Chapter 4

The Challis Episode

The Demise of the Kula Plate

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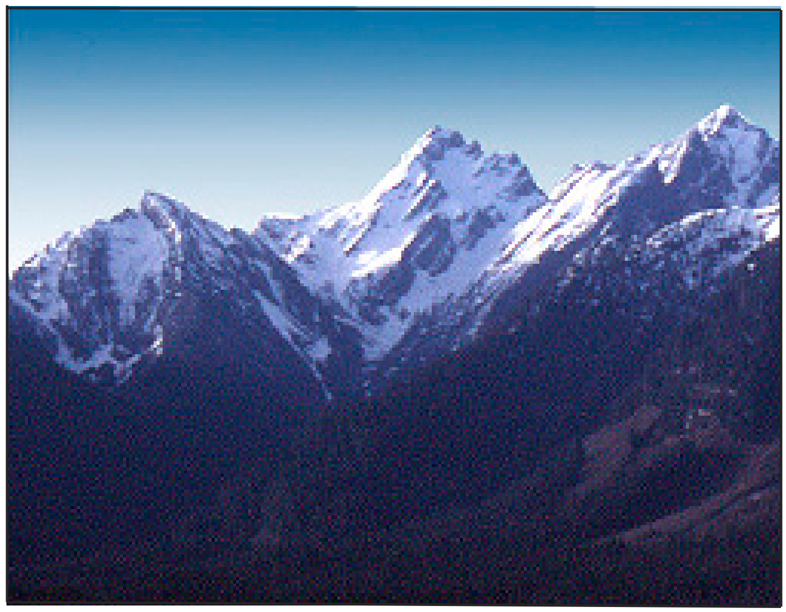
58 - 38 Million Years Ago

Introduction



Of all the episodes which make up the geologic history of the southern end of the Pacific Northwest, none were more dramatic or more enigmatic than the Challis Episode of the Eocene. Over a span of some 20 million years, the events of this period present a complex and often confusing set of conditions. The extensive sedimentary and volcanic accumulations of this episode provide a wealth of information on the course of events here, but they chart a course that presents a challenge to modern plate-tectonic theories. In the end, the Challis Episode appears to represent a somewhat exotic set of plate tectonic relationships, the relationships surrounding the demise of an oceanic plate.

The Challis Episode is known for a seemingly disparate set of events. It is best known for the broad belt of felsic arc-magmatism (the Challis Arc) which extends from south-central British Columbia to southwestern Idaho. At the same time, it is also known for the voluminous eruption of the submarine basalt flows of the Crescent Formation, and for its accretion as a major component of the Olympic Coast Belt. It is known for large-scale strike-slip faulting along the western side of the province, but at the same time for low-angle extensional faulting in the southern Intermontane Belt, and for folding in the southern Insular Belt. It was known for uplift and erosion in the Intermontane Belt, while across the southwestern end of the province it was marked by extensive subsidence and sedimentation.

As noted, these seemingly-disparate sets of events are owed to a complex and rather exotic regime of plate-tectonic relationships. Those relationships provide the context which extracts a sense of order from this panoply of geologic events. Unraveling that story is the special challenge posed by the Challis Episode. Accordingly, we will start by examining that issue.

Figure 4-1 *(Cover Page) The North Cascades, Challis-age rocks of the Golden Horn Pluton in the foreground.*

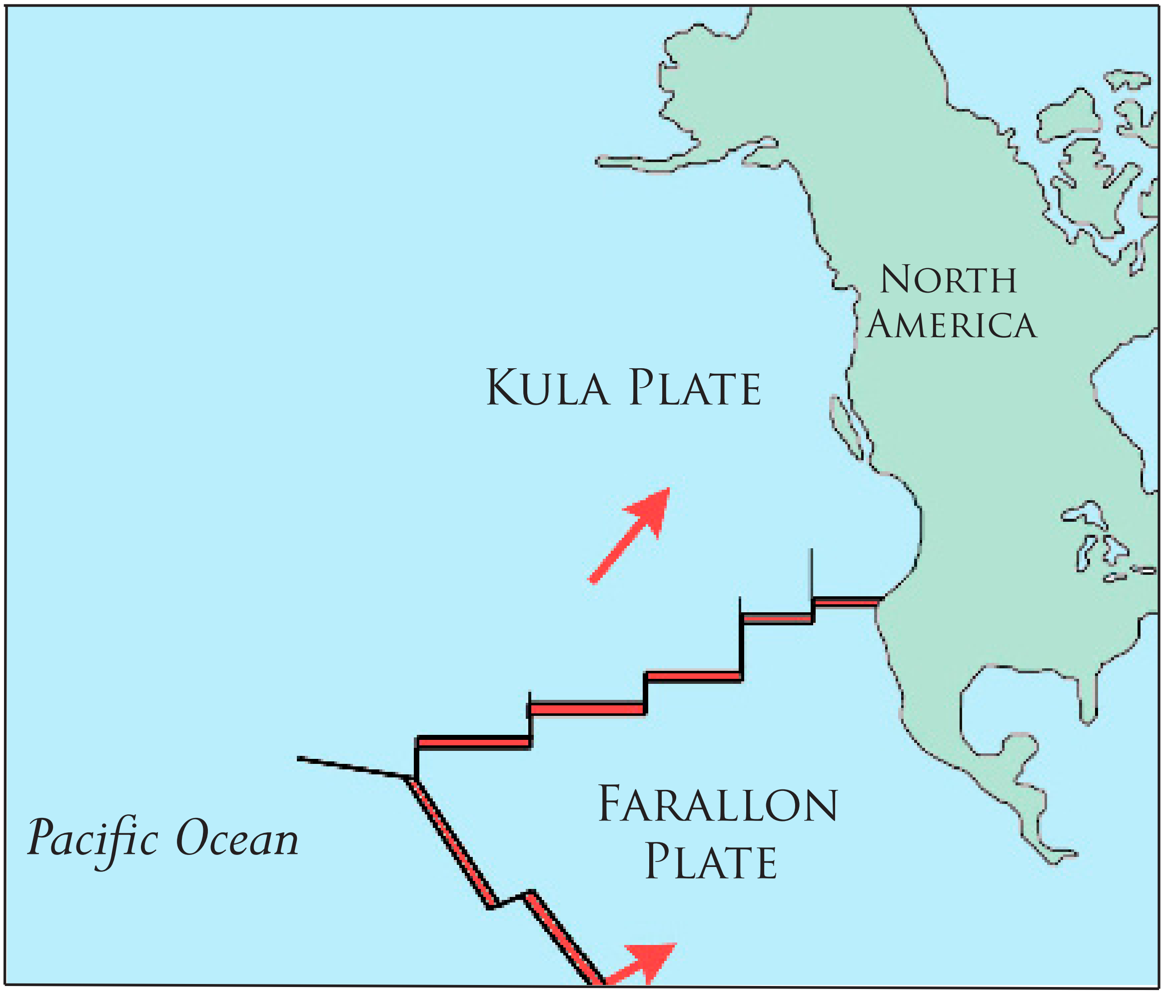
Figure 4-2 *(Left) Rocks of the Long Alec Creek Pluton, east of Curlew. .*

Figure 4-3 *(Above Right) Folded rocks of the Chuckanut Formation, Del Campo Peak, above the town of Silverton.*

Figure 4-4 (Right)

Map (diagrammatic) illustrating the development of the Kula-Farallon Ridge,about 120 million years ago. This established the Kula Plate in the northerastern Pacific Basin. Red arrows show direction of oceanic plate motion.

Prior to this date, the Farallon Plate had covered the entire eastern Pacific Basin.



Overview

Modeling the Demise of the Kula Plate

The early history of the Pacific Northwest, at least that surrounding the accretion of the Intermontane Belt, was accomplished under the auspices of an oceanic plate regime known as the ***Farallon Plate*** (after the Farallon Islands in California). At the time, that plate covered most of the northeast Pacific Basin. In Cretaceous time however, the Farallon Plate was split by a new spreading ridge, forming the ***Kula Plate*** to the north. While the date of this development is poorly constrained, it was marked by the inception of a spreading ridge which intersected the North American continent along the coast of what is now Northern California. The development that spreading center was likely responsible for exhumation and northward transport of the Melange Belts. Because subduction-zone metamorphism in the Northwest Cascades System of the Melange Belts dates from about 120 Ma, this ridge likely developed around that date. It thus appears that most of the Coast Range Episode was conducted under the auspices of the Kula Plate.

As noted in the last chapter, the movement direction of the Kula Plate became increasingly oblique (north-directed) over the course of the Coast Range Episode, finally becoming a transform setting along the western margin by ~58 Ma. By that date, the Kula - Farallon ridge was apparently oriented along a broadly east-west axis, intersecting the North American Continent at a point north of Cape Mendicino, California. Here, in a unique and somewhat enigmatic course events over the next twenty million years, the Kula Plate appears to have met its demise in this area.

In contrast to the events of the more distant past, the events of this episode have preserved a true abundance of information on the course of geologic evolution here. We can map the appearance of magma species, the orientation and magnitude of folds, the character and displacement of faults, and we can read volumes about the paleogeography from the thick sedimentary record of this episode. What we don't have however, are pieces of the Kula Plate. We don't have an ocean-floor record from which we can extrapolate its behavior. There are no pieces of the Kula Plate left. Its name, a term from the native Tlingit people of Vancouver Island, means "all gone."

Without that ocean-plate record, we are left to infer that course of plate tectonic events from the rock record of the continent. This means that we are left to model a "most probable" course of plate relationships which are consistent with that continental record. Fortunately, that record is extensive enough that it places major constraints on such a model. It is to be cautioned that the actual course of events was likely a more complex affair than those offered here, and may have some substantive differences from it.

The model offered here for the demise of the Kula Plate assumes that the Kula-Farallon ridge, oriented along a broadly east-west axis, occupied the southern end of the Columbia Embayment about 60 million years ago. Along the north side of that ridge, over the next twenty million years, it appears that the Kula Plate broke up along a series of north-south transform faults. This is similar to the scenario which the modern Juan De Fuca Plate occupies now, in its last 20 million years of existence. Over the last twelve million years, it has been broken twice by major transform faults, a process which will probably accelerate as the remainder of the plate is overridden by the continent. This appears to be the process which accompanies the demise of oceanic plates and their mid-ocean spreading centers.

On the Kula Plate, the "master" transform fault in this system was located along the southern end of the 500 km-long ***Fraser Fault System***, which extends into northern Canada to meet the Tintina – Northern Rocky Mountain Fault. This

Figure 4-5 *(Right)*

Map (diagrammatic) showing relations between the Kula and Farallon Plate during the Challis Episode.

This map reflects relationships at about 48 million years ago, at the inception of the Fraser Fault.

Compare with figure 4-4 (left), illustrating the northwestward movement of the North American Continent.

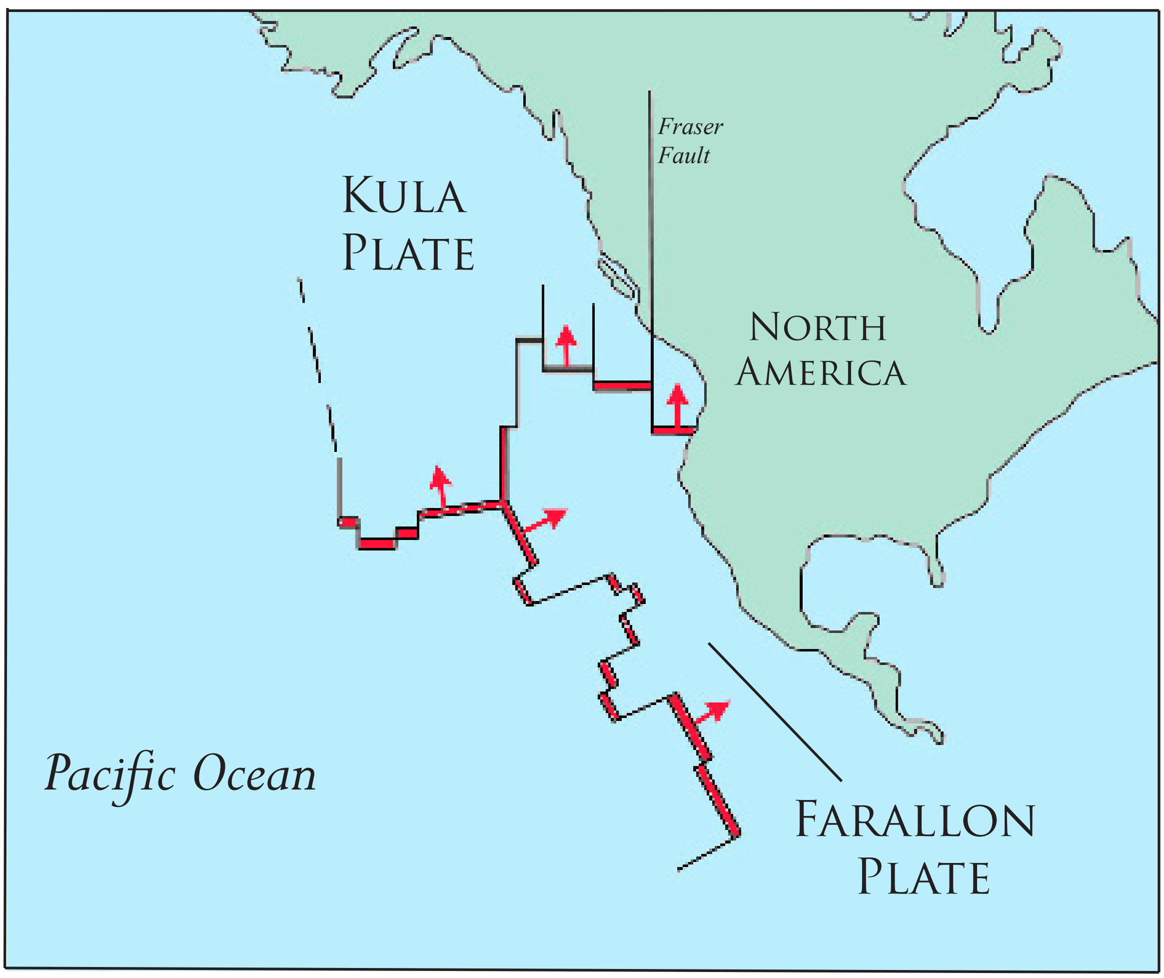


Figure 4-6 *(Right)*

Map (diagrammatic) illustrating the demise of the Kula Plate, and the northward advance of the Kula-Farallon Ridge.

The map depicts conditions at about 42 million years ago, just after the emplacement of the Olympic Coast Belt.

Five million years beyond this date, the Kula Plate ceases to exist as the ridge advances north. This marks the end of the Challis Episode.

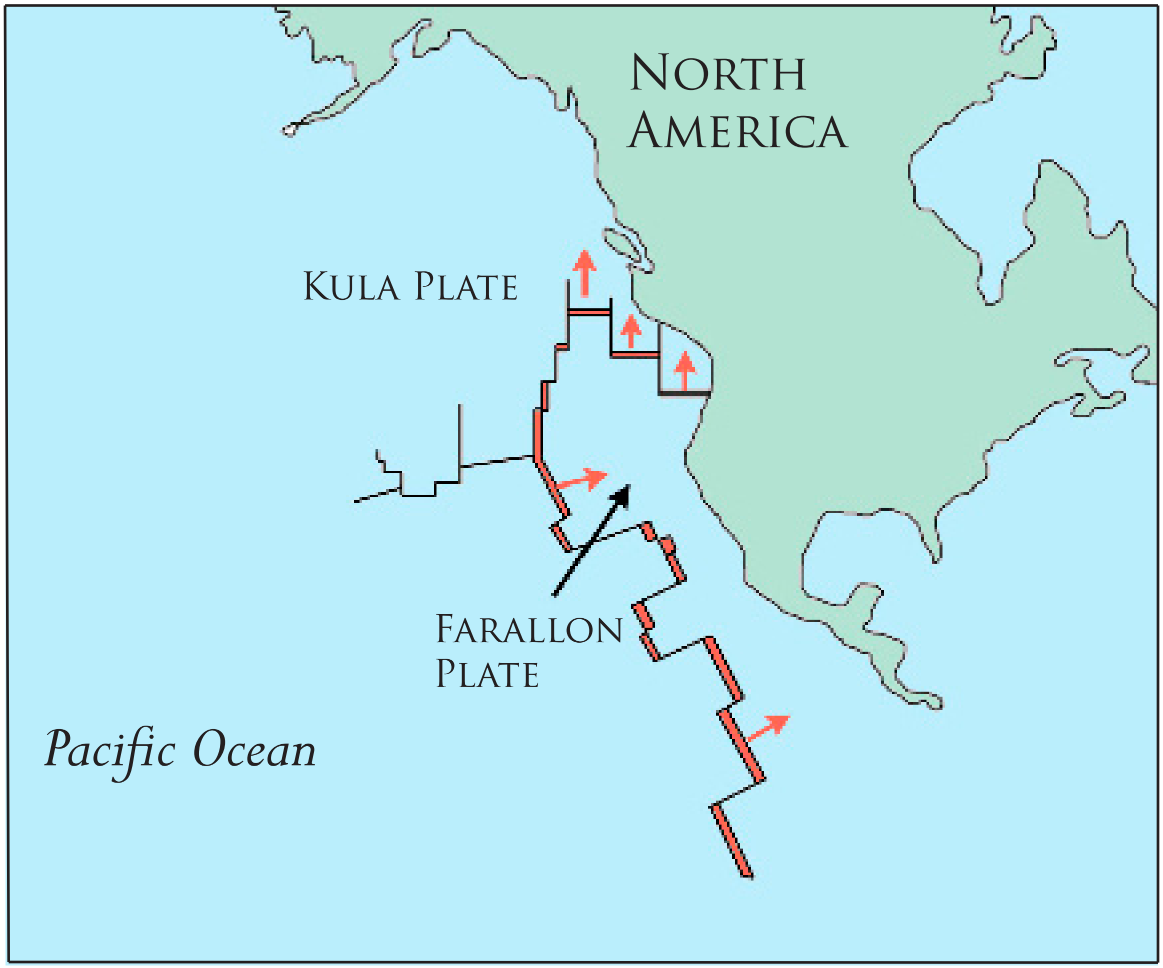
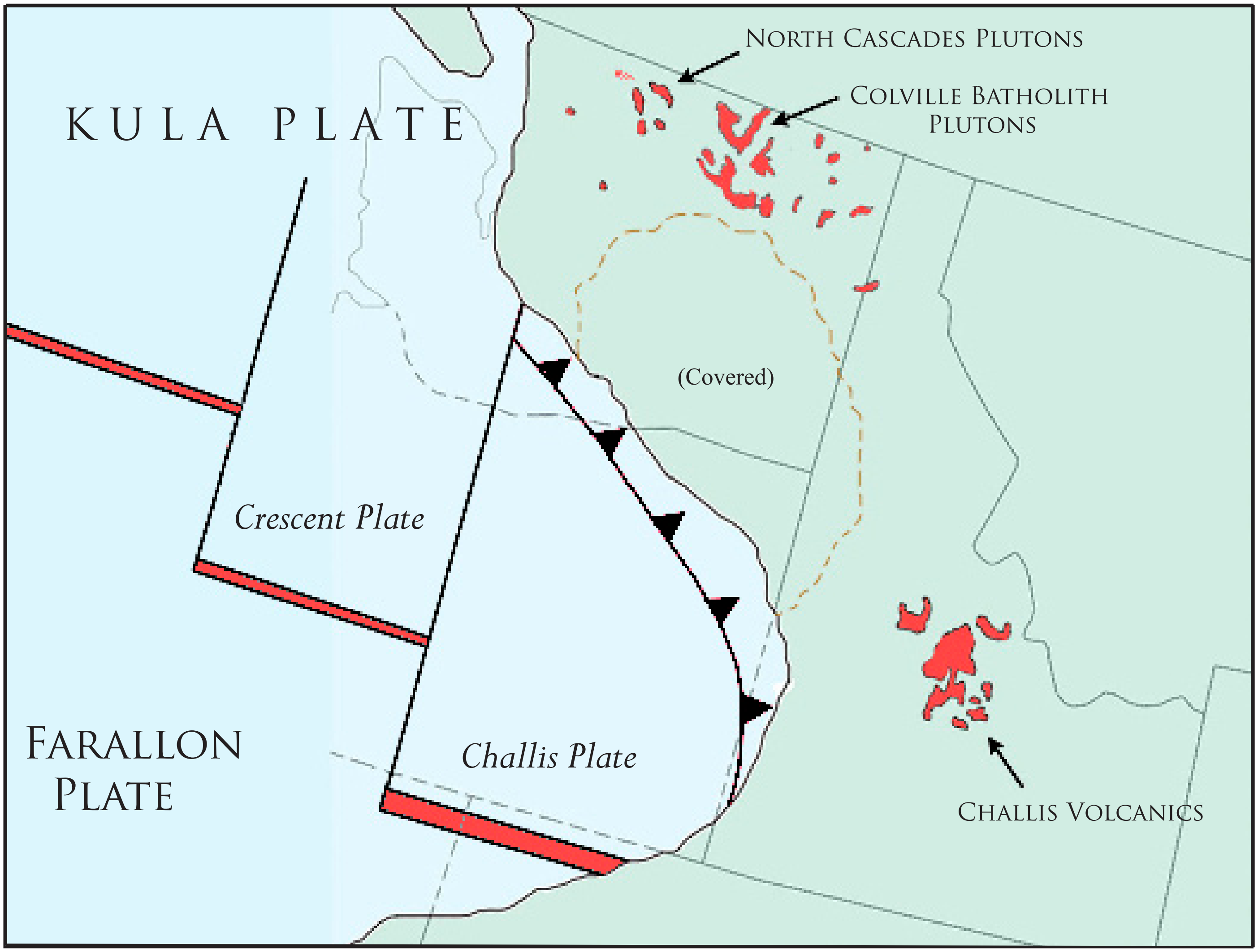


Figure 4-7 *(Right) Map showing the major plutonic and volcanic centers of the Challis Arc in Washington State, , and the plate-tectonic relationships suggested by their distribution. Note that additional Challis plutons lie north of the border, in the "core complexes" of southeastern British Columbia (see figure 4 - 17). Barbed line is a subduction zone, with the barbs on the upper plate.*

is the major Eocene fault in our area. Long before this fault ruptured as a continental feature, it appears that an oceanic transform fault here separated two elements of the Kula Plate in the Columbia Embayment. The eastern of these two plates was subducted underneath the continental rocks along the northeastern end of the embayment. This gave rise to the continental-arc magmatism of the ***Challis Arc,*** extending from south-central British Columbia southeast into Idaho.

The western of these two oceanic plates, by contrast, maintained a passive relationship with the continental margin. Along this segment of the spreading center, rather than intruding magmas to generate new oceanic plate rocks, those magmas apparently "leaked" to the surface along transform faults which cut this part of the Kula plate. These erupted vast quantities of basaltic magma on the ocean floor, an accumulation known as the ***Crescent Basalts***. These were later emplaced into the continental margin in a terminal phase of transform motion. That transform motion also included large-scale displacement of the continental margin along the Fraser Fault. In that terminal phase, the last of the Kula-Farallon ridge was abandoned, as the Farallon Plate finally moved northward into this area. This was accomplished by about 38 million years ago, re-establishing a convergent margin setting here. This event marked the end of the Challis Episode.



The Challis Arc

The Eastern Regime

As the Kula-Farallon ridge moved into the Columbia Embayment, it appears that subduction to the east of the Fraser Transform gave rise to a continental arc regime known as the ***Challis Arc***. The Challis Arc extends in a rather broad swath from the North Cascades east into the southern Intermontane Belt, and then southeast into central Idaho. This is the eastern half of the same region which hosted the Coast Range Arc, again reflecting the orientation of the continental margin here. The Challis Arc takes its name from a small town in Idaho.

It should be noted that a continental-arc origin for the Challis magmas is not at all a universally-accepted interpretation. The unique qualities of the Challis magmas, their broad geographic distribution, and their shallow level of emplacement have compelled a number of researchers to suggest that this may be something more exotic than a continental-arc setting. A variety of alternative interpretations have been advanced over the years, including the rapid sinking of a partially-subducted slab of oceanic lithosphere, or the decompressional re-melting of older Coast Range plutons. In the end however, there is little empirical evidence for such events, nor are there clear modern examples of such exotic phenomena. It seems much more likely that this is the result of arc magmatism – albeit with some unique qualities. Among these, it is a broader arc than is common, suggesting that the oceanic crust was being subducted at a shallow angle. This would be expected, given the immaturity of the oceanic plate rocks here.

Many of the plutons of the Challis Arc are unique in the Northwest in that they are “true” granites, characterized by alkali (potassium) feldspar. They are often characterized by a distinctive pink color. Similarly, many of the volcanic rocks of this episode are dacitic to rhyolitic in composition. The magmas of the other continental-arc regimes here have been dominantly quartz dioritic and andesitic / dacitic in composition. The chemistry of the Challis Arc magmas may in part reflect large amounts of continental sediments being fed into the subduction zone, and/or may reflect large quantities of water entering the system. Challis plutons characteristically rose to shallow depths of just a few kilometers, and were often accompanied by extensive volcanism on the surface. Owing to their chemistry, they had a tendency toward explosive eruptions.

Plutons of the Challis Arc are fairly abundant in the modern-day North Cascades east of the Fraser Fault. In the Chelan Mountains Terrane, Challis magmatism is recorded in a suite of shallow intrusions, including the ***Duncan Hill, Railroad Creek and Cooper Mountain Plutons*** of the central region, and the ***Golden Horn Pluton*** along the Ross Lake Fault. The Golden Horn is a classic Challis intrusion, featuring the pink feldspar (microcline) associated with the true granite species. In the Skagit “core” region, Challis magmatism appears in a set of ***granitic pegmatite dikes*** which seam the area. These dikes may emanate from the cupola (top) of the pluton not far below the present erosional level.

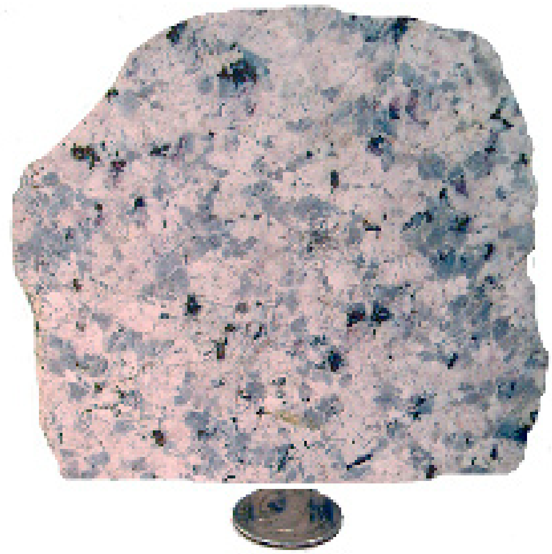


Figure 4 - 8 *(Top)*
Early Winters Spires, rocks of the Golden Horn Batholith. From the summit of Liberty Bell Mountain, looking south.

Figure 4 -9 *(Above)*
Hand sample of Golden Horn rock, cut and polished. Note the pink K-Feldspar, a characteristic of many Challis Arc plutons.

Heat associated with the Challis Arc may have reset the isotopic systems (radioisotope proportions used for dating) in older rocks across the region. Accordingly, most older plutons of the Coast Range episode in the North Cascades and the Intermontane Belt may erroneously evidence Eocene cooling ages. Once again, this is not a universally-held view. American researchers in particular are disposed to viewing the Late Coast Range plutons as being uplifted and cooled into Early to Mid-Eocene time. This would be a protracted orogenic cycle compared to that evidenced in the Early Coast Range Orogen, and seems contrary to the shallow character of Challis magmatism. Canadian researchers have been more inclined to view these as reset ages.

To the east, Challis-age plutons intruded the southern end of the Intermontane Belt, intruding into older plutonic rocks of the Coast Range and Omenica Episodes, and the original rocks of the Quesnel Terrane. Many of these rocks are part of the ***Colville Batholith***. These include an older group known as the *Keller Butte Suite* (Keller Butte, Storm King, Mt. Bonaparte and Lyman Creek Plutons, among others), a younger Devils Elbow Suite which includes the Devils Elbow and Kettle Crest plutons (among others), and a youngest *Herron Creek Suite*, including the Herron Creek Pluton and the Long Alec Creek Batholith. These were important components in the development of the "core complexes" in this area, as detailed below. Volcanic rocks of this episode are ubiquitous across the region, and are known as the ***Sanpoil Volcanics.***

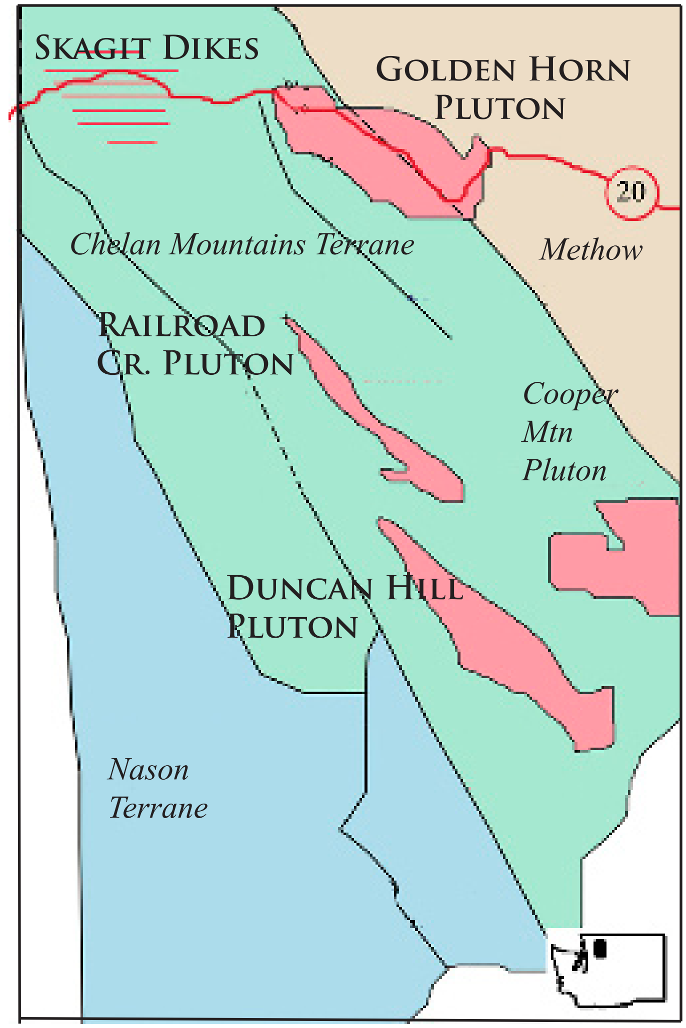


Figure 4 - 10 *(Above) Map showing Challis plutons of the North Cascades*
Figure 4 -11 *(Below) The Sanpoil Volcanics, along the Sanpoil River north of Keller. Snow enhances detail.*

Figure 4 - 12 *(Above) Roadcut in the Skagit Gneiss, above Diablo Lake. White pegmatite dikes are Challis-age intrusives dated at ~ 45 Ma. They occupy the core of the Skagit Antiform, established a few million years earlier.*

Figure 4 -13 *(Below) Megacrystic gneiss, featuring large K-feldspar crystals. Megacrystic rocks are common among the Challis plutons. Rocks of the Corkscrew Grade Granodiorite, east of Omak.*

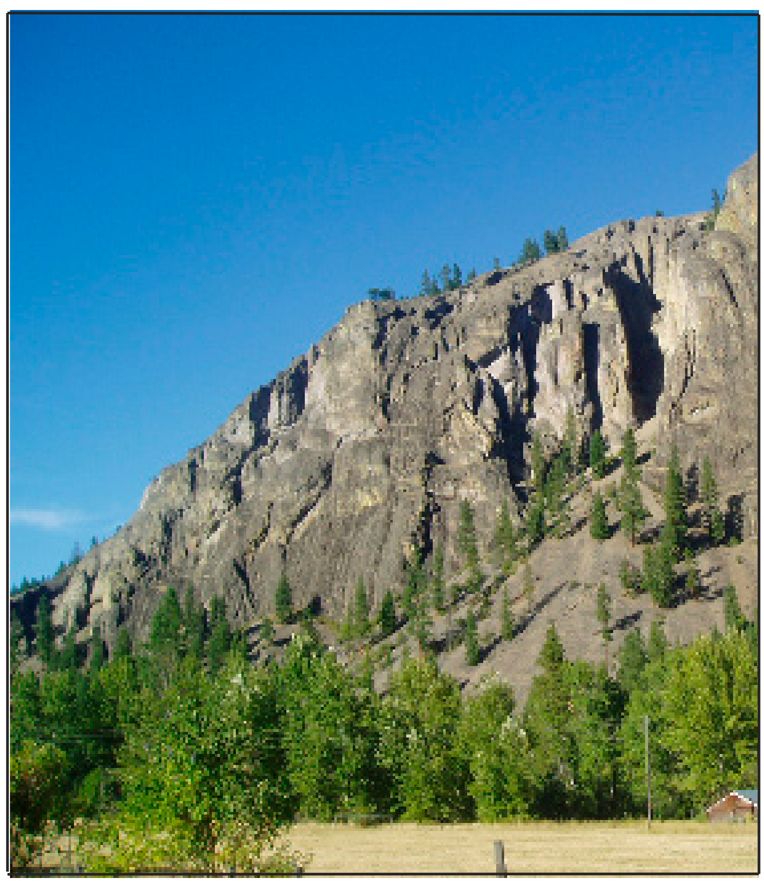
Further east, Challis magmatism extended across northeastern Washington. These rocks include the ***Loon Lake*** and ***Ahern Meadows pluton***s, the ***Silver Point Quartz Monzonite,*** along with a host of smaller outcrops. Also preserved are limited exposures of the Sanpoil Volcanics. To the south and east, the Challis Arc continued into northern and west-central Idaho. There as elsewhere, they have played an important role in concentrating gold and silver. Challis magmas rose to shallow levels and generated superheated water, which is effective in placing such metals into solution. As these hydrothermal fluids cooled, the precious metals were precipitated out in veins and dikes. Mining these deposits has historically been an important enterprise in north-central Washington and in Idaho. Most of our more successful gold mines owe their mineral wealth to the actions of Challis Arc magmas.

Challis Arc igneous rocks range from about 55 to 40 million years in age, with most falling between 50 and 45 million years ago. Most (but not all) of these plutons appear to have intruded along fault zones, shear zones or other tectonic features. They characteristically rose to shallow depths, and were frequently accompanied by surface volcanism. Much of that volcanism appears to have been relatively explosive in character. Because these volcanic rocks are an integral element in the regional stratigraphic record, we will consider them as part of the depositional package.

Well to the west of the Fraser Fault, Challis-age plutons appear in the northwest portion of the Coast Range Belt, extending to its western edge in southeast Alaska. These plutons probably result from the subduction of a western section of the Kula Plate in the Pacific Basin. That section lies west of the modern-day Queen Charlotte transform. This development lies somewhat out of our area of focus, but indicates that Kula Plate elements further west continued to be subducted over at least the early part this period.

Figure 4 - 14 *(Above)*
Challis (Sanpoil) volcanic rocks above Ellisford, north of Tonasket. These are on the displaced upper plate of the Okanogan detachment.

Figure 4 - 15 *(Right)*
The Sanpoil Volcanics, along the Sanpoil River south of Republic. These are the volcanic component of the Colville Pluton, and are widespread across the Okanogan region.



Challis Arc magmatism is largely absent in the region between the Queen Charlotte Fault and the Fraser Fault. Instead, as detailed below, this region hosted an episode of mafic ocean-ridge magmatism. In those few places where felsic magmas did arise in this region, they are in fault-controlled settings adjacent to the Fraser (Straight Creek) Fault. The most cited example is the small ***Mount Pilchuck Stock***, intruded along the Darrington-Devils Mountain fault in the Granite Falls area east of Everett. Other limited examples can be found in the modern South Cascades region of Washington. In large part however, Challis magmatism is restricted to the region east of the Fraser Fault.

Figure 4 -16 *(Above) "Flatirons" along the Okanogan River, north of Riverside. These strain-hardened surfaces mark the dip of the Okanogan Fault, which floors the valley here.*

Metamorphic Core Complexes

The Dilemma of Detachment Faults

One of the more curious regional events of the Challis Episode was the development of the "***metamorphic core complexes***" in the Intermontane Belt, and on the old continental margin to the east. These features are often cited as the northern end of a belt of over 25 such "complexes" which extend from southern Canada to northern Mexico. Their origins in the Pacific Northwest are a subject open to considerable debate, and involve issues of tectonics, magmatism, and the structural integrity of the accreted margin.

In the Northwest, these include the ***Valhalla, Pinnacles, Thor-Odin and Shuswap Complexes*** in British Columbia. They extend south into Washington in the large ***Okanogan Dome***, the smaller ***Kettle Dome***, and the smaller ***Lincoln and Vulcan Mountain Domes***, all of which reside within the Intermontane Belt. To the east, the ***Priest River Complex*** extends from the Spokane Area north and east into Idaho, while the ***Bitterroot Dome*** lies on the eastern side of the Idaho Batholith. All of these features share the common characteristics of "core complexes": They are bordered by low-angle mylonitic (ductile) detachment zones along which upper-plate rocks have been displaced laterally over considerable distances. These zones (usually called detachment faults) consist of 0-4 km of mylonitic rocks in amphibolite to greenschist facies, capped by cataclastic (brittle shear) rocks in greenschist or lower facies.

The concept behind the prevailing interpretation on the "metamorphic core complexes" goes back to the days before modern theories of plate tectonics. In that day, features of this character were thought to be the infrastructural "core" zone of orogenic belts, just above where granitic rocks were being formed from the melting and/or recrystallization of continental material ("granitization"). In the later stages of orogeny, these were thought to have been deformed as they were rapidly uplifted, and then cooled at relatively shallow depths.

With the advent of modern plate-tectonic theories, these structures have been reinterpreted as extensional features. A leading interpretation is that they are Tertiary extensional features which developed in regions which underwent large-scale compression in the late Mesozoic. With the loss of the convergent margin setting here at about 60 Ma, it has been suggested that extension developed as the overthickened continent "relaxed" from its earlier compression. In this interpretation, these detachment zones are mid-crustal features which developed as the continental margin extended by as much as 200% to the west, exposing the deep-seated metamorphic "core" rocks as the continent was thinned in this process. .

In the end however, the case for large-scale extension here is less than compelling. While the associated detachment zones clearly record the displacement of upper plate rocks, there is little to suggest that the underlying continent was extended on a large scale. While such conditions appear to have developed in the (later, Miocene) "core complexes" of the American southwest, they are not in evidence here. As outlined in the last chapter, one would expect that the crustal thickening associated with the Coast Range Orogen had been resolved prior to this date. The wide swath of the Challis Arc and its shallow level of intrusion both argue against an overthickened continental crust at this time.

Instead, it appears more likely that the "core complexes" in this region are genetically related to the Challis plutons which accompany them. The Challis suite of plutons intruded to relatively shallow depths, often to within just a few kilometers of the surface. Locally, those surface rocks included elements of the ancestral continental margin, metamorphosed rocks of the Quesnel Terrane, orthogneisses of the Omenica Episode, and more recent intrusives of the Coat Range Episode.

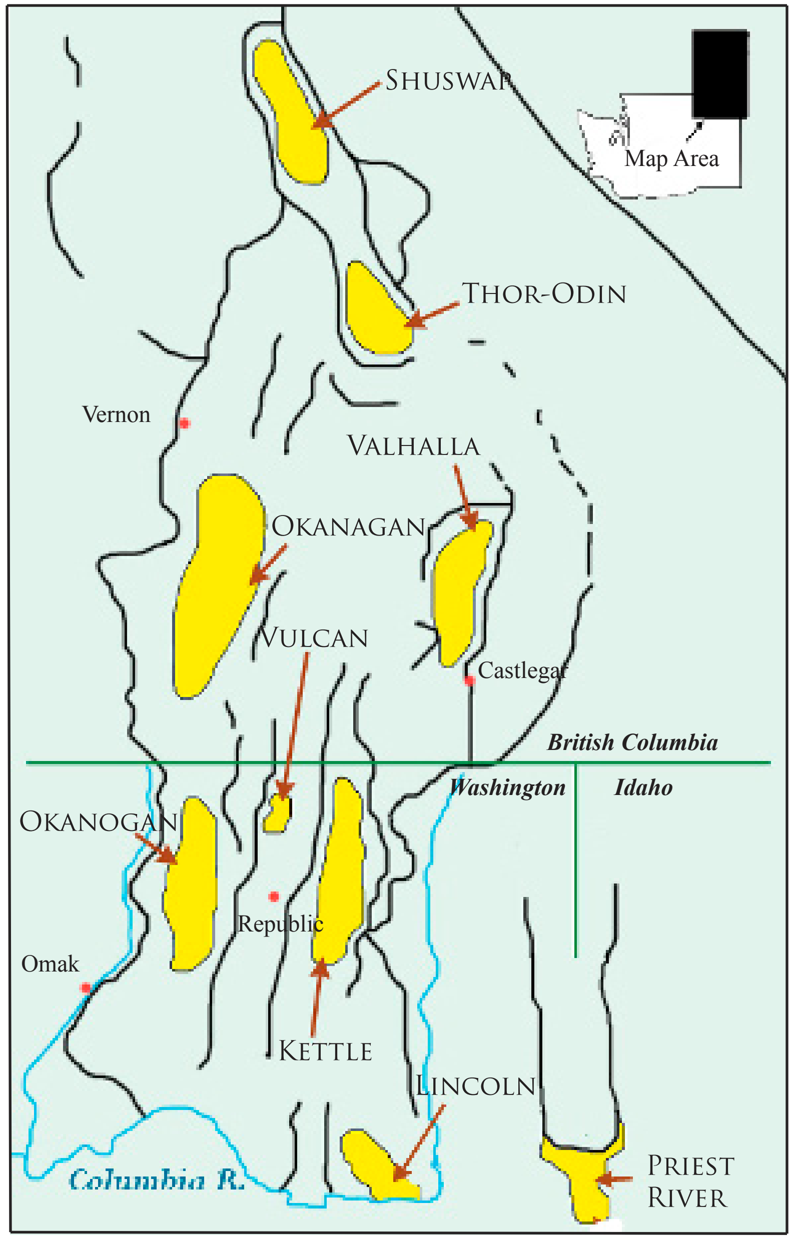


Figure 4 -17 (Above Right) Map showing the location of the major "core complexes" in the Pacific Northwest.

Figure 4 -18 (Right) Mylonitic Tonasket Gneiss in the lower plate of the Okanogan Detachment. Mineral lineations parallel the dip of the fault. On State Route 20, east of Tonasket.

Figure 4 -19 *(Above) Spectacular deformational features in the lower plate of the Kettle Detachment. Sense of motion is top to the right. East side of Deer Creek Pass, east of Curlew. Outcrop is about 40 feet (13 meters) tall.*

Figure 4 - 20 *(Right) Mylonitic amphibolite gneiss in the lower plate of the Kettle Detachment, west of Kettle Falls.*

Figure 4 -21 *(Below Right) Sheath folds in gneiss in the lower plate of the Kettle Detachment, west of Kettle Falls. Hammer provides scale.*

It would seem more likely that shallow intrusion of the Challis plutons uplifted these roof rocks as a structural domes, and then shed them by simple gravitational unloading. That unloading took place along ductile shear zones developed in and above the hot plutonic rocks, permitting movement even at relatively low angles.

The Okanogan Dome is a good example of such a feature. It is underlain by elements of the Challis Colville (composite) Batholith. It is bound on the west by the ***Okanogan Fault***, which is a low-angle detachment feature. Below this feature the mylonite zone is well preserved, consisting of highly-deformed gneisses in the upper part of the (syntectonic) Keller Butte Suite, and in the lower part of the overlying roof rocks. Along this feature, which makes up the Okanogan Valley,

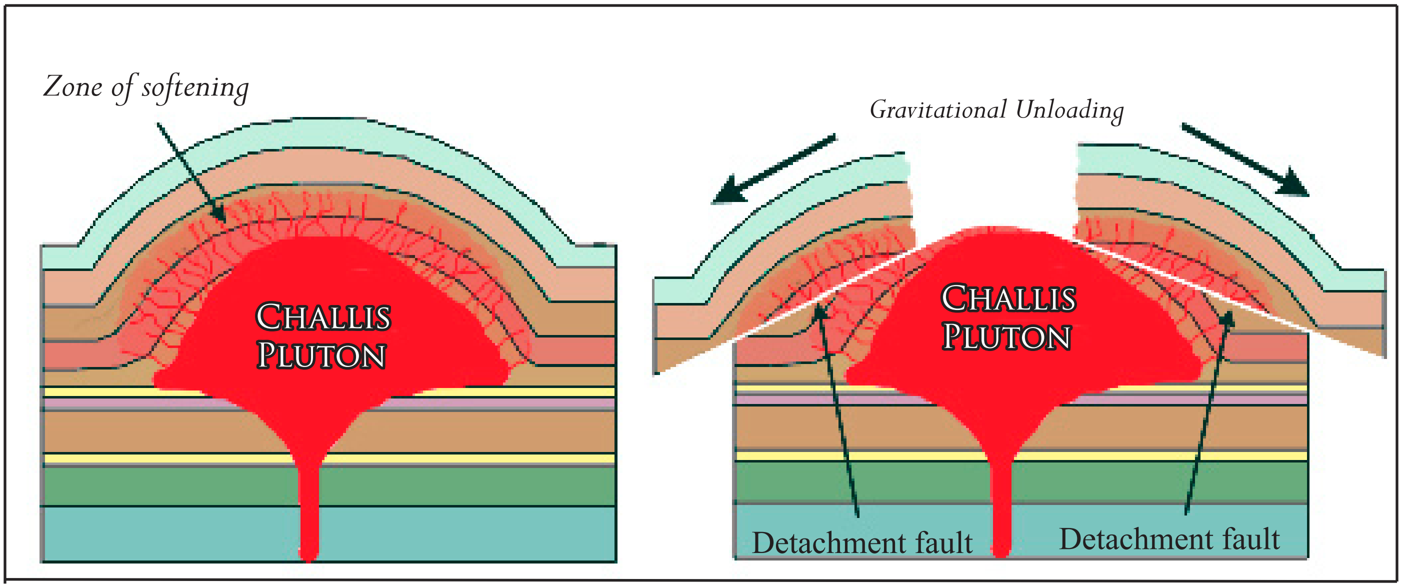


Figure 4 -22 *(Above)*
Diagram illustrating the formation of the "Core Complexes" in the Northwest, as interpreted here. This is in contrast to more popularly-held views.

Figure 4 - 23 *(Right)*
Upper part of the mylonite zone on the north end of the Vulcan Dome, at an outcrop along the Kettle River Road. Light-colored rocks are Challis intrusives, illustrating their role in the unloading of these features. Note the boudinage shape of the large body, a reflection of shear dynamics.

the large massif which now lies on the west side of the Okanogan River has been displaced from a location formerly atop the Okanogan Dome to the east.

Along the eastern side of the Kettle Dome, the mylonite zone beneath the displaced upper plate extends west from the ***Kettle River Fault*** for at least 10 kilometers (6 miles). The upper plate extends east from the Kettle River Fault to the ***Huckleberry Range*** and ***Columbia River Fault***. The Huckleberry Range – Columbia River Fault may be the eastern end of the low-angle ***Kettle River Detachment Fault***, along which the overlying plate was displaced to the east off of the rising Kettle Dome. In this interpretation, the original "suture" zone between the Intermontane Belt and the ancestral continent probably lies buried under this displaced section. Excellent similar examples of upper-plate displacement have been studied in the Shuswap and Valhalla Complexes to the North.

The hypothesis that these features reflect large-scale continental extension was first advanced by researchers who had studied the (Miocene) "core complexes" of the American Southwest, where such tectonics are clearly in evidence. Those complexes are now being reinterpreted as the product of deep-seated rift-tectonics, with a new emphasis on

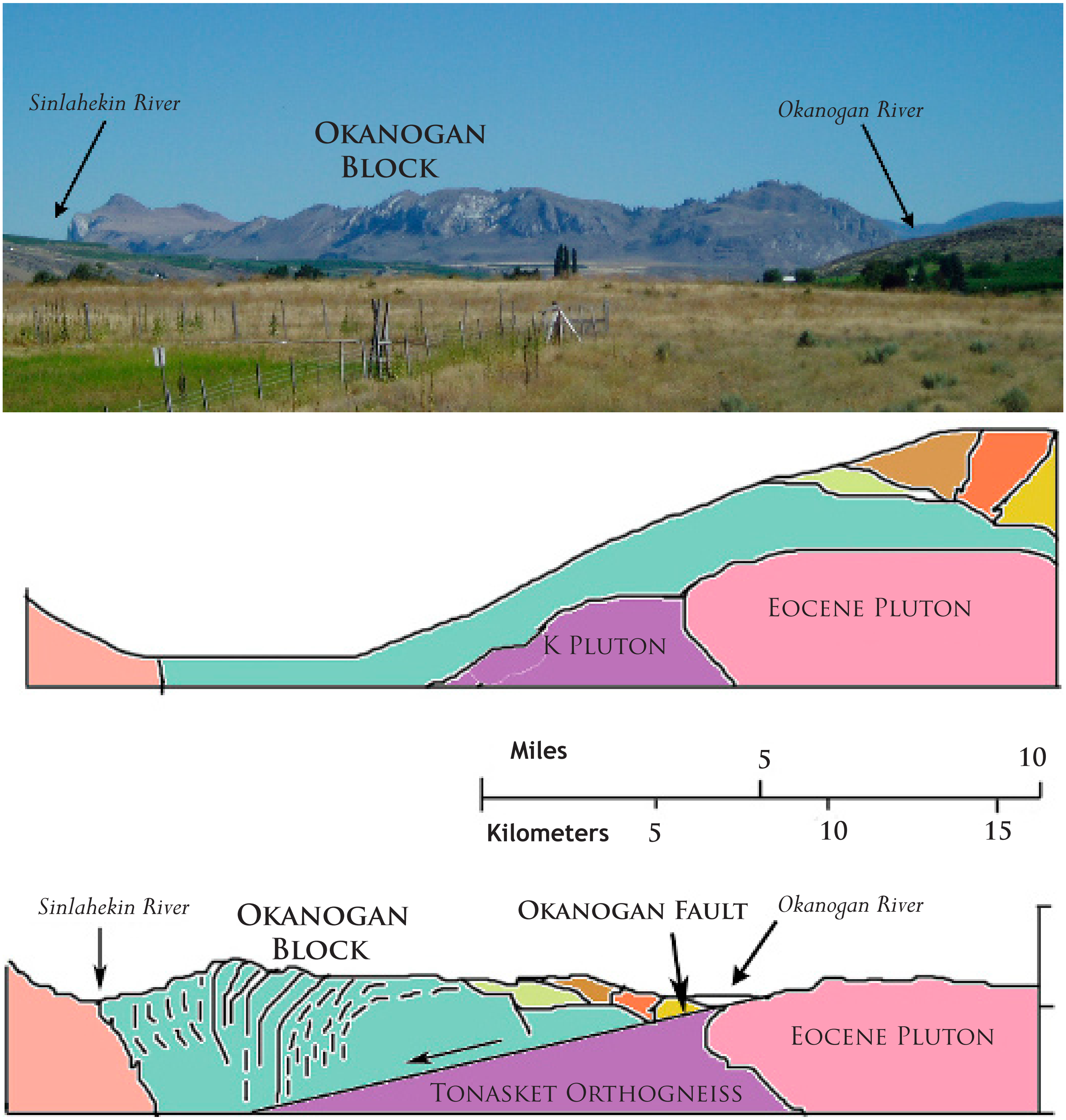


Figure 4 - 24 *(Above)*

(Top) The Okanogan Block, the upper plate of the Okanogan Detachment. Photograph above, along with the two diagrams, show a view to the north.

Diagrams illustrate how this upper plate was detached from the top of the Okanogan Dome, and was displaced to the west along the Okanogan Fault. This appears to have developed as the Okanogan Dome rose above intrustions of the Colville Batholith.

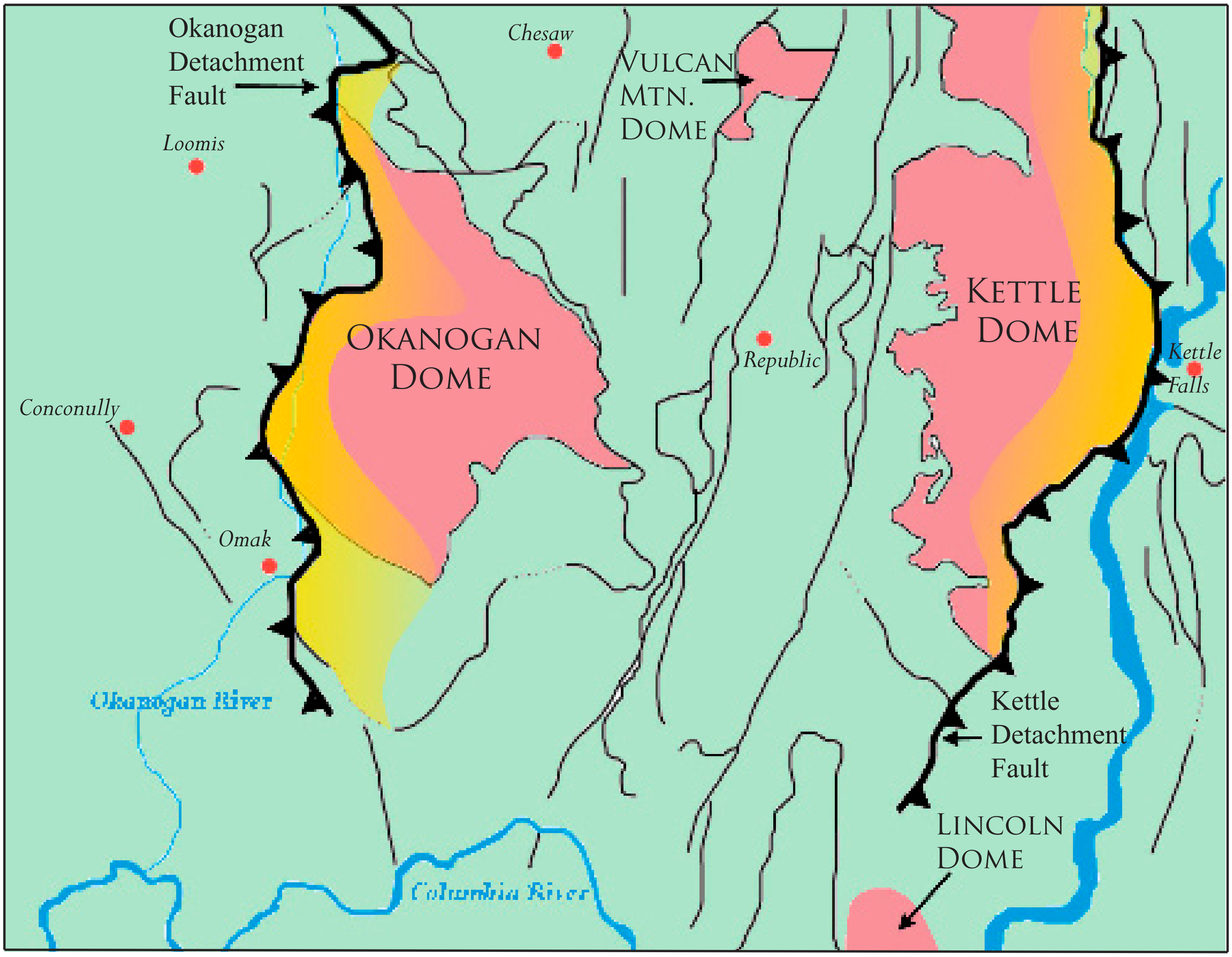


Figure 4 -25 *(Above) Map showing location of the Core Complexes in the Okanogan Region. Heavy black lines are detachment faults, with barbs on the overthrust plate. Areas shaded in yellow show ductile deformation.*

the role of accompanying magmatism. Here in the Pacific Northwest, it seems more likely that the "core complexes" are relatively shallow features recording gravitational unloading of roof rocks off of structural domes formed by rising Challis plutons. As we will examine shortly, the tectonics of large-scale east-west extension don't seem compatible with those characteristic of the Challis Episode.

While not a deep-seated phenomena, the displacement of roof rocks off of the rising Challis Plutons was a geologically dramatic affair. Between the Okanogan and Kettle Domes much of the region is veritably seamed with dikes of volcanic rock (the Sanpoil Volcanics), apparently formed as confining pressures were reduced. Violent magmatic eruptions are recorded in extensive ash layers dating from this episode, and form an important local marker bed. In the region between the rising Okanogan and Kettle Domes, upper-plate rocks were deformed and faulted as they slid into a common basin. Diamictite sections (unstratified and unsorted deposits) in local sedimentary beds of this age may record large-scale rock avalanches or other events associated with the unloading of the gneiss domes. We will examine these events again in a later section.

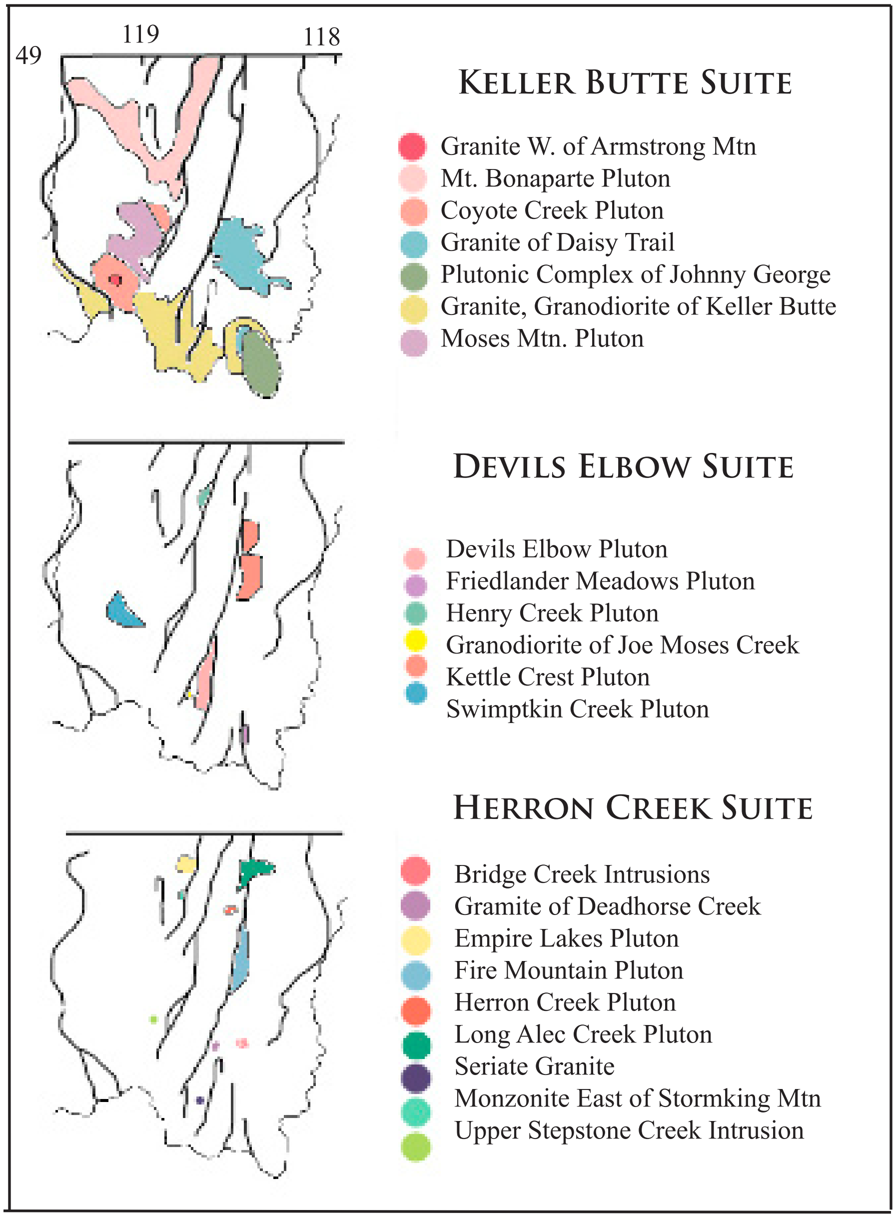
The different "core complexes" appear to have matured at different rates, with the effect that they did not all unload at the same time. In general, it appears that most of these features developed between 58 and 48 million years ago, with the older ages coming from the Shuswap Complex in British Columbia. In Washington State, the unloading of the Kettle and Okanogan Complexes probably dates from around 50 Ma.

Figure 4 - 26 *(Right)*
Maps showing the distribution of the three suites of intrusive rocks associated with the Challis Colville Batholith in the Okanogan region. The Keller Butte suite is the oldest, the Herron Creek Suite is the youngest. Adapted from Holder et al. 1989

Figure 4 - 27 *(Bottom left)*
Rock of the Devils Elbow Pluton, Devils Elbow Suite. From an outcrop along SR 21 north of Keller.

Figure 4 - 28 *(Bottom center)*
Rock of the Coyote Creek Pluton, part of the Keller Butte Suite. Note K-feldspar megacryst. Hammer provides scale. From an outcrop along SR 155 west of Nespelem

Figure 4 -29 *(Bottom Right)*
Rock of the Moses Mountain Pluton, part of the Keller Butte Suite. From an outcrop along the Lyman Lake - Moses Meadow Road, northeast of Disautel.



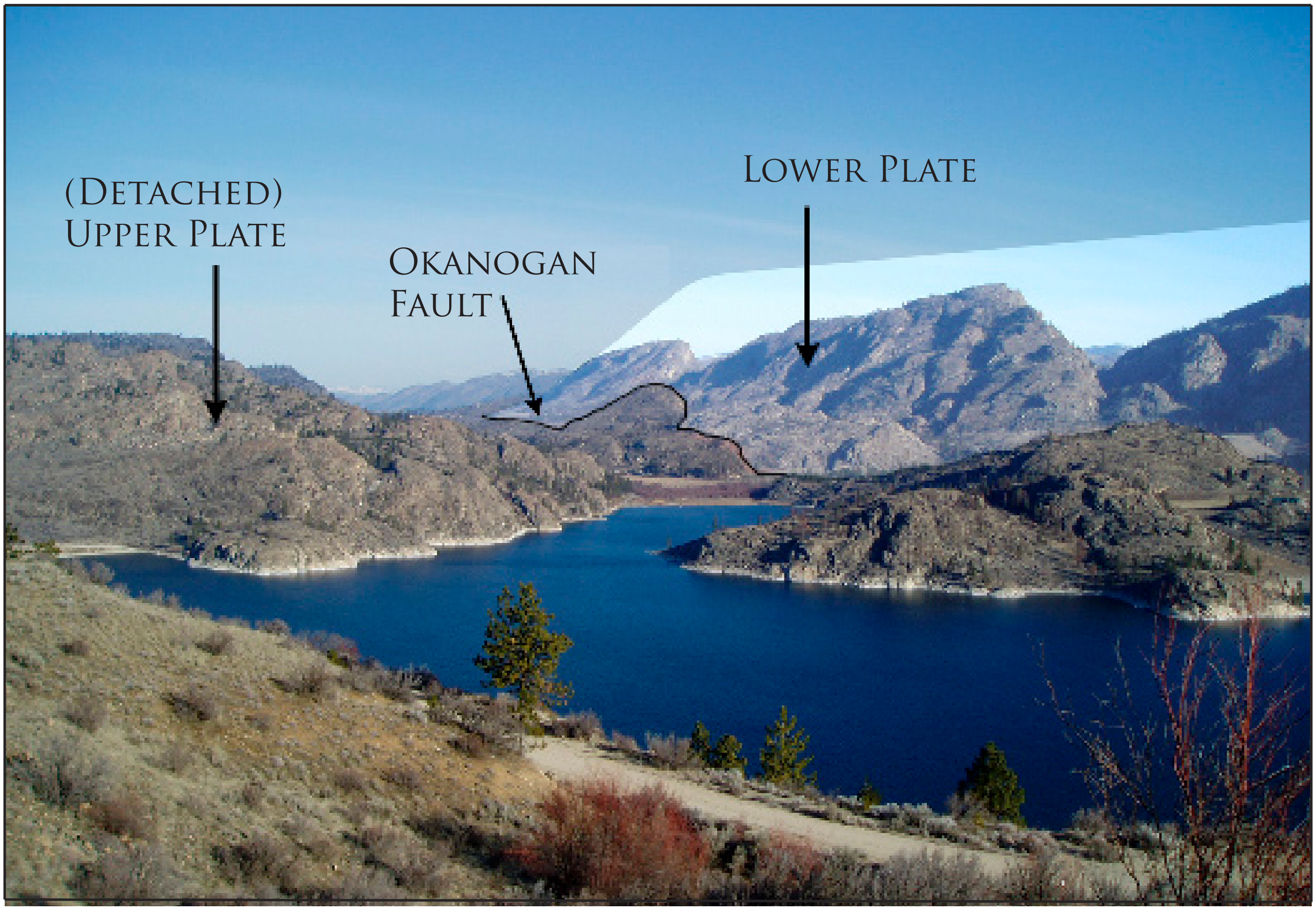


Figure 4 - 30 (Above)
The Okanogan Detachment Fault at Omak Lake. View is looking north. Detached upper plate has been transported to the left (west). Note also the classic trough shape of the valley, carved by numerous advances of the Okanogan Glacier over the Pleistocene.

Figure 4- 31 (Right)
Rocks of the Long Alec Creek Pluton, east of Curlew. This is part of the Herron Creek Suite. This outcrop illustrates the sequence of intrusion and unloading of the Kettle Complex. Coarse-grained rocks were intruded first, and crystallized slowly at depth. Decompression associated with the unloading of the Kettle Complex resulted in the brecciation of the older rocks and intrusion of the fine-grained rocks, which cooled quickly at relatively shallow depths. This is a common pattern seen in rocks of the Herron Creek Suite.

Ultramylonites

True World-Class examples from the Okanogan and Kettle Complexes

Mylonites are rocks which are structurally changed under conditions of ductile shear. Adjacent to the detachment faults of the Core Complexes, rocks have been sheared under conditions of high heat and pressure, producing some spectacular mylonites. These fabrics overprint a variety of orthogneiss and paragneiss rocks, resulting in a wide range of variations on this deformational style. Common features include rotated inclusions ranging from porphroblasts to meter-scale blocks. At the higher levels of deformation, felsic and mafic minerals become segregated into distinct bands, lending a distinctive "streaky" appearance to the rocks.

The most distinctive mylonites occur in orthogneiss, particularly in intermediate to felsic varieties. Here, mafic and felsic minerals segregate into distinctive bands, often on even a small scale. Very rarely, this process proceeds to the degree that mafic bands are reduced to laminae-scale features, and the felsic minerals form "cherty" bands within the rock. These rocks are called ***ultramylonites***, and we have some world-class examples in the "core complexes" of the Okanogan and Kettle Domes.

In the Orient Gneiss, along the base of the Kettle River Detachment near the town of Orient, the *Orient Ultramylonite* is a beautiful example of this exotic breed (below, left). Here, the mafic minerals appear in distinct bands with a decidedly wavy appearance to them. Even more spectacular is the *Tonasket Ultramylonite*, which appears in the Tonasket Gneiss at the base of the Okanogan Fault (above, and below right). Here the felsic minerals have segregated out into distinct "cherty" bands, and mafic bands are reduced to nearly a microscopic scale. These are truly world-class examples of these very exotic rocks.

The Crescent Basalts

The Western Regime

Over the course of the Challis Episode, a very large, thick pile of ocean-floor basalts were erupted onto the western half of the Kula Plate here. That assemblage was eventually thrust underneath the edge of the continent and was accreted as the Olympic Coast Belt. These volcanic rocks are known as the ***Crescent Basalts***, and they make up much of the Olympic Peninsula and southeast Washington State. The Crescent Basalts are an anomalously thick pile of basalt, several times thicker than one expects to see in a normal oceanic crust. Normal processes of divergent plate tectonics, as best as we call tell, do not produce such thick sequences of basalt. We can assume that the Farallon-Kula Ridge to the south is the source for this extensive mafic extrusion. What is not clear is how it erupted so voluminously onto the surface.

Figure 4-32 *(Above) Pillow Basalts, on the Hurricane Ridge Road, Olympic Peninsula. These are the characteristic form of submarine eruptions.*

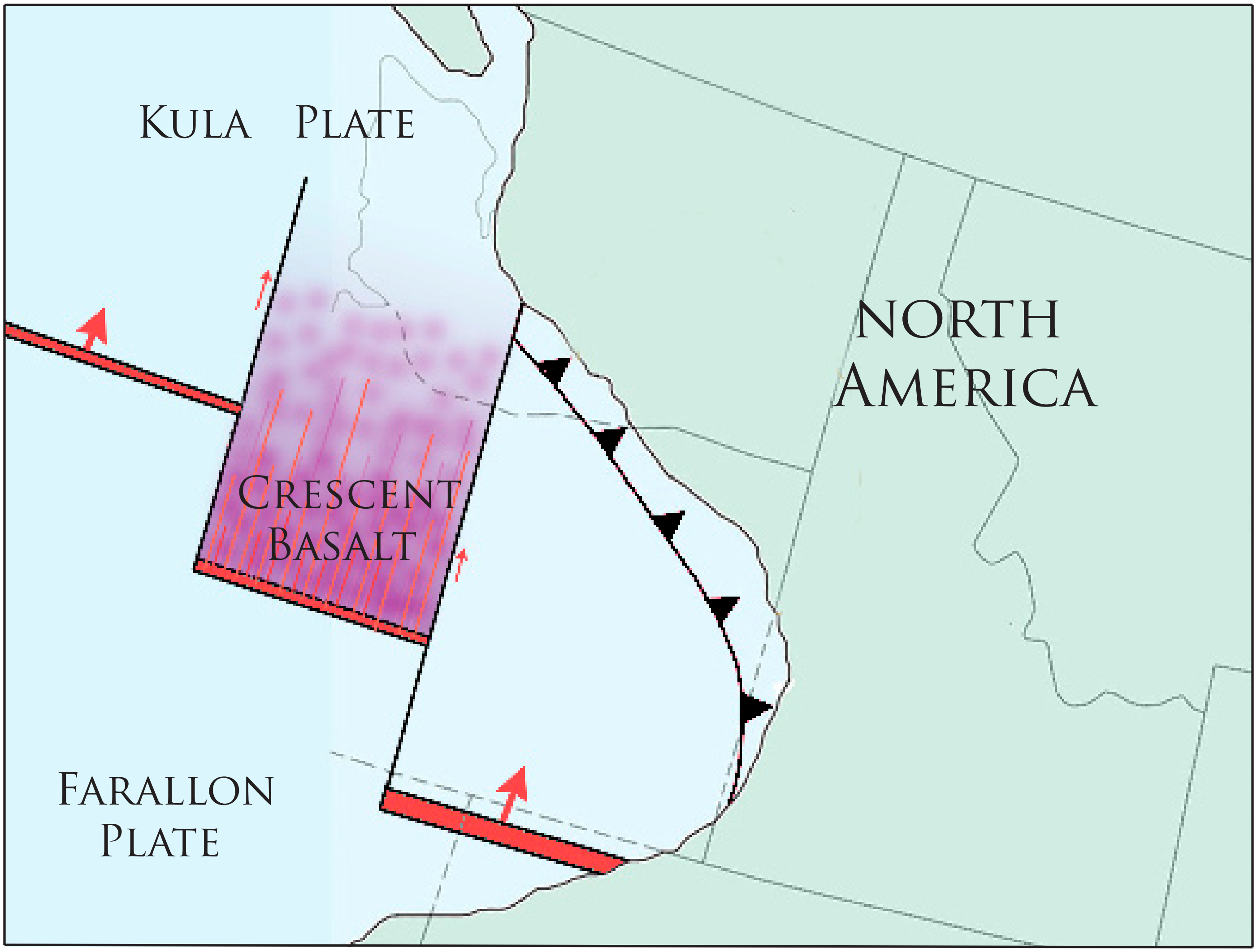


Figure 4 - 33 (Above) Map illustrating the inferred origins of the Crescent Basalt. These appear to have erupted on a central portion of the Kula Plate, a transiently immobile section where ocean-ridge basalt was erupted along shear zones or transform faults. Until about 43 Ma, it maintained a passive margin with respect to the continent. At about that date, it was thrust northward beneath Vancouver Island. The transform fault between the eastern and central portions of the Kula Plate is the Fraser Transform.

Several important observations have a bearing on this matter. The first is the distribution of the Challis and Crescent magmas, which are almost exclusively limited to opposite sides of the Fraser Fault. Continental-arc magmatism, as an indicator of convergent margin tectonics, does not appear to have developed between the Fraser Fault and the west coast of Vancouver Island. This observation is verified in the sedimentary rocks of this age. The marine sedimentary facies observed here (particularly, the deltaic portions of the Cowlitz Formation) are not the kind which develop along active-margin settings. Instead, they are typical of relatively quiescent, passive margin environs. For whatever reason, it seems evident that the Kula Plate was not being subducted in this area over most of this period.

The Crescent Basalts were erupted on a deep-water section of turbidite and sandstone deposits which had accumulated on the Kula Plate, known as the ***Blue Mountain Unit***. The basalts appear to date from as early as 57 Ma, and extend to about 45 Ma. Cumulatively, they comprise an estimated 100,000 cubic kilometers of material. It has been estimated that they include 8.4 km of submarine flows (largely pillow basalts), topped by 7.8 km of subaerial volcanics. It is an extraordinary thickness of material. The varying radiometric ages obtained across the unit imply that the Crescent series was erupted from a variety of different centers at different times.

Figure 4 - 34 *(Above)*

Outcrops of the Crescent Basalt at Crescent Beach. They take their name from this type-section locale.

Figure 4 - 35 *(Right)*

The Northcraft Volcanics, part of the Crescent suite northeast of Centralia. On the Johnson Creek Road, southeast of Tenino. Four miles (7 km) west, Northcraft rocks are brecciated where they erupted into (presumably, marine) waters.

A variety of possible mechanisms have been advanced for the eruption of the Crescent Basalts, including the formation of island-seamounts along the Farallon-Kula Ridge, or the influence of local hot-spots. A scenario more concordant with what appear to be the prevailing regional tectonics is what has been called the "leaky transform" model. In this model, the section of Kula Plate between the Fraser Fault and the west coast of Vancouver Island was fragmented by a multitude of transform faults, faults which likely formed as a transform margin was achieved along the west coast. Because these faults served to break up the oceanic plate, magmas which would normally accumulate at the base of the mid-ocean ridge were free to "leak" to the surface along these fractures. By this process, vast quantities of magma could have been erupted onto the surface of the Kula Plate here.

Figure 4-36 (Above)
A dike of Teanaway Basalt cuts rocks of the Swauk Formation. On the old Blewett Pass Highway. Such dikes are common features in the Swauk.

Figure 4-37 (Right)
A dike of Teanaway Basalt cutting rocks of the Swauk Formation, on the Teanaway River.

The largest outcrop of the Crescent Basalts forms a broad horseshoe - shaped ring around the eastern flanks of the Olympic Mountains, a pattern which reflects later deformational events. The Crescent Suite includes a number of similar outcrops and formations, including the ***Black Hill***s area south of Olympia, the ***Northcraft Volcanics*** in the Tenino area, the ***Grays River Volcanics*** to the southwest and the rocks of the ***Willipa Hills*** to the south. To the north, the ***Metchosin Volcanics*** on the southern end of Vancouver Island are part of this suite, but they also include gabbroic rocks and sheeted dike complexes more typical of the underlying Kula Plate.

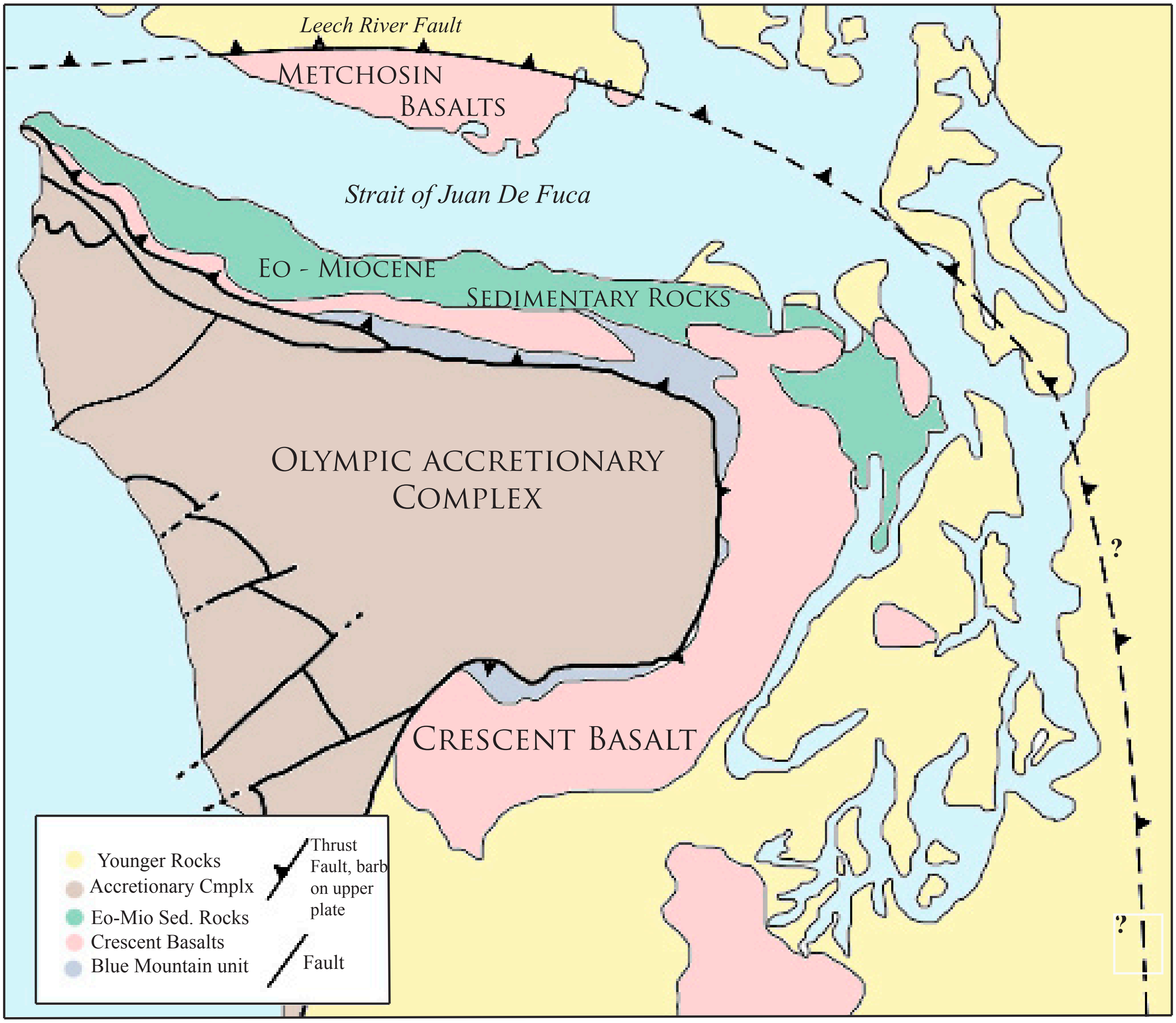


Figure 4- 38 *(Above) Rocks of the northern Olympic Coast Belt. The Crescent Basalts have been deformed into a horseshoe - shaped belt, around Miocene-to-recent rocks of the Olympic Accretionary Complex. Large outcrop at the south end of Puget Sound is the Black Hills area. The southern end of the bounding fault through the Puget Basin is conjectural. Adapted from Babcock et al. 1994.*

Local extrusions of basaltic rocks do occur east of the Fraser Fault. As with Challis Arc rocks which appear to the west, these appear to have migrated across the fault along tectonic zones. The most commonly-cited example is the ***Teanaway Basalts*** to the north of Cle Elum, erupted at about 47 Ma. These lie just east of the Fraser Fault. More distant is the ***Corbelay Dike Swarm***, to the northeast of Wenatchee. All of these rocks intruded along tectonic zones, and are fed by dike systems.

Eruption of the Crescent Basalts ended by about 45 Ma. It is probably not a coincidence that this appears to be coeval with the onset of the major movement period on the Fraser Fault to the east. By this date the accumulated basalt cover may have effectively "healed" the transform faults which earlier riddled the plate. With this accomplished, magmas could no longer "leak" off of the mid-ocean ridge, so the normal processes of ocean plate production would have resumed. This would have resulted in the expansion of the plate away from the ridge, and the resulting movement on the Fraser Fault. These aspects are considered in more detail below.

Figure 4-39 *(Above)*
The Corbelay Dike Swarm, east of Wenatchee. These mafic to felsic (bimodal) dikes may be part of the Crescent Suite, erupted along shear zones. If so, this is the most distal expression of Crescent magmatism. Alternately, they may be a Challis-Arc feature, but one with a unique mafic component. The dikes strike northwest - southeast.

Figure 4-40 *(Right)*
The Crescent Basalts. At an outcrop near Beaver Falls on the Burnt Mtn. Road (Highway 113) between Sappho and Clallam Bay. This is a classic exposure of the Crescent, covered in moss.

The Eocene Resources of Washington

The Denny-Renton Coal Mine, Circa 1914   Image courtesy of the Museum of History and Industry

While the mineral resources of Washington State cover the entire span of geologic history, no period has contributed more to this bounty than the Challis Episode. The rocks of the Challis Episode have provided building materials, energy, and even gold for the people who reside here. Without these resources, the development of this region would have certainly followed a different path.

Perhaps the most valuable of these, from a historical standpoint, has been coal. Coal beds in the various Eocene formations were critical resources in the early development of many of our towns and cities. Coal was a critical element for attracting the railroads, a service which was essential for communities which planned on growing. The town of Centralia was established to provide the railroads with access to the Skookumchuck Coal Fields, at a strategic location half-way between Seattle and Portland. The town of Roslyn was established to provide coal for locomotives heading west over the mountains or east to Spokane. Access to the Renton Coal Fields was what finally brought the rails to Seattle, while their extension up to Bellingham served to tap the deposits of the Chuckanut Formation. Without local coal, these services would have taken decades to arrive in this corner of the country. That coal was a primary source for household heating and industrial energy well into the 1930's, and is currently used for electrical generation at a large plant in Centralia. Unfortunately, most local deposits are relatively low-grade, and are high in sulfur. In of themselves, they are not particularly clean-burning fuels.

The Challis sandstones have historically been important resources for building materials. Transportation costs being a critical factor, Chuckanut sandstones were commonly used from Seattle north, while Macintosh and Carbonado sandstones were used to the south. The sandstone-block buildings of the Pioneer Square district in Seattle are built out of Chuckanut sandstone, while the Capitol buildings in Olympia were built out of Carbonado (Wilkinson) sandstone.

Finally, Challis rocks have played a major role in the mining history of this region. As Challis magmas rose to relatively shallow depths (compared to earlier episodes), they encountered water. That water became superheated, under pressure, and migrated through the country rocks. As it did, gold in those rocks became dissolved in the water, and was concentrated where it cooled. This process served to concentrate gold in deposits across the region which hosted the Challis Arc. The gold fields of the Blewett, Conconully, Oroville and Republic districts largely reflect this process.

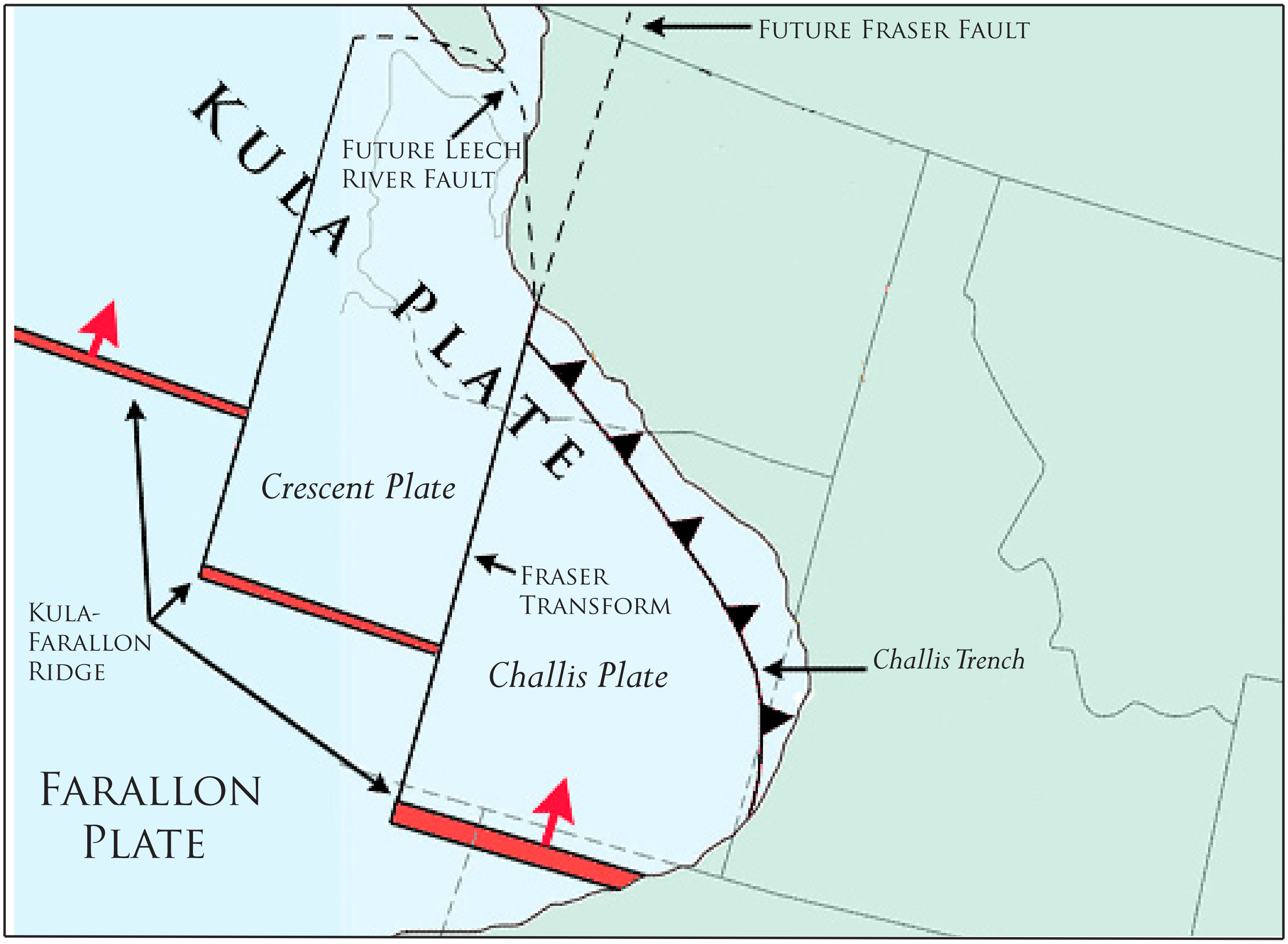


figure 4-41 *Map illustrating the inferred tectonic setting of the Challis Episode. Deformation and accretion in the Challis Episode largely centers on the periodic movement of the Crescent Plate. The initial movement of the Crescent Plate resulted in a transform setting, wherein the continental margin was split by the Fraser Fault. Later, the continent yielded along the Leech River Fault, and the Crescent Plate became accreted as it was thrust beneath Vancouver Island and the contiental margin.*

Deformation and Accretion in the Challis Episode

The Dynamics of a Changing Margin

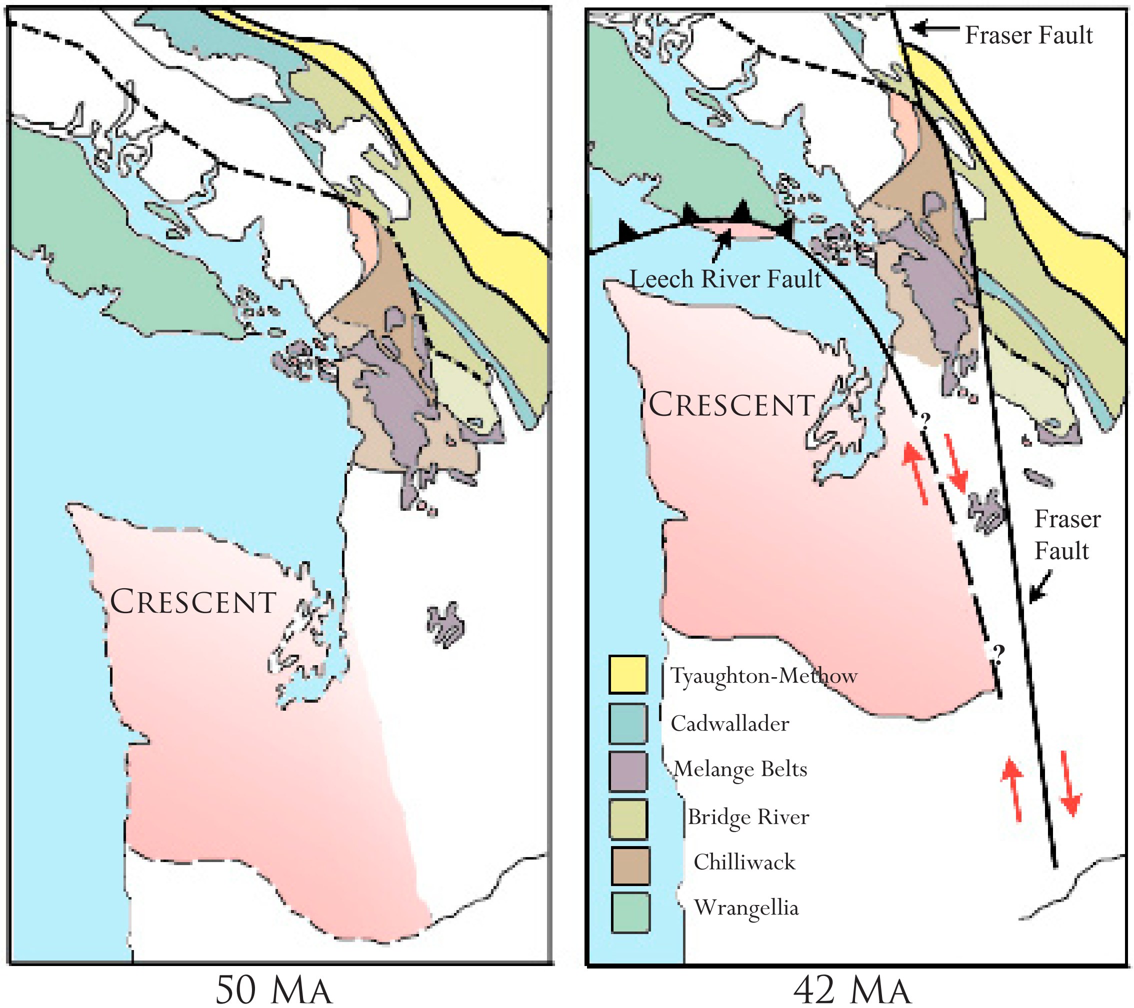
Regional deformation over the Challis Episode was the product of a complex set of plate relationships which developed along the southern end of the province. Those developments are largely centered on the evolution of the Fraser Fault (known locally in Washington State as the Straight Creek Fault). As described earlier, that feature originally appears to have developed as a transform fault in the Kula Plate, accommodating subduction to the east against a passive margin to the west. That fault would have extended from the Kula-Farallon Ridge north to the trench, where the eastern portion of the Kula Plate was being subducted. From there it would continue underneath the overriding continental plate, at increasing depth, at least to the trace of the Challis Arc.

Figure 4 - 42 *(Above)*
Angular unconformity in the Chuckanut Formation, illustrating the regional ~48 Ma folding event which affected the early Challis formations here. To the right is the >49 Ma Bellingham Bay Member, to the left and above is the <47 Ma Padden Member. Arrow and line marks contact. This folded landscape was eroded back down to a planar surface before deposition of the Padden member.

East of the transform, this would have been a workable albeit awkward arrangement. The descending oceanic plate was isolated along the thrust fault which marks the top of the subduction zone, and along the intersecting transform to the west. To the west however, it appears that the Kula and North American Plates were effectively locked together, in a passive-margin setting. As described above, this was likely supported by a "leaky transform" arrangement along the Kula-Farallon ridge, extending into the Kula Plate. This stable albeit awkward setting could persist as long as magmas could effectively "leak" out onto the surface.

This system existed from ~55 Ma, the earliest dates on Challis Arc magmatism, and likely dates from the inception of the Challis Episode. By about 50 Ma however, it would appear that plate motion west of the Fraser Transform started, at least for a short period. This may reflect the effects of thousands of meters of accumulated basalt flows, which may have effectively "healed" the previously-"leaking" transform faults. As plate production resumed on the Kula-Farallon ridge here, it drove the western half of the Kula Plate north. The initial effect of this motion was apparently the development of NW-SE trending folds across the region. This folding episode is well-evidenced in western and central Washington, and is dated between 49 and 47 Ma.

Figure 4 - 43 *(Right) Map diagrams illustrating the inferred tectonics of the Challis Episode. In an early stage, the entire western margin of the continent is displaced northward about 150 km on the Fraser Fault. In a later stage, the Crescent Plate is thrust northward beneath Vancouver Island and the contienntal margin, effectively accreting it to the continent.*



The expected outcome of this development would be the re-establishment of the subduction zone along this portion of the continental margin, a setting that was inherited from the Coast Range Episode. This would result in an expansion of the Challis Arc to the west and the (functional) elimination of the Fraser Transform. For whatever reason however, that zone refused to yield at this time.

Eventually, the forces of plate expansion won out over the structural integrity of the continental margin. The Fraser Fault, which eventually developed as a 500 km-long feature, ruptured the continent over the earlier trace of the Fraser Transform. It extended from the Columbia Embayment north to the Tintina-Northern Rocky Mountain Fault. As it did, the continent on the west side of the fault began to move north relative to the east side. Over a period of perhaps a few million years, it may have accumulated something like 50 km of displacement. At this point however, it appears that fault motion ceased for several million years.

The Crescent Basalts continued to erupt up until about 45 million years ago. At about that time, it appears that motion on the Fraser Fault resumed. Over the period of about 44 to perhaps 40 million years ago, continued right-lateral movement on the Fraser Fault added about 100 km of displacement across the southern end of the region. Along both sides of the fault, blocks appear to have been rotated clockwise in a shear response to fault motion. This means that many of the northwest-trending features dating from before this movement period were probably rotated from what was originally a more westerly orientation.

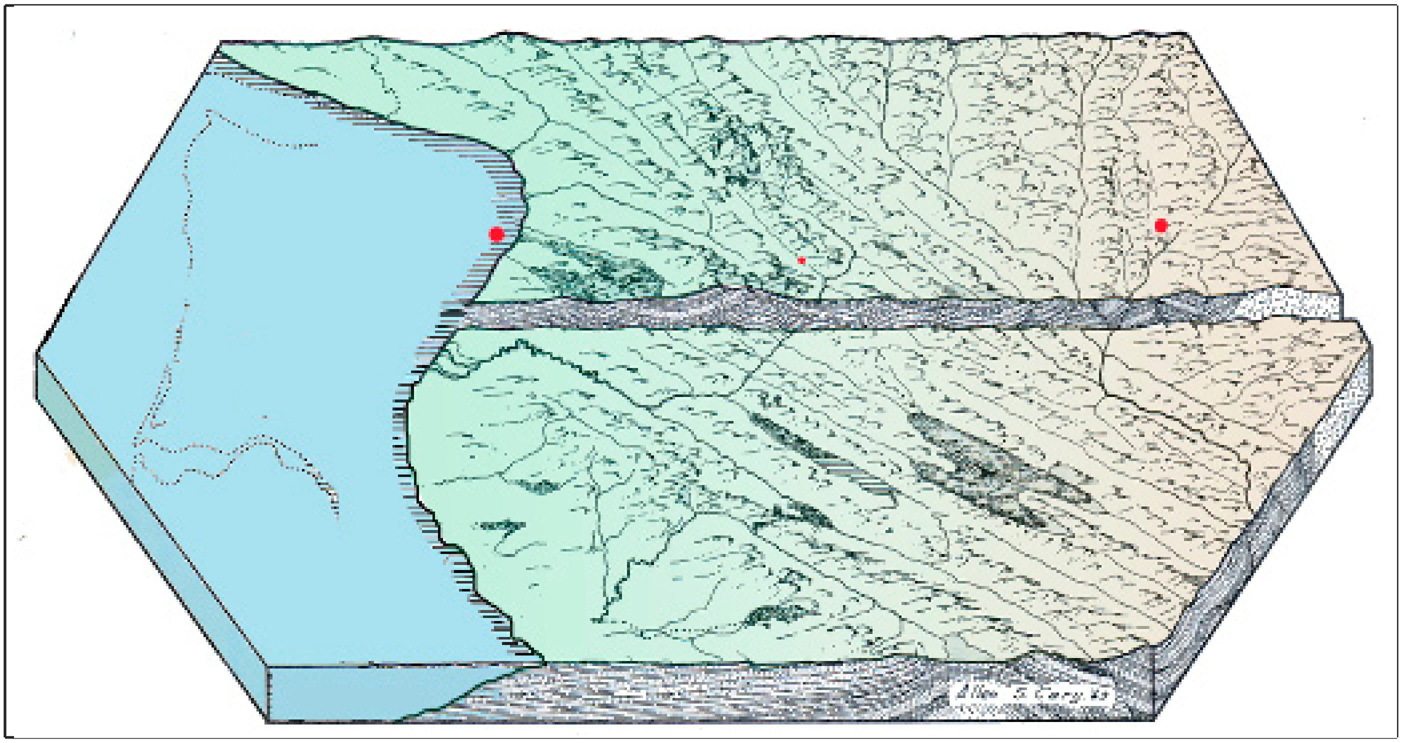


Figure 4 -44 *(Above)*
Paleogeographic reconstruction of this region about 48 Ma, after a major regional folding event associated wtih the inception of the Fraser Fault. Note the dominant NW-SE trend of the folds. This was a relatively short-lived setting, and was eroded back down to a coastal plain by ~47 Ma. Red dot shows the location of Seattle.

This reconstruction is slighly modified from the original by Allen Cary, first published back in 1965 (Mackin and Cary 1965). The authors named the mountain ranges raised in this event the "Calkins Range," after Frank Calkins of the USGS. This was probably the earliest attempt at reconstructing the Early Tertiary paleogeography here.

Across the international border, total displacement on the Fraser Fault appears to be on the order of about 145 km. This reconstruction places the White River Shear Zone and the Ross Lake Fault Zone in Washington in alignment with the Coast Range Megalineament (Central Coast Belt Thrust Fault) and the Bralorne-Kwoik Fault in British Columbia. In addition to offsetting all of their bounding faults, this fault offsets elements of the Bridge River (-Napeequa) Terrane, the Cadwallader (-Cascade River) Terrane, the Methow-Tyaughton Group, the Coast Range Orogen, and various elements of the Northwest Cascades System terranes, as well as early sedimentary deposits of the Challis Episode. Recognition of this offset is critical in reconstructing the pre-Tertiary geology of this region.

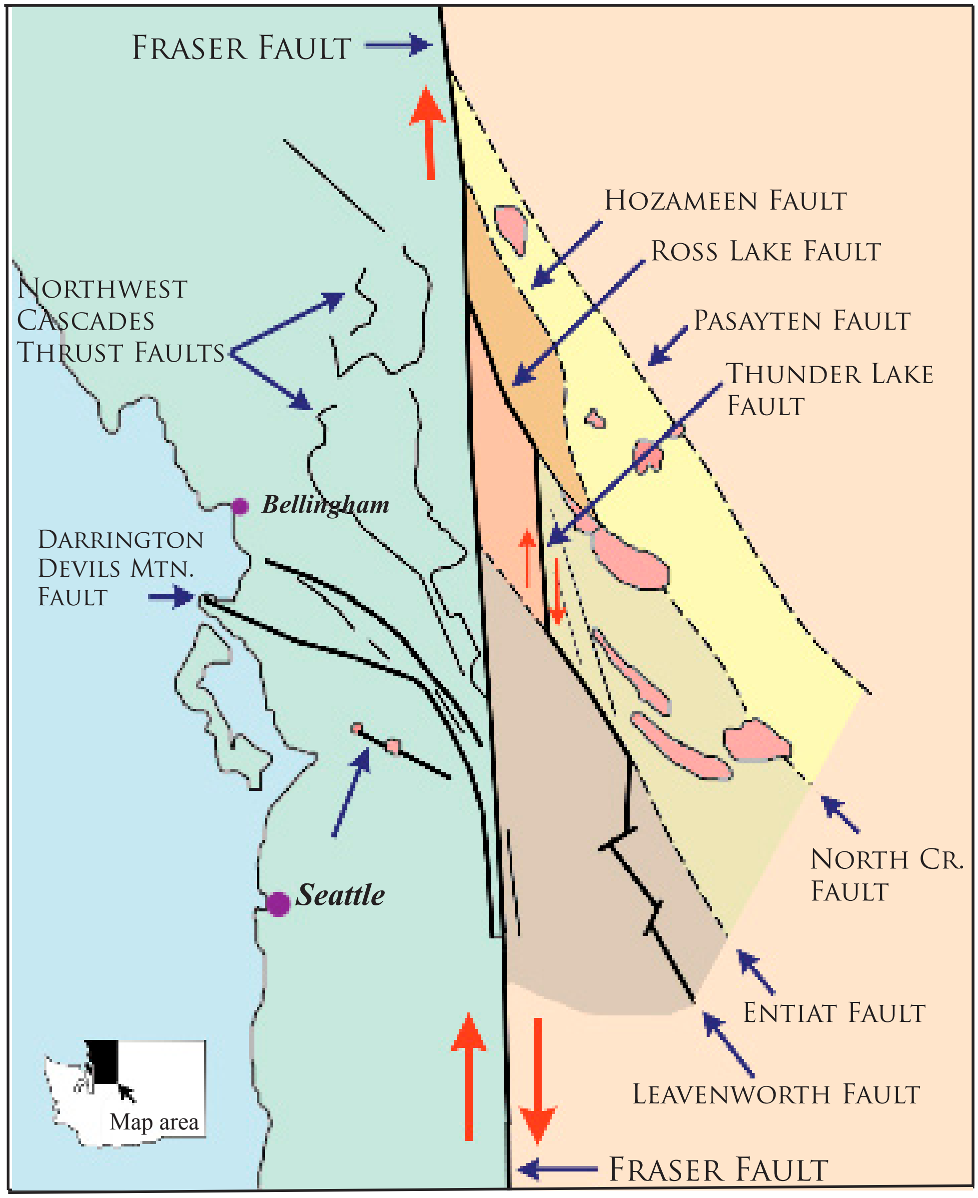
Late in this episode, it appears that the old subduction zone along the southern end of Vancouver Island finally yielded to northward plate motion. A transform fault developed west of the Fraser Fault, and the Kula Plate to the west (perhaps along with fragments of the continental margin) was forced northward underneath the southern edge of Vancouver Island along the Leech River Fault. This event has been dated at about 43 Ma. Exactly how much Kula Plate was subducted in this episode is uncertain, but it was probably not a great distance. It may have been only a few hundred kilometers or less, and ceased when the great thickness of the Crescent Basalts reached the trench. In doing so however, it accreted that portion of the Kula Plate to the continent as the Olympic Coast Belt. This was the last major accretionary event in the evolution of the Pacific Northwest.

Movement on the Fraser Fault system probably continued until something like ~40 Ma. The tectonic setting which supported it appears to have become inactive by 38 Ma. With no datable rocks to constrain the event, we know only that motion had ceased by 36 Ma. With the demise of Challis magmatism at ~40 Ma, it appears that the Kula-Farallon Ridge was falling into disarray, and that northward movement had ceased to be a dominant force.

Figure 4-45 *(Right)*
The Fraser Fault and adjoining tectonic features in the North Cascades region. On the east side, the Leavenworth and Thunder Lake Faults developed as blocks to the west were sheared northward adjacent to the Fraser Fault.

West of the fault, the Darrington-Devils Mountain Fault was active over this period, as were faults of the Northwest Cascades System. A subsidiary fault of the Darrington-Devils Mountain system hosted felsic (Challis Arc) magmatism in the Pilchuck and Bald Mountain stocks (blue arrow).

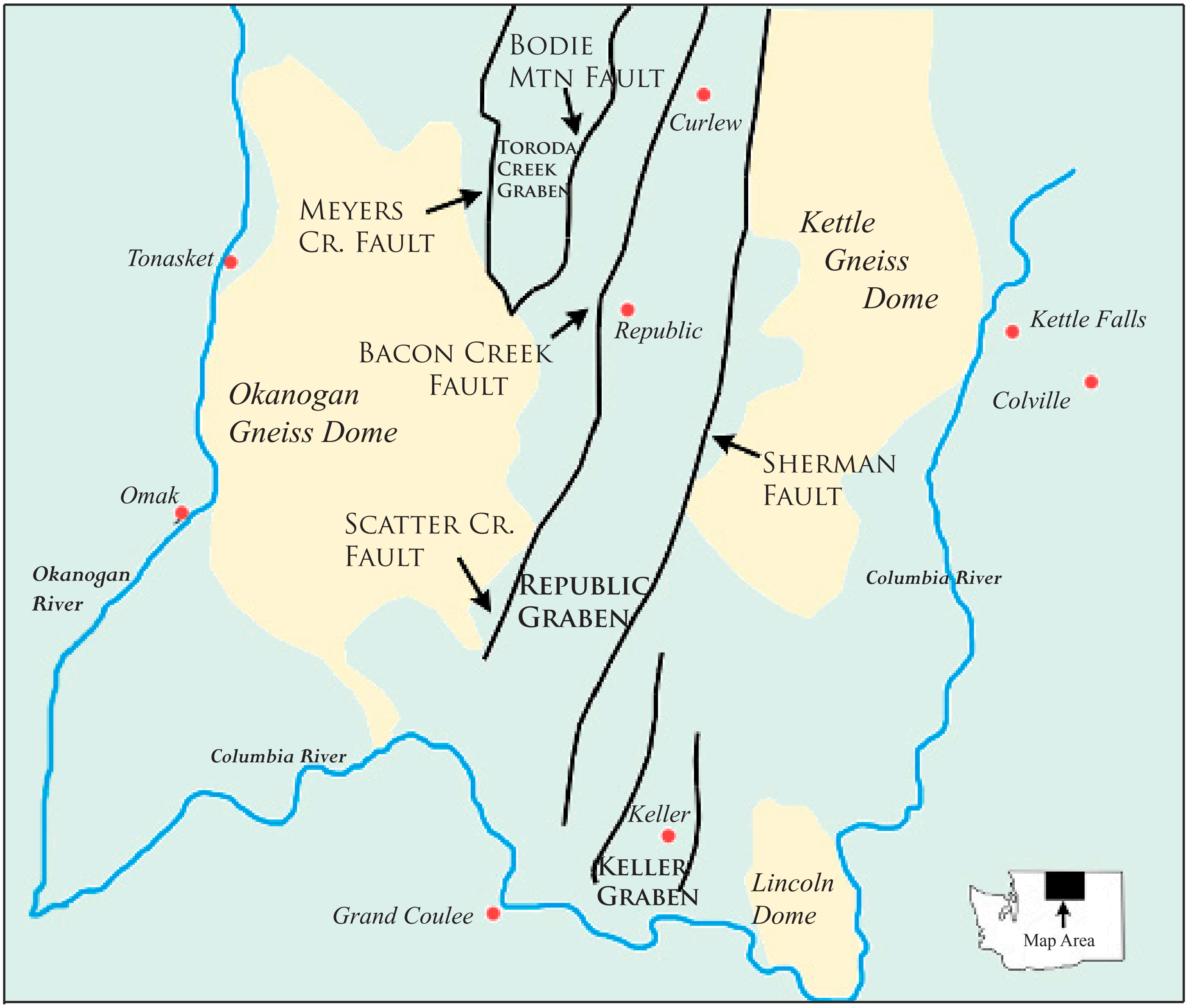
Figure 4-46 *(Far Right)*
Eocene faults of the Okanogan Highlands, excluding the detachment faults. The faults post-date the formation of the "core complexes" and most of the Eocene sedimentary record. The down-dropped "grabens" preserve that record.



Other Faults and Features

Beyond the shallow extensional faults of the metamorphic "core complexes," as discussed earlier, a large number of other faults and tectonic features characterized the Challis landscape. In most cases, these can be seen as reflections of the same tectonic regime which accompanied the development of the Fraser Fault System. This is a view somewhat contrary to the more popular interpretation, where these faults are seen as developing within an extensional regime. Instead, much of what has been interpreted as east-west extension more properly appears to have been a shear response to movement on the Fraser Fault, with a clockwise sense of rotation in adjoining blocks.

This clockwise rotation appears to have been responsible for the development of the various "graben" basins along the east side of the Fraser Fault. In the "core complexes" of the Okanogan highlands, the ***Keller, Republic*** and ***Toroda Creek "grabens***" all generally widen to the south, consistent with this sense of rotational displacement. The bounding faults on these features (e.g. the *Sherman, Bacon Creek, and Bodie Mountain faults*) cut the older detachment faults and post-date the local Challis depositional sequence. It is important to note that these are preservational, not depositional features.



On the east side of the Fraser Fault in the Nason Terrane, a limited amount of strike-slip displacement is indicated for the Entiat Fault over this period. The ***Entiat Fault*** probably dates from ~65 Ma or younger, and may have accommodated the late phases of uplift in the northeastern Coast Range Orogen. Its western counterpart in British Columbia is probably the ***Harrison Lake Fault,*** and this system may have seen limited strike-slip displacement prior to being truncated by the Fraser Fault. The ***Leavenworth Fault*** appears to have developed early in the movement history of the Fraser Fault. Its northern extension in the ***Thunder Lake Fault*** appears to have developed in the later stage of movement, transferring motion from the southern Entiat Fault to the northern end of the Ross Lake Fault. This movement appears to be a shear response to motion on the Fraser Fault to the west, and was accompanied by a clockwise rotation of fault-bound blocks.

On the west side of the Fraser Fault, a similar regime appears to have been in effect in the Bridge River area to the north. Here, motion on the ***Mission Ridge Fault*** appears to be a shear response along the Fraser Fault Zone. The ***Yalakom Fault***, the west-side equivalent of the *Pasayten Fault* in Washington, may have held a role in the early motion on the Fraser Fault. Several tens of kilometers of Early Eocene displacement have been proposed for this feature. To the south, some of the thrust faults involved in the accretion of the Northwest Cascades System contain slivers of Challis-age (Chuckanut) sedimentary rocks, indicating that they were re-activated in this episode.

The ***Darrington-Devils Mountain Fault*** (DDM) and its eastern extension in the Cle Elum area appear to have been important features in this episode. It has its apparent origins in the accretion of the Western and Eastern Melange Belts, serving as the "suture" zone with the Northwest Cascades System to the north. Like the Entiat Fault, it is a northwest-trending feature which was truncated by the Fraser Fault. The deep-seated character of this structure is evidenced by the fact that it hosts Challis (felsic) intrusions not commonly seen west of the Fraser Fault (the Mt. Pilchuck and Bald Mountain Plutons). At the same time it hosted mafic (Crescent) extrusives of the Barlow Pass Volcanics. The eastern extension of the DDM is uncertain. It may be an extension of the Taneum Lake Fault, or it may feed directly from the Olympia – Wallowa Lineament (OWL). The dike swarms which feed the Teanaway Basalts parallel this feature, attesting to its deep-seated character. Some of these faults will be discussed in greater detail in the next chapter.

Figure 4 - 46 *(Above) White sandstone of the Roslyn Formation, along the Teanaway River Road. The white color is an alteration product derived from feldspar. This is part of the extensive suite of Eocene sandstones which are preserved in western and west-central Washington.*

Figure 4-47 *(Opposite Page)*
Crossbedding in fine-grained sediments of the Wilkinson Sandstone, in the Carbonado Formation. Crossbeds are a paleocurrent indicator, here reflecting water flow from left to right. This sandstone is cut and polished as an ornamental rock. The state capitol buildings are made of this sandstone, from the Wilkinson Quarry.

Regional Deposition in the Challis Episode

The Great Eocene Blanket of Sand

For all of the very exciting and dramatic events of the Challis Episode, most of what we know has been drawn from the extensive sedimentary deposits which blanketed the southern end of the region over this period. In places, these deposits may have accumulated to nearly 5 km of strata, making them among the thickest non-marine sedimentary formations in North America. These rocks retain a detailed record of the regional tectonics, magmatism, and the general paleogeography of the Challis Episode.

The source of this immense volume of fill has been a subject of some debate. In considering this issue, it is important to recognize that existing exposures probably only represent a small fraction of the volume of material which was originally deposited over this episode. It is a volume which clearly renders local sources to be of secondary importance. It is in large part a quartzo-feldspathic (arkosic) sandstone and siltstone, most likely derived from a plutonic or metamorphic source terrain. To the degree that the Coast Range Belt had completed its uplift and erosion cycle prior to the onset of this episode, it is not a particularly good candidate as a source terrane for this material. Moreover, the sedimentary facies seen here are not consistent with a proximal setting to a mountainous area. More likely candidates exist in the rapidly-uplifting structures of the "metamorphic core complexes" along the southern end of the Intermontane Belt and the ancestral continental margin, and in the Rocky Mountains of Canada.

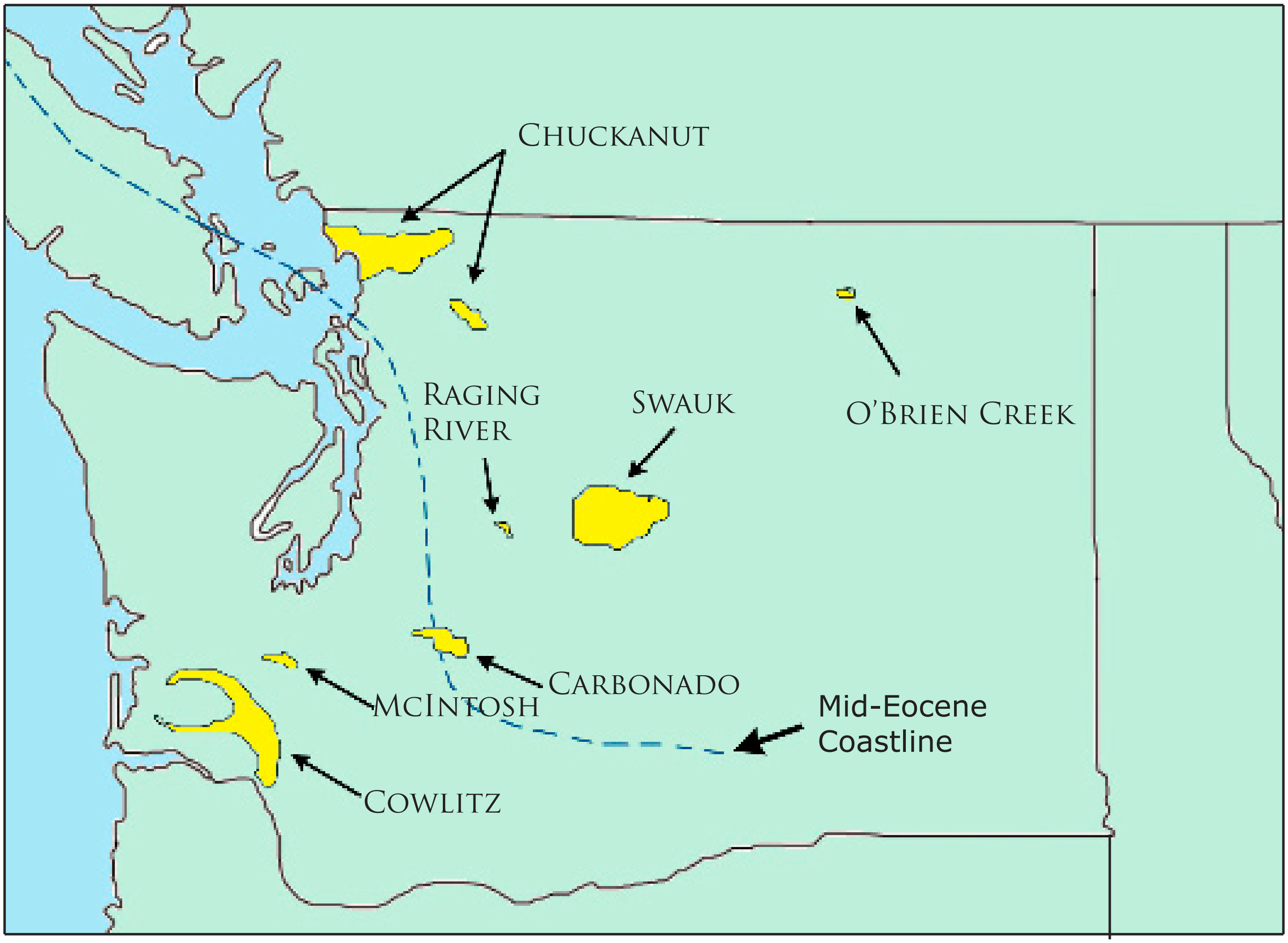
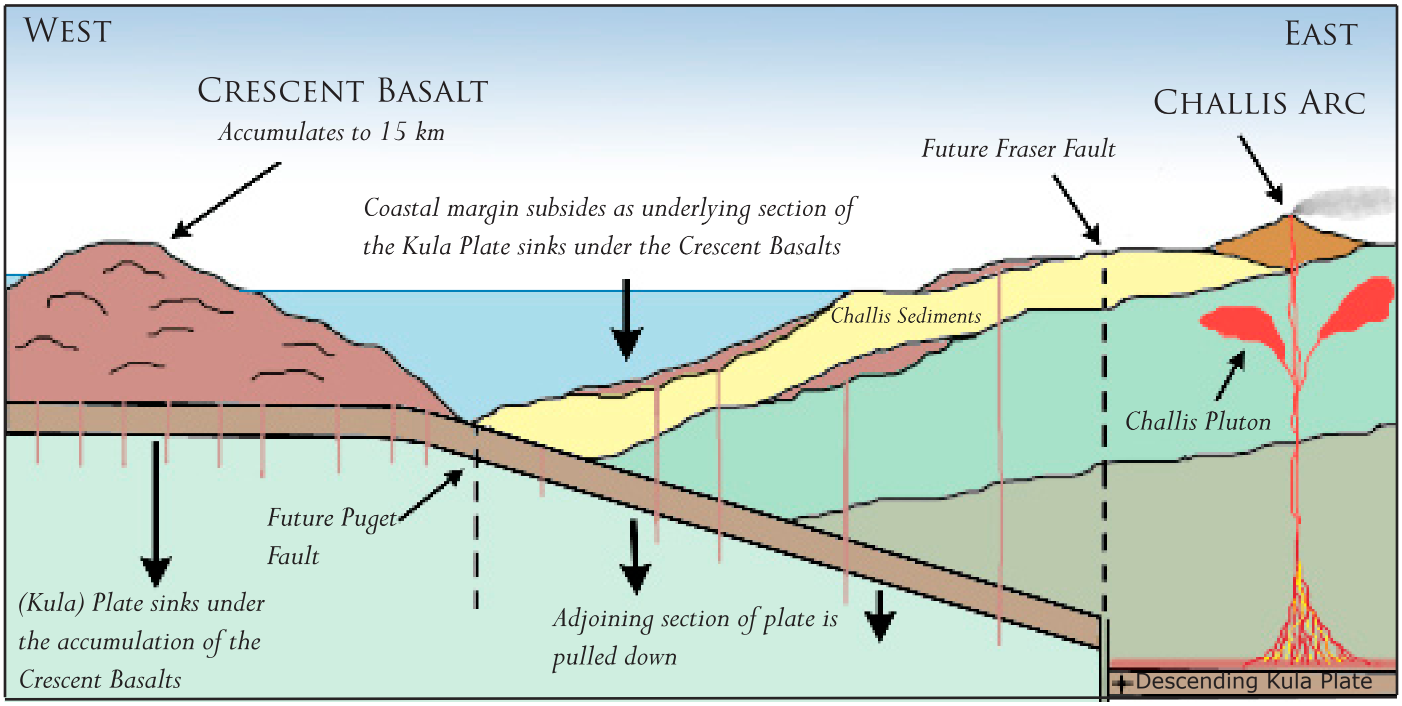


Figure 4 - 48 *(Above) Map showing the distribution of the early suite of Eocene sedimentary formations. Dashed blue line represents the coastline at that time. At the time of deposition, the western (Chuckanut, Raging River, Carbonado, etc) units were located some 145 km to the south. These were later displaced on the Fraser Fault.*

Figure 4 - 49 *(Above Right) Diagram illustrating the interpreted mechanism for coastal subsidence, allowing for the accumulation of great thicknesses of sediment over this period. The Kula Plate is passive to the west of the Fraser Fault. East of the Fault, the Kula Plate descends to the north. View is to the north.*

Perhaps the most contentious issues of all surround the circumstances by which these sediments were accumulated. The prevailing interpretation is that these formations accumulated in a number of relatively small basins which developed over this period. This view is reflected in the multitude of formation names which have been applied to these deposits. These basins are interpreted to have formed by wrench-faulting or graben development between local faults, as developed within the tectonic regime of the Fraser Fault. The development of such basins is common in strike-slip fault settings, so it seems a natural "fit" for this situation.

The problems with this interpretation, however are multifold. Most significantly, the faults which supposedly bound these subsiding basins have not been found. Of equal importance, it can be pointed out that a large proportion of these sediments were deposited prior to the early motion on the Fraser Fault, making that regime an unlikely component in accumulating those early deposits. Finally, it has been pointed out that the distribution of sedimentary rock types (facies) on a regional basis is inconsistent with deposition in a multitude of independent basins. Contrary to this popular model, the evidence more strongly supports an interpretation that these sediments were deposited in a large contiguous setting, perhaps even as the product of a single drainage system.



As will be detailed in this section, at least the earlier deposits of this episode appear to have been the products of a single continuous drainage system which flowed through this region over this period. Deposition along the continental margin here was accommodated by large-scale subsidence in what appears to have been a broad coastal floodplain setting. That subsidence does not appear to have been a product of fault-mediated tectonics. Instead, it likely reflects depression of the oceanic lithosphere remaining under the continental margin from the Coast Range Episode. That depression resulted from the accumulation of some 15 kilometers of Crescent Basalts on that same oceanic plate to the west. This is a viable mechanism for large-scale coastal subsidence over this period.

Judging by the thickness of the accumulated deposits, subsidence of this coastal floodplain may have started at something like 53-54 Ma, three to four million years into the accumulation of the Crescent Basalts. Large-scale subsidence around this date appears to have attracted the drainage of a large river system across this region, a system which may have previously drained along a more easterly course into the Columbia Embayment. With this development, a southwesterly drainage was established across this area, and sediments began to accumulate along the continental margin here. These were the "early" deposits of the Challis Episode, accumulated prior to the folding and faulting associated with the Fraser Fault.

In the (upstream) Okanogan region of Washington, the earliest deposits of this sequence are known as the ***O'Brien Creek Formation***, while to the southeast in the Cle Elum area they are known as the ***Swauk*** (also, *Manastash)* Formations. In the Bellingham area (at this time, located at the latitude of Seattle), rocks of this age are known as the ***Chuckanut Formation*** (*Bellingham Bay Member*), while in the area further south (east of Seattle) they are known as the ***Raging River Formation***. Still further south, rocks in this series are marine facies known as the ***Carbonado Formation*** to the east of Tacoma, as the ***McIntosh Formation*** around Tenino, and finally as the ***Cowlitz Formation*** to the south. Traditionally, these units have been interpreted as developing in relatively small isolated basins, which is why they all are considered individual formations.

Alternately, these rocks can be interpreted as representing different elements of a common drainage system. The O'Brien Creek rocks appear to have been deposited in an upland setting, an interpretation supported by the fossil record. They may represent part of a tributary basin to this larger system. Downstream, the Swauk Formation represents deposition on the coastal floodplain below. They are the deposits of meandering rivers and floodwater events. Prior to

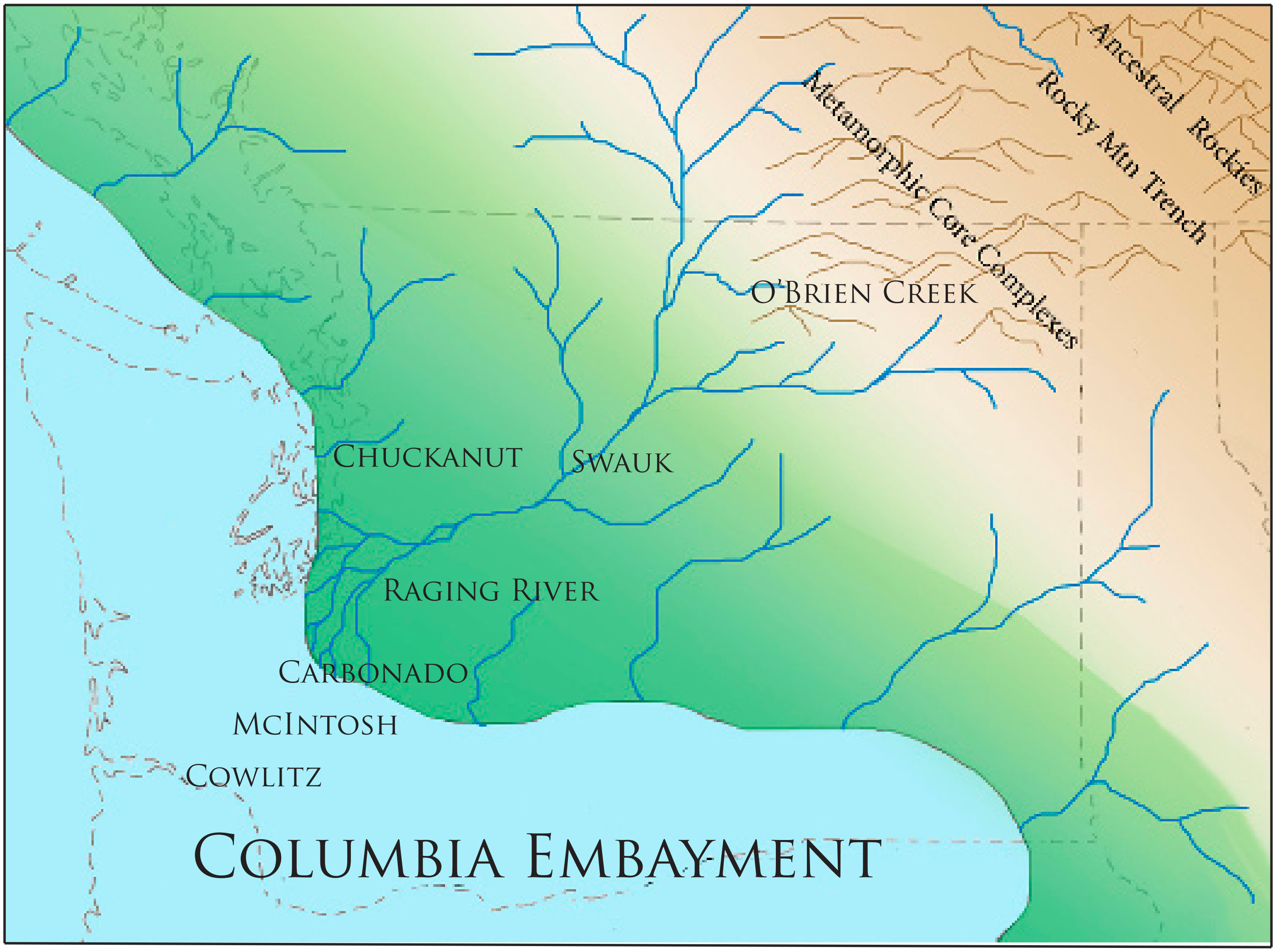


Figure 4 -50 *(Above)*
Illustration showing the Mid-Eocene Paleogeography of the region, with the various Early Challis sedimentary formations depicted as the products of a continuous drainage system.

displacement across the Fraser Fault, the Swauk and Chuckanut Formations were contiguous, and share an identical petrology. No marine facies have been found in the Chuckanut. These rocks may have been thrust underneath Vancouver Island, along with a northern portion of the Kula Plate.

Further south, rocks of the Raging River and Carbonado Formations are non-marine to marine transitional facies. The shoreline at this time is evident in the ripple marks preserved in the Carbonado Formation near Wilkerson. Now displaced some 145 km to the north, this was the former coastline on the Columbia Embayment. Further south, the rocks of the McIntosh Formation are shallow marine accumulations, while the Cowlitz Formation has the characteristics of a deltaic setting. Collectively, these rocks can be seen as representative of a single drainage system, from an upland source area to its terminus at a river delta. Across its flood plain, this river may have developed an extensive distributary system.

This system appears to have persisted from ~55 to 50 Ma, prior to the inception of the Fraser Fault. As the region was folded at the conclusion of this episode, that river system was diverted. In the Swauk region, this event is marked by a redirection of water flow to the southeast, along with the accumulation of local conglomerates. Lacustrine deposits of transient lakes are common in this section.

Figure 4 -51 *(Above) Rocks of the O'Brien Creek Formation, at a locale just north of Republic. These are planar - bedded arkose sandstones, with occasional cross-bedded sections. Paleocurrent directions are dominantly southwest.*

Figure 4 -52 *(Below) An outcrop of the Raging River Formation, along the I-90 on-ramp south of Preston. This outcrop is part of a marine pebble-conglomerate unit. The Raging River Formation includes both marine and non-marine facies.*

Rocks of the Swauk Formation

Figure 4 -53 *(Top) Planar-bedded sandstone, Swauk Formation. These are floodplain deposits. From an outcrop northeast of Liberty.*
Figure 4 - 54 *(Above left) Siltstone of the Swauk Formation. Much of the Swauk is more silt than sand. From an outcrop along the old Blewett Pass Highway.*
Figure 4 - 55 *(Above Center) Lacustrine deposits of the Swauk Formation, showing soft-sediment deformtion. From an outcrop northeast of Liberty.*
Figure 4 - 56 *(Above Right) Conglomeratic rocks of the Swauk Formation. These are a common occurrence in the Swauk. From an outcrop along Tronsen Ridge.*

Rocks of the Chuckanut Formation

Figure 4 - 57 *(Top) The Chuckanut Formation, along Bellingham Bay. The Chuckanut is nearly 15,000 feet (5 km) thick here.*
Figure 4 - 58 *(Above) Tilted Chuckanut strata, Mt. Higgins, northwest of Darrington.*
Figure 4 - 59 *(Right) Crossbedded Chuckanut sandstone, along Chuckanut Drive.*

Figure 4 - 60 *(Right) Quarried blocks of the McIntosh Formation. City Park, Tenino. The McIntosh is a shallow marine arkose, much of it well - bioturbated. Trace fossils can be seen in these rocks . This is a premium building stone.*

Figure 4 - 61 *(Below) Rocks of the Cowlitz Formation, near Vader. Major portions of the Cowlitz are distinctly deltaic in character. It is a richly fossiliferous formation.*

Figure 4 -62 *(Above)*
Ripple marks in the Carbonado Formation, near Wilkinson. These ripples are broadly symmetrical, suggesting a tidal setting. Other aspects of the Carbonado also reflect a transitional (marine to non-marine) setting. Hammer provides scale.

In the Okanogan region, this was the period in which the Challis plutons were intruded and the "core complexes" were being unloaded. Deposition associated with these events include the ***Sanpoil Volcanics*** and the ***Klondike Mountain Formations***. The Klondike Mountain unit contains diamictites which appear to represent landslide deposits, and lacustrine ash beds which preserve a detailed fossil record.

The early Challis sedimentary packages which were variably folded in the early movement history of the Fraser Fault had been eroded back down to a flat plain by 47 Ma. From what evidence we have, deposition between 47 and ~45 Ma appears to be limited to volcanic rocks. In their absence, this period represents an unconformity in the record. With few exceptions, volcanic rocks of this period continue to follow the Challis pattern of felsic rocks to the east, mafic rocks to the west of the Fraser Fault. The Teanaway Basalts in the Cle Elum area erupted at about 47 Ma, on an angular unconformity with those older rocks.

Sedimentary deposition appears to have resumed again at about ~45 Ma, about the time that the Fraser Fault appears to have entered its major movement period. In the Cle Elum area, this included the ***Roslyn Formation*** (also, known as the *Chumstick Formation*). On the west side of the Fraser Fault it included the ***Tiger Mountain Formation*** in the Issaquah area, the ***Skookumchuck*** and ***Spiketon Formations*** in the Centralia area, while deltaic deposition in the Cowlitz Formation resumed to the south. As a group, these rocks show a higher proportion of volcanic components

Figure 4 - 63 *(Above)*

The Klondike Mountain Formation. This is the Tom Thumb Member, the lacustrine volcanic-ash unit which preserves the Stonerose fossil assemblage.

This outcrop is at historic Eureka Gulch, just west of Republic. The Knob Hill Mine in Republic has been the most productive gold mine in Washington state, recovering over a million ounces of the precious metal from Challis-age hydrothermal deposits.

Figure 4 - 64 *(Right)*

The Klondike Mountain Formation in the Toroda Canyon, southeast of Chesaw. This section is a diamictite, a probable landslide deposit. These may well be the remains of massive landslides unleashed in the unloading of the Okanogan and Kettle "core complexes." Hammer provides scale.

Figure 4- 65 *(Above)*
The Roslyn Formation, at an outcrop southwest of Cashmere. The Roslyn is distinctly white, the result of an alteration product. Much of the Roslyn features meter-scale bedding. It has historically been an important coal-bearing unit.

Figure 4 - 66 *(Right)*
The Chumstick Formation, a lateral equivalent of the Roslyn Formation. This outcrop is southeast of Leavenworth. A portion of the Chumstick is lacustrine, the legacy of a lake in this area over part of that time.

than earlier deposits, a reflection of the maturing Challis Arc. The exception to this is in the rocks of the upper Chuckanut Formation, an area by this date disconnected from that system. Continued deposition in this formation involved re-working of older deposits, with supplemental contributions from the north in the upper sections.

These formations suggest that the resumption of deposition represents the restoration (at least in part) of the fluvial system which existed prior to ~50 Ma. The Roslyn and Tiger Mountain Formations appear to represent river and alluvial floodplain deposits of a meandering lowland river system. To the south, the Skookumchuck and Spiketon Formations are transitional from non-marine to marine, with the Skookum-

Figure 4-67 *(Right)*
A xenolith of the Swauk Formation (Swauk Pass Member) in the Teanaway Basalt. Location is along the east shore of Lake Cle Elum, north of Roslyn. Author provides scale.

Figure 4 - 68 *(Below)*
An outcrop of the Renton Formation, along Highway 18 south of Issaquah. Plant fossils can be found in this outcrop.

chuck containing abundant coal deposits. To the south, the Cowlitz continued to represent the deltaic end-facies of the system.

If that system was restored over this period, it was likely destroyed by a regional folding event that dates from about 43 Ma. Although not as strong as the folding which accompanied the inception of the Fraser Fault, it was certainly an event capable of rearranging drainage patterns. It probably in part reflects accretion of the Olympic Coast Belt to the west. The remainder of Challis-age deposition tends to be volcanic and volcaniclastic in character, and probably represents more localized accumulations. These include the ***Naches Formation*** in what is now the Snoqualmie Pass area,

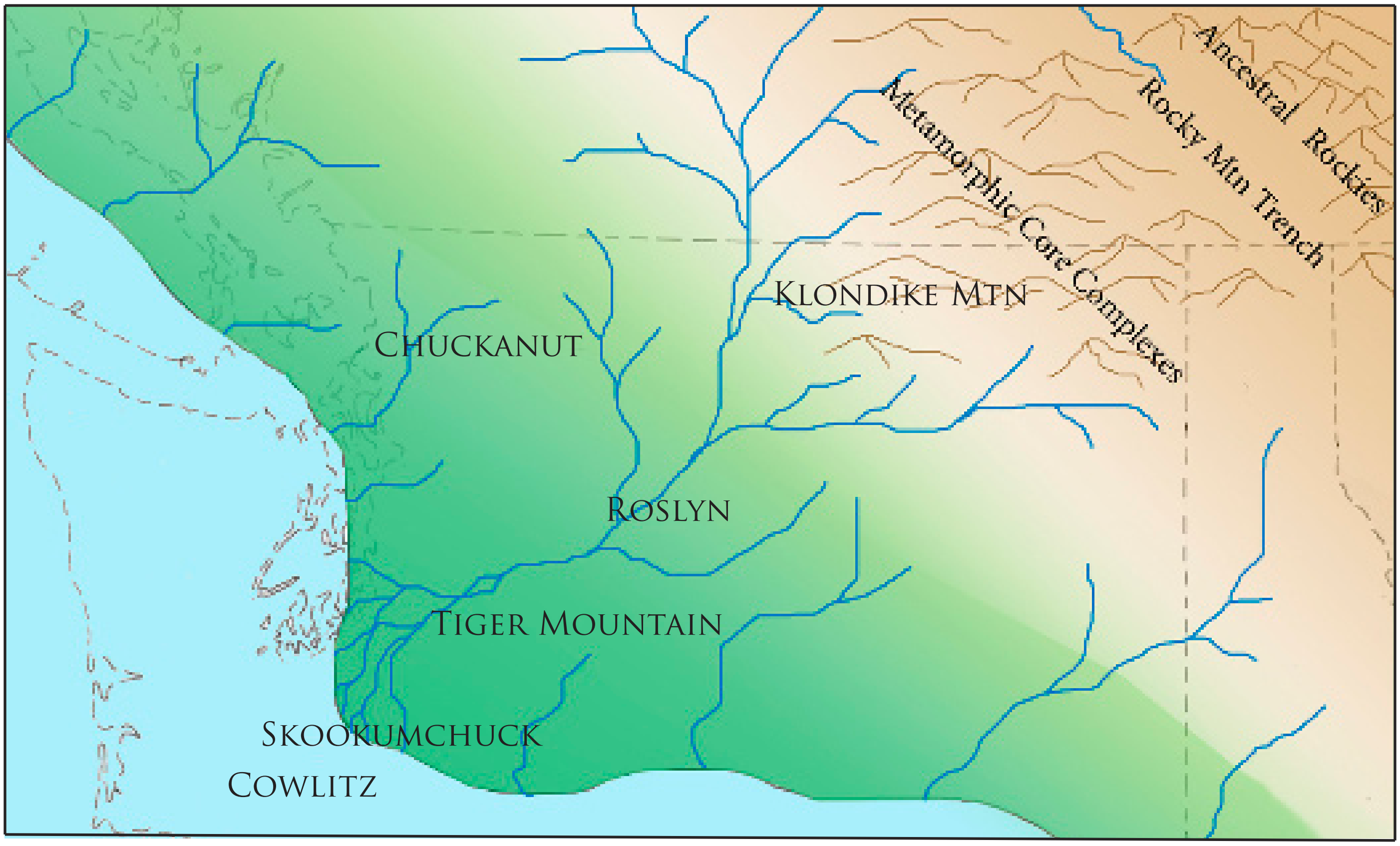


Figure 4 - 69 *(Above) Illustration showing the local paleogeographic setting in Mid-Eocene time. Most formations are here interpreted as deposits of a single drainage system. Upper members of the Chuckanut Formation are now displaced from that system.*

Figure 4 - 70 *(Below) Arkose sandstone of the Tiger Mountain Formation. On the Preston Road west of Preston. These are riverine deposits.*

and the ***Tukwila Formation*** which overlies the Tiger Mountain Formation in the Issaquah area. The Tukwila is overlain by the ***Renton Formation***, a historically-important coal-producing unit. To the south, the ***Hatchet Mountain Formation*** unconformably overlies the Skookumchuck Formation, while the ***Goble Volcanics*** unconformably overlie Cowlitz rocks.

To the west, in the Olympic Coast Belt, sedimentation followed eruption of the Crescent Basalts. Perhaps at about 46 Ma, deposition of the ***Aldwell Formation*** commenced, a largely siltstone and sandstone unit. Much of the formation is a deep-water sequence marked by turbidite (submarine landslide) flows. The western part consists of a chert-rich sandstone, interpreted as having been derived from rocks of

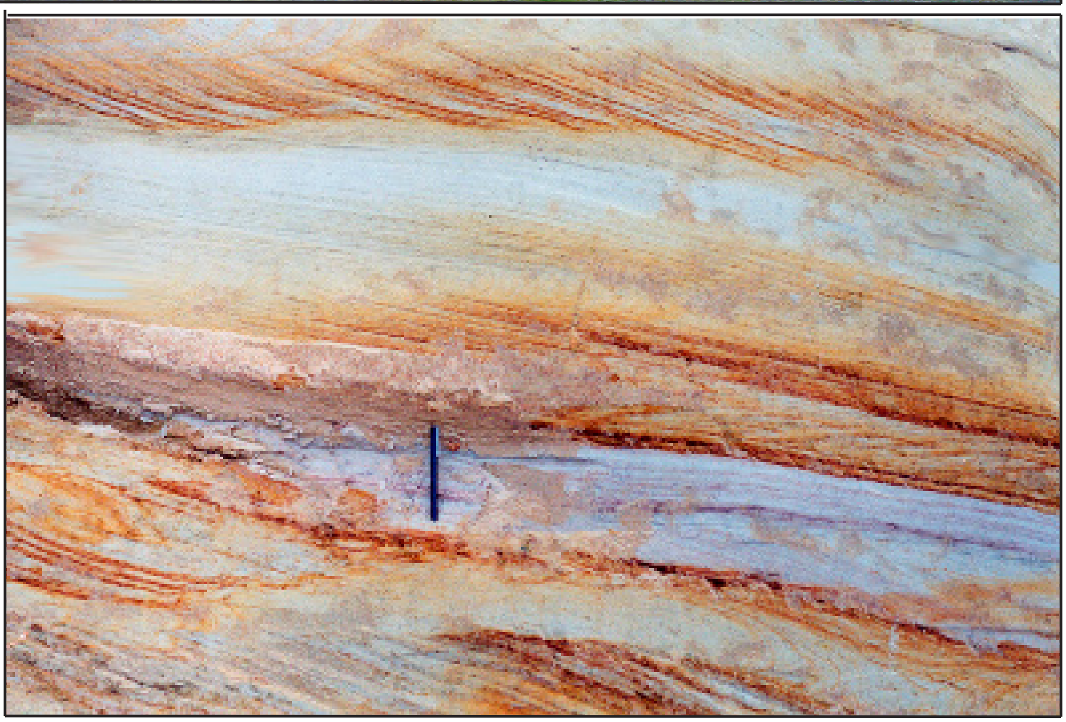


Figure 4-71 *(Above)*
An outcrop of the Skookumchuck Formation. Note coal beds to the right. The Skookumchuck is a transitional formation, which some have characterized as an estuarine or barrier-island complex. This outcrop in Chehalis no longer exists.

Figure 4-72 *(Right)*
Detail from the outcrop above, showing crossbed features. Note that some are reversed, suggesting a tidal setting. Pen provides scale.

southern Vancouver Island. If so, it may in part reflect the underthrusting of Vancouver Island by the Olympic Coast Belt along the Leech River Fault. Overlying the Aldwell in a gradational contact is the Lyre Formation, in large-part a quartz-bearing sandstone. These sediments appear to reflect a shallower depositional setting. Conformably overlying this is the ***Hoko River Formation***, part of what is called the *Twin Rivers Group.* This member includes massive to thin-bedded sandstone, with lesser amounts of conglomerate. Breccia conglomerates may reflect tectonism associated

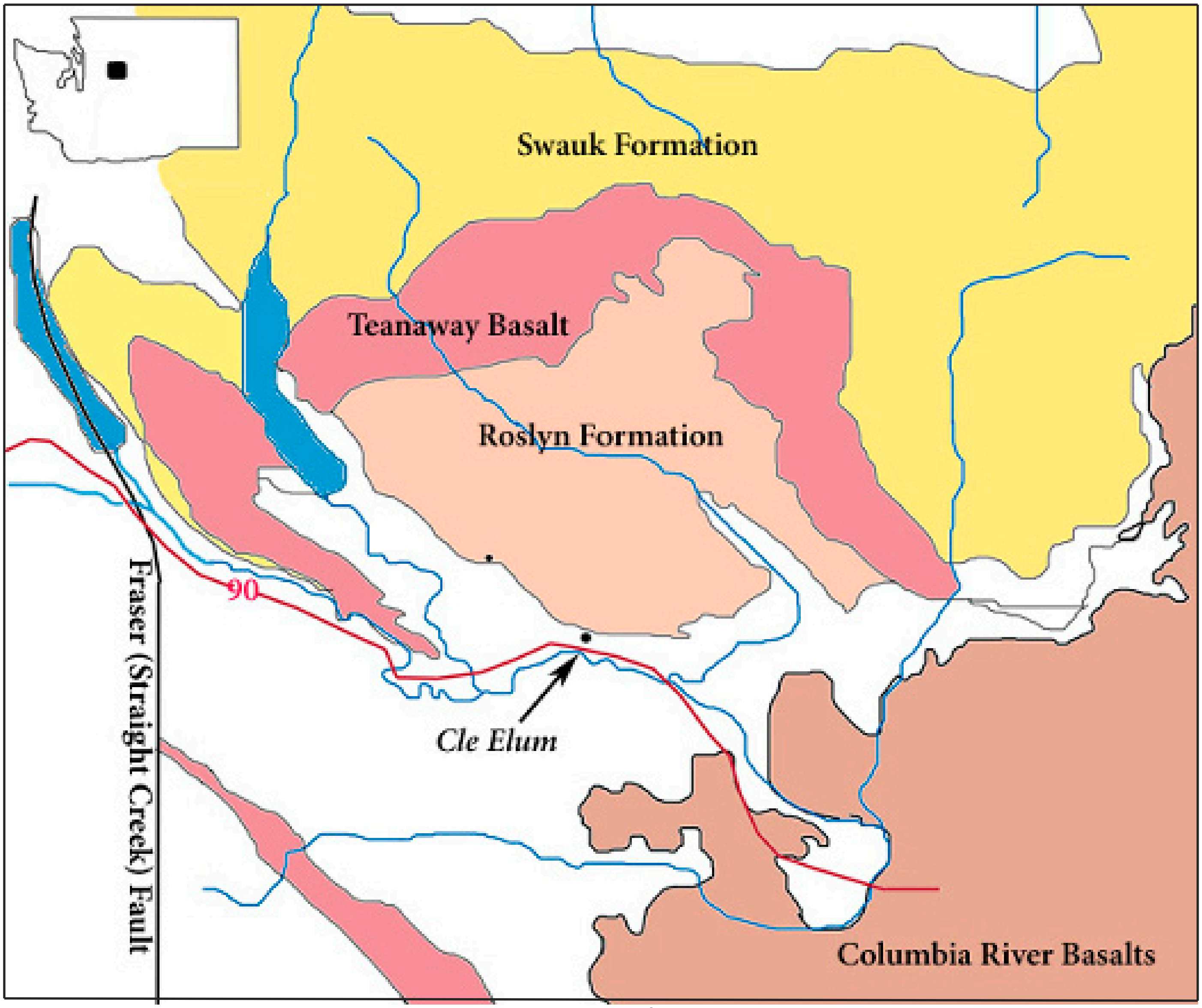


Figure 4-73 *(Above)*

Map of the area east of Snoqualmie Pass, showing the distribution of the Swauk, Teanaway and Roslyn units. The structure here is a broad syncline, dipping to the southeast. White areas are Pre-Tertiary rocks. The Columbia River Basalts are a Miocene feature.

Figure 4-74 *(Right)*

The Tukwila Formation, near Ravensdale. Most of the Tukwila Formation is volcaniclastic in character, but significant sedimentary beds also characterize the unit. Sediments and structures here reflect a shoreline setting, including large dune features. Note the prominent coal seam, illustrating the dip of strata. This mining operation extracted quartzose sands for glassmaking. People provide scale. This pit has since been filled for reclamation.

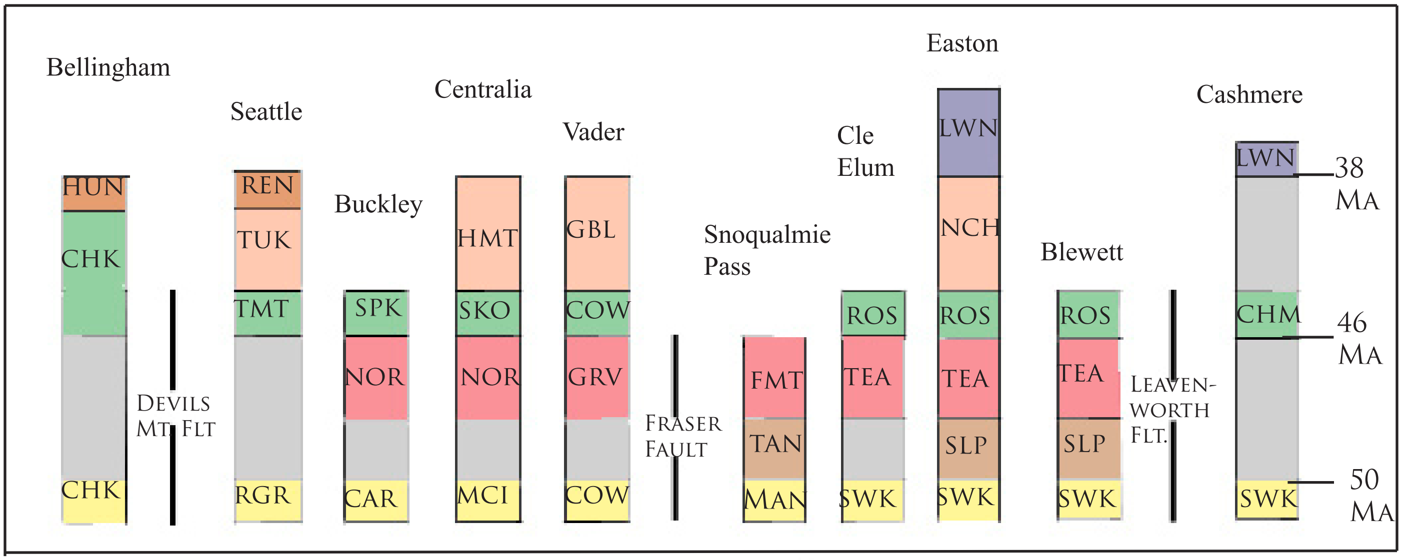


Figure 4 - 75 *(Above) Stratigraphic columns for Challis-age sedimentary and volcanic formations from the east slope of the Cascades to the Puget Sound. CAR=Carbonado, CHK = Chuckanut, CHM = Chumstick, COW = Cowlitz, FMT = Frost Mtn. GBL - Goble, GRV= Grays River HMT= Hatchet Mtn, HUN = Huntingdon LWN = Lower Wenatchee MCI = McIntosh NCH = Naches NOR = Northcraft, REN = Renton ROS= Roslyn, RGR = Raging River, SKO = Skookumchuck, SLP = Silver Pass, SPK = Spiketon, SWK = Swauk, TEA = Teanaway, TMT = Tiger Mtn. TUK = Tukwila. All units are unconformity-bounded. Modified from Cheney, 1994.*

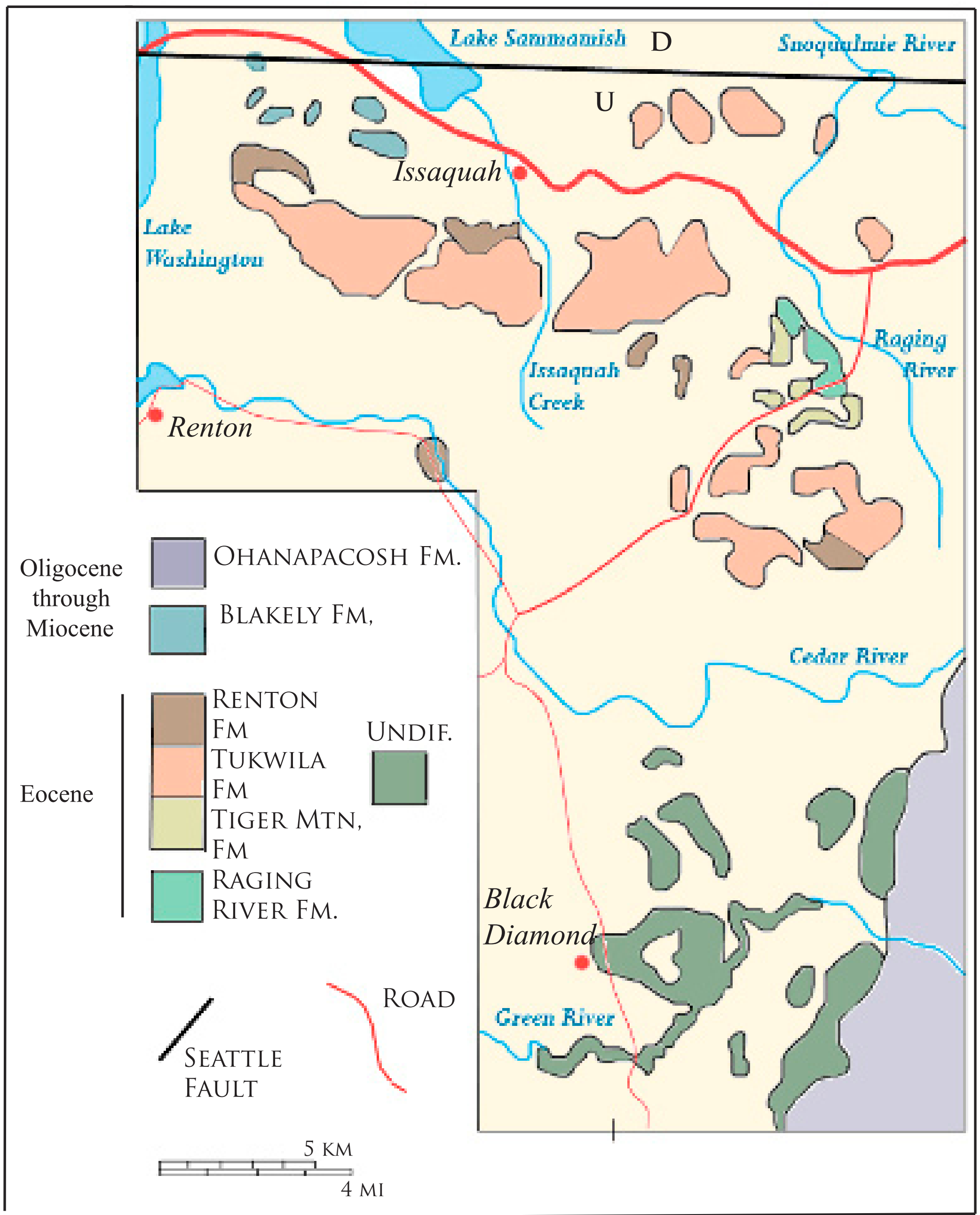


Figure 4 -76 *(Right) Challis - age (and younger) sedimentary formations in the Issaquah - Black Diamond area east of Seattle. The Seattle Fault is a Miocene - recent feature. Map area shown below.*

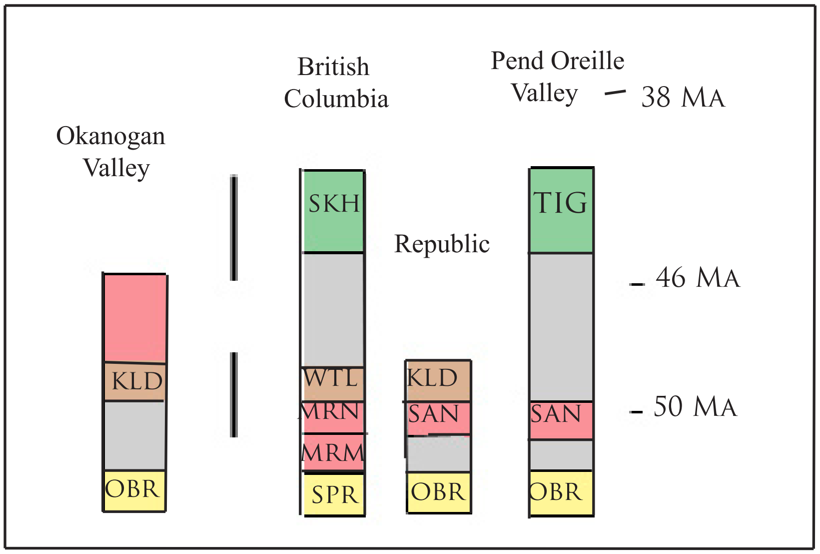


Figure 4 - 77 *(Left)*

Stratigraphic columns for the region between the Okanogan Valley and the Idaho border. Adapted from Cheney, 1994. British Columbia location is northeast of Oroville.

Formation names: KLM=Klondike Mtn, MRM=Marron, MRN =Marama, OBR = O'Brien Creek, SAN = Sanpoil, SKH = Skaha, SPR - = Springbrook, TIG = Tiger, WTL = Whitehall.

with the underthrusting of Vancouver Island. Like the underlying Lyre Formation, it reflects a shallower marine setting than was seen in the Aldwell Formation. The direction of transport here apparently remained to the south, from Vancouver Island.

The depositional record of this episode provides an abundance of information on the prevailing conditions along the southern end of the province. It is a record which contrasts with the paucity of similar deposits from the Coast Range and Omenica Episodes, and provides us with our first good views on the evolving paleogeography of the region.

Figure 4 -78 *(Below)*
Rocks of the Blue Mountain Unit, at an outcrop on Hurricane Ridge. These are ocean-floor submarine fan deposits which accumulated on the Kula Plate prior to the eruption of the Crescent Basalts. Their age and source terrane remain speculative.

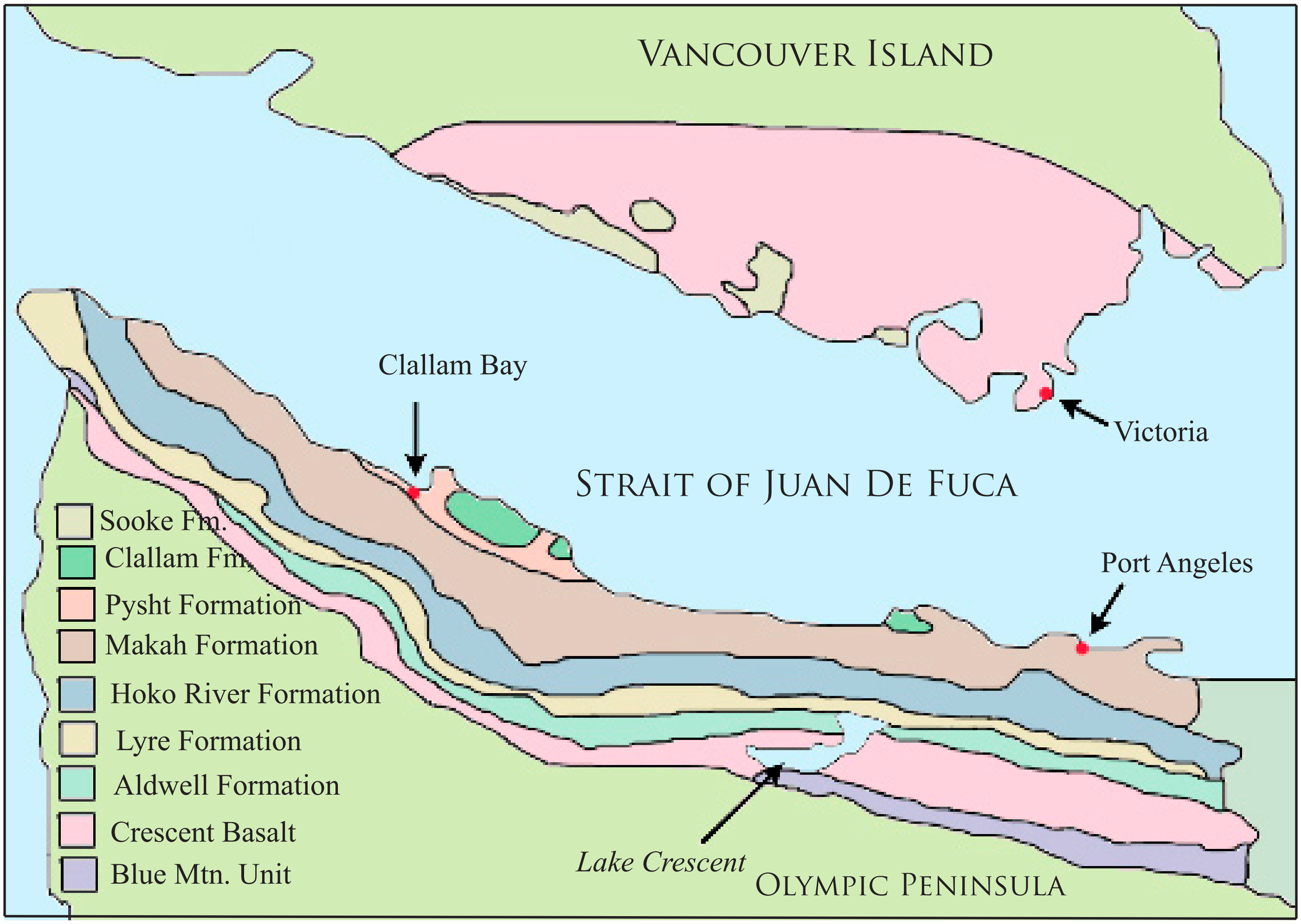


Figure 4 -79 *(Above)*
Map showing the distribution of various sedimentary formations along the northern end of the Olympic Peninsula. Adapted from Babcock et al. 1994

Figure 4 -80 *(Right)*
An outcrop of the Aldwell Formation, Along Highway 101 east of Lake Crescent.

These rocks are fine-grained silt and sandstone. Some beds display the distinctive fining-upwards sequence typical of turbidite flows.

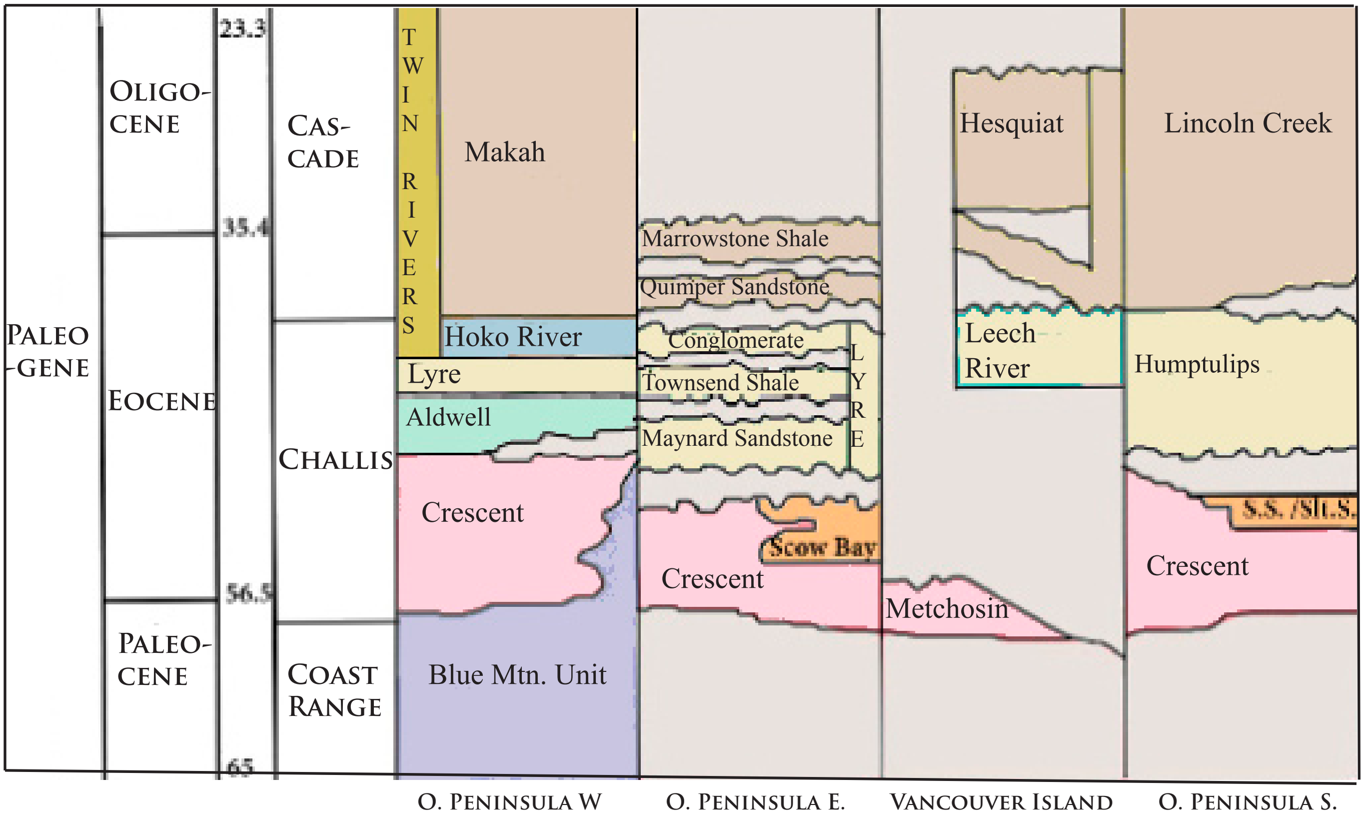


Figure 4 - 81 *(Above) Stratigraphic column for Eocene - Oligocene rocks of the Olympic Peninsula and Vancouver Island. Adapted from Babcock et al. 1994*

Figure 4 - 82 *(Below) Rocks of the Hoko River Formation, along the Hoko River southwest of Clallam Bay. These rocks were derived from sediments shed south off of Vancouver Island.*

Figure 4 - 83 *(Right)*

Rocks of the Lyre Formation, at an outcrop east of Lake Crescent. The tree is about 1 meter tall.

The Lyre Formation appears to represent a shallower depositional setting than the underlying Aldwell Formation. While the contact between the two is gradational, some have suggested that this change in depth may reflect the underthrusting of Vancouver Island by the Kula Plate.

Figure 4 - 84 *(Below)*

Lake Crescent, from the east. Lake Crescent and Lake Sutherland appear to have been formed as waters flowed around the margin of the Juan De Fuca Lobe, during the recent ice ages.

Figure 4 - 85 *(Right)*

Conglomerate of the Hoko River Formation, at an outcrop astride the Hoko River south of Clallam Bay. Note that this is a breccia, comprised of angular fragments. These may have been produced as the northern end of the Crescent Plate underthrust the southern end of Vancouver Island.

The Stonerose Fossil Site In Republic, Wa.

A World-Class Fossil Locale

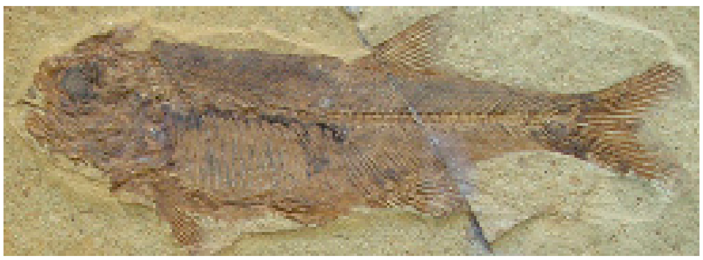
The north central-Washington town of Republic is best known as the site of the Knob Hill Mine, the most productive gold mine in the state. Since it's beginnings in 1896, it has always been a community tied to mining. Like most mining towns, its fortunes have risen and fallen with the price of gold, and the various impediments to extracting it. Unlike most mining towns it remains a rather charming settlement, a well-kept community catering to the entire Okanogan Highlands. It is popular with sportsmen, tourists and others who pass through this sparsely-populated region.

At the north end of town is a small cut dug into tuffaceous lacustrine sediments of the Klondike Mountain Formation. In these fine-grained sediments are preserved one of the world's best collections of fossil flowers from the Eocene. Known as the "Boot Hill" dig, it is more popularly known as the Stonerose fossil site. The site is managed by a non-profit foundation (the Stonerose Interpretive Center), and visitors can dig for a modest fee, and take a few samples. The center offers interpretive displays of some of their finest specimens.

Fossils from this site include a variety of tree species (metasequoia, pine, spruce, fir, yew) a pleathora of leaf specimens, and a fine selection of insects including flies, grasshoppers, dragonflies, mayflies and beetles. Vertebrate fossils are limited to a few fish, although feather imprints have been found.

The site is best known for its remarkable collection of fossil flowers, notably including the early appearance of members of the Rose family. The flowers of apple, raspberry, salmonberry, plum and cherry have been preserved in equisite detail in these fine-grained sediments. Many of the original finds were made by Lisa Barksdale, the original curator of the site, and by Wes Wehr, a paleobotanist at the Burke Museum. The site was featured in an issue of National Geographic Magazine, lending international attention to this remarkable locale. For more information, you can visit the Stonerose and Burke Museum websites.




Fossils from the Stonerose Site, ca. ~ 48 Ma

(Above) Fish, Dragonfly, Beetle, March Fly (Right) Tiger Moth.

(Below) (top) Cocoa Flower, Maple Seed, Feather
(Bottom) Metasequoia, Hazelnut, Cherry, Rose Leaves







Regional Paleogeography

Reflections on the Evolving Landscape

The sedimentary and volcanic record of the Challis Episode gives us our earliest opportunity to evaluate the regional paleogeography in some detail. The rocks of this episode reveal volumes about the region in which they were deposited.

In early Challis time, much of that region now identified as Washington State appears to have been a coastal setting along the northern end of the Columbia Embayment. The Olympic Coast belt had not yet been accreted, and much of modern-day Oregon was occupied by an ocean basin. The northern shoreline of that basin probably ran at about the modern-day latitude of Centralia and Yakima, then extending northwest to the coast of Vancouver Island. Behind that shoreline, a broad coastal floodplain extended perhaps 125-150 km inland, at least as far as modern-day Wenatchee. That coastal plain, by fossil evidence in the Swauk, Chuckanut and Raging River Formations, was a warm, lush paratropical setting. Among the most common fossil species of this period are palm fronds.

In the interpretation offered here, a major river system drained through this area, probably rising from the interior provinces of British Columbia, and/or northeastern Washington and Idaho. The rocks of the Swauk, Chuckanut and Raging River Formations reflect meandering rivers wandering across an alluvial floodplain, rapidly depositing material and frequently changing course. Abandoned channels became oxbow lakes, accumulating finer sediments and serving as site for coal formation as they filled with vegetation. That river reached the coastline at the Raging River

Figure 4 - 86 *(Left) The imprints of palm fronds in the Chuckanut Formation, along highway 542 west of Glacier.*

Figure 4-87 *(Above) A modern analogue for the Mid-Eocene setting in Washington. Image courtesy of the USGS.*

and Carbonado Formations, in part spreading sediment onto the shallow adjoining shelf as the McIntosh Formation. Finally, that river flowed into the ocean, creating an extensive delta system of the Cowlitz Formation.

Much of the region above the coastal plain probably consisted of gently rolling uplands at this time. The earlier Coast Range Mountains had largely been eroded away by this date, and the southern end was apparently a province of subdued topography. To the northeast however, evidence suggests considerable uplift in the "core complexes" over this period, along with the unloading of surface rocks along detachment faults. It would appear that this region was characterized by a more rugged topography. As noted earlier, this province represents a likely source area for some of the arkosic Challis sediments.

As previously described, there is a regional break in the sedimentary record between ~49 and ~45 Ma, where the rock record is marked by either an unconformity, or an unconformity-bound section of volcanic rock. As described in the last section, a major event early in this period had major but transient effects on the topography. At the same time, this also appears to represent the climax period of Challis magmatism, which certainly had significant effects on the local geography. Most visibly, a chain of volcanoes probably developed along the broad swath of the Challis Arc, the record of which has largely been lost to time. Of equal significance, local uplift over shallowly-intruded Challis plutons probably affected portions of what is now the North Cascades region. While uplift was not enough to develop "core complexes" here, it still probably supported a province of somewhat greater relief over parts of this period. These de-

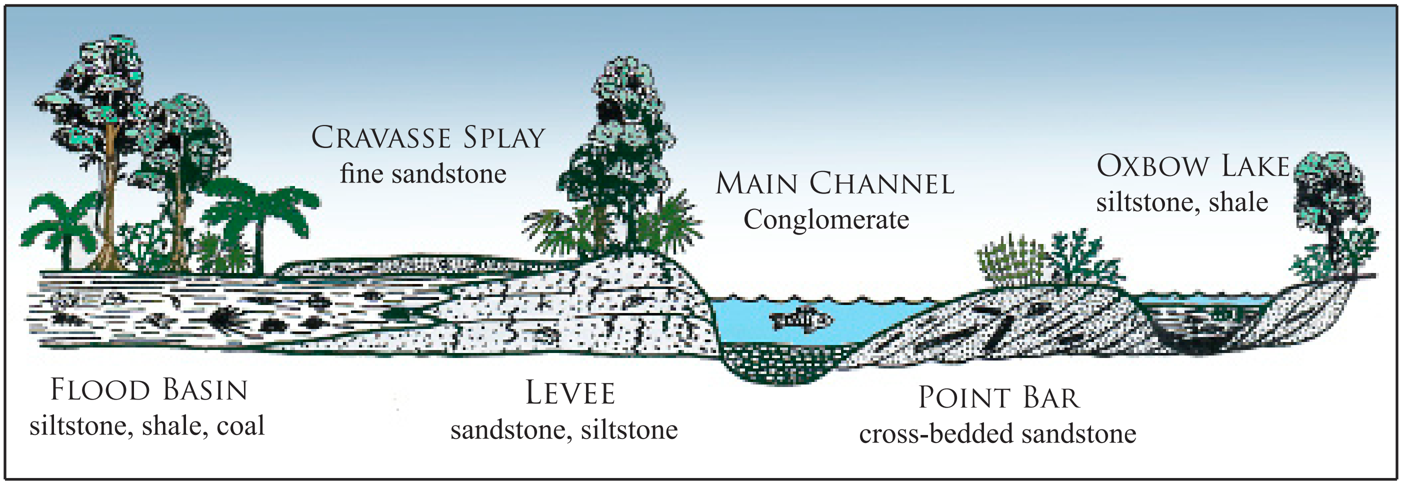


Figure 4 - 88 *(Above) Depositional setting for the Chuckanut Formation, showing the distribution of sediment types. Adapted from Mustoe, 1997*

Figure 4 -89 *(Near Right) Clam fossil, from the Tukwila Formation near Ravensdale (see figure 4 - 74). In company with terrestrial fossils found in the same locale, this reflects a transitional setting during Tukwila time.*

Figure 4 -90 *(Below) Leaf imprints in the Chuckanut Formation. On Higgins Mountain, above Darrington. Many of these appear to be Magnolia species. This thick mat is likely a storm deposit.*

Figure 4 - 91 *(Top far right) Animal trackways in the Chuckanut Formation, in the foothills east of Bellingham. From Mustoe, 1997.*

Figure 4 - 92 *(Bottom far right) Fossils from the Chuckanut Formation, at a location along the Finney Creek Road south of Rockport. Much of what is seen here is woody debris, along with a variety of leaf imprints.*

velopments all probably contributed to the unconformity which marks this part of the sedimentary record.

These events are reflected in the next depositional series, which commenced somewhere around 45 Ma. As noted earlier, his date apparently marks the resumption (at least in part) of the fluvial system which formerly drained across the region prior to ~50 Ma. The Roslyn /Chumstick sediments in the Cle Elum area, the Tiger Mountain Formation in the Issaquah area, the Skookumchuck and Spiketon Formations around Centralia and the Cowlitz Formation to the south may represent the deposits of a continuous river system.

These rocks all display a higher volcanic content than their prececessors, a reflection of the maturing Challis Arc across the region. They also display a higher percentage

Figure 4 - 93 *(Right) Bird trackways in rocks of the Puget Group. Trackways like this have been found in a number of Eocene sedimentary formations in Washington State. A good example is on display at the Burke Museum in Seattle. Image from Washington Geology V 25 #4..*

Figure 4 - 94 *(Below) Rocks of the Tiger Formation, near Tiger, Washington. These are crudely-stratified breccia-conglomerates, produced during the unloading of the Priest River "Core Complex". Paleocurrent directions are from the northeast.*

Figure 4 - 95 *(Right) Rocks of the Tiger Formation, from the outcrop pictured on the opposing page. Note the angular character of this breccia - conglomerate. These were derived from the unloading of the Priest River "Core Complex: to the east.*

Figure 4 - 96 *(below right) Fossils in Tukwila siltstone, from the Ravensdale area. Most of these appear to be Salix (Willow) species. In the same area, clam fossils are found (figure 4 - 89), indicating a transitional shoreline setting.*

of materials from local sources. Significantly, the rocks of the Roslyn /Chumstick Formation in the Cle Elum area contain a proportion of detrital kyanite, a high-pressure metamorphic mineral common to the Nason and Chelan Mountains Terranes. Kyanite is a relatively soft mineral, so its presence argues for a local source. To some degree, these areas appear to have been eroding at this time.

As discussed earlier, it appears that this system was broken up at about 43 Ma, the date of a regional folding event. Subsequent formations appear more localized, and contain large amounts of volcanic rock. The Naches Formation in the Cle Elum – Snoqualmie Pass area contains a large proportion of felsic volcanic rocks. Similarly, the Tukwila Formation to the west is largely volcanic and volcaniclastic. These formations reflect one or more volcanic cones in the area over this period, the youngest volcanoes of the Challis Arc.

To the north, some of these developments are similarly reflected in the later members of the Chuckanut Formation. This area was displaced from the main drainage system at ~50 Ma, and subsequently developed in isolation from it. After folding and erosion of the earlier (Bellingham Bay)

Figures 4 - 97 (*Above and Right)*
Fossils fromt the Chuckanut Formation, from outcrops along Racehorse Creek, east of Deming. Samples above are probably magnolia species, samples to the right are fern types. The flora of the Chuckanut Formation have not been thoroughly studied, and contain many species which have never been classified. At this date, only the fern and horsetail species have been cataloged. Western Washington University has a fine collection of fossils from this formation.

member, the subsequent Padden and Slide Mountain Members largely reflect re-working of those older sediments. This indicates some measure of uplift along the Fraser Fault to the east. The post-43 Ma deposits of the Maple Falls and Warnick Members include abundant materials from the surrounding pre-Tertiary rocks, and evidence faulting along the northern end of that basin. Lying west of the Fraser Fault and north of the main drainage system, it does not contain appreciable amounts of Challis volcanic material.

To the west, we know that some of the Crescent Basalts accumulated in subaerial exposures, so it appears that a number of volcanic islands dotted the western entrance to the Columbia Embayment from time to time. Most of the Olympic Coast Belt however, remained a deep water setting through most of the Challis Episode. After that belt was accreted at about 43 Ma, sedimentation in the Lyre and Hoko River Formations reflect a shallower setting, largely fed by sediments eroding off of Vancouver Island to the north.

While the various sedimentary formations of this period can tell us a great deal about the paleogeography of the region, some of the most fascinating insights come from the rich fossil record which these formations hold. That record reflects a dense cover of paratropical broadleaf vegetation, among the most common fossils being palm fronds. This climatic setting extended all the way up the coast into southeast Alaska, reflecting the warm, moist conditions which characterized much of this period world-wide. As described in the accompanying presentation, the fossils of the Republic area are particularly noteworthy. Additionally, excellent specimens of gastropod (clam and snail) fossils have been collected from the Cowlitz Formation. These species reflect the warmer and more equitable temperatures of this period, and the relatively quiescent passive-margin setting which prevailed west of the Fraser fault.

Of some significance, that warm paratropical climate began to cool in the Late Eocene. The fossil record of the younger (<45Ma) sedimentary rocks stands in contrast to the older Mid-Eocene strata. The imprints of palm fronds, which are common in the Bellingham Bay and Slide Members of the Chuckanut Formation, are not in evidence by the time the Padden, Maple Falls and Warnick Members were being deposited. Similar contrasts are found between the Swauk and the Roslyn Formations, and between the Raging River and the Renton Formations. These contrasts are valuable indices used in evaluating rock outcrops from this period.

What are not preserved here are vertebrate fossils. This may in large part be attributed to the fact that most of the terrestrial "fossils" in these formations are actually imprints rather than fossils. The only vertebrate fossils to be found have included a fish from the Republic area and a turtle carapace from the Chuckanut Formation. There is evidence, however, that the region teamed with animal life over this period. Trackways have been found in the Chuckanut and Raging River Formations, revealing the paths of birds and ungulate-type (hoofed) animals (Figure 4-91, 4-93).

Figure 4 - 98 *(Below) Leaf fossils from the Chuckanut Formation, from an outcrop along Chuckanut Drive. These are Cinnamonium species.*

Foliar Physiognamy and the Tertiary Climate of the Pacific Northwest

Plant fossils, or at least imprints, are common in most of the (terrestrial) Tertiary sedimentary formations of the Pacific Northwest. Most of what are found are leaf imprints, as flower parts are seasonal and much more fragile. Unfortunately, plants are botanically classified by their floral parts, making identification from simple leaves a difficult task. The standard paleobotanical approach has always been to find flower parts, identify the species, and from that infer the most likely environmental setting that it grew in. From a single flower, a great deal can be inferred about the environment. As noted however, those floral parts are only rarely preserved in the fossil record.

Back in the 1970's, a paleobotanist with the U.S. Geological Survey (Jack Wolfe) studied the relationships between leaf types and environmental conditions, based on the premise that those conditions were the primary determinant of leaf design. Studying modern flora around the world, he noted that certain leaf types (foliar physiognomy) dominated certain environmental settings, regardless of the specific flora of the ecosystem. He noted that large leaves were favored in warm, wet climates, as were whole leaves (as opposed to divided leaves) and those leaves which had "entire" margins (edges which are not serrated, pinnated or otherwise irregular). From a very large body of data, Wolfe found that if you could determine the percentage of various leaf sizes, and the percentage of those leaves which had entire margins, those percentages correlated extremely well with measurements of annual mean temperature and annual temperature range.

With this new tool, Wolfe studied the abundant fossil record of the Tertiary strata of the Pacific Northwest, all the way up to Southeast Alaska. He found that during Mid-Eocene time the climate here was one of a marginally tropical rainforest, with mean temperatures between 20 and 25 degrees centigrade (~70 degrees farenheit), varying by only perhaps 5 degrees over the year. Those conditions existed not only locally, but extended all the way up the coast into southeast Alaska. Tertiary formations there include feather and fan palms, mangroves, and members of other families found only in tropical climates. Tropical to paratropical species dominated the landscape over this period, and are abundantly preserved in the fossil record. One of the most common fossils found in the Swauk and Chuckanut Formations are fan palms.

Examining the flora of later Challis formations, he noted a declining trend in the average mean temperature and an increase in the annual temperature range. By the end of the Eocene, the annual mean temperature had dropped to about 10 degrees, and the mean annual range of temperatures had increased to 20 – 25 degrees. By the time this decline was over, the Pacific Northwest was a region of mixed coniferous forests. The exact same pattern was noted in the floras of southeast Alaska. This decline over the latter half of the Eocene is what Wolfe called the "Eocene Terminal Event", now recognized as a world-wide phenomena.

Image: *Palm frond from the Chuckanut Formation, from above the town of Darrington*

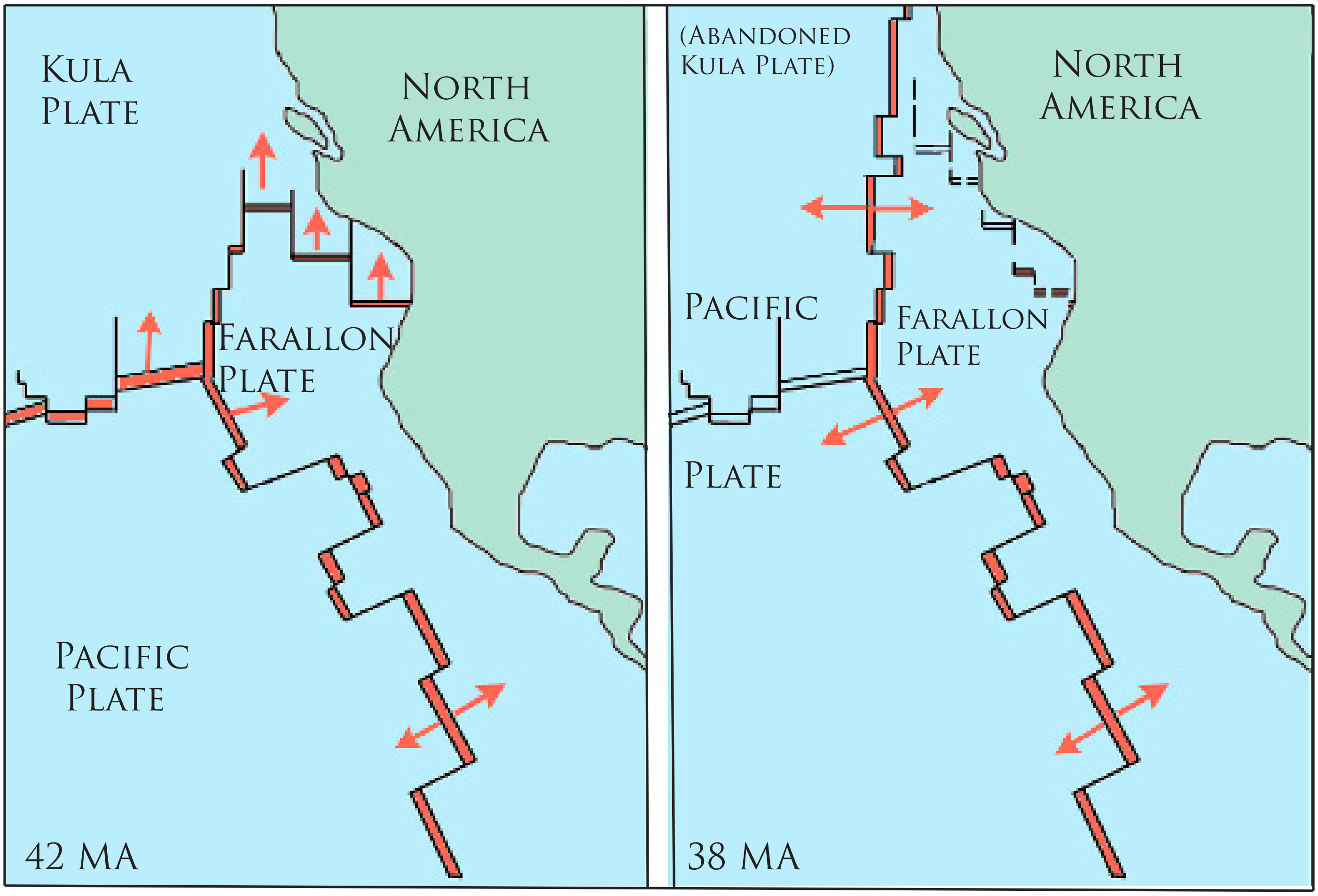


Figure 4 - 99 *(Above) Maps illustrating the decay of the Kula-Farallon Ridge between 42 and 38 Ma. As the Farallon Plate returned to this area, the Challis Episode ended and the modern Cascade Episode began.*

The End of the Challis Episode

The Return of the Farallon Plate

As outlined in the introduction to this chapter, the Challis Episode appears to represent the terminal phase of the Kula Plate, as it was broken up along a series of transform faults, over-ridden by the advancing North American Plate from the east, and finally overpowered by the advancing Farallon Plate to the south. The magmatic and tectonic regimes characteristic of this episode appear to have dissolved by ~40 Ma, which is the youngest age for Challis magmatism. It would appear that the Kula Plate ceased to become an active feature here at about this date, as the Kula-Farallon ridge fell into disarray.

With the demise of the Kula-Farallon Ridge, the old Kula-Pacific Ridge to the west became the northern end of the new Farallon-Pacific Ridge. Formerly not a particularly important element in the local tectonic picture, that ridge now produced Farallon-Plate rocks directed with an easterly sense of motion. This arrangement re-established the western margin of the continent here as a convergent tectonic setting. That setting yielded to the development of a new subduction zone along the western margin of Vancouver Island and the newly-accreted Olympic Coast Belt. This may have been related to an episode of regional folding dating from 40 - 38 Ma. This marks the inception of the most recent episode in regional geologic evolution, the Cascade Episode.

Summary: The Challis Episode

The Demise of the Kula Plate

The Challis Episode represents what is arguably the most dramatic and enigmatic of times in the evolution of the Pacific Northwest. The record from this episode includes a seemingly disparate collection of events along virtually every parameter, including aspects of magmatism, tectonism and deposition. So varied are these characteristics that it would be easy to conclude that no one plate-tectonic setting could have been responsible for such a course of events. Over the last three decades since the dawn of modern plate-tectonic theories, resolution of the "Challis Enigma" has always been one of the most perplexing of geologic puzzles here.

It is broadly recognized that this episode represents the demise of the Kula Plate in this area. How that process of plate decay might support the varying events of this episode is not a subject broadly explored in the professional literature, at least on a regional scale. To that degree, the model presented here represents an attempt to resolve those seemingly disparate events into a "most probable" course of plate-tectonic relationships, as inferred from the continental record. As noted in the introduction to this chapter, this is not a model which "most" researchers would accept at this date – as no such model currently exists. This model is unique in that it does appear to address the range, scope and scale of events which have transpired here. While the actual setting here was likely a far more complex arrangement, it provides a valuable sense of context to this remarkable episode in our geologic past.

Regardless of how one interprets the specifics of the plate-tectonic setting over this period, it does seem evident that oceanic plates don't die quietly. The last twenty million years of the Kula Plate in this area spawned an amazing array of magmatic, tectonic and depositional events in a dynamic, constantly-evolving setting. In its wake, it left behind a uniquely felsic suite of igneous rocks across the northern end of the state, intruded to shallow levels, accompanied by explosive volcanism and the unique phenomena associated with the "core complexes" of northeastern Washington and southeastern British Columbia. It left behind the remarkably thick suite of mafic volcanics in the Crescent Formation, including dike complexes which extend into Central Washington. It left the topography and geology re-arranged in an episode of transform faulting and terrane accretion along the continental margin, in a regime attended by several episodes of regional deformation. As it passed into history, it left the region a much different-looking place.

As we seek to interpret the evolving paleogeography of this region over time, the Challis Episode represents our first, and in many ways our best, opportunity to detail the landscapes of the past. The abundant sedimentary record of this episode, including some of the thickest non-marine sedimentary formations in North America, reveal volumes about conditions along the southwestern end of this region over this time. The early formations illustrate a broad coastal floodplain setting, carpeted in a paratropical cover of palms and broadleaf vegetation, hosting a meandering river system of significant scale. Later formations reveal a cooling climate of temperate vegetation, in perhaps a region of somewhat more variable topography. In that same record we see evidence for the animals, birds, fish, insects and other life which called this province home, filling out this remarkable window on the past.

This unique setting came to an end with the final demise of the Kula Plate, as the Farallon Plate advanced back into the region. As this happened, an Andean-type convergent setting was re-established along the coast here. With this development, the region advanced into the modern Cascade Episode.

Figure 4-100 *(Left)) Local faulting in the Swauk Formation (Tronsen Ridge Member). Strata are tilted vertically.*

Figure 4-101 *(Below) Deformed mafic dike in the Laclede Gneiss, in the Newport Fault Zone (Priest River Complex).*

Chapter 4: The Challis Episode
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