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REGIONAL TECTONICS OF SOUTHERN ALASKA: EXTRACTING THE "GOLD" FROM EXISTING GPS DATA

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TECHNICAL ABSTRACT

The goal of this project was to evaluate existing tectonic models for so southern Alaska based on the existing geodetic data, and if necessary to develop a new self-consistent regional model. Existing Global Positioning System (GPS) data were analyzed, and selected sites were resurveyed (Figure 1, Table 1). GPS positions from old surveys in 1991-1996 were combined with the 1997 surveys to estimate a velocity field for southern Alaska. One disappointment of the project was the poor condition of a few of the old sites, which made them unsuitable for tectonic purposes. Nevertheless, the project produced significant new results, although these were concentrated at sites within the range of subduction-related elastic strain. Based on these data, and data collected under other support, we find that subduction-related strain is highly variable along strike, which suggests significant variations in seismic coupling. Slip rates on faults in the overriding plate are probably no larger than several mm/year. The only fault we can assign a preliminary geodetic slip rate to is the Denali fault, which appears to have a slip rate of 5-10 mm/yr. There is some evidence to support the idea that southern Alaska south of the Denali fault is rotating counter-clockwise, but additional data are needed to confirm this. Data from southeast Alaska show very little motion of sites in Juneau relative to Fairbanks, but rapid motion at essentially plate rate between Yakutat and Fairbanks. These results suggest that the Fairweather fault is a pure strike-slip fault, and that the compressional component of relative plate motion is accommodated offshore.

NON-TECHNICAL ABSTRACT

We analyzed existing Global Positioning System (GPS) data and resurveyed selected sites in order to study the regional tectonics of southern Alaska. The observed motions of these sites are due to a combination of two main sources of deformation: deformation associated with the strain accumulation and release on the interface between the Pacific and North American plates, and deformation associated with faulting in the North American plate itself. We found that strain associated with the plate interface is variable along strike. This suggests that there may also be significant variations in the earthquake hazard associated with the plate interface, and that this needs further study. The only fault on the North American plate that has observable deformation is the Denali fault, which probably slips at a rate of between 5 and 10 mm/yr. Data from southeast Alaska show very little motion of sites in Juneau relative to Fairbanks, but rapid motion at essentially plate rate between Yakutat and Fairbanks. These results suggest that the Fairweather fault is a pure strike-slip fault, and that the compressional component of relative plate motion is accommodated offshore.

In summary, we found a lot of "gold" in the existing geodetic data, although much of it needs further refinement.

Background – Existing Tectonic Models

No adequate tectonic models for southern Alaska have yet been published. Lahr and Plafker (1980) published a simple kinematic block model for southern Alaska, in which the crust of southern Alaska is composed of three blocks, the Wrangell block, Yakutat block and St. Elias block. Aside from the locations of active faults and the rate of Pacific-North America relative motion, much of this model was based on speculation since few reliable slip rates were available at the time of publication (the same is true today). The key element of the Lahr and Plafker model is that the Wrangell block rotates counter-clockwise relative to North America, with the curving Denali fault representing the boundary between this block and North America.

Lundgren *et al.* (1995) published finite-element models of Alaskan crustal deformation based on assumed fault geometries, slip rates, and VLBI baseline rates. Lundgren *et al.* present four different models, each using different constraints on fault slip and the VLBI data. Their preferred model applies the loosest *a priori* constraints on fault motions, and resembles the Lahr and Plafker model in general features. The Lundgren *et al.* and Lahr and Plafker models differ locally where the assumed fault geometries differ, and the Lundgren *et al.* model also predicts significant northwestward motion of a large portion of southeastern Alaska, and rapid shortening in the Mackenzie mountains of northwestern Canada, neither of which is suggested in the Lahr and Plafker model.

A feature of both the Lahr and Plafker and Lundgren *et al.* models is that most of southern Alaska is rotating counter-clockwise to maintain strike-slip motion on the Denali along its entire length. The rate of translation of and rotation of this block of crust is uncertain, and depends on the slip rate on the Denali fault and other features. The western part of this block could have a significant velocity relative to North America depending on the pole of rotation of the block and the rate of rotation. The location of the western boundary of this block is uncertain.

Investigations Undertaken

Under support from this grant we made GPS observations at 14 sites spread across southern and central Alaska (Table 1). Most of these sites had been surveyed during 1993-1996 by National Geodetic Survey field crews. A few sites had existing data from other sources, and two had no previous measurements. Several sites were observed at no cost to this grant (or no cost other than equipment shipping costs) by Seismological Laboratory or Alaska Volcano Observatory field crews. A GPS system was sent to Yakutat to continue observations there, but no data were recorded due to equipment failure.

Table 1. GPS Site occupations supported by this project.

ID	*Site Name*	*Region*	*Dates*	*Support*
TALK	Talkeetna	Southcentral	97 May	field, analysis
REED	Reedy	Cook Inlet	97 May	field analysis
FSHL	Big Lake	Cook Inlet	97 May	field, analysis
POWE	Valdez	Prince William Sound	97 Sep	field, analysis
STRI	Tok	East Interior	97 August	field, analysis
BSB4	Delta Junction	Interior	97 July	field, analysis
CGLO	Cantwell	Denali	97 August	field, analysis
4A1A	Wasilla	Cook Inlet	97 August	field, analysis
Z22A	Willow	Southcentral	97 August	Field, analysis
ANCR	Anchor	Prince William Sound	97 June	analysis
HEID	Port Heiden	Alaska Peninsula	97 July	shipping, analysis
SATT	Cold Bay	Alaska Peninsula	97 July	shipping, analysis
KATY	Unimak Island	Alaska Peninsula	97 July	shipping, analysis
THOM	Unimak Island	Alaska Peninsula	97 July	shipping, analysis
PANK	Unimak Island	Alaska Peninsula	97 July	shipping, analysis

In addition, we analyzed data from all of the past NGS surveys for 1991-1996 (Table 2). NGS surveyed a number of sites earlier than 1991, but we did not have time to analyze those data, and most likely the quality of the data would not be adequate for our purposes. As a result of this work, we now have precise GPS solutions for a large number of sites, but precise velocities are not available for most of these sites since some have not been resurveyed, and others have been surveyed more than once but with too short a time span to compute a good velocity. For many sites, the initial survey was not of high enough precision to justify a resurvey, but was high enough precision to provide useful information in case of a significant earthquake. The results section will focus on the results for the sites we resurveyed for this project and others with good velocities.

In addition to the results presented in this report, we have poorly-resolved velocities or single-epoch positions for many sites in southeast and southcentral Alaska. Velocities for some of these sites will be improved within the next few years as continuing measurements are made with support from various sources. Several sites in southeast Alaska were resurveyed in 1998 with support from the National Science Foundation, and other sites will be resurveyed as funding permits. The future geophysical results from these sites will be a long-term payoff of this project. Finally, when the next significant earthquake in southern Alaska occurs, other data analyzed by this project will provide the pre-earthquake epoch positions that will allow precise coseismic displacements to be observed.

Table 2. GPS Campaigns Analyzed during this project.

Year	Campaign	Region	#Sites
1991	NGS GPS 332 SW Alaska HARN	Southwest Alaska/Aleutians	21
1991	NGS GPS 334 FAA Radar sites	Interior, Southeast	15
1992	NGS GPS 444	Prince William Sound	38
1993	AK Peninsula 1993	Alaska Peninsula	39
1993	PWS93 (USGS)	Southcentral	28
1993	SCAT93	Southcentral	23
1993	NGS GPS 753 Airports survey	Southeast, southcentral	15
1994	NGS GPS 832 Airports survey	Southcentral	9
1995	NGS 1995 Airports survey	Southcentral	8
1995	AK Peninsula 1995	Alaska Peninsula	27
1995	PWS95	Southcentral	28
1995	SCAT95	Southcentral	22
1996	NGS CORS survey ties	Southcentral, Alaska Peninsula	10

Results

Velocities relative to Fairbanks are shown for selected sites in Figure 1. This figure shows velocities for sites we resurveyed in 1997 as well as for other sites with velocities determined by this project. Velocities of coastal sites approach 4 cm/year in the relative plate motion direction for sites in the Prince William Sound area and the eastern Kenai Peninsula (145°-149° W). However, there is a sudden and dramatic change in the pattern of the velocities at about 150° W. West of 150° W, velocities in the western Kenai Peninsula are oriented in the opposite direction (sites NIK and HOMA). Other sites in the area (not shown here) show the same pattern. Further west, at Kodiak Island (KOD2), the velocity vector once again is oriented in the direction of relative plate motion. Note also the higher western component of velocities of sites MIDD and 4050, compared to sites further west. This western component may indicate the influence of the motion of the Yakutat block, the coastal terrane located east of Prince William Sound and west of the strike-slip Fairweather fault.

1. Variable Coupling along the Alaska Peninsula

The strong variation in the velocities of coastal sites seen in Figure 1 continues for sites along the Alaska Peninsula, further to the west (Table 3). The velocity of Port Heiden (HEID), about halfway down the Alaska Peninsula, is about 0.7 cm/year in the direction of relative plate motion. The velocity of Cold Bay (SATT), at the western end of the Alaska Peninsula, is essentially zero in the direction of relative plate motion. Except for HOMA and SATT, velocities of all of the sites are compatible with a simple model in which the part of the main thrust zone at seismogenic depths is locked (not slipping). At HOMA, the observed velocity is opposite in direction to that predicted by the simple model. This is best explained by a combination of aseismic slip on the plate interface and continuing postseismic slip downdip of the seismogenic zone (Freymueller et al., in preparation). The velocity of SATT is a small fraction of the predicted, which may indicate that aseismic slip predominates in the western part of the Shumagin seismic gap, as it appears to do in the eastern part (Lisowski et al., 1991; Larson and Lisowski, 1994).

Beavan (1995) has previously reported apparently significant strain variations in the overriding plate along the Alaska Peninsula. These strain variations, and the velocity variations observed through this project, suggest that the degree of seismic coupling varies substantially along the strike of the Alaska-Aleutian trench. In addition, the rapid trenchward velocities of the western Kenai Peninsula sites are best explained by a continuing postseismic response to the 1964 Prince William Sound earthquake. Earthquake hazard models based on average recurrence times of subduction events would seem to be overly simplistic based on these data. Additional research into the patterns of strain (and hence seismic coupling) along strike is required to adequately characterize the complexity of the Pacific-North America plate boundary. Because the elastic strain due to the plate interface is so large and widespread (significant strain should be observed up to 400-500 km from the trench), it is necessary to understand the along-strike variations in plate interface geometry and coupling in order to confidently interpret the velocities of sites away from the coast.

Table 3. Velocities of selected sites along the Alaska Peninsula, listed from east to west. Distance gives the approximate distance of each site from the trench. Dist: distance from the trench (km); Rate: velocity relative to Fairbanks (cm/yr); Sigma: uncertainty in rate (cm/yr); Azimuth: azimuth of velocity vector (degrees clockwise from north); Proj. Rate: velocity in direction of relative plate motion; Model: predicted velocity in plate motion direction from simple dislocation model. Note the azimuth of the velocity of HOMA (in italics) is almost opposite in direction from the model.

Site	Longitude	Dist	Rate	Sigma	Azimuth (°)	Proj. Rate	Model
MIDD	-146.33456	80	3.30	0.28	-37	3.10	5.12
T19	-149.42861	265	3.37	0.36	-18	3.37	3.31
HOMA	-151.49155	325	*1.85*	0.28	*150*	-1.80	0.73
KOD2	-152.49722	255	1.59	0.14	-39	1.47	1.44
HEID	-158.61226	305	0.74	0.36	-15	0.74	0.50
SATT	-162.73197	230	0.38	0.36	-92	0.09	0.68

2. Deformation of the Overriding Plate

Only three sites are located far enough away from the coast to show deformation within the overriding plate. Sites Strip (STRI) and Sourdough (SOUR) span the Denali fault (DF in Figure 1), and clearly show right-lateral motion on the Denali fault, at a rate of 1 cm/year or less. Note that this velocity for Sourdough is quite different from the VLBI estimate for the same site, which was oriented southwest with about the same magnitude. This velocity is very similar to GPS velocity for Sourdough published by Sauber et al. (1997), which used a subset of the data used in this study. The Alaskan VLBI results may be biased by network rotations about Fairbanks, since only the Fairbanks permanent site and the one mobile unit observed together. The motion of STRI relative to FAIR is only marginally significant, but is consistent with slow left-lateral slip on the

northeasterly-trending seismic zones north of the Denali fault. Site Talkeetna (TALK) shows northwestward motion similar to that of the sites further south, but with a higher westward velocity than would be predicted from a subduction model alone. The velocities of Sourdough and Talkeetna may include a component of elastic strain due to the subduction zone, but also clearly show a westward component that may be due to counter-clockwise rotation (relative to North America) of the block south of the Denali fault. If this model is correct, sites just south of the Denali fault should show a progressive rotation of their velocity vectors from, and more data are being collected to address this problem.

Our measurements are roughly consistent with the geological evidence for 8-12 mm/yr of slip in the Holocene (Plafker et al., 1994). Past geodetic measurements of the slip rate on the Denali fault give apparently different results. Two EDM networks across the Denali fault were measured by the U. S. Geological Survey during the period 1975-1988, one at the Nenana River (near Mt. McKinley) and one due north of Sourdough at the Delta River. Data from both networks are consistent with no significant right lateral slip on the Denali fault (Savage and Lisowski, 1991), although a close inspection of their results shows that they are equally consistent our result of several mm/yr of slip.

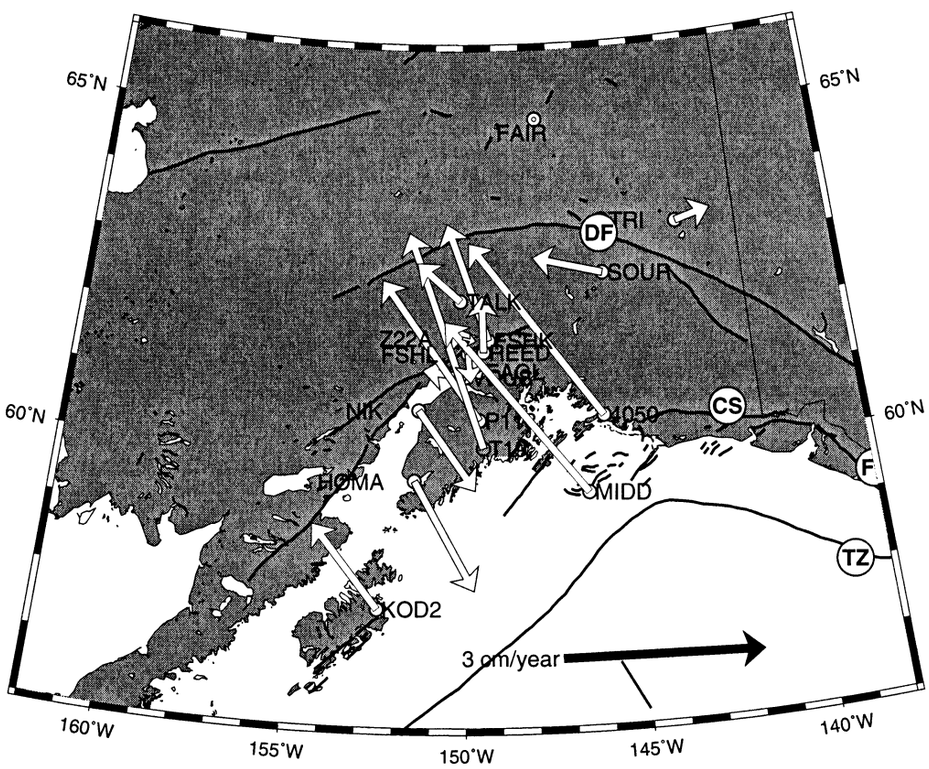

Figure 1. Velocity vectors for sites in southcentral Alaska, relative to Fairbanks (FAIR). Error ellipses have been omitted for clarity. Velocity vectors for coastal sites from 145-150° W are oriented in the direction of plate motion. In contrast, velocity vectors for coastal sites near 150° W are oriented in the opposite direction. Sites in the vicinity of the Denali Fault (DF) clearly show right-lateral slip on the Denali fault. The motions of Sourdough (SOUR) and Talkeetna (TALK) give a hint of rotation of southern Alaska.

3. Deformation in the Strike-slip Regime of Southeast Alaska

The velocity of Yakutat relative to Fairbanks is 4.4 ± 0.2 cm/yr toward -37°. The motion of Yakutat is almost exactly parallel to the strike of the Fairweather fault, and is almost exactly equal to the component of relative plate motion in the Fairweather-parallel direction. The azimuth of Pacific-North America relative motion at Yakutat is –11°, 26° eastward of the velocity of Yakutat. The significant Fairweather-normal component of relative plate motion (1.9 ± 0.2 cm/yr) must be accommodated offshore of Yakutat, perhaps on the Transition Zone (TZ in Figure 1).

Velocities of two sites in Juneau are very small relative to Fairbanks, suggesting that further south the Fairweather-normal component of relative plate motion is accommodated outboard of the Fairweather fault rather than inboard. This observation, and the similar conclusion drawn from the Yakutat data, are contrary to the predictions of the finite-element model of Lundgren et al. (1985). Lundgren et al. (1985) assumed that the Fairweather-normal component would be taken up inboard of the Fairweather fault, which led to predicted northwest-directed compression in southeast Alaska and the Yukon. This aspect, at least, of the Lundgren model is clearly ruled out by our data.

Reports Published

No reports have been published yet. Some data collected or analyzed as part of this project is included in a paper soon to be submitted to Journal of Geophysical Research (Freymueller et al., in preparation). A paper soon to submitted to Geophysical Research Letters (Fletcher and Freymueller, in preparation) has made use of older data analyzed under this support. Titles and authors are given below:

Freymueller, J.T., S.C. Cohen, and H.J. Fletcher, Variations in present-day deformation, Kenai peninsula, Alaska, to be submitted to Journal of Geophysical Research.

Fletcher, H.J., and J.T. Freymueller, New GPS constraints on the motion of the Yakutat block, to be submitted to Geophysical Research Letters.

Personnel Supported

Funds from this project supported salary time for the PI, Jeff Freymueller, and for an undergraduate summer intern, Ingrid Johanson. Ingrid's salary was split between this project and a National Science Foundation Research Experience for Undergraduates grant. Following her summer research experience, Ingrid has decided to attend graduate school in geophysics.

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