Improving the Arctic Gravity Project grid and making a gravity anomaly map for the State of Alaska

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Incremental improvements to the Arctic Gravity Project (AGP) grid have accumulated through the steady acquisition of marine gravity anomaly data in the Arctic Ocean and other data sets. The explosion of data collected to establish the Extended Continental Shelves of the Arctic coastal states has increased the available data in and around the Arctic Ocean.

A consistent issue with the AGP grid has been a very irregular distribution of gravity anomaly data in Alaska. While parts of the state have been well-surveyed (e.g. the North Slope) much of this remote region has not. Access is difficult. Control points for gravity ties are non-existent. As a result, the anomalous field for Alaska has not been well determined.

This may be changing due to the extensive airborne survey conducted by the US National Geodetic Survey. Nearly all of continental Alaska has been flown at ~6 km elevation with a 10 km line spacing as a part of the GRAV-D project. These data have been collected by a single group, using consistent procedures and the same equipment. These data form an ideal basis for a new gravity anomaly map for the State of Alaska.

Using the new data, collected from ships and the airborne data collected through the GRAV-D project in conjunction with satellite and land data will substantially improve knowledge of the gravity field. All of the new data will be included in the updated AGP grid, which should be available in a year, updating the last release from 2008.

Keywords: Alaska, Arctic Ocean, gravity anomaly data, Arctic Gravity Project, GRAV-D, airborne gravity measurement

Introduction

Properly collected and reduced (e.g. Long & Kaufman 2013; Dehlinger 1978), gravity anomaly data track mass beneath the earth's surface, providing a means to study geologic structures at depth. Any proposed structure defines a distribution of mass. Calculating what the gravity anomalies would be if this structure were correct and comparing it to the observed gravity data test the hypothetical structure. Refinement of the proposed structure to improve the fit of the calculated anomaly to the observed anomaly makes it possible to, through successive adjustments, find a structure that best reproduces the observed anomalies.

Gravity anomaly data can be collected through a variety of techniques. Static gravimeters are used on land or other fixed surfaces (e.g. sea ice). Gyro-stabilized platforms are used on ships and airplanes. Combining measurements made using different gravimeters on different platforms at different times relies, first and foremost, on the calibration of the systems through gravity ties to known fixed points. Utilizing these diverse measurements to create a consistent representation of the anomalous gravity field requires careful post-processing and some post hoc recalibration of data. Typically, these corrections can be estimated by cross-over analysis (e.g. Wessel & Watts 1988; Chandler & Wessel 2008). Prior to the introduction of continuous GPS navigation in 1993, cross-over errors were also subject to navigational uncertainties, which influenced the anomaly estimates through the Eötvös correction for ship's motion on a rotating earth (Dehlinger 1978). Now, in most circumstances, navigation uncertainties are small (10's of meters) and cross-over errors are due entirely to gravimeter performance and effective drift corrections (Chandler & Wessel 2008).

Data collected on land and at sea share a common reference to sea level. Airborne gravity anomaly measurements rely on both horizontal and vertical positioning. To combine these data with land and marine data it is necessary both to correct for the elevation of the survey platform, which, being GPS positioned, is referenced to the WGS-84 ellipsoid (Smith 1987), a rotationally symmetric figure that approximates the Earth's shape, and to correct for the difference between the ellipsoid and the geoid, which is a defined as a level surface conforming to static sea level undisturbed by oceanographic processes.

The advantages of airborne data lie largely in the ability to consistently sample a large area using a single gravimeter and integrated navigation system (Figure 1). To be able to utilize airborne measurements with other gravity data sets and create a consistent representation of the anomalous gravity field, it is necessary to process these data to correct for defects of measurement and impose a consistent common reference frame. This paper reports on that process.

GRAV-D Airborne Gravity Surveys

The GRAV-D project was started by the National Geodetic Survey to collect a homogeneous gravity anomaly data set across the coasts of the United States and all of its territories. While there is a substantial database of point measurements on land and ship measurements along tracks at sea, the littoral zone has not been well sampled. The airborne gravity data collected during GRAV-D covers that gap, bridging between land and sea data as well as filling in other data gaps. These data will be used to determine an improved geoid for US territory, which will result in improvements to the vertical datum. For more information and data see; https://www.ngs.noaa.gov/GRAV-D/

Surveys were planned for primary lines every 10 km, linked by orthogonal cross lines every 80 km. Lines were planned to be flown at an altitude of 20,000 feet (6,096 m) and a velocity of 250 knots (~463 km/hr; Smith 2007). Local conditions have dictated (e.g.

topography) some deviations from these design parameters, resulting in blocks and lines flown at different altitudes. These lines were flown with either a Turnkey Airborne Gravity System Air III (TAGS Air III) or a Turnkey Airborne Gravity System 7 (TAGS 7; LaCoste Micro-G, 2010) on a variety of planes.

Gravity anomaly measurements vary predictably with elevation. Correcting for elevation is accomplished through the free air correction (Long & Kaufmann 2013). For most land surveys the first order correction (0.3086 mGal/m) is adequate to correct for variations in orthometric elevation across a survey. Given the substantial elevation of the GRAV-D measurements, the 2^{nd} order free-air correction is preferred (Hinze et al. 2005).

GPS position data (latitude, longitude and elevation) is collected along each flight line, providing position and elevation information necessary to reduce the raw gravity measurements. The measurement, referenced to the GRS80 ellipsoid (Macomber 1984), is referred to as a free-air disturbance to distinguish it from free air anomalies that are referenced to orthometric height. To be able to utilize these data with land and sea measurements it is necessary first to correct for the flight elevation relative to the ellipsoid and the elevation difference between the ellipsoid and the geoid. The EGM 2008 geoid (Pavlis et al. 2012) was used to estimate differences between the ellipsoid and the geoid.

Alaska Gravity Maps

The first gravity anomaly map of Alaska (Barnes 1977) utilized widely scattered measurements that had been taken in separate places at various times for diverse purposes. Some offshore areas and areas of commercial interest were relatively well sampled (e.g. the National Petroleum Reserve Alaska). Much of interior and western Alaska were not (see data source map in Barnes 1977). The GRAV-D survey samples all continental Alaska and nearby offshore areas at uniform scale with similar instruments and consistent survey parameters. A map constructed from this data will present an image of the anomalous gravity field, without distortions due to irregularly distributed measurements, poor locations or elevations or bad gravity ties.

This map will, owing to the distance between profiles and measurement elevation, both of which will attenuate and under-sample local anomalies, not be useful for resource exploration. The resulting map will be useful for crustal scale anomalies that might result from the history of terrane accretion that has built Alaska (e.g. Colpron et al. 2007 and references therein).

Construction of the free air gravity anomaly map in Figure 2 was accomplished using the GMT software package version 6.0.0 (pre-release; Wessel et al. 2013). Estimated free air anomalies were calculated for each data point from the source files for each GRAV-D block (Figure 1). A 10 minute grid spacing was chosen to preserve shorter wavelengths in the data without aliasing. This version of the map also incorporated the Canadian point land measurements (see; http://gdr.agg.nrcan.gc.ca/gdrdap/dap/search-eng.php; Figure 1). The data were pre-processed using the program block_median, which decimates the data by selecting the median measured value for each grid box. A surface was fitted (Smith & Wessel 1990) to the decimated data, contoured and plotted to produce Figure 2.

The anomalous field in Figure 2 appears continuous without obvious steps or discontinuities between survey blocks. Crossover analysis both internal to individual blocks and between blocks support the expectation that these data are consistent. Mean crossovers errors between adjacent blocks are mostly 1 mGal or less, after discounting a few “fliers.” Producing a final grid of the highest possible resolution will require correction of offsets both within blocks and between blocks (Figure 1), as well as ensuring that land and sea data sets are on a constant reference level.

The blocky structure of the field appears to correlate well with known geologic provinces of Alaska. Figure 2 shows regional faults extracted from a database of active faults in the Alaskan interior (Koehler 2013), as well as the position of the trench. The correlation between these independently mapped faults and steep gravity anomaly gradients is quite good, demonstrating that the reduced gravity data will be useful for studying the crustal structure and history of offset along these continental scale features.

Arctic Gravity Project

The Arctic Gravity Project (AGP) was started in 1998 to develop a new image of the anomalous field north of 64˚ N. Since the first release in 2001, it has been updated once (Kenyon et al. 2008). In both versions, the Arctic Ocean and Alaska were among the least consistently sampled regions. Owing to the explosion of data collected for establishing the seaward limit of national territories in the Arctic (Coakley et al. 2016) the ocean has, over the last ten years, been extensively explored. GRAV-D data fill in all of the remaining blank areas in and around Alaska and will substantially improve the next update of the AGP grid. While there will be substantial improvements in the next AGP grid, the current grid, released in 2008 (Kenyon et al. 2008) provides a useful standard for validating the GRAV-D reduction and the resultant gravity map presented in this paper.

Canadian Point Data Comparisons

The GRAV-D lines extend east across the US – Canada Border (grey lines; Figure 1). East of the border, there is a zone of overlap with Canadian land data (black crosses; Figure 1), enabling a comparison of the land and airborne data. Examination of the gridded GRAV-D data (Figure 3a) and the gridded point data (Figure 3b) reveals differences that can be explained by the elevation of the observations. The airborne data, collected along flight lines at approximately

6 km elevation, agree well in long wavelength features, but contrast in the details of the contoured grid. The point data show greater detail in the anomalous field as would be expected of measurements made at the land surface.

Direct overflight of the land points is infrequent, so grids of both data sets were compared (Figure 3). Figure 3 shows the grid to grid comparison. Figure 4 shows the results of sampling the GRAV-D grid at the location of the land stations. This comparison is accomplished with a histogram of the mis-fits and a cross plot of the independent values. On this basis, some of the land points were rejected.

Early land surveys in Alaska and Western Canada followed rivers and often did not correct for meter drift. Many of these data were collected early in the last century. These data stand out in comparison to the gridded GRAV-D data (Figure 3a), perhaps due to inaccurate location and elevation information supporting the measurement. Screening all measurements prior to 1965 improved the grid made by combining the values (Figure 3d).

Using the independently controlled land (Figure 3b) and airborne measurements (Figure 3a) made it possible to calculate a grid of differences (Figure 3c). Comparison to the scale shows that most of the calculated differences are restricted to a narrow band around zero. Larger differences are associated with substantial topography, south of 66˚ N.

The mean of the differences is -1.15 mGal (Figure 4a), indicating good agreement of level between the data sets. Figure 4b is a cross-plot of the values. For values less than zero, the cloud of points is well-clustered around the 1 to 1 line, but shows a wider spread for positive values of the anomalies.

Arctic Gravity Project Grid Comparison

The existing AGP grid (Figure 5b; Kenyon et al. 2008) also provides a basis for comparison and validation of the revised Alaska gravity anomaly grid (Figure 5a). Figure 5a shows the same 10-minute grid that was used in Figure 2. Data offshore are restricted to places the GRAV-D lines crossed the coast.

The difference grid documents change in the resolution of the gravity field due to new data. To the east, across the Canada border, the Canadian point data set is nearly identical to the data used to create the underlying grid for Figure 5a. As a result, the difference grid (Figure 5c) shows almost no change east of the limit of the GRAV-D lines (Figure 1). Again the larger differences are associated with the topography of the Brooks Range and the northern limit of the Rocky Mountains.

Figure 6a shows a histogram of the differences between the two grids. The mean difference is 1.25 mGal, indicating that the reduction of the GRAV-D data to the geoid was largely successful. The cross plot of co-registered grid values again crowds around the 1 to 1 line, while showing larger scatter at positive anomaly values. It seems, on the whole, that the GRAV-D data is more nearly comparable to the point data in Canada and the point data used in the AGP grid (Kenyon et al. 2008) across the gravity lows, with the gravity highs showing greater variation.

Final Grid

Figure 7 presents the final grid, which includes the Sandwell satellite gravity grid (version 27.1; Sandwell et al. 2013; 2014). The satellite data were used to fill in the empty parts of the grid to the west and north seen in Figures 2, 5a and 5c. Careful study of this image of the grid will reveal some suspect offsets and issues in the underlying GRAV-D data, though, on the whole, the grid interval of 10 minutes, through spatial sampling of points in each grid cell, tends to smooth these out and make them less obvious.

Further improvement of this grid will be achieved by incorporating the marine data, which is particularly dense through the Bering Strait and on the Beaufort Shelf, the point data from interior Alaska, and other airborne data such as those collected during the NASA Icebridge program (e.g. Tinto et al. 2015). While there are some discrepancies between individual GRAV-D blocks and lines (Figure 1), these are, for the most part, less than 2 mGal. Crossover adjustment of the airborne and marine data sets (Chandler & Wessel 2008) will be necessary to improve the resolution of the final map. If correctly done, it is anticipated that the updated AGP grid will have a 2 or 3 minute spacing between points.

Conclusions

Successfully creating a continuous map from diverse data sets is one of the basic problems encountered in Marine Geology and Geophysics. The next version of the AGP map will combine marine data, land data, satellite and airborne data (Figure 3). Placing these data sets on a common reference, both by means of first principle calculations (e.g. 2^{nd} order free-air correction) and by post-hoc adjustments will be necessary to make a map that can be used to effectively analyze the distribution of mass (geologic structure) and the state of isostatic compensation in and around the Arctic Ocean. The GRAV-D data in particular, by providing consistent data for continental Alaska, improves the representation of the gravity field and opens new possibilities for the analysis of the structure and history of Alaska itself.

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Figure Captions

Figure 1 - Blocks of airborne gravity data collected during various GRAV-D campaigns in Alaska from 2008 to 2018 are shown in the inset map. The block over the remainder of the Aleutians Islands will be collected in 2020. For program plans, source data and survey documentation visit https://www.ngs.noaa.gov/GRAV-D/. The larger map shows the datasets used to construct the gravity anomaly map in this paper, particularly the GRAV-D flight lines, shown in grey, and the distribution of Canadian land and sea-ice collected data, indicated by individual crosses. The offshore areas, indicated in blue, exclusive of the GRAV-D lines, were filled in with satellite gravity data (version 27.1; Sandwell et al. 2013; 2014). All data grids, maps and figures in this paper were constructed with GMT v. 6.0.0 (pre-release; Wessel et al. 2013).

Figure 2 – Comparison of 10 minute gridded GRAV-D gravity anomalies (2a) and gridded Canadian point measurements (2b) from the area east of the international boundary, where both sets of measurements overlap (Figure 1). The long wavelength features are clearly evident in both maps, which differ in the details, as might be expected when comparing data collected at ~6 km to data collected on the land and ice surface, much nearer the source. Figure 2c shows the differences between the two grids, which are largely small and clearly associated with topography, which increases dramatically to the south of the coastal plain. Gridding both the point data and the airborne data together results in Figure 2d. Here the shorter wavelength near source and airborne data mesh fairly well, but small isolated anomalies are the result of the places where the land data "bleeds through" the less densely sampled airborne tracks. Contour interval is 10.0 mGal.

Figure 3 – Comparisons of Canadian point data and GRAV-D anomaly data sampled at common points from each grid in Figures 2A and 2B. Clearly, the observations are strongly influenced by the elevation of the measurement, but the histogram (Figure 3a) of the differences demonstrate that the two data sets are consistent, indicating that the ellipsoidally referenced airborne measurements have been correctly reduced to the geoidal reference of the land data. The mean value of the differences (1.15 mGal) is distinct from the mode, which is slightly negative. This is consistent with the skew of the histogram towards higher positive difference values. Figure 2b shows a crossplot of GRAV-D values versus Canadian point values. The value pairs plot close to the 1 to 1 line, with a skew towards higher values above 50 mGal. Contour interval is 10.0 mGal.

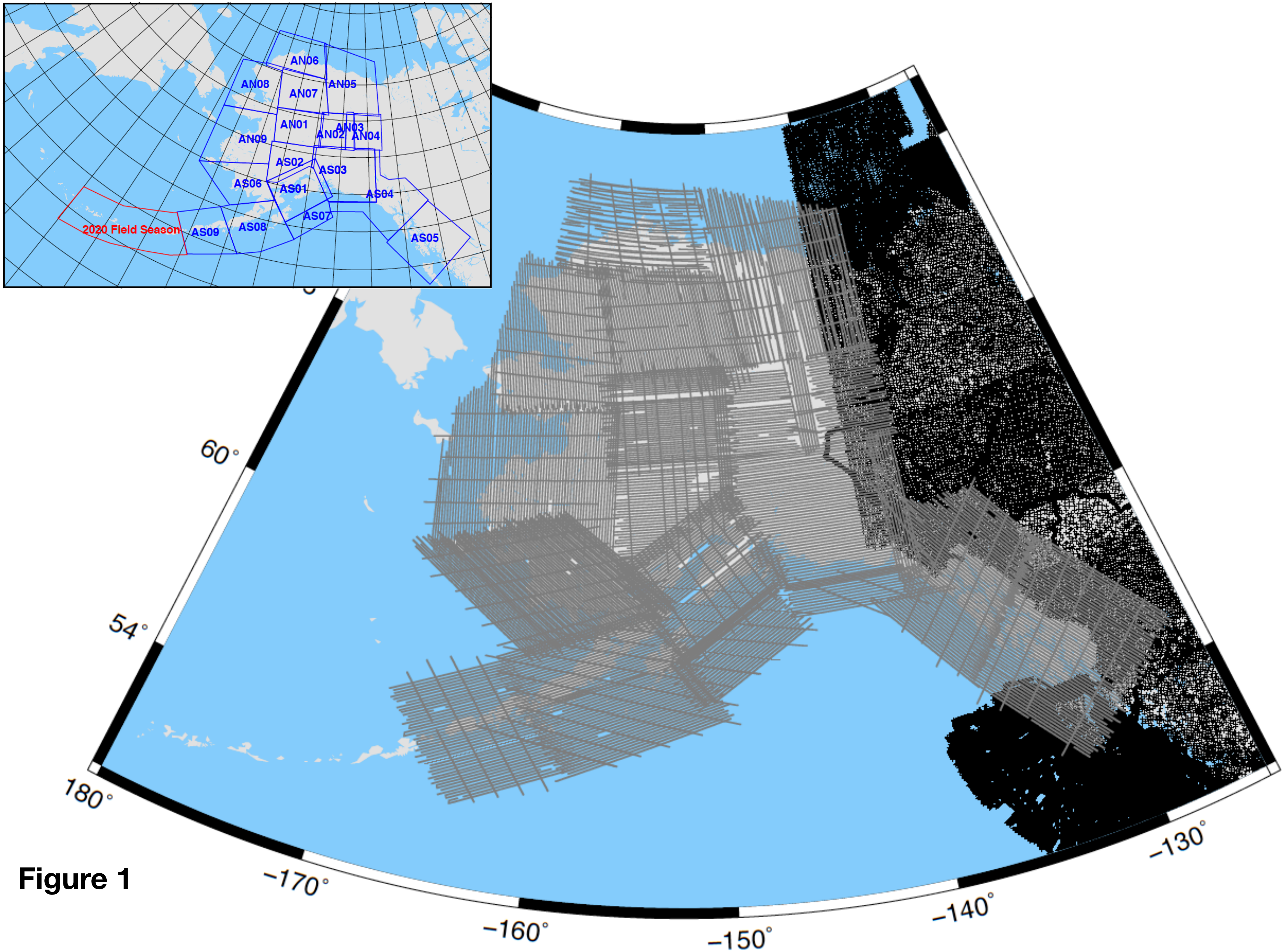
Figure 4 - Free air anomalies estimated from airborne gravity data collected during GRAV-D combined with Canadian point data east of the international boundary. Estimation of the GRAV-D anomalies requires correction from the survey altitude (~6 km) to sea level, both for the ellipsoidal elevation and for the difference between the ellipsoid and geoid reference frames. Contour interval is 10 mGal. Data show good correlation with topography and the different structural domains of Alaska. The advantage of the consistent GRAV-D dataset for crustal scale analysis is shown by plotting some of the recently active regional faults, shown in red (Koehler 2013), that subdivide the Alaskan crust. These faults are well-correlated with locally steep gravity gradients. Tracing these faults in areas of high relief is not difficult. The gravity anomaly data will make it possible to trace these faults into other regions and test models of their origin and activity.

Figure 5 – Comparison of the gridded data (Figure 5a) from Figure 4 with the coincident Arctic Gravity Project grid (Kenyon et al. 2008) for Northern Alaska and adjacent Canada (Figure 5b). The long wavelength and, presumably, more deeply sourced, anomalies are in good agreement. Areas of relatively dense land measurements and low relief are also in good agreement. Differences appear to be modest (Figure 5c) and are associated with areas of high, variable topography. Contour interval is 10.0 mGal.

Figure 6 – Comparison of differences between GRAV-D gridded values and Arctic Gravity Project gridded values. The histogram of differences (Figure 6a) is nearly symmetric, but the mean difference (1.25 mGal) is distinct from the mode, which is slightly negative, indicating the distribution is skewed to higher positive values. The crossplot of GRAV-D values against coregistered Arctic Gravity Project gridded values plot well against the 1 to 1 line (Figure 6b). The consistency of the reduced GRAV-D values, compared to Arctic Gravity Project gridded values and the Canadian point data (Figure 3) document both the quality of the original GRAV-D measurements and the efficacy of the data reduction to the geoid.

Figure 7 – Ten minute gridded reduced GRAV-D, Canadian point and satellite altimetric gravity anomaly values reveal the crustal segmentation of continental Alaska and adjacent regions of Canada and the gravity field of the Northern Pacific. While there are some grid artifacts in this map, due to uncorrected offsets between individual flight lines and blocks (Figure 1), these are mostly negligible. Future work will focus on correcting these offsets and incorporating the

marine offshore measurements collected by various research vessels transiting through the Bering Strait and working north of Alaska. Contour interval is 10.0 mGal.



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2020 Field Season
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AS08
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60°
54°
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−160°
−150°
−140°
−130°

Figure 1

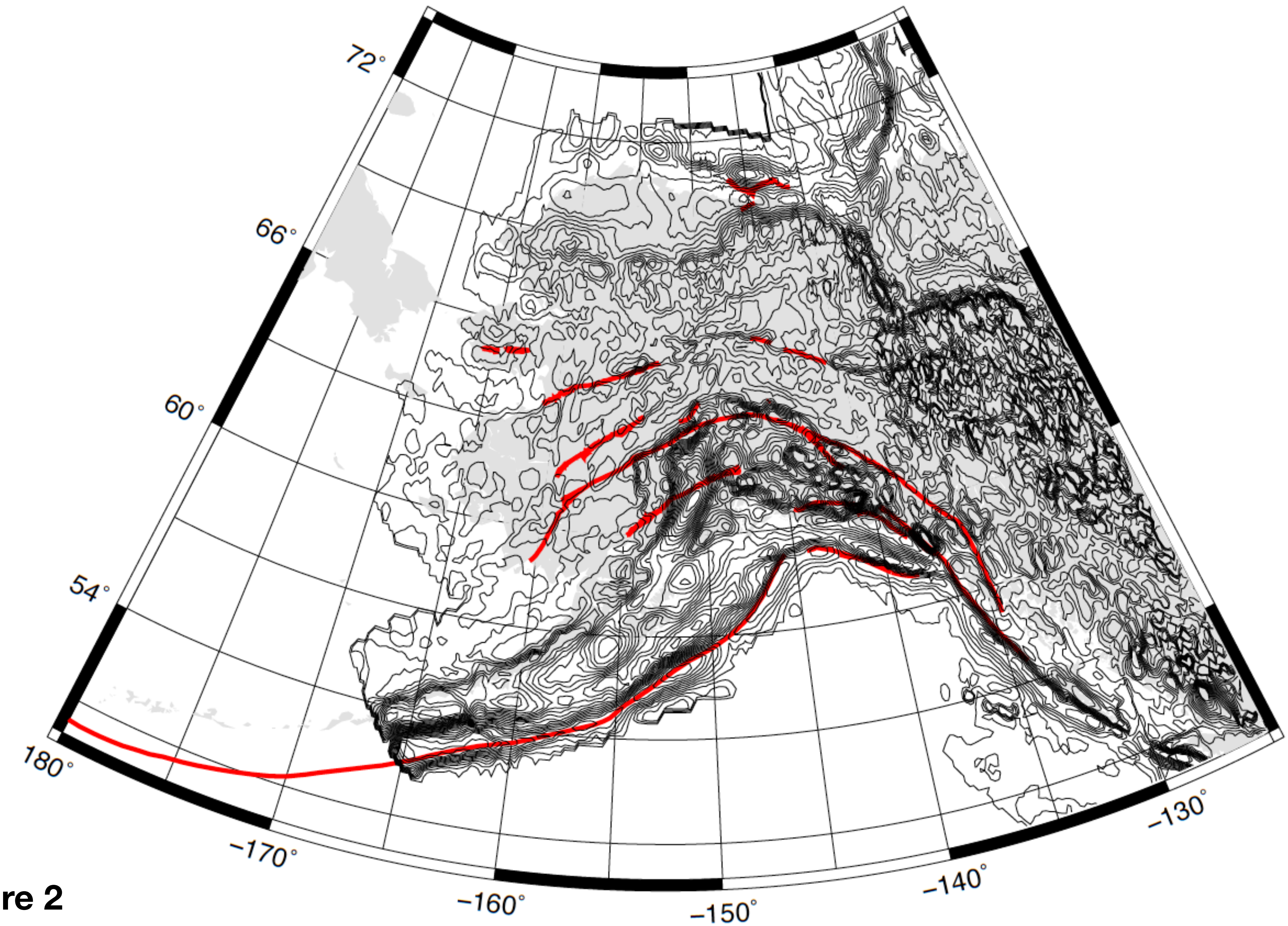
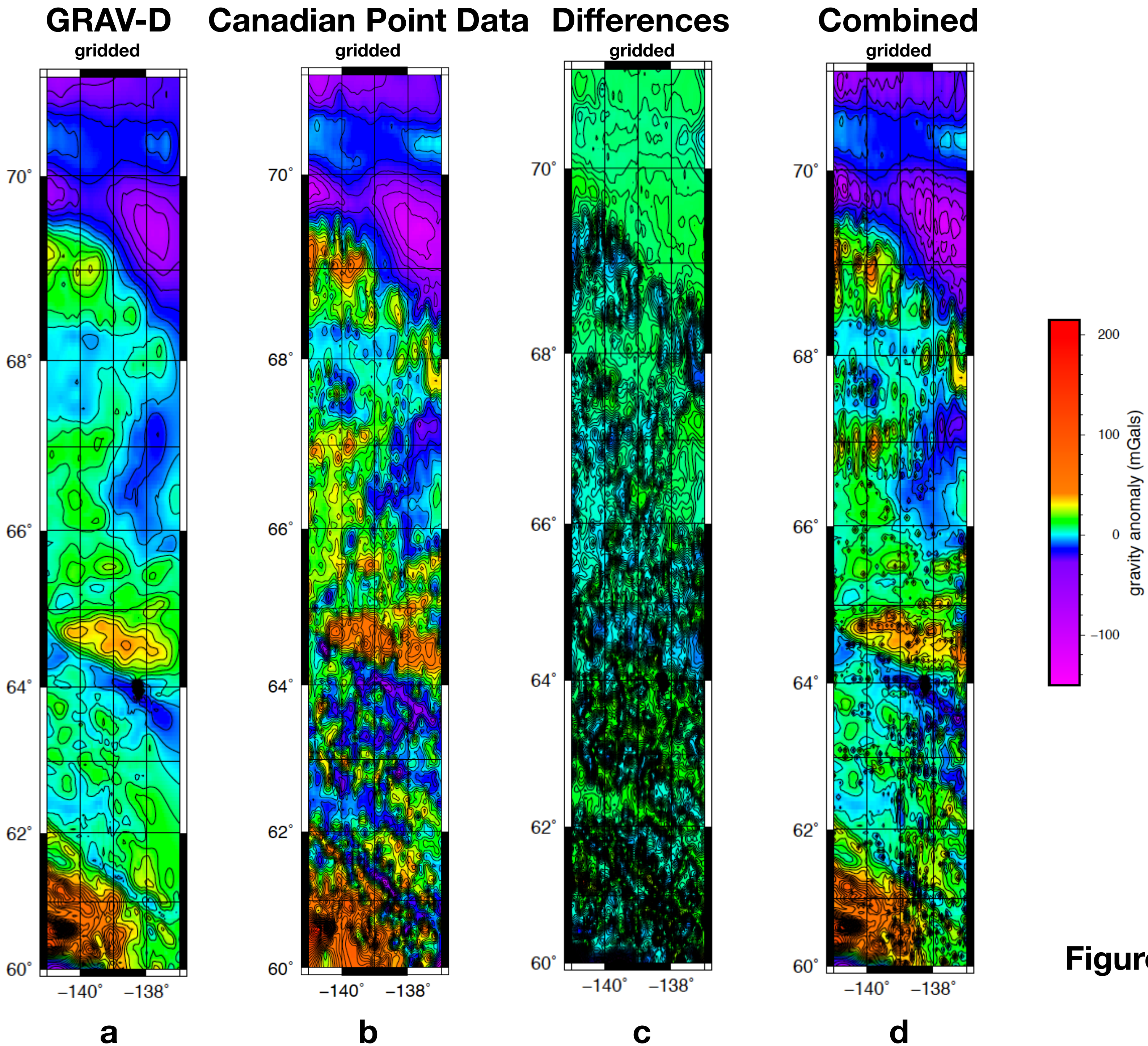


Figure 2



GRAV-D
gridded
Canadian Point Data
gridded
Differences
gridded
Combined
gridded
70°
68°
66°
64°
62°
60°
−140°
−138°
a
b
c
d
200
100
0
−100
gravity anomaly (mGals)

Figure 3

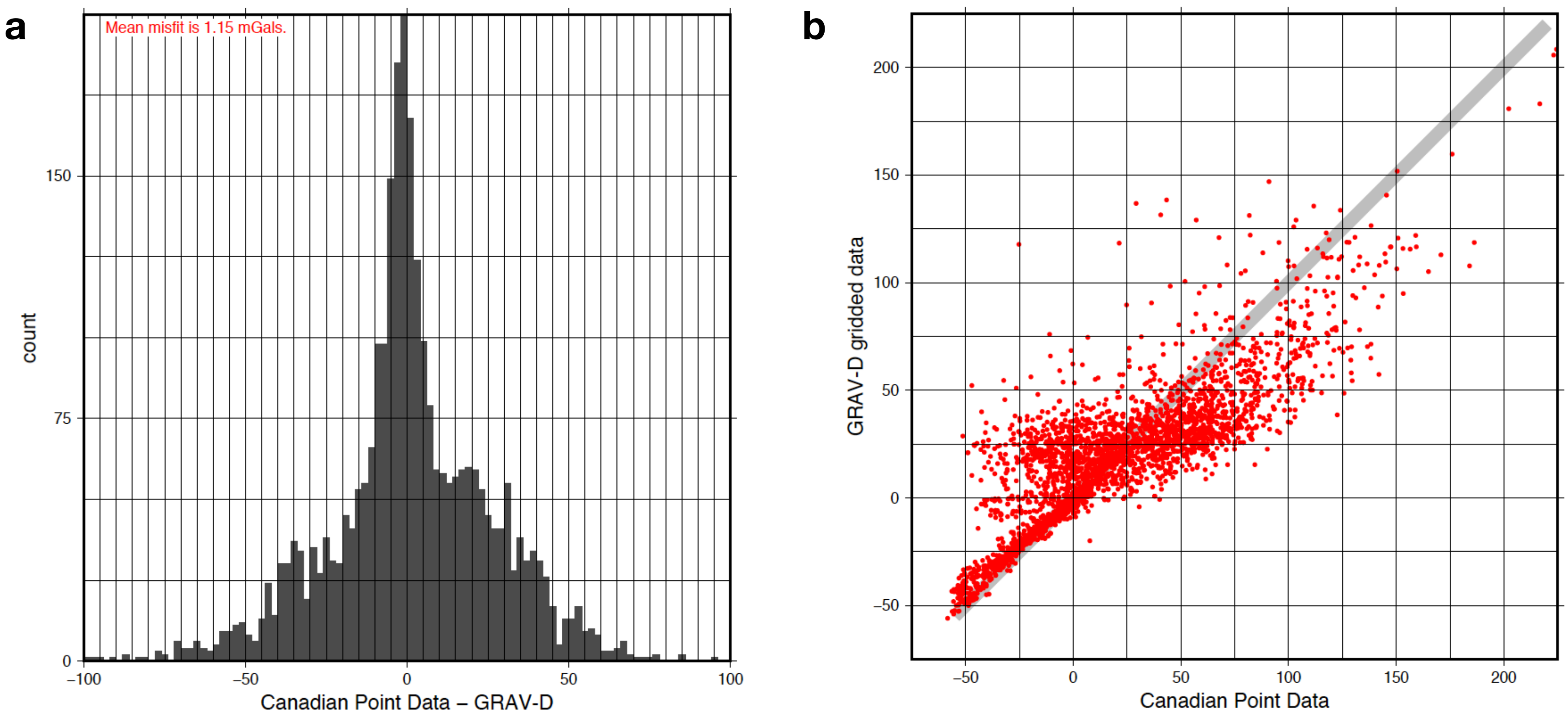

a
Mean misfit is 1.15 mGals.
count
150
75
0
−100
−50
0
50
100
Canadian Point Data – GRAV-D
b
GRAV-D gridded data
200
150
100
50
0
−50
−50
0
50
100
150
200
Canadian Point Data

Figure 4

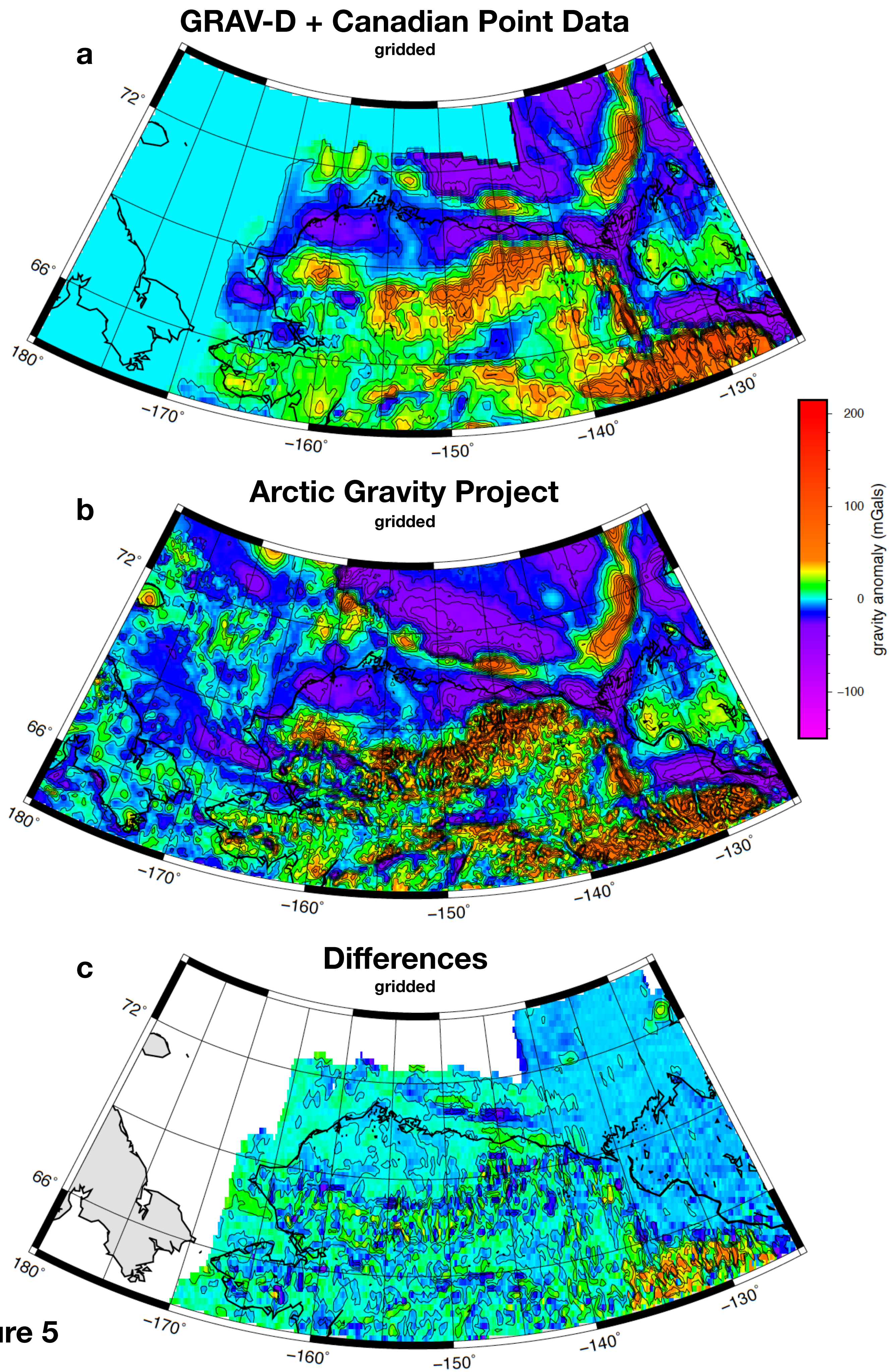

a
GRAV-D + Canadian Point Data
gridded
b
Arctic Gravity Project
gridded
c
Differences
gridded
72°
66°
180°
−170°
−160°
−150°
−140°
−130°
200
100
0
−100
gravity anomaly (mGals)

Figure 5

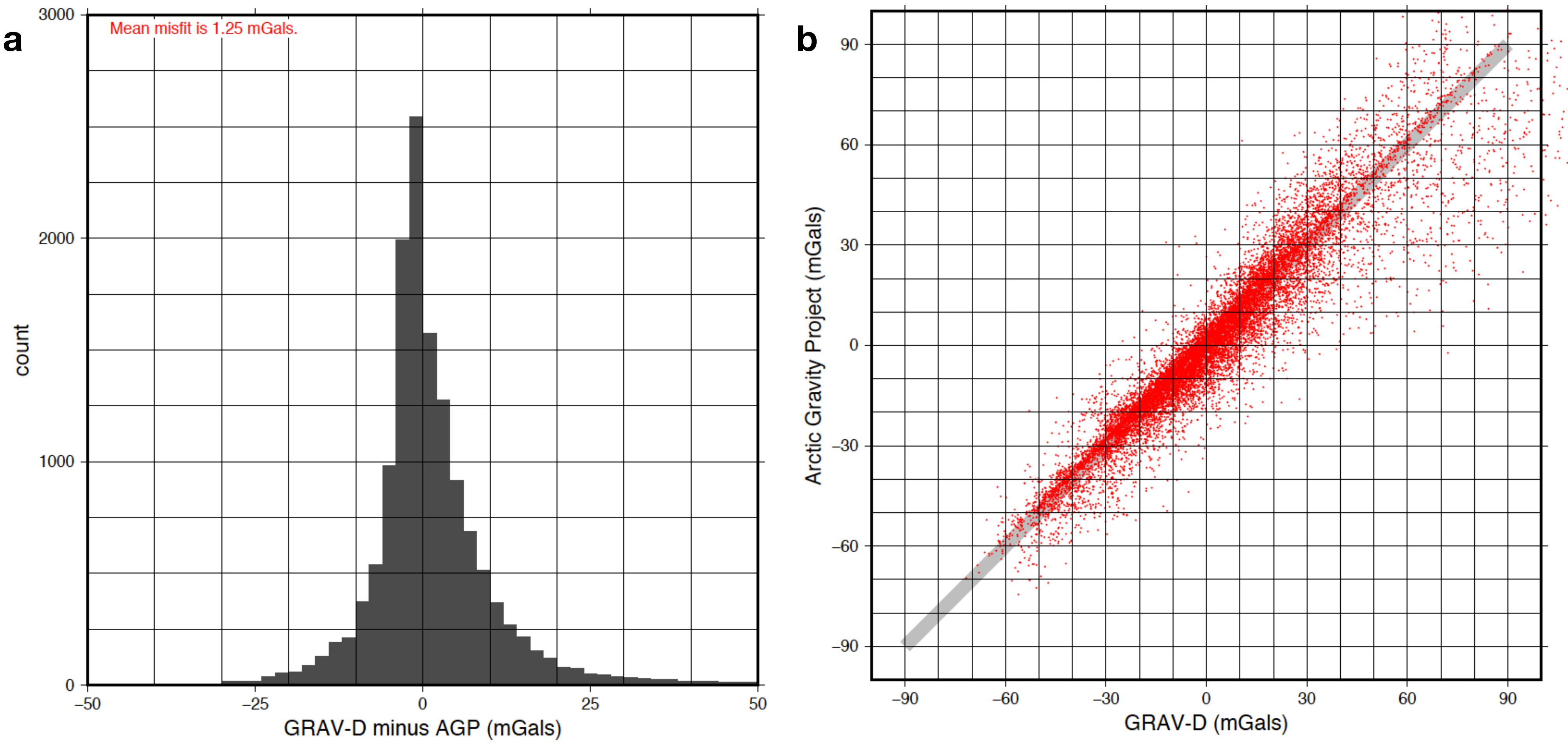

a
Mean misfit is 1.25 mGals.
count
3000
2000
1000
0
–50
–25
0
25
50
GRAV-D minus AGP (mGals)
b
Arctic Gravity Project (mGals)
90
60
30
0
–30
–60
–90
GRAV-D (mGals)

Figure 6

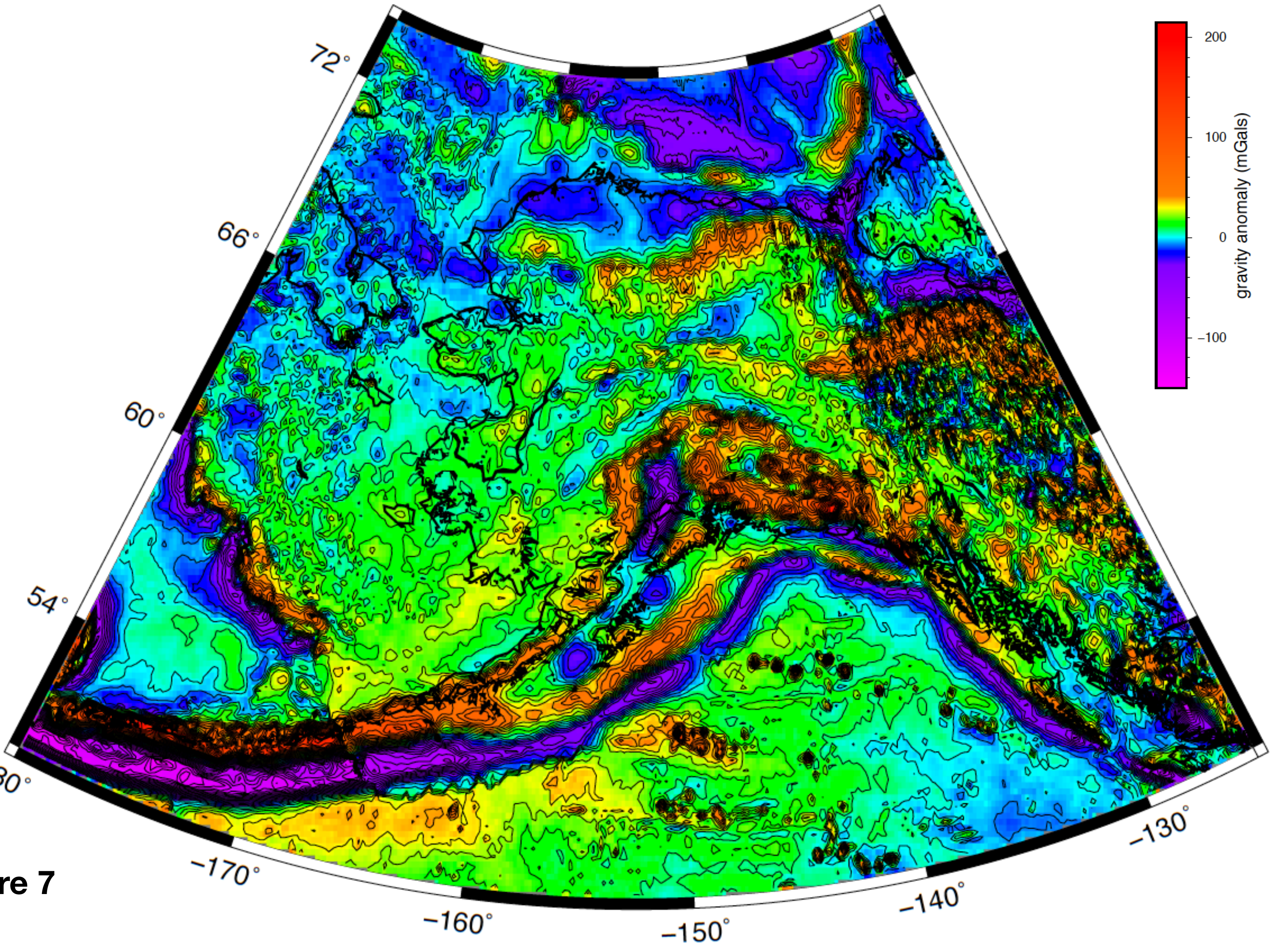

72°
66°
60°
54°
180°
−170°
−160°
−150°
−140°
−130°
200
100
0
−100
gravity anomaly (mGals)

Figure 7