Postseismic deformation after the 1964 Great Alaskan earthquake: Collaborative research with Goddard Space Flight Center

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Jeffrey T. Freymueller
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Cooperative research carried out with Dr. Steven Cohen, Goddard Space Flight Center

Personnel Receiving salary support from NCC5-89:
Jeff Freymueller

Summary

The purpose of this project was to carry out GPS observations on the Kenai Peninsula, southern Alaska, in order to study the postseismic and contemporary deformation following the 1964 Alaska earthquake. All of the research supported in this grant was carried out in collaboration with Dr. Steven Cohen of Goddard Space Flight Center. The research funding from this grant primarily supported GPS fieldwork, along with the acquisition of computer equipment to allow analysis and modeling of the GPS data. A minor amount of salary support was provided by the PI, but the great majority of the salary support was provided by the Geophysical Institute. After the expiration of this grant, additional funding was obtained from the National Science Foundation to continue the work.

This grant supported GPS field campaigns in August 1995, June 1996, May-June and September 1997, and May-June 1998. We initially began the work by surveying leveling benchmarks on the Kenai peninsula that had been surveyed after the 1964 earthquake. Changes in height from the 1964 leveling data to the 1995+ GPS data, corrected for the geoid-ellipsoid separation, give the total elevation change since the earthquake. Beginning in 1995, we also identified or established sites that were suitable for long-term surveying using GPS. In the subsequent annual GPS campaigns, we made regular measurements at these GPS marks, and steadily enhanced our set of points for which cumulative postseismic uplift data were available.

From 4 years of Global Positioning System (GPS) measurements, we find significant spatial variations in present-day deformation between the eastern and western Kenai peninsula, Alaska. Sites in the eastern Kenai peninsula and Prince William Sound move to the NNW relative to North America, in the direction of Pacific–North America relative plate motion. Velocities decrease in magnitude from nearly the full plate rate in southern Prince William Sound to about 30 mm/yr at Seward and to about 5 mm/yr near Anchorage. In contrast, sites in the western Kenai peninsula move to the SW, in a nearly trenchward direction, with a velocity of about 20 mm/yr. The data are consistent with the shallow plate interface offshore and beneath the eastern Kenai and Prince William Sound being completely locked or nearly so, with elastic strain accumulation resulting in rapid motion in the direction of relative plate motion of sites in the overriding plate. The velocities of sites in the western Kenai, along strike to the southwest, are opposite in sign with those predicted from elastic strain accumulation. These data are incompatible with a significant locked region in this segment of the plate boundary. Trenchward velocities are found also for some sites in the Anchorage area. We interpret the trenchward velocities as being caused by a continuing postseismic transient from the 1964 great Alaska earthquake. There may be significant along-strike differences in the long-term behavior of the plate interface between the western and eastern Kenai, based on roughly coincident boundaries in the coseismic slip distribution, cumulative postseismic uplift, present-day plate coupling, and stress field. The present postseismic response appears to

generate purely trenchward motion, suggesting a creep process that is purely dip slip. Our observations suggest that postseismic processes after the largest earthquakes can influence patterns of deformation for decades after the event.

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Freymueller, J. T., S. C. Cohen, and H. J. Fletcher, Variations in present-day deformation, Kenai peninsula, Alaska, and their implications, *Journal of Geophysical Research*, in press.

Cohen, S. C., and J. T. Freymueller, Crustal Uplift in the Southcentral Alaska subduction zone: A new analysis and interpretation of tide gage observations, in preparation, *to be submitted to Journal of Geophysical Research*, November 1999.

Zweck, C., Freymueller, J. T., and S. C. Cohen, Three-dimensional elastic dislocation modeling of the postseismic response to the 1964 Alaska earthquake, in preparation, *to be submitted to Journal of Geophysical Research*, December 1999.

GPS Field Measurements

This grant supported GPS field campaigns in August 1995, June 1996, May-June and September 1997, and May-June 1998. All field campaigns were carried out by the PI and graduate students at the University of Alaska. Cohen helped plan and participated in all of the field campaigns except for the September 1997 campaign. Approximately 20-30 sites were occupied in each survey. Individual observing sessions were 8 hours or longer per day, and in almost every case sites were occupied at least two times in each campaign. Most sites established for GPS are suitable for unattended operation and were occupied for several 24-hour observing sessions each year. A few of the leveling resurveys used short occupation times (a few hours or less), and in a few cases we made GPS observations at a temporary point near the benchmark and leveled between the temporary point and the benchmark. In total, we observed 65 sites (Figure 1) and have obtained velocities for 24 sites.

We initially began the work by surveying leveling benchmarks on the Kenai peninsula that had been surveyed after the 1964 earthquake. Changes in height from the 1964 leveling data to the 1995+ GPS data, corrected for the geoid-ellipsoid separation, give the total elevation change since the earthquake. Beginning in 1995, we also identified or established sites that were suitable for long-term surveying using GPS. In the subsequent annual GPS campaigns, we made regular measurements at these GPS marks, and steadily enhanced our set of points for which cumulative postseismic uplift data were available. All GPS data were analyzed using the GIPSY/OASIS II software developed at NASA's Jet Propulsion Laboratory.

Cumulative Postseismic Uplift

Cumulative postseismic uplift in the Kenai peninsula forms a broad dome trending northeast-southwest [*Cohen and Freymueller*, 1997]. There appears to be a greater concentration of uplift in the northeast Kenai peninsula relative to the southwest (Figure 2). If true, then the along-strike variations in peak uplift would have a similar pattern as the along-strike variations in coseismic slip. Spatial variations in postseismic uplift cannot be mapped in detail because a large part of the interior of the Kenai peninsula is devoid of historical leveling data. An intriguing possibility, consistent with the available data, is that spatial variability in the cumulative postseismic uplift is due to heterogeneities in the postseismic slip similar to those in the coseismic slip, although occurring at a greater depth along the plate interface.

We attributed the cumulative uplift for three decades to 2.25-2.5 meters of slip on the North America–Pacific plate boundary at a depth below the locked portion of the megathrust [*Cohen et al.*, 1995]. Since the (NUVEL1A) convergence rate of the North America and Pacific plates is only 55 mm/yr [*DeMets et al.*, 1994], or about 1.65 meters in 30 years, about 35% of the slip must be transient creep at depth in response to the earthquake. *Gilpin* [1995] used the same creep-at-depth, elastic rheology, mechanism to explain tide gauge records and the postseismic uplift of tidal benchmarks on Kodiak island. *Cohen* [1996] argued that viscoelastic flow occurring in the lower crust or upper mantle most likely does not contribute to the observed deformation, since this process would cause subsidence where we observed uplift. However, this could be counteracted by adding more transient creep than required by a creep-at-depth model.

Spatial Variations in Contemporary Deformation

We observe significant spatial variations in present-day deformation between the eastern and western Kenai peninsula (Figure 3). Sites in the eastern Kenai peninsula and Prince William Sound move to the NNW relative to North America, in the direction of Pacific–North America relative plate motion. Velocities decrease in magnitude from nearly the full plate rate in southern Prince William Sound to about 30 mm/yr at Seward and to about 5 mm/yr near Anchorage. In contrast, sites in the western Kenai peninsula move to the SW, in a nearly trenchward direction, with a velocity of about 20 mm/yr. Small trenchward velocities are also found for some sites north of Anchorage, and have been reported at a similar distance from the trench near Kodiak Island. Trenchward velocities are not found anywhere else in southern Alaska where GPS observations exist.

These observations are consistent with a model in which there is a sharp contrast in the coupling of the plate interface between the eastern and western Kenai profiles, and a continuing postseismic response to the 1964 earthquake that takes the form of transient creep downdip of the seismogenic zone. In our interpretation, the shallow plate interface offshore and beneath the eastern Kenai and western Prince William Sound is completely locked or nearly so, resulting in rapid motion in the direction of relative plate motion of sites in the overriding plate (Figure 4). The shallow plate interface offshore and beneath the western Kenai, along strike to the southwest, is slipping freely (Figure 5). A small locked patch extending as much as 150 km from the trench is allowed by our data. A postseismic transient from the 1964 great Alaska earthquake continues along most or all of the length of 1964 rupture zone, which results in trenchward velocities. In the western Kenai, the absence of a large shallow locked zone and the postseismic transient combine to give trenchward velocities of all sites there.

Several lines of evidence suggest that there may be a significant along-strike boundary between the western and eastern Kenai that results in long-term differences in the behavior of the plate interface. Roughly coincident boundaries in the coseismic slip distribution, cumulative postseismic uplift, and present-day plate coupling also coincide with a boundary in the inferred stress [*Lu and Wyss*, 1996]. If these boundaries coincide, they suggest a fundamental along-strike change in the behavior of the plate interface. An alternate explanation is that the along-strike variations in the present-day deformation and stress and the cumulative postseismic uplift are consequences of the along-strike variations in the 1964 moment release.

The present postseismic response appears to generate purely trenchward motion, suggesting a creep process that is purely dip slip. One possible explanation for a purely dip-slip postseismic response is that the 1964 earthquake itself was dominantly dip-slip. Another is that the physical process responsible for the ongoing creep 30 years following the earthquake is excited by dip-slip and not strike-slip motion.

It is surprising to find a strong postseismic signal 30 years after the earthquake. Our observations suggest that postseismic processes after the largest earthquakes can influence patterns of deformation for decades after the event. The time decay of the postseismic uplift rate in the first decade or two following the earthquake suggested a decay process with a characteristic time of a few to several years, and after 30 years such a process would have decayed to zero. One possible explanation is that multiple physical processes are involved, which act on different timescales.

Figure 1. Map of GPS sites surveyed over the course of this project. The rectangle shows the area covered by the maps in Figures 2 and 3. The 1964 aftershock zone is shown with a dashed line, and major crustal faults active in the Quaternary are shown by heavy lines. CI: Cook Inlet; PWS: Prince William Sound; DF: Denali fault.

Figure 2. Cumulative postseismic uplift, 1964-1995. Site T19 in Seward is assumed to have zero vertical motion based on nearby tide gage observations. From *Cohen and Freymueller* [1997].

Figure 3. Velocities 1993-1997 for the Kenai peninsula region, relative to North America. From *Freymueller et al.* [in press].

Figure 4. East Kenai profile and model. From *Freymueller et al.* [in press].

Figure 5. West Kenai profile and model. From *Freymueller et al.* [in press].

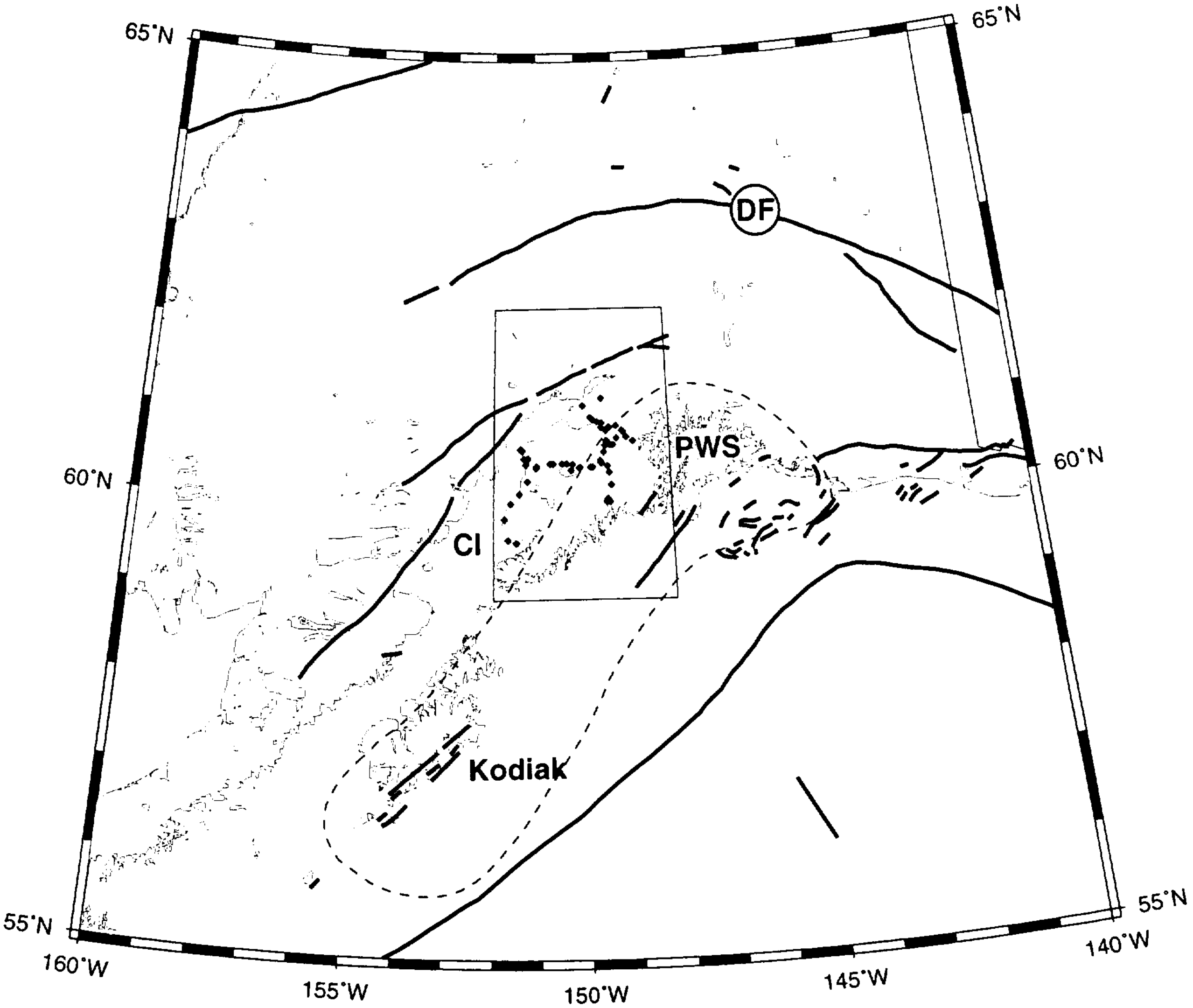

65°N
65°N
60°N
60°N
55°N
55°N
160°W
155°W
150°W
145°W
140°W
DF
PWS
CI
Kodiak

Figure 1

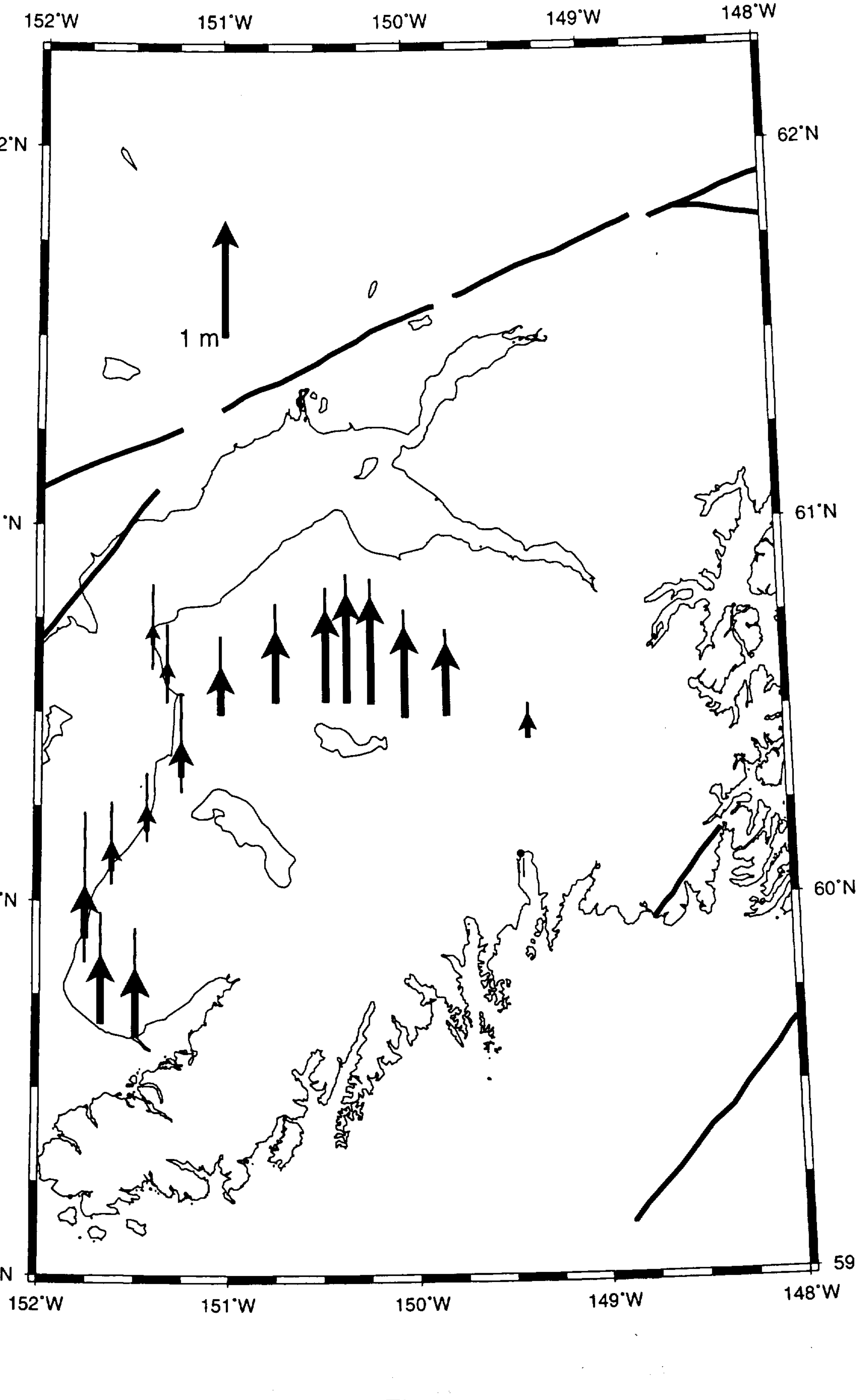


Figure 2

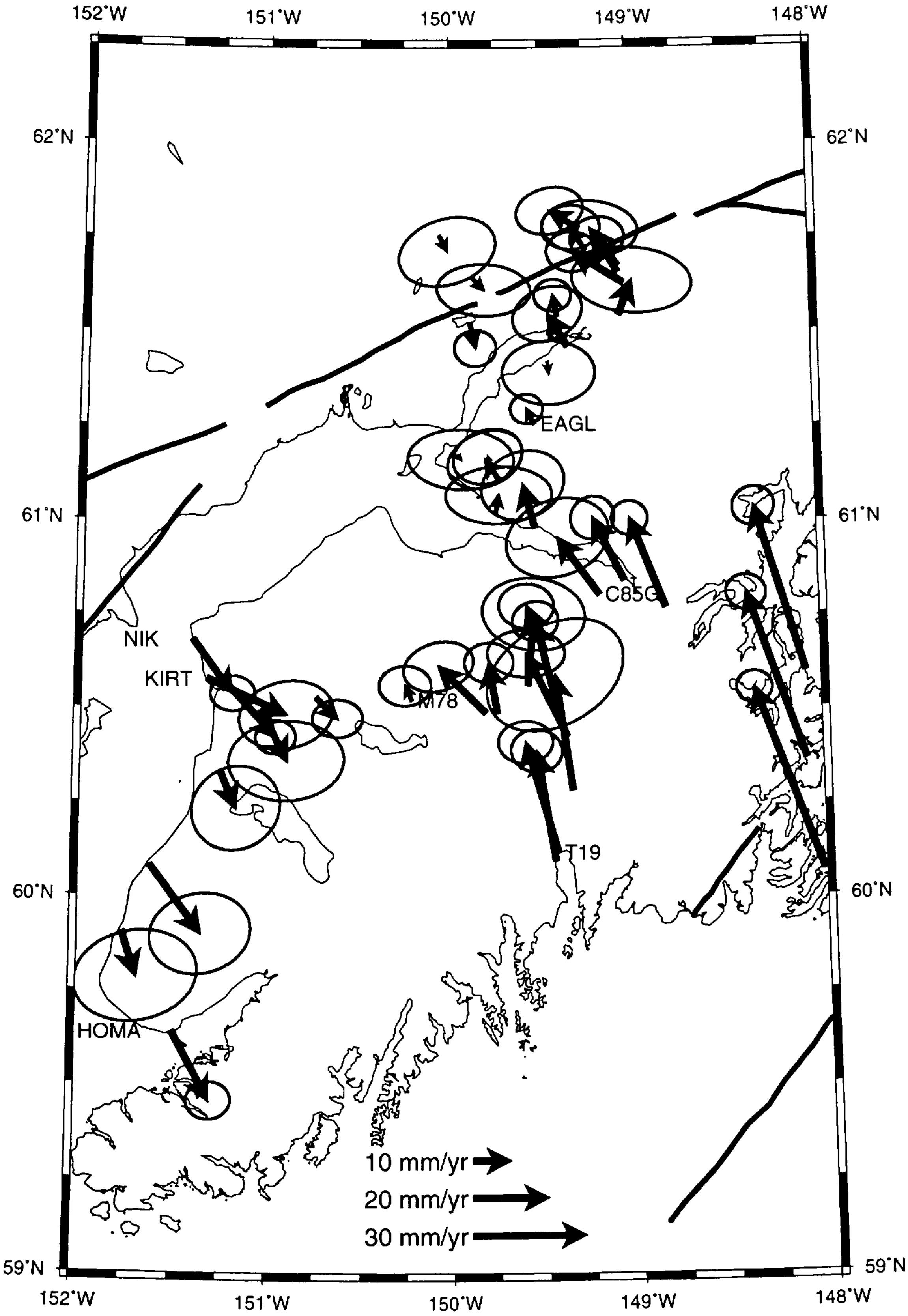
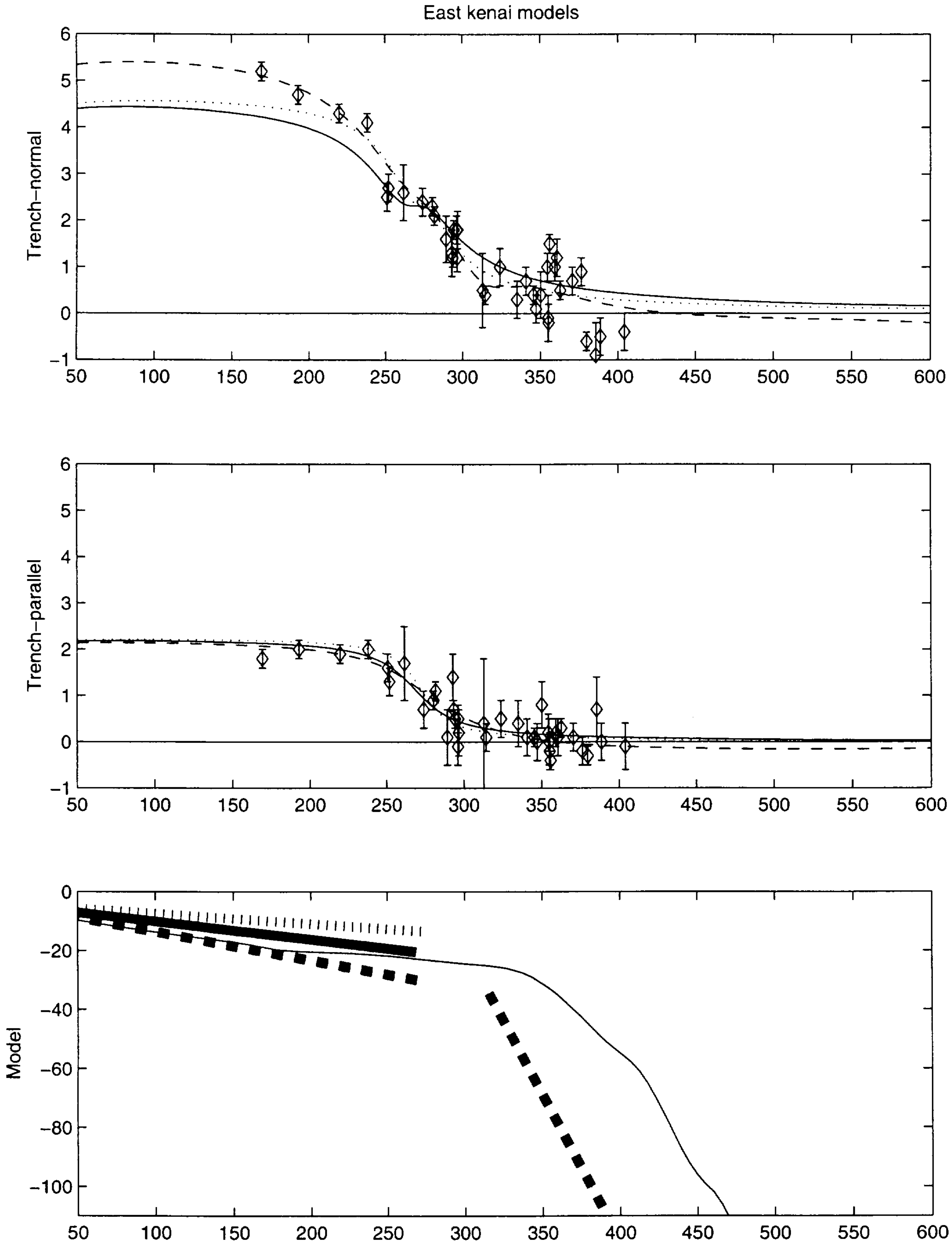

152˚W
151˚W
150˚W
149˚W
148˚W
62˚N
61˚N
60˚N
59˚N
EAGL
C85G
NIK
KIRT
M78
T19
HOMA
10 mm/yr
20 mm/yr
30 mm/yr

Figure 3



East kenai models
Trench−normal
6
5
4
3
2
1
0
−1
50
100
150
200
250
300
350
400
450
500
550
600
Trench−parallel
6
5
4
3
2
1
0
−1
50
100
150
200
250
300
350
400
450
500
550
600
Model
0
−20
−40
−60
−80
−100
50
100
150
200
250
300
350
400
450
500
550
600

Figure 4

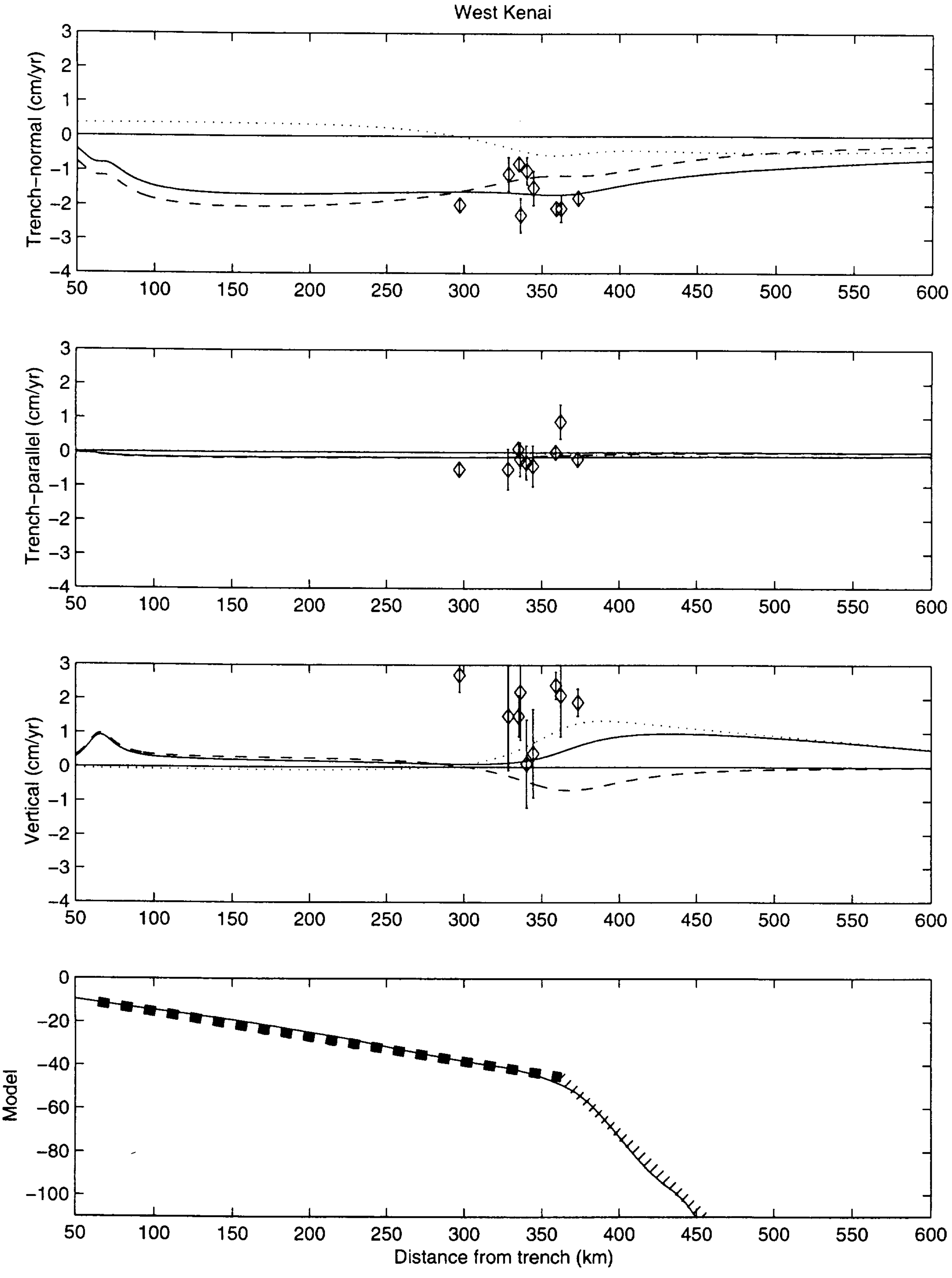

West Kenai
Trench−normal (cm/yr)
Trench−parallel (cm/yr)
Vertical (cm/yr)
Model
3
2
1
0
−1
−2
−3
−4
−20
−40
−60
−80
−100
50
100
150
200
250
300
350
400
450
500
550
600
Distance from trench (km)

Figure 5