Chapter 2 The Test Area: Kenai Peninsula

2.1. General

Scientific understanding of earthquakes may make it possible to anticipate their future occurrences at those places where earthquakes have occurred or elsewhere. This on the other hand helps to adequately cope with their disastrous effects. The Alaska earthquake of March 27, 1964 is perhaps the world's best-documented and most thoroughly studied event. Following the earthquake a committee was established in order to fulfill the following tasks:

1) To evaluate the efforts being made to gather scientific and engineering information about the earthquake and its effects,
2) To encourage the filling of gaps in the observational records,
3) To compile and publish comprehensive reports.

An eight-volume report comprehensively covering various aspects of the earthquake from engineering, human ecology, … to geology, seismology and geodesy (Konrad and Krauskopf, 1972) was the result of this fruitful research program. These results and future further studies together with the related data have furnished an excellent framework for further scientific researches. Students can find comprehensive literature on various aspects of the earthquake. Seasoned scientists can verify the efficiency of newly developed theories and methods using the available information in this area, and compare them to the results of other existing approaches, etc. In this research also, the best has been tried to make use of this opportunity. For this purpose, first the existing geodetic literature on the Alaskan earthquake is briefly reviewed. More emphasis is put on publications that can provide the required evidences for verifying results of this research to be presented and discussed in Chapter seven. Geologic terms used in the context of tectonic settings of the study area are given in footnotes according to Allabay and Allabay (1990). This will not only add rigor to this text but also makes it self-sufficient and assists the reader to easily follow the discussion. However, it is beyond the scope of this thesis to go for the corresponding detail of the geologic concepts.

2.2. Tectonic Setting of Kenai Peninsula

Southern Alaska together with Aleutian Islands chain, extending from Fairbanks on the north to the Gulf of Alaska on the south, is one of the world's most active seismic zones. Figure 2.1 illustrates the distribution of the earthquake epicenters in this area since the beginning of instrumental measurement of earthquakes in 1961.

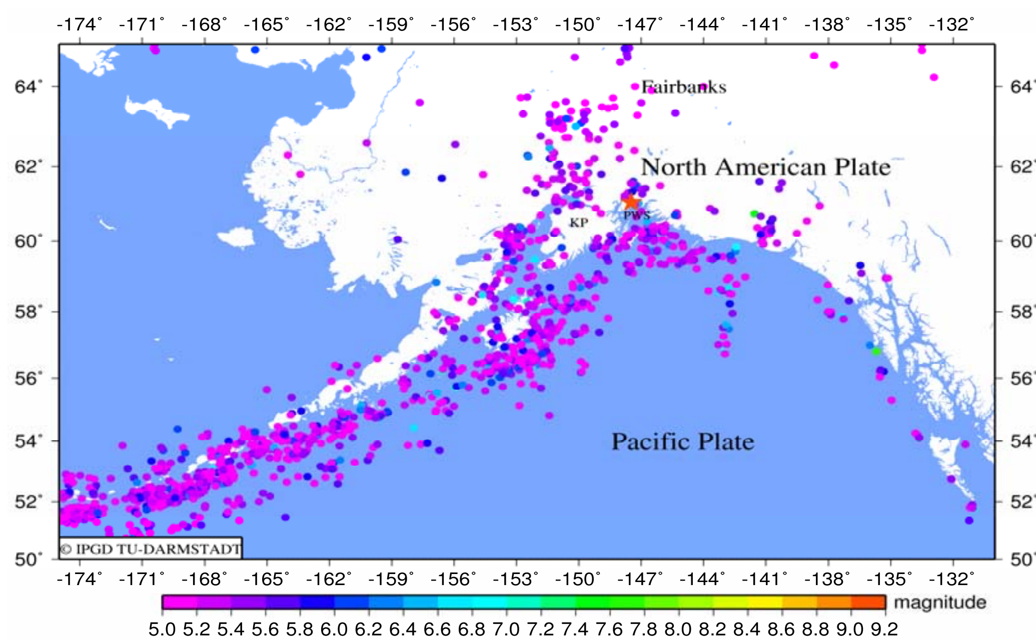

Figure 2.1: The seismicity of southern Alaska earthquakes from 1961 to 1999. Circles show the earthquake epicenters with different magnitudes. Star shows the Prince William Sounds earthquake's epicenter that happened in 1964.

The area is a part of a vast near-continuous seismic zone known as Circum-Pacific seismic belt that coincides with the world's orogenic belt[1] and contains most of active volcanoes. More than 80 percent of the Earth's tremors occur in this seismic belt (Stacy, 1977). The tectonic setting of south-central Alaska is highly affected by this seismic feature such that about 7 percent of the seismic energy released annually on the globe originates in the Alaskan seismic zone (Gutenberg and Richter, 1949). Seismicity along the Circum-Pacific belt, and

[1] A linear or arcuate zone, on a regional scale, which has undergone compressional tectonics. The history of many orogenic belts have been interpreted using plate tectonics models involving the subduction of oceanic lithosphere (e.g. Andean orogenic belt), the collision of major continental masses (e.g. the Himalayan orogenic belt) or the accretion of terranes (e.g. the Cordillera of the western USA and Canada).

thereby the south-central Alaska, is due to the anticlockwise motions of the Pacific Plate, subducting in the north and west (from Alaska, Japan to New Zealand) and the subduction of the Nazca and Cocos plates in the east beneath South and Central America.

South central Alaska was severely affected by the 1964 Prince William Sound earthquake (Figure 2.2). The earthquake is famous for its three features: large magnitude, long duration and the great breadth of its damage zone. It is the biggest event in the instrumentally recorded earthquake history in North America. Kanamori (1977) estimated a moment magnitude of $M_w = 9.2$ for this earthquake. According to eyewitnesses the earth was shacking for at least 3 to 4 minutes. The main shock was reportedly felt throughout most parts of Alaska, points 600 to 800 miles distant from the epicenter. Ground and structural damage was seen on an area of 50,000 square miles and it cracked ice on lakes and rivers in an area of 100,000 square miles (Hansen and Eckel, 1966).

The central portion of Kenai is dominated by the Kenai Mountains which is composed of metamorphosed Jurassic and Cretaceous age rocks, with some volcanic rock on the western margin of this terrane[2]. These mountains are thought to be part of the accretionary[3] Chugach terrane, a Mesozoic subduction zone complex that migrated northward and whose contact with more northerly peninsular terrane probably dates to some time in Jurassic. The southern portion of Kenai Mountains is overlain by the massive Harding ice field. The Border Range Fault marks the contact between Kenai Mountains and Kenai lowlands, constituting mostly of glacial till[4] and other debris[5] lying to the west. The western region is also punctuated by Moraines[6] reflecting several episodes of glacier advance and retreat. The glacial till and alluvium[7] of the lowlands cover the peninsular terrane, which is an island arc plateau system that collided with north America in Cretaceous (Plafker et al., 1989 and Pavlis and Crouse, 1989). Southern Alaska active faults are illustrated in Figure 2.2.

[2] A fault bounded area or region which is characterized by stratigraphy, structural style and geologic history distinct from those of adjacent areas.
[3] Process by which an inorganic body- like continents-grows in size by the addition of new particles to its exterior is known as accretion.
[4] Collective term for group of sediments laid down by direct action of glacial ice without the intervention of water.
[5] In geology, debris usually applies to the remains of geological activity like landslides, volcanic explosions, and lava eruptions.
[6] Moraine is the general term for debris of all sorts originally transported by glaciers or ice sheets that have since melted away.
[7] An alluvial-a term applied to environments, action and products of rivers or streams-deposit.

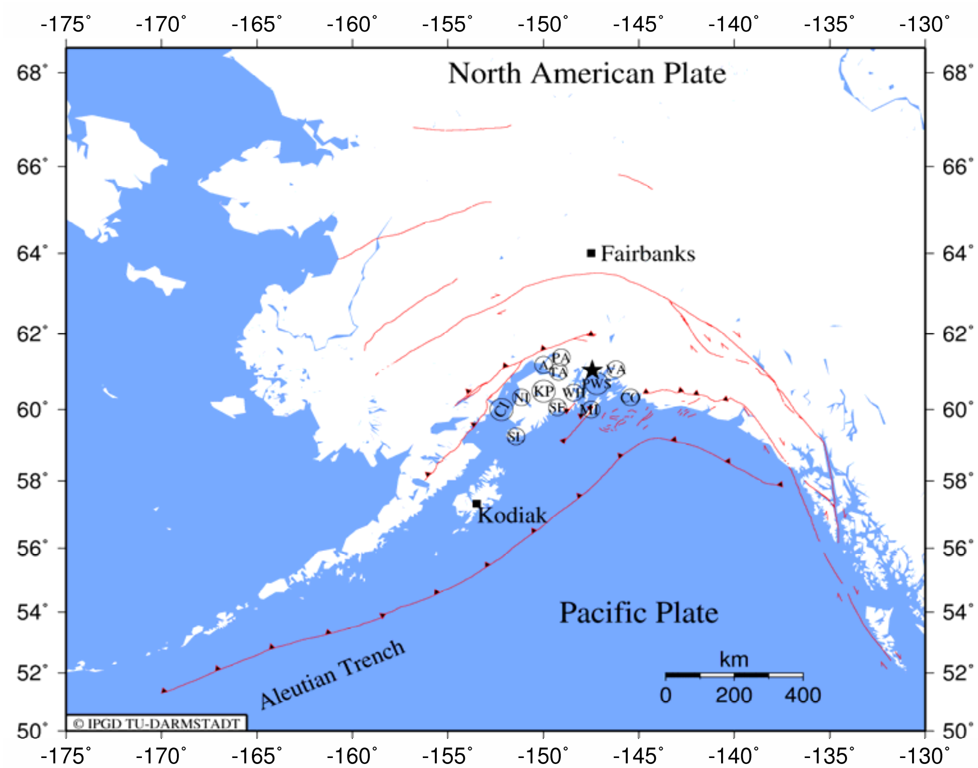

Figure 2.2: The southern Alaska active faults. KP: Kenai Peninsula, PWS: Prince William Sounds, CI: Cook Inlet, TA: Turnagain Arm of Cook Inlet, A: Anchorage, NI: Nikishki, SL: Seldovia, SE: Seward, WH: Whitter, CO: Cordova, VA: Valdez, PA: Palmer. Star shows the epicenter of the 1964 Alaskan Earthquake.

2.3. Seismic Deformation in Kenai Peninsula since the Event of 1964

The co- and post-seismic deformation in this area has been subjected to extensive research by geo-scientists. Some rough estimates of pre-seismic uplift rate within the area affected by this large event are also available.

2.3.1. Horizontal Deformations

2.3.1.1. Horizontal Displacement Field

Parkin (1972) studied co-seismic surface displacements of the Prince William Sound (PWS) earthquake. For this purpose, he used the triangulation data prior to the earthquake together with the post earthquake measurements in 1964 and 1965 within the damaged area of this event. The triangulation network consisted of a mixture of first, second and (largely) third order surveys, made principally for mapping purposes. The network extended from about latitude of 59° to 62° north and longitude 145° to 154° west. Station Fishhook 1944, about 9 miles north of Palmer (see Figure 2.3), was held fixed. This was because seismologists believed that the section on which this station was located was the most stable in the study area. Estimated horizontal movements of this study have been recompiled in Figure 2.3. Parkin suspected that the western Kenai was undertaking a co-seismic dilation. To clarify this phenomenon in further detail, he suggested extending the triangulation network to Kodiak Islands. Horizontal displacements of 15 m at Seward (southeast of Peninsula) were reported in this study. Co-seismic horizontal displacements exceed 20 m in some parts of the affected area.

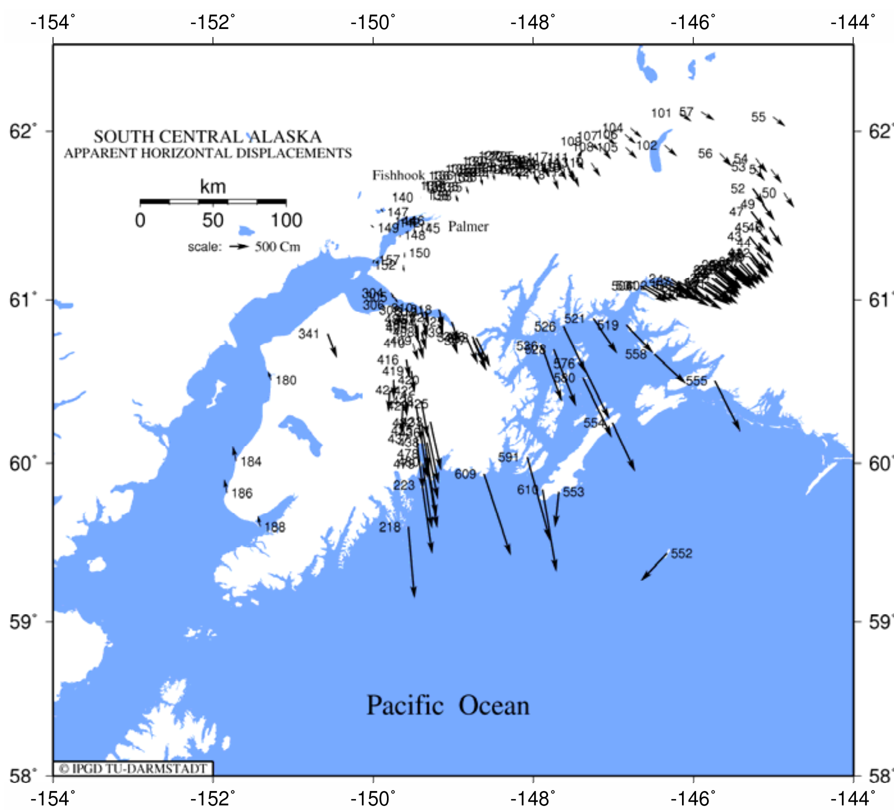

Figure 2.3: Co-seismic horizontal crustal movements of the event 1964 in south-central Alaska, after Parkin E., 1972.

2.3.1.2. Horizontal Strain Field

To assist the better understanding of co-seismic horizontal displacement field, Pope (1972) computed the horizontal strain parameters and rigid body rotations for the same triangulation surveys. Using a finite element approach and a simplified stochastic model, the horizontal principal strains and their orientation as well as maximum shear and rotations of the area were computed for the same period of time. Totally 155 sets of deformations parameters were computed from which 77 sets were reported and studied in detail. Estimated principal strains of these are reproduced in Figure 2.4.

Since the pre- and post-earthquake observations were made over a relatively large time span (almost 35 years for pre-earthquake measurements and 1 year for post-earthquake measurements), it is too difficult to precisely localize the estimated distortions (strain parameters and rotations) in time. This analysis could drew the following geophysical implications for the co-seismic deformations of the Alaskan earthquake:

1) The significant widespread and relatively uniform shear that conforms to a good extent to the direction of the surface rupture in the lowland part of Kenai (western Kenai) was observed.

2) The general trend of the principal strain parameters was found to be in a good agreement with the trend of geological features in the area.

3) Computed strains were not representative of the elastic strain and its corresponding state of stress for the poor resolution of observations in space (long distances between the stations) and time. These parameters can only be used for a better interpretation of estimated horizontal movements.

4) These results together with other evidences from seismology and geodesy demonstrated that the Alaskan earthquake of 1964 was indeed a large scale and complex phenomena covering an extremely large area.

5) The fault plane solutions of the initial shock involved an essential ambiguity between the planes of faulting roughly characterized as thrust or normal. The strain analysis supported significant horizontal components favorable to thrust hypothesis.

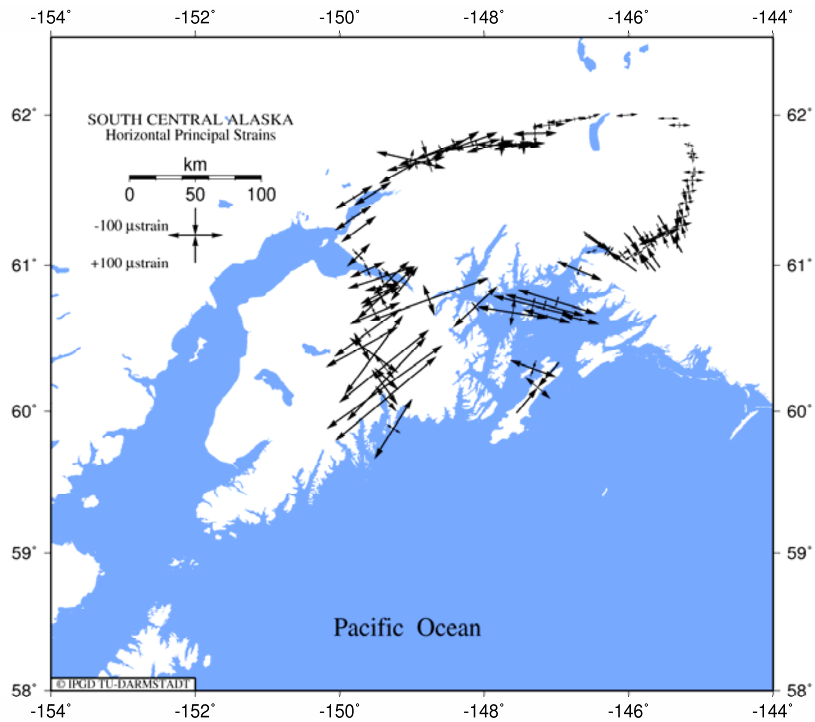

Figure 2.4: Horizontal principal strains reproduced from the published data in Pope, (1972).

2.3.2. Vertical Deformations

Small and Wharton (1972) reported on the history of leveling surveys that had been carried out in south-central Alaska from 1910 to 1965. They reviewed the indications of the height changes in different parts of this area both before and after the Alaskan earthquake of 1964.

During this event, most of Kenai settled co-seismically whereas the area east of it (the oceanic crust) underwent a co-seismic uplift. Co-seismic uplift exceeded 12 m on Montague Islands-see Figure 2.2 –(Plafker, 1971). It is believed that rupture on a subsidiary fault in the area has magnified the vertical deformation due to the slip on shallow dipping North American-Pacific Plate convergence zone (Cohen, 1996). Plafker (1971) reported a maximum co-seismic subsidence of 2 m in the area. Maximum co-seismic subsidences occurred on the southeast portion of Kodiak Islands, along the east central portion of Kenai Peninsula and at the eastern end of Turnagain Arm (see Figure 2.2). The most profound effect of this event was seen in south-central Alaska, notably at Anchorage, Valdez, Cordova and Kodiak Island in southwest of Kenai Peninsula (see Figure 2.2). Other scientists have also confirmed the results of this study (Holdahl and Sauber, 1994).

2.4. Post-seismic Deformation

The ongoing post-seismic uplift of the Kenai Peninsula was first observed by Brown et. al. (1977). Their study was based on tidal observations at Anchorage and four leveling surveys between Whittier and Anchorage, carried out by National Geodetic Survey over the decade following the great Alaska earthquake. Maximum uplift amplitude of 0.55 m was derived at a location midway between these two cities. The region of maximum uplift had subsided as much as 1.9 m during the earthquake. They argued that the location of maximum uplift was possibly propagating toward the Aleutian trench. The results of this investigation also revealed that the rate of uplift has exponentially decreased since the event of 1964. The authors suspected that the observed uplift followed an elongate pattern. They found evidence of domical pattern for the ongoing post-seismic uplift in this area. Later derivations of Cohen and Freymueller (1997) confirmed the domical pattern of post-seismic deformation within the Kenai Peninsula. Savage and Plafker (1991) updated this study by analyzing tide gage records in Seward, Seldovia and Nikishka. They also observed post-seismic uplifts at those places where co-seismic subsidence had occurred and post-seismic subsidence at those where co-seismic uplift had occurred.

The main deficit of tidal data is its limitation to coastlines. Moreover, interpretation of tidal data in terms of crustal deformation requires adequate oceanic models to account for short as well as long tem variations of the sea surface. The later was taken into account in the work of Savage and Plafker (1991).

Several important geodetic observations were also made in the year and a half following the PWS earthquake some of which were later used by other scientists. For example: Rice (1972) reported on the gravity observations and Small and Wharton (1972) reported on the results from geodetic leveling.

GPS measurements were added later to the list of geodetic measurements to help scientists improve their understanding of the mechanism that controls the ongoing crustal deformation of this area.

Cohen et. al. (1995), reported on the combined usage of GPS results, gravity measurements and leveling results of the 1964 survey. They reoccupied six of the 1964 leveling benchmarks in the Kenai Peninsula between Seward and Nikishka using geodetic GPS receivers. Using gravity measurements a new high-resolution local geoid was computed. Estimated geodetic heights were later transformed to orthometric height using the geoid model and compared to the leveling results. This study provided an insight to the cumulative 1964-1993 post-seismic vertical deformations in this area. Based on their analysis, a maximum uplift of 0.90 to 1.1 m was seen at the middle of the peninsula. The authors suggested that a broad arch of post-seismic uplift extending at least from Kodiak Islands to northeast of Anchorage was taking place in this area.

Cohen and Freymueller (1997) combined the results of leveling survey immediately after the Prince William Sound earthquake of 1964 and the GPS results of 1993 and 1995. They used NGS geoid height model GEOID96 for transforming the geometric to orthometric heights. The GPS data in this study were processed more carefully compared to Cohen et al. (1995). For example, site-specific troposphere parameters were estimated to account for the tropospheric error and antenna phase center variation model was applied to account for different antenna types used in measurements. This analysis proposed an elongate domical pattern for the post-seismic uplift in the Kenai Peninsula (see Figure 2.5). They argued that the elongate dome is approximately of 125 km wide with its major axis orienting southwest northeast following the trend of major tectonic features of the region. They estimated a maximum uplift of about 0.90 m near the center of peninsula with an averaged rate as high as 30 mm/yr. Since the previous geodetic studies of uplift in this area were profile studies in nature, they couldn’t directly portray the pattern of deformation over this extensive area. Cohen and Freymueller (1997) presented the first detailed look at the spatial distribution of cumulative uplift over 30 years.

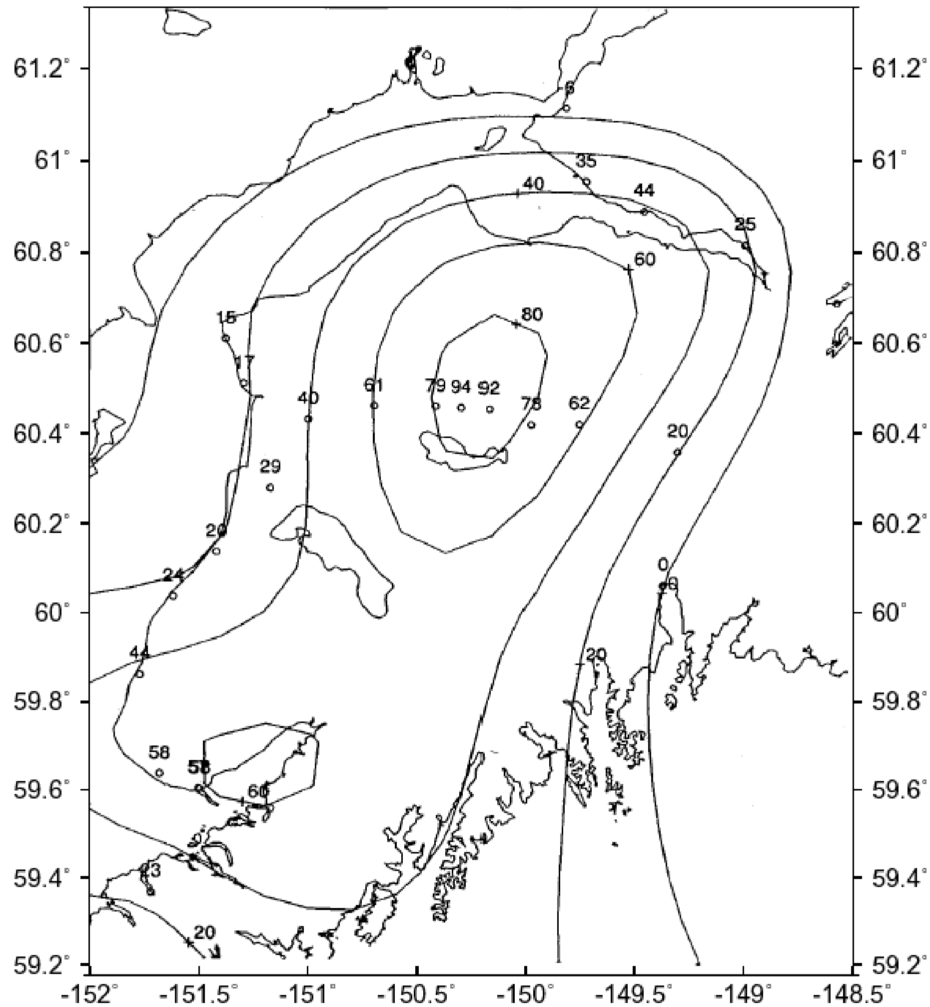

Figure 2.5: Domical pattern of vertical deformation computed using tidal, gravity and leveling observations, reproduced from Cohen and Freymueller (1997).