Fault strength and transpressional tectonics along the Castle Mountain strike-slip fault, southern Alaska

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ABSTRACT

Analyses of structures along the Castle Mountain fault reveal the mechanical relations and relative timing of orogen-parallel strike-slip faulting to distributed wrenching and shortening and to plate motion in the southern Alaskan transpressive margin. The Castle Mountain fault is a >200-km-long, orogen-parallel, right-lateral seismogenic fault in the southern Alaskan plate margin. Exposures of the fault in the study area have been exhumed from 3–4 km depth and ~80 °C. Moment tensor summations and stress inversions of slip data from fault networks within 400 m of the Castle Mountain fault and analyses of structures in forearc deposits 2–4 km from the fault yield maximum incremental shortening and maximum compressive stress (σ3) axes that are subhorizontal and trend ~325°. This trend is close to the 340° North American–Pacific plate convergence direction. The inferred σ3 makes a 70°–80° angle with the ~070°-striking Castle Mountain fault, indicating that the fault slips at a lower shear stress than predicted by laboratory rock friction experiments if hydrostatic pore pressure exists in the fault (i.e., coefficient of friction ~0.85, Byerlee’s Law). The forearc structures record coaxial strain and apparently remain in their formative orientations, showing that previously documented distributed shearing in the form of vertical-axis block rotations in the forearc ceased prior to formation of the structures in late Oligocene time. The mechanical weakness of the Castle Mountain fault probably results in part from its clay-rich gouge, which averages about 43 wt% clay phases. However, the gouge composi-
nisms include elevated pore pressure (e.g., Sibson et al., 1988; Rice, 1992), phyllosilicate-rich fault rocks with low coefficients of friction (e.g., Wang, 1984), and pervasive shearing of fault gouge (e.g., Marone et al., 1990).

This paper reports on the paleostress state and the history of deformation in the forearc and along the Castle Mountain fault, southern Alaska (Fig. 1). The Castle Mountain fault is a seismogenic, orogen-parallel strike-slip fault that bounds part of the forearc between the obliquely convergent Pacific and North American plates. The Castle Mountain fault provides an opportunity to investigate the issues involving the shear strength of strike-slip faults and strain partitioning at obliquely convergent margins. Studying the Castle Mountain fault also elucidates its role in the tectonics of the southern Alaska margin. Slip data from faults along the Castle Mountain fault and exhumed structures in the forearc indicate that the Castle Mountain fault is weak, having slipped in response to $\sigma_1$ at $70^\circ$–$80^\circ$, and that recent motions are right lateral. The mineralogy of gouge samples retrieved from exposures of the Castle Mountain fault's core is compared with published rock friction data to estimate the fault's bulk coefficient of friction to be $-0.5$. The development of forearc folds, faults, and dikes is analyzed, revealing that early Tertiary clockwise vertical-axis block rotations (Stamatakos et al., 1988, 1989) ceased by late Oligocene time, possibly in response to the partitioning of shearing onto the Castle Mountain fault as it weakened.

BACKGROUND

Geologic Setting and History of the Castle Mountain Fault

The Castle Mountain fault cuts Peninsular terrane basement, Cretaceous and younger forearc overlap sedimentary rocks, and Tertiary shallow intrusive rocks (Figs. 1 and 2) (Grantz, 1966; Dettman et al., 1976; Fuchs, 1980). Deformation was broadly contemporaneous with sedimentation throughout the Cook Inlet and Matanuska Valley during early to mid-Tertiary time, resulting in conglomerates overlying lower strata in angular unconformities (Fig. 2) (Clardy, 1974; Winkler, 1978). Sedimentation probably ceased in the Matanuska Valley in late Oligocene or Miocene time, possibly in response to impingement of the Yakutat block on south-central Alaska (Little and Naeser, 1989). Today and throughout much of their history, the Cook Inlet and Matanuska Valley have been bound-ed by mountains to the north and south, from which they have received sediments (e.g., Clardy, 1974; Little, 1988).

The Castle Mountain fault apparently formed in Late Cretaceous or early Tertiary time and led to the deposition of conglomerates along the fault. Continued movement in Paleogene time is manifest in additional coarse sediments derived from the north and deposited immediately to the south of the fault (Clardy, 1974). There is evidence for both vertical (north side up) and right-lateral motion on the $80^\circ$–$90^\circ$N dipping fault (Grantz, 1966; Fuchs, 1980); but there is no consensus on the timing of dip-slip versus strike-slip motion, or for the magnitude of right slip. Fuchs (1980) inferred $20$ km of total right slip and $5$ km since Eocene time. Grantz (1966) suggested tens of kilometers of right-lateral offset on the basis of juxtaposed dissimilar Cretaceous rocks, and Meisling et al. (1987) estimated at least $35$ km of slip since $75$ Ma. Fuchs (1980) inferred $3$–$3.5$ km of north-side-up motion from the difference in stratigraphic levels exposed north and south of the fault. Redfield and Fitzgerald (1993) proposed a model for motions on the orogen-parallel faults of southern Alaska, including the Castle Mountain fault. They suggested that if slip is driven directly by plate motion, it should be dextral in the east, where the faults have more northerly strikes, and sinistral in the west, where the faults have more westerly strikes (Fig. 1). Their model also predicts that the Castle Mountain fault slip sense should have changed over time from left lateral to right lateral near Anchorage.

Recent activity on the Castle Mountain fault is revealed by scarp in soils and glacial sediments in the Susitna Lowlands (Fig. 1) (Dettman et al., 1976; Haeussler et al., 2000) and earthquakes along the mapped trace of the fault in 1984 (body wave magnitude 5.7; Lahr et al., 1986) and 1996 (local magnitude 4.6) (Fig. 2). The earthquakes occurred very near each other, and the focal mechanism solutions have right-lateral nodal planes subparallel to the Castle Mountain fault. There is no evidence for postglacial activity on the fault east of the earthquake epicenters (Haeussler et al., 2000). The fault is locally well exposed in the study area (Fig. 2). Rocks in these exposures have been exhumed from $-3$–$4$ km depth and $80$–$100$ °C, based on estimates of the thickness of missing, eroded strata, vitrinite reflectance data from correlative strata in the Matanuska Valley (Little, 1988), and fault-gouge clay mineralogy.

Regional Strain, Stress, and Plate Motions

The relative motion of the North American and Pacific plates, stress inferred from borehole breakouts in the Cook Inlet, and strain...
estimates from faults in the Matanuska Valley provide information on regional stress and strain.

Current and past motion across the southern Alaskan plate boundary is estimated by the NUVEL-1a global plate motion model (DeMets et al., 1990, 1994), and various plate reconstructions (Engebretson et al., 1985; Lonsdale, 1988; Stock and Molnar, 1988). Since ca. 40–45 Ma, there has been convergence toward ~340° with a slight component of right-lateral obliquity across the southern Alaskan margin. Norton (1995) and Kelley and Engebretson (1994) noted that there may have been slight changes in plate motion at 33 Ma and 5 Ma, but these changes are not well resolved. It is unclear whether the Kula or Pacific plate was subducting beneath North America between ca. 55 and 40 Ma. If the Kula plate was present, convergence probably was more rapid and toward ~350° (Engebretson et al., 1985).

Zajac (1997) used borehole breakout data from 21 deviated wells in the Cook Inlet to infer
stress. With few exceptions, inversions of the breakout data revealed a uniaxial compressive stress field, with \( \sigma_1 \) subhorizontal and trending \( \sim 340^\circ \), subparallel to the plate motion vector (Zajac, 1997). Bruhn and Pavlis (1981) used the orientations and slip sense of Tertiary faults to infer that maximum finite shortening in the Matanuska Valley has been oriented \( 00^\circ/340^\circ \) since Tertiary time.

**RIGHT-LATERAL DISPLACEMENT ON THE CASTLE MOUNTAIN FAULT**

Previous studies have failed to definitively document the slip history of the Castle Mountain fault. However, the earthquakes in 1984 and 1996 and exposures of slip surfaces along the core of the Castle Mountain fault near Puddingstone Hill (Fig. 2) show that recent motions on the fault have been right lateral. The orientation of the fault at Puddingstone Hill is \( 070/85^\circ \)N, similar to other locations. Slickensides bound the fault core and contain subhorizontal corrugations formed by abrasion during slip. Extensional, calcite-filled veins cut the slickensides. The veins are subvertical and strike at \( 30^\circ-45^\circ \) from the slickensides, in a clockwise sense, which is consistent with right-lateral strike slip.

**STRAIN AND STRESS ADJACENT TO THE CASTLE MOUNTAIN FAULT**

Whether the Castle Mountain fault slips directly in response to Pacific—North American plate motion and to a high angle \( \sigma_1 \) can be addressed by inferring strain and stress from fault networks along the fault. The orientations, slip directions, and shear senses of faults (collectively, fault-slip data) record information on applied strain and stress. Such fault-slip data have been recorded from six localities along the Castle Mountain fault (Fig. 2). Incremental strain is inferred by plotting M poles (movement-plane poles) (Arthaud, 1969) and summing the incremental strains from the faults using the moment tensor summation technique (Kostrov, 1974; Molnar, 1983; Marrett and Allmendinger, 1990). Best-fit stress tensors are found by inverting the fault-slip data using Gephart’s (1990) focal mechanism stress inversion method.

**Sampling Methods**

I used 351 faults, 144 of which had shear-sense indicators. Only faults within \( \sim 400 \) m of the Castle Mountain fault were sampled, and the majority were within 200 m, where faults are most abundant. At each locality, faults were randomly sampled along a several-hundred-meter length of the Castle Mountain fault. The six study localities are spaced roughly equally along the 200 km length of the Castle Mountain fault and two of the localities are from the Caribou fault and Castle Mountain splays of the Castle Mountain fault (Fig. 2). The Caribou fault locality actually represents data collected at several locations along an \( \sim 25 \) km portion of the splay. The data were grouped because no one site had enough faults with shear-sense indicators to be treated as a separate locality.

**Strain Analysis**

**Methods**

For a small amount of slip on a fault, the intermediate incremental strain axis (zero strain for an individual fault) lies in the fault plane at \( 90^\circ \) to the slip direction. \( \hat{e}_2 \) and \( \hat{e}_3 \) (minimum and maximum shortening, respectively) lie in the movement plane, which is orthogonal to the fault plane and parallel to the slip direction. \( \hat{e}_1 \) is the pole to the movement plane, or the M pole. \( \hat{e}_1 \) and \( \hat{e}_3 \) are at \( 45^\circ \) to the fault plane, which axis makes a \( 45^\circ \) clockwise angle with the fault plane depends on the sense of shear. The fault in the figure is left lateral, so \( \hat{e}_3 \) is clockwise from the fault plane when viewed downdip. If the fault were right lateral, \( \hat{e}_1 \) and \( \hat{e}_3 \) would swap positions.
information). This plane contains the maximum ($\varepsilon_1$) and minimum ($\varepsilon_3$) shortening axes. The pole to this plane is the intermediate strain axis ($\varepsilon_2$), and is called the M pole (Arthaud, 1969). The $\varepsilon_1$, $\varepsilon_2$, and $\varepsilon_3$ axes make clockwise and counterclockwise angles of 45° to the fault plane, with shear sense determining which is clockwise. The M pole is equivalent to the B axis, $\varepsilon_1$ to the F axis, and $\varepsilon_3$ to the T axis in an earthquake focal mechanism solution.

Plotting M poles for faults with unknown shear sense can reveal the three principal axes of strain for the fault population as a whole. In a general case of three-dimensional strain, the M poles from a fault population are expected to form three populations on a stereonet, with one concentration for each of the principal strain directions (Arthaud, 1969).

If the shear senses, as well as orientations and slip directions, of faults in a population are known, then a moment tensor summation can quantify the strain imposed on the volume of rock that contains the faults, as follows (Kostrov, 1974; Molnar, 1983; Marrett and Allmendinger, 1990). An incremental strain tensor, containing the orientations of $\varepsilon_1$, $\varepsilon_2$, and $\varepsilon_3$, is determined for each fault. The tensors from each fault in the population are then summed into a global tensor, which gives the total incremental strain from the fault population. The orientations and magnitudes of the principal axes of incremental strain are then calculated from the global tensor. The result is equivalent to simultaneously averaging the orientations of $\varepsilon_1$, $\varepsilon_2$, and $\varepsilon_3$, of each fault in the population. Moment tensor summations for fault populations along the Castle Mountain fault were computed with the program Faultkin (Marrett and Allmendinger, 1990).

The three major assumptions are that the measured faults all record a single, spatially homogeneous strain event, that the faults have not been rotated since formation, and that the faults contribute equally to the total strain. Sampled faults crosscut one another, and there is no systematic relationship between fault orientation and the relative age of the faults, which supports the assumption that the faults represent a single strain event. More than one set of slip lineations on a single fault is rare, whereas multiple sets of lineations would be indicative of faults affected by block rotations (Twiss et al., 1991). Another test of the first two assumptions is whether the strain axes for individual faults have broadly similar orientations to each other and the global strain axes; this is evaluated below. Each fault is assumed to contribute equally to the total strain because the magnitude of slip on the faults is unknown. The global incremental strain tensor does not capture the rotations of the finite strain axes that result from large amounts of finite simple shear. However, if the strain accommodated by the fault network includes a significant component of simple shearing, the calculated global incremental strain axes may deviate slightly from the actual axes, and the maximum concentrations of $\varepsilon_1$, $\varepsilon_2$, and $\varepsilon_3$, from individual faults will be nonorthogonal (Twiss and Unruh, 1998).

M Pole Results

Kamb-contoured stereoplots of M poles to faults along the Castle Mountain fault are shown in Figure 5, and mean M pole orientations are given in Table 1. All localities have a dominant concentration of M poles, and all except Anthracite Ridge are deeply dipping. Pinochle Creek, Caribou fault, and possibly Glory Hole show weak girdles about the primary M pole concentration. However, the girdles are only evident at the lowest contour level. The contour plot of all the data shows that the M poles are generally subvertical. The M pole concentrations are deeply plunging because the faults along the Castle Mountain fault are generally steeply dipping with shallowly plunging slip lineations. In addition, this result shows that the intermediate strain axis is subvertical, as expected in a strike-slip faulting regime. The more shallowly plunging M poles at Anthracite Ridge reflect oblique slip on steeply dipping faults with northwest-plunging slip directions.

Moment Tensor Summation Results

Moment tensor summation calculations were made on fault populations from the Little Susitna, Glory Hole, Puddingstone Hill, and Caribou fault localities, as well as on all fault data with shear sense grouped together (Figs. 5 and 6; Table 1). I sampled an insufficient number of faults with known shear sense at the Pinochle Creek and Anthracite Ridge localities, so they are excluded from this analysis. The moment tensor summation solutions are good fits to the data because for each locality the strain axes of the sampled faults have orientations similar to each other and to the global axes. Several trends are evident in the moment tensor summation results. The $\varepsilon_1$, $\varepsilon_2$, and $\varepsilon_3$ strain axes are generally subhorizontal, the faults have accommodated triaxial incremental strain, and maximum shortening ($\varepsilon_3$) is generally at more than 70°–80° to the Castle Mountain fault (Figs. 5 and 6; Table 1).

All fault populations, except the Caribou fault data, accommodate maximum and minimum incremental shortening in a subhorizontal plane. The trend of $\varepsilon_1$ for the Caribou fault locality, however, is very similar to the other localities, and the steeply plunging M pole concentration suggests faults with known shear sense are biased toward a shallower $\varepsilon_2$ and steeper $\varepsilon_1$. The generally shallowly plunging $\varepsilon_1$ and $\varepsilon_2$ axes are in accord with strike-slip faulting and the steeply dipping M pole concentrations. The magnitudes of $\varepsilon_1$, $\varepsilon_2$, and $\varepsilon_3$ are all distinct from each other, indicating that the fault populations accommodate triaxial incremental strain. This is reflected in the R values for the moment tensor summation results (Table 1), which vary from 0.50 to 0.66 ($R = |\varepsilon_1 - \varepsilon_3|/|\varepsilon_2 - \varepsilon_3|$; $R = 1$ for uniaxial shortening or flattening strain, $R = 0$ for uniaxial extension or constrictional strain). In general, calculated global $\varepsilon_1$, $\varepsilon_2$, and $\varepsilon_3$ axes match the maximum concentrations of the axes from individual faults, consistent with dominantly pure shear. The concentrations of the Little Susitna axes, however, show some nonorthogonality, which may reflect a component of simple shear (Twiss and Unruh, 1998). The global axes for the combined data match the maxima of the axes for the individual faults reasonably well.

At all localities except Puddingstone Hill, $\varepsilon_1$ is at more than 70° to the Castle Mountain fault (Figs. 5 and 6). For all the data together, $\varepsilon_1$ is subhorizontal, trends 144°, and makes an angle of −74° to the Castle Mountain fault’s average strike, −070°. Including the Caribou fault locality in the grouped data set does not markedly change the results.

Stress Inversions

Methods

An alternative to extracting strain from fault populations is to seek a stress model that provides a best fit to the fault-slip data. The method utilized here is focal mechanism stress inversion (Gephart, 1990). This method makes no a priori assumptions about the strength of the faults, unlike other methods (e.g., Reches, 1987; Michael, 1984). The focal mechanism stress inversion method also is unique in performing a grid search that determines a best-fit stress model and all models that fit the data within desired confidence intervals.

The focal mechanism stress inversion method requires the same fault-slip data as the moment tensor summation technique and assumes that the faults formed in response to a single, homogeneous stress field and that they remain in their original orientations. A stress model comprises a set of orientations of the principal stresses and an R value ($|\sigma_2 - \sigma_3|$/
Figure 5. Summary plots of strain and stress analyses. Four stereoplots are shown for each locality with faults of known shear sense. The leftmost three plots are Kamb contoured $\hat{e}_3$, $\hat{e}_2$ (the M pole), and $\hat{e}_1$ axes for sampled faults. The results of the moment tensor summation (MTS) (global strain) for each location are also shown in these plots; the global $\hat{e}_1$, $\hat{e}_2$, and $\hat{e}_3$ axes are labeled as 1, 2, and 3 (large square, triangle, and circle, respectively). Kamb contours are 2σ. The number of faults included in each plot is indicated. Some localities have more $\hat{e}_2$ than $\hat{e}_3$ and $\hat{e}_1$ axes plotted because only $\hat{e}_2$ could be determined for faults with unknown shear sense. No shear-sense data are available for Anthracite Ridge and Pinochle Creek, so only plots of $\hat{e}_2$ are shown. The right column contains summary results for the stress inversions. Squares and circles represent $\sigma_1$ and $\sigma_3$ orientations, respectively, for acceptable stress models. Stress models fitting within 95% confidence interval are plotted with open symbols (outlined with black line), models within 68% confidence interval are plotted with gray symbols, and best-fitting models (0% confidence interval) are plotted with black symbols. Thus black square and circle pairs mark $\sigma_1$ and $\sigma_3$ orientations for best-fitting models; regions of gray squares and circles mark orientations of $\sigma_1$ and $\sigma_3$ for models that fit within 68% confidence interval; and white areas outlined with black squares and circles mark orientations of $\sigma_1$ and $\sigma_3$ for models that fit within 95% confidence interval. Stars on Puddingstone Hill and Caribou fault plots show 00/125$^\circ$ and 10/335$^\circ$ orientations, respectively, about which the 68% confidence interval results cluster (see text for discussion). Histograms on right side of figure show distribution of R values ($\sigma_2/\sigma_1$) for models meeting the 95%, 68%, and best-fit criteria, using same shading scheme as the stereoplots. See Table 1 for orientations and R values of MTS results and best-fit stress models, and Figure 6 for summary plots showing MTS and stress inversion results in relation to the Castle Mountain fault. Plots are equal area.

$[\sigma_1 - \sigma_3]$ that gives the relative magnitudes of the principal stresses. A stress model is a perfect fit with an observed fault if the direction and sense of slip on the fault are coincident with the direction and shear sense imposed on the fault by the stress model. Hence, there is no assumption about the orientation the maximum principal stress makes with the fault plane, or about the strength of the fault. The results consequently contain no information about the absolute magnitudes of the principal stresses.

Because fault-slip data fit stress models imperfectly, misfit is measured and minimized. The measure of misfit used is the minimum angle required to rotate an individual fault plane and slip vector datum into perfect alignment with the stress model being tested. The one-norm absolute values of the misfits from all of the faults are summed and averaged to find the measure of misfit between the fault data and the stress model as a whole. A set of stress models comprising a complete range of principal stress orientations (5° grid increments) and R values (0.1 increments) is tested for each data set. The best-fit stress model is the model with the lowest misfit, and acceptable models are those that fit the data at 95% or 68% confidence levels. The uniqueness of the solution can be evaluated by examining the range of models that provide acceptable fits to the data.

Stress Inversion Results

Stress inversions were performed on each of the four localities for which there are shear-sense data and for the four localities grouped together. Figure 5 shows the orientations of $\sigma_1$ and $\sigma_3$ for stress models that have average...
misfits <95%, 68%, and 0% (best fit) confidence intervals. Histograms of R values for acceptable models are also shown. The misfits compare well with misfits of 10.4° and 12.6° for fault-slip data from along a splay of the San Andreas fault that were inverted with the focal mechanism stress inversion method (Chester et al., 1993).

The inversion results have several attributes in common. All best-fit models are for R = 0.9, a uniaxial compressive stress field (Fig. 5; Table 1). The girdles of acceptable σ₁ orientations for the Glory Hole, Little Susitna, Puddingstone Hill, and combined data show that the model fits are insensitive to σ₁ versus σ₉ orientation, which also reflects a uniaxial compressive stress field. However, the Caribou fault and to a lesser extent the Little Susitna and Puddingstone Hill localities also have acceptable models with separate clusters of steeply plunging σ₁ orientations. These models with steep σ₁ plunges tend to have better fits with lower R values, showing that some uniaxial extension models can provide reasonable fits to the data from these locations.

The easternmost localities, Glory Hole and Little Susitna, both have best-fit stress models with σ₁ oriented ~00/150° and σ₉ subhorizontal. The best-fit model of the Puddingstone Hill inversion is σ₁ oriented 00/286° and σ₉ subhorizontal. However, the acceptable models cluster about a σ₁ trend of 125° (indicated by a star in Fig. 5), which probably better reflects σ₁ at this locality. The extensional veins that cut the Castle Mountain fault’s slip surface at Puddingstone Hill are oriented ~122/90°, which supports the 125° trend, because σ₁ should lie in the plane of the veins. A range of stress models provides acceptable fits to the Caribou fault locality. The best-fit model is σ₁ oriented 56/300°, σ₉ at 18/058°, and R = 0.9, but the acceptable models cluster about a σ₁ of 10/335° (marked by a star in Fig. 5), which probably is a better estimate of σ₁.

Inverting all the fault-slip data together produces the narrowest range of acceptable fits and the largest misfits. The best-fit model is σ₁ 00/330°, σ₉ 05/060°. At the 68% confidence level, all acceptable σ₁ orientations are subhorizontal, with trends ranging from 141° to 162°. Acceptable models form a girdle of σ₁ orientations and the majority of acceptable models have large R values, showing that uniaxial compressive stress models provide the best fit to the combined data. The best-fit principal stresses closely match the strain results and σ₁ makes a high angle with the Castle Mountain fault except at Puddingstone Hill.

CASTLE MOUNTAIN STRIKE-SLIP FAULT DATA ANALYSIS RESULTS

<table>
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</table>

Note: N.D.—not determined. Strain analyses include the average M pole (ε₁) and moment tensor summation (MTS) results. MTS results comprise principal directions of incremental strain, their relative magnitudes and the R value ratio of their relative magnitudes (ε₁ = minimum incremental shortening, ε₂ = maximum incremental shortening). FMSI results comprise the principal directions of the best fit model, the average misfit of the best fit model and the R value ratio of the relative magnitudes of the best fit principal stresses. The number of subsidiary faults included in each analysis is given also.

Figure 6. Stereoplots of principal axes of incremental strain and stress for each sample locality along the Castle Mountain fault with shear sense data and all data combined. Principal stresses and incremental strains are plotted with open and filled symbols, respectively. The arrows on the perimeters of the stereoplots show σ₁ trends. Plots are equal area.

STRUCTURES, STRAIN, AND STRESS
2–4 km FROM THE CASTLE MOUNTAIN FAULT

The Wishbone Hill district is a large early Tertiary syncline 2–4 km south of the Castle Mountain fault (Fig. 7). The fold is cut by a basal thrust, strike-slip faults, and dikes (Barnes and Payne, 1956), which provide consistent markers of strain and stress contemporaneous with faulting along the Castle Mountain fault.

The syncline and its minor folds are developed in the Paleocene–Eocene Chickaloon and Eocene Wishbone Hill strata, and are unconformably overlain by the gently folded Oligocene Tsadaka Formation. Hence most of the folding is post-Eocene, pre-late Oligocene in age. The mapped hinge of the main Wishbone Hill syncline, the π pole to bedding, and the measured hinges of minor folds all are oriented ~00°70° (Fig. 8A). The folds are upright and thus accommodated maximum finite shortening directed toward ~00°340°.
Figure 7. Geologic map of the Wishbone Hill area. Note left-lateral faults, synclinal axis, the Moose Creek thrust, and dikes. Key to map units: Qag—alluvial and glacial deposits; Qls—landslide debris; Ti—intrusive rocks (dikes); Tt—Tsadaka Formation; Tw—Wishbone Formation; Tc—Chickaloon Formation; Tar—Arkose Ridge Formation. See Figure 2 and text for rock descriptions. Modified from Barnes and Payne (1956) and Barnes (1962).

Figure 8. Structural data from Wishbone Hill area. (A) Poles to bedding (dots) with best fit great circle, associated π pole (n = 123), and fold hinges (plus signs, n = 7). (B) Moment tensor summation of map-scale faults (all strike-slip faults are subvertical, n = 11). (C) Dikes and their average orientation. (D) Summary of data, with North American–Pacific plate motion vector shown for comparison.

The Moose Creek thrust is exposed along the north side of the Wishbone Hill syncline (Fig. 7), and forms a detachment between tightly folded strata below the thrust and more open folds above. The thrust is oriented 064/45°SE at several exposures, and grooves formed by abrasion show that the latest motion was virtually pure dip slip. Vertical offset, as shown by displaced strata, is on the order of tens of meters, and because the thrust dips 45°, total displacement probably is similar. This allows determination of incremental strain from slip on the thrust as described in the moment tensor summation section. The \( \sigma_3 \) from slip on the thrust is oriented −00/334°, with \( \varepsilon_3 \) subvertical. If the fault slipped in the direction of maximum resolved shear stress, then \( \sigma_3 \) trends parallel to \( \varepsilon_3 \), and its plunge should be similar, although it may vary depending on the fault’s rheology.

Nine previously mapped strike-slip faults cut the Paleocene and Eocene strata and the folds on Wishbone Hill (Fig. 7) (Barnes and Payne, 1956). It is possible that these faults displace the poorly exposed Tsadaka Formation, and at least one cuts the Moose Creek thrust. Thus, the faults are post-early Eocene in age, and possibly younger. Barnes and Payne (1956) inferred displacement on the faults from displaced strata and grooving on fault surfaces, and field checking five of the faults in this study confirmed their conclusions. Displaced strata mark displacements ranging from −10 to 300 m. The orientations of the faults are known from direct field measurements and mapped traces (Barnes and Payne, 1956). All are subvertical, and their strikes range from 164° to 217°. A moment tensor summation of these faults and the Moose Creek thrust gives \( \varepsilon_3 \) oriented 00/330°, with the intermediate strain axis vertical (Fig. 8B).

Two well-exposed mafic dikes on Wishbone Hill, which are meters in width and at least tens of meters in length, cut the Paleocene–Eocene Chickaloon Formation, and thus are post-early Eocene in age (Fig. 7) (Barnes and Payne, 1956). They are mapped as subvertical and strike 133° and 147°. The latter dike was field checked and its measured orientation is 153/75°NE. If the dikes formed by hydraulic fracturing, and pure opening accommodated their emplacement, then the minimum shortening and minimum compressive stress axes are orthogonal to the dikes (Anderson, 1951). The mapped orientations and field-checked orientation average to 146/82°NE, so the minimum shortening and minimum principal stress axes are probably oriented −08/236° (Fig. 8C). The other principal axes of strain and stress must be in the plane of the dikes. If \( \varepsilon_3 \) and \( \sigma_1 \) are subhorizontal, as the other structures on Wishbone Hill indicate, then the dikes constrain them to trend −326°.

FAULT-GOUZE MINERALOGY

Phyllosilicate minerals have coefficients of friction less than most other minerals (e.g., Wang, 1984), and when they compose −30% or more of a gouge, can weaken a fault (e.g., Shea and Kronenberg, 1993). For these reasons, 17 samples of gouge from the core of the Castle Mountain fault were collected from
the 4 localities where the core is exposed, i.e., Caribou fault, Glory Hole, Pinochle Creek, and Puddingstone Hill (Fig. 2). The compositions of these samples can be compared to published experimental results to estimate the coefficient of friction of Castle Mountain fault gouge. Gouge modal compositions were found by inverting X-ray fluorescence whole-rock chemistry, using as a constraint mineralogy determined by X-ray diffraction analyses. Clay mineralogy methods follow Moore and Reynolds (1997) and Srodon (1980). The gouges have total clay contents ranging from 26 to 60 wt%; the average is 43 wt%. Clays present are illite/smectite (typically 80% illite, R1 ordering), kaolinite, and chlorite. Carbonate content is 0%–7% at Caribou fault and Glory Hole and 6%–31% at Puddingstone Hill and Pinochle Creek. The illite/smectite clay, kaolinite, and possibly carbonate and chlorite are probably authigenic to the fault zone (Bunds, 1997).

DISCUSSION

Strain and Stress Results

The principal incremental strains and stress-estimates from the fault populations along the Castle Mountain fault have similar orientations, although the relative magnitudes differ. The majority of faults are steeply dipping with shallowly plunging slip vectors, and the \( \hat{e}_1 \) and \( \hat{e}_2 \) axes of these faults are near the perimeters of the stereoplots in Figure 5. This configuration does not accommodate much strain in the vertical direction, and consequently the relative magnitudes of the strain axes are distinct from each other. In contrast, uniaxial compressive stress models produce the best fits to the faults, because they are reasonably good fits to both the strike-slip and less-numerous reverse faults in the populations (for reverse faults, \( \hat{e}_1 \) axes plot near the center and \( \hat{e}_2 \) axes plots near the perimeter of the stereoplots in Fig. 5). The northwest-southeast maximum incremental shortening and maximum compressive stress described by the moment tensor summation and stress inversion approaches suggest that these results are robust.

The folds, faults, and dikes on Wishbone Hill provide direct estimates of broadly contemporaneous finite strain, incremental strain, and stress fields. The folds and dikes yield maximum finite shortening trends of 343° and 326°, the faults indicate that maximum incremental shortening is subhorizontal and trends 330°, and the dikes show that \( \sigma_3 \) probably parallels maximum shortening. The similar incremental and finite shortening directions obtained from the different structures suggest coaxial strain (pure shear) at the 2 km scale of the Wishbone Hill syncline. Furthermore, even large finite strains on the faults at Wishbone Hill would not accommodate significant orogen-parallel shearing. These results are very similar to those from faults adjacent to the Castle Mountain fault, and to the estimated 340° plate convergence direction when the structures were formed.

In the context of Andersonian faulting (Anderson, 1951), uniaxial compressive stress with \( \sigma_3 \) subhorizontal can produce both strike-slip and thrust faults, because \( \sigma_1 \) and \( \sigma_3 \) have the same magnitude. This is consistent with the structures present at Wishbone Hill, where both a thrust fault and strike-slip faults apparently have formed in response to the same stress and strain. It is also compatible with a history of both thrust and right-lateral displacements on the Castle Mountain fault (e.g., Grantz, 1966; Fuchs, 1980). One possibility is that the stress field has been temporally variable as a result of great earthquakes on the Pacific–North American subduction zone. Before the earthquake, the stress field may be of the Andersonian thrust type, with \( \sigma_3 \) directed toward \(-340°\); then a great earthquake releases stress in the horizontal plane, leaving \( \sigma_{3\text{max}} \) intermediate in magnitude and producing a strike-slip environment (Lahr et al., 1986).

The estimated maximum shortening and maximum principal stress directions adjacent to the Castle Mountain fault coincide fairly closely with estimates from Wishbone Hill, the regional studies of Bruhn and Pavlis (1981) and Zajac (1997), and the relative motion of the Pacific and North American plates since Eocene time (Figs. 6 and 8). The 10°–15° discrepancies between data sets are small relative to the scatter within individual data sets, and probably are insignificant. The consistency of results from such a wide range of scales and techniques lends credibilty to the analyses and suggests that plate motion has driven dextral slip on the Castle Mountain fault and pure shear deformation in the Matanuska Valley.

Weakness of the Castle Mountain Fault

Because the Castle Mountain fault slips in response to \( \sigma_1 \) at 70°–80° to the fault zone (except at Puddingstone Hill), it is a weak fault. The fault slips at lower resolved shear stress than predicted by the Coulomb failure criterion combined with a coefficient of friction of \(-0.85\) (the term Byerlee’s Law has not been defined) and hydrostatic pore pressure, and it is weaker than the surrounding crust. The fault must be weaker than the surrounding rocks because other potential fault planes at lower angles to \( \sigma_1 \) have more shear stress resolved on them, yet failure occurs on the Castle Mountain fault (Sibson, 1985).

At Puddingstone Hill \( \sigma_1 \) is at \(-30°\) to the Castle Mountain fault, in close agreement with the Coulomb failure criterion combined with a coefficient of friction of \(-0.85\) (the term Byerlee’s Law has not been defined) and hydrostatic pore pressure. Carbonate cementation may have increased the Castle Mountain fault’s shear strength at this location. Geochemical data suggest that the two units the fault juxtaposes at Puddingstone Hill contain two chemically distinct formation waters that have mixed in the fault zone, resulting in extensive carbonate cementation (Bunds, 1997; Bruhn et al., 2000). The gouge zone is <1 m wide in places at Puddingstone Hill, which may have enabled carbonate cementation to effectivity glue the fault together, forming an asperity that has concentrated shear stress (Bunds, 1997). Whether this mechanism may have operated at Pinehole Creek as well is uncertain, because the fault strength and gouge zone width there are unknown.

Mechanisms that potentially weaken the Castle Mountain fault along most of its length include the presence of clay minerals that impart a low coefficient of friction to the fault gouge (e.g., Wang, 1984), reduction in the fault’s effective coefficient of friction from distributed shearing in the gouge (Marone et al., 1992), and elevated pore pressure. The coefficient of friction of the fault can be estimated from published results of friction experiments on materials similar to Castle Mountain fault gouge. The Castle Mountain fault gouge is compositionally variable, probably due to its varying host rocks. The 17 analyzed samples contain 26–60 wt% clay phases that have friction coefficients of 0.6–0.7, significantly lower than the \(-0.85\) of most minerals at confining pressures <200 MPa (Byerlee, 1978). Experiments have shown that fault rocks can have a frictional strength approaching that of the low-friction minerals when they are present in these abundances (Shea and Kronenberg, 1993). Experiments also suggest that a gouge can deform at lower shear stress than predicted by the Coulomb criterion if the gouge zone deforms pervasively along P shears (Marone et al., 1990, 1992). In this mechanism, termed Coulomb plasticity, slip along the P shears occurs at the friction angle and coefficient of friction required by the gouge material. This allows
Figure 9. Plot of the effective stress ratio \((\sigma'_3/\sigma'_1)\) required for fault reactivation at various reactivation angles (\(\theta_r\)) for coefficient of friction \(\mu = 0.8, 0.5, \) and 0.2, calculated using equation 3. \(P_f \geq \sigma_3\) is necessary for conditions that fall within the shaded region of the figure. For \(\mu = 0.5\), reactivation angles \(\geq 55^\circ\) are expected only if \(P_f \geq \sigma_3\). Modified from Ribson (1985) and Ribson et al. (1988).

Table 2: Evidence for Preservation of CMF Damage Zone Fault Networks and Wishbone Hill District Structures in Their Formative Orientations

<table>
<thead>
<tr>
<th>Damage zone faults</th>
<th>Similarity of inferred principal incremental strains and stresses from Caribou fault, Glory Hole, and Little Susitna localities. Ceiling of strain onto the Castle Mountain fault. Principal increments of stress and strain inferred for Cook Inlet (Zajac, 1997) and principal strain from individual faults at each locality. No clear pattern to data scatter at each locality. Principal increments of strain similar to principal stresses inferred for Cook Inlet (Zajac, 1997) and principal strain from individual faults at each locality. No clear pattern to data scatter at each locality.</th>
</tr>
</thead>
</table>
| Block Rotations and Implications for Transpressional Tectonics | Clockwise vertical-axis block rotations in the Matanuska Valley have produced average declinations of \(-50^\circ\) in Eocene shallow intrusive rocks and up to nearly \(90^\circ\) in Paleogene sedimentary rocks (Smillie et al., 1988, 1989). Vertical-axis block rotations have been documented along other strike-slip faults (Beck, 1976; Horns and Verosub, 1995). Stamatatos et al. (1988, 1989) suggested that the rotations in the Matanuska Valley were accommodated by slip on southwest-northwest--trending left-lateral faults, such as those at Wishbone Hill (Fig. 7). Several lines of evidence show that the faults along the Castle Mountain fault and the structures at Wishbone Hill are unrotated (Table 2). First, the inferred principal strain and stress axes have similar orientations, except for Pudding Hill, which has principal axes that make an \(\sim 30^\circ\) counterclockwise angle with the other localities. A clockwise rotation of \(330^\circ\) is required to produce this orientation, which is inconsistent with the paleomagnetic observations (Stamatatos et al., 1988, 1989). Second, the faults along the Castle Mountain fault were sampled in elongate areas. Hence, vertical-axis block rotations would have to occur in many small blocks that would probably be rotated to varying degrees. This probably would create larger scatter in the fault orientations and moment tensor summation results than is observed. Last, the \(-330^\circ\) trends of the inferred principal axes have orientations that are very similar to, and do not deviate in a clockwise sense from, the \(-340^\circ\) trending axes inferred from regional studies (Bruhn and Pavlis, 1981; Zajac, 1997). The structures on Wishbone Hill record subparallel principal strains, suggesting no rel-
CONCLUSIONS

Recent right-lateral motion on the Castle Mountain fault is evidenced by structures along the fault core at Puddingstone Hill and two recent earthquakes. Populations of faults within 200–400 m of the Castle Mountain fault and structures at Wishbone Hill, 2–4 km from the Castle Mountain fault, record a uniaxial compressive stress field with $\sigma_1$ oriented $\sim 0^\circ/324^\circ–340^\circ$. Incremental strain accommodated by the faults is triaxial, with maximum shortening subparallel to $\sigma_1$. These results match those of regional studies and the relative motion of the Pacific and North American plates. Except in one locality, $\sigma_1$ makes an angle of $70^\circ–80^\circ$ with the Castle Mountain fault. This requires the fault to be weaker than the surrounding crust and weaker than predicted by the Coulomb failure criterion combined with Byerlee’s Law and hydrostatic pore pressure. Castle Mountain fault gouge contains 26–60 wt% clay, which according to published experiments should have an effective coefficient of friction of $\sim 0.5$ if sheared pervasively (Wang, 1984; Marone et al., 1990, 1992). This accounts for the Castle Mountain fault being weaker than the surrounding crust and slip localizing onto it, but does not satisfy $\sigma_1$ at $70^\circ–80^\circ$ to the fault. Thus some other mechanism, such as elevated pore pressure, probably weakens the fault and enables it to slip in response to the oblique convergence between the North American and Pacific plates. Development of the Castle Mountain fault into a weak fault may have led to the partitioning of deformation onto it and cessation of distributed deformation and block rotations in the adjacent forearc, markedly modifying deformational style along part of the obliquely convergent southern Alaskan plate boundary.

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CASTLE MOUNTAIN STRIKE-SLIP FAULT, ALASKA

Figure 10. Proposed structural development of Alaskan forearc along the Castle Mountain fault. (A) Distributed shearing and vertical-axis block rotations in response to dextral-oblique plate convergence in early Tertiary time. (B) In late Tertiary time right slip is focused onto the Castle Mountain fault, and coaxial shortening strain subparallel to the plate convergence direction forms the Wishbone Hill district structures. Analogous structures to the east possibly formed at this time as well.
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