the Blue Dragon flow were all formed as a plumbing system to feed the Blue Dragon flow to the east.

Decker--Ref#12--The rivers of pahoehoe quickly crust over and leave streams of lava moving in tunnels under the crust. When the supply of lava feeding the stream stops, the lava drains out leaving an empty tunnel or lava tube.

Greeley--Ref#16--Lava tubes from only in basaltic lava flows and are common in many young basalts of the western US. As molten basalt flows away from its source, the upper surface cools and forms a solid crust while flow of molten lava continues beneath the crust. Eventually, active flow is restricted to a conduit within the basalt flow that feeds the advancing flow front. Cessation of the eruption at the source limits the lava supply and fluid material drains from the conduit by gravity, leaving a hollow void, or lava tube.

The single most important factor in tube formation is low viscosity, which is directly related to temperature, chemistry and the amount of gas dissolved in the lava. The lava flow is more fluid land less viscous at higher temperatures and/or with a higher gas content. As the lava cools, loses gases, and crystallizes, it becomes more viscous. Basalt is the only volcanic material fluid enough to permit development of tubes, but even some basalt flows are too viscous for tube formation.

Tubes are so common in pahoehoe flows that they are evidently the primary means of flow advance. Small distributary tubes branch from the main lava tube to feed the flow front. These feeder tubes usually do not drain an are seldom preserved. If drainage does occur, feeder tubes often fill with lava from later flows.

H. Cinders and Bombs

MacDonald--Ref#10--Fragments of rock thrown out by volcanic explosions are called ejecta, and accumulations of such fragments are known as pyroclastic rocks...[the term tephra may also be used]. [These materials are further classified by size as bombs, lapilli or ash].

The cinder fragments range from a fraction of an inch to several feet in diameter, but most of them are between 1/4 inch and a foot. Within individual layers the size of the fragments generally decreases upward, because in general in any one explosion the larger fragments are thrown less high, fall faster, and strike the ground sooner than the smaller ones. The size of the fragments depends in part on the strength of the explosion, more violent expansion of the gas tending to tear the magma into smaller shreds. Commonly, individual cinder cones are characterized throughout by a more or less uniform size of fragments resulting from fairly uniform explosiveness to the entire eruption. However, it is also common to find a systematic increase in the size of fragments in the uppermost layers resulting from a decrease in gas content of the magma and explosiveness toward the end of the eruption. It is also common to find occasional large bombs imbedded in a haphazard manner in finer cinder.

Fusiform and spherical bombs often are associated with cinder, though generally, in very minor proportion, and in some cones they are lacking. Commonly, they are most abundant in the outer portion of the cone, and this also seems to result from a decrease in the gas content of the erupting magma and, consequently, in the explosiveness of the last stages of eruption.

Bullard--Ref#6--Volcanic bombs are masses of new lava blown from the crater and solidified during flight, becoming rounded or spindle-shaped as they are hurled through the air.

I. Tree Molds and Lava Trees

Bullard--Ref#6--A tree mold, or lava tree, is formed when fluid lava encases the trunk of a tree. Commonly the tree burns, but some portions may be converted to charcoal, especially the root system in the soil zone beneath the flow. In some cases the tree may be pushed over by the advancing flow, and the resulting tree mold will be more or less horizontal. When the tree remains upright, the depth of the tree mold well is determined by the thickness of the enclosing flow. Spatter from nearby lava fountains may accumulate on and round the tree so that a whole "lava tree" is formed. The volatiles released as the trunk of the tree burns make the lava in contact with the tree more fluid, so that minute details in the structure of the bark or wood (now in the form of charcoal) may be preserved.

[The charcoal excavated from the bottoms of some of the tree molds at CRMO was dated using C14 methods. This enabled Bullard to measure the age of some of the flows in this area]

MacDonald--Ref#10--Tree molds are formed where fluid lava surrounds the trunk of a tree and is chilled against it resulting in a cylinder of solidified lava encasing the tree. The tree is burned and when the charcoal is removed [weathering/rotting] a well-like opening is left. In forming, the charcoal on the outer part of the trunk often develops a pattern of shrinkage cracks, and the liquid lava invades these cracks and preserves the pattern.

Kuntz--Ref#8--Lava trees can be formed by either of two methods. The first is where trees are coated with spatter from a nearby eruption and then the spatter congeals and hardens around the tree. Another way that lava trees are formed is when a flow moves around a tree and later is deflated as gas escapes or lava flows out from underneath the crust. A coating that will eventually harden is left on the tree as the lava flow recedes.

J. Coloration

Kuntz--Ref#8--The reddish color of the cinders is due to oxidation of the iron contained in the basalt. Most of this oxidation takes place at the time that the cinders are deposited and not later on. If a clot of lava is erupted at 1000 C, it comes out of the throat of a volcano and is thrown a couple of hundred meters into the air. By the time it falls to the ground, it has cooled to about 900 C, but in the time it has cooled down only 100 kC it has already congealed. On the ground, it is surrounded by other pieces of lava also at 900 C. It continues to cool, but it may take days or weeks to cool another 100 C because it is surrounded by other hot material and is also very well insulated. If the material is exposed to steam during this period, the oxygen in the steam will further accelerate the oxidation and the cinders may turn red in a matter of only days or weeks.

The coloration of the lavas themselves is much more complicated. The reason for the blue color of the Blue Dragon lavas is very complex. Theory has it that it involves the ratio between ferrous and ferric iron and has something to do with titanium as well. Suffice to say that it is due to a unique chemical composition.

This blue coloration occurs only in the top couple of millimeters of the crust and under this you find the normal color of the rock. And the deeper you go into the rock, the darker the color becomes. Evidently as you get deeper into the rock there is a difference in not only temperature, but also the ratio of ferrous and ferris iron and possible the state of oxidation. There may be even more oxygen trapped in the form of gas in the lavas than in the outside atmosphere. Red coloration on the inside of the rock are the result of oxidation that takes place on cooling.

Miller--Ref#21--The unusual color of the "Blue Dragon" lava is due to intense blue light being reflected from clusters of tiny titanian magnetite crystals, which, together with crystallites of plagioclasde and olivine are dispersed throughout an outer layer of clear brown glass...the blue Dragon lava seems to be unique in that its outer oxidized layer is strikingly blue in reflected light, but rich brown in transmitted light. Blue light, which reflects from the surface of small, partly oxidized, titanian magnetite particles, and which is caused by electron transfer between Fe2+--Fe3+, and probably Fe2+--Ti4+ pairs, may account for this phenomenon.

LeFebvre--Ref#22--Iridescence in cinders... The iridescence is caused by microscopically thin veneer of glass which forms as the exploding cinders hit the cool air. The thickness of the glass is just one-quarter of the wavelength of the light reflecting from it. For example, normal sunlight that hits a veneer of glass just one-quarter the wavelength of blue light, will be reflected back (and reinforced) as blue light. If the veneer of glass becomes thicker or thinner than visible wavelengths of light, the iridescence will disappear. This glass contains no special mineral and is the same composition as the rest of the lavas.

K. Lava Depth

Malde--Ref#33--The silicic volcanics reach a depth greater than 3 km at the bottom of well INEL-1 at INEL, and seismic evidence indicates that the base of the volcanics may be as deep as 6 km.

...[The basalt that overlies the rhyolite on the eastern SRP] Resistivity measurements and drilling indicate that the basalt is from less than 1 km to at most 2 km thick. The basalt thins at the margins....

Kuntz--Ref#8--An exploratory well at INEL went through about a kilometer of basalt and then through almost 2 km of rhyolite. Elsewhere on the SRP, studies have indicated that the basalt is anywhere from a half kilometer to about one and one half KM in depth. You can only guess at the depths of the lavas at CRMO. Since it is on the northern extremity of the SRP it would probably not be as deep as if measured farther out on the plain and 150 to 300 meters in depth would probably be a good guess.

L. Minerals

Leeman--Ref#2--CRMO lava field...Contaminated and differentiated lavas ranging from ferrobasalt to ferrolatite (44 to 63% SIO2). Some flows contain common xenoliths of granitic to gneissic crystalline rocks, silicic volcanic clasts, and alkali feldspar and quartz xenocrysts.

Evolved and hybrid lavas from the SRP are widely dispersed in space and time, yet they display surprisingly systematic compositional relations to one another. Some may have originated by high-pressure crystallization of olivine tholeiitic magmas, although details of this process are obscure. Subsequently, mafic variants of these lavas (ferrobasalts) evolved further via lower pressure crystallization to produce ferrolatite magmas. The most extreme ferrolatite differentiates at CRMO lava field may reflect 90% or more crystallization of an olivine thoeiite parental magma.

Karlo--Ref#17-- Extensive deposits of various sulfate minerals have been found in a number of Holocene lava fields within the SRP basalt province in Idaho. The sulfate minerals (gypsum, mirablite, bassanite, thenardite, bleodite, epsomite and jarosite) were found in various combination in sheltered areas in the flows, mostly in vent craters and lava tubes.

A compromise hypothesis seems most likely; an original series of deposits were fumarolic in origin, and the Jarosite powders and gypsum=bassanite crusts are the only remaining examples of this primary deposition. More soluble minerals were affected by groundwater and underwent solution, leaching, transport and redeposition to varying degrees and in various combinations.

M. Bedrock Composition

Kuntz--Ref#8--Under CRMO the bedrock composition directly beneath the lavas is mostly Challis Volcanics and high-grade metamorphic rocks such as granulites--as evidenced by inclusions in the basalts. Possibly, there may also be Paleozoic sedimentary rocks and granitic rocks that are exposed in the mountains north of CRMO, but they have not been seen as inclusions.

As for the rest of the Plain, mostly rhyolite ash flow tuffs and rhyolite lava flows at shallow depths, then deeper crustal rocks--probably granulites--also identified from inclusions in the basalts. It would probably not include the Paleozoic rock in that occurs in the mountains outside the Plain, except very close to the boundaries.

Mabey--Ref#3--Only one deep hole has been drilled on the eastern SRP. This hole, which is on the INEL about 30 km east of Arco, was 3,155 meters deep and was bottomed in a rhyodacite porphry. The rock in the lower part of the hole, which has been dated at 11.2 MY, may be an ash-flow tuff or a high-level intrusive rock. Doherty suggests that this hole was drilled into a caldera. Drillings and resistivity soundings suggest that Quaternary basalt is generally less than 1 km thick on the eastern plain, although in part of the area it may be thicker.

What rock and structures underlie the SRP at great depths remains unknown. One of the deep drill holes on the western plain apparently bottomed in granite, which could be part of an extensive Cretaceous was of granite that makes up the Idaho Batholith north of the plain....The upper crust of the eastern plain is composed of more magnetic units than in adjoining areas, indicating a greater abundance of igneous rocks in the crust under the plain. The response of the eastern plain to the regional stress is very different from areas to the north and south. This suggests that the structure and perhaps lithology are different. The average density of the upper crust under the eastern plain is probably not greatly different from the adjoining areas, but intense igneous activity in Cenozoic time has probably produced major changes in the lithology and destroyed most of the older structure.

N. Vesicles

MacDonald--Ref#19--Vesicles in pahoehoe generally have fairly regular spheroidal shapes, whereas vesicles in aa tend to have twisted irregular shapes. This apparently occurs because the high fluidity of the pahoehoe lava allows the gas bubbles to retain their spheroidal shapes, but the gas bubbles in the more viscous aa lava are easily deformed.

Identification of the type of flow from the shape of the vesicles is not entirely infallible, because sometimes some of the bubbles in pahoehoe become deformed and sometimes aa bubbles retain their regular shape. It probably is accurate 7 or 8 times out of 10.

O. Joints in the Lava

MacDonald--Ref#19--All types of lava flows are usually broken by cracking into innumerable polygonal blocks. The cracks are known as joints...Most of the joints in lava flows result from the stresses that arise in rock during cooling. As the rock cools, it shrinks. The rock literally pulls itself apart. The principally cracks develop approximately perpendicular to the cooling surface--in the case of a lava flow, the top and bottom surfaces of the flow. The cracking is analogous to that of mud in a dried-up puddle. In the mud, the cracks open at right angles to the drying surface, and the intersection of the cracks ideally forms short columns that tend to be six-sided. In lava flows, also, there is a tendency to form six-sided columns...although five or seven-sided columns are also common.

P. Xenoliths

MacDonald--Ref#19--Fragments of older solid rock enclosed in the magma, and eventually left frozen into solidified igneous rock, are known as xenoliths, or simply inclusions. Some of them may be picked up from the ground surface over which lava is flowing, but most are acquired as the magma rises toward the surface. Some are torn from the walls of the conduit; others are loosened from the roof of the magma chamber and sink into the magma. Xenoliths may be fragments of older lava similar to that in which they are found, or they may also be pieces of sedimentary rock.

Leeman--Ref#20--Xenoliths from CRMO....analysis indicates...an affinity between the xenoliths and many exposed granulite-facies metamorphic terranes (from intermediate crustal depths)...to establish the presence of early Archean crust beneath south-central Idaho. These samples record the presence of a deep Archean basement complex at least several; hundred kms west of other known outcrops in the northern Rocky Mountains.

Q. Silica Levels

MacDonald--Ref#19--The explosiveness of an eruption depends largely on two factors: the fluidity or viscosity of the lavas and their gas content. Three factors govern the viscosity of a lava: its chemical composition, its temperature, and the amount of gas it contains. In general, the higher the silica content of the lava the more viscous it is, and the higher the temperature and gas content, the lower the viscosity. Low viscosity fluid lava allows moderate amounts of gas to bubble out with little more than minor spattering; but in very viscous lava it is difficult for the gas to work its way upward and break through the surface of the liquid, and it accumulate until the pressure is sufficiently high to allow it to burst free. With high enough gas pressure, a large amount of gas, and viscous enough lava, a major explosion of series of explosions may result.

Kuntz--Ref#8--We do know that silica levels vary throughout the monument, tend to be higher in the northern section of the Rift and what the results will be on the surface as the silica level changes. What we do not know is exactly why these variances in the silica levels occur. One possibility is that as the basalt begins to collect, it pools in a pocket at depth and build up enough heat to begin the melting of crustal rock. The magma becomes a mixture of basalt and rhyolite that results in higher silica levels than pure basalt. There could also be a preferential absorption of certain elements such as silica.

Whatever the process is that changes the composition of basalt and leads to higher silica levels has progressively increased the silica content of basalts of the more recent eruptions. The higher silica levels indicate that eruptions will be more explosive in the future. In a typical eruption, however, the silica rich lava is erupted first and then followed by eruptions of low silica lava.

Silica levels also have an effect on the type of lava flows that develop. Pahoehoe flows at CRMO typically have a silica level of 52% or lower. AA flows that are completely aa (even at the source vent) have a silica composition of 51% or higher. Blocky lava flows are even higher in silica content. Of course temperature, gas content, and other conditions may also play a role in determining the type of lava flow that will develop at any given place.

IV. Miscellaneous

A. Idaho Batholith

Maley--Ref#39--The Idaho Batholith is a composite mass of granitic plutons covering approximately 15,400 square miles in central Idaho. The outer perimeter of the batholith is irregular and in plan view it has an hour-glass shape. It is approximately 200 miles in the north-south direction and averages about 75 miles wide in an east-west direction.

...Radiometric dates and field relationships, where plutons of the batholith cut older rocks, restrict the age of the idaho Batholith to an interval between 180 to 45 million years ago; however, the dominant interval of emplacement was Early to Middle Cretaceous. There is a general west-to-east decrease in age for plutons of the batholith.

Redfern--Ref#38--For a period lasting about 100 my, which began around 180 Ma, the Pacific West Coast was the scene of traumatic change as ocean crust subducted beneath the continent. Subduction caused a magmatic arc of batholiths to form on the surface above the zone of subduction. The resulting mountains were of Andean proportions. The Idaho, Sierra, and Baja batholiths were part of the same arc when they were formed, but they were later separated along the line of the SRP between Idaho and Utah and Nevada.

...The friction caused by interaction between the ocean crust and the continental crust about 100 km below the surface was sufficient to melt the rocks to form what are called "plutons." A multiplicity of plutons joined together to form a "batholith."

...Whether plutonic magma on continental margins forms in curtains or in blobs is not known, but it is known that plutons gravitate toward the surface. Being very hot, they are lighter volume for volume than the rock that surrounds them. Plutons form steep-sided chambers of semi-liquid magma, which eventually crystallizes as granite from the top of each chamber to the bottom. During this process, as in the crystallization of all substances, water is released as a necessary by-product. In plutonic magmas minerals that may have been transferred from the subducting ocean crust into the liquid magma or that may already be present in the original continental crust concentrate as metal-rich compounds in the water to form hydrothermal solutions. It is these super-saturated solutions which are injected into fissures and other weaknesses in the granite matrix as it solidifies. Different combinations of minerals in these solutions at different levels and at different times in the plutonic cycle precipitate to form copper, silver, lead, tungsten, and gold deposits in a variety of forms and degrees of richness.

Fiero--Ref#34--The subducting plate melted as it plunged to the depths below the continent. The lightweight oceanic sediments , traveling piggyback down with the subducting slab, melted. As these former sediments melted, the light elements separated from the heavy. The low-density distillations were lighter than the surrounding deep rocks. They rose as giant tear drop--shaped masses. The rising silica-rich magmas were further contaminated by the silicic chemistry of the deep crustal rock through which they intruded, such as old sedimentary, volcanic, or granitic rocks. The ascending molten blobs were thus heavily influenced by continental chemistry, and the composition of the magmas was altered. These high-silica rocks have the right chemistry, when melted and then cooled slowly, to make granites....

The plutons rose almost vertically as hot, mobile masses. As the magmas elbowed their way to the crust, they needed room. They shoved the sediments aside while simultaneously baking and pressure-cooking them into metamorphic rocks...

B. Soils

Malde--Ref#33--A large part of the basalt of the eastern SRP is covered by loess more than a meter thick, and a still larger area has scattered patches of loess at least 0.5 m thick. Where not more than 30% of the basalt is exposed, loess commonly is 1-4 m thick, and where less than 1% of the basalt is exposed, the loess is as much as 30 m thick, big commonly thicker than 3 m.

...Eolian sand occurs on the eastern SRP as stabilized dunes and as a few hills of active dunes.

C. Big Southern Butte

Malde--Ref#33--Near the center of the SRP, NW of Blackfoot, the basalt is intruded by four prominent rhyolite domes of Quaternary age. Big Southern Butte (0.304+/-0.022 MA); Middle Butte; an unnamed butte (1.42+/-0.02 Ma); and East Butte (0.58+/-0.09 Ma). The domes are aligned parallel to the northwesterly trend of the plain, and their alignment is thought to express structural control or control by ring fracturing along the margin of a buried caldera. Maley--Ref#39--...Middle Butte appears to be an uplifted block of basalt. Although no rhyolite is exposed at the surface, the butte was probably formed by a silicic intrusion forcing the basalt upwards into the form of a butte. Big southern and East Buttes are rhyolite domes. East Butte has been dated at 600,000 year whereas Big Southern has been dated at 300,000.

Big southern Butte, because of its prominence and size , was an important landmark for the early settlers. It rises 2,500 feet above the plain and is approximately 2,500 feet across the base...The butte was formed by two coalesced cumulo domes of rhyolite that uplifted a 350-foot section of basalt. The basalt section now covers most of the northern side of the butte. The done on the southeastern side was developed by internal expansion. Rupture of the crust at the surface caused breccia to form. Obsidian, pumice and flow-banded rhyolite are important components.

Spear--Ref#41--Three conspicuous buttes rise above the relatively flat...eastern SRP between Arco and Idaho Falls-Blackfoot areas. These prominent landmarks, known as Big Southern, Middle and East Buttes in their order from southwest to northeast, can be seen from distances of 150 km or more.

Big Southern Butte, the largest of the three, rises 760 m above the surrounding plain. It has a diameter of 8 km at its base and is somewhat elongated...Armstrong and others report K-Ar dates of .30 +/- .02 MY and .6 +/- .01 MY for Big Southern and East Buttes respectively. They state that Middle Butte could not be dated precisely because of contamination with atmospheric argon but is still relatively young (1.9 +/- 1.2 MY)....

...Big southern Butte consists of two coalescing cumulo domes, each which may have had more than one intrusive center....
...Ascending the road which enters from the north side, one passes through a narrow section which in turn opens up into a larger amphitheater about 800 m across. Whether or not this is the vestige of a crater or an erosional feature is yet to be determined.

...East Butte apparently has a simpler history than Big Southern. It is interpreted to be a single cumulo done without any evidence for a crater.

...Middle Butte is composed entirely of stratified basalt...The mechanism responsible for elevating relatively young basalts to form Middle Butte is thought to be the intrusion of viscous silicic magma

D. Earthquakes

Malde--Ref#33--The eastern SRP is a region of low seismicity, even though its eastern end lies across the north-south trend of the Intermountain Seismic Belt, and across the trend of a corresponding belt of neotectonic activity. Shear wave velocities under the eastern SRP also are lower than in the Basin and Range province to the south. Mabey infers from such evidence that strain in the eastern SRP is accommodated without brittle fracturing because of the high temperature of the crust.

E. Snake River

Malde--Ref#33--The present canyon of the SR downstream from

Milner Dam is the last of a series of ancestral canyons successively filled with basaltic lava flows, which erupted from vents near the western end of the eastern SRP. Because of these canyon-filling basalts, the river was diverted progressively farther south, each time cutting a new canyon that became filled with subsequent lava flows. In this way the westward course of the Snake River was displaced about 30 km south, and the present north-flowing reach of the river around the western limits of the lava flows was established.

..The canyon-filling basalts differ from most basaltic eruptions exposed in the eastern SRP in that they consist largely of subaqueous pillow lava and, in places, fragmental glassy basalt. Such deposits accumulated in deep lakes upstream from lava dams.

F. SR Aquifer

Malde--Ref#33--Basalt of the eastern SRP is the reservoir for the SRP Aquifer, one of the world's most productive ground-water systems...The depth to water typically is less than 150 m, although the depth locally exceeds 300 m. All basalt below the water table, extending to depths of 1 km or more over much of the eastern SRP, probably is saturated...

...The aquifer is intercepted by the northern and eastern wall of the SR canyon between Milner Dam and King Hill, where it discharges extraordinary amounts of water in spectacular springs, especially near Hagerman. This reach of the canyon, which is known as the Thousand Springs area, has 11 of the 65 large springs in the US, several of which have average discharges of 7 to 34 m3/sec.

Maley--Ref#39--An aquifer is a body of saturated rock through which water can easily move. Aquifers must be both permeable and porous and include such rock types as sandstone, conglomerate, fractured limestone and unconsolidated sand and gravel. Fractured volcanic rocks such as columnar basalts also make good aquifers. The rubble zones between volcanic flows are generally both porous and permeable and make excellent aquifers....

...The SRP north of the Snake River is a remarkable aquifer of great resource and economic significance. It is not a single homogeneous geologic formation. Rather it consists of a volcanic pile of Quaternary SR Group basalts. In eastern Idaho, these basalts may be about 1 mile thick. The individual flows are 20 to 30 feet thick with the upper 3 to 6 feet consisting of very permeable rubble zone. Interbedded alluvial sediments are also found between many of the flows. In the eastern SRP, the SR lies near the southern edge of the plain, about 40 to 50 miles southeast of the ranges of central Idaho. The rivers in the ranges north of the plain all disappear into the surface of the SRP near the mountain front....For about 100 miles downstream from Milner Dan in the vicinity of Twin Falls an estimated total volume of approximately 200 billion cubic feet of water (1.4 cubic miles) enter the SR from gigantic springs on the north side of the canyon. This is the well-known Thousand Spring Area.

G. Boneville Flood

Malde--Ref#33--The Bonnevile Flood is the name given to catastrophic outflow from Pleistocene Lake Bonneville, which overtopped its rim at Red Rock Pass in SE Idaho about 15,000 years ago and discharged a vast volume of water down the Snake River. The flood descended the Portneuf valley, built a boulder fan on the SRP at the mouth of the Portneuf, swept down the Snake River, in places forming scabland channels on the nearby upland, descended Hells Canyon to the Lewiston basin , and ultimately joined the Columbia River.

...Shoshone Falls, near [Twin Falls] is a scenic remnant of the flood..

...Discharge equaled 935,000 m3/sec as compared with a 70,000 m3/sec flood on the Mississippi River and 385,000 m3/sec for a flood on the Amazon River.....Volume discharged equaled 4,700 km3...At a constant discharge...a flood of this volume would have lasted 8 weeks.

Redfern--Ref#38--The Great Salt Lake averages about 3 meters in depth, and this depth fluctuates considerable, depending on the volume of water flowing into it and the counterbalancing effect of evaporation. In contrast to the GSL, Lake Bonneville at its peak level was over 300 meters in depth and would of course have completely submerged Salt Lake City and neighboring towns. Bonneville, however was quite suddenly reduced, by about a third of its volume, to the Provo shoreline level during an event that occurred about 15,000 years ago...

Malde's work had shown that a breach of the shore of Lake Bonneville had occurred at Red Rock Canyon on the summit of a pass between present-day Utah and Idaho to the north of SLC. The breach was critical, causing LB to be lowered by 1'00 meters in a period of about six weeks. During this time the discharge rate at the breach averaged between 700,00 and 935,000 cubic meters of water per second. .. This is equivalent of six times the present average flow at the mouth of the Amazon River, but the speed of the water from the breached lake was more than ten times the velocity of the Amazon.

Normally the lake did not accumulate sufficient water to overflow; evaporation prevented such excess. But at some point tin the lake's history, perhaps during or after the capture of the Bear River (a previous tributary of the Snake river) by the LB basin, extra water accumulated to an unprecedented level. This caused an overflow stream to form at Red Rock Canyon. The overflow stream is believed to have cut back into retaining alluvial fan lying on a rock sill. Eventually a hairtrigger situation was reached. A meter or so of extra cutback into the uncollapsed rock or tow downstream, and the overflow of water became a torrent and the torrent a catastrophic flood.

As lake water gained momentum through the spillway, it opened a gap that eventually became a breach some 3 km wide. The enormous volume of water that then poured through the breached caused absolute havoc in the downstream basalt canyon of the SRP to their north...New channels and spillways cut into the basalt surface of the SRP measured 30 km long, 300 meters wide, and 100 meters deep. in some places--as much as 300 km below the breach--where lava formations were softer the flood cut new channels 200 meters deep. Huge chunks of lava were ripped from the surface of the plain and from the walls of the original canyons and then were rolled along by the floodwaters to form what has ben termed "melon-gravel" bars. Some of these melons were almost house size, and thousands of them accumulated to form chaotic piles on the river bed when the water velocity dropped.

Once the level of LB had dropped to the point where there was consolidated rock at Red Rock Canyon that could withstand the flow of water, the flood subsided and the lake assumed a new shoreline, the Provo shoreline.

H. Yellowstone

Maley--Ref#39--The Island Park area occupies the western part of the Yellowstone Plateau volcanic field. It is transitional between the eastern SRP and the active part of the field in Yellowstone National Park.

Most of the field has originated in three cycles of rhyolitic volcanism during the past 2.2 Ma. Each cycle began with the eruption of small volumes of rhyolite followed by rhyolites erupting every hundred years from a growing system of arcuate fractures above a large and growing magma chamber. Each cycle climaxed with an explosive eruption of a large volume of fragmented rhyolitic magma. Emptying part of the magma chamber as a result of the eruption caused the chamber roof to collapse and form a large caldera. After each cycle, rhyolite again erupted for several hundred thousand years and partly filled the caldera by the end of each cycle.

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The magma within the magma chambers of the first two cycles has now solidified. The rhyolitic source areas and associated calderas of each cycle covered different but overlapping areas. Each successive caldera is positioned east of the previously formed caldera.

Basalt eruptions were limited to the margins of the rhyolitic source area; however, when the silicic magma could penetrate through fractures in the caldera.

the three ash-flow sheets...are collectively named the Yellowstone Group and include the Huckleberry Ridge (2.0 MA), the Mesa Falls Tuff (1.3 my) and Lava Creek Tuff (0.6 MA). The first volcanic cycle in Yellowstone began 2.2 Ma with the eruption of the Huckleberry Ridge Tuff. During the second cycle, the Mesa Falls Tuff was erupted...After the first two cycles the rhyolitic activity shifted away from the Island park area to the Yellowstone Plateau....

The third cycle began 1.2 MA. Approximately 600,000 years ago rhyolitic lavas erupted from gradually-forming arcuated fractures....The climatic eruption vented through the ring fracture 630,000 years ago. After the eruption, the magma chamber collapsed along two ring fractures to form the Yellowstone caldera. Calderas form by the collapse of large magma-chamber roofs...

The Yellowstone system, like the Hawaiian system, is stationary relative to the deep mantle. It migrates relative the NA plate in the direction opposite to plate motion. This system is a stationary hot spot above a mantle convection plume.

Redfern--Ref#38--The SRP is a feature of tremendous interest to tectonic scientists. It is not know how or why the mantle plume that was once beneath it formed--only that the hot spot still exists at the head of the plain. Warren Hamilton, of the USGS...suggested that the SRP may be a rift in the continental crust with a magmatic feature at its point. In other words there is a hole through the continental crust there--not simply thick layers of volcanic rock piled up on existing rock but a lava-filled hole that may be necking down through the lithosphere into the asthenosphere. Research recently completed suggests that there have been a series of Yellowstones that formed and became extinct in a successive string...There is for example, another now completely extinct caldera to the west of Yellowstone, the Island Park Caldera, which formed about 1 million years ago. At present the mantle plume that caused the IP caldera is below Yellowstone....

Yellowstone is an enormous caldera formed by mega-explosions. The materials that normally forms a volcano--the ash, the pumice, and the breccia--was so violently distributed that traces of it are found for many hundreds of km around. When the eruptions from the magma chambers stopped, the region collapsed into the caldera, a thin and slowly inflating crust now lying querulously upon the surface.

I. Geothermal

Maley--Ref#39--...In order for a spring to be considered thermal it must be at least 68^F. Some of Idaho's hot springs reach temperatures as high as 200^F.

Hot springs develop when rain and melted snow waters infiltrate into the ground. This ground water then sinks deep into the earth and is warmed by the heat contained in the earth's interior. Because hot water is less dense it is pushed back to the surface by the continued sinking of heavier, cold water. Annual replenishment to the system by cold meteoric water creates a continuous system which is called hydrothermal convection. Hot springs develop when the upwelling hot waters rise along faults or other fractures in the earth's crust and flows out onto the surface.

Why do some areas of their earth have hot springs and others do not? For example, there are few if any hot springs identified in Idaho north of Idaho County. While there is heat in the earth beneath any spot on the surface, this heat is concentrated closer to the surface in some areas. One means of near surface concentration is a shallow magma chamber within the earth's crust such as would exist beneath a volcano. Yellowstone is centered on such a volcano. We know from measuring the way in which the vibrations of distant earthquakes pass through the Yellowstone area that there is a body of molten rock (magma chamber) at a depth of about 3 to 6 miles. The resulting hydrothermal systems are world famous.

Another area where the heat of the surface can be concentrated near enough to the surface to generate hydrothermal systems is where the crust of the earth is stretched and thinner than normal. Such a condition exists over southern Idaho in the SRP and Great Basin areas. A number of large warm water systems occur in this region of Idaho including Boise, Twin Falls, Bruneau-Grandview, Raft River and Mountain Home systems...

The SRP area of southern Idaho is being stretched. this is a very advantageous geological situation for the formation of hydrothermal systems because this not only creates a thin crust to bring heat closer to the surface but it also develops numerous normal faults and keeps them relatively open so that water can easily circulate through them.

Malde--Ref#33--Excluding Yellowstone NP, southern Idaho has the largest known resources of thermal water in the US. Of the amount of energy discovered in geothermal systems with temperatures of 90^C or higher, 85% is in an area in the southern part of the western SRP called the Bruneau-Grand View area...This thermal resource...is related to the large volume of the ground-water reservoir, not to exceptionally high temperatures.

A small geothermal system at Boise is the source of hot water for the Boise Warm Springs Water District, which is the oldest geothermal heating company in the US. The first wells were drilled in 1890, and the district currently provides heat for more than 250 houses.

J. Formation of the Rocky Mountains

Redfern--Ref#38--...about 80 Ma the Atlantic Ocean had begun to widen rapidly. Before this time NA had been moving slowly away from NW Africa, with the result that the edge of the Pacific Ocean bed had descended at a relatively steep angle below the westward-moving continental crust, the process of subduction. But at 80 million years there seems to have been a more rapid hingelike opening of the North Atlantic. As a consequence there was a sudden and considerable increase in the interaction between the western edge of the continent and the Pacific bed. The increase in motion and the angle of descent of the ocean crust caused part of the continental craton to rotate through a few degrees. The rotated section was the roughly circular part of the craton [the thick block of granitic continental crust is called the craton], which many millions of years later, became the Colorado Plateau. The general speedup in the interaction between continental crust and ocean crust caused the ocean crust to subduct at a shallower angle than it did before. The combination of rotation of part of the craton plus the now shallow angle of subduction resulted in a tremendous upwarp of the continent. The uplift was formed where the Southern Rocky Mountains are today. These events obviously took place over an extended period of time, about 40 million years, and during this period the top surfaces of the uplift eventually eroded to form the mountains and the hogbacks we see today.

But I gathered that it would be an error to relate the uplift of the Colorado Plateau itself to the formation of the S. Rockies or to the Laramide orogeny. The plateau is related to a general uplift o the whole of western NA...This later uplift began not earlier than 30 million years ago and included all the features that had already form in the craton: the mountains, the plains, the prairies, and the region of the Colorado Plateau. Almost half the NA continent was simply arched upward thousands of meters on an axis roughly coincident with a line through the Rocky Mountains form end to end. Why did the whole lot uplift? There is no established answer, but hamilton's hunch is that the Pacific crust, which had been subducted at a shallow angle beneath the continent during the Laramide orogeny, was at first cold and dense. The subducted ocean crust heated up as it gradually assumed the temperature of the mantle beneath the continent. The expansion of such an enormous mass of basalt as it heated up might have caused the general uplift, but that is an extremely conjectural thesis.

Raymo--Ref#42--Geologists generally agree that the lifting of the Rockies, like the stretching and downfaulting that produced the basin and range topography further west, is somehow related to the complex clash of plates that is taking place along the Pacific coast of NA. But there is no agreement about how the influence of those scraping and colliding plates can be felt so far inland....

...Then, beginning about 70 Ma, the area was subjected to the series of thrusts and uplifts known as the Laramide Orogeny or mountain-building episode. The revolution may have begun with broad islands folded up in the shallow inland seas of the late Cretaceous period.

Fiero--Ref#34--Remnant magnetism on the floor of the pacific Ocean indicates that it was moving northward at a rate of about 6 inches per year between 80 and 40 MA. These high-speed motions of both the NA and Pacific sea floor plates increased the impact velocity between the westerly oceanic plates and the NA continent beginning about 80 MA. This acceleration would have caused a flattening of the angle by which the sea floor plate subducted below the continent. A lower angle of subduction would put the young, hot oceanic Farallon Plate in direct contact with the overriding continental slab. The easterly compression and the migration of volcanic activity to the east during the laramide is thought to be the direct result of the increasingly low angle of impact. The easterly shift of activity was also undoubtedly compounded by the easterly movement of the downward bend of the subducting plate.

The inclination of the subducting slab approached horizontal when the plates accelerated to maximum velocity. Arc Magmatism died. The slab did not penetrate sufficiently into the depths of the earth to generate magma.this move to the east signaled the beginning of the Laramide phase of the Cordilleran orogeny. During the height of Laramide compression when the plates were colliding with maximum velocity and the angle of underthrusting was the lowest, the effects of subduction would be felt as far east as the rising Rocky Mountains, more than 600 miles distant from the plate margins. The activity had 40 million years to deform and uplift the Rockies before plate movements would again slow down and terminate the Cordilleran mountain building.

K. Accreted Terrains

Maley--Ref#39--Most of the pre-Cretaceous rocks west of the Idaho Batholith in west-central Idaho and east-central Oregon ore oceanic or island arc assemblages. These rocks were formed offshore in island arcs and adjacent basins and were accreted to the NA continent between late-Triassic and mid-Cretaceous time. This means that before Jurassic time, the west coast of NA was situated near Riggins, Idaho. ...

The accreted terrane was deformed in the Late Triassic and again in the Late Jurassic. the Late Triassic deformation occurred following deposition of most of the volcanic rock units. The time of accretion is estimated to have occurred 118 MA. Deformation and metamorphism of the Riggins Group at the contact with continental rocks occurred at that time. However, the accretion process probably occurred over a period of time ranging between Late Triassic and mid-Cretaceous. During this time and for a period afterwards, the idaho Batholith was formed by magmas generated from subduction of the eastward-moving plate.

L. Dating Flows

Bullard--Ref#6--The typical conclusion as to its [the lavas of CRMO] age is similar to that stated by I. C. Russel (US Geologic Survey) in 1902: "Although it is impossible to make a well formed estimate of the time that has elapsed since the last eruption, it seems probable that it is no more than 100 or possibly 150 years."

Limbert--Ref#32--[After exploration of CRMO in early 1920's] In appearance the flows seem as if they had appended only yesterday, but in reality the latest probably occurred about 150 or possible 200 years ago.

Sterns--Ref#31--The "Triple Twist Tree" growing out of a crack in the North Crater flow died in 1961 with a rotted heart. A core 16 1/2 inches long removed from this tree by the Park Service in 1954 had 1350 years of growth as determined by a count of the annual growth rings by the laboratory of Tree Ring Research at the University of Arizona. It is estimated that the tree is about 1500 years old allowing for the missing heartwood. This means that the lava is at least 1650 years, if time is allowed for the lava to cool and soil to accumulate. The lava flow may be several times this old.

Bullard--Ref#6--[Radiocarbon dating done by Bullard in 1970 at CRMO] The solution was to locate vegetation which had been burned by the advancing lava and was still protected from weathering. This might be done by tunneling beneath the flow, where carbonized roots of shrubs killed by advancing lava were, hopefully, still intact...The soil from beneath the "bush impressions" [on the underside of the lava flows] contained tiny carbonized rootlets, and with careful collecting, enough material was obtained for two samples for radiocarbon age determinations...the average age of the two samples gave an age of 2080 +/- 85 years. The date is valid for the particular flow involved, which may not have been the last activity in the area but certainly was a part of the final phase of activity...[samples of carbonized roots were also collect from the bottom of vertical tree molds and analysis of these gave very similar ages to another set of flows].

Yulsman--Ref#30--[Paleomagnetic dating was used by USGS in studying CRMO from 1978 to 1985 and was correlated to the movement of the earth's magnetic poles] The tectonic plates are like gigantic conveyors that cycle crust to and from the mantle. Magma welling up through the rifts in mid-ocean ridges hardens into new crust, which is carried away as plates move in opposite directions. Crust returns to the mantle at subduction zones, where the edge of one plate dives beneath the edge of another.

Magma rising at ridges contains magnetized particles, which align themselves like compass needles with Earth's magnetic field and become locked in place when the magma hardens. The Earth's magnetic field has flipflopped repeatedly--at least 171 times in the past 76 million years--magnetic north becoming south and vise versa. Hence crust is characterized by alternating bands of rock whose magnetic particles point in opposite directions.

Raymo--Ref#42--The study of paleomagnetism (ancient magnetism) of the earth's crust began in ernest in the 1950's with the development of highly sensitive instruments for measuring the strength of weak magnetic fields. Volcanic rocks can be absolutely dated using radioactivity. It turned out that the paleomagnetism of most rocks of the same age on a given continent pointed to roughly the same place on the globe. That place can be assumed to have been the magnetic pole of the earth at the time the rocks formed. In this way it became possible to reconstruct the positions of the magnetic poles in times past--with respect to the present continents. The position of the poles have apparently changed. A trace of such positions is called a "path of polar wanderings."

Most geologists are inclined to believe that the earth's magnetic poles have never wandered far from the geographic poles defined by the earth's axis of rotation. If this is the case, then it is not the magnetic poles that have wandered, but the continents. [USGS studies of paleomagnetic dating at CRMO involved the taking of drill samples of many different lava flows. These were all orientated to the current magnetic north and then later the alignment of iron particles was checked. This alignment was correlated with other paleomagnetic data and a date at which the lava was deposited was determined. This date had an error factor of +/- 100 years.]

V. Future and Conclusions

A. Prediction of Future Eruptions

LeFebvre--Ref#9--There is no evidence to support the idea that the Great Rift is extinct. The fact that it has been an active eruptive fissure for at least 13,000 years and that it time of repose, 2,000 y.b.p., is much shorter than the length of its eruptive history is good reason to call it an active volcanic rift zone that is presently in a dormant state. The Great Rift's approximate 2,000 year periodicity is also reason why we can expect an eruption anytime from the present through the next few hundred years to at most one thousand years.

Kuntz--Ref#18--Although it is speculative to predict the time and character of future eruptions based on the past history of a volcano or volcanic rift zone, the data suggest that reasonable forecasts for future volcanism along the Great Rift can now be formulated. Because it has been more than 2,000 years since the last eruption, we are near the end of a normal repose interval and it seems reasonable to expect another eruption in the next 500 years. The steady state nature of the volcanism and constancy of the most recent output rate suggest that 5 to 6 km3 of lava will be erupted in the next eruptive period.
In the past, successive eruptions have generally shifted to parts of the CRMO segment of the Great Rift that have experienced the longest repose interval. this factor suggests that the next eruptive period will begin on the central part of the CRMO segment, but may will propagate to the northern part of the Rift. The SiO2 vs. time relationship suggests that noncontaminated lava flows with SiO2 contents as high as 54% will be erupted first and will be followed by flows with decreasing SiO2 contents. These eruptions would be relatively nonexplosive and would likely produce large volume pahoehoe flows.

Eruptions from potential vents on the northern part of the CRMO segment of the GR may produce lava flows of the contaminated magma type with SiO2 content as high as 66%. The eruption of lavas of this composition may be comparatively explosive and be accompanied by more than normal amounts of tephra, destruction of cinder cones by collapse and explosions, and emplacement of domes.

B. Warning Signs

Decker--Ref#12--(The prediction of imminent volcanic activity based on :) Earthquakes. As molten rock accumulates within a volcano, it exerts pressures that can crack solid rock, causing earthquakes. Swarms of hundreds of even thousands of small, mostly unfelt quakes are recorded on the seismographs of the Hawaiian Volcano Observatory during the month of weeks before an eruption. The number, size and location of the earthquakes are all important in interpreting their meaning with regard to a potential eruption.

Tremor. A peculiar type of ground vibration detected by the seismographs is called harmonic tremor. this unfelt but continuous shaking of the ground produces a broad, wiggling record on the seismograph that may last for a few minutes or many days. Tremor is always recorded during an eruption, and its intensity varies with the rate at which lava is being poured out. Tremor indicates that molten rock is on the move, and its occurrence when an eruption is not in progress suggests that molten lava is moving rapidly in underground conduits.

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