GRAVITY CONTOUR MAP AND INTERPRETATION OF GRAVITY DATA FOR THE CHUGACH NATIONAL FOREST, ALASKA

by

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STUDIES RELATED TO WILDERNESS

The Wilderness Act (Public Law 88-577, September 3, 1964) and related acts require the U.S. Geological Survey and the U.S. Bureau of Mines to survey certain areas on Federal lands to determine their mineral resource potential. Results must be made available to the public and be submitted to the President and the Congress. This report presents the results of a geophysical survey of the Chugach National Forest, Alaska, including the Nellie Juan-College Fiord Wilderness Study Area established by Public Law 96-487, December 2, 1980.

INTERPRETATION OF GRAVITY DATA

INTRODUCTION

The gravity map of the Chugach National Forest shows variations in the densities and thicknesses of the lithologic units that underlie the forest. Some gravitational features may represent structures deep in the crust, and much of the gravity field is an expression of the crustal thickness variations associated with the region's large (as much as 13,300 ft) topographic relief. Other variations seem to be related to the distribution of mineral resources, and some may even be expressions of active tectonic processes. However, present gravity coverage, although adequate for a regional reconnaissance, is not sufficiently detailed for much quantitative analysis or detection of anomalies associated with local mineralization.

Gravity data for the national forest have accumulated over a thirty year period and now include about 750 land measurements. The earliest measurements were reported by Thiel and others (1958) and were later interpreted by Woollard and others (1960). The most extensive surveys in the area were made after the 1964 earthquake (Case and others, 1966; Rice, 1969) and included an analysis of the gravity changes that accompanied that event (Barnes, 1966). In the following eight years a small amount of additional data accumulated as part of the data base for a state gravity map (Barnes, 1977). Additional gravity measurements in 1976 provided new detail around Resurrection Peninsula and Knight Island, and they led to a refined interpretation of part of the area as a contribution to the mineral appraisal of the Seward and Blying Sound quadrangles (Case and others, 1979a). A small number of additional measurements were made near College Fiord, Valdez, and Cordova as part of the current investigation, which was also helped by two other sources of new data. One of these sources is a few measurements made as part of the hydrologic study of Columbia Glacier by Donald L. Peterson and Mark F. Meier (written commun., 1978). In addition, the crew of the USC&GS SURVEYOR made marine gravity measurements in Prince William Sound during the summer of 1964 (H.B. Stewart, written commun., 1964), and a few of these measurements have been used to guide the offshore contouring.

GRAVITY MEASUREMENTS

Position control for almost all of the nonmarine data was obtained from 1:63,360-scale topographic maps of the U.S. Geological Survey, although 1:250,000-scale maps and nautical charts were used for a few early stations. A large proportion of the measurements were made close to sea level using skiffs from the research vessels DON J MILLER I and II. Station elevations were obtained from graphical plots of tidal level as obtained from the Pacific Coast tide tables (National Oceanic and Atmosphere Administration, 1964 and successive years) and are referenced to mean tide level. Similar elevation calculations have been made for stations at tidal benchmarks in other parts of coastal Alaska, and many comparisons suggest that 90 percent of the shoreline elevations have a precision of ±2 ft (Barnes, 1972a). Elevations along the Alaska Railroad and most highways were obtained from benchmarks and highway or railroad surveys and are probably more accurate than ±2 feet. Altimetry was used for measurements that were reached by aircraft and (or) unsurveyed roads and rivers. Evaluations in other parts of Alaska suggest that 90 percent of the altimetry elevations have an accuracy of ±15 feet, although foggy weather in the national forest may tend to increase slightly the magnitudes of air density and, thus, altimetry errors in this survey.

Gravity datum for the survey was obtained from stations of the Alaskan Gravity Base Station Network (Barnes, 1968), which has now been adjusted to the International Gravity Standardization Net 1971 (IGSN-71) (Morelli and others, 1974). Reoccupiable bases at the four principle towns in the survey area are described below along with their gravity values adjusted to this new datum:

(1) Seward, station SEWB at northeast corner of 5th and Adams Streets on concrete step at L.V. Ray building and above USC&GS tidal benchmark 11, where the gravity is 981,919.12 mGal based on the 1971 datum.

(2) Whittier, station PW23 on the railroad platform at the base of the north side of a large rock monument with a bronze plaque commemorating the "ARR Whittier Cut Off," where the gravity is 981,912.78 mGal.

(3) Valdez, station VALP at corner of Galena Drive and Tatitlek Street on edge of post office parking lot, at base of a flagpole and above USC&GS tidal benchmark 4240K, where the gravity is 981,993.06 mGal.

(4) Cordova, station CRDB at northwest corner of Eyak Lake Municipal airport, southwest of hanger and at base of a bank sloping up to cemetary, on top of a boulder and above USC&GS benchmark C71, where the gravity is 981,941.83 mGal.

Data reduction followed techniques of Barnes (1972b), but used the 1967 geodetic reference system (International Association of Geodesy, 1971) and a standard specific gravity at 2.67. Data in the eastern three-quarters of the national forest have been terrain corrected to a radius of 99 km (Hayford Bowie zone N) using a digital elevation model (Barnes, 1983). However, data in the western part of the forest could not be terrain corrected by this method, because the digital elevation model for the western Seward quadrangle (between 60^0-61^0 N. and 149^0-150^0 W.) involved a distorted north-south scale that produced very erroneous local terrain corrections. However, we judged the model adequate for outer-zone corrections for eastern stations. Terrain corrections for the western area have thus been delayed until a better digital terrain model becomes available.

GEOLOGIC SUMMARY AND DENSITIES OF THE LITHOLOGIC UNITS

Nelson and others (1985) provide the most recent summary of the geology of the national forest, and the geology for this map was generalilzed from their report. Other recent summaries of the geology of some of the component quadrangles have been published by Tysdal and Case (1979, Seward and Blying Sound); Winkler and Plafker (1981, Cordova and Middleton Island), Winkler and others (1981, Valdez); and Magoon and others (1976, parts of Anchorage and Se^w^-d). Many earlier studies are referenced in those reports. The geology used in this report has been simplified in order to show the stratigraphic units that have the widest areal extent and display probable geophysical expression. Some units are shown that cannot be delineated on the present aeromagnetic and gravity maps, but they may be distinguishable on later more detailed geophysical surveys.

The predominant geologic unit in the national forest is a flysch sequence that ranges in age from Late Cretaceous through early Tertiary; its possibly older and more metamorphosed rocks are located on the north and west. This sequence of sedimentary and associated igneous rocks has traditionally been divided into two groups, the Orca Group and the older more metamorphosed Valdez Group. However, for more than a hundred years geologists have debated the distinguishing characteristics of the two groups and the location of the contact between them (Moffit, 1954; Nelson and others, 1985). In this paper, the distinction is maintained for the sedimentary rocks of the two groups, but grain size and most metamorphic characteristics within each group have not been considered. The igneous rocks that are interbedded and intruded within the two groups are not distinguished as belonging to an individual group because the host rocks do not affect either the physical properties or the geophysical expression of their igneous components. However, some of the lithologic distinctions have been retained although several units on the detailed geologic map have been combined as shown in the explanation.

In addition to the predominant flysch, two other major units are present. On the extreme west edge of the national forest, the flysch is in fault contact with the older melange of the McHugh Complex. At the southeast corner of the map sedimentary rocks of Eocene to Miocene age have been combined into a single unit that is in probable fault contact with the older Orca Group. Outcrops of volcanic rocks in one of these younger formations (Poul Creek Formation) are separately labeled because they have distinguishing geophysical properties. On the generalized map, most of the alluvial cover has been omitted except where this cover makes the drawing of other geologic boundaries uncertain. Similarly, most of the structural symbols have been omitted from the generalized geologic map.

The rock units that have the best geophysical expression are probably the volcanic rocks intruded and interbedded in the flysch sequence of both the Orca and Valdez Groups and the large granitic and mafic plutons intruded into the same groups. Most of these have been shown on the map, although many are small enough to have been missed by both the gravity survey and the aeromagnetic flight lines.

Many density measurements have been made of hand specimens collected during the gravity survey and geologic mapping. Most of these measurements were reported in earlier interpretations of the gravity data (Case and others, 1966, 1979a) and are summarized in table 1 as excerpted from publications with the addition of new data from the younger Tertiary formations.

Comparison of densities between the sedimentary rocks of the Orca and Valdez Groups showed no significant difference (Case and others, 1966); both groups consist of hard indurated graywackes, metagraywackes, argillites, and slates. Measured densities of the granitic rocks average lower than the density of the Orca Group and Valdez Group flysch, but the sampling is small and may emphasize the more silicic and weathered phases.

INTERPRETATION OF THE GRAVITY DATA

The most obvious feature of the Chugach National Forest gravity map is a regional decrease in Bouguer gravity from south to north and west. This 130-mGal decrease primarily represents an approximate 10-mi increase in crustal thickness between the continental shelf and the Chugach Mountains, although the thick section of sedimentary rock composing the mountains may be a factor contributing to the low gravity. The amount of crustal thickening represented by the gravity decrease is estimated from the empirical relation developed by Woollard and Strange (1962), but these authors recognized that their empirical relation may not be valid in areas of tectonic convergence, such as island arcs and the south coast of Alaska, where gravitational effects of tectonic processes predominate over processes of isostatic adjustment.

Measurements of crustal thickness are rare in Alaska, but much of the available data come from the vicinity of Prince William Sound and are worth reviewing in this report. The earliest reported measurements of Alaskan crustal thickness came from some explosions in College Fiord, which Tatel and Tuve (1956) seismically recorded on the highway system to the north and east. The data were first studied by Woollard and others (1960) and later reinterpreted by Hales and Asada (1966), who calculated crustal thicknesses of 30-35 mi to the northeast and 22 miles to the southwest. However, their analysis may have been hampered by lack of detailed knowledge of the large variations in geology and gravity along the seismic lines. Another pertinent crustal thickness measurement was obtained by Shor and others (1970) south of the national forest in the oceanic crust of the eastern Gulf of Alaska, where they measured a crustal thickness (below ocean bottom) of a little less than 8 mi. The thickness thus increases from about 8 mi in the Gulf of Alaska to 20 to 30 mi or more in and north of the Chugach Mountains. A third pertinent study is a series of earthquake epicenter determinations by Lahr (1975), which showed that the depth of the Benioff zone increases from about 15 mi near the south end of Montague Island to about 28 mi under the Chugach Mountains. If all or most of a layer of oceanic crust underlies the Benioff zone this combined crustal thickness probably increases from 23 to 35 mi from south to north within the national forest. The latter figures are a little larger than those determined from the refraction studies of Hales and Asada (1966) and the empirical gravimetric estimates from the Woollard and Strange (1962) relation. However, both probable compaction of sediments during a subduction process and consideration of hidden (shadowed) low-velocity layers in refraction calculations would tend to make the refraction and combined thicknesses more consistent. If the combined model is reasonable, the crust beneath the national forest is multilayered with at least the bottom layer an oceanic layer and the intermediate layer a mixture of reworked sediments and intrusive igneous rocks plus either oceanic or continental crust. It is a tectonicly active area of mantle-crust mix where gravitational estimates of crustal thickness are subject to greater possibility of error (Demenitskaya and Belyaevsky, 1969). Furthermore, thickness may not be a good criteria for whether the crust can be considered compositionally oceanic or continental, and the available unreversed seismic refraction data do not provide sufficiently accurate seismic velocities to make the distinction.

However, better knowledge of crustal thickness and composition beneath the Chugach National Forest should soon become available. The Trans Alaska Crustal Transect (TACT) was initiated after the completion of this gravity survey and mineral appraisal. This transect (Page and others, 1986) included three seismic refraction profiles which are largely within the National Forest boundaries. Interpretation of these new data (Daley and others, 1985; Wilson and others, 1987) is not yet complete, but their preliminary inspection shows some correlation between features of the gravity field and the seismic travel times. The locations of the seismic recorders and shot locations within the National Forest have thus been added to the gravity map as a possible aid to the seismic interpretation.

Another significant feature of the gravity field is the arcuate high that diagonally traverses the map from southwest to northeast. This feature was named the Prince William Sound high by Case and others (1966). It is best developed on Knight Island, where it is obviously associated with outcrops of mafic volcanic rocks and associated intrusions. The high gravity begins near Evans and Bainbridge Island in the south and extends northward through Knight Island, western Naked Island, and Storey Island, and there curves eastward through southern Glacier Island to Bligh Island and the Ellamar peninsula. Scattered gravity measurements in the mountains south and east of Valdez indicate an eastward extension south of the Tasnuna River and across the Copper River. Even more scattered regional data (Barnes, 1977) suggest a farther eastward extension across the Bering Glacier quadrangle, and the anomaly may extend an additional 300 mi farther southeastward to the gravity high associated with the Mount La Perousse ultramafic body in Glacier Bay National Monument (Barnes and others, 1978). Although the amplitude of the anomaly varies along its strike, the locally high magnitudes and great length of the feature suggest that it may represent a major geologic structure of southern Alaska, even though it crosses other structural trends such as the Contact fault. The massive iron-copper-zinc sulfide deposits of Prince William Sound and many sulfide mineral occurrences have been found along the axis and flanks of the anomaly.

The gravity high reaches its maximum amplitude at Knight Island, where a transverse gravity profile was initially interpreted and modeled by Case and others (1966) and later slightly modified for Case and others (1979a). After removal of the regional gradient caused by crustal thickness increase, they found that the anomaly could be closely approximated by a two-dimensional, trapezoidal mass with a specific gravity contrast of 0.2 and a total thickness of 40,000 ft. Similar modeling of a nearby transverse aeromagnetic profile (Case and others, 1979b) suggested that the associated magnetic anomaly could be explained by an object having a thickness of only 5,000 ft or less. This contradiction in calculated thicknesses suggests a lack of uniformity of magnetic properties and densities of the rocks causing the anomaly. The deeper parts of the anomalous mass may have a higher density and may have either lower susceptibility or reversed remanant magnetization. Thus, greater proportions of gabbro and (or) peridotite at depth may be suggested by the differences between the two interpreted profiles. The modeling of the gravity profile indicates that both the east and west flanks of the dense rock mass dip westward with the shallower dip on the west side, so that the rock mass broadens at depth but maintains a westward dip. However, neither the gravity nor aeromagnetic data may be sufficiently closely spaced to adequately define the structure and attitudes of the anomalous mass boundaries.

Wherever data are available along its strike, the Prince William Sound gravity high has an amplitude of at least 10 mGal, but this amplitude is small in comparison with the 55-mGal amplitude observed near Knight Island, which is the highest but not the only maximum measured along the trend. This variation in anomaly amplitude could suggest that the trend is not continuous, so the amplitude variations should be briefly discussed, although actual amplitude figures may vary with decisions concerning the level of the regional field or slope of its gradient. South of Knight Island, the local anomaly amplitude drops sharply to about 10 mGal over Knight Island Passage, where the axis is also shifted about 5 mi westward. Farther south, somewhat higher Bouguer gravity values were measured over southern Evans Island, where the maximum is again farther east and the regional field may be higher. Marine data do not show a significant offshore extension of the anomaly to the south, where the field is dominated by an increased thickness of younger sedimentary rocks combined with the gravity increase associated with the continental margin.

On northern Knight Island and on Eleanor Island, the anomaly amplitude again decreases, but a lower high continues across the channels south and north of Naked Island. A +11.5-mGal measurement on the west end of Storey Island suggests that the anomaly has an amplitude of at least 10 mGal and possibly as high as 25 mGal, depending on the choice of regional gradient. At Storey Island, the anomaly is again west of the axis of the anomaly maxima through Knight Island. No outcrops of mafic rocks have been found on either Naked or Storey Islands, but they are probably present at depth and 3 to 5 mi west of their shallower outcrops on Knight Island. North of Storey Island, high gravity was measured on southern Glacier Island, where the anomaly has an amplitude of 15 to more than 35 mGal, depending on the regional field. Here, the anomaly axis begins curving eastward, and more high gravity values were measured on Bligh Island and the Ellamar peninsula, where the anomaly amplitude is about 10 mGal lower.

East of Ellamar, the anomaly amplitude decreases rapidly to Bouguer measurements near 0 mGal at Silver Lake and in the valley northeast of Mount Denson. This break and saddle along a fairly continuous trend is important because it approximately coincides with the Jack Bay strand of the Contact fault. More gravity data are needed between Valdez Harbor on the north and Port Fidalgo on the south to determine the continuity of the trend, the sharpness of the break, and the depth of the rocks causing the change. However, the available regional data do show that a broad regional high does continue eastward with an amplitude of at least 15 mGal and a width of about 20 mi. Bouguer gravities below -20 mGal are typical of measurements in the mountains north of Valdez and along the shoreline of Port Gravina, and these measurements probably represent the regional field in this part of Alaska. However, the 20-mi width of the gravity high and its gentle bounding gradients suggest that the dense rocks causing the anomaly may here be much deeper than at Knight Island—perhaps 5 to 10 mi below the surface. Farther east, higher gravities were measured in the mountains south of the Lowe and Tasnuna Rivers, where a Bouguer gravity as high as 30.5 mGal was measured near the northern terminous of Wortmann's Glacier, and where the anomaly amplitude could be as high as 60 mGal if -30 mGal is considered the regional level. The width of the latter anomaly is close to 30 mi, and the gradients, although poorly defined by the reconnaissance data, suggest that the cause of the anomaly could be as much as 5 mi below the surface. One TACT seismic refraction profile, "The Chugach Strike Line" (Daley and others, 1985) was deployed along the Tasnuna River and thus approximately paralleled the north flank of this gravity anomaly.

The anomaly trend continues eastward and crosses the Copper River between its junctions with the Tasnuna and Bremner Rivers. Here the gravity field seems to be very complex over the broad, flat flood plain between the Copper and Bremner Rivers, and the present data are inadequate to define it. However, one of the best explanations of the observed values is that the broad high associated with the Prince William Sound anomaly has a narrow, possibly meandering, low superimposed on it that could be caused by thick sediments in a buried channel of the Copper River. This assumption was used during the contouring, but other explanations and contour patterns are possible. An attempt to obtain a detailed profile across the high at this point was not successful due to the complex gravity field and to bad weather limiting data collection in the mountains on the flanks of the high. However, the available data do suggest that the gradients are sufficiently gentle to represent a very deep source. A few stations in the mountains north of the Wernicke River show the presence of the gravity high east of the Copper River. Farther east in the Bering Glacier quadrangle almost no data are available along the trend until 142 30' W. longitude, where a north-south gravity traverse found a 30-mGal high on the north side of the Bagley Icefield.

As a broad feature flanked by gentle gradients, the Prince William Sound gravity high thus seems to be an essentially continuous feature across the national forest and eastward toward the St. Elias Mountains. The gravity data are still too widely spaced for accurate mathematical analysis, but they suggest that the broad, continuous feature has a deep source and could represent a thinning of the Earth's crust along a zone of buckling. Local highs along the trend represent shallower features where high density rocks approach or crop out at the Earth's surface, such as at Knight and Glacier Islands. Such local highs are generally east or south of the axis of the broad high and suggest that they may have been localized by west and north dipping structures associated with the high.

Another gravity high that is related to similar mafic rocks was mapped near the southeast corner of the national forest in the vicinity of the Resurrection Peninsula. Here the highest Bouguer gravities were measured west of the national forest boundary on Renard Island and the west shore of the peninsula. The anomaly in this area has a magnitude of about 30 mGal and a width of about 20 mi, so its amplitude and dimensions are somewhat smaller than those of the Prince William Sound high. The associated aeromagnetic anomaly has its maximum amplitude near the east shore of the peninsula and from there extends northward into an area where no gravity data are available. The gravity data thus provide no information concerning the thickness of this interesting extension of the magnetic anomaly northward beyond the mafic rock outcrops. Case and others (1979a) modeled an east-west gravity profile across the peninsula and the northern end of Renard Island. The station spacing does not justify detailed analysis of gradients along this line, but the profile did show that if the mafic rocks have a density contrast of 0.2 g/cm^3 with the adjacent sedimentary rocks, the thickness of the mafic rocks must be at least 3 mi. Furthermore, the model and width of the gravity anomaly suggest that mafic rocks must extend a long distance westward across Resurrection Bay before thinning under the western shore of the bay and Bear Glacier, although they do not crop out on this western shore.

Adjacent to the two large gravity highs are some broad areas of low gravity that represent either thick flysch sequences or crustal thickening beneath regions of high relief. The lowest gravity values in the national forest were measured near its northwest corner where Bouguer gravity values range from -80 to -100 mGal a little northwest of the boundary. Anomalies of about -80 were measured along Harvard Glacier 8-10 mi southeast of the summit of Mount Marcus Baker, the highest elevation within the national forest. Here, both the crust and flysch are probably close to their maximum thicknesses within the area. The low gravity probably extends eastward along the axis of the Chugach Range, although few measurements are available north of the coast between Unakwik Inlet and Valdez Harbor. The magnitude of the low, however, decreases to about -10 mGal in the mountains north of the city of Valdez. Similarly, southwest of Mount Marcus Baker the gravity remains low until Turnagain Arm, where simple Bouguer anomalies in the minus eighties were measured. However, south of Turnagain Arm the gravity rises gradually until it levels off at about -50 mGal near the center of the Kenai Peninsula. On the Kenai Peninsula the gravity field seems to be more dependent on proximity to the continental margin than on topographic elevation. Higher Bouguer anomalies in the +10 to -20 mGal range were measured in the 4,000- to 5,000-ft mountains around the Sargent and Harding Icefields, where such topographic elevations might suggest lower gravity. Interpretation of the smaller gravity anomalies on the Kenai Peninsula is risky since measurements west of 149 have not been terrain corrected. However, there does seem to be a trend of slightly higher gravity southward along the west side of the Placer River fault. An aeromagnetic anomaly also follows this trend, and both anomalies may be caused by metamorphism of the flysch to schist along this trend (Case and others, 1979b), although more recent geologic mapping (Nelson and others, 1985) did not distinguish the schist.

Another broad low lies on the south side of the Prince William Sound gravity high and extends eastward from the open water southwest of Naked Island through the mountains north of Cordova and across the Copper River. In the west, the low probably primarily represents a large sequence of marine sediments and flysch in the central part of the sound. In the east, the low probably primarily results from a combination of flysch and isostatic thickening of the crust below the mountains, although granitic intrusives could contribute to the anomaly.

Laboratory measurements of the densities of rock specimens collected during the gravity survey and geologic mapping suggest that most of the plutonic rocks have densities very close to those of the flysch sequence. However, the gravity contours do suggest that some of the plutons may have some gravity expression. For example, the lowest gravity anomalies measured along the shore of Port Gravina were on an outcrop of the Sheep Bay pluton, where the Bouguer gravity was about 5 mGal lower than at nearby locations. If this low does represent the granite, the pluton may be thickest north of Orca Inlet where no granite outcrops are present, but where the lowest Bouguer anomalies were measured. The gravity stations are too widely spaced to determine whether the pluton margins are marked by steep gradients, but more detailed data might provide information about the form of the Sheep Bay pluton, which may have a greater thickness and (or) lower density than most of the other plutons in the national forest.

Small or negligible gravity expression seems to be typical of most of the plutons and tends to confirm the similar density suggested by the laboratory measurements of hand specimens. One exception is the northwestward flexure of contours at Esther Island, which indicates a small gravity high over the gabbro at the southeast corner of the island. The anomaly amplitude is only about 5 to 10 mGal, and the thickness of the pluton may be approximately 0.5 mi if the gabbro has a density contrast of about 0.3 mGal. Similarly, the pluton north of Passage Canal may have a small positive anomaly of about 3 mGal, although its composition may not differ significantly from that of other granitic plutons. Certainly most of the plutons are not apparent on the gravity map.

The final rock unit on the map is the sequence of younger Tertiary formations (Stillwater through Yakataga Formations; see Nelson and others, 1985), which crop out near the southeast corner of the national forest, and which drilling has indicated reach thicknesses of nearly 10,000 ft (Plafker, 1967). The available gravity stations are too widely spaced to reveal any detectable gravity anomaly, but more detailed supplemental data obtained by industry (Atlantic Richfield Corp., written commun., 1965) show some small negative anomalies with amplitudes of less than 5 mGal centered near the elbow of the Bering River and southwest of Bering Glacier. The amplitude of these lows seems inconsistent with the expected densities and thicknesses of the sedimentary rocks. However, the aeromagnetic data suggest a broad magnetic high from a probable deep source in this area. If the sediments overlie a deeply buried and dense rock mass, such as peridotite, their expected negative anomaly could be almost totally exceeded by the positive anomaly caused by the deeper rock mass. Only detailed analysis would be able to isolate the anomalies and to analyze the result.

REFERENCES CITED

Barnes, D.F., 1966, Gravity changes during the Alaska earthquake: Journal of Geophysical Research, v. 71, no. 2, p. 451-456.

——1968, Alaska gravity base station network: U.S. Geological Survey Open-File Report, 21 p.

——1972a, Summary operational report of a preliminary gravity survey of Southeastern Alaska: U.S. Geological Survey Open-File Report, 12 p.

___1972b, Notes on the processing and presentation of U.S. Geological Survey Alaskan gravity data: U.S. Geological Survey Open-File Report, 25 p.

——1977, Bouguer gravity map of Alaska: U.S. Geological Survey: U.S. Geological Survey Geophysical Investigations Map GP-913, scale 1:2,500,000, 1 sheet.

——1984, Digital elevation models improve processing of Alaskan gravity data, In Coonrad W.L., ed., The United States Geological Survey in Alaska: Accomplishments during 1981, U.S. Geological Survey Circular 868.

Barnes, D.F., Morin, R.L., and Watts, R.D., 1978, Interpretation of the gravity and ice-thickness data, In Brew and others, Mineral resources of the Glacier Bay National Monument Wilderness Study Area, Alaska: U.S. Geological Survey Open-File Report 78-494, p. B51-B75.

Case, J.E., Barnes, D.F., Plafker, George, and Robbins, S.L., 1966, Gravity survey and regional geology of the Prince William Sound epicentral region, Alaska, U.S. Geological Survey Professional Paper 543-C, p. C1-C12.

Case, J.E., Sikora, R.F., Tysdal, R.G., Barnes, D.F., and Morin, R.L., 1979a, Geologic interpretation of the gravity anomaly map of the Seward and Blying Sound quadrangles, Alaska: U.S. Geological Survey Miscellaneous Field Studies Map MF-880-C, scale 1:250,000, 1 sheet.

Case, J.E., Tysdale, R.G., Hillhouse, J.W., and Gromme, C. S., 1979b, Geologic interpretation of the aeromagnetic map of the Seward and Blying Sound quadrangles, Alaska: U.S. Geological Survey Miscellaneous Field Studies Map MF-880-D, scale 1:250,000.

Daley, M.A., Ambos, E.L., and Fuis, G.S., 1985, Seismic refraction data collected in the Chugach Mountains and along the Glenn Highway in southern Alaska in 1984: U.S. Geological Survey Open-File Report 85-531, 32 pp., 12 plates.

Demenitskaya, R.M., and Belyaevsky, N.A., 1969, The relation between the Earth's crust, surface relief, and gravity field in the USSR, in Hart, P. J., ed., The Earth's crust and upper mantle: American Geophysical Union Geophysical Monograph 13, p. 312-319.

Hales, A.L., and Asada, Toshi, 1966, Crustal structure in coastal Alaska, in Steinhart, J.S. and Smith, Y.J., eds., The Earth beneath the continents: American Geophysical Union Geophysical Monograph 10, p. 420-432.

International Association of Geodesy, 1971, Geodetic Reference System, 1967: Paris, Bureau Central de l'Association Internationale de Geodesie, Special Publication 3, 116 p.

Lahr, J.C., 1975, Detailed seismic investigation of Pacific-North American plate interaction in southern Alaska: Columbia University, New York, Ph.D. thesis, University Microfilms International, Ann Arbor, Michigan, 141 p.

Magoon, L.B., Adkinson, W.L., and Egbert, R.M., 1976, Map showing geology, wildcat wells, Tertiary plant fossil localities, K-Ar age dates, and petroleum operations, Cook Inlet area, Alaska: U.S. Geological Survey, Miscellaneous Investigations Series Map I-1019, scale 1:250,000, 3 sheets.

Moffit, F.H., 1954, Geology of the Prince William Sound region, Alaska: U.S. Geological Survey Bulletin 989-E, p. 225-310, 1 map (scale 1:250,000).

Morelli, Carlo, Gantar, C., Honkasalo, Tauno, McConnell, R. K., Tanner, J.G., Szabo, Bela, Uotila, U.A., and Whalen, G.T., 1974, The international gravity standardization net 1971 (I.G.S.N.71): Paris, Bureau Central de l'Association Internationale de Geodesie, Special Publication 4, 194 p.

National Oceanic and Atmospheric Administration, 1964, also 1965, 1968,1972, 1976, 1981; Tide tables, west coast of North and South America: U.S. Coast and Geodetic Survey, annual publication, C 225 p.

Nelson, S.W., Dumoulin, J.A., Miller, M.L., 1985, Geologic map of the Chugach National Forest, Alaska: U.S. Geological Survey Miscellaneous Field Studies Map MF-1645-B, scale 1:250,000, 1 sheet, 15 p.

Page, R.A., Plafker, George, Fuis, G.S., Nokleberg, W.J., Ambos, E.L., Mooney, W.D., and Campbell, D.L., 1986, Accretion and subduction tectonics in the Chugach Mountains and Copper River Basin, Alaska: Initial results of the Trans-Alaska Crustal Transect: Geology, v. 14, no. 6, p. 501-505.

Plafker, George, 1967, Geologic map of the Gulf of Alaska Tertiary Province, Alaska: U.S. Geological Survey Miscellaneous Geologic Investigations Map I-484, scale 1:500,000, 1 sheet.

Rice, D.A., 1969, Gravity observations in Alaska, 1964-1965, including some repeat observations, in Leipold, L.E., and Wood, F.J., eds., The Prince William Sound, Alaska, earthquake of 1964 and aftershocks, v. 3: U.S. Department of Commerce, Environmental Science Services Administration, Coast and Geodetic Survey Publication 10-3, p. 5-20.

Shor, G.G., Sr., Menard, H.W., and Raitt, R.W., 1970, Structure of the Pacific Basin, in Maxwell, A.E., ed., The Sea, v. 4, pt. 4, New concepts of sea floor evolution: regional observations and concepts, New York, John Wiley, p. 3-28.

Tatel, M.E. and Tuve, M.E., 1956, The Earth's crust: seismic studies: Carnegie Institution of Washington Year Book, v. 55, p. 81-85.

Thiel, Edward, Bonini, W.E., Ostenso, N.A., and Woollard, G. P., 1958, Gravity measurements in Alaska: Woods Hole Oceanographic Institution Technical Reports Reference 58-54, 104 p.

Tysdal, R.G., and Case, J.E., 1979, Geologic map of the Seward and Blying Sound quadrangles, Alaska: U.S. Geological Survey Miscellaneous Investigations Series Map I-1150, scale 1:250,000, 1 sheet.

Wilson, J.M., Meador, P.J., and Fuis, G.S., 1987, Data for the 1985 seismic-refraction survey, south central Alaska: U.S. Geological Survey Open-File Report 87-440, 78 pp.

Winkler, G.R., and Plafker, George, 1981, Geologic map and cross sections of the Cordova and Middleton Island quadrangles, southern Alaska: U.S. Geological Survey Open-File Report 81-1164, 25 p., scale 1:250,000, 1 sheet.

Winkler, G.R., Silberman, M.L., Grantz, Arthur, Miller, R.J. and MacKevett, E.M., Jr., 1981, Geologic map and summary geochronology of the Valdez quadrangle, southern Alaska: U.S. Geological Survey Open-File Report 80-892-A, scale 1:250,000, 2 sheets.

Woollard, G.P., Ostenso, N.A., Thiel, Edward, and Bonini, W. E., 1960, Gravity anomalies, crustal structure and geology in Alaska: Journal of Geophysical Research, v. 65, no. 3, p. 1021-1037.

Woollard, G.P., and Strange, W.E., 1962, Gravity anomalies and the crust of the Earth in the Pacific Basin, in MacDonald, G.A., and Kuno, Hisaki, eds., The crust of the Pacific basin: American Geophysical Union Geophysical Monograph No. 6, p. 60-80.