The Active Yakutat (Kula?) Plate and Its Southcentral Alaska Megathrust and Intraplate Earthquakes

John W. Reeder
Terra International, 6005 Calle Maggioni, Cannaregio, Venice 30121, Italy

Abstract: Alaska geology and plate tectonics have not been well understood due to an active Yakutat plate, believed to be part of the remains of an ancient Kula plate, not being acknowledged to exist in Alaska. It is positioned throughout most of southcentral Alaska beneath the North American plate and above the NNW subducting Pacific plate. The Kula? plate and its eastern spreading ridge were partially “captured” by the North American plate in the Paleocene. Between 63 Ma and 32 Ma, large volumes of volcanics erupted from its subducted N-S striking spreading ridge through a slab window. The eruptions stopped at 32 Ma, likely due to the Pacific plate flat-slab subducting from the south beneath this spreading ridge. At 28 Ma, magmatism started again to the east; indicating a major shift to the east of this “refusing to die” spreading ridge. The captured Yakutat plate has also been subducting since 63 Ma to the WSW. It started to change to WSW flat-slab subduction at 32 Ma, which stopped all subduction magmatism in W and SW Alaska by 22 Ma. The Yakutat plate subduction has again increased with the impact/joining of the coastal Yakutat terrane from the ESE about 5 Ma, resulting in the Cook Inlet Quaternary volcanism of southcentral Alaska. During the 1964 Alaska earthquake, sudden movements along the southcentral Alaska thrust faults between the Yakutat plate and the Pacific plate occurred. Specifically, the movements consisted of the Pacific plate moving NNW under the buried Yakutat plate and of the coastal Yakutat terrane, which is considered part of the Yakutat plate, thrusting WSW onto the Pacific plate. These were the two main sources of energy release for the E part of this earthquake. Only limited movement between the Yakutat plate and the North American plate occurred during this 1964 earthquake event. Buried paleopeat age dates indicate the thrust boundary between the Yakutat plate and North American plate will move in about 230 years, resulting in a more “continental” type megathrust earthquake for southcentral Alaska. There are, therefore, at least two different types of megathrust earthquakes occurring in southcentral Alaska: the more oceanic 1964 type and the more continental type. In addition, large “active” WSW oriented strike-slip faults are recognized in the Yakutat plate, called slice faults, which represent another earthquake hazard for the region. These slice faults also indicate important oil/gas and mineral resource locations.

Key words: 1964 Alaska earthquake, oceanic and continental types of megathrust earthquakes, WSW subducting Yakutat plate, large active WSW striking slice faults, Alaska geology and tectonics, oil and gas resources.

1. The Situation

The Yakutat plate is an active plate that extends under a major part of Alaska. The plate and associated tectonic processes have been influential in creating WSW striking features of the W limb of the Alaska orocline, in driving volcanic processes in the Cook Inlet volcanic arc, in influencing the volcanism of the Katmai region, in influencing the Wrangell volcanic chain, in helping cause the Mt. Edgecumbe volcanic field, in causing the large Copper Valley, in causing numerous large and active strike-slip faults called slice faults, in causing active reverse faults, and more significantly in causing at least two different types of active megathrust earthquakes in S Alaska. None of these items have been previously recognized as being caused/influenced by the Yakutat plate. The proper recognition of the active behavior and the extent of the Yakutat plate changes the earthquake hazard and volcanic hazard situations for Alaska significantly and it helps better define Alaska’s resources.

Southern Alaska consists of a complex tectonic boundary that is gradational from subduction of Pacific plate (PAC) beneath the North American plate (NA) in the W to a transform fault between these two
plates in the SE. Adding complexity, a major part of the Yakutat plate has been sandwiched between these two large plates. The Yakutat plate consists of two parts; the main body called YAK, which dominates southcentral Alaska, and the “being added” part called yak after the commonly called coastal Yakutat terrane, which is to the SE (Fig. 1). In the scientific literature, the E part of YAK has been recognized as the Yakutat slab (Fig. 2), which has been considered a NNW extension of the coastal Yakutat terrane (the yak), having been placed there by the fast NNW moving PAC [1-10]. But, it is next to impossible to physically subduct a narrow yak along with PAC for 600 km as a flat-slab beneath NA [11, 12]. In addition, YAK’s now recognized larger size makes such a yak subduction during just the late Miocene to present unrealistic. Then, where did this very large and active YAK actually come from?

YAK is strongly suspected to be part of the still active remains of the ancient Kula plate, meaning in Athabascan the “all gone” plate, which has been partially captured by NA beneath Alaska from the Pacific Ocean basin. The Kula plate (KULA) was N of the PAC in the Paleocene and Eocene with a PAC-KULA spreading ridge between. It along with a KULA-RESUR? (Resurrection, Farallon or another unknown plate) spreading ridge and corresponding plate to the E subducted together under Alaska [13, 14]. It has been assumed they subducted completely into the mantle as the oceanic remaining part of the KULA-RESUR? ridge marched with time from the W to the E [3, 15] across the Pacific basin. Apparently,

Fig. 1  The Yakutat plate in southcentral Alaska, which consist of YAK and yak as shown. BC is the Buzzard Creek slice, MC is the Montana Creek slice, MS is the Mount Spurr slice, MSS is the Mount Spurr South slice, RED is the Redoubt slice, ILI is the Iliamna slice, AUG is the Augustine slice and KAT is the Katmai slice strike-slip faults.
The Active Yakutat (Kula?) Plate and Its Southcentral Alaska Megathrust and Intraplate Earthquakes

Fig. 2  Accepted generalized tectonics of southern Alaska [51]. Red dashed line indicates the extent of the “assumed” subducted Yakutat flat slab. The red short dashed lines represent the depth supposedly of the Pacific plate.

This was not entirely the case. The KULA stopped moving relatively N away from the PAC in early Paleocene [13] about when a subducting N-S oriented KULA/RESUR? ridge was captured by NA beneath southcentral Alaska. This ridge capture also included a significant piece of KULA underneath SW and southcentral Alaska and most likely a significant piece of RESUR? underneath E Alaska [16, 17]. The captured KULA steeply subducted to the WSW along with extensive volcanics being extruded along its subducted KULA-RESUR? spreading ridge slab-window [18], which started 63 Ma in the N Talkeetna Mountains [19] (Fig. 2). Extensive volcanics continued with a southward shift into the S Talkeetna Mountains of southcentral Alaska, which ended 35.5 Ma [20].

The PAC underwent a 60° ccw rotation about 43 Ma [13, 21, 22] when it initiated its oblique subduction beneath the nonactive (?) PAC-KULA ridge [23-25], which caused the pronounced Hawaiian-Emperor bend. This PAC rotation turned off subduction magmatism at 43 Ma in E Alaska, leaving a large block of underplated oceanic crust and mantle of RESUR? [16, 26]. In the Prince William Sound (PWS, Fig. 2), 38 Ma near trench plutons formed [14] due to a PAC-KULA ridge slab window. These plutons were then shut off underneath by the oblique NNW flat-slab subducting PAC from the S. The subducted KULA-RESUR? spreading ridge volcanic extrusions then ended 35.5 Ma and also the subduction related magmatism by YAK ended about 32 Ma for southcentral Alaska, both caused by this oblique NNW flat subducting PAC extending underneath YAK [26]. But, this new NNW subducting PAC left the region to the E unsubducted. At 28 Ma extensional magmatism started again in this unsubducted region, indicating a major shift to the east of the “refusing to die” KULA-RESUR? spreading ridge. Finally, at 22 Ma the subduction magmatism ended for the SW part of Alaska as the NA partially captured WSW subducting YAK.
The Active Yakutat (Kula?) Plate and Its Southcentral Alaska Megathrust and Intraplate Earthquakes

expanded as a flat-slab further W with PAC subducting NNW underneath part of it.

Today, the YAK extends at least 100 km N of Denali (Mount McKinley) to depths of over 200 km, extends 700 km SW at depth to the NW side of the Katmai volcanic region of the Alaska Peninsula, and extends 400 km SE to the PWS at its shallowest depth (Figs. 1 and 2). The E part of the YAK is spreading from the Copper Valley and the Wrangell volcanic belt, and the W part is subducting WSW into the Cook Inlet and Denali part of the Aleutian subduction zone [27, 28]. YAK is sliced into a number of long slice fragments called “slices”, which are bound on their long sides by WSW active strike-slip faults. Such faults are not transforms and they are not strike-slip faults related to slivers.

The other part of the Yakutat plate, yak, has been called the Yakutat microplate, block and/or terrane (Fig. 1). It extents 700 km from PWS to southeast Alaska. The yak is exposed on the continental region NE of the Gulf of Alaska and has been extensively mapped [29]. It is bound to the E by the NA at the Fairweather transform fault and to the S by the PAC at the Transition fault. It is unknown where yak originated [1, 3, 30, 31]. It has been argued to be an oceanic plateau that has docked against NA and then move N. Most likely, yak is the remains of an inactive PAC-KULA ridge that did not subduct under Alaska during the Eocene-Oligocene when the rest of the KULA-PAC ridge did. Relative to NA, yak is moving 5 cm/yr NNW [5, 32, 33] at its E end (Fig. 1). To the WNW, yak continues beneath the NA as a flat slab [2-4] and connects with YAK in the PWS [27, 34]. This connection in the PWS is actually a marriage with the larger YAK dominating. The yak motion at this contact is WSW [35], which is the same as YAK. Because they are moving together, yak is included as part of the Yakutat plate even though it has a different origin.

Jumping ahead, based on surface displacement data for the large 27 March 1964 Alaska earthquake [35], called here the 1964 Alaska earthquake, relative plate displacements were determined (Fig. 16). The E part of the 1964 Alaska earthquake occurred principally as relative down dip movement NNW of the PAC beneath the Yakutat plate (YAKp, which is YAK & yak) on a megathrust fault beneath the PWS region [36]. A major part of the E part of this earthquake was also caused by the yak thrusting WSW onto the PAC along an NNW striking shallow thrust fault [37]. In addition, WSW relative movement along another distinct megathrust fault between YAKp and NA in the PWS region occurred. Its movement stopped completely just NNW and was small just W of the PWS (Fig. 16).

Why did the YAKp movement beneath NA stop during this large earthquake? It appears, based on crustal displacements, the impact of yak with YAK has actually disrupted the NA to YAKp thrust fault enough to stop relative movement between them at least during the 1964 Alaska type of earthquakes. As folding develops NNW and WSW of the PWS in the NA, the NA will eventually decouple from the YAKp. Such decoupling will allow the YAKp to complete its WSW movement relative to NA. This more “continental” megathrust event as will be shown should occur in about 230± years as based on paleo-peat studies of the Knik Arm tidal flats [34, 38]. After this continental megathrust in another 570± years a more “oceanic” Pacific megathrust earthquake like 1964 should again occur. Therefore, there are at least two types of megathrust earthquakes occurring in southcentral Alaska: the Pacific (oceanic) and the continental types.

2. The Copper Valley Enigma

A long perplexing problem with geologist has been “Why the very large Copper Valley exist [39] in a zone of crust transport by the PAC against the NA, which is all within the limbs of the Alaska orocline?” The Copper Valley has been considered a region of flat-slab subduction from the S that is not well understood [16, 17, 26]. This large valley has some
small basins on its far E, which are along the dextral Denali fault zone, and the large Wrangell volcanic belt covers its SE part [40]. The valley should be a region of mountains like its surroundings. Instead, it consists mainly of a large basin of Mesozoic and possibly Paleozoic sedimentary rocks as exposed in mountains to the W, N, E, and SE [41] with only shallow Cenozoic deposits [42]. The valley is too large to be due to subsidence from flexural loading by the Alaska Range suture zone to the E [43].

Except for a few earthquakes associated with the Wrangell Wadafi-Benioff zone (WBZ) and the Wrangell volcanoes, an approximate NNW oriented 200 km by up to 175 km wide zone exist of missing seismic activity just W of the Talkeetna Mountains (Figs. 2 and 3). This seismic gap, which includes all of the Copper Valley, was described as missing Yakutat terrane (YAK & yak) and PAC [17]. Later, the cause was described as a “tear” in the Yakutat terrane and PAC beginning to the far SSE in the E Chugach Mountains [8]. Actually, a PAC tear starts as a dextral N 29° W striking fault on the Pacific Ocean floor where it offsets the recently recognized N-S oriented Gulf of Alaska shear zone [44, 45] (Fig. 14). On the continent to the W of this N 29° W striking fault, it was believed the YAK and PAC were subducting together as one slab to the NNW [6-9]. To the E, the PAC is subducting into the Wrangell subduction zone [46] with a large block of RESUR? underplated to NA and generating most of the deep earthquakes (Fig. 4a). This underplated block was subducting ESE from the KULA-RESUR? captured ridge when it was stranded between 32-28 Ma when the eastward shift of this spreading ridge occurred. At these depths, it is still actively being metamorphosed by relatively high pressure/low temperature fluids from the PAC; i.e., the earthquakes. Below 85 km, the RESUR? block is absent, which allows magma from the PAC to rise to the Wrangell volcanic range. This captured block by NA, which shows well in local earthquake tomography [47] is the main cause of the ESE oriented Wrangell mountain range. The Wrangell volcanics are just the partial top of this large range. The “actual” Wrangell subduction zone part of the WBZ has very few earthquakes (Fig. 4a) and represents very young PAC crust and mantle.

But, a significant amount of the yak must be absorbed by subduction somewhere given the mass balance of the Saint Elias Range with its high rates of internal deformation and exhumation [16, 48-54], which does not even come close to the estimated amount of N transport of yak; i.e., nearly 100 km of yak within 2 Ma [33]. Then, where has the missing yak and even YAK to the NW gone?

The subduction of the Yakutat plate (YAK & yak) is occurring; but, not into the Wrangell subduction zone with the PAC and not to the NNW as flat-slab with the PAC. Instead, the YAK & yak are moving to the WSW into and toward, respectively, the N part of the Aleutian subduction zone, which YAK has been actually doing beneath NA since the Paleocene [19]. The YAK is principally influenced/controlled by NA instead of PAC. The yak has not underplated the Saint Elias Range in contrast with what has been argued [8] and it has not even allowed the PAC to subduct beneath its E end [31]. Instead, it is completely changing directions with its SE end moving NNW [33] and its far W end moving WSW [35] where it has joined with YAK [34]. Obviously, a lot of deformation has gone on between the two ends of yak (Fig. 1) as well as with the Saint Elias and E Chugach Ranges [55].

With respect to the Copper Valley seismic gap, to its W the YAK and deeper PAC exist beneath the NA as flat slabs [4, 6, 7] with each independently moving with respect to each other as distinct plates [27]. The YAK is identified by extensive earthquake activity while the less rigid PAC has hardly no seismic activity [46, 56]. W of the N 29° W striking fault, the PAC is moving principally to the NNW. To the E of this fault, the PAC is subducting into the Wrangell subduction zone. The YAK has moved to the WSW from the E,
forming a gap for older overlying NA crust to collapse into, which is the Copper Valley. The result is a Paleozoic and Mesozoic basin surrounded by mountains. The clear boundary between the zone of seismic activity (YAK) and the seismic gap (Copper Valley) has pronounced offsets to the WSW (Figs. 1 and 3). These offsets are actually marked by large strike-slip faults, which reflect the present mechanism of WSW movement of YAK.

3. Evidence for YAK Subduction to the WSW

These regional seismic zone offsets to the W, which have caused the seismic Copper Valley gap, are caused by nearly flat WSW movement of elongated blocks or “slices” of the YAK. The slices are bound by long strike-slip faults called “slice” faults. These faults extend WSW through the YAK into the Aleutian subduction zone. It is believed these faults are actually reactivated transform fracture zones in the Yakutat plate from the 63 Ma subducted KULA-RESUR spreading ridge. If such an active spreading ridge still exists today, it is covered by the NA to the E. Most of these slice faults cannot be considered transform faults because transforms must mark plate tectonic boundaries of a spreading ridge [57]. Fracture zones resulting from transforms do not have movement unless they have been reactivated, which is what is believed happened here. These large slices of the YAK are subducting at different rates with the long strike-slip slice faults marking their N
Fig. 4  Earthquake vertical profiles as located on Fig. 3, with each profile (a-e) having the following references: (a) Stephens et al., 1984 [46], (b) Pulpan & Frohlich, 1985 [78], (c) Veilleux & Doser, 2007 [84], (d) Veilleux & Doser, 2007 [84], and (e) Doser et al., 2008 [141] with the yellow diamonds representing the 1964 Alaska earthquake and its aftershocks.
and S elongated boundaries. Slivers can form when an underlying plate subducts at an oblique direction and such slivers are bound by a large strike-slip fault [58, 59]. But, the PAC is subducting at a near perpendicular angle to YAK (Fig. 1) and therefore should not be producing any slivers in YAK. The YAK slices do not appear to be slivers and the PAC basically has little to do with at least the direct subduction of the YAK.

3.1 Montana Creek Slice Fault

One of the largest slice fault offsets of YAK has surface expressions at Montana Creek between 62°06′ N and 62°10′ N at the 150° W longitude. It extends at depth approximately at an azimuth of S60°W toward the most N Cook Inlet volcano, Hayes, and it extends at an azimuth of N60°E just beyond the N Talkeetna Mountains at the N part of the Copper Valley (Figs. 1-3). This slice fault marks the N boundary of the Copper Valley seismic gap. Dextral SW to WSW strike-slip motion on numerous faults within a 10 km wide zone, with one at Montana Creek having a ten meter thick gauge zone, have been documented (Fig. 5) [60]. In addition, an S60°W bearing fault scarp cutting Holocene deposits has been mapped [61] in the Susitna Valley just to the WSW of this location.

On a regional scale, the Montana Creek slice fault (MC) is recognizable. Nikoli Greenstone has been found in the Talkeetna Mountains just S of this MC on Iron Creek [62, 63], which is 70 km further SW of any other mapped Nikoli Greenstone. Interestingly, the

![Fig. 5 Suspected location of the Montana Creek slice fault zone as based on elongated magnetic highs in red and on elongated magnetic lows in blue [67]. Some observed fault locations are indicated in green [60, 61].](image-url)
size of the seismic gap offset in the N Copper Valley is over 100 km (Fig. 3). The fault zone extends through mainly unmapped Wrangellia terrane [64, 65]. The large S Alaska magnetic high correlates with the Wrangellia terrane [66]. Based on magnetic data [67], the fault is regionally recognized as a 10± km wide zone with a WSW orientation along the NW margin of this large S Alaska magnetic high (Fig. 5). The fault zone has narrow ENE oriented magnetic highs and depressions with azimuths of about N60°E. This fault zone appears to be aseismic [68-70] at least for the N Talkeetna Mountains.

3.2 The Seismic Vp 7.8 km/sec Depth Contour Slice Fault Offsets

The 7.8 km/sec Vp 70 km depth contour, which represents the YAK [7], shows a 90 km offset for MC at an azimuth of N60°W (Fig. 6). Based on these 7.8 km/sec Vp depth contours, even with poor resolution, 7 more offsets are recognized in the subducted YAK. The largest indicates a sinistral displacement of about 160 km at depth and is located about 190 km N of the MC. It is called the Buzzard Creek slice fault (BC) because it passes under the Buzzard Creek Maars [71]. N of the MC, the YAK is believed to be subducting WSW at a very slow rate [27, 28] into the Denali volcanic gap (Figs. 1 and 3). The primary evidence for YAK movement into this gap is the dextral movement of the Denali fault [9] in the region of the N edge of YAK. The second evidence for such subduction is the existence of BC itself (Fig. 6). The subduction rate is slow because the Aleutian trench approaches YAK’s E boundary, making its WSW subduction length much smaller. The total gravity force per unit width on the YAK N of MC would be smaller for subducting the YAK [72] compared to the total gravity force per unit width on the YAK to the S, which subducts faster and has associated active volcanoes. The mantle wedge above the subducting YAK N of MC is therefore too small and cold to form a required “pinch zone” beneath the crust to accumulate much melt [73]. This is why the Denali Gap exists even though the YAK is actively subducting WSW. The Buzzard Creek maars consist of subduction arc magma [74] like the Cook Inlet volcanoes. Its magma would originate from the YAK by means of the BC. This must be the case because the PAC is actually absent at this location. PAC does exist to the W of these maars; but, any rising magma from it would be blocked by YAK. Then, as final evidence for the WSW movement of YAK N of MC, the NA is moving WSW against the YAK [33] and therefore NA is actually forcing YAK to also move WSW.

Just 20 km and then another 10 km S of the MC, two more dextral offsets occur in the 7.8 km/sec Vp 70 km depth contour of 40 km each (Fig. 6). These faults trend beneath the Mount Spurr volcanic complex and are called the Mount Spurr (MS) and Mount Spurr South (MSS) slice faults. They strike NNE through unmapped Peninsula terrane of the Talkeetna Mountains. They both appear to be associated with two roughly linear N60°E azimuth seismic zones in the Talkeetna Mountains [68-70]. A shallow 7.1 mb (7.4 Ms) magnitude dextral strike-slip earthquake occurred on 3 November 1943 [75] on the MSS just to the W of the Talkeetna Mountains. The two slice faults with a 10 km separation are recognized in the Talkeetna Mountains on digital relief [76] as linear features at again an azimuth of N60°E. The N MS trends into the N Mount Spurr magma conduit and the MSS trends into its S magma conduit. Based on Vp/Vs ratios, these two Mount Spurr magma bodies are, as would be expected, 10 km apart [77].

The next two 7.8 km/sec Vp 70 km depth contour offsets occur about 80 km and another 40 km further S with 25 km and 20 km dextral offsets, respectively (Fig. 6). These offsets appear to be associated with Redoubt and Illiamna volcanoes, respectively. At another 50 km S, a large 100 km dextral offset occurs with the 7.8 km/sec Vp 70 km depth contour, which corresponds to Augustine volcano. Then with another 80 km S, the 7.8 km/sec Vp 70 km depth contour
disappears, which would correlate with the sinistral Katmai slice fault (KAT). The KAT represents the S limit of YAK in the Alaska Peninsula. This S boundary aligns with the very linear Katmai N55°E azimuth volcanic chain. But, these actual deep offsets seen on the 7.8 km/sec Vp depth contours are actually about 60 km N of the actual feature near the earth surface due to the NNW regional subduction of PAC.

### 3.3 Two Independently Subducting Plates

The WSW subduction of YAK into the Cook Inlet and N Alaska Peninsula regions is also supported by the existence of a fairly pronounced double seismic zone in the Wadati-Benioff zone (WBZ) [78, 79]. Double seismic zones within a subduction zone are actually not rare [80] and have been explained due to differential thermal stresses, bending and/or unbending of plates, phase changes, and preexisting interplate faults [81, 82]. For simple subduction cases, the upper part of the subducting plate has tentional forces pulling the plate in the direction of subduction and the bottom part of the subducting plate would reflect downward compression in the direction of subduction. For the Cook Inlet region, the upper part of the YAK has a maximum downward compression perpendicular to the WNW subduction direction with the tensional component being WNW [79, 83]. In contrast, the stress pattern for the deeper PAC in the subduction zone has little seismic activity and indicates a strong horizontal compression to the NNW. Upon closer examinations, the deeper part of the YAK has been found to have in the Cook Inlet region a pronounce WSW maximum compression plunging 40 to 60 degrees [84], which was originally considered.

---

**Fig. 6** Depth contoured plot of 7.8 km/s isovelocity [7] with slice faults indicated as white lines. The estimated slice fault offsets are indicated in red.
incorrectly as the PAC. Even deep “shear wave splitting” investigations indicate two pronounced compressional fast directions in this region, one WSW and the other NNW [83, 85-88]. Also, the stress field throughout most of the Aleutian volcanic arc has been recognized by using volcanic edifice orientations; but, such recognition was not possible for the Cook Inlet region [89] due to the lack of any one prominent edifice orientation. The simplest explanation for the Cook Inlet double seismic layer is the existence of two plates having different subduction directions!

From seismic earthquake locations [78], a pronounced 20° change in the orientation of the WBZ exist between the Katmai region and the Cook Inlet region at about 59° N latitude (Fig. 3), which indicates a major change in subduction mechanism. There is even a larger 37° orientation difference between the very linear N 18° E Cook Inlet volcanic chain and the very linear N 55° E Katmai volcanic chain. In fact, extending the linear Cook Inlet volcanic arc to the Katmai volcanic arc, the intersection occurs at the Kaguyak volcano instead of at the most E Mount Douglas volcano of the Katmai volcanic chain [90], which is a 35 km difference. Such a large distance again suggests a different mechanism of subduction between the two regions and not just due to bending of a subducting plate. The WBZ is also at least 15 km thicker N of this “bend”, which is additional evidence for the existence of two different subducting plates operating in the Cook Inlet and Katmai regions.

3.4 Katmai vs. Cook Inlet Volcanic Magma Sources

But, even of more interest, is the fact the Katmai volcanoes are located about 70-80 km above the top of the WBZ, while the Cook Inlet volcanoes are located at a more expected 100 km depth above the WBZ [91]. The magmas feeding the Cook Inlet volcanoes are coming from YAK when its top is at an approximate 100 km depth, while the magmas feeding the Katmai volcanoes are principally coming from the top of the PAC when it is also at a 100 km depth. The PAC is subducting steeply beneath a flat-slab WSW subducting YAK with its top at a 70-80 km depth. Even though the YAK is oriented with the dip of the PAC at this location (Fig. 4b), it is not subducting NNW and it is not producing much of the Katmai magma! Instead, it is subducting/moving WSW. This would be similar to the Wrangell WBZ (Fig. 4a), which reflects an active but in this case probably not moving RESUR? captured slab. Also, similarly to the PAC in the Wrangell WBZ [47], the PAC has little seismic activity at depth in the Katmai region with the YAK actually producing most of the earthquakes [68, 78]. These are both examples of the WBZ not representing the actual subducting plate.

3.5 The Katmai Slice Fault

The most S YAK boundary is the KAT, which cuts across the N part of the Alaska Peninsula and across the S Kenai Peninsula and S PWS (Figs. 1 and 9). On a regional basis over time, a lot more seismic activity occurs to the N of it than to its S (Fig. 3) [78, 79]. The KAT extends under the Hallow Creek fault of the Katmai region and it is the boundary of the S limit of the Bruin Bay fault (Becharof-Iniskin fault) [92] to the SW (Fig. 1). Interestingly enough, the Holocene Katmai volcanoes (Peulik, Trident, Katmai caldera, Kukak) are at a near perfect N55°E orientation. This would reflect the direction of the KAT as well as its approximate location in this region. In 1983, it was proposed a deep fault was controlling the location of the Katmai volcanoes [93]. This fault would be the KAT.

Surface expressions of the KAT in the above NA is also well exposed along its E part as reflected by the Rude River, Cordova, Etches, Evak, Heney, and numerous other faults [92] and by numerous WSW oriented linear features [94]. An N 60° E projection from Mount Douglas volcano crosses this region of faults and linear features. The regional sinistral offset just N of Cordova (Fig. 9) in the form of sinistral bending and faulting in an estimated total amount of 60 km can be inferred between the Prince William and Chugach terranes as marked by the Contact fault
[95-97]. This also supports sinistral motion on the KAT. The 70 km of sinistral offset, inferred by the 7.8 km/sec Vp depth contours (Fig. 6), is probably correct with less of the offset being reflected by the surface NA.

The KAT extends under the PWS region without any apparent Holocene sinistral movement [92]. Such movement might not be occurring because the yak has penetrated into YAK sometime in the Pliocene and is now moving with it [27, 34]. The bending of the old surface expression of the KAT on Montague Island could represent such an impact (Figs. 1 and 12). Significant uplift occurred on the Montague Island part of this fault during the 1964 Alaska earthquake with reverse fault movements observed on the Patton Bay fault of just over 7 meters and on the Hanning Bay fault of 5.5 meters (Figs. 3, 12 and 16) [98]. Minor sinistral movements were observed on both of the S ends of these faults. The Johnstone Bay fault (Fig. 3) on the mainland has had Holocene uplift with some sinistral motion [92]. There is a cause for such movements, which will be explained later. Even though the KAT shows no evidence for Holocene movements on its E end, it is seismically active in this region with three more near vertical seismic zones having similar activity to the S at distances of 20 km (Katmai South slice fault, KATS), 32 km, and 45 km, respectively (Fig. 4e).

3.6 The Augustine Slice Fault

The KAT is seismically active on its E end; but, just 50 km N is an even more active seismic zone [56]. On this zone, there was a 6.2 mb dextral strike-slip Columbia Glacier earthquake on 12 July 1983 with a hypocenter depth of 22-32 km [99], which would put it in the YAK. Based on aftershocks, the fault was oriented S 58° W with a near vertical NW dip (Fig. 7). If one extended this fault S 60° W, Augustine volcano would be encountered, which is one of the most active volcanoes of the Cook Inlet volcanic chain [100, 101] (Fig. 8). This Columbia Glacier earthquake was on the Augustine slice fault (AUG), which would be about 45 km N of the KAT (Figs. 6 and 9).

3.7 1964 Alaska Earthquake Epicenter; Multiple Events and Aftershocks, Which All Locate on Slice Faults

The AUG extends across the main epicenter of the 1964 Alaska earthquake [102, 103] (Fig. 9). Of even more interest, most of the 5 or greater magnitude aftershocks of this earthquake that occurred N or on KAT are also on slice faults (Fig. 9). The largest cluster occurred near Seldovia on KAT. Even more amazing, the 1964 Alaska earthquake consisted of at least six recognizable multiple pulse events in addition to the initial event and most of these locate on slice faults [102]. These pulse events were originally labeled in their order of occurrence as A, B, C, X, Y and Z (Figs. 9 and 10). The A and B initial pulse events occurred on the KAT just S of the main 1964 Alaska earthquake epicenter. These A and B events are in the region of impact between yak with YAK. Then, the event X occurred on the AUG along with several aftershocks. The Y followed and it is on the Iliamna slice fault (ILI).

![Fig. 7 Map of the 1983 Columbia Bay two main shocks and corresponding aftershocks [99]. The solid circle is the 7 September 1983 19:22:05 UT 6.2 mb event at 30 km depth. The solid triangle is the 12 July 1983 15:10:03 UT 6.4 Ms event at 30 km depth.](image-url)
Fig. 8  Augustine volcano with active nuée ardente of 9 February 1976 at 00:02:40 UT, which was taken by the University of Washington Cloud and Aerosol Physics Group [101].

Fig. 9  Map of the 27 March 1964 Alaska earthquake epicenter, its aftershocks and its six recognized multiple rupture events A, B, C, X, Y and Z [102]. The locations of the slice faults are shown in red.
3.8 The Iliamna and Iliamna South Slice Faults

Just short of one week after the 1964 Alaska Earthquake, a large aftershock occurred of special interest. It was strongly felt in the Anchorage area, causing panic during my Friday Wasilla Junior High School student council meeting. It occurred at 04/03/64 at 22:33 UT, had a 6.5 Mw and an amazing hypocenter depth of 56 km [104]. Its focal mechanism had a strike of 76° ± 16°, a dip of 75° ± 10° and a plunge of -5° ± 5°. This aftershock is on the ILI (Fig. 9) and had sinistral strike-slip fault movement with a hypocenter at the bottom of the YAK if not in the upper PAC [99, 102, 104]. The net displacement on the ILI has been determined by 7.8 km/s isovelocity 70 km depth contour (Fig. 6) to be about 20 km dextral. This event suggests sinistral displacements are presently occurring on the ILI. In order for this to happen, the Augustine/Iliamna (AUG/ILI) slice of the YAK must be “snagged” with either the PAC underneath and/or with the NA above. The ILI/RED slice, which is bound by the ILI and the Redoubt slice fault (RED), appears to be freer to move to the WSW due to the force of gravity [72] than the snagged AUG/ILI slice. Such a snag appears to possibly exist at the depth of 55 km on the AUG/ILI slice (Fig. 4c) at about 60.2° N and 151.1° W [84]. A double-seismic zone exists at this location in the WBZ that marks the boundary between the YAK and the PAC underneath. Extensive seismic activity is occurring in the PAC at this location when normally the PAC is fairly aseismic. It might be due to a seamount or an accretionary wedge at this boundary; but, the actual cause is presently unknown. Never the less, it is possible that the PAC has partially snagged the YAK even at these depths, causing the AUG/ILI slice to slow in its subduction rate [105, 106].

Several other deep sinistral strike-slip earthquakes have also occurred on the ILI (Fig. 11b). The 10/21/62 earthquake at 02:05 UT of 6.0 Ms occurred in the Turnagain Arm area just S of Anchorage [107]. It had an amazing hypocenter depth of roughly 71 km, which would put it well into the PAC. Another ILI earthquake occurred 10/03/54 at 11:18 UT just SW
of Anchorage, which was 6.8 Mw at a hypocenter depth of 60 ± 10 km. It caused damage in the Anchorage area, including landsliding of some of the Alaska railroad tracks into the Turnagain Arm [108].

Further WSW, these deep sinistral strike-slip earthquakes appear to shift to another parallel slice fault 20 km to the SE, which has not been previously described and is called the Iliamna South slice fault (ILIS). The 01/24/58 6.4 Ms at 52 km hypocenter depth, the 06/18/34 6.8 Mw at 76 km hypocenter depth and the recent 01/24/2016 7.1 ml at 123 km hypocenter depth (USGS National Earthquake Information Center) have sinistral displacements on this ILIS.

The ILI/ILIS slice is suspected to be moving more with the ILI/RED slice due to it being well NW of the large seismic PAC anomaly at 52 km depth (Fig. 4c). In fact, the 10/03/54 event also had a slight SW deviation from the ILI toward the ILIS. As the AUG/ILI slice moves into the WBZ, gravity forces on this slice [72] help the ILI/ILIS slice to form. This could explain why the large Iliamna volcano has had no historical volcanic eruptions [100]. The AUG/ILI slice is presently not subducting as it has in the past. Such a stall would actually apply stresses on the PAC beneath because the PAC is believed to be partially deviating to the WSW with the YAK, which would have been initiated under the yak and then developed more under the KAT/AUG slice. This might be why the ILI and ILIS are having sinistral strike-slip movements that actually begin deep in the highly stressed PAC instead of in the YAK. However, at the great depths of 50 km, not much blockage would be expected from any anomalies/underplating between the PAC and YAK [109]. Could then the principal cause for this blockage of YAK be by the NA above?

3.9 Underplating beneath AUG/ILI Slice at the West Chugach Mountains

Underplating the NA in the heart of the W Chugach Mountains would be very effective in slowing down the AUG/ILI slice movement to the WSW. In fact, the most vertical uplift has occurred on the S edge of the W Chugach Mountains in the PWS, which is on the AUG, with determined exhumation rates of up to 0.7 mm/yr as based on Apatite thermal/age investigations.
Uplift is also obvious just N on the ILI as marked by the 3,269 m altitude Mount Marcus Baker, the highest peak in the Chugach Range. The NA is probably what is principally slowing down the subduction of the AUG/ILI slice.

3.10 Evidence for Active ILI and ILIS during the 1964 Alaska Earthquake

These deep originating ILI and ILIS faults were likely active during the 1964 Alaska earthquakes. This would explain the numerous and deep dominantly SSW oriented and up to 10 m wide fissures found by the U.S. Geological Survey throughout the region between ILI and ILIS [112]. These observations were made just after the 1964 Alaska earthquake on the N Kenai Peninsula, which is just SW of Anchorage. Surprisingly, ejected small solid pieces of freshly broken coal and lignite from the beneath Kenai Group were found at some of the larger fissures. A deep fault involvement at that time was strongly suspected in this region during this earthquake [112] along with obvious evidence for liquefaction of the unconsolidated Quaternary deposits covering the entire region.

3.11 Other Sinistral Slice Fault Movements

Sinistral strike-slip displacement occurred with the 09/05/61 M 6.1 shallow earthquake on the KAT (Fig. 11a), which is just ENE of Seldovia (Fig. 9). Seismic activity along and just N of the KAT in this area has been and still is occurring as based on the Alaska Earthquake Information Center Database. Father N, another sinistral 03/25/32 Mw 6.8 earthquake occurred above the BC at a depth of 40 km, which would put it in the NA. This event occurred near the Denali fault, which has had dextral strike-slip movement and was the fault involved with the generation of the Mw 7.9 earthquake of 3 November 2002, which started just to the E of this 1932 event [9]. Such documentation of sinistral strike-slip earthquake events on sinistral faults such as the BC and KAT as well as sinistral strike-slip earthquakes on a net dextral ILI and ILIS indicate some sinistral fault movements do indeed occur in S Alaska [113] with regional dextral movements obviously dominating [114, 115].

3.12 Redoubt Slice Fault

The Redoubt slice fault (RED) has had shallow dextral strike-slip earthquakes (Fig. 11a). The 9 km hypocenter depth 04/27/33 dextral strike-slip event just W of Anchorage is such an example. Other even deeper events on RED have been detected S of the Knik Arm just ENE of Anchorage (Fig. 11b). A little further ENE, the Eklutna hydroelectric powerhouse, which is on the Knik River flood plain, experienced extensive ground cracking and subsidence during the 1964 Alaska Earthquake [116]. Liquefaction naturally would be expected to occur in these water saturated fluvial deposits; but, the amount of subsidence and the size of the ground cracking was unusual compared to other braided streams in the region. What occurred at this power plant appears to be similar in degree to what was observed on and between the ILI and ILIS just SW of Anchorage [112]. Did the RED move during the 1964 earthquake? Inside the Eklutna Powerplant water-supply tunnel about 2/3 of the way to the Eklutna Lake, a 10 m wide near vertical fault exist [116]. This fault is directly above the RED and it is suspected to be part of the RED. This concrete lined tunnel had extensive debris in it following the 1964 Alaska earthquake; but, the tunnel has never been actually surveyed in detail after this earthquake.

3.13 Mount Spurr and Mount Spurr South Slice Faults

A fair amount of seismic activity occurs in the region of the Mount Spurr slice faults [68-70]. In the Talkeetna Mountains, this activity is more intense and roughly aligns ENE along these faults. To the W of the Talkeetna Mountains a large 7.4 Ms earthquake occurred on 11/03/43 as previously described (Sect. 3.2) [107]. It had a hypocenter at 27 km depth, had WSW dextral slip motion and was located directly on the MSS (Fig. 11a). The MSS trends beneath Crater...
Peak on the S summit region of Mount Spurr volcano, which is the most active vent of this volcano [100].

A nice double layer in the WBZ also exist in the S Talkeetna Mountains [84] where numerous earthquakes occur in the YAK and also in the underneath PAC at about 61.8° N and 149.7° W (Fig. 4d), which is just S of MSS. At this location, the boundary between the YAK and the PAC is at a depth of 45 km. The anomaly is like the one described under the AUG/ILI slice except this one is much larger, not as deep, and extends to the SSW beyond the Castle Mountain fault [84]. It appears to be associated with the apex of a PAC anticline (Fig. 4d) just as the PAC begins its plunge NNW into the Aleutian subduction zone. The YAK appears to have been disrupted as it moved WSW over and just beyond this PAC apex. A large slip event was recognized at this depth [117] in this region during 1998 to 2001. But, the PAC and YAK thrust fault contact could still be partially locked even at these great depths [105, 106]. Again, like with the AUG/ILI slice, the NA is probably locking more to the YAK than the underneath PAC is locking to YAK.

3.14 Vertical 1964 Crustal Deformation Also Reflects Slice Faults

The existence of the slice faults fit well with horizontal strike deviations of the vertical fold deformation of the crust that occurred during the 1964 Alaska earthquake. The earthquake caused extensive uplift along the southcentral Alaska Pacific side with subsidence inward in a form of a large fold [36], which effected an estimated 300,000 km² region (Fig. 12). By transposing the slice faults over this 1964 fold, a pronounced change in fold direction occurs across the KAT, AUG and even RED. A fold strike of N 34° E changes to a nearly N strike for the KAT/AUG slice with an apparent offset on the AUG of 50 km before the fold goes back to its roughly N 34° E strike. The total offset on the AUG has been estimated as 100 km dextral. Apparently, the displacement by this deep fault has been partially passed upward to the surface. Only a slight sinistral 6° deviation occurs with the strike of the fold across the ILI. This is probably because the WSW subduction of the AUG/ILI slice is blocked by NA from above, which is resulting in the sinistral ILI offsets as previously discussed. The offset represented at the surface is only about 2 km sinistral. Given that the estimated total offset for the ILI is 20 km dextral (Fig. 6), this opposite deviation from the norm has probably not been going on very long with respect to geologic time. Another offset occurs on the RED near the A-A’s line (Fig. 12). The strike of the fold deviates on this slice fault from N45°E to N64°E on the RED and then after a 35 km displacement on the slice deviates back to N46°E, which fits with a deep dextral offset for the RED. This offset is actually 10 km larger than the dextral total offset estimate of 25 km (Fig. 6); but, it is still barely within the 10 km resolution of the 7.8 km/s isovelocity depth contour plot. It appears that the total offset of the RED is reflected at the surface with this dextral offset total being about 30 km. This RED offset reflects the existence of the Knik Arm and the Matanuska Valley enclave in the W Chugach Mountains (Fig. 2). Because the Eklutna Powerplant water supply tunnel from Eklutna Lake was built before the 1964 Alaska earthquake, it should be carefully resurveyed for any offsets since its construction. Movements along the Katmai, Augustine, Iliamna, Iliamna South and Redoubt slice faults during the 1964 Alaska earthquake are very strongly suspected.

3.15 The Slice Faults Also Fit the Geology of the Cook Inlet Basin

These recognized slice faults also fit the geology of the Cook Inlet basin [118] (Fig. 13). Bends of anticlines and actual fault offsets of some anticlines in the Tertiary Kenai Group exist due to the slice faults. Even a correlation with known oil and gas reservoirs exist with respect to these deep faults. Possibly the effect of active movement of the slice faults have helped to fracture the generally impermeable Mesozoic
underlying strata, which would help with hydrocarbon migrate to the above Tertiary strata. These slice faults have probably even helped create structures in the Tertiary strata for catching any rising hydrocarbons. For example, the West Foreland field (structure 20) S of the RED is dextral of the Trading Bay field (structure 19) N of RED by several kilometers. On the same slice fault, the Middle Ground Shoal oil field to the S of the RED is dextral by about 4 km to the Granite Point oil field to the N. The anticline 14 S of RED is offset as a dextral 5 km bend across the RED with the large North Cook Inlet gas field to the N on the same anticline 14.

The deep ILI shows as predicted sinistral offsets of anticlines (Fig. 13). The West Fork gas field (structure 29) terminates at the ILI with the Swanson River oil field (structure 24) having a 4 km sinistral offset as the suspected continuation to the N. The Sterling gas field (structure 30) is S of this ILI and the Beaver Creek field (structure 23) would be its continuation to the N with an approximate 7 km sinistral offset. The large Kenai gas field (structure 31) is S with only
minor discoveries found to the immediate N of ILI. One should look offshore N of ILI by an 8 km sinistral offset amount from the Kenai gas field for another possible large field. Further to the S is the active ILIS. It truncates the N end of the Falls Creek field (structure 33) and another anticline structure is recognized again with an 8 km sinistral offset just N of ILIS (structure 32). This needs obvious exploration.

The AUG has dextral bend offsets of anticlines (Fig. 13). Anticline 41 is offset by about 9 km and anticline 36 is offset by about 5 km, both being dextral bending. Then, the KAT cuts through a region lacking any structure when structures exist immediately N and S. The KAT is actually located 7.5 km NNW of the

Fig. 13  Location of anticlines and faults in the Tertiary part of the Cook Inlet Basin, Alaska [118]. The locations of the slice faults are shown in red.
Mount Douglas volcano summit and it is actually located 4.5 km NNW of “downtown” Seldovia. Even though these slice faults are originating deep within the YAK, their influence are not only recognized with regional geology of the Cook Inlet basin, but they can even be more accurately located based on this shallower geology!

3.16 Wrangell Volcanoes, Mud Volcanoes and the Iliamna Slice Fault

The Wrangell volcanoes and associated mud volcanoes with respect to YAK would be associated with its E spreading ridge with the YAK moving to the WSW. Due to this WSW spreading of YAK from NA, the Totschunda fault (Fig. 3) would be the new W developing Denali strike-slip fault. But, with respect to PAC and NA, the Wrangell volcanoes are associated with a subduction zone [46], which would be why Wrangell volcanism show some calc-alkaline subduction zone characteristics even though their major character is tholeiitic [40, 119]. Indeed, justification exist for these volcanoes being associated with both subduction and spreading ridge processes because tholeiitic magma is characteristic of spreading ridges and calc-alkaline magma is characteristic of continental subduction zones. But, surprisingly with respect to slice faults, several of the Copper Valley mud volcanoes [120] as well as Mount Stanford and Mount Drum are in rough alignment with the ILI (Fig. 12). Naturally, the slices have moved to the WSW millions of years ago; but, their slice fault fractures in the above NA appear to possibly still remain in the Copper River collapsed basin of NA crust. Such fractures would have influence on geothermal fluid and magma migration.

4. The “Yak” Part of the Yakutat Plate

The P wave of the 1964 Alaska earthquake was clearly divided into two first motion pulse fields [37] with the second pulse nodal plane having a strike azimuth of 344° with a dip of 26° to the NE and with an epicenter at about 59°31.25’ N and 147°22.5’ W; i.e., the large pulse “C” (Figs. 9 and 10). The very initial shock had an N66°E azimuth with a dip of thrusting by PAC of 15° to the NNW with an epicenter at 61.05° N and 147.5° W [121]. Excluding the Kodiak Island part of the “megathrust” between PAC and NA [102, 122], three different megathrusts actually occurred during the 1964 Alaska earthquake with two of them occurring as movement between the Yakutat plate (YAKp) and PAC, and the third occurring as movement WSW of the YAKp with respect to the NA [123]. In this report, any large and sudden thrust movement between two plates would be a megathrust. The two PAC to YAKp megathrusts would be the initial shock and then pulse “C”. This C pulse was the yak thrusting WSW onto PAC. This large yak megathrust occurred as movement over a region completely S of the KAT. For example, the largest yak thrust aftershock occurred 30 March 07:09:34.0 UT at 59.9° N and 145.7° W with a 15 km hypocenter depth and with a 5.6 mb [102]. It had an azimuth of 310° with a 6° dip to the NE. In fact, most of the recognized aftershocks for the E part of the 1964 Alaska earthquake [103, 121] occurred S of the KAT in the above NA (Figs. 4e and 9). The main megathrust of PAC moving NNW beneath the YAKp toward the Aleutian subduction zone had next to no recognized aftershocks!

The E edge of yak with NA is marked by the Fairweather transform fault. Relative to NA, yak is moving 50.3 ± 0.8 mm/yr at an azimuth of N 22.9 ± 0.6° W, which was measured at the community of Yakutat, Alaska [5, 32, 33]. PAC is theoretically predicted to be moving 50.9 mm/yr at an azimuth of N14.6°W at this same location relative to NA. As the Fairweather fault curves sharply to the W from its nearly true NNW strike at the SE end of the yak, it remains a dextral near vertical strike-slip with some thrusting [55, 124]. To the NW, this transform is called the Contact fault and/or Bagley Glacier fault [29, 92]. It remains a transform between NA and the
The Active Yakutat (Kula?) Plate and Its Southcentral Alaska Megathrust and Intraplate Earthquakes

Fig. 14  Earthquake and fault location map of southern Alaska margin [130]. CSE, Chugach-St. Elias fault; PZ, Pamplona fracture zone; and RMT, Ragged Mountain thrust. The yak2 is indicated, which is forming and is expected to join yak.

deformed yak beyond the Pamplona fracture zone (Fig. 14). The Pamplona zone reflects extensive deformation in the yak by means of a maze of oblique faults [125] compounded with folding [126]. The Fairweather fault upon reaching the YAK continues as the KAT (Fig. 1). If the Bagley Glacier (Contact) part of this Fairweather fault is locked, which is indicated by seismic studies and seismic history [127, 128], then there is truly a Yakutat seismic gap (Fig. 21) that needs to be of major concern. The large Pamplona zone earthquakes such as the great Yakutat Bay earthquakes of September 1899 [129] probably are not the largest type of earthquakes to occur in this seismic gap region.

A pronounced roughly N-S fracture zone called the Gulf of Alaska shear zone (Figs. 1 and 14) has been recognized [44-45] S of the Pamplona fracture zone intersection with the Transition fault at the S edge of the yak. This active Gulf of Alaska shear zone extends S to the 57° N latitude of the NE Pacific and is probably the S continuation of the Pamplona fracture zone into the Gulf of Alaska PAC, where dextral strike-slip movements dominate. The shear zone has in its middle a major dextral offset by an N29°W fracture as indicated by small seismic activity in the PAC [45]. This fracture extends into the Aleutian Trench where it marks a pronounced boundary between seismic activity to the W and the Wrangell WBZ to the E. Its strike is the same as the motion of the PAC. This NNW fracture would be the beginning of the “tear” rift postulated to exist [8]. It originates from at least the 57° N latitude. Another fracture is forming as based on small seismic activity perpendicular to the Gulf of Alaska shear zone just N of this 57° N latitude. It extends E toward the Fairweather fault just N of the Mt. Edgecumbe volcanic field [130]. This new fracture, named the 57° N PAC fracture, should be dextral. The Gulf of Alaska
shear zone, the Transition fault, the Fairweather fault and the new 57° N fracture mark the boundary of the yak2 slab, which is forming at the expense of PAC.

The PAC is pulling away from NA, resulting in the Mt. Edgecumbe spreading ridge just SW of the S end of the Fairweather fault. The Mt. Edgecumbe consists entirely of tholeiitic mid-ocean ridge basalt, which is unique for SE and S Alaska [119, 131, 132]. Mt. Edgecumbe represents the only true spreading ridge of the region except for the Explorer ridge off the British Columbia coast to the S [133]. Just WSW of this volcanic field, the Queen Charlotte transform fault joins the Mt. Edgecumbe ridge. Just ENE of this ridge, the Fairweather transform fault starts [133, 134] as dextral movement between yak2 and NA with some compression [33, 135]. The NA is moving WSW against it, pushing the entire yak2 W and pushing even more the yak W. This would mean the Transition fault, which is the near vertical boundary between yak and yak2 must be a sinistral strike-slip as was originally proposed in 1983 [1] in contrast with other interpretations [3, 29, 30]. Based on GPS motions [32], sinistral motion is occurring and must be at a rate less than 10 mm/year and most likely much less (Fig. 1). Seismic lines across the Transition fault indicate it is near vertical [31] with no obvious displacements, although detecting such displacements, especially lateral, would be very difficult given the resolution of the data. Deep deformation of the PAC is occurring at the E part of the Transition fault with the PAC not subducting beneath the yak [37]. The Moho has been determined to be very deep in this region, reaching a depth of just over 30 km under the yak [136].

Yet the NW part of yak has collided as a flat slab with YAK in the PWS and the yak is principally moving WSW [35] with YAK, both being beneath the NA [4]. A structural profile of the Cook Inlet to the Aleutian Trench from seismic data (Figs. 12 and 15) shows the effect of the WSW moving thrust of yak onto the PAC. This thrust has caused an N-S striking anticlinal fold in the PAC just to its W. The structural profile represents refraction/reflection seismic investigations for its ESE end [4] and represents scattered-wave dVs/Vs imaging for its W end [137]. The zone of maximum surface horizontal displacements observed for the 1964 Alaska earthquake (Fig. 16) includes the region of the apex and the E side of the N-S oriented anticline in the PAC. This PAC anticline apex reflects the approximate W limit of maximum locking between PAC and the Yakutat plate (YAKp) released during the 1964 Alaska earthquake. The yak thrust onto the PAC was not only a major part of the 1964 Alaska earthquake, but it also is causing this PAC anticlinal fold that continues beneath the YAK in a nearly true N direction. Such an orientation is due to the PAC NNW movement combined with the slower yak WSW movement. The yak, by causing this PAC anticlinal fold, is also causing the main locked megathrust zone between PAC and YAKp, which is considered the main cause of energy release for the

Fig. 15 Structural profile determined by seismic data from the Cook Inlet of Alaska point C'' to the Aleutian Trench point C (Fig. 12). The profile consists of scattered wave dVs/Vs seismic image [137] for C'' to C’ and seismic refraction/reflection velocity model [4] for C’ to C. The apex of the Pacific plate anticline is indicated.
The Active Yakutat (Kula?) Plate and Its Southcentral Alaska Megathrust and Intraplate Earthquakes

Fig. 16  Vector components of relative horizontal plate displacements for southcentral Alaska resulting from the 1964 Alaska earthquake [35]. YAKp is the Yakutat plate (YAK & yak), PAC is the Pacific plate, NA is the North American plate. The Patton Bay (P) and Hanning Bay (H) faults are on Montague Island. Middleton Island (M) is indicated. The N-S striking Kenai lineament N of Seward is also roughly shown (Fig. 2).

1964 Alaska earthquake [36]. There would not have been a 1964 Alaska earthquake if it was not for the existence of yak thrusting to the WSW. The Kenai lineament [92] is the approximate surface reflection of the apex of this PAC anticline (Fig. 16). It trends N from Seward, a coastal community on KAT (Figs. 2 and 9), until it is terminated by AUG (Fig. 12). But, the anticlinal fold of the PAC continues straight N under the YAK beyond the AUG to the E part of the Holocene scarps of the Castle Mountain fault (Fig. 16) where PAC starts it more steep subduction. This anticlinal fold is suspected to be associated with these
Holocene scarps as well as with the E edge of a deep seismic anomaly in PAC in the S Talkeetna Mountains (Fig. 4d).

The yak at its far W end moved WSW 9.32 m during the 1964 Alaska earthquake (Fig. 16) as measured at Middleton Island [35]. With more recent GPS measurements, a WSW movement of crust for the SW part of PWS has also been recognized [138], which has been called the Bering Deformation Zone. WSW movement for yak has also been suggested for the offshore Pamplona fracture zone region of central yak [126, 139, 140].

5. Evidence for Two Types of Megathrust Earthquakes for Southcentral Alaska

Until now, it has not been actually clarified whether the 1964 Alaska earthquake for the southcentral Alaska part of the thrust was between the Yakutat plate and NA and/or between the Yakutat plate and PAC. Most have argued the Yakutat plate is attached to the PAC and as such is travelling directly with it to the NNW [1-10, 141] resulting in the Yakutat slab (Fig. 2). Actually, most of the recorded aftershocks for the E part of this great earthquake occurred in the NA above the yak thrust, which had moved WSW over the PAC (Figs. 4e and 9). It was not realized the Yakutat slab (Fig. 2) of the YAK had actually originated as a KULA-RESUR captured ridge in the Paleocene. It was also not realized that most of the seismic activity is occurring in the YAK, yak and NA in contrast to the somewhat seismically quiet PAC beneath (Fig. 4a-e). The 1964 Alaska earthquake movements for southcentral Alaska were principally between PAC and the Yakutat plate (YAKp). But, a limited amount of movement between the YAKp and NA did occur during this earthquake, which will be explained.

The horizontal ground displacements caused by the 1964 Alaska earthquake [35] for southcentral Alaska show a clear surface crustal movement that rotates from a near SSE direction in the W region to a more SE direction to the E. This eastward rotation is believed to reflect an actual increasing movement of the YAKp with respect to NA to the WSW along the thrust between them (Fig. 16). This movement started at the “Y” pulse event [102] for the 1964 Alaska earthquake (Fig. 9) and extended into the PWS, staying S of the epicenter and then extending W into the Turnagain Arm of the Cook Inlet. The region N, which includes the W Chugach Mountains and the S Talkeetna Mountains, did not indicate any movement between YAK and NA. This zone appears to be locked.

The maximum horizontal movement for the earthquake was 19.6 m to the SSE (Fig. 16), which occurred on the mainland of the SW region of PWS [35, 36]. The nearly NS striking Kenai lineament (Fig. 2) is just NNW of this maximum movement, which had 1.5 meters of differential dextral displacement alone across its 6 km wide zone. It would represent the strike of the PAC anticline axis (Fig. 15), which appears to represent the W side of the main locked zone between YAK and PAC as based on these large displacements. Yet the dominant slip direction of S 18°E (Fig. 16) at this location reflects a combined regional PAC motion of 6.5 cm/yr N29°W [130] and by vector analysis about a 1.35 cm/yr S60°W YAK motion. Surprisingly, this PAC anticline apex does not appear to be blocking YAK from its WSW movement at their fault contact, at least not during the 1964 Alaska earthquake.

Middleton Island had 9.45 m of movement S50°W during the 1964 earthquake [36]. This would represent 9.32 m to the S60°W for the yak thrust onto PAC and only 1.64 m to the S30°E for the yak to PAC thrust. The Patton Bay and Hanning Bay reverse faults have taken up most of the movement caused by PAC in this region [36, 98]. It will be shown the recurrence interval for the 1964 Alaska type of megathrust earthquake is about 850 years. Assuming this is the recurrence interval for the 9.32 m WSW movement for Middleton Island, this would represent an average movement of about 10.8 mm/yr WSW for Middleton Island and for the W end of yak. This is a little low
compared to the 1.35 cm/yr WSW previous vector component determination for the YAK, or more likely, the YAK is simply moving faster due to the larger combined mass of YAK and NA [72].

6. The Significance of Castle Mountain and 1964 Reverse Faults

6.1 The Patton Bay and Hanning Bay 1964 Reverse Fault Movements

The Patton Bay and Hanning Bay faults (Figs. 3 and 16) are the only faults with 1964 Alaska earthquake surface breaks to have been found [92, 98], which were interpreted to represent a “short circuit” reverse thrust branching from the main 1964 Alaska megathrust [36]. These faults would be the reactivation of the past NA expression of the KAT. The axis of maximum uplift caused by the 1964 Alaska earthquake of over 10 m occurred parallel to both of these faults, striking NE up Montague Island (Figs. 12 and 16). Uplift is actually occurring along the Patton Bay and Hanning Bay faults due to S movement of the YAKp from the Aleutian WBZ and due to W movement of the yak. Because the movement from the Aleutian subduction is greater, slight sinistral movements would be expected, as was observed [36]. The lack of ruptures at the surface in the region of the KAT N and E of the Patton Bay and Hanning Bay faults [92] suggest a locked yak with the YAK due to their collision.

6.2 Castle Mountain Reverse Fault

The Castle Mountain fault, located about 65 km to the SE of the MC, is oriented N65°E (Fig. 16). It is considered an ancient YAK dextral slice fault like the present MSS and MS just to its N. The fault is late Paleocene in age [97, 142], which was when late Paleocene volcanics first appeared in the S Talkeetna Mountains [20]. Significant dextral offsets of at least 26 km since 39 Ma [143] have been documented on the Lake Clark fault to the E, which is the linear slice fault extension of the Castle Mountain fault.

A major part of the Susitna Valley (Figs. 2 and 16) segment of the Castle Mountain fault, which is just E of the Talkeetna Mountains, has pronounced Holocene scarps with a vertical offset for the main scarp of up to 2.1 m for the N block [144] with steeply dipping N slip motion [145]. The N block of the Castle Mountain fault is indeed rising. At least 0.6 km of uplift on its bedrock N block in the Susitna Valley has been recognized [146]. On the Talkeetna Mountains part of the fault just E, it has been estimated at least 1.2 km of uplift on its N side has occurred [147]. Up to 3 km of uplift on the very E end has also been recognized [148], which is 200 km to the E of the present Holocene scarps.

During a continental megathrust event, YAK would be expected to move to the WSW along the YAK and NA thrust fault contact. But, at the same time, the YAK at its contact to the PAC if locked would be expected to move SSE with a smaller WSW component as well. A large slip event at this depth between PAC and YAK did recently occur [117], suggesting extensive slip is occurring. Despite the depth of the top of the PAC of 48 km (Fig. 4d), some locking could occur in the zone of disturbance due to the PAC anticline apex [105, 106]. For the Susitna Valley, any earthquake movement along the PAC and YAK thrust fault would probably be concentrated along and just WSW of the PAC apex from the Castle Mountain fault to the immediate N where the PAC plunges into the Aleutian subduction zone. The WSW movement between the shallower YAK and NA thrust fault would be regional as shown (Fig. 21), extending from the region of the PAC apex at the MSS to as far as the Copper Valley and the PWS. The expected results would be Castle Mountain fault reactivation as reverse motion with slight dextral offsets for the region WSW of the PAC anticline apex, which is where the YAK has actually been extensively disrupted by the PAC apex (Fig. 4d). This appears to be what has happened during the Holocene as based on LIDAR imaging of the fault [149], which shows
clearly some dextral en echelon horst and graben faulting behind the main reverse scarp.

As implied, the S Talkeetna Mountains uplift is likely due to the apex of the PAC extending well beyond the formation of this apex at the W edge of the WSW moving yak. The yak has been moving WSW at a rate of about 10.8 mm/yr, which is a rough estimate. The anticline apex of the PAC, which is caused by the loading by the yak, is migrating from the E to the W at this same rate. At this speed, the yak would have had 18.5 Ma of uplift influence on the 200 km length of the S Talkeetna Mountains. Such a period of time fits with uplift and exhumation of the S Talkeetna Mountains as based on apatite thermochronology ages of 15-20 Ma [150]. But, most likely the yak did not lock completely with the YAK until about 5 Ma when the PAC had a recognized change in movement direction [151] and when the W Chugach Mountains reinitiated major uplift [110, 111].

7. Additional Evidence for Two Megathrust Types: Folding of the Crust

Coseismic vertical crustal deformation occurred as a large fold during the 1964 Alaska earthquake [36] with a maximum wave length of 475 km as measured on the cross-section A-A’ (Figs. 12 and 17a), which extends from Denali (Mount McKinley) SSE to the Aleutian trench. The wave length observed can be related to the bending of a rigid layer [152] by the relationship:

$$\lambda = CT,$$

where C is a constant,

\(\lambda\) is the wavelength of the vertical crustal fold, and

\(T\) is the thickness of the crust being folded.

The same fold measured from Kodiak Island to the Aleutian Trench, B-B’, had a wave length of only 300 km. Using a measured average continental crustal thickness for Kodiak Island of 18 km [153] and the observed \(\lambda\) of 300 km, then the C would be 300 km/18 km = 16.7. Using the observed \(\lambda\) for the 1964 Alaska earthquake crustal folding along A-A’ of 475 km and the measured T of about 28 km [4] for the PWS, the C would be 17.0. As would be expected, this is about the same as the Kodiak C value of 16.7. The T crustal thickness for southcentral Alaska included the NA and YAKp as if it was one solid layer. For Kodiak, the T was only for the NA thickness because the YAK is absent. Based on this crustal fold analysis, the YAK for southcentral Alaska was acting as if it was actually attached to the NA during the 1964 Alaska earthquake. This would explain the lack of any significant WSW movement of the YAK N of the central PWS with respect to NA (Fig. 16). By such a model test, the 1964 Alaska earthquake has been shown to have been slip between PAC and YAKp with the NA attached to YAKp. This would mean the YAKp maximum SSE movement near the PAC anticline apex would have been with the NA “somewhat” attached. In fact, the entire bend of the old KAT from a 30° to a 45° SW direction on Montague Island in the PWS could be due to this SSE movement of the YAKp with NA numerous times in the past with the NA not fully returning to its pre-megathrust positions [154].

Present folding of the crust in southcentral Alaska indicates the NA is partially folding as its own detaching layer from YAK. This would happen if YAK after the 1964 Alaska earthquake is freer to move with the PAC because it moved SSE a little during the 1964 Alaska earthquake. The YAK therefore would be able to detach from the above NA. In fact, the NA is presently folding as based on vertical crustal velocities with a wave length of just above 200 km [155], cross-section A’-A” (Figs. 17b and 18). Such detachment between the YAK and NA would continue until failure occurs between the two, resulting in a megathrust between NA and YAK with WSW relative movement. This is what is considered the principal part of the continental megathrust earthquake for southcentral Alaska. Because the YAK contact with the PAC is much deeper in this more continental region than it was for the oceanic 1964 type of megathrust, creep slip would be expected.
Such slip is actually occurring [109, 117]. Yet some strain must still accumulate between YAK and PAC at these depths as indicated by the Holocene fault scarps above the PAC apex at the Castle Mountain fault (Sect. 6.2). Locking between PAC and YAK would be more likely to the SE, E, and NE due to the shallower depth of the PAC and YAK boundary [109]. Such locking is occurring along this as well as along the YAK and NA megathrust faults as indicated by high rates of uplift (>15 mm/yr) and horizontal velocities of the crust for W Chugach and SE Talkeetna Mountains. For example, at 61.76° N and 148.55° W, the horizontal velocity of the surface crust is N 60° W at 16 mm/year [155]. This would represent components of 14 mm/yr...
Fig. 18  Contoured vertical crustal velocities between 1992 and 2007 in mm/year for southcentral Alaska [155]. The A" to A‴ is position of the one complete wavelength in vertical crustal velocity for the fold analysis. The locations of the slice faults are shown in red.
NNW for PAC and 8 mm/yr WSW for the YAK. Strain is actually accumulating for both at fairly high rates.

Based on vertical crustal velocities between 1992 and 2007 [155], the fastest uplift, which is this over 15 mm/yr, is occurring on the RED just E of the Knik Arm tidal flats (Figs. 12 and 18) in the W Chugach Mountains. The other two significant peaks are greater than 10 mm/yr with one occurring on the ILI and the other on the AUG, with both reflecting an approximate 150 km wave length WSW from the >15 mm/yr peak. SE along the A"-A" cross-section (Fig. 18) from the >15 mm/yr peak, the vertical velocity drops to 10 mm/yr at the ILI, drops to 5 mm/yr at the AUG and finally reaches a slightly negative value at the KAT. Going in exactly the opposite direction from the >15 mm/yr peak, the vertical velocity drops to a -12 mm/yr at the MSS. This entire zone of extreme fold growth between the ILI and MSS is a major part of the region that was locked between YAK and NA during the 1964 Alaska earthquake (Fig. 16); i.e., there was no SW motion indicated between YAK and NA. The pre-seismic expected fold build-up for a decoupled NA before a continental megathrust event (Fig. 17b) would be very different in wave-length from the expected pre-seismic oceanic megathrust event, which should be the opposite of the 1964 coseismic deformation (Fig. 17a). Both are building now (Figs. 18 and 19) and both movements would be expected during the southcentral Alaska continental megathrust event. When this ILI/RED/MSS slices release to the WSW, which would involve the W Chugach and SE Talkeetna Mountains, SSE movement would also be expected of YAK with
respect to PAC under most of the same region. This would be in addition to the relative PAC and YAK movement previously discussed for the PAC apex region of the Castle Mountain fault (Sect. 6.2).

For the AUG/ILI slice, which is to the S and SW in the heart of the W Chugach Mountains and N Kenai Peninsula, the expected shorter wavelength type of fold is yet to fully occur (Fig. 18). The YAK is likely still stuck under the NA due to NA underplating. A large fold is actively forming along the length of this AUG/ILI slice with a wave length of about 400 km (Fig. 19), indicating the NA is indeed attached to the YAK as one slab, at least for this slice. Therefore, the NA is indeed being underplated by YAK along the AUG/ILI slice (Sect. 3.9). The NA needs to detach from YAK by allowing a 200 km wave length of a fold to fully form before the continental type of megathrust earthquake would be expected to occur. Or, an alternative and even more interesting possibility would be more than one type of continental megathrust earthquake is actually occurring in southcentral Alaska, with the second more S type occurring along the AUG/ILI slice at a different time than the more N MSS/RED/ILI slices continental megathrust event!

8. The Large Knik Arm Tidal Flats Subsidence Events and Other Paleopeat Age Records

8.1 Knik Arm Tidal Flats and Its Paleopeat Age Dates

A 5 km N-S trending gas pipeline trench, excavated in 1984 across the Knik Arm tidal flats (Knik Arm duck flats) at the E end of the Knik Arm, which is about 50 km NE of Anchorage, exposed two continuous buried peat horizons (Figs. 12 and 20). Two bulk C-14 dates for the bottom part of the upper buried peat horizon were determined to be 730 and 735 cal median BP [156]. The depth of this peat horizon varied from 1.0 to 1.8 m. The bottom part of the deeper paleopeat horizon had a single bulk C-14 date of 1,115 cal med. ybp. Its depth varied from 1.7 to greater than 2.4 m (depth of trench). In February 1989, the section was resampled using a CME continuous-sample-tube system in conjunction with the hollow stem auger [157]. One good sample was obtained for the upper horizon, with the upper part of this paleopeat horizon yielding a 570 cal med. ybp date. Another good sample was obtained for the lower horizon with the upper part of this paleopeat horizon yielding an 850 cal med. ybp date (Table 1, Fig. 20).

Turbulent organic (principally grass) mixing with tidal silt and clay immediately above both of these paleopeat horizons is interpreted to reflect tidal flooding due to sudden subsidence. The 1964 Alaska earthquake caused recognized subsidence over these tidal flats of up to a maximum of 0.3 m at the S end of the trench. Recent glacial Lake George break-out floods of the Knik River [158] had no effect on this area, because such floods never reached the upper tidal zone of the Knik Arm [159].

The existence of an over 5 km continuous paleopeat horizon is significant because it reflects an additional large subsidence event not expected with the 1964 Alaska megathrust type of earthquakes. In addition, movements on regional crustal faults, such as the Castle Mountain fault, would not be enough to account for such a large amount of subsidence observed on the Knik Arm tidal flats. Instead, the unexpected subsidence event can be explained as significant thrust movement of the YAK beneath the NA. The mechanics would be WSW movement of the YAK into the Cook Inlet subduction zone as a continental megathrust. This would occur in combination with movements of regional faults such as the Castle Mountain reverse fault and the RED along with movement NNW of the PAC beneath it all.

8.2 Other Paleopeat and Related Organic Age Dates

The U.S. Geological Survey collected samples from the upper parts of exposed paleopeat horizons found throughout the Turnagain Arm, Knik Arm and upper Cook Inlet [160] from 1982 through 1988. They
Table 1  Radiocarbon age determinations using Reimer et al., 2004 [156] calibration for samples from the Knik Arms tidal flats (Fig. 20).

| Lab code | Sample ID | Stratigraphic position of sample | $^{14}$C BP | SD | Cal Range [156] 2 sigma BP | Median Cal Age |
|----------|-----------|---------------------------------|-------------|----|-----------------------------|----------------|
| GX-10456 | Enstar 8-84-1 | Bottom of peat layer | 775 ±170 |    | 915-545 | 730 |
| GX-10457 | Enstar 9-84-1 | Bottom of peat layer | 790 ±160 |    | 920-550 | 735 |
| GX-10458 | Enstar 9-84-2 | Bottom of peat layer | 1190 ±80 |    | 1275-945 | 1115 |
| GX-10459 | Enstar 9-84-3 | Small log 3 cm below peat layer | 1300 ±80 |    | 1310-1070 | 1190 |
| GX-15237 | KA6-3.0 | Top of peat layer | 560 ±70 |    | 650-490 | 570 |
| GX-15238 | KA6-4.35 | Upper part of weak peat layer | 930 ±115 |    | 975-685 | 830 |
| GX-15239 | KA6-7.85 | Top of peat layer | 1800 ±125 |    | 1920-1535 | 1728 |
| GX-15226 | KA1-5.85 | Top of peat layer | 955 ±75 |    | 970-730 | 850 |

Fig. 20  Geologic cross-section across the Knik Arm tidal flats, which is locally called the Palmer bay flats and the Knik Arm duck flats. The cross-section was mapped by John W. Reeder on 20-21 January 1984 along the just exposed ENSTAR gas line trench [38].

determined bulk C-14 age dates from these samples and found the ages fell into the following groupings:

I (directly above ILI at mouth of Turnagain Arm) 330 cal med. ybp,
II 612 cal med. ybp,
III 790 cal med. ybp,
IV (directly above ILI at the mouth of Turnagain Arm) 1,040 cal med. ybp,
V 1,362 cal med. ybp,
VI 1,750 cal med. ybp, VII 2,280 cal med. ybp,
VIII 2,578 cal med. ybp,
IX 3,162 cal ybp, Missing this horizon (should be 3,162 cal ybp), and
IX 3,495 cal med. ybp.

Based on the large Knik Arm tidal flats subsidence events observed along the 5 km long trench (Fig. 20), the previous continental megathrust occurred 570 cal med. ybp (years before 1950) plus 14 years; i.e., 584 years before 1964. This age of 570 cal med. ybp correlates with their Group II. Then an oceanic...
megathrust occurred 280 years earlier; i.e., 850 cal med. ybp; which correlates with their Group III. Assuming the oceanic and continental megathrust earthquakes alternated following the same time period repeat interval of 584 (570 + 14) years before the oceanic megathrust and 280 years before the continental event, which is not going to be the exact case [154, 161], the following simple age estimates result:

- 570 ybp continental megathrust, their II
- 850 ybp oceanic megathrust, their III
- 1,434 ybp continental megathrust, their V
- 1,714 ybp oceanic megathrust, their VI
- 2,298 ybp continental megathrust, their VII
- 2,578 ybp oceanic megathrust, their VIII
- 3,162 ybp continental megathrust, their VII
- 3,442 ybp oceanic megathrust, their IX
- 4,026 ybp continental megathrust, and
- 4,306 ybp oceanic megathrust.

There is a fit with the U.S. Geological Survey age determinations with the predicted age estimates. Unfortunately, these U.S. Geological Survey age determinations have been ignored by others because only C-14 conventional gas-proportional age determinations were undertaken on these samples [162]. Numerous other paleopeat and fossil age dating investigations have been undertaken for southcentral Alaska, which have been done without realizing at least two distinct types of megathrust earthquakes are occurring in southcentral Alaska [162-168]. Each of these megathrust types would result in their own distinct pattern of uplift and subsidence (Fig. 17a, b). This has made a significant number of paleopeat horizon age determinations look spatially heterogeneous to investigators [162-168] when trying to make fits to the recurrence interval for just one type of megathrust earthquake.

The U.S. Geological Survey did also observe peat horizons in the mouth region of Turnagain Arm (Groups I and IV) just S of Anchorage (Fig. 13), which had enough regional extent to be noted [160]. These were positioned directly over the very active ILI and therefore they might relate to large events on this fault, which could have resulted in large regions of liquefaction and related subsidence. Or, more likely, these subsidence horizons related to thrust movements between NA and YAK for just the AUG/ILI slice. Such a thrust event cannot be ruled out as occurring separately from the previously proposed continental megathrust. Such an event would be another type of
continental megathrust earthquake, called here the AUG/ILI slice continental megathrust. Such a possible event was discussed earlier under folding (Sect. 7). This event, if real, might be occurring every 700 years as based on the U.S. Geological Survey data [160]. It would be represented by the U.S.G.S. age clusters I, IV, VI and VIII; with clusters VI and VIII actually being oceanic megathrusts combined with it. This AUG/ILI slice continental megathrust would be expected to occur on its own in another 320 years or more likely to occur jointly with the expected continental megathrust in about 230 years.

8.3 Earthquake Megathrust Predictions

It will be about 230 years (280 years after the 1964 Alaska earthquake) before the continental megathrust earthquake would be expected for southcentral Alaska. The notion that it will be a very long time after 1964, i.e., 550 to 950 years, before the next large megathrust earthquake will occur [162-168] is unfortunately very misleading. Fortunately, the expected large continental megathrust earthquake, even if combined with a possible AUG/ILI slice continental megathrust, would have a smaller duration and a smaller magnitude compared to what occurred on 27 March 1964.

9. The Implications of This New Tectonic Model for Alaska

The arcuate structures of major Alaskan faults such as the Denali are the bases of the Alaska orocline [169], which has attracted numerous models such as rotation of blocks about a point [48, 155, 170, 171], the nonrigid world of escape tectonics [172] and finite element diffusion [173], and the multiple bending of rigid layers like megakinks [39] or multiple thrust bending [69]. But, for all, the expected extensional and compressional structures on appropriate arc sides [174] and specifically rotated and/or arched structures in the Talkeetna Mountains [175] are mainly lacking. None explain the existence of the large Copper Valley. Another serious problem is the large offset disparities between E and W of the curved fault systems [114, 176] of the Alaska orocline. As an example, the total displacement on the SW Alaska faults, which are on the W limb of the Alaska orocline, is about 450 km [114]. This is only about half of the total fault displacements determined for the E limb of the orocline [177]. There might be missing strike-slip faults and thrust faults; but, the main reason for this displacement discrepancy between these two limbs is because the WSW subduction of the YAK between them has taken up most of this discrepancy. So again, why all of these problems and discrepancies? It has been the lack of the recognition for WSW subduction of the Yakutat plate into the very E part of the Aleutian subduction zone, which has basically allowed the Alaska orocline to form in the first place.

The recognition of at least two major types of megathrust earthquake events; i.e., the oceanic and the continental, completely redefines the large earthquake hazards of this region as well as tsunami hazards of the Pacific basin. The hazards posed by the Yakutat plate slice faults need to also be recognized. The Montana Creek slice fault extends beneath the proposed Watana Dam reservoir of the Susitna Project (Fig. 5), beneath the proposed Alaska gas line to southcentral Alaska as well as through the “rail belt” of Alaska. In fact, Mount Spurr, Mount Spurr South, Redoubt, Iliamna, Augustine and Buzzard Creek slice faults all underlay at depth the Alaska “rail belt.” For Anchorage, any Knik Arm road crossing would need to take into account the Redoubt slice fault and any Turnagain Arm road crossing would need to take into account the Iliamna slice fault. In addition, these slice faults have offset/deformed structures in a predictable fashion, which would help with future oil/gas exploration as well as with hard rock mineral exploration in Alaska.

In conclusion, a simple question is asked. Is the magma of the Quaternary Cook Inlet volcanoes of the eastern Aleutian subduction zone originating from the
Pacific plate? The answer from the “experts” has been always “Yes” [74, 93, 115, 132, 178, 179]. But, the magmas for the Cook Inlet volcanoes are actually originating from the Yakutat plate. These experts would not listen to new ideas and instead kept with their old territorial ways of controlling Alaska research. Yet, without their valuable research, this report would not have been possible. It is truly hoped the new ideas presented here will have a significant and enduring influence on Earth sciences, earthquake hazard assessments and mineral resource evaluations for Alaska. Alaskans need and want to know the truth about their wonderful State. More importantly, all deserve to know the truth about our fascinating Earth.

References

[1] Bruns, T. R. 1983. “Model for the Origin of the Yakutat Block, an Accreted Terrane in the Northern Gulf of Alaska.” Geology 11: 718-21.
[2] Griscom, A., and Sauer, P. E. 1990. “Interpretation of Magnetic Maps of the Northern Gulf of Alaska, with Emphasis on the Source of the Slope Anomaly.” U.S. Geological Survey Open-File Report 90-348: 18.
[3] Plafker, G., Moore, J. C., and Winkler, G. R. 1994. “Geology of the Southern Alaska Margin.” In The Geology of Alaska, edited by Plafker, G., and Berg, H. C. Geological Society America, Boulder, Colorado, Geology of North America G-1: 389-450.
[4] Brocher, T. M., Fuis, G. S., Fisher, M. A., Plafker, G., Taber, J. J., and Christensen, N. I. 1994. “Mapping the Megathrust beneath the Northern Gulf of Alaska Using Wide-Angle Seismic Data.” Journal Geophysical Research 99: 11663-85.
[5] Fletcher, H. J., and Freymueller, J. T. 1999. “New GPS Constraints on the Motion of the Yakutat Block.” Geophysical Research Letters 26: 3029-32.
[6] Ferris, A., Aber, G. A., Christensen, D. H., and Veenstra, E. 2003. “High Resolution Image of the Subducted Pacific (?) Plate beneath Central Alaska, 50-150 km Depth.” Earth and Planetary Science Letters 214: 575-88.
[7] Eberhart-Phillips, D., Christensen, D. J., Brocher, T. M., Hansen, R., Ruppert, N. A., Haeussler, P. J., and Aber, G. A. 2006. “Imaging the Transition from Aleutian Subduction to Yakutat Collision in Central Alaska, with Local Earthquakes and Active Source Data.” Journal Geophysical Research 111: B11303.
[8] Fuis, G. S., Moore, T. E., Plafker, G., Brocher, T. M., Fisher, M. A., Mooney, W. D., Nokleberg, W. J., Page, R. A., Beaudoin, B. C., Christensen, N. I., Levander, A. R., Lutter, W. J., Saltus, R. W., and Ruppert, N. A. 2008. “Trans-Alaska Crustal Transect and Continental Evolution Involving Subduction Underplating and Synchronous Foreland Thrusting.” Geology 36 (3): 267-70.
[9] Haeussler, P. J. 2008. “An Overview of the Neotectonics of Interior Alaska: Far-Field Deformation from the Yakutat Microplate Collision.” In Active Tectonics and Seismic Potential of Alaska, edited by Freymueller, J. T., Haeussler, P. J., Wesson, R. L., and Ekstrom, G. American Geophysical Union, Washington D. C., Geophysical Monograph Series 179: 83-108.
[10] von Huene, R., and Ranero, C. R. 2009. “Neogene Collision and Deformation of Convergent Margins along the Backbone of the Americas.” In Backbone of the Americas: Shallow Subduction, Plateau Uplift, and Ridge and Terrane Collision, edited by Kay, S. M., Ramos, V. A., and Dickinson, W. R. Memoirs Geological Society America 204: 67-83.
[11] Cloos, M. 1993. “Lithospheric Buoyancy and Collisional Orogenesis: Subduction of Oceanic Plateaus, Continental Margins, Island Arcs, Spreading Ridges, and Seamounts.” Geological Society America Bulletin 105: 715-37.
[12] van Hunen, J., van den Berg, A. P., and Vlaar, N. J. 2002. “On the Role of Subducting Oceanic Plateaus in the Development of Shallow Flat Subduction.” Tectonophysics 352: 317-33.
[13] Atwater, T. 1989. “Plate Tectonic History of the Northeast Pacific and Western North America.” In The Eastern Pacific Ocean and Hawaii, edited by Winterer, E. L., Hussong, D. M., and Decker, R. W. Geological Society of America, Boulder, Colorado, the Geology of North America N: 21-72.
[14] Bradley, D. C., Haeussler, P., and Kusky, T. M. 1993. “Timing of Early Tertiary Ridge Subduction in Southern Alaska.” U.S. Geological Survey Bulletin 2068: 163-77.
[15] Haeussler, P. J., Bradley, D. C., Wells, R. E., and Miller, M. L. 2003. “Life and Death of the Resurrection Plate: Evidence for Its Existence and Subduction in the Northeastern Pacific in Paleocene-Eocene Time.” Geological Society of America Bulletin 115: 867-80.
[16] Page, R. A., Plafker, G., Fuis, G. S., Nokleberg, W. J., Ambos, E. L., Mooney, W. D., and Campbell, D. L. 1986. “Accretion and Subduction Tectonic in the Chugach Mountains and Copper River Basin, Alaska: Initial Results of the Trans-Alaska Crustal Transect.” Geology 14: 501-5.
[17] Fuis, G. S., and Plafker, G. 1991. “Evolution of Deep Structure along the Trans-Alaska Crustal Transect, Chugach Mountains and Copper River Basin, Southern
The Active Yakutat (Kula?) Plate and Its Southcentral Alaska Megathrust and Intralate Earthquakes

52

[18] Dickinson, W. R., and Snyder, W. S. 1979. “Geometry of Triple Junctions Related to San Andreas Transform.” Journal of Geophysical Research 84: 561-72.

[19] Cole, R. B., Layer, P. W., Hooks, B., Cyr, A., and Turner, J. 2007. “Magmatism and Deformation in a Terrane Suture Zone South of the Denali Fault, Northern Talkeetna Mountains, Alaska.” The Geological Society of America Special Paper 431: 477-506.

[20] Cole, R. B., Nelson, S. W., Layer, P. W., and Oswald, P. J. 2006. “Eocene Volcanism above a Depleted Mantle Slab Window in Southern Alaska.” Geological Society of America Bulletin 118 (1/2): 140-58.

[21] Lonsdale, P. 1988. “Paleogene History of the Kula Plate; Offshore Evidence and Onshore Implications.” Geological Society of America Bulletin 100: 733-54.

[22] Doubrovine, P. V., and Tarduno, J. A. 2008. “A Revised Kinematic Model for the Relative Motion between Pacific Ocean Plates and North America since Late Cretaceous.” Journal Geophysical Research Solid Earth 113: JB005585.

[23] Grow, J. A., and Atwater, T. 1970. “Mid-Tertiary Tectonic Transition in the Aleutian Arc.” Geological Society of America Bulletin 84: 2169-92.

[24] Scholl, D., Buffington, E., and Marlow, M. 1975. “Plate Tectonics and the Structural Evolution of the Aleutian-Bering Sea Regions, In Contributions to the Geology of the Bering Sea Basin and Adjacent Regions, edited by Forbes, R. B. Geological Society of America Special Paper 151: 1-31.

[25] Byrne, T. 1979. “Late Paleocene Demise of the Kula-Pacific Spreading Center.” Geology 7: 341-4.

[26] Finzel, E. S., Trop, J. M., Ridgway, K. D., and Enkelmann, E. 2011. “Upper Plate Proxies for Flat-Slab Subduction Processes in Southern Alaska.” Earth and Planetary Science Letters 303: 348-60.

[27] Reeder, J. W. 2013. “A New Tectonic Model for Southern Alaska.” EOS Trans. Am. Geophysical Union 94, Fall Meeting: Abstract T24A-95.

[28] Reeder, J. W. 2014. “The Significance of the Yakutat Plate to the Alaska Orocline.” Seismol. Res. Lett. 85 (2): 506.

[29] Pfafker, G. 1987. “Regional Geology and Petroleum Potential of the Northern Gulf of Alaska Continental Margin.” In Geology and Resource Potential of the Continental Margin of the Western North American and Adjacent Ocean Basins—Beaufort Sea to Baja California, edited by Scholl, D. W., Grantz, A., and Vedder, J. G. Circum-Pacific Council for Energy and Mineral Resources Earth Science Series 6: 229-68.

[30] Gulick, S. P. S., Lowe, L., Pavlis, T. L., Gardner, J. V., and Mayer, L. A. 2007. “Geophysical Insights into the Transition Fault Debate: Propagating Strike Slip in Response to Stalling Yakutat Block Subduction in the Gulf of Alaska.” Geology 35: 763-6.

[31] Christeson, G. L., Gulick, S. P. S., van Avendonk, H. J. A., Worthington, L. L., Reece, R. S., and Pavlis, T. L. 2010. “The Yakutat Terrane: Dramatic Change in Crustal Thickness across the Transition Fault, Alaska.” Geology 38: 895-8.

[32] Fletcher, H. J., and Freymueller, J. T. 2003. “New Constraints on the Motion of the Fairweather Fault, Alaska, from GPS Observations.” Geophysical Research Letters 30 (3): 1139.

[33] Elliott, J. L., Larsen, C. F., Freymueller, J. T., and Motyka, R. J. 2010. “Tectonic Block Motion and Glacial Isostatic Adjustment in Southeast Alaska and Adjacent Canada Constrained by GPS Measurements.” Journal Geophysical Research 115: B09407.

[34] Reeder, J. W. 2015. “The Yakutat Plate and Its Southcentral Alaska Megathrust Earthquakes.” Seismol. Res. Lett. 86 (2B): 686.

[35] Parkin, E. J. 1966. “Horizontal Displacements, Pt 2.” Alaskan Surveys to Determine Crustal Movement. U.S. Coast and Geodetic Survey: 11.

[36] Pfafker, G. 1969. “Tectonics of the March 17, 1964 Alaska Earthquake.” U.S. Geological Survey Professional Paper 5431: 1-74.

[37] Berg, E. 1965. “The Alaska Earthquake, Its Location and Seismic Setting.” In Science in Alaska, 1964. Proc. Alaskan Science Conference, 15th, College, Alaska, Aug. 31-Sept. 4, 1964. American Association for the Advancement of Science: 218-32.

[38] Reeder, J. W. 2012. “Earthquake-Caused Subsidence Events of the Duck Flats at the Eastern End of the Knik Arm, Alaska.” EOS Trans. Am. Geophysical Union 93, Fall Meeting: Abstract T13B-2613.

[39] Grantz, A. 1966. “Strike-Slip Faults in Alaska.” U.S. Geological Survey Open-File Report 66-53: 82.

[40] Trop, J. M., Hart, W. K., Snyder, D., and Idleman, B. 2012. “Miocene Basin Development and Volcanism along a Strike-Slip to Flat-Slab Subduction Transition: Stratigraphy, Geochemistry, and Geochronology of the Central Wrangell Volcanic Belt, Yakutat-North America Collision Zone.” Geosphere 8 (4): 805-34.

[41] Andreassen, G. E., Grantz, A., Zietz, L., and Barnes, D. F. 1964. “Geologic Interpretation of Magnetic and Gravity Data in the Copper River Basin, Alaska.” U.S. Geological Survey Professional Paper 316 (H): 135-53.

[42] Meyer, J. F., and Boggess, P. L. 2003. “Principle Facts for Gravity Data Collected in the Copper River Basin Area, Southcentral Alaska.” Alaska Division of Geological and Geophysical Surveys Preliminary Investigative Report 2003-2: 12.
[43] Ridgway, K. D., Trop, J. M., Nokleberg, W. J., Davidson, C. M., and Eastham, K. R. 2002. “Mesozoic and Cenozoic Tectonics of the Eastern and Central Alaska Range: Progressive Basin Development and Deformation in a Suture Zone.” Geological Society of America Bulletin 114: 1480-504.

[44] Lahr, J. C., Page, R. A., and Stephens, C. D. 1988. “Unusual Earthquakes in the Gulf of Alaska and Fragmentation of the Pacific Plate.” Geophysical Research Letters 15: 1483-6.

[45] Pegler, G., and Das, S. 1996. “The 1987-1992 Gulf of Alaska Earthquakes.” Tectonophysics 257: 111-36.

[46] Stephens, C. D., Fogleman, K. A., Lahr, J. C., and Page, R. A. 1984. “The Wrangell Benioff Zone, Southern Alaska.” Geology 12: 373-6.

[47] Zabelina, I., Ruppert, N. A., and Freymueller, J. T. 2014. “Velocity Structure of the Saint Elias, Alaska Region from Local Earthquake Tomography.” Bulletin Seismological Society America 104 (5): 2597-603.

[48] Lahr, J. C., and Plafker, G. 1980. “Holocene Pacific-North American Plate Interaction in Southern Alaska—Implications for the Yakataga Seismic Gap.” Geology 8: 483-6.

[49] Meigs, A., Johnston, S., Garver, J., and Spotila, J. 2008. “Crustal-Scale Structural Architecture, Shortening, and Exhumation of an Active, Eroding Orogenic Wedge (Chugach/St. Elias Range, Southern Alaska).” Tectonics 27 (TC4003).

[50] Wallace, W. K. 2008. “Yakataga Fold-and-Thrust Belt: Structural Geometry and Tectonic Implications of a Small Continental Collision Zone.” In Active Tectonics and Seismic Potential of Alaska, edited by Freymueller, J. T., Haeussler, P. J., Wesson, R., and Ekstrom, G. American Geophysical Union, Washington D.C., Geophysical Monograph Series 179: 237-56.

[51] Enkelmann, E., Zeiter, P. K., Garver, J. I., Pavlis, T. L., and Hooks, B. P. 2010. “The Thermochronological Record of Tectonic and Surface Process Interaction at the Yakutat-North American Collision Zone in Southeast Alaska.” American Journal of Science 310: 231-60.

[52] Spotila, J. A., and Berger, A. L. 2010. “Exhumation at Orogenic Indicator Corners under Long-Term Glacial Conditions: Example of the St. Elias Orogeny, Southern Alaska.” Tectonophysics 490: 241-56.

[53] Pavlis, T. L., Chapman, J. B., Bruhn, R. L., Ridgway, K., Worthington, L. L., Gulick, S. P. S., and Spotila, J. 2012. “Structure of the Actively Deforming Fold-Thrust Belt of the St. Elias Orogen with Implications for Glacial Exhumation and Three-Dimensional Tectonic Processes.” Geosphere 8 (5): 991-1019.

[54] Headley, R. M., Enkelmann, E., and Hallet, B. 2013. “Examination of the Interplay between Glacial Processes and Exhumation in the Saint Elias Mountains, Alaska.” Geosphere 9 (2): 229-41.

[55] Bruhn, R. L., Pavlis, T. L., Plafker, G., and Serpa, L. 2004. “Deformation during Terrane Accretion in the Saint Elias Orogen, Alaska.” Geological Society America Bulletin 116: 771-87.

[56] Doser, D. I., and Veillette, A. M. 2009. “A Comprehensive Study of the Seismicity of the Kenai Peninsula-Cook Inlet Region, South-Central Alaska.” Bulletin Seismological Society America 99 (4): 2208-22.

[57] Wilson, J. T. 1965. “A New Class of Faults and Their Bearing on Continental Drift.” Nature 207: 343-7.

[58] Beck, M. E. Jr. 1983. “On the Mechanism of Tectonic Transport in Zones of Oblique Subduction.” Tectonophysics 93: 1-11.

[59] Karig, D. E. 1978. “Material Transport within Accretionary Prism and the ‘Knocker’ Problem.” Journal of Geology 88: 27-39.

[60] McGee, D. L. 1978. “Bedrock Geology and Coal Occurrences, Talkeetna-Kashwitna Area, Susitna River Basin, Alaska.” Alaska Division of Geological and Geophysical Surveys Open-File Report 107E: 1 sheet.

[61] Reed, B. L., and Nelson S. W. 1980. “Geologic Map of the Talkeetna Quadrangle, Alaska.” U.S. Geological Survey Misc. Invest. Series Map J-1174.

[62] Schmidt, J. M., Werdon, M. B., and Wardlaw, B. 2003. “New Mapping near Iron Creek, Talkeetna Mountains, Indicates Presence of Nikolai Greenstone.” In Short Notes on Alaskan Geology 2003, edited by Clautice, K. H., and Davis, P. K. State of Alaska Division of Geological and Geophysical Surveys Professional Report 120: 101-8.

[63] Schmidt, J. M., and Rogers, R. K. 2007. “Metallogeny of the Nikolai Large Igneous Province (LIP) in Southern Alaska and Its Influence on the Mineral Potential of the Talkeetna Mountains.” In Tectonic Growth of a Collisional Continental Margin: Crustal Evolution of Southern Alaska, edited by Ridgway, K. D., Trop, J. M., Glen, J. M. G., and O’Neill, J. M. Geological Society of America Special Paper 431: 623-48.

[64] Csejtey, B. Jr., Nelson, W. H., Jones, D. L., Silberling, N. J., Dean, R. M., Morris, M. S., Lanphere, M. A., Smith, J. G., and Silberman, M. L. 1978. “Reconnaissance Geologic Map and Geochronology, Talkeetna Mountains Quadrangle, Northern Part of Anchorage Quadrangle, and Southwest Corner of Healy Quadrangle, Alaska.” U.S. Geological Survey Open-File Report 78-558-A: 62.

[65] Werdon, M. B., Riehl, J. R., Schmidt, J. M., Newberry, R. J., and Pessel, G. H. 2002. “Geologic Map of the Iron Creek Area, Talkeetna Mountains B-5 Quadrangle, Alaska.” Alaska Division of Geological and Geophysical Surveys Preliminary Interpretive Report PIR 2002-4: 1
Ascent during the 2004-2005 Unrest at Mt. Spurr Inferred: Koulakov, I., West, M., and Izbekov, P. 2013. “Fluid sheet.”

McDonald, J., and Atwater, A. 1988. “Implications for Crustal Evolution.” In “The Geophysical Character of Southern Alaska—Implications for Crustal Evolution.” In Tectonic Evolution of Southern Alaska, edited by Ridgway, K. D., Trop, J. M., Glen, J. M. G., and O’Neill, J. M. Geological Society of America Special Paper 431: 1-20.

Csejtey, B. Jr., and Griscom, A. 1978. “Preliminary Aeromagnetic Interpretive Map of the Talkeetna Mountains Quadrangle, Alaska.” U.S. Geological Survey Open-File Report 78-558C: 14.

Ratchkovsky, N. A., Pujol, J., and Biswas, N. N. 1997. “Relocation of Shallow Earthquakes in Southern Alaska Using Joint Hypocenter Determination Method.” Journal Seismology 2: 87-102.

Glen, J. M. G. 2004. “A Kinematic Model for the Southern Alaska Orocline Based on Regional Fault Patterns.” In Orogenic Curvature: Integrating Paleomagnetic and Structural Analyses, edited by Sussman, A. J., and Weil, A. B. The Geological Society of America, Boulder, Colorado. Geol. Soc. Am. Special Paper 383: 161-72.

Flores, C., and Doser, D. I. 2005. “Shallow Seismicity of the Anchorage, Alaska Region.” Bulletin Seismological Society America 95: 1865-79.

Péwé, T., Wahrhaftig, C., and Webber, F. 1966. “Geologic Map of the Fairbanks Quadrangle, Alaska.” U.S. Geological Survey Misc. Geologic Invest. Map I-455.

Forsyth, D. W., and Uyeda, S. 1975. “On the Relative Importance of the Driving Forces of Plate Motion.” The Geophysical Journal of the Royal Astronomical Society 43: 163-200.

Rondenay, S., Montési, L. G. J., and Abers, G. A. 2010. “Seismic Anisotropy under Central Alaska from SKS Splitting Observations.” Journal of Geophysical Research v. 115: B04315.

Rasendra, N., Bonnin, M., Mazzotti, S., and Tiberi, C. 2014. “Crustal and Upper-Mantle Anisotropy Related to Fossilized Transpression Fabric along the Denali Fault, Northern Canadian Cordillera.” Bulletin Seismological Society America 104 (4): 1964-75.

Pettu, A., Christensen, D., Abers, G., and Song, X. 2014. “Insights into Mantle Structure and Flow beneath Alaska Based on a Decade of Observations of Shear Wave Splitting.” Journal Geophysical Research Solid Earth 119 (11): B011359.

Wang, Y., and Tape, C. 2014. “Seismic Velocity Structures and Anisotropy of the Alaska Subduction Zone Based on Surface Wave Tomography.” Journal Geophysical Research Solid Earth 119: 21.

Nakamura, K., Jacob, K. H., and Davies, J. N. 1977. “The Denali Volcanic Gap—Magmatism from Seismic Tomography.” Geophysical Research Letters 40: 4579-82.

Pulpan, H., and Frohlich, C. 1985. “Geometry of the Subducted Plate near Kodiak Island and Lower Cook Inlet, Alaska, Determined from Relocated Earthquake Hypocenters.” Bulletin Seismological Society America 75 (3): 791-810.

Ratchkovsky, N. A., Pujol, J., and Biswas, N. 1997. “Stress Pattern in the Double Seismic Zone Beneath Cook Inlet, South-Central Alaska.” Tectonophysics 281: 163-72.

Rietbrock, A., and Waldhauser, F. 2004. “A Narrowly Space Double-Seismic Zone in the Subducting Nazca Plate.” Geophys. Research Letters 31: L10608.

Lay, T. 1994. “Seismological Constraints on the Velocity Structure and Fate of Subducting Lithospheric Slabs: 25 Years of Progress.” Advances in Geophysics 35: 117-21.

Ranero, C. R., Villaseñor, A., Morgan, J. P., and Weinrebe, W. 2005. “Relationship between Bend-Faulting at Trenches and Intermediate-Depth Seismicity.” Geochim. Geophys. Geosys. 6: Q12002.

Ruppert, N. A. 2008. “Stress Map for Alaska from Earthquake Focal Mechanisms.” In Active Tectonics of Seismic Potential of Alaska, edited by Freymueller, J. T., Haeussler, P. J., Wesson, R., and Ekstrom, G. American Geophysical Union, Washington D.C., Geophysical Monograph Series 179: 351-67.

Veilieux, A. M., and Doser, D. I. 2007. “Studies of Wadati-Benioff Zone Seismicity of the Anchorage, Alaska Region.” Bulletin Seismological Society America 97: 52-62.

Christensen, D. H., and Abers, G. A. 2010. “Seismic Anisotropy under Central Alaska from SKS Splitting Observations.” Journal of Geophysical Research v. 115: B04315.
The Active Yakutat (Kula?) Plate and Its Southcentral Alaska Megathrust and Intraplate Earthquakes

Geophysics (Pageoph) 115: 87-112.

[90] Marsh, B. D. 1982. “The Aleutians.” In Andesites, edited by Thorpe, R. S. New York: John Wiley & Sons: 99-114.

[91] Ratchkovski, N. A., and Hansen, R. A. 2002. “New Evidence for Segmentation of the Alaska Subduction Zone.” Bulletin Seismological Society America 92: 1754-65.

[92] Pfafker, G., Gilpin L. M., and Lahr, J. C. 1994. “Neotectonic Map of Alaska.” In The Geology of Alaska, edited by Pfafker G., and Berg H. C. Geological Society of America, Boulder, Colorado, The Geology of North America G1: Plate 12.

[93] Kienle, J., and Swanson, S. E. 1983. “Volcanism in the Eastern Aleutian Arc: Late Quaternary and Holocene Centers, Tectonic Setting and Petrology.” Journal Volcanism and Geothermal Research 17: 393-432.

[94] Condon, W. H. 1965. “Map of Eastern Prince William Sound Area, Alaska Showing Fracture Traces Inferred from Aerial Photographs.” U.S. Geological Survey Miscellaneous Geologic Investigations Map I-453.

[95] Winkler, G. R., and Pfafker, G. 1981. “Geologic Map and Cross Sections of the Cordova and Middleton Islands Quadrangles, Southern Alaska.” U.S. Geological Survey Open-File Report 81-1161: 26.

[96] Dusel-Bacon, C., Csejty, B. Jr., Foster, H. L., Doyle, E. O., Nokleberg, W. J., and Pfafker, G. 1993. “Distribution, Facies, Ages, and Proposed Tectonic Associations of Regionally Metamorphosed Rocks in East- and South-Central Alaska.” U.S. Geological Survey Professional Paper 1497-C: 1-72.

[97] Trop, J. M., and Ridgway, K. D. 2007. “Mesozoic and Cenozoic Tectonic Growth of Southern Alaska: A Sedimentary Basin Perspective.” In Tectonic Growth of a Collisional Continental Margin: Crustal Evolution of Southern Alaska, edited by Ridgway, K. D., Trop, J. M., Glen, J. M. G., and O’Neill, J. M. Geological Society of America Special Paper 431: 55-94.

[98] Pfafker, G. 1967. “Surface Faults on Montague Island Associated with the 1964 Earthquake.” U.S. Geological Survey Professional Paper 543 G: 1-42.

[99] Page, R. A., Stephens, C. D., and Lahr, J. C. 1989. “Seismicity of the Wrangell and Aleutian Wadati-Benioff Zones and the North American Plate along the Trans-Alaska Crustal Transect, Chugach Mountains and Copper River Basin, Southern Alaska.” Journal Geophysical Research 94: 16059-82.

[100] Wood, C. A., and Kienle, J., eds. 1990. Volcanoes of North America. Cambridge University Press: 354.

[101] Reeder, J. W., and Lahr, J. C. 1987. “Seismological Aspects of the 1976 Eruptions of Augustine Volcano, Alaska.” U.S. Geological Survey Bulletin 1768: 32.

[102] Wyss, M., and Brune, J. N. 1967. “The Alaska Earthquake of 28 March 1964: A Complex Multiple Rupture.” Bulletin Seismological Society America 57: 1017-23.

[103] Page, R. 1968. “Aftershocks and Microaftershocks of the Great Alaska Earthquake of 1964.” Bulletin Seismological Society of America 58 (3): 1131-68.

[104] Doser, D. I., Veilleux, A., and Velasquez, M. 1999. “Seismicity of the Prince William Sound Region for Thirty Two Years following the 1964 Great Alaskan Earthquake.” Pure Appl. Geophys. 154: 593-632.

[105] Pacheco, J. F., Sykes, L. R., and Scholz, C. H. 1993. “Nature of Seismic Coupling along Simple Plate Boundaries of the Subduction Type.” Journal of Geophysical Research 98: 14133-59.

[106] Tichelaar, B. W., and Ruff, L. J. 1993. “Depth of Seismic Coupling along Subduction Zones.” Journal of Geophysical Research 98: 2017-37.

[107] Doser, D. I., and Brown, W. A. 2001. “A Study of Historic Earthquakes of the Prince William Sound, Alaska Region.” Bulletin Seismological Society America 91: 842-55.

[108] Miller, R. D., and Dobrovolny, E. 1959. “Surficial Geology of Anchorage and Vicinity, Alaska.” U.S. Geological Survey Bulletin 1093: 128, 5 sheets.

[109] Hyndman, R. D., and Wang, K. 1995. “The Rupture Zone of Cascadia Great Earthquakes from Current Deformation and the Thermal Regime.” Journal of Geophysical Research 100 (B11): 22133-54.

[110] Arkle, J. C., Armstrong, P. A., Haeussler, P. J., Prior, M. G., Hartman, S., Sendziak, K. L., and Brush, J. A. 2013. “Focused Exhumation in the Syntaxis of the Western Chugach Mountains and Prince William Sound, Alaska.” Geological Society America Bulletin 125 (5/6): 776-93.

[111] Buscher, J. T., Berger, A. L., and Spotila, J. A. 2008. “Exhumation in the Chugach-Kenai Mountain Belt above the Aleutian Subduction Zone, Southern Alaska.” In Active Tectonics and Seismic Potential of Alaska, edited by Freymueller, J. T., Haeussler, P. J., Wesson, R., and Ekstrom, G. American Geophysical Union, Washington D. C., Geophysical Monograph Series 179: 151-66.

[112] Foster, H. L., and Karlstrom, T. N. V. 1967. “Ground Breakage and Associated Effects in the Cook Inlet Area, Alaska, Resulting from the March 27, 1964, Earthquake.” U.S. Geological Survey Professional Paper 543-F: 1-28.

[113] Redfield, T. F., and Fitzgerald, P. G. 1993. “Denali Fault System of Southern Alaska, an Interior Strike-Slip Structure Responding to Dextral and Sinistral Shear Coupling.” Tectonics 12: 1195-208.

[114] Miller, M. L., Bradley, D. C., Bundtzen, T. K., and McClelland, W. 2002. “Late Cretaceous through Cenozoic Strike-Slip Tectonics of Southwestern Alaska.” Journal of Geology 110: 247-70.
[115] Plafker, G., and Berg, H. C. 1994. “Overview of the Geology and Tectonic Evolution of Alaska.” In *The Geology of Alaska*, edited by Plafker, G., and Berg, H. C. Geological Society America, Boulder, Colorado, Geology of North America G-1: 989-1021.

[116] Logan, M. 1967. “Effects of the March 27, 1964, Alaska Earthquake on the Eklutna Hydroelectric Project, Anchorage.” *U.S. Geological Survey Professional Paper 545-A*: 1-30.

[117] Ohta, Y., Freymueller, J. T., Heinsdóttir, S., and Suito, H. 2006. “A Large Slow Slip Event and the Depth of the Seismogenic Zone in the South Central Alaska Subduction Zone.” *Earth Planet. Sci. Letters* 247: 108-16.

[118] Haeussler, P. J., and Saltus, R. W. 2011. “Location and Extent of Tertiary Structures in Cook Inlet Basin, Alaska, and Mantle Dynamics that Focus Deformation and Subsidence.” In *Studies by the U. S. Geological Survey in Alaska, 2008-2009*, edited by Dumoulin, J. A., and Galloway, J. P. U.S. Geological Survey, Professional Paper 1776-D: 1-26.

[119] Richter, D. H., Smith, J. G., Lanphere, M. A., Dalrymple, G. B., Reed, B. L., and Shew, N. 1990. “Age and Progression of Volcanism, Wrangel Volcanic Field, Alaska.” *Bulletin of Volcanology* 53: 29-44.

[120] Sorey, M. L., Werner, C., McGimsey, R. G., and Evans, W. C. 2000. “Hydrothermal Activity and Carbon-Dioxide Discharge at Shrub and Upper Klawasi Mud Volcanoes, Wrangell Mountains, Alaska.” *U.S. Geological Survey Water-Resources Investigations Report 00-4207*: 12.

[121] Stauder, W., and Bollinger, G. A. 1966. “The Focal Mechanism of the Alaska Earthquake of March 28, 1964, and of Its Aftershock Sequence.” *Journal Geophysical Research* 71 (22): 5283-96.

[122] Holdahl, S. R., and Sauber, J. 1994, “Coseismic Slip in the 1964 Prince William Sound Earthquake: A New Geodetic Inversion.” *Pure Appl. Geophysics.* 142: 55-82.

[123] Reeder, J. W. 2014. “The Occurrence of Two Types of Megathrust Earthquakes in South Central Alaska.” *Seismol. Res. Lett.* 85 (2): 486.

[124] Doser, D. I. 2012. “Revisiting the 1979 St. Elias, Alaska, Aftershock Sequence and Its Regional Significance.” *Bulletin Seismological Society America* 102 (6): 2392-404.

[125] Doser, D. I., Pelton J. R., and Veilleux, A. M. 1997. “Earthquakes in the Pamplona Zone, Yakutat Block, South Central Alaska.” *Journal Geophysical Research* 102: 24499-511.

[126] Gulick, S. P. S., Reece, R. S., Christeson, G. L., van Avendonk, H., Worthington, L. L., and Pavlis, T. L. 2013. “Seismic Images of the Transition Fault and the Unstable Yakutat-Pacific-North American Triple Junction.” *Geology* 41 (5): 571-4.

[127] Doser, D. I., and Lomas, R. 2000. “The Transition from Strike-Slip to Oblique Subduction in Southeastern Alaska from Seismological Studies.” *Tectonophysics* 316: 45-65.

[128] Brunn, R. L., Sauber, J., Cotton, M. M., Pavlis, T. L., Burgess, E., and Ruppert, N. 2012. “Plate Margin Deformation and Active Tectonics along the Northern Edge of the Yakutat Terrane in the Saint Elias Orogeny, Alaska, and Yukon, Canada.” *Geosphere* 8 (6): 1384-407.

[129] Plafker, G., and Thatcher, W. 2008. “Geological and Geophysical Evaluation of the Mechanisms of the Great 1899 Yakutat Bay Earthquakes.” In *Active Tectonics of Seismic Potential of Alaska*, edited by Freymueller, J. T., Haeussler, P. J., Wesson, R., and Ekstrom, G. American Geophysical Union, Washington D.C., Geophysical Monograph Series 179: 216-36.

[130] Worthington, L. L., Gulick, S. P. S., and Pavlis, T. L. 2008. “Identifying Active Structures in the Kayak Island and Pamplona Zones: Implications of Offshore Tectonics of the Yakutat Microplate, Gulf of Alaska.” In *Active Tectonics of Seismic Potential of Alaska*, edited by Freymueller, J. T., Haeussler, P. J., Wesson, R., and Ekstrom, G. American Geophysical Union, Washington D.C., Geophysical Monograph Series 179: 257-68.

[131] Karl, S. M., Baichtal, J. F., Calvert, A. T., and Layer, P. W. 2013. “Pliocene to Recent Alkaline Volcanic Centers in Southeast Alaska: Western Component of the Northern Cordilleran Volcanic Province.” *Alaska Geology. Newsletter of the Alaska Geological Society* 44 (1): 1-2.

[132] Miller, T. P., and Richter, D. H. 1994. “Quaternary Volcanism in the Alaska Peninsula and Wrangell Mountains, Alaska.” In *The Geology of Alaska*, edited by Plafker, G., and Berg, H. C. The Geological Society of America, Boulder, Colorado, Geology of North America G-1: 389-450.

[133] Hyndman, R. D., and Hamilton, T. S. 1993. “Queen Charlotte Area Cenozoic Tectonics and Volcanism and Their Association with Relative Plate Motion along the Northeastern Pacific Margin.” *Journal of Geophysical Research* 98: 14257-77.

[134] Doser, D. I. 2010. “A Reevaluation of the 1958 Fairweather, Alaska, Earthquake Sequence.” *Bulletin Seismological Society America* 100 (4): 1792-9.

[135] Mazzotti, S., and Hyndman, R. D. 2002. “Yakutat Collision and Strain Transfer across the Northern Canadian Cordillera.” *Geology* 30: 495-8.

[136] Christeson, G. L., van Avendonk, H. J. A., Gulick, S. P. S., Reece, R. S., Pavlis, G. L., and Pavlis, T. L. 2013. “Moho Interface beneath Yakutat Terrane, Southern Alaska.” *Journal Geophysical Research Solid Earth* 118: 5084-97.

[137] Li, J., Abers, G. A., Kim, Y., and Christensen, D. 2013.
“Alaska Megathrust 1: Seismicity 43 Years after the Great 1964 Alaska Megathrust Earthquake.” Journal Geophysical Research Solid Earth 118: 4861-71.

[138] Elliott, J., Freymueller, J. T., and Larsen, C. F. 2013. “Active Tectonics of the St. Elias Orogeny, Alaska, Observed with GPS Measurements.” Journal Geophysical Research Solid Earth 118: 5625-42.

[139] Pavlis, T. L., Picornell, C., Serpa, L., Bruhn, R. L., and Pfafker, G. 2004. “Tectonic Processes during Oblique Convergence: Insights from the Saint Elias Orogen, Northern North America Cordillera.” Tectonics 23: 14.

[140] Worthington, L. L., van Avendonk, H. J. A., Gulick, S. P. S., Christeson, G. L., and Pavlis, T. L. 2012. “Crustal Structure of the Yakutat Terrane and the Evolution of Subduction and Collision in Southern Alaska.” Journal Geophysical Research 117: B01102.

[141] Doser, D. I., de la Peña, A., and Veilleux, A. M. 2008. “Seismicity of the Prince William Sound Region and Its Relation to Plate Structure and the 1964 Alaska Great Earthquake.” In Active Tectonics and Seismic Potential of Alaska, edited by Freymueller, J. T., Haeussler, P. J., Wesson, R., and Ekstrom, G. American Geophysical Union, Washington D.C., Geophysical Monograph Series 179: 201-14.

[142] Fuchs, W. A. 1980. Tertiary Tectonic History of the Castle Mountain Fault System in the Talkeetna Mountains. University of Utah, Salt Lake City, Utah, Ph. D. Thesis: 52.

[143] Haeussler, P. J., and Saltus, R. W. 2005. “Twenty Six Kilometers of Offset on the Lake Clark Fault since Late Eocene Time.” In Studies by the U.S. Geological Survey in Alaska, 2004, edited by Haeussler, P. J., and Galloway, J. P. U.S. Geological Survey, Professional Paper 1709-A: 1-4.

[144] Bruhn, R. L. 1979. “Holocene Displacements Measured by Trenching the Castle Mountain Fault near Houston, Alaska.” In Short notes on Alaskan Geology-1978. State of Alaska Division of Geological and Geophysical Surveys Geologic Report 61: 1-13.

[145] Detterman, R. L., Pfafker, G., Hudson, T., Tysdal, R. G., and Pavoni, N. 1974. “Surface Geology and Holocene Breaks along the Susitna Segment of the Castle Mountain Fault, Alaska.” U.S. Geological Survey Miscellaneous Field Studies Map MF-618.

[146] Kirschner, C. E., and Lyon, C. A. 1973. “Stratigraphic and Tectonic Development of the Cook Inlet Petroleum Province.” American Association Petroleum Geologist Memoir 19: 396-407.

[147] Barnes, F. F., and Payne, T. G. 1956. “The Wishbone Hill District, Matanuska Coal Field, Alaska.” U.S. Geological Survey Bulletin 1016: 85.

[148] Grantz, A. 1965. “Geologic Map and Cross Sections of the Nelchina Area, South-Central Alaska.” U.S. Geological Survey Open-File Report 65-65: 4 sheets.

[149] Koehler, R. D., and Reger, R. 2014. “The Castle Mountain Fault, South-Central Alaska: Sense of Slip and Slip Rate.” Seismol. Res. Lett. 85 (2): 475.

[150] Hoffman, D. D., and Armstrong, P. A. 2006. “Miocene Exhumation of the Southern Talkeetna Mountains, South Central Alaska, Based on Apatite (U-TH)/He Thermochronology.” Geological Society of America Abstracts and Programs 38: 9.

[151] Cox, A., and Engebretson, D. C. 1985. “Change in Motion of Pacific Plate at 5 M.Y.B.P.” Nature 313: 472-4.

[152] Biot, M. A. 1961. “Theory of Folding of Viscoelastic Media and Its Implications in Tectonics and Orogenesis.” Geological Society America Bulletin 72: 1595-632.

[153] von Huene, R., Klaeschen, D., Gutscher, M., and Fruehn, J. 1998. “Mass and Fluid Flux during Accretion at the Alaskan Margin.” Geological Society of America Bulletin 110 (4): 468-82.

[154] Thatcher, W. 1984. “The Earthquake Deformation Cycle, Recurrence, and the Time-Predictable Model.” Journal Geophysical Research 89 (B7): 5674-80.

[155] Freymueller, J. T., Woodard, H., Cohen, S. C., Cross, R., Elliott, J., Larsen, C. F., Heirisdottir, S., and Zweck, C. 2008. “Active Deformation Processes in Alaska, Based on 15 Years of GPS Measurements.” In Active Tectonics and Seismic Potential of Alaska, edited by Freymueller, J. T., Haeussler, P. J., Wesson, R. L., and Ekstrom, G. American Geophysical Union, Washington D.C., Geophysical Monograph Series 179: 1-42.

[156] Reimer, P. J., et al. 2004. “INTCAL04 Terrestrial Radiocarbon Age Calibration, 0-26 CAL KYR BP.” Radiocarbon 46 (3): 1029-58.

[157] Combivellick, R. A. 1991. “Paleoseismicity of the Cook Inlet Region, Alaska: Evidence from Peat Stratigraphy in Turnagain and Knik Arms.” Alaska Division of Geological and Geophysical Surveys Professional Report 112: 52 .

[158] Hulsing, H. 1981. The Breakout of Alaska’s Lake George. U.S. Government Printing Office, Reston, Va.: 8.

[159] Trainer, F. W. 1960. “Geology and Ground-Water Resources of the Matanuska Valley Agricultural Area, Alaska.” U.S. Geological Survey Water Supply Paper 1494: 116.

[160] Bartsch-Winkler, S. R., and Schmoll, H. R. 1992. “Utility of Radiocarbon-Dated Stratigraphy in Determining Late Holocene Earthquake Recurrence Intervals, Upper Cook Inlet Region, Alaska.” Geological Society America Bulletin 104: 684-94.

[161] Sykes, L. R., and Menke, W. 2006. “Repeat Times of...
Large Earthquakes: Implication for Earthquake Mechanics and Long-Term Prediction.” *Bulletin Seismological Society America* 96 (5): 1569-96.

[162] Carver, G., and Plafker, G. 2008. “Paleoseismicity and Neotectonics of the Aleutian Subduction Zone—An Overview.” In *Active Tectonics and Seismic Potential of Alaska*, edited by Freymueller, J. T., Haeussler, P. J., Wesson, R. L., and Ekstrom, G. American Geophysical Union, Washington D.C., Geophysical Monograph Series 179: 43-63.

[163] Combellick, R. A. 1993. “The Penultimate Great Earthquake in Southcentral Alaska: Evidence from a Buried Forest near Girdwood.” In *Short Notes on Alaskan Geology 1993*, edited by Solie, D. N., and Tamian, F. Alaska Division of Geological and Geophysical Surveys Professional Report 113: 7-15.

[164] Hamilton, S., and Shennan, I. 2005. “Late Holocene Great Earthquakes and Relative Sea-Level Change at Kenai, Southern Alaska.” *Journal of Quaternary Sciences* 20 (2): 95-111.

[165] Hamilton, S., Shennan, I., Combellick, R., Mulholland, J., and Noble, C. 2005. “Evidence for Two Great Earthquakes at Anchorage, Alaska and Implications for Multiple Great Earthquakes through the Holocene.” *Quaternary Science Reviews* 24: 2050-68.

[166] Shennan, I., Barlow, N., and Combellick, R. 2008. “Paleoseismological Records of Multiple Great Earthquakes in Southcentral Alaska: A 4000-Year Record at Girdwood.” In *Active Tectonics and Seismic Potential of Alaska*, edited by Freymueller, J. T., Haeussler, P. J., Wesson, R., and Ekstrom, G. American Geophysical Union, Washington D.C., Geophysical Monograph Series 179: 185-99.

[167] Shennan, I., Bruhn, R., and Plafker, G. 2009. “Multi-segment Earthquakes and Tsunami Potential of the Aleutian Megathrust.” *Quaternary Science Reviews* 28: 7-13.

[168] Shennan, I., Bruhn, R., Barlow, N., Good, K., and Hocking, E. 2014. “Late Holocene Great Earthquakes in the Eastern Part of the Aleutian Megathrust.” *Quaternary Science Reviews* 84: 86-97.

[169] Carey, S. W. 1955. “The Orocline Concept in Geotectonics, Part I.” In *Proceedings of the Royal Society of Tasmania* 89: 255-88.

[170] Coe, R. S., Globberman, B. R., Plumley, P. R., and Thrupp, G. A. 1989. “Rotation of Central and Southern Alaska in the Early Tertiary: Oroclinal Bending by Megakinking?” In *Paleomagnetic Rotations and Continental Deformation*, edited by Kissel, C., and Laj, C. Kluwer Academic, Boston, NATO-ASI Series: 327-39.

[171] St. Amand, P. 1957. “Geological and Geophysical Synthesis of the Tectonics of Portions of British Columbia, the Yukon Territory, and Alaska.” *Geological Society America Bulletin* 68: 1343-70.

[172] Redfield, T. F., Scholl, D. W., Fitzgerald, P. G., and Beck, M. E. 2007. “Escape Tectonics and the Extrusion of Alaska: Past, Present, and Future.” *Geology* 35: 1039-42.

[173] Finzel, E. S., Flesch, L. M., and Ridgway, K. D. 2011. “Kinematics of a Diffuse North America-Pacific-Bering Plate Boundary in Alaska and Western Canada.” *Geological Society America Bulletin* 39 (9): 835-8.

[174] Schultz, R. A., and Aydin, A. 1990. “Formation of Interior Basins Associated with Curved Faults in Alaska.” *Tectonics* 9: 1387-407.

[175] Csejtey, B. Jr. 1992. “Discrepancies between Geologic Evidence and Rotational Models—Talkeetna Mountains and Adjacent Areas of South-Central Alaska.” In *Geologic Studies in Alaska by the U. S. Geological Survey, 1990*, edited by Bradley, D.C., and Ford, A. B. U.S. Geological Survey Bulletin 1999: 71-80.

[176] Lanphere, M. A. 1978. “Displacement History of the Denali Fault System, Alaska and Canada.” *Canadian Journal Earth Sciences* 15: 817-22.

[177] Dover, J. H. 1994. “Geology of Part of East-Central Alaska.” In *The Geology of Alaska*, edited by Plafker, G., and Berg, H. C. Geological Society America, Boulder, Colorado, The Geology of North America G1:153-204.

[178] Nye, C. J., and Turner, D. L. 1990. “Petrology, Geochemistry, and Age of the Spurr Volcanic Complex, Eastern Aleutian Arc.” *Bull Volcanology* 52: 205-26.

[179] Power, J. A., Coombs, M. L., and Freymueller, J. T., eds. 2010. “The 2006 Eruption of Augustine Volcano, Alaska.” *U.S. Geological Survey Professional Paper* 1769: 684.