



# Magnetic susceptibilities measured on rocks of the upper Cook Inlet, Alaska

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Open-File Report 02-0139

2002

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**U.S. DEPARTMENT OF THE INTERIOR  
U.S. GEOLOGICAL SURVEY**

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## Abstract

We have measured magnetic susceptibility in the field on most of the geologic rock formations exposed in the upper Cook Inlet near Anchorage and Kenai, Alaska. Measured susceptibilities range from less than our detection limit of  $0.01 \times 10^{-3}$  (SI) to greater than  $100 \times 10^{-3}$  (SI). As expected, mafic igneous rocks have the highest susceptibilities and some sedimentary rocks the lowest. Rocks of the Tertiary Sterling Formation yielded some moderate to high susceptibility values. Although we do not have detailed information on the magnetic mineralogy of the rocks measured here, the higher susceptibilities are sufficient to explain the magnitudes of some short-wavelength aeromagnetic anomalies observed on recent surveys of the upper Cook Inlet.

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## Introduction

The Cook Inlet Basin is a complex structural region. It is a deformed forearc basin, bounded by the Border Ranges fault to the east, and the Castle Mountain and Bruin Bay faults to the north and west (Kirschner and Lyons, 1973; Haeussler and others, 2001). The thick package of upper Mesozoic and Cenozoic sediments that fills the basin were faulted and folded under northwest-southeast regional contraction. Aeromagnetic surveys, compiled and analyzed by the U.S. Geological Survey (Saltus and others, 2001), show abundant linear, short wavelength magnetic anomalies in the upper Cook Inlet Basin (Figures 1 and 2). These anomalies are generally parallel to the northeast-southwest-striking structural fabric of the region. Saltus and others (2001) postulated that these anomalies originate from truncated and folded Tertiary and Quaternary sedimentary units within the upper 800 to 4000 m of the basin.

In this investigation, magnetic susceptibility was measured at forty-eight field sites and on core from the Deep Creek borehole, to characterize the rocks of the upper Cook Inlet Basin that may be responsible for the observed aeromagnetic anomalies (Figure 2). Using susceptibility values based on the field measurements, we have constructed a magnetic model that replicates the magnitudes of some of the observed aeromagnetic anomalies.

## Magnetic susceptibility data

We measured magnetic susceptibilities in the field using hand-held magnetic susceptibility meters including an older EDO K2 meter (Bruhn data) and the Kappameter KT-5 (Haeussler data) and KT-6 (Altstatt data) models produced by Geofyzika a.s. These instruments measure apparent susceptibility with an accuracy of about  $1 \times 10^{-5}$  SI. Care was taken in our measurements to place the reading face of the instrument against a flat surface of the rock being measured. However, surface roughness of the field samples will result in measurements that are lower than the true susceptibility of the rock. For example, a surface roughness of 2 mm will lower the apparent value by 15% whereas surface roughness of 6 mm will lower the apparent value by as much as 50%. Also, surficial weathering of exposed rocks could further lower the apparent susceptibility relative to the true bulk susceptibility of unweathered rocks.

Volume susceptibility is a dimensionless quantity, but the values depend on the unit system that is used. Susceptibilities are reported here in SI volume units. To convert these values to the cgs system (often used in older studies), divide by  $4\pi$  (about 12.57). For example,  $12.57 \times 10^{-3}$  SI equals  $1.0 \times 10^{-3}$  cgs. Unfortunately there is some confusion in the scientific literature over the units for susceptibility, so care is required when comparing susceptibility information from multiple sources.

In general an attempt was made to make enough measurements at each site to characterize the variation in susceptibility at that site. For the Altstatt measurements on sea cliff exposures of the Sterling and Beluga formations, susceptibility measurements were made at 0.5 m intervals on traverses that ranged from a few meters to 30 m in length up section.

To categorize the magnetic susceptibility measurements we constructed a simplified stratigraphy for the upper Cook Inlet (Figure 3, Table 1). Correlation of our stratigraphic units with rock units from different geologic maps of the region (Magoon and others, 1976; Winkler, 1992; and Wilson and others, 1998) is also listed. We have also categorized our samples by rock type (Table 2) based on our field identifications.

The data table (Table 3) summarizes 1292 measured susceptibilities on rocks of twenty-four formations. Susceptibilities range from less than our instrument sensitivity of  $0.01 \times 10^{-3}$  SI to more than  $100 \times 10^{-3}$  SI. A box-and-whisker plot by formation (Figure 4) gives an overview of the data grouped by rock type and age. We categorize susceptibilities less than  $1 \times 10^{-3}$  SI as “low”, between 1 and  $10 \times 10^{-3}$  SI as “moderate”, and greater than  $10 \times 10^{-3}$  as “high”. As expected given their greater amount of ferromagnetic and high paramagnetic minerals, the igneous rocks have the highest magnetic susceptibility on average – from moderate to high. Susceptibilities in the metamorphic rocks are variable from low (the Valdez and McHugh formations) to high (amphiboles and some dikes in the schists at Hatcher Pass). The sedimentary rocks have generally low magnetic susceptibility with the exception of the Sterling (low to high, low mean), Arkose Ridge (low to moderate, low mean) and Talkeetna (low to high, moderate mean) Formations. The Jurassic Talkeetna Formation is considered to be the magnetic basement in this region.

Characterizing the magnetic susceptibility of the Sterling Formation is particularly important because it appears to correlate with the presence of short wavelength aeromagnetic anomalies that reflect folding within the basin (Saltus and others, 2001). The Sterling Formation has a wide range of measured susceptibility (Figures 5 and 6, Table 4), but we do not know the details of the magnetic mineralogy of these rocks. In the susceptibility measurements by Altstatt we attempted to characterize rocks of the Sterling Formation by rock types that might correlate with magnetic susceptibility (Figure 6). With the possible exception of coal, the other rock types do not differ in a statistically significant way from the overall susceptibility distribution for the entire formation. We interpret this to mean that any systematic susceptibility differences by rock type, if present, are too subtle to be picked up by the limited number of samples we

have measured. Although not statistically significant, there is a suggestion that massive sandstone is more magnetically susceptible than the other rock types. It also appears that the organic rich and orange stained rock types may have lower susceptibilities than average, but, again, this is not statistically proven in our data.

Tephra layers have been studied in the Sterling and Beluga Formations on the Kenai Peninsula (Reinink-Smith, 1995). These beds, although very thin (1 to 10 cm) were found to contain titaniferous magnetite phases (Reinink-Smith, 1995). We do not have susceptibility measurements on these tephra layers.

Some early geologic investigations of the shallow Tertiary section contain information that may be pertinent to understanding the magnetic properties of the rocks. In sea cliffs in the Homer region, Adkison and others (1975) report that the Beluga and Sterling Formations consist of interbedded shale, siltstone, and sandstone with occasional iron staining and iron nodules. A preliminary study of heavy minerals in the same rocks (Biddle, 1977) found measurable quantities of the weakly magnetic mineral siderite, primarily in the upper part of the Beluga Formation rocks in the section. Biddle (1977) interpreted the siderite to be authigenic whereas other the heavy minerals were transported. A preliminary heavy mineral study on cores of the Deep Creek well (Kelley, 1973) did not report any siderite. In both of the heavy metal studies (Kelley, 1973; Biddle, 1977) the procedures specified that “tramp iron and magnetite were removed by hand magnet.” We suspect these mineral phases were removed because they were sufficiently prevalent to present a problem with separating enough of the other heavy minerals that were the primary interest of the study. Thus, while we do not know anything from these studies about the relative abundance of magnetite and other iron minerals, they are probably present. On-going laboratory studies at the University of Utah should shed light on this issue.

Although the heavy mineral study procedures were not conducive to direct conclusions about magnetic minerals, they do provide some indirect information. In the Biddle (1977) study, rocks of the Sterling Formation showed a high percentage of “igneous” minerals (60% to 80% - igneous minerals defined as mainly hornblende and hypersthene but also including apatite, monazite, sphene, zircon, and rutile) relative to the Beluga Formation rocks with a higher percentage of “metamorphic” minerals (40% to 80% - metamorphic minerals defined as mainly epidote and garnet but also including andalusite, chlorite, staurolite, tourmaline, clinozoisite, kyanite, sillimanite, tremolite, and zoisite). This observation is consistent with the interpretation (Kirschner and Lyon, 1973) that the Beluga Formation sediments have their source to the southeast in the Kenai-Chugach Mountains and that the Sterling Formation sediments came from the Alaska Range to the northwest. Based on this provenance we expect that primary igneous minerals of the magnetite to ulvospinel solid-solution series form the main source for the magnetic susceptibilities of the Sterling Formation rocks.

## Modeling of shallow magnetic anomalies

We generated a simple magnetic model (Figure 7) using commercial modeling software (GM-SYS from NGA, Inc.). Susceptibility variations used in the model are based on our field measurements. This observed susceptibility range was applied to an hypothetical cross-section through the upper 1.5 km of the Sterling Formation, as it may appear near the Clam Gulch area. The topography was generated to mimic the sea cliff present in that region. The resulting anomalies produced by the truncation, both in folds and by the sea cliff, of layers assigned different susceptibilities have amplitudes of 4-5 nT and wavelengths of ~500 m. The sea cliff truncation produced a distinct anomaly, similar in scale and polarity to those observed in the shortest wavelengths of the aeromagnetic data (Figure 2).

## Conclusions

We measured magnetic susceptibility of many of the mapped geologic rock formations in the upper Cook Inlet region near Anchorage and Kenai, Alaska. The measurements generally fall within typical ranges for the rock types (e.g., Telford and others, 1976). For example, the igneous rocks in the study area have generally moderate to high susceptibilities, with the higher values occurring in the more mafic rocks. Metamorphic rock types have generally low to moderate susceptibilities with the exception of some highly magnetic schists. Cretaceous to Tertiary sedimentary rocks of the upper Cook Inlet have generally low susceptibility with the exception of some moderate susceptibilities measured in rocks of the Arkose Ridge formation and moderate to high susceptibilities measured in rocks of the Sterling formation. We do not, at present, know the magnetic mineralogy of any of the rocks we have studied. We suspect that most of the moderate-to-highly magnetic rocks have susceptibilities caused by titanomagnetite. The rocks with generally low susceptibilities may contain a variety of magnetic minerals, in addition to titanomagnetite, including siderite as reported previously in some rocks of the Sterling and Beluga Formations.

In general, the measured susceptibilities are consistent with the observed aeromagnetic anomalies in the region. In particular, we constructed an hypothetical magnetic model cross-section to demonstrate how truncations of magnetic layers within the Sterling Formation can give rise to some of the observed anomalies. This work supports the conclusion by Saltus and others (2001) that at least some of the short-wavelength aeromagnetic anomalies are related to the truncation or offset of magnetic layers within the shallow sedimentary rock section

## Acknowledgements

Dan and Courtney Neuffer helped extensively with field and lab measurements of susceptibility for this report. Ann Altstatt was supported as an intern under the North American Geology Teachers (NAGT) program at the USGS while working on this report. This work was performed as part of the USGS Anchorage Urban Region Aeromagnetism (AURA) project. We thank Mark Hudson and Joe Rosenbaum for review comments.

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