= Siletzia =

Siletzia is the massive formation of early to middle Eocene epoch marine basalts and interbedded sediments in the forearc of the Cascadia subduction zone ; this forms the basement rock under western Oregon and Washington and the southern tip of Vancouver Island . It is now fragmented into the Siletz and Crescent terranes .

Siletzia corresponds geographically to the Coast Range Volcanic Province (or Coast Range basalts) , but is distinguished from slightly younger basalts that erupted after Siletzia accreted to the continent and differ in chemical composition . The Siletzia basalts are tholeiitic , a characteristic of mantle @-@ derived magma erupted from a spreading ridge between plates of oceanic crust . The younger basalts are alkalic or calc @-@ alkaline , characteristic of magmas derived from a subduction zone . This change of composition reflects a change from marine to continental volcanism that becomes evident around 48 to 42 Ma (millions of years ago) , and is attributed to the accretion of Siletzia against the North American continent .

Various theories have been proposed to account for the volume and diversity of Siletzian magmatism , as well as the approximately 75 ° of rotation , but the evidence is insufficient to determine Siletzia 's origin ; the question remains open .

The accretion of Siletzia against the North American continent approximately 50 million years ago (contemporaneous with the initiation of the bend in the Hawaiian @-@ Emperor seamount chain) was a major tectonic event associated with a reorganization of the earth 's tectonic plates . This is believed to have a caused a shift in the subduction zone , termination of the Laramide orogeny that was uplifting the Rocky Mountains , and major changes in tectonic and volcanic activity across much of western North America .

= = Exposures and discovery = =

The rock of Siletzia has been exposed in various places by tectonic uplift (as around the periphery of the Olympic Mountains) , anticlinal folding (such as the Black Hills and Willapa Hills in southwestern Washington) , and overthrusting onto other formations (along various faults in central and southern Oregon) . These exposures have been variously named the Metchosin Formation of Vancouver Island , the Crescent Formation , Black Hills , and Willapa Hills volcanics of Washington , and the Siletz River Volcanics and Roseburg Formation of Oregon . (See map . The Grays River Volcanics of Washington and Tillamook Volcanics of Oregon are now considered post @-@ Siletz .) Elsewhere Siletzia is covered by younger volcanic and sedimentary deposits .

The discovery of Siletzia began in 1906 with Arnold 's description and naming of a small exposure on the north side of the Olympic Peninsula near Port Crescent . Though this exposure is small , he recognized as very likely that much more of it was buried under younger deposits . With recognition that similar rock exposed at other outcrops is part of the same formation , the name is now generally applied to all early and middle Eocene basalts on the Olympic Peninsula and Puget Lowland .

The Metchosin formation at the southern tip of Vancouver Island was described in a series of reports (1910 , 1912 , 1913 , 1917) by Clapp , who recognized it as correlative with the Crescent formation on the other side of the Strait of Juan de Fuca . Weaver recognized that these " Metchosin volcanics " included various Eocene basalts in western Washington and the Oregon Coast Range as far south as the Klamath Mountains . The Siletz River Volcanics was described in 1948 by Snavely and Baldwin after exposures near the Siletz River , Oregon , and the Roseburg and related formations in southern Oregon described in various reports from the 1960s on .

" Siletzia " was coined in 1979 by Irving to describe the full extent of these Eocene basalts and interbedded sedimentary formations .

= = Extent = =

The map shows the exposures (black) and inferred near @-@ surface extent (pink) of Siletzia , the latter being what can be detected in the upper crust by aeromagnetic , gravitational , or

seismological studies .

There are only two exposed contacts of Siletzia with the older (pre @-@ Cenozoic) North American basement . One is near Roseburg , Oregon , where it is thrust against formations of the Klamath Mountains (discussed below) , the other is along the Leech River Fault on the southern end of Vancouver Island , where it has pushed the pre @-@ Cenozoic Pacific Rim formation beneath the Wrangellia Terrane) . Everywhere else the contact between Siletzia and the rest of the continent is concealed under younger deposits , especially the Cascade Range volcanics . The contact around the Olympic Mountains is actually the bottom contact with the underlying oceanic sediments , tilted up by the uplift of the Olympics and exposed by erosion of about 10 to 12 km of overlying deposits .

The location of the near @-@ surface contact between the Crescent Formation and the pre @-@ Cenozoic metamorphic basement of the continent ? what has been the termed the Coast Range Boundary Fault (CRBF) ? is largely uncertain . The Leech River Fault extends southeast past Victoria , B.C. to cross the Strait of Juan de Fuca , possibly connecting with the southeast striking Southern Whidbey Island Fault (SWIF) . This extends to the Rattlesnake Mountain Fault Zone (RMFZ) , some 25 kilometers east of Seattle , which is believed to be the western edge of the pre @-@ Cenozoic basement . However , gravity data indicates that at this latitude the Crescent Formation (at least near the surface) extends no further east than Seattle .

Further south , near Mount St. Helens , is a similar situation , where the St. Helens Fault Zone (SHZ) is believed to be the eastern edge of the Crescent Formation , but the pre @-@ Cenozoic continental basement is near Mount Rainier . Separating these is the marine sedimentary formation known as the Southern Washington Cascades Conductor (SWCC) ; it is possible that it was deposited over a fragment of Siletzia . Or not : the oldest parts of the SWCC likely predate Siletzia , and the nature and location of the contact between these two formations is unknown .

In central Oregon , Siletzia forms a platform on which the older , now defunct volcanoes of the Western Cascades rest . The younger High Cascades to the east are believed to rest on sediments that accumulated in the basin between Siletzia and the continent .

In southern Oregon , Siletzia has been thrust against the Mesozoic Klamath Mountains of southern Oregon along the Klamath ? Blue Mountain Lineament (KBML) . Near Roseburg this contact is exposed at the Wild Safari Fault where the Late Jurassic Dothan Formation has been thrust over the Roseburg Formation .

Off the coast of southern Oregon , the western edge of Siletzia is the Eocene Fulmar fault . This is a strike @-@ slip fault , where part of Siletzia has been split off ; the missing piece may be the Yakutat terrane now at the head of the Gulf of Alaska . Further north , the terrane boundary is believed to come ashore near the Columbia River .

The way the Crescent Formation wraps around the Olympic Mountains (" Oly " on the map) may reflect oroclinal bending as a result of being crushed against Vancouver Island . It has also been attributed to loss of the deposits originally overlying the Olympics prior to their uplift , resembling a dome where top and western end has been removed .

Siletzia 's actual thickness , and the estimates of that thickness , vary . Under Oregon , the Siletz terrane appears to extend 25 to possibly 35 km into the trough between the subducting Juan de Fuca plate and the edge of the continent , where it is slipping over sediments accumulated in the bottom of the trough . The Crescent terrane (under Washington) is believed to be thinner , from as little as 12 and 22 km under the western and eastern ends of the Strait of Juan de Fuca , but possibly as much as 20 and 35 km thick .

= = Composition = =

The various formations of Siletzia are characterized as marine tholeiitic pillow basalts and volcanic breccia , often interbedded with sedimentary layers of continental origin , lying on oceanic crust . These are usually capped by a layer of alkalic volcanics deposited subaerially . All this suggests these formations were initially deposited in an oceanic environment , possibly as seamounts or an island arc .

On the Olympic Peninsula the Blue Mountain unit at the base of the Crescent Formation includes sediments (including large boulders of quartz diorite) of continental origin , showing that the continent was close by ; other sediments were eroded from the pre @-@ Cenozoic rock of Vancouver Island and the northern Cascade Range . At the southern end are sediments derived from the Klamath Mountains , while sand of the overlying Tyee Formation has an isotopic composition corresponding to rock of the Idaho Batholith .

= = Age = =

Eruption of the Siletzia basalts has been placed roughly in the late Paleocene through the mid Eocene ; more specific dates have been difficult to obtain and somewhat variable . Early K @-@ Ar (potassium @-@ argon) and 40Ar @-@ 39Ar (argon @-@ argon) radiometric dating by Duncan gave dates of 57 and 62 Ma (million years ago) to the northern and southern ends , and a date of 49 Ma for the Grays River volcanics near the center of Siletzia . This is suggestive of a spreading ridge (as previously noted by McWilliams 1980) , and has been a strong constraint on models of how Siletzia formed . Other researchers have since found younger dates (50 @-@ 48 Ma) for the Crescent basalts , removing much of the age symmetry .

More recent dating based on 40Ar @-@ 39Ar , U @-@ Pb (uranium @-@ lead) , and coccoliths shows a narrower range of ages from 56 Ma in the south to 50 or 49 Ma in the north .

= = Size = =

Siletzia is massive : over 400 miles (600 kilometers) long , almost half that much across (and likely further at depth) . The original deposits were from 16 to 35 kilometers thick . Weaver , reckoning a minimal thickness of only 3 @,@ 000 feet , still estimated " nearly 10 @,@ 000 cubic miles of rock " ; he put the total volume to be as great , if not greater , than the better known Columbia River Basalts . Snavely et al . , recognizing at least 10 @,@ 000 feet of thickness , and as much as 20 @,@ 000 feet under eruptive centers , estimated the volume to be in excess of 50 @,@ 000 cubic miles (over 200 @,@ 000 km3) . Duncan (1982) estimated around 250 @,@ 000 km3 (about 60 @,@ 000 cubic miles) , which exceeds the volume of most continental rift zones , and some flood basalt provinces . A recent estimate put the volume at 2 million cubic km .

= = Paleorotation = =

When lava solidifies it retains an imprint of the earth 's magnetic field , thus recording how it was oriented . Measurements of such paleomagnetic fields in the Oregon Coast Range show rotations of 46 to 75 ° , all of it following the presumed accretion to the continent (alternately , formation) of the Siletz terrane at about 50 Ma . These rotations are all clockwise , and show a strong correlation with the age of the rock : about one and a half degrees of rotation per million years . These paleomagnetic rotations and other evidence show that Siletzia ? or the part of it constituting the Siletz terrane (" SZ " on map , above) , from the Klamath Mountains to the Columbia River ? has rotated clockwise as a single , coherent block .

Did Siletzia pivot about its northern end or southern end ? This question has attracted considerable attention , with the evidence now favoring a northern pivot . A key piece of evidence is that the Crescent Formation is laid over sediments (the Blue Mountain unit) derived from the continent , including boulders of quartz diorite some 65 million years old ; this requires the Crescent Formation to have formed close to the continent .

This model has Siletzia forming on the continental margin along what is now the Olympic @-@ Wallowa Lineament (OWL ; a zone of topographical features of unknown age and tectonic significance) , with the southern end of Siletzia and the Klamath Mountains (joined to Siletzia) near the Idaho Batholith in central Idaho . Further evidence for this comes from the sand of the Tyee Formation that overlie the Roseburg Formation . Not only does this sand have the same isotopic composition of rock in the Idaho Batholith (and of sand now coursing down the Snake and

Columbia Rivers) , but it appears to have not been transported very far from its source . This implies that the Tyee Formation was much closer to the Idaho Batholith when it was deposited , and subsequently rotated away . Geodetic surveys show that the region continues to rotate , likely as a result of extension of the Basin and Range province and asthenospheric flow around the southern edge of the subducting Juan de Fuca plate .

North of the Columbia River , matters are more complicated . First , in southwestern Washington there is only half as much rotation as seen in rocks of similar age in Oregon . This is the basis for believing the Crescent terrane has broken from the Siletz terrane (perhaps because they formed on different oceanic plates) , and undergone a different rotational history . Second , in Washington there is more variation in the amount of rotation and more faulting , which has led to a speculation that the Crescent terrane has broken up into eight or nine crustal blocks .

At Bremerton , on the east side of the Olympics , the measured rotations are less , and within the statistical error bounds of being zero ; while further north , near Port Townsend , the rotation is slightly counter @-@ clockwise . On Vancouver Island the paleorotations are counter @-@ clockwise , and other evidence shows that the tip of the island has been bent , presumably as a result of the collision of Siletzia . The northwestern tip of the Olympic Peninsula also shows counter @-@ clockwise rotation , of around 45 degrees . This raises a question of how much of the arcuate shape of the Crescent Formation is due to loss of material from the center after uplift by the Olympic Mountains , and how much reflects oroclinal bending .

= = Origin = =

Siletzia 's origin is not yet determined , and (as of 2011) lacks a definite answer . Theories are still being developed , and even the details the theories depend on " have remained enigmatic " . Following are several of the most notable models .

Models of how Siletzia formed are of two general types : (1) Formation well offshore (possibly as seamounts , like the Hawaiian @-@ Emperor seamount chain , or a hotspot at a spreading ridge , like Iceland) and then accretion to the continent ; (2) formation inshore , on or near the continental margin (perhaps as a result of transcurrent extension , or of a slab window) . All current models then have Siletzia rifting away from the continental edge about a northern pivot . Studies of Siletzia 's origins have generally focused on accounting for two principal observations : the large paleorotation (described above) , and the voluminous output (over 50 @,@ 000 cubic miles , exceeding the volume of most continental rift zones , and some flood basalt provinces) . Accounting for the observed volumes of basalt requires an enhanced magmatic source , for which most models invoke either the presence of the Yellowstone hotspot , or slab windows . The latter would have resulted from the subduction of the Farallon ? Kula (or possibly Farallon ? Resurrection) spreading ridge . The relation with the Kula @-@ Farallon spreading ridge is an important element in all models , though its location through that epoch is not well determined .

= = = Simpson & Cox 1977 : Two models = = =

Seeking to explain the observed clockwise paleorotation , and noting that Siletzia appeared to have rotated as a rigid block , Simpson & Cox (1977) proposed two models . First was rotation about a southern pivot in contact with the Klamath Mountains . This has various problems , especially because at the northern end sediments and even boulders from the continent are found at the base of the Crescent Formation , showing that it was near the continent from the beginning . In the second model (subsequently refined by Hammond 1979) , Siletzia was originally adjacent to the Olympic @-@ Wallowa Lineament , then rifted from the continent and rotated about a northern pivot near the Olympic Peninsula . Because sediments also show the Klamaths in close contact from the start , this requires the Klamaths to have moved with Siletzia . Originally there were conflicts in the understanding of when the Klamaths moved , and with the age and amount of rotation of the Clarno Formation in central Oregon . These were largely cleared up in a study of the Clarno Formation by Grommé et al . (1986) and illustrated with a palinspastic reconstruction as of 38 Ma .

= = = Offshore model : A captured island chain ? = = =

An early and widely cited paper by Duncan (1982) (drawing on features of the fairly new theory of plate tectonics) exemplifies the off @-@ shore or " seamount " type of models . It featured a set of radiometrically determined (K @-@ Ar and 40Ar @-@ 39Ar) ages that were younger in the center (for the Grays River volcanics) and older at the ends . This dihedrally symmetric age progression strongly suggested the pattern seen at spreading ridges , where the older rock is carried away on both sides from where the new rock erupts . Duncan considered five models (but none involving rifting or ridge subduction) , favoring one where a hotspot ? presumably the Yellowstone hotspot ? intersected the Farallon @-@ Kula spreading ridge (such as at Iceland) to generate a chain of islands . These islands were then accreted to the continent as the underlying oceanic crust was subducted .

This study has been criticized on multiple grounds , particularly regarding the ages . Duncan himself noted that measurement of the northern ages may have been affected by loss of argon due to low @-@ grade metamorphism , and that there might be bias in respect of stratigraphic position . The latter was demonstrated by a recent study that showed , on the basis of geochemistry , that the Grays River volcanics followed the Siletzia eruptions , and thus are not representative of the initial phase of Siletz magmatism . Recent dating also shows a more monotonic trend of south to north age progression (" younging ") .

The range of the original ages was also a problem , as the rate of Kula @-@ Farallon spreading over that time would produce a chain of seamounts much longer than observed , and too far away from the continent to explain the continentally derived sediments . This objection is attenuated somewhat in that the newer ages show a smaller range of ages .

= = = Inshore models = = =

Various models have Siletzia forming inshore , on or near the continental margin . While all current models have Siletzia rifting away from the continent after accretion or formation , a subclass of " rifted " models consider the rifting to have caused the Siletzia eruptions .

Wells et al . 1984 proposed that the Siletzia basalts might have " leaked " through transform faults (perpendicular to a spreading ridge) during changes in direction of the tectonic plates . The size of these eruptions and their location in this region is attributed to proximity to the Yellowstone hotspot . This " leaky transform " theory seems to be largely rejected , likely because the plate motion model it was based on was shown to be faulty .

Wells , et al . , alternately suggested that as a terrane at the margin of the continent was pushed over the Yellowstone hotspot , it was rifted away from the continent by the upwelling magma , which then formed the Siletzia basalts . This idea was further developed by Babcock et al . (1992) , who suggested rifting might have been initiated by a change in plate direction , or by kinematic effects as the Kula @-@ Farallon ridge migrated along the continental margin . One such effect is the formation of a slab window (or slab gap) which would allow increased upwelling of magma .

= = = Slab windows = = =

That spreading ridges could be subducted was recognized early in the development of plate tectonic theory , but there was little consideration of the ensuing effects . In the 1980s came realization that the magma welling up from the asthenosphere through the subducted ridge would not reach seawater , and thus not be quenched to form rock and close the gap . Continued spreading would lead to a widening gap or " window " in the subducting plate through which there could be increased flow of magma The implications of this for Siletzia were first shown by Thorkelson & Taylor (1989) and Babcock et al . (1992) (following the pioneering work by Dickinson & Snyder 1979) . Breitsprecher et al . (2003) subsequently identified the fan @-@ shaped wake of volcanics of distinctive geochemistry left by the widening Kula @-@ Farallon slab

window across northeastern Washington and into Idaho .

Madsen et al . (2006) showed that most of the Eocene and subsequent magmatism from Alaska to Oregon " is explainable in terms of ridge subduction and slab window tectonics . " That is , a slab window ? and a single subducted ridge can give rise to multiple slab windows ? can provide adequate magmatism without having to invoke a hotspot (mantle plume) . (So much so that it has been suggested that the Yellowstone hotspot may have been initiated by a slab window .) Mantle plumes and slab windows both feature voluminous magmatism ; the main difference is that slab windows would form only where the spreading ridge is subducted . This implies formation at the continental margin , and then rifting , in the manner of the second class of models .

= = = Gulf of Alaska = = =

Any model of the origin of Siletzia must account for interactions with plate boundaries that were being subducted under North America through the Eocene . Early studies were plagued by indeterminate locations for these boundaries , particularly of the Kula @-@ Farallon (K @-@ F) spreading ridge : basalts at the head of the Gulf of Alaska (along the Alaska panhandle) have ages and compositions corresponding to the Siletz volcanics , suggesting that the K @-@ F ridge was offshore of the Yukon at the same time it was offshore of Washington . This can be resolved by assuming that by about 56 Ma the eastern part of the Kula plate had broken away to form the Resurrection plate , with the new Kula @-@ Resurrection (K @-@ R) spreading ridge running up the Gulf of Alaska towards Kodiak Island , and the former K @-@ F (now R @-@ F) ridge reaching Washington . Subduction of this plate under western Canada was rapid , and it disappeared entirely with subduction of the K @-@ R ridge about 50 Ma .

This scenario then permits rapid transport north of crustal blocks such as the Yakutat terrane . Now lying southeast of Cordova at the head of the Gulf of Alaska , paleomagnetic evidence indicates it was formed at a latitude corresponding to Oregon or northern California . Similarly , certain schists on Baranof Island are believed to have been contiguous with the Leech River Schists (Leech River Complex) on Vancouver Island around 50 Ma , and subsequently transported northward with other elements of the Chugach @-@ Prince William terrane .

= = After accretion : 50 @-@ 42 Ma = =

Whether formed far offshore as seamounts , or close inshore by a slab window , the Siletzian basalts were laid down on a subducting oceanic plate : the Siletz terrane on the Farallon plate , and the Crescent terrane most likely on the adjoining Resurrection plate (previously broken away from the Kula plate , which had previously broken away from the Farallon plate) . In both cases the Siletzia mass was drawn toward the subduction zone , which possibly ran diagonally across what is now Washington , approximately at the position of the Olympic @-@ Wallowa Lineament . However , Siletiza was too big to be subducted , and it accreted to the continent . Accretion is sometimes called " docking , " but is more akin to a collision : various peripheral structures are first folded or crushed , then the main structures are deformed when they come into contact , and various parts get pushed over other parts , all this playing out over several million years . To the extent that the accretion of Siletzia to North America can be given a definite date most studies give it as about 50 Ma . This date has added significance as it is also the start of a change in direction of the Pacific plate , as seen in the bend in the Hawaiian @-@ Emperor seamount chain , and also a change in the Pacific Northwest from compressional to extensional tectonics . This may also be when the last of the Resurrection plate was subducted under British Columbia . Initiation of the north @-@ striking right @-@ lateral Straight Creek Fault at ~ 48 Ma likely resulted from strain accumulated during the accretion of Siletzia .

As Siletzia accreted it also jammed the existing subduction zone , halting subduction of the Farallon plate . This terminated the Laramide orogeny that had been uplifting the Rocky Mountains , and triggered the ignimbrite sweep , a wave of large @-@ volume silicic magmatism that swept over much of western North America between 50 and 20 Ma . This undoubtedly affected the enigmatic

and controversial Challis Arc (stretching from southeastern British Columbia to the Idaho Batholith , roughly parallel with the Olympic @-@ Wallowa Lineament) , but the details of this are unknown .

Subduction , having ceased at the existing zone , eventually reinitiated further to the west as the current Cascadia subduction zone . Volcanism from the new subduction zone (such as the Grays River Volcanics and Northcraft Volcanics) reached the surface about 42 Ma , thereby initiating the rise of the ancestral Cascade Range .

Several other significant events occurred around 42 Ma , including cessation of metamorphism of the Leech River Schists (resulting from the Metchosin / Crescent Formation being thrust under Vancouver Island) and the end of strike @-@ slip motion on the Straight Creek Fault ; these may reflect the last movement of Siletzia relative to North America . On a broader scale , there was a change in absolute direction of the Pacific plate (marked by the end of the bend in the Hawaiian @-@ Emperor seamount chain) , and a change in the convergence of the Kula plate with the North American plate .

As subduction waned so did the force that had clamped Siletzia against the continent , and the tectonic regime shifted from compressional to extensional . Deposition of sand from the then proximal Idaho Batholith into the Tyee Formation in southern Oregon may have continued as late as 46 @.@ 5 Ma , but was interrupted when Siletzia rifted from the continent and began rotating away . What initiated rifting is unknown . Wells et al . (1984 , p . 290) suggested that as the continent overrode the Yellowstone hotspot , the upwelling plume tore away a previously accreted terrane . Babcock et al . (1992) suggested a change in the rate at which the plates were converging , or the " kinematic effects " (such as a slab window) from the passage of the Kula @-@ Farallon ridge (or Resurrection @-@ Farallon ridge) .