NGU Report 2009.010

CIRCUM-ARCTIC MAPPING PROJECT-
GRAVITY AND MAGNETIC MAPS

NGU
Norges geologiske undersøkelse
Geological Survey of Norway

Geological Survey of Norway
N-7441 Trondheim, Norway
Tel.: 47 73 90 40 00
Telefax 47 73 92 16 20

REPORT

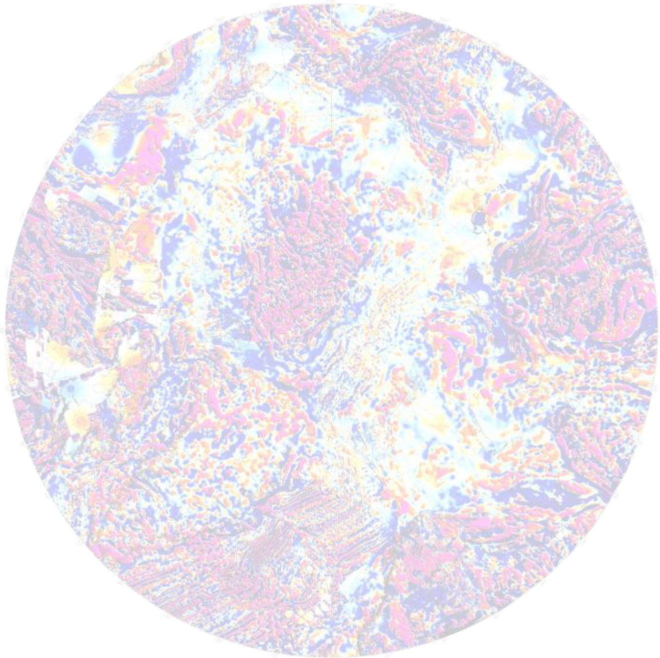
Report no.: 2009.010	ISSN 0800-3416	Grading: Public
Title: CIRCUM-ARCTIC MAPPING PROJECT-GRAVITY AND MAGNETIC MAPS (CAMP-GM)		

Authors: Gaina, C., Werner, S.C. and the CAMP-GM group	Client: NGU
County:	Commune:
Map-sheet name (M=1:250.000)	Map-sheet no. and -name (M=1:50.000)
Deposit name and grid-reference:	Number of pages: 21 Price (NOK): Map enclosures:

Fieldwork carried out:	Date of report: 01.10.09	Project no.: 318000	Person responsible: Gaina

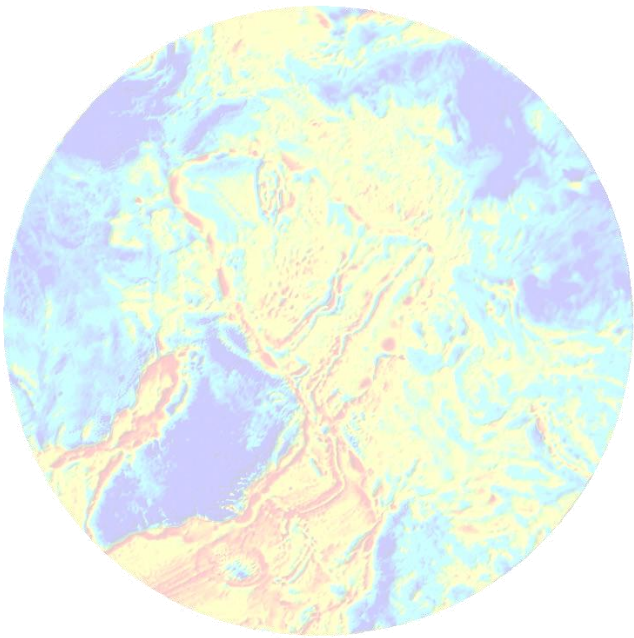
Summary:
An international effort to compile Circum-Arctic geophysical and bedrock data has been conducted by several national agencies (Russia, Sweden, Finland, Denmark, USA, Canada, Germany and Norway). This project produced an atlas that comprise geological and geophysical digital maps at a scale of 1: 5 million for the Arctic region limited by the 60 degree North latitude.
New published and classified magnetic and gravity anomaly gridded data from each participant group were gathered and converted to a common datum and format. The magnetic anomaly compilation relies on 1 km gridded data for Canada (based on the Canadian Aeromagnetic Data Base), Alaska (based on Alaska USGS aeromagnetic database) and NW Europe (Fennoscandia compilation and the NGU NE Atlantic compilation) regions, and 5 km gridded data for oceanic and Russian regions. The grids have been merged using Hemant et al (2007) methodology and the GEOSOFT routines. The final grid resolution of this compilation is 2x2 km upward continued to 1 km.
The gravity anomaly compilation includes one map of the Free Air gravity anomaly for the Circum-Arctic region and one map of combined Free Air ***(for oceanic area)*** and Bouguer ***(for land)***, both at 10x10 km grid resolution. Satellite gravity models are used for quality control on the long wavelengths of the new compilation.

Keywords: Geophysics	Gravity/Magnetics	Arctic



CIRCUM-ARCTIC GEOPHYSICAL MAPS 2009

Carmen Gaina, Stephanie C. Werner, and the CAMP-GM group (S. Aaro (SGU), D. Damaske (BGR), R. Forsberg (DNSC), V. Glebovsky (VNIIO), K. Johnson (USGS), J. Jonberger (SGU), T. Koren (VSEGEI), J. Korhonen (GTK), T. Litvinova (VSEGEI), S. Maus (NGDC), G. Oakey, (NRCan), O. Olesen (NGU), O. Petrov (VSEGEI), M. Pilkington (NRCan), T.Rasmussen (GEUS), R. Saltus (USGS), B. Schreckenberger (BGR), and M. Smelror (NGU).



CONTENTS

1. INTRODUCTION

2. CAMPGM-M MAGNETIC ANOMALY MAP

2.1.1. Preliminary formatting and processing
2.2. MAGNETIC ANOMALY MAP
2.2.1. COMPILATION OF INDIVIDUAL GRIDS
2.2.2. SATELLITE DATA/MODEL
2.2.3. FINAL MAP

3. CAMPGM-G GRAVITY ANOMALY MAP

3.1.1. Preliminary formatting and processing
3.2. GRAVITY ANOMALY MAPS
3.2.1. SATELLITE DATA/MODEL
3.2.2. GRAVITY MAP - FREE AIR
3.2.3. GRAVITY MAP – BOUGUER
3.3. FINAL MAP – BOUGUER/FREE AIR GRAVITY ANOMALY

REFERENCES

APPENDICES (DVD attached**)**

A. Conference presentations –abstract and posters/talks
B. Magnetic anomaly data – Original Data Distribution/Quality and Magnetic profiles through overlapping areas
C. Gravity and Magnetic maps in digital format
D. Geosoft/ASCII format of magnetic and gravity compilations

1. INTRODUCTION

An international effort to compile Circum-Arctic geophysical and bedrock data has been conducted by several national agencies (Russia-VSEGEI and VNIIO, Sweden-SGU, Finland-GTK, Denmark-GEUS, USA-USGS, Canada-GSC and Norway-NGU) since 2005. This project aimed to produce an atlas with geological and geophysical digital maps at a scale of 1: 5 million for the Arctic region bounded by the 60 degrees northern latitude. Here we present the new Circum Arctic Magnetic Anomaly (2 km gridded data, upward continued 1 km) and the Circum Arctic Gravity Anomaly (Free Air and Bouguer corrected, 10 km gridded data) compilations.

2. CAMPGM-M MAGNETIC ANOMALY MAP

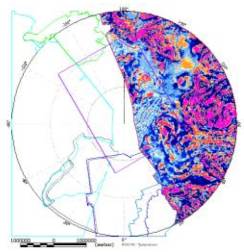
2.1. MAGNETIC ANOMALY DATA

New published and classified magnetic anomaly gridded data from each participant group were gathered and converted to a common datum (WGS84) and format (see Table 1 for a detailed description of original data format and next section for data extent and location of various contributions). The Greenland region magnetic anomaly grid (Verhoef *et al.*, 1996) has been updated with new aeromagnetic surveys performed in West Greenland between 1992-2001 (Rasmussen, 2002), and in the Nares Strait area (Damaske & Oakey, 2006; Oakey & Damaske, 2006). The oceanic area east of Greenland (NE Atlantic) contains most of the aeromagnetic data used in the Verhoef *et al.*, (1996)'s compilation (pre-1990) plus new aeromagnetic surveys over offshore Norway collected up to 2007 (Olesen *et al.*, 1997; Olesen *et al.*, 2007; Gernigon *et al.*, 2008).

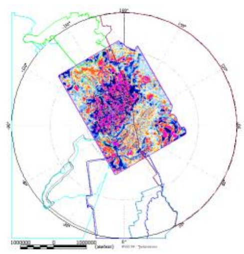
2.1.1. Preliminary Formatting and Processing

The data sets were provided following national standards. The gridded data has been re-projected to Polar Stereographic projection (datum: WGS 84). The original projection details are listed here:

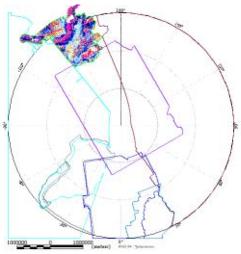
Russia-VSEGEI
Projection - Equidistant Conic
Datum - Pulkovo 1942
Ellipsoid - Krassowsky 1940
Grid-cell size 5 km, upward continued 5 km



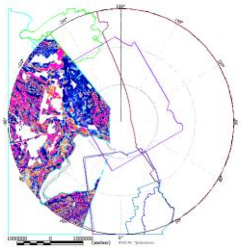
Russia-VNIIO
Projection – Polar Stereographic
Datum – WGS 84
Ellipsoid – WGS 84
Grid-cell size 5 km



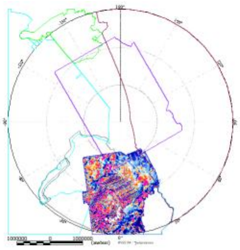
USA (Alaska) – USGS
Projection – Lambert Conic Conformal
Datum – NAD 83
Ellipsoid – GRS 1980
Grid-cell size 1 km



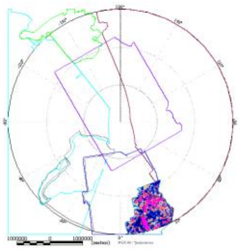
Canada – GSC
Projection – Lambert Conic Conformal
Datum – NAD 83
Ellipsoid – GRS 1980
Grid-cell size 1 km



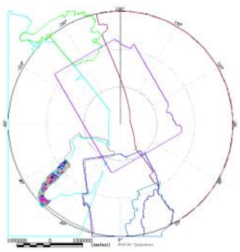
NE Atlantic/Norway – NGU
Projection – UTM 33N
Datum – ED50
Ellipsoid – International 1924
Grid-cell size 1 km



Fennoscandia – GTK/NGU/SGU
Projection – UTM 21E
Datum – WGS 84
Ellipsoid – WGS 84
Grid-cell size 1 km



West Greenland – GEUS
Projection – Geographic
Datum – WGS 84
Ellipsoid – WGS 84
Grid-cell size 3 mins



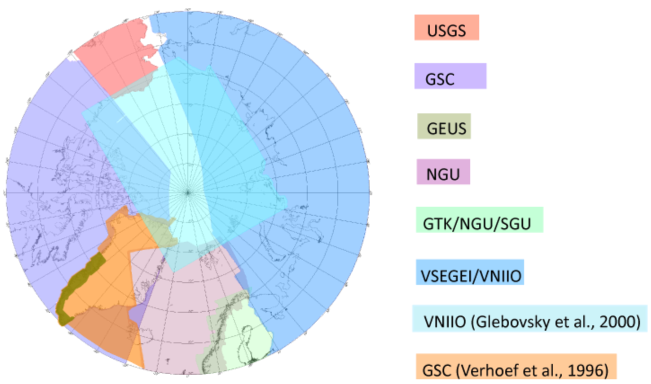


Fig. 2. CAMPGM-Gridded magnetic anomaly data sources.

Table 1. Original format of magnetic data sets

	ORIGINAL GRIDDED DATASET/AUTHOR	Grid cell	Upward continued	Projection	Datum	Ellipsoid	Ground clearance
NEATL	NE ATLANTIC (NGU) *O. Olesen*	2 km	1 km	UTM 33N	ED50	International 1924	Mainly 300
FENNOSC	FENNOSCANDIA (compiled by GTK, includes gridded data from NGU, SGU and GTK) *J. Korhonen*	1 km	1 km	UTM 21E	WGS84	WGS84	30-600
VSEGEI	RUSSIA and RUSSIAN continental shelf (VSEGEI and VNIIO) *T. Litvinova and V. Glebovsky*	5 km	5 km	Equidistant Conic	Pulkovo 1942	Krassovsky 1940	500
AKM07	ALASKA (USGS) *R. Saltus*	1 km		Albers Equal Area Conic	NAD27	Clarke 1866	305
CAN	CANADA (GSC) *M. Pilkington*	1 km		Lambert Conic Conformal	NAD83	GRS 1980	305
NAR	Nares Strait (GSC) *G. Oakey*	1 km		Geographic	WGS84	WGS84	305
NGRN	North Greenland (BGR) *D. Damaske*	1 km		Geographic	WGS84	WGS84	2000 ?
VNIIO	ARCTIC OCEAN (VNIIO) *V. Glebovsky*	5 km		Polar Stereographic	WGS84	WGS84	300-800
WGRN	WEST GREENLAND (GEUS) *T.M. Rasmussen*	3 min	5 km	Geographic	WGS84	WGS84	5000
GAMMA 5	GAMMA 5 *Verhoef et al.*	5 km		Geographic	WGS84	WGS84	

Table 2. Statistical parameters for original gridded data

	STDEV	Min	Max	Median	Mean
AKM07	185.7	-21890	14950	-26.3	-2.3
CAN	234.59	-4376	18931	-20.56	15.4
VSEGEI	208.9	-598.96	6931.16	-38.88	-7.2

NEATL	143.33	-1273.68	2053.56	-24.3	-6.6
FENNOSC	247.03	-2858.6	4956.76	-42.14	5.41
VNIIO	132.8	-1008	1516	-11.63	2.26
GAMMA 5 (GRN)	176.36	-1576.3	1807.71	-11.61	1.96

Grid merging order:
Step 1: Extract Greenland polygon from GAMMA 5 grid and use it as a base for adding NGRN and NAR smaller grids
Step 2: Merge the main grids at 1 km altitude after trimming to reduce large overalps: AKM07, VNIIO, CAN, newGRN, NEATL, FENNOSC, VSEGEI

2.2. MAGNETIC ANOMALY MAP

2.2.1 COMPILATION OF INDIVIDUAL GRIDS

The gridded data has been upward continued to 1 km above ground or sea-level and trimmed around the areas of major overlaps (note: a serious mismatch has been observed between the GSC grid (Canada) and the VNIIO grid (Arctic oceanic area) and a less serious mismatch between the VNIIO and VSEGEI (Russian continental area and continental shelf) grids. Profiles extracted from this area and grid differences are presented in the Annex). The Alaska USGS aeromagnetic compilation has been used as the "master grid" for merging the major gridded data sets together (see Table 2 for a detailed merging order) and the downward continued lithospheric magnetic field model MF6 derived from satellite data (Maus *et al.*, 2008) has been used as a regional reference surface. We have used a blending function over the area of overlap in order to smooth the transition from one grid to the other (GridKnit, GEOSOFT). The resulting grid has been re-sampled to a 2 km grid cell.

2.2.2. SATELLITE DATA/MODEL

For the CAMPGM-M grid compilation we have used the downward continued lithospheric magnetic field model MF6 derived from satellite data (Maus *et al.*, 2008) as a regional reference surface during the merging process, to substitute the long (> 400 km) wavelength data and to fill in the areas missing ground/airborne data.
Previous efforts to compile regional or global gridded data sets have shown that the long wavelength of compiled grids are not accurately represented, and therefore chose to substitute them with the satellite derived models (eg. Hemant et al., 2007; Maus et al, 2007, Maus et al., 2009). For this purpose, we have used the latest magnetic field model MF6 (Maus et al., 2008). MF6 is a lithospheric magnetic field model built on the 2004-2007 CHAMP data (Figure 3). Preliminary CAMPGM-M compilation used the MF4 and MF5 models, but the availability of the latest, higher resolution satellite derived model, MF6, prompted us to use it for the final magnetic anomaly map. Note that apart from a different set of data, MF6 is also based on a slightly different processing techniques than the previous models MF models. MF6 was built to spherical harmonic degrees 120 that can resolve features with a wavelength of 333 km and larger. Although the CHAMP data has been found to be sensitive to crustal field variations up to degree 150 (equivalent to 266 km wavelength), a clean separation of the lithospheric signal from ionospheric and magnetospheric noise sources was possible only to degree 120.

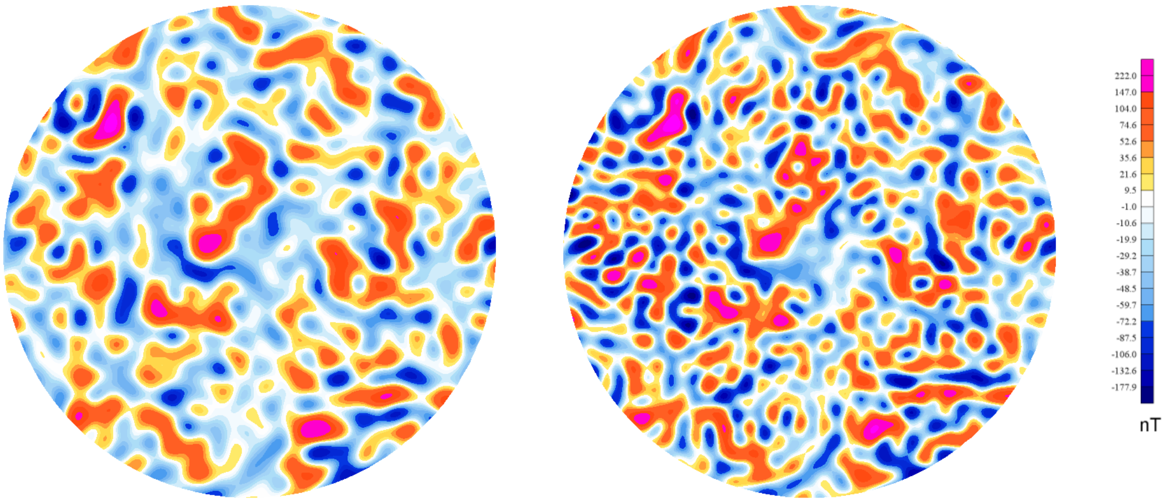


Fig 3. MF6 lithospheric magnetic field model derived from satellite data (Maus *et al.*, 2008), left: to spherical harmonic degree 100 (corresponding to 400 km wavelength), and right: to spherical harmonic degree 120 (corresponding to 333 km wavelength).

2.2.3. FINAL MAP

In order to construct the final Circum-Arctic magnetic anomaly grid (CAMP-M) we have adopted the approach used by several research groups for compiling the World Digital Magnetic Anomaly Map (WDMAM) and used near-surface magnetic data for the short wavelength component of the compilation and the satellite derived magnetic anomalies for the long wavelength (Hemant *et al.*, 2007; Maus *et al.*, 2007). MF6 extends to spherical harmonics degree 120 (333 km wavelength) and therefore it is able to provide consistent long wavelength information between 300 and 400 km. This information is mainly related to regional deeper and/or thicker portions of the magnetic sources within the crust.
We have prepared two versions for the CAMP-M magnetic anomaly grid. The first one combines short wavelength components of regional grids (less than 400 km) with long wavelengths (400 km, Figure 4) of the MF6 model (Figure 3). The second one combines short wavelengths of regional datasets (obtained by filtering with a cosine squared taper to remove the wavelengths in the waveband between 307 and 333 km and larger, with the MF6 model (to degree 120, Figure 4). Our preferred model is Model 1.

Fig.4 . Two models of magnetic anomaly of the Circum-Arctic area: Model 1 combines short wavelength (less than 400 km) of the regional compilation (a) with long wavelengths (400 km) of the MF6 satellite model (b). Model 2 combines short wavelengths (less than 300-330 km) of the regional compilation (a) with long wavelengths (330 km) of the MF6 satellite model (b).

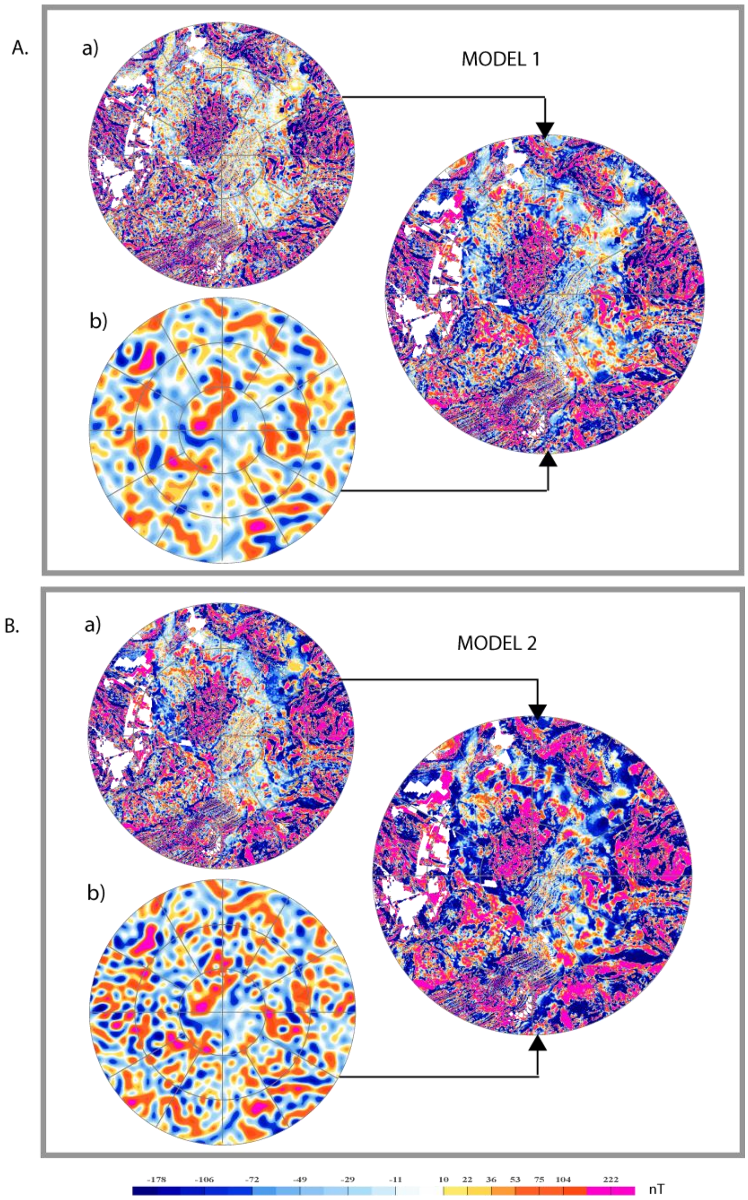
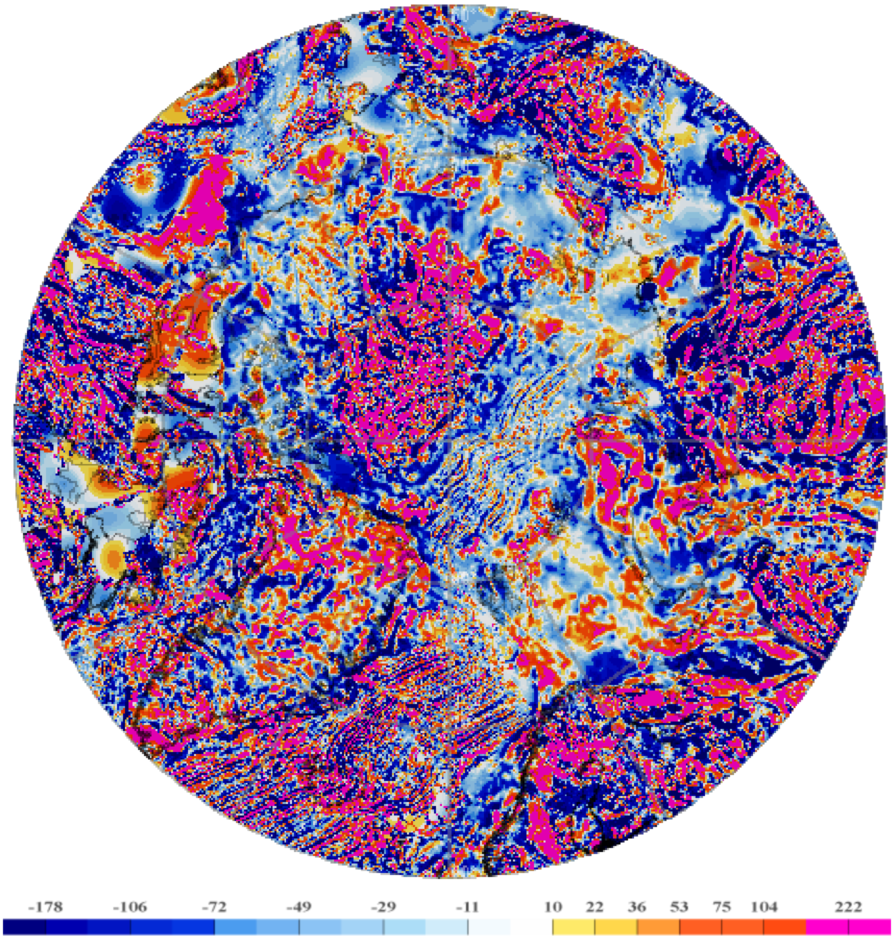
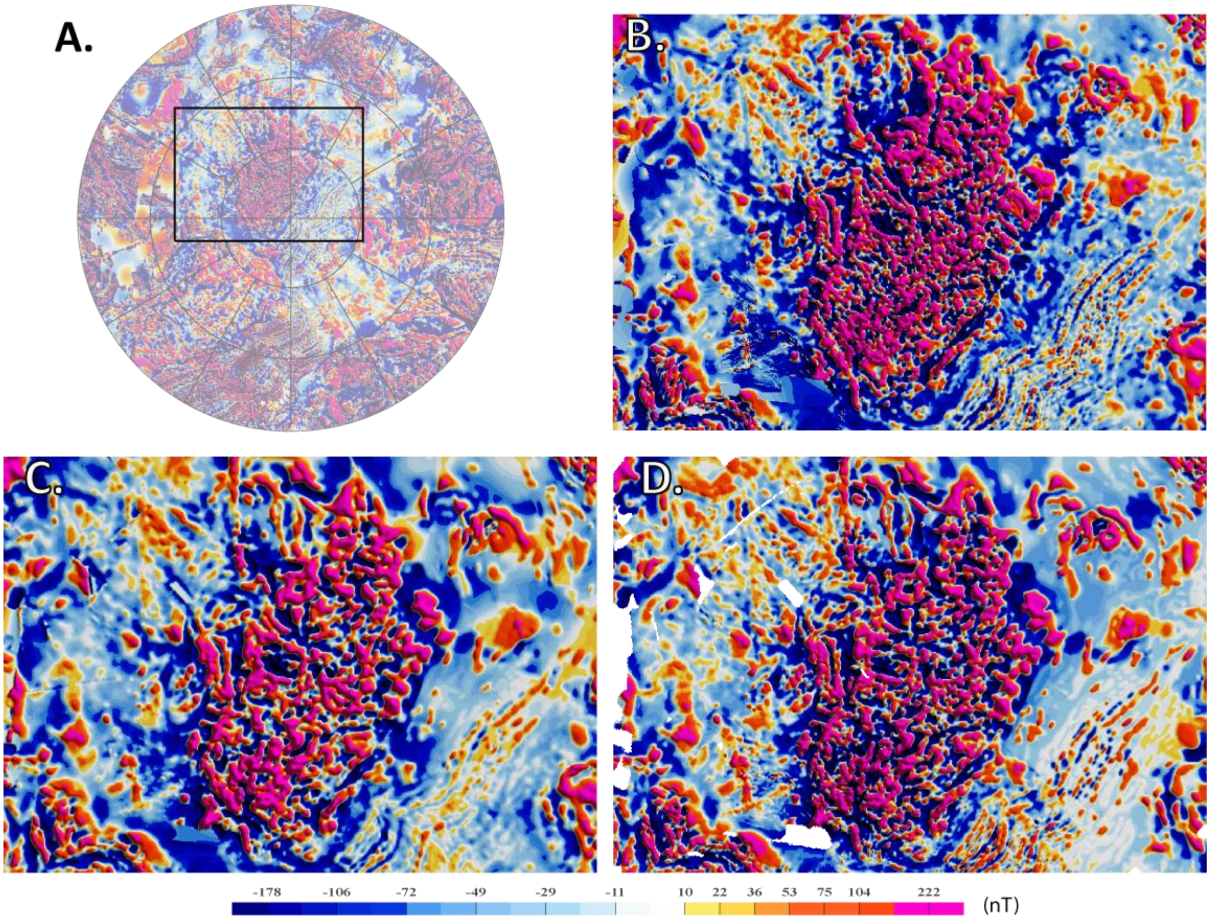


Fig 5. CAMPGM-M magnetic anomaly compilation of gridded data (to 60 deg N) based on ground/airborne regional compilations and global model of lithospheric field based on satellite data (MF6).



The new CAMP-M compilation is superior to similar gridded data over the Circum-Arctic area due to its better coverage (includes updated aeromagnetic data in the High Arctic, west and north of Greenland and in the NE Atlantic), preserves smaller wavelength structures by keeping the grid resolution at 2 km, and has a consistent regional long wavelength component introduced by the MF6 satellite based lithospheric magnetic model. Figure 6 shows a comparison between magnetic anomaly compilations (CAMP-M, WDMAM and GAMMA 5) in the Circum-Arctic region.

Fig 6. Comparison of a selected region of the new CAMP-M magnetic anomaly grid (location shown by rectangle in A., zoom in selected location: B) with previous compilations (C. WDMAM and D. GAMMAA 5).



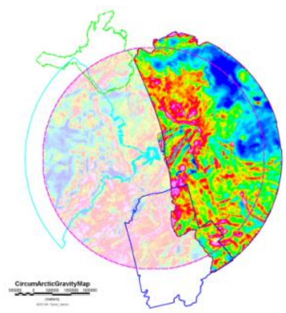
3. CAMPGM-G GRAVITY ANOMALY MAP

The goal was to provide digital maps of free air (FA) and Bouguer (BA) gravity anomalies and a combination of free air gravity offshore and Bouguer gravity anomalies onshore, while the printed version shall show a combination of BA onshore and FA offshore, as well as a FA map which includes an insert map showing bathymetric and topographic information. The digital gridded data will be presented in a grid-cell size of 10 km by 10 km – same grid cell size FA from Fennoscandia, and in polar-stereographic projection as used for the IBCAO bathymetry. The deadline for delivery of the gridded gravity anomaly data was end of March 2007.

3.1.1. Preliminary formatting and processing

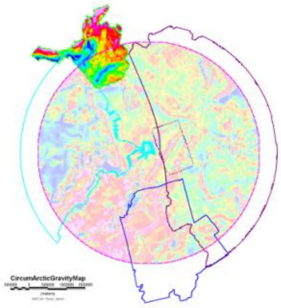
The data sets were provided following national standards. The outline and projection details are listed here:

Russia
Projection - Equidistant Conic

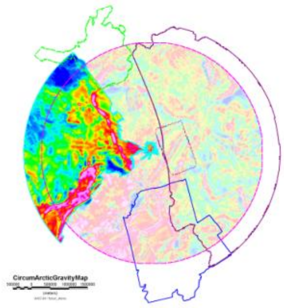


Datum - Pulkovo 1942
Ellipsoid - Krassowsky 1940
Grid-cell size 10 km

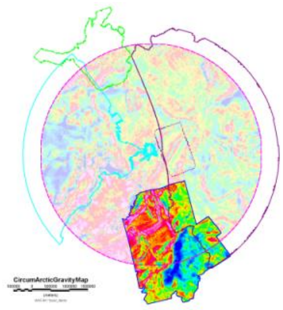
Alaska
Projection Lambert Conic Conformal
Datum NAD83
Ellipsoid GRS 1980
Grid-cell size 5 km



Canada
Projection Lambert Conic Conformal
Datum NAD83
Ellipsoid GRS 1980
Grid-cell size 5 km



Fennoscandia
(N-Atlantic, Norway, Sweden, Finland, European Russia)
Projection Transverse Mercator, UTM 33N
Datum ED50
Ellipsoid International 1924
Grid-cell size 2 km



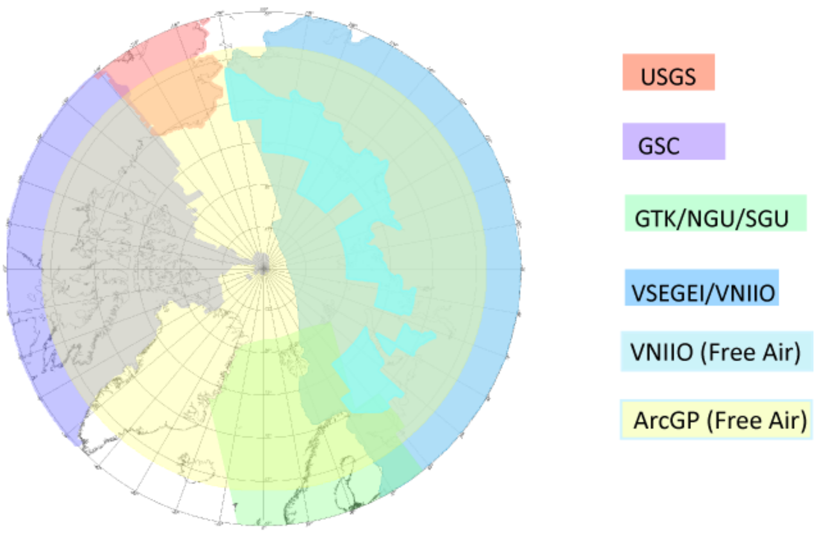


Fig. 7. CAMPGM-Gridded gravity anomaly data sources.

The data provided from the Russian side needed update for the oceanic areas, because a mismatch of the gravity data when compared to magnetic and bathymetric data was observed, and higher resolution data became available from newly digitised maps marked in yellow on Fig. 7. Therefore, the latest version of existing ArcGP project map was used to proceed with the correction, which included several steps:

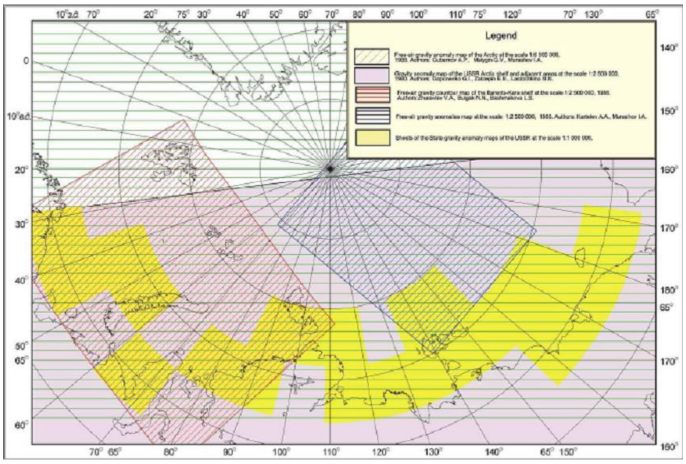


Fig. 8. Available gravity anomaly maps for the Russian territory. Areas shown in yellow are in a map scale 1:100 000, others in 1: 2500 000.

1. The area in question was cut from the existing ArcGP grid (which includes the same data as used in the project on which is reported here) in the limits of the area to be corrected.
2. The substitute grid was shifted to best fit with magnetic and bathymetry grids and merged with the remainder of the ArcGP grid.
3. The gaps between original and modified grid outline were filled by interpolation between the data, to minimize artefacts at the edges of the Russian and ArcGP merged grids, but having corrected the Russian part.
4. At the northern edges of the Russian free air gravity maps at scale 1:1000000, the data positioning is more reliable (free of noise) than satellite data. To the north of these maps the joint VSEGEI/VNIIO grid is based on small scale maps with initial data of poor navigation (pink colour; near the pole), therefore the data of the joint VSEGEI/VNIIO grid to the north of 1:1000000 maps were substituted partly with the ArcGP grid which uses altimeter data and submarine measurements. The final Russian grid is shown in Fig. 8.

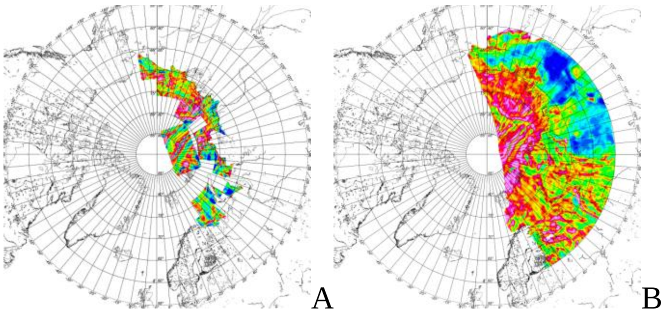


Fig. 9. Map A shows separately the substituted compilation parts, and map B the final Russian grid.

All grids as delivered were merged and areas lacking information were filled with data from the ArcGP project. Information for Greenland was treated separately as discussed below. Fig. 9 shows the merged data sets.

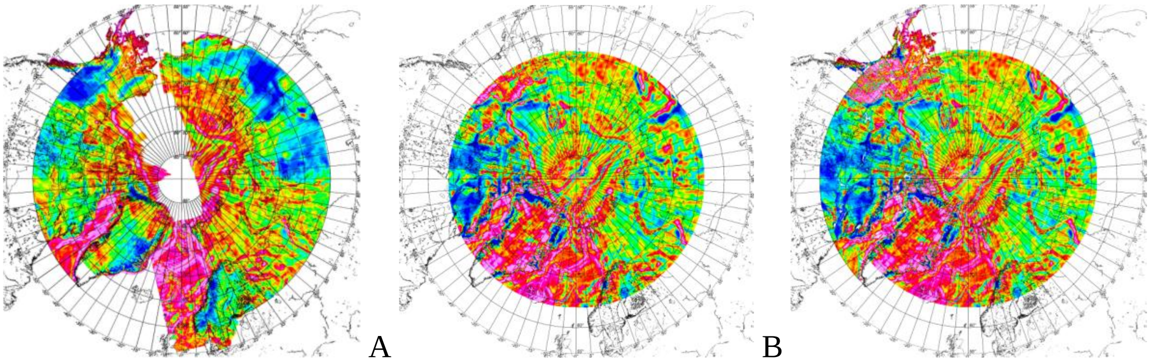


Fig. 10. A) represents the input grid database, B) represents data from the ArcGP and C) is the merged version.

3.2. GRAVITY ANOMALY MAPS

The final product was supposed to include one map of the Free Air gravity anomaly for the Circum-Arctic region and one map of combined Free Air (for oceanic area) and Bouguer (for land) in a 1: 5000000 scale, both at 10x10 km grid resolution. These maps are supplemented by maps of topography/bathymetry (open source data, since the Russian topography data cannot be released). Since René Forsberg and collaborators planned to release a new free air gravity anomaly gridded data set, this product was not the main task of the CAMP-GM group anymore. A new grid of the Free Air gravity anomaly was produced under the lead of René Forsberg (DNSC), within the ArcGP (Kenyon and Forsberg, 2008). Vladimir Glebovsky (VNIIO) contributed the improved gridded data of some parts of the Arctic Ocean (see data description above). Satellite models were used for checking the final grids.

3.2.1. SATELLITE DATA/MODEL

Global high-resolution gravity field models commonly are described by spherical harmonic coefficients from which gridded descriptions can be derived. For comparison and crosschecking of the merged grids here, a model produced at GFZ Potsdam is used (EIGEN GL04C; *Förste et al. 2008*). Such models are derived from a combination of satellite and surface gravity data. The model used here was released in March 2006 and is given in a resolution of order and degree 360. The input data from satellites includes GRACE and LAGEOS orbital information, which allows for a pure satellite data model up to degree 70, while the overlapping range between satellite and terrestrial data is between degree 70 and

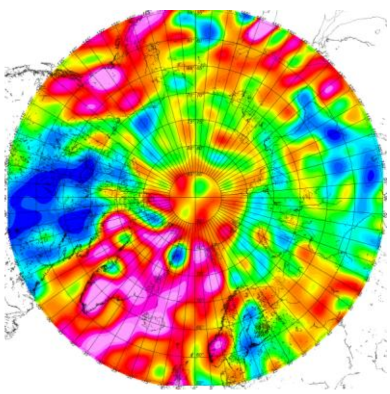


Fig. 11. Image of the EIGEN GL04C gravity model at a grid cell resolution of 0.5 degree.

150, and above degree 150 the model describes purely terrestrial data.

Fig. 11 shows an image of the model, calculated with a grid resolution of 0.5 degree, ranging from 55 to 90 N. Compared to earlier standard gravity models such as EGM96 these models are corrected for the long wavelength content by satellite data and considerably improved. New global models are available meanwhile, which are corrected for the long-wavelength content (EGM2008), at a nominal spatial resolution of 0.0167 degree (roughly 2 km).

3.2.2. GRAVITY MAP - FREE AIR

The original plan for this project was to present a newly compiled free air gravity anomaly map, but not all contributing organisations were permitted to deliver free air gravity anomaly. Nevertheless, those contributions (in lower resolutions as anticipated for the CAMP project) were available to the ArcGP project (Fig. 12; *Kenyon & Forsberg 2008*). Therefore, no separate map was finally produced in this project. Oceanic units are partly covered by data derived form satellite radar altimetry; the eastern Artic Ocean is covered by Russian data (see above). This data set is corrected using the EGM96, which has not yet been corrected for the long wavelength content available only after the ArcGP and this project was finalized.

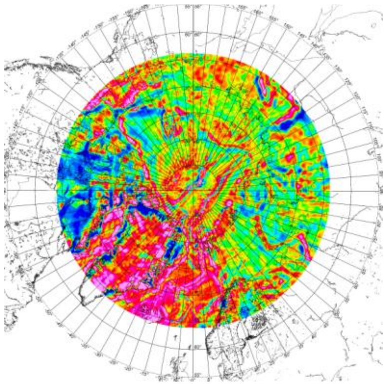


Fig. 12. Image of the ArcGP free air gravity anomaly data.

3.2.3. GRAVITY MAP – BOUGUER

For calculating the Bouguer gravity anomaly the International Bathymetric Chart of the Arctic Ocean (IBCAO; *Jakobsson et al., 2008*) in the form of a digital grid on a Polar Stereographic projection with grid cell spacing of 2 x 2 km, was used. Additionally the Arctic Gravity Project (ArcGP) free air gravity compilation of the Arctic Ocean, which was assembled from airborne, surface, submarine gravity and satellite measured altimetry data (*Kenyon and Forsberg, 2001*) was used. The free air 5-minute grid, updated by the ArcGP in 2006 (*Kenyon & Forsberg 2008*), has been used in the IBCAO compilation process to check for potentially unmapped features or offsets of mapped features, a procedure specifically useful in regions with sparse bathymetric data coverage, and valuable if the gravity data source is completely independent from the bathymetric mapping, e.g. airborne or satellite gravity. For the project this two data sets are considered independent, because the Bouguer gravity anomaly is calculated only for the land units.

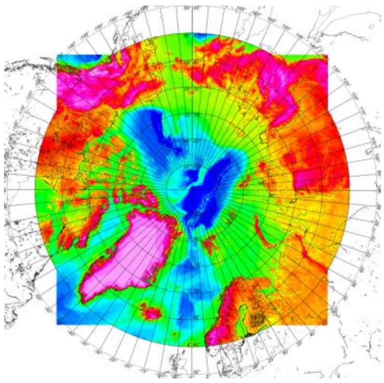


Fig. 13. Merged IBCAO and GEBCO topographic and bathymetric data.

For the final Bouguer gravity anomaly map, topographic data from IBCAO and GEBCO data sets were merged where IBCAO data were lacking (Fig. 13). Thereafter, the standard Bouguer anomaly was calculated. The density used for calculating the Bouguer anomaly is 2670 kg/m^3. For Greenland, first the ice sheet height was recalculated to a rock equivalent topography by using the ice thickness and topographic information provided by the National Snow and Ice Data Center DAAC, University of Colorado, Boulder, CO. This Digital Elevation Model (DEM), ice thickness grid, and bedrock elevation grid of Greenland is compiled from a combination of ERS-1 and GeoSat satellite radar altimetry data, Airborne Topographic Mapper (ATM) data, and photogrammetric digital height data. Ice thickness data are based on approximately 700,000 data points collected in the 1990s from University of Kansas airborne ice penetrating radar (IPR). Nearly 30,000 data points were collected in the 1970s from a Technical University of Denmark (TUD) airborne echo sounder. The ice thickness grid was subtracted from the DEM to produce a grid of bedrock elevation values (*Bamber et al. 2001 a, b*).

The rock equivalent topography was used to calculate the Bouguer gravity anomaly in a similar manor as for the other land units (Fig. 14). In a final step, all data sets were merged.

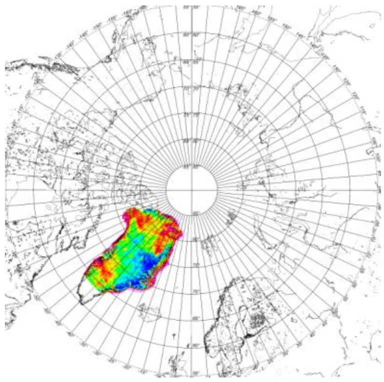
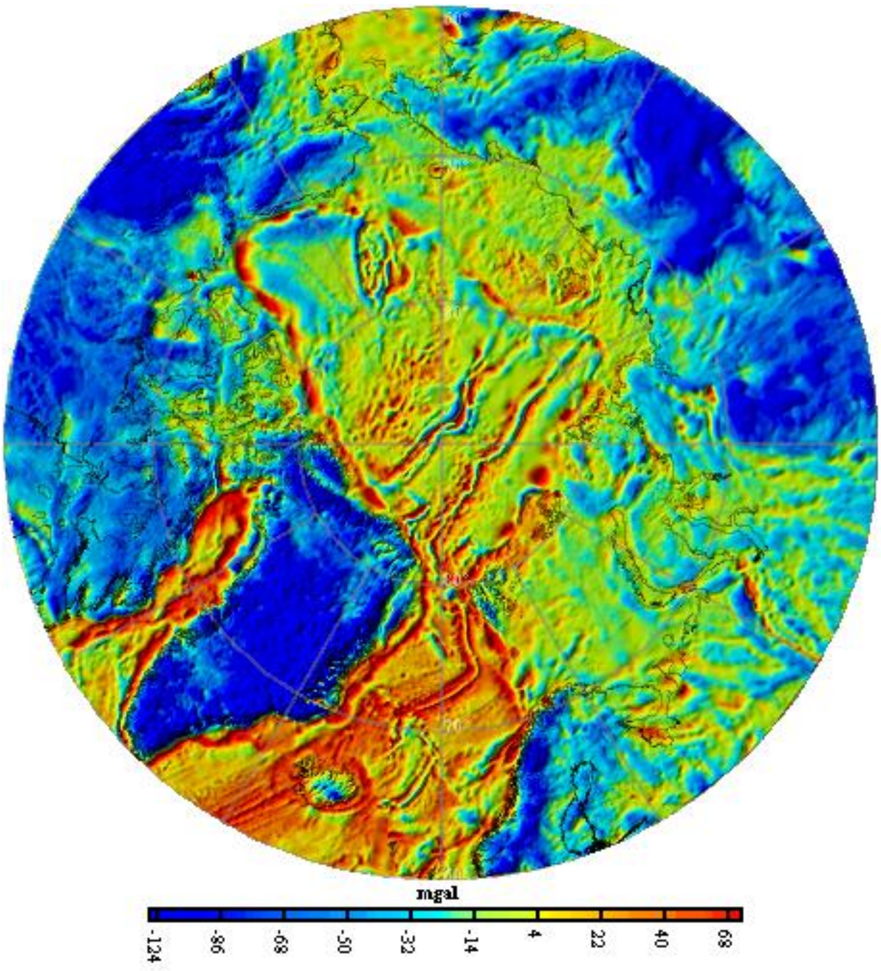


Fig. 14. Greenland's Bouguer gravity anomaly.

3.3. GRAVITY MAP – BOUGUER/FREE AIR

For the final product the a data set was compiled with contained free air gravity anomalies for the oceanic units, and Bouguer gravity anomalies for the land units, where the ice sheet over Greenland was treated specifically as described above. Finally, the Russian original contribution (available only as Bouguer gravity anomaly) was used to substitute the onshore data of the Russian territory, because they are in higher resolution, than the data contained in the ArcGP data compilation. From this data base the final map image was produced with a grid resolution of 10 x 10 km, which is shown in Fig. 15.

Fig. 15. Final map product with Bouguer gravity anomaly data onshore and Free Air gravity anomaly data offshore, at a grid resolution of 10 x10 km in a polar stereographic projection.



REFERENCES

Bamber, J.L., R.L. Layberry, S.P. Gogenini. 2001a. A new ice thickness and bed data set for the Greenland ice sheet 1: Measurement, data reduction, and errors. Journal of Geophysical Research 106 (D24): 33773-33780.

Bamber, J.L., R.L. Layberry, S.P. Gogenini. 2001b. A new ice thickness and bed data set for the Greenland ice sheet 2: Relationship between dynamics and basal topography. Journal of Geophysical Research 106 (D24): 33781-33788.

Damaske, D. & Oakey, G. (2006). Volcanogenic sandstones as aeromagnetic markers on Judge Daly promontory and in Robeson Channel. Polarforshung 74, 9-19.

Förste, C., Schmidt, R., Stubenvoll, R., Flechtner, F., Meyer, U., König, R., Neumayer, H., Biancale, R., Lemoine, J.-M., Bruinsma, S., Loyer, S., Barthelmes, F., Esselborn, S. 2008. The GeoForschungsZentrum Potsdam/Groupe de Recherche de Gèodésie Spatiale satellite-only and combined gravity field models: EIGEN-GL04S1 and EIGEN-GL04C. Journal of Geodesy, 82 (6):331-346.

Gernigon, L., Olesen, O., Ebbing, J., Wienecke, S., Gaina, C., Mogaard, J. O., Sand, M. & Mykelbust, R. (2008). Geophysical insights in early spreading history in the vicinity of the Jan Mayen Fracture Zone, Norwegian-Greenland Sea. Tectonophysics (Magmatism, rifts and rifted margins, Special Issue), 468, 185-205.

Glebovsky, V.Yu., Kovaks, L.C., Mashchenkov, S., and Brozena, J.M., 2000, Joint compilation of Russian and US Navy aeromagnetic data in the central Arctic seas, Polarforschung, 68, 35-40.

Hemant, K., Thebault, E., Mandea, Ravat, D. and Maus, S., Magnetic anomaly map of the world: merging satellite, airborne, marine and ground-based magnetic data sets, 2007, EPSL, 260, 56-71.

Jakobsson, M., Macnab, R., Mayer, L., Anderson, R., Edwards, M., Hatzky, J., Schenke, H-W., and Johnson, P., 2008, An improved bathymetric portrayal of the Arctic Ocean: Implications for ocean modeling and geological, geophysical and oceanographic analyses, Geophysical Research Letters 35, L07602, doi:10.1029/2008GL033520.

Kenyon, S., Forsberg, R., Coakley, B. 2008. New Gravity Field for the Arctic. Eos, Transactions American Geophysical Union, 89 (32): 289-290.

Maus, S., Yin, F., Luhr, H., Manoj, C., Rother, M., Rauberg, J., Michaelis, I., Stolle, C. & Muller, R. D. (2008). Resolution of direction of oceanic magnetic lineations by the sixth-generation lithospheric magnetic field model from CHAMP satellite magnetic measurements. Geochemistry Geophysics Geosystems 9,

Oakey, G. & Damaske, D. (2006). Structural elements of the Kane Basin region of Nares Strait constrained by aeromagnetic data. Polarforshung 74, 51-62.

Olesen, O., Gellein, J., Habrekke, H., Kihle, O., Skilbrei, J. R. & Smethurst, M. A. (1997). Magnetic anomaly map, Norway and adjacent areas, pp. map scale 1:3000000. Geological Survey of Norway, Trondheim.

Olesen, O., Ebbing, J., Lundin, E., Mauring, E., Skilbrei, J. R., Torsvik, T. H., Hansen, E. K., Henningsen, T., Midboe, P. & Sand, M. (2007). An improved tectonic model for the Eocene opening of the Norwegian-Greenland Sea: Use of modern magnetic data. Marine and Petroleum Geology 24, 53-66.

Rasmussen, T. M. (2002). Aeromagnetic survey in the central West Greenland: project Aeromag 2001. Geology of Greenland Survey Bulletin 191, 67-72.

Verhoef, J, Roest, W.R., et al., 1996, Magnetic anomalies of the Arctic and North Atlantic oceans and adjacent areas, CD compilation, GSC, Ottawa, Canada.

APPENDIX A – PUBLICATIONS

(Conference Abstracts, Invited talks and Short Articles)

1. Saltus, R., and Gaina, C., 2007,Circum-Arctic Map Compilation: *Second Workshop of the Circum-Arctic Geophysical Maps Project, Trondheim, Norway, 12–13 February 2007,* Eos Trans. AGU, 88(21), 227.

The eyes of the world are increasingly focused on the polar regions. Exploration and assessment of energy and mineral resources for the growing world economy are moving to high-latitude frontier areas. The effects of climatic changes are particularly pronounced at these ends of the Earth and have already attracted worldwide attention and concern. Many recent articles related to the International Polar Year underscore the importance of even basic mapping of the Arctic and Antarctic. Against this backdrop, an international cooperative effort to produce an updated folio of geologic and geophysical maps for the circum-Arctic has developed from an initial agreement signed in 2003 between several national agencies (from Canada, Denmark, Finland, Norway, Russia, Sweden, and United States). Various agencies have taken the lead on separate components (e.g., geologic, tectonic, resources, and geophysical) of the overall effort. The Geological Survey of Norway (Norges Geologiske Undersøkelse, NGU), in Trondheim, Norway, is the headquarters for the gravity and magnetic map compilations and production. Carmen Gaina is the project leader.

The second workshop of the Circum- Arctic Mapping Project–Gravity/Magnetics (CAMP-GM) was held in Trondheim, on 12 and 13 February 2007. The meeting consisted of technical presentations on contributed magnetic data compilations along with detailed discussions of map compilation and production issues. Gravity data were also discussed and included a presentation of the Arctic Gravity Project (ArcGP) free-air gravity compilation by Rene Forsberg (Danish Space Agency). The minutes for this and the previous technical workshop, held in St.Petersburg, Russia, in 2006, are available at www.geodynamics.no (follow the Circum-Arctic Project link).

The assembly of regional geophysical data, especially magnetic compilations, offers a number of interesting technical and theoretical challenges. The ability of the resulting products to reveal large-scale tectonic features makes these challenges worthwhile. The CAMP-GM working group has engaged in interesting practical discussions about the pros and cons of various approaches to the effective merging of individual magnetic surveys into regional grids. Juha Korhonen brings expertise and experience from his role as a lead scientist for the World Magnetic Anomaly Map to this project. Many of the other regional experts in the group bring unique perspectives based on their own work with national-scale compilations. The participating scientists have found that the working group has provided a fertile forum for interchange of ideas and perspectives on technical aspects of data compilation as well as the utility of these regional data for geologic and tectonic interpretation.
The overall goal of the CAMP-GM project is to produce printed maps and make accompanying digital data available to the scientific community during the International Geological Congress, in Oslo in August 2008. The project members invite additional participation by interested scientists and institutions worldwide.

2. Gaina, C., and CAMP-GM group, 2007, Circum-Arctic mapping project: new magnetic anomaly map of the Arctic (to 64/60 degrees N), ***IUGG***, Perugia, Italy.

An international effort to compile Circum-Arctic geophysical and bedrock data is currently being conducted by several national agencies (Russia, Sweden, Finland, Denmark, USA, Canada and Norway). This project aims to produce an atlas that will comprise geological and geophysical digital maps at a scale of 1: 5 million scale for the Arctic region limited by the 64 degree North latitude (and 60 degree North latitude for the NW Europe and Canadian regions).
New published and classified magnetic and gravity anomaly gridded data from each participant group were gathered and converted to a common datum and format. The magnetic anomaly compilation relies on 1km gridded data for Canada (based on the Canadian Aeromagnetic Data Base), Alaska (based on Alaska USGS aeromagnetic database) and NW Europe (Fennoscandia compilation and the

NGU NE Atlantic compilation) regions, and 5 km gridded data for oceanic and Russian regions. The grids have been merged using two separate methods: the GEOSOFT routine GridKnit and an alternative method proposed by Hemant et al (2007). The final grid resolution of this compilation will be 2x2 km upward continued to 1 km. Preliminary Circum-Arctic magnetic anomaly maps will be presented and technical details will be discussed. As the input gridded data contain improved national geophysical datasets compared to previous compilations (Verhoef 1996 Arctic/North Atlantic and Glebovsky et al, 1999 Arctic ocean magnetic anomaly compilations) we consider that the new product will supplement the WDMAM compilation and make a substantial contribution to the geoscientific community.

3. Gaina, C., and CAMP-GM group, 2007, Circum-Arctic mapping project: new magnetic and gravity anomaly maps of the Arctic, ***ICAM V***, Tromsø, Norway

Abstract An international effort to compile Circum-Arctic geophysical and bedrock data is currently being conducted by several national agencies (Russia, Sweden, Finland, Denmark, USA, Canada and Norway). This project aims to produce an atlas that will comprise geological and geophysical digital maps at a scale of 1: 5 million for the Arctic region limited by the 60 degree North latitude.
New published and classified magnetic and gravity anomaly gridded data from each participant group were gathered and converted to a common datum and format. The magnetic anomaly compilation relies on 1 km gridded data for Canada (based on the Canadian Aeromagnetic Data Base), Alaska (based on Alaska USGS aeromagnetic database) and NW Europe (Fennoscandia compilation and the NGU NE Atlantic compilation) regions, and 5 km gridded data for oceanic and Russian regions. The grids have been merged using two separate methods: the GEOSOFT routine GridKnit and an alternative method proposed by Hemant et al (2007). The final grid resolution of this compilation will be 2x2 km upward continued to 1 km. Preliminary Circum-Arctic magnetic anomaly maps will be presented and technical details will be discussed.
The planned gravity anomaly compilation includes one map of the Free Air gravity anomaly for the Circum-Arctic region and one map of combined Free Air ***(for oceanic area)*** and Bouguer ***(for land)***, both at 10x10 km grid resolution. Satellite gravity models are used for quality control on the long wavelengths of the new compilation.

4. Gaina, C., Who owns the North Pole: political and tectonic boundaries in the ARCTIC, 2008, Invited talk, University of Sydney, Australia

5. Gaina, C., Werner, S., and CAMP-GM group, 2008, Circum-Arctic mapping project: New magnetic and gravity anomaly maps of the Arctic, ***33rd IGC***, Oslo, Norway

Abstract An international effort to compile Circum-Arctic geophysical and bedrock data has been conducted by several national agencies (Russia, Sweden, Finland, Denmark, USA, Canada, Germany and Norway). This project produced an atlas that comprise geological and geophysical digital maps at a scale of 1: 5 million for the Arctic region limited by the 60 degree North latitude.
Newly published and classified magnetic and gravity anomaly gridded data from each participant group were gathered and converted to a common datum and format. The magnetic anomaly compilation relies on 1 km gridded data for Canada (based on the Canadian Aeromagnetic Data Base), Alaska (based on Alaska USGS aeromagnetic database) and NW Europe (Fennoscandia compilation and the NGU NE Atlantic compilation) regions, and 5 km gridded data for oceanic and Russian regions. New gridded data from Greenland and some adjacent areas have also been added. The grids have been merged using Hemant et al (2007) methodology and GEOSOFT routines. The final grid resolution of this compilation is 2x2 km upward continued to 1 km.
The gravity anomaly compilation includes one map of the Free Air gravity anomaly for the Circum-Arctic region and one map of combined Free Air ***(for oceanic area)*** and Bouguer ***(for land)***, both at

10x10 km grid resolution. Satellite gravity and magnetic models were used for quality control on the long wavelengths of the new compilations.

6. Gaina, C., Saltus, R., and Alvey, A., 2008, Structure and evolution of the Arctic oceanic crust in the light of new regional compilations, ***33^rd^ IGC***, Oslo, Norway.

Abstract Recent Circum-Arctic digital compilations of magnetic, gravity and bathymetry data have been analysed in order to provide a consistent view of the tectonically complex Arctic basins and surrounding continents. The new grids have been mathematically filtered in order to assist in the regional characterization of magnetic and gravity domains and boundaries. The frequency content, amplitudes, and patterns of regional magnetic anomalies provide a window into the tectonic character and structure of the crust. A range of kinematic scenarios for the Arctic ocean domains based on geophysical and geological data are also presented. Finally, continental lithosphere thinning factor maps were constructed by inverting gravity data from the Arctic Gravity Project. The lithosphere thermal model used to predict the lithosphere thermal gravity anomaly correction used plate reconstruction models to provide the age and location of oceanic lithosphere. We show that the gravity inversion method could be used for discriminating between various plate tectonic scenarios, especially in remote or poorly surveyed regions.

7. Saltus, R., C. Gaina , and P. Brown, 2008, Large scale geophysical domains from circum-Arctic magnetic and gravity anomalies - A framework for tectonic reconstructions, ***33rd IGC***, Oslo, Norway.

8. Gaina, C**.,** Saltus, R., Harrison, C., St-Onge, M., Alvey, A. and N. Kusznir, 2008, Circum-Arctic Mapping Project: New Magnetic Anomaly map Linked to the Geology of the Arctic, *Eos Trans.* ***AGU****, 89*(53), Fall Meet. Suppl., Abstract GP53B-04 (**invited**)

Abstract Recent Circum-Arctic digital compilations of magnetic, gravity and bathymetry data have been analyzed in order to provide a consistent view of the tectonically complex Arctic basins and surrounding continents. The new grids have been mathematically filtered in order to assist in the regional characterization of magnetic and gravity domains and boundaries. In particular, we have analyzed the frequency content, amplitudes, and patterns of regional magnetic anomalies in areas with disputed crustal structure and tectonic evolution (Alpha-Mendeleev Ridge, Canada Basin, Makarov and Podvodnikov basins). The interpretation of the potential field and its derivatives has been compared with a recently released map of Arctic geology. Based on our data analysis, we present a range of kinematic scenarios for the Arctic Ocean domains. Gravity inversion methods were used for discriminating between various plate tectonic scenarios.

9. Gaina, C., R. Saltus, CAMP-GM group, and CAMP-geology group, 2009, Circum-Arctic Mapping Project: New Magnetic Anomaly map Linked to the Geology of the Arctic, ESA/GFZ, Potsdam, Germany.

Abstract Recent Circum-Arctic digital compilations of magnetic, gravity and bathymetry data have been analyzed in order to provide a consistent view of the tectonically complex Arctic basins and surrounding continents. The new grids have been mathematically filtered in order to assist in the regional characterization of magnetic and gravity domains and boundaries. In particular, we have analyzed the frequency content, amplitudes, and patterns of regional magnetic anomalies in areas with disputed crustal structure and tectonic evolution (like Alpha-Mendeleev Ridge). The interpretation of potential field and its derivatives has been compared with recently released map of Arctic geology.

10. Gaina, C., Werner, S., Torsvik, T., Saltus, R., Alvey, A, Kusznir, N., Maus, S., and the CAMP-GM group, Structure and evolution of the Arctic oceanic crust in the light of new geophysical compilation *(in review, Geol. Soc. London Spec. Publ.)*

Abstract New Circum-Arctic maps of magnetic and gravity anomalies have been produced by merging regional gridded data. Satellite magnetic and gravity data were used for quality control of the long wavelengths of the new compilations. The new Circum-Arctic digital compilations of magnetic, gravity and some of their derivatives have been analyzed together with other freely available regional and global data and models in order to provide a consistent view of the tectonically complex Arctic basins and surrounding continents. Tectonic boundaries (including continent-ocean boundaries and sutures) have been mapped mainly based on potential field data and their derivatives. In areas where the crustal age remains speculative we compare the crustal thickness derived from gravity inversion with other geophysical constraints. Based on our data analysis, we present a kinematic scenario as part of a larger tectonic framework, where subduction of the Pacific and South Anyui oceans led to the opening of the Amerasian Basin in the Early Cretaceous, motion between the North American plate relative to a fixed Eurasian/Lomonosov plate led to opening of small basins between the Lomonosov Ridge and Alpha Ridge area, and a mantle thermal anomaly (precursor of Iceland hotspot) weakened the crust along the north/northeast part of the American craton facilitating the opening of the Canada Basin, rifting in the Baffin Bay and creating a zone of weakness in the area of the future Eurekan orogeny.

Understanding the tectonic evolution of the Amerasian basins (Figure 1) is of fundamental importance to future hydrocarbon exploration. Significant constraints could be placed upon the development of the petroleum provinces of Alaska's North Slope, the Canadian Arctic Islands, the East Siberian platform, Barents Sea and other less proven areas. Because the physical confines of the circum-Arctic are small, their histories are inter-related: for example, reconstructing the history of the Canada Basin requires an understanding of the plate trajectories of the continental Chuckchi Borderlands and Northwind Ridge crustal bodies as well as the closure of the ancestral South Anyui Ocean. Given the vast hydrocarbon potential of the entire Arctic region was estimated to as much as "30% of the world's undiscovered gas and 13% of the world's undiscovered oil" (Gautier, 2008), the wild cards posed by the Amerasian basins must be addressed as fully as possible.

11. Saltus, R. W., Miller, E.L., Gaina, C., Olesen, O., and P. J. Brown, Regional Magnetic Domains of the Circum-Arctic – A Framework for Tectonic Interpretation *(in review, Geol. Soc. London Spec. Publ.)*

Abstract The circum-Arctic is heating up both in a literal and scientific sense. Decreasing sea ice cover is allowing for increased physical access to this remote region. Increasing global concern over presence and environmental cost of natural resources is driving societal and commercial interest in the Arctic.

We identify and discuss 64 magnetic anomaly pattern domains spanning the circum-Arctic. The domains are based on analysis of a new circum-Arctic data compilation. The magnetic anomaly patterns can be related to general geodynamic classification of the crust into stable, mobile, extended shelf, oceanic, large igneous province, and deep magnetic high domains. We compare the magnetic domains with topography/bathymetry, regional geology, regional free air gravity anomalies, and estimates of the relative magnetic "thickness" of the crust. Most of the domains and their geodynamic classification assignments are consistent with their topographic/bathymetric and geologic expression. A few of the domains are potentially controversial. For example, the extent of the Iceland hotspot track as identified by magnetic anomalies may disagree with other definitions for this feature. Also the lack of definitive magnetic expression of oceanic crust in Baffin Bay and the Amerasian Basin is at odds with some previous interpretations. While somewhat subjective, the domains and their boundaries provide constraints on tectonic models for this poorly understood portion of the globe.

The geologic and tectonic framework of the circum-Arctic remains controversial. No single model is uniformly accepted for the tectonic development of the Arctic, particularly in terms of the details and history of the formation of the Amerasia Basin (Fig. 1). The tectonic affinities and geodynamic character of the terranes surrounding the Arctic basins are still being studied and established (e.g., Lawver and Pease, 2009).