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Slip on the Suckling Hills splay fault during the 1964 Alaska earthquake

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ABSTRACT

The Suckling Hills in southern Alaska experienced localized, anomalously large coseismic uplift in the M_w 9.2, 1964 Alaska earthquake. Large uplift at the Suckling Hills can be explained by increased slip, or an asperity, on the Alaska-Aleutian megathrust; however, this paper suggests that increased uplift may be a result of slip on the Suckling Hills splay fault. We present a series of models that demonstrate how the inclusion of the Suckling Hills fault improves the fit between modeled vertical displacement and measured coseismic uplift in comparison to slip on the Alaska-Aleutian megathrust alone. Our results suggest that ~3 m of average slip on the Suckling Hills fault during the 1964 earthquake can help explain the large coseismic uplift data. These results are consistent with recent studies indicating Pleistocene slip on the Suckling Hills fault and together highlight the potential seismic and tsunami risk associated with this segment of the Alaskan subduction complex.

1. Introduction

Megathrust splay faults branch upward from the plate boundary in subduction zones and play an important role in tsunami genesis when triggered during megathrust rupture (Lay et al., 2005; Moore et al., 2007; Park et al., 2002; Plafker, 1965; Wendt et al., 2009). Localized areas of coseismic surface uplift are a key signature of slip on splay faults (Plafker, 1969). However, using surface uplift to distinguish between areas of increased slip on a megathrust or slip along a steeper dipping splay fault is nontrivial and can have significant consequences for seismic and tsunami risk assessment as well as understanding subduction zone dynamics. In this study, we examine a relatively small area in the Suckling Hills that experienced anomalously large coseismic uplift in the 1964 Alaska earthquake (Fig. 1).

Plafker (1969) originally noted large coseismic surface uplift in the Suckling Hills area and speculated that there may have been local warping or faulting. A later detailed study by Holdahl and Sauber (1994) inverted coseismic surface deformation and suggested that an area of increased slip, or asperity, may be present on the megathrust beneath the Suckling Hills area. Recent geologic mapping and geometric modeling have demonstrated that there is a thrust fault at the base of the Suckling Hills, the Suckling Hills fault, that likely connects with the Alaska-Aleutian megathrust at depth (Chapman et al., 2011; Plafker, 2005). Deformed structural and geomorphic markers indicate that the Suckling Hills fault has been active since the Pleistocene (Chapman et al., 2011). In light of the existence and recent activity on the Suckling Hills fault, we reexamine the area of anomalously large surface uplift to determine if the Suckling Hills splay fault slipped in the 1964 Alaska earthquake.

We generated a series of models that compare predicted vertical displacement to observed coseismic uplift. The first set of models examines vertical uplift resulting from slip on the Alaska-Aleutian megathrust alone (Fig. 2). We argue that the model parameters required to match the observed data are physically improbable with slip on the megathrust alone. Next, we present a second set of models that include slip on the Suckling Hills fault and have more physically reasonable slip on the megathrust beneath the Suckling Hills (Fig. 3). The inclusion of slip on the Suckling Hills fault improves the overall fit of the models, is consistent with previous slip distribution estimates, and simplifies the regional pattern of coseismic surface uplift resulting from the megathrust (Plafker, 1969). Our second set of models suggest that ~5 m of slip averaged across the Suckling Hills splay fault could have occurred during the 1964 Alaska, but the best-fit models indicate an average of ~3 m of slip on the fault.

2. Coseismic slip in the 1964 Alaska Earthquake

The M_w 9.2 1964 Alaska earthquake ruptured a >100,000 km^2 area from east of Valdez to Kodiak Island (Kanamori, 1970; Plafker, 1969) (Fig. 1). The fault slip distribution on the megathrust was uneven, with the greatest slip occurring on two large asperities beneath Prince William Sound and Kodiak Island (Christensen and Beck, 1994). The Prince William Sound asperity generated ~20 m of slip and the Kodiak

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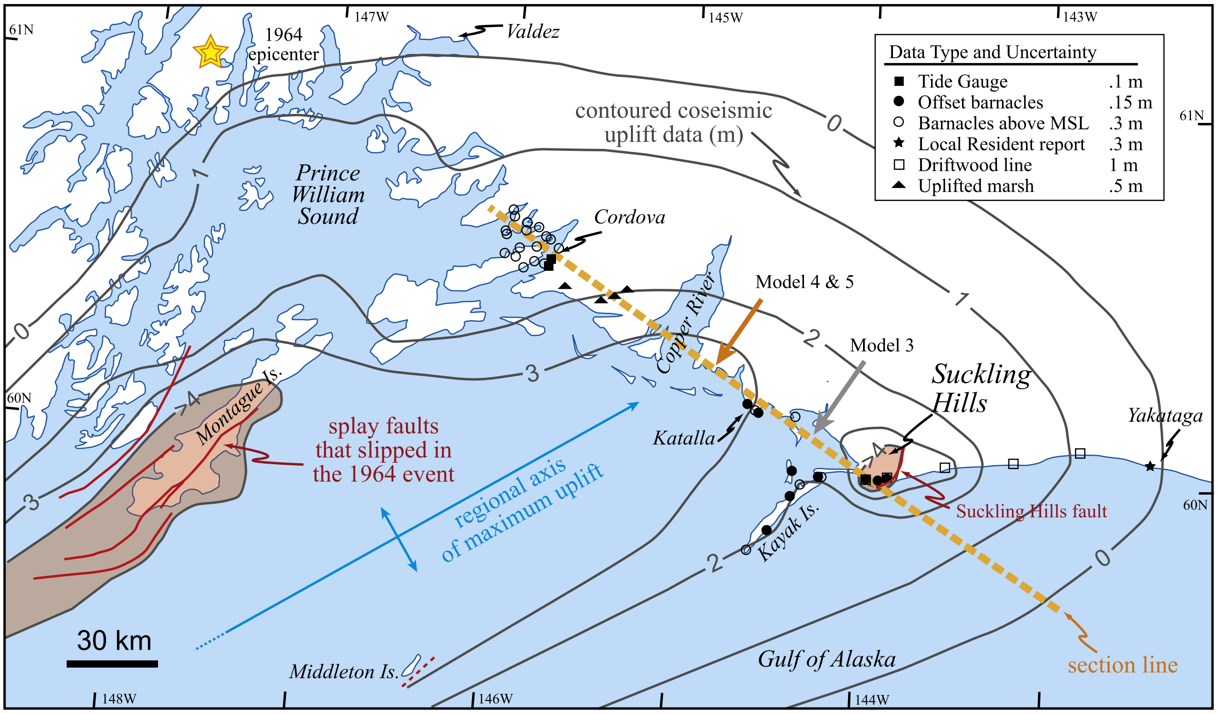

Fig. 1. Regional map of the northeastern area affected by coseismic deformation in the 1964 Alaska earthquake. Coseismic uplift data is from Plafker (1969). Only the data points used in this study are shown on the map. Offset barnacles refer to the distance between uplifted barnacles and barnacle populations that colonized the new shoreline after the 1964 event. Splay fault locations are from Liberty et al. (2013). Areas with greater than 4 m coseismic uplift are shaded. Arrows point to the location on the section line with the maximum predicted vertical displacement for Model 3 (slip on the Alaska-Aleutian megathrust only) and Models 4 and 5 (slip on the Aleutian megathrust and Suckling Hills fault).

Island asperity produced ~15 m of slip (Christensen and Beck, 1994; Holdahl and Sauber, 1994; Johnson et al., 1996; Santini et al., 2003). In addition to slip on the megathrust, several splay faults that root into the megathrust ruptured during the 1964 event. The most prominent of these splay faults are the Patton Bay fault (~8 m slip) and the Hanning Bay fault (~6 m slip) that Plafker (1969) recognized on either side of Montague Island (Fig. 1). Recently, Liberty et al. (2013) used marine seismic reflection and bathymetric survey data in western Prince William Sound to identify several additional splay faults that ruptured in 1964 including the Cape Clear fault (7 m vertical uplift) and Montague Strait fault (2 m vertical uplift) (Fig. 1). Many more active megathrust splay faults that have ruptured since the Last Glacial Maximum have been recognized from offshore seismic data (Fruehn et al., 1999; Liberty et al., 2013). Collectively, these studies indicate that megathrust splay faults are common features in the Alaskan subduction complex and that they may play an important role in the dynamics of subduction zone earthquakes.

2.1. The Suckling Hills area

Following the 1964 Alaska earthquake, the U.S. Geological Survey mapped net uplift and subsidence along the southern Alaskan coast using tide gauge records, offset biologic markers, driftwood lines, and reports from local residents (Plafker, 1969). Data from the Suckling Hills suggest unusually large uplift (4–5 m) compared to surrounding areas and the position of the Suckling Hills is offset from the regional axis of maximum uplift (Fig. 1). The increase in coseismic uplift in the Suckling Hills area is significantly higher than the associated errors in the measurements and the area of anomalously large uplift does not extend regionally along strike. Plafker (1969) originally suggested that the uplift at the Suckling Hills may be related to local faulting or warping.

There are numerous previous studies that have modeled fault slip in the 1964 Alaska earthquake from coseismic uplift data; however, most have either excluded the geologic uplift data from the Suckling Hills region (Ichinose et al., 2007; Santini et al., 2003) or have used large model geometries that did not resolve the localized slip in the Suckling Hills area (Johnson et al., 1996; Suito and Freymueller, 2009). To date, the study by Holdahl and Sauber (1994) is the only attempt to rigorously address the uplift in the Suckling Hills area. They divided the rupture area into 50 km^2 sub-faults and inverted geologic and geodetic data. Holdahl and Sauber (1994) proposed three areas of increased slip, the previously recognized Prince William Sound and Kodiak asperities plus a small area that includes the Suckling Hills. They indicated that slip on the megathrust in the Suckling Hills area was ~14 m. A plot of Holdahl and Sauber's (1994) calculated vertical displacement across the Suckling Hills region as shown in Fig. 2.

Until recently, the existence and characteristics of the Suckling Hills fault were not widely known. A compilation map by Plafker (2005) provides the first published account of the fault. The Suckling Hills fault is part of a larger splay fault system that includes the Kayak Island fault zone and the Bering Glacier fault zone that emanates from the Aleutian trench (Chapman et al., 2011). The Suckling Hills fault is a reverse fault that dips to the northwest and has a Pleistocene slip rate of <5 mm/yr (Chapman et al., 2011). The neighboring Kayak Island zone has a better constrained slip rate of ~3 mm/yr (Chapman et al., 2011). Geophysical studies near the Suckling Hills suggest that the Alaska-Aleutian megathrust is located at ~15 km depth locally and dips to the northwest at 5–6° (Brocher et al., 1994; Eberhart-Phillips et al., 2006; Elliott et al., 2013). The deformation front for the megathrust system lies ~100 km east of the Suckling Hills at the Pamplona fault zone (Worthington et al., 2008).

3. Models and results

We evaluated surface deformation in the Suckling Hills area using a series of elastic dislocation models in both two (2D) and three dimensions (3D). For the 2D models, we created a section line along the coast from Cordova to the town of Yakataga and projected observed coseismic uplift data onto the section (Fig. 1). Dense data coverage exists further to the northwest towards Valdez; however, inclusion of

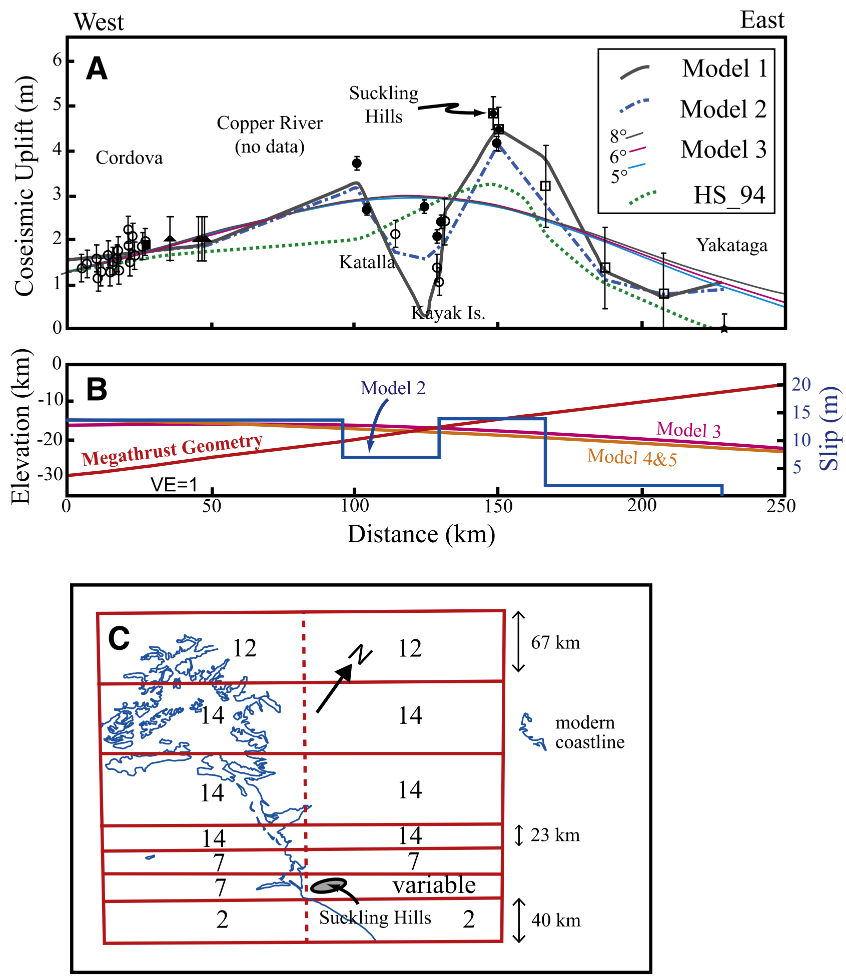

Fig. 2. A. Measured coseismic uplift data points and vertical displacement predicted from elastic dislocation models of the Alaska-Aleutian megathrust without slip on the Suckling Hills fault for the plane of section shown in Fig. 1. The results of Model 3 are shown with different dip values for the megathrust. HS_94 = the dislocation model of Holdahl and Sauber (1994) that includes increased slip on the megathrust in the Suckling Hills area. Labels refer to place names along the line of section. B. Cross-section showing geometry of the Alaska-Aleutian megathrust with an 8 degree dip and a plot of the slip magnitude on the megathrust for Models 2–5. C. Map view of the sub-fault geometry used in Models 1, 2, and 6. Model 1 used long rectangular fault planes and Model 2 doubled the number of fault planes by dividing them in half along the dashed line. The numbers within the fault plane boxes represent the amount of slip prescribed for Models 1, 2, and 6, with the fault plane beneath the Suckling Hills variable (Table 1). The width of the fault planes is shown at the right. Note the north arrow.

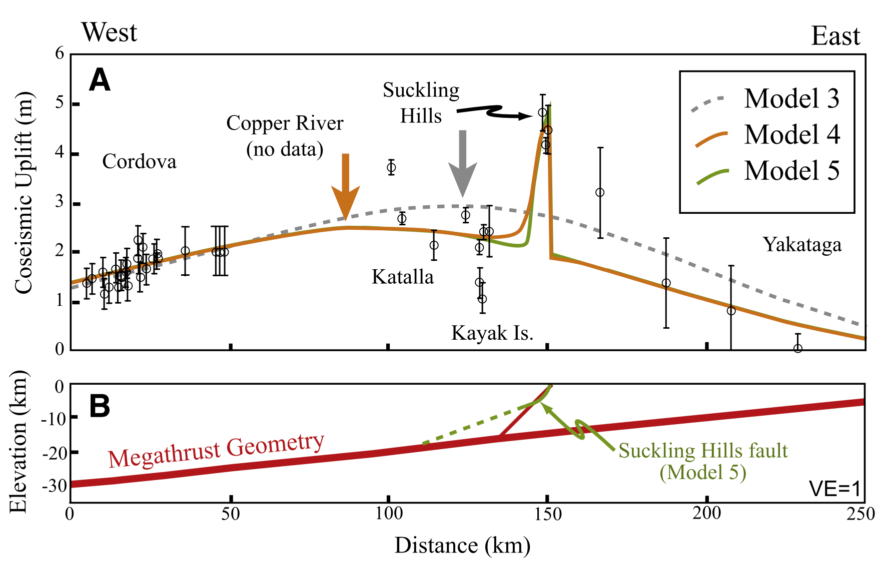

Fig. 3. A. Best-fit vertical displacement of Model 3 (slip on megathrust only) plotted against Model 4 and Model 5 (slip on the Alaska-Aleutian megathrust as well as the Suckling Hills fault). Model 4 is a forward modeled elastic dislocation and Model 5 is a forward modeled kinematic model. Note the improved fit to the coseismic uplift data. Bold arrows indicate the position of the maximum predicted vertical displacement. Positions also plotted on Fig. 1. B. Cross-section showing geometry of the Alaska-Aleutian megathrust and Suckling Hills fault used in Model 4 (solid line) and Model 5 (dashed line).

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this data diluted the influence of the relatively sparse data coverage around the Suckling Hills. The projected data is within 10 km of the section line except at Kayak Island where data from around the island is projected ≤ 30 km perpendicular to the section and east of the Suckling Hills where data is projected ≤ 40 km perpendicular to the section. No data are available across the Copper River delta. The projected data form a coseismic uplift profile across the Suckling Hills area that provides the basis for all our following 2D modeling studies. For the 3D models, we created a series of sub-faults and varied the geometry, size, and slip on the sub-faults to match the coseismic uplift data. We weight the uplift data according to the type of measurement using uncertainties reported in Plafker (1969) (Fig. 1). We do not solve for fault motion in the along-strike direction and the resulting models assume pure dip-slip and may underestimate total slip if there is a large oblique component to motion. Previous studies suggest a small component (<20%) of strike-slip motion throughout the rupture area (Ichinose et al., 2007). We model surface displacement resulting from slip on the megathrust alone and then add the Suckling Hills fault.

3.1. Alaska-Aleutian megathrust dislocation models

For the first megathrust model (Model 1), without the Suckling Hills fault, we forward modeled vertical displacement resulting from an elastic dislocation on a rectangular fault surface (Okada, 1985). We divided the shallowly dipping megathrust into multiple planar sub-faults in the down-dip direction with uniform slip across each sub-fault (Fig. 2). We varied the magnitude of uniform slip on each sub-fault as well as the width of the sub-fault until we produced the best-fit match to the coseismic uplift data. This type of fault model closely resembles those used in previous studies (e.g. Holdahl and Sauber, 1994; Ichinose et al., 2007; Johnson et al., 1996; Suito and Freymueller, 2009), but we focused specifically on the Suckling Hills area and forced the model to fit the anomalously large coseismic uplift data. The results of Model 1 suggest that a patch of at least 14 m of slip localized on megathrust beneath the Suckling Hills provides the best fit to the data (Fig. 2). These results are consistent with the modeling of Holdahl and Sauber (1994) who also predicted ~14 m slip on the megathrust beneath the Suckling Hills. However, there are several reasons why we think that the results of Model 1 may be unrealistic: 1) the maximum slip required on the megathrust is high, only moderately less than estimates for the Prince William Sound and Kodiak asperities; 2) the model requires a sub-fault beneath the Suckling Hills that does not extend offshore towards Kayak Island, suggesting a very localized asperity; 3) the slip gradient between sub-faults beneath the Suckling Hills and surrounding areas is very large, with changes in slip magnitudes up to 85%; and 4) even the best-fit model contains a fairly large misfit to the data (Table 1).

Table 1
Results for various runs of Model 6. All reported numbers are slip in meters, except error which is reported as the weighted residual sum of squares (WRSS). Model 6 was run for various values of slip on the Alaska-Aleutian megathrust (Mega Slip) and used the megathrust geometry (Mega_Geom) from Model 1 or Model 2.

	Mega slip	Suckling Hills fault slip			
Mega_Geom		Lower	Middle	Upper	WRSS
Model 1	5	7	4.5	4.5	52
	6	7	4	4	52
	7	7	3	3	53
	8	4.5	3.5	2.5	55
	9	4.5	3	2	58
	14	–	–	–	95
Model 2	5	7	4.5	4.5	55
	6	7	4	4	54
	7	7	3	3	53
	8	4.5	3.5	2.5	55
	9	4.5	3	2	52
	10	4.5	2.5	1.5	52
	14	–	–	–	57

In the next model (Model 2), we added additional sub-faults to isolate the Suckling Hills from Kayak Island (Fig. 2), where some of the greatest misfit was occurring in Model 1. Model 2 also indicates ~14 m of slip on the Alaskan-Aleutian megathrust beneath the Suckling Hills and ~7 m of slip on the megathrust beneath Kayak Island. The inclusion of a sub-fault beneath Kayak Island significantly decreased our misfit, but did not change the suspicious fault geometry or slip gradients.

If the anomalously high coseismic uplift data at the Suckling Hills was ignored, all of the data in our 2D models could be fit well by a single polynomial function that may approximate a continuous decrease in slip magnitude away from the main Prince William Sound asperity. This led us to the creation of Models 3, 4 and 5. We started with Model 3 that includes the coseismic uplift data at the Suckling Hills. In Model 3 we again used an elastic dislocation model (Okada, 1985) to predict vertical displacements; however, unlike Models 1 and 2, we employed a variable slip function for a single plane representing the megathrust (Freund and Barnett, 1976; Wang and He, 2008). Whereas the previous models used increasingly small fault planes and variations in slip to fit the data, this model attempts to fit the entire data set at once. We used a symmetrical slip distribution along the fault plane with maximum slip at the center of the fault segment and zero slip at the segment edges. We intended for Model 3 to approximate a megathrust event that is dominated by a single region of large slip that decreases in both the up-dip and the down-dip directions. This setup compares favorably with most independent models for slip during the 1964 Alaska earthquake that resolve a large asperity in the Prince William Sound or around Kodiak Island along strike (Ichinose et al., 2007; Johnson et al., 1996; Suito and Freymueller, 2009).

We solved for maximum slip on the megathrust interface in Model 3 by minimizing root mean square error (RMSE) of forward modeled vertical displacement compared to coseismic uplift. Model 3 suggests 13 ± 1 m maximum slip on the megathrust in our plane of section and ~11 m of slip beneath the Suckling Hills (Fig. 2). Maximum slip determined from previous studies ranges from 5 to 20 m in the plane of section of our model (Holdahl and Sauber, 1994; Ichinose et al., 2007; Johnson et al., 1996; Santini et al., 2003; Suito and Freymueller, 2009). Model 3 predicts the largest vertical displacement ~20 km west of the Suckling Hills (gray arrow, Fig. 3). This is offset ~30 km to the east of the regional axis of maximum coseismic uplift (Plafker, 1969), located near the western edge of the Copper River delta (Fig. 1). In the following section we demonstrate that the anomalously large coseismic uplift recorded at the Suckling Hills is causing the shift of the maximum predicted vertical displacement.

To understand the effect of megathrust dip on the results of Model 3, we ran the model with dip ranging from 5 to 10°. Regardless of the dip chosen, the effect on coseismic uplift was well below the uncertainty magnitude with a difference of <0.05 m except at the eastern edge of the model near Yakataga where data coverage is sparse (Fig. 2). The steepest dips resulted in the lowest RMSE; however, geophysical studies have suggested megathrust dip to be 5–6° (Eberhart-Phillips et al., 2006; Elliott et al., 2013). We chose a fixed dip of 8° to provide a direct comparison to the models of Holdahl and Sauber (1994) who also prescribed an 8° dip on the megathrust.

We suggest that Model 3 results in an adequate approximation of surface uplift in the Suckling Hills region and use it as a reference model to compare later models that include slip on the Suckling Hills fault. It is important to note that we are not modeling the entire 1964 rupture area and the megathrust models (Models 1–3) presented above are not intended to fully capture the complexities of the main megathrust event or supersede the conclusions of previous studies. The models are intended to provide a reasonable estimation of surface uplift resulting from slip on the megathrust alone that will highlight the effects of adding a secondary splay fault in later models. We emphasize that the inclusion of the Suckling Hills fault should have comparable

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effects on any model examining slip and surface deformation in the 1964 Alaska earthquake.

3.2. Suckling Hills fault dislocation and kinematic models

In the next series of models we include slip on the Alaska-Aleutian megathrust as well as slip on the Suckling Hills splay fault (Fig. 3). Parameters for the megathrust portion of the model remain the same as Models 1–3. For the first of the combined Suckling-Megathrust models (Model 4), we ran Model 3 with the anomalously large coseismic uplift data points from the Suckling Hills removed to estimate how much uplift may be attributable to regional slip on the megathrust. We subtracted the regional uplift calculated from the original data and then used the remaining uplift values to model slip on the Suckling Hills fault. As a result, Model 4 is an end-member scenario without a high slip patch on the megathrust beneath the Suckling Hills and the following slip estimates for the Suckling Hills fault can be considered maximum estimates. We used the elastic dislocation equations of Okada (1985) assuming uniform slip on a single fault plane to model the Sucking Hills fault. We assigned the Suckling Hills fault a dip of 45° to the northwest, perpendicular to our section line, as a linear approximation of the listric fault geometry presented in Chapman et al. (2011). We extended the fault plane from the surface to ~15 km depth where it intersects the Alaska-Aleutian megathrust. We combined predicted vertical displacement resulting from slip on the Suckling Hills fault with the results from the modified Model 3 and forward modeled to minimize error as above. The results of Model 4 indicate 3.4 m $\pm$ 0.8 m slip on the Suckling Hills fault (Fig. 3).

Although Model 4 presented above uses a linear approximation for the Suckling Hills fault at depth, geometric modeling based on deformed bedding and geomorphic markers suggest that the fault is listric in the near subsurface (Chapman et al., 2011). For Model 5, we used the listric geometry of the Suckling Hills fault estimated by Chapman et al. (2011) and forward modeled vertical displacement resulting from various amounts of slip on the Suckling Hills fault with the fault parallel flow algorithm in Midland Valley's Move software. We used a surface dip of 60°, a listric fault segment and a transition to a planar fault dipping ~25° at depth. Because of the listric geometry, vertical uplift rapidly decreases away from the fault. As a result, uplift is particularly sensitive to the distance from the coseismic data points to the fault trace. To account for potential uncertainty in the horizontal direction, we assumed an accuracy of $\pm$500 m for each measured coseismic data point. The assumed uncertainty inherently applies to the location of the projected fault trace. We then used a Monte Carlo routine to solve for slip. We used a normal probability distribution for vertical error on uplift and a uniform probability distribution for horizontal error. We sampled randomly from 10^4 runs using these distributions and then minimized misfit between coseismic uplift and vertical displacement resulting from various slip values in the forward model. The best fit to the coseismic uplift data for Model 4 suggests 3.1 $\pm$ 0.5 m slip on the Suckling Hills fault (Fig. 3). The averaged best-fit slip of Model 4 (elastic dislocation) and Model 5 (kinematic) is 3.3 $\pm$ 0.5 m.

For both Models 4 and 5, the best-fit solution for the megathrust is identical away from the Suckling Hills and is best modeled with a maximum of 14 $\pm$ 1 m slip in our 2D section, with ~11 m of slip on the megathrust beneath the Suckling Hills. This places the maximum predicted vertical displacement at the western edge of the Copper River delta (orange arrow, Fig. 3), coincident with the regional axis of maximum coseismic uplift (Plafker, 1969) (Fig. 1), resolving the mismatch observed when the Suckling Hills fault was not included in the models.

Since Models 4 and 5 are end-member models that suggest no high slip patch or asperity beneath the Suckling Hills, there is the possibility that both elevated megathrust slip and slip on the Suckling Hills splay fault are contributing to the observed coseismic uplift at the Suckling Hills. The large displacement splay faults around Montague Island are all clustered near the Prince William Sound asperity (Fig. 1), potentially indicating a relationship between splay fault rupture and asperity location. To test for this possibility at the Suckling Hills, we created an additional forward elastic dislocation model (Model 6) that included variable slip on both the Suckling Hills fault and the Alaska-Aleutian megathrust.

Model 6 results in a range of non-unique, but acceptable (low misfit) values for slip on the megathrust and the Suckling Hills splay fault (Table 1). The range of acceptable results is presented in Fig. 4 as an envelope of solutions. We ran the model first using the megathrust geometry from Model 1 and then again using the geometry from Model 2. For the Suckling Hills splay fault, we estimated the listric nature of the fault by using three fault planes; an upper and middle fault plane dipping 45° and a lower fault plane dipping 30°. Each fault plane was 4 km wide in the dip direction. In all of the Model 6 runs, slip tended to decrease updip on the Suckling Hills splay fault. Because Models 1 and 2 fit the observed uplift data away from Suckling Hills well, slip on the Alaska-Aleutian megathrust in Model 6 was held constant on all of the subfaults, except beneath the Suckling Hills. The suite of acceptable models suggest 5 m–10 m of slip on the megathrust beneath the Suckling Hills and 3 m–5 m of average slip on the Suckling Hills splay fault itself. We report slip on the Suckling Hills splay fault as an average from each of the three sub-fault planes (Table 1). The similar measures of misfit between the various reported runs in Model 6 do not allow us to robustly choose a best fit solution. However, the runs using the megathrust geometry from Model 1 (no sub-fault beneath Kayak Island) result in the lowest data misfit by employing the smallest values of megathrust slip (5 m to 6 m) and the highest values of slip on the Suckling Hills splay fault (7 m slip at depth decreasing to 4.5 m slip at the surface) (Table 1). These slip magnitudes suggest that slip on the megathrust beneath the Suckling Hills would be lower than the 7 m–11 m of slip on the megathrust beneath the Suckling Hills calculated in the range of models discussed above. For this reason, in addition to the somewhat large values for slip on the Suckling Hills fault, we prefer the runs in Model 6 that used the megathrust geometry from Model 2 with a subfault beneath Kayak Island (Fig. 4). These runs result in the smallest data misfit by employing the intermediate values of megathrust slip (9 m–10 m) and intermediate values of slip on the Suckling Hills splay fault (4.5 m slip at depth decreasing to 1.5 m slip at the surface) (Table 1). Thus, our preferred results for Model 6 are 9 m–10 m of slip on the megathrust beneath the Suckling Hills and ~3 m of average slip on the Suckling Hills splay fault. This value of slip on the Suckling Hills splay fault is consistent with Models 4 and 5 that independently estimated ~3 m of average slip on the Suckling Hills splay fault. The amount of slip on the megathrust beneath the Suckling Hills may be slightly elevated from the regional trend, but it falls within our estimates for relatively smoothly varying slip, suggesting that a significant asperity was not present beneath the Suckling Hills during the 1964 Alaska earthquake.

4. Discussion and conclusions

M_w >9 subduction zone earthquakes are rare and only three have been recorded since global seismic network monitoring began. Understanding the complexities of these earthquakes is important for hazard risk assessment and refining rupture models. In addition, the Suckling Hills splay fault presents a rare opportunity to examine a possible megathrust splay fault onshore; most megathrust splay faults occur offshore (e.g. Cascadia, Nankai, Sumatra).

The results presented above suggest that slip on the Suckling Hills splay fault during the 1964 Alaska earthquake is a viable explanation for a small area of large coseismic uplift. Holdahl and Sauber (1994) previously suggested that uplift at the Suckling Hills may be related to a megathrust asperity that slipped ~14 m in the 1964 event. An asperity model and splay fault model can both be optimized to yield a good fit to the coseismic uplift data; however, there are several reasons why we favor the splay fault model. First, the Suckling Hills area was not

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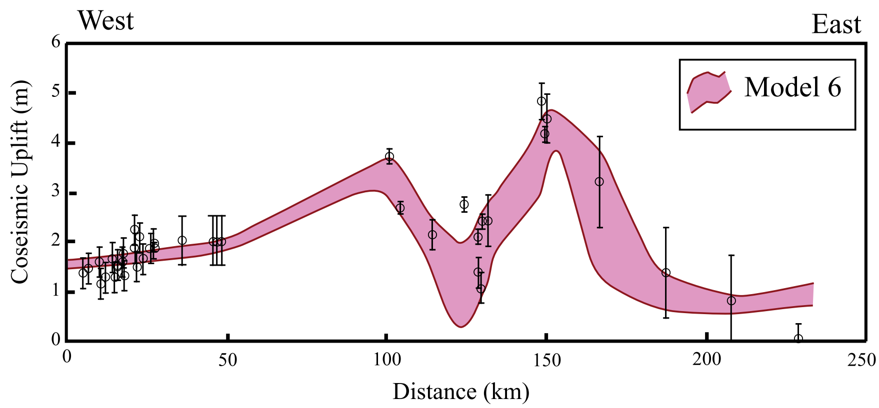

Fig. 4. Range of acceptable Model 6 results.

characterized by significant seismicity and aftershocks, in contrast to the Prince William Sound and Kodiak asperities, despite similar amounts of predicted slip (Cohen and Freymueller, 2004; Doser et al., 1999). Second, the region of large coseismic uplift beneath the Suckling Hills is offset from the regional axis of maximum uplift and is unusually localized. Adding the Suckling Hills fault to our models removed this offset. Third, a splay fault is present at the Suckling Hills that has been active in the Pleistocene (Chapman et al., 2011; Plafker, 2005). Finally, our models provide a better fit to the observed coseismic uplift data with the Suckling Hills splay fault included.

In our results we presented two groups of models; slip on the megathrust only (Models 1, 2, and 3), which required a patch of high slip or asperity beneath the Suckling Hills, and slip on the Suckling Hills splay fault above a megathrust with more smoothly varying slip (Models 4 and 5). We demonstrated that increased slip on the Alaska-Aleutian megathrust alone does not provide the best fit to the coseismic uplift data and may be physically improbable. To assess the possibility of both elevated slip on a Suckling Hills asperity and slip on the Suckling Hills splay fault in the 1964 Alaska earthquake, we presented a final model (Model 6) that yielded a group of non-unique values that nonetheless provide some boundaries to possible slip on the megathrust and Suckling Hills splay fault. Models 4 and 5 and our preferred result for Model 6 all indicate ~3 m of slip on the Suckling Hills splay fault. Our preferred result for Model 6 also indicates the possibility of slightly higher slip (9 m–10 m) on the megathrust beneath the Suckling Hills compared to the neighboring sections of the megathrust with ~7 m of slip in Model 6, although we do not interpret this as a significant asperity.

The average recurrence interval for great earthquakes in the Prince William Sound region is ~600 years (Carver and Plafker, 2008). If the Suckling Hills fault were to characteristically slip ~3 m during every megathrust event it would result in a ~5 mm/yr slip rate, comparable to estimates for Pleistocene slip for the Suckling Hills and Kayak Island (Chapman et al., 2011). Shennan et al. (2009) suggests that great earthquakes may rupture multiple fault segments in the southern Alaska subduction complex, but there is no compelling argument for reoccurring slip on the Suckling Hills fault during every megathrust event, implying 5 mm/yr may be a maximum estimate for slip rate unless the Suckling Hills fault slips independently of the megathrust during interseismic periods or involves slip mechanisms other than stick–slip. The potential for slip on the Suckling Hills fault and specifically on the Kayak Island fault zone during megathrust events may present a tsunami risk.

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References

Brocher, T.M., Fuis, G.S., Fisher, M.A., Plafker, G., Moses, M.J., 1994. Mapping the megathrust beneath the northern Gulf of Alaska using wide-angle seismic data. J. Geophys. Res. 99, 11663–11685.

Carver, G., Plafker, G., 2008. Paleoseismicity and neotectonics of the Aleutian subduction zone—an overview. In: Freymueller, J.T., Haeussler, P.J., Wesson, R., Ekstrom, G. (Eds.), Active Tectonics and Seismic Potential of AlaskaGeophys. Monogr. 179. American Geophysical Union, Washington D.C.

Chapman, J.B., Worthington, L.L., Pavlis, T.L., Bruhn, R.L., Gulick, S.P., 2011. The Suckling Hills Fault, Kayak Island Zone, and accretion of the Yakutat microplate, Alaska. Tectonics 30, TC002945.

Christensen, D.H., Beck, S.L., 1994. The rupture process and tectonic implications of the great 1964 Prince William Sound earthquake. Pure Appl. Geophys. 142, 29–53.

Cohen, S.C., Freymueller, J.T., 2004. Crustal deformation in the southcentral Alaska subduction zone. Adv. Geophys. 47, 1–58.

Doser, D.I., Veilleux, A.M., Velasquez, M., 1999. Seismicity of the Prince William Sound region for over thirty years following the 1964 Great Alaskan earthquake. Pure Appl. Geophys. 154, 593–632.

Eberhart-Phillips, D., Christensen, D.H., Brocher, T.M., Hansen, R., Ruppert, N.A., Haeussler, P.J., Abers, G.A., 2006. Imaging the transition from Aleutian subduction to Yakutat collision in central Alaska, with local earthquakes and active source data. J. Geophys. Res. 111, B11303.

Elliott, J., Freymueller, J.T., Larsen, C.F., 2013. Active tectonics of the St. Elias orogen, Akaska, observed with GPS measurements. J. Geophys. Res. 118, 5625–5642.

Freund, L.B., Barnett, D.M., 1976. A two-dimensional analysis of surface deformation due to dip-slip faulting. Bull. Seismol. Soc. Am. 66, 667–675.

Fruehn, J., von Huene, R., Fisher, M.A., 1999. Accretion in the wake of terrane collision: the Neogene accretionary wedge off Kenai Peninsula, Alaska. Tectonics 18, 263–277.

Holdahl, S.R., Sauber, J., 1994. Coseismic slip in the 1964 Prince William Sound earthquake: a new geodetic inversion. Pure Appl. Geophys. 142, 55–82.

Ichinose, G., Somerville, P., Thio, H.K., Graves, R., O'Connell, D., 2007. Rupture process of the 1964 Prince William Sound, Alaska, earthquake from the combined inversion of seismic, tsunami, and geodetic data. J. Geophys. Res. 112, B07306.

Johnson, J.M., Satake, K., Holdahl, S.R., Sauber, J., 1996. The 1964 Prince William Sound earthquake: joint inversion of tsunami and geodetic data. J. Geophys. Res. 101, 523–532.

Kanamori, H., 1970. The Alaska earthquake of 1964: radiation of longperiod surface waves and source mechanism. J. Geophys. Res. 75, 5029–5040.

Lay, T., et al., 2005. The great Sumatra_Andaman earthquake of 26 December 2004. Science 308, 1127–1133.

Liberty, L.M., Finn, S.P., Haeussler, P.J., Pratt, T.L., Peterson, A., 2013. Megathrust splay faults at the focus of the Prince William Sound asperity, Alaska. J. Geophys. Res. 118, 5428–5441.

Moore, G.F., Bangs, N.L., Taira, A., Kuramoto, S., Pangborn, E., Tobin, H.J., 2007. Three-dimensional splay fault geometry and implications for tsunami generation. Science 318, 1128–1131.

Okada, Y., 1985. Surface deformation due to shear and tensile faults in a half-space. Bull. Seismol. Soc. Am. 75, 1135–1154.

Park, J.O., Tsuru, T., Kodaira, S., Cummins, P.R., Kaneda, Y., 2002. Splay fault branching along the Nankai Subduction Zone. Science 297, 1157–1160.

Plafker, G., 1965. Tectonic deformation associated with the 1964 Alaska earthquake. Science 148, 1675–1687.

Plafker, G., 1969. Tectonics of the March 27, 1964, Alaska earthquake. U.S. Geological Survey Professional Paper 543-I.

Plafker, G., 2005. Geology of Bering Glacier and Icy Bay quadrangles. U.S. Geological Survey Open-File Report 2005–1342, (pubs.usgs.gov/of/2005/1342).

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Santini, S., Dragoni, M., Spada, G., 2003. Asperity distribution of the 1964 Great Alaska earthquake and its relation to subsequent seismicity in the region. Tectonophysics 367, 219–233.

Shennan, I., Bruhn, R., Plafker, G., 2009. Multi-segment earthquakes and tsunami potential of the Aleutian megathrust. Quat. Sci. Rev. 28, 7–13.

Suito, H., Freymueller, J.T., 2009. A viscoelastic and afterslip postseismic deformation model for the 1964 Alaska earthquake. J. Geophys. Res. 114, B11404.

Wang, K., He, J., 2008. Effects of frictional behavior and geometry of subduction fault on coseismic seafloor deformation. Bull. Seismol. Soc. Am. 98, 571–579.

Wendt, J., Oglesby, D., Geist, E., 2009. Tsunamis and splay fault dynamics. Geophys. Res. Lett. 36, L15303.

Worthington, L.L., Gulick, S.P., Pavlis, T.L., 2008. Identifying active structures in the Kayak Island and Pamplona Zone—implications for offshore tectonics of the Yakutat microplate, Gulf of Alaska. In: Freymueller, J.T., Haeussler, P.J., Wesson, R., Ekstrom, G. (Eds.), Active Tectonics and Seismic Potential of AlaskaGeophys. Monogr. 179. American Geophysical Union, Washington D.C.

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