GEOPHYSICAL CORRELATION OF ONSHORE AND OFFSHORE GEOLOGY, SOUTHWESTERN NOVA SCOTIA

by

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ABSTRACT

The geology of southwestern Nova Scotia is characterized by plutons of varying compositions intruding a Meguma host rock. Onshore, the Shelburne and Barrington Passage plutons intrude the folded Halifax and Goldenville Formations of the Meguma Group. The striped magnetic signature of the Meguma contrasts with a smooth, relatively uniform signature, in some cases positive, associated with the plutons. Previous studies of southwestern Nova Scotia have used gravity and aeromagnetic data to extend interpretations of this onshore lithology into the offshore. More recently, swath bathymetric studies have shown granite bedrock exposed at the surface. This study correlates between the coast and the outer portion of the continental shelf based on forward modelling of magnetic data. A series of profiles constrained by magnetic susceptibility values were used to create 2D cross-sections of lithology. An onshore profile investigates the Shelburne and Barrington Passage plutons. A database of magnetic susceptibility values measured for each lithologic unit provided information on composition and the possible genetic relationships between plutons. These onshore results were extrapolated into the offshore to develop a profile through Mud and Seal Islands to determine the relationship to the onshore plutons and put limits on the extent of the Seal Island Pluton. Areas of positive anomaly on the continental shelf were investigated and linked to the Seal Island profile. The extent of plutons in the offshore has been mapped and correlated to regional geology based on their magnetic anomaly and other geophysical characteristics.

Key Words: Pluton, magnetic susceptibility, magnetic anomaly, gravity anomaly

Table of Contents

List of Figures:

List of Tables:

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CHAPTER I
Introduction

The geology of southwestern Nova Scotia has been studied extensively onshore and partially on the continental shelf offshore. The area offshore between mainland Nova Scotia and the edge of the continental shelf is problematic to study given that it is underwater and that bedrock is partially covered by marine sediments. As a result the geology has been inferred through the study of onshore geology with geophysical techniques such as seafloor mapping, magnetic anomaly and gravity being used to extend units into the offshore. Previous studies of the area have found it to be characterized by plutons intruding a Meguma host rock. Recent swath bathymetric surveys have identified areas of bedrock that may be plutons exposed on the sea floor. This study investigates the relationships and extent of plutonic emplacement in the region.

1.1 OBJECTIVE

The objective of this study of southwestern Nova Scotia's geology is to correlate bedrock geology between the coast and the continental shelf based on forward modeling of magnetic and gravity anomaly data. In order to determine the relationship of known onshore geology the following steps will be taken:

(1) The extent of the Goldenville and Halifax Formations of the Meguma Group will be investigated through a series of 2D profiles to determine their lateral and vertical extent

(2) The Seal Island Pluton will be modeled to determine its extent and relationship to regional geology

(3) Areas of high positive magnetic anomaly on the continental shelf will be modeled in an attempt to determine their origin

The study will involve a compilation of magnetic anomaly, gravity anomaly and swath bathymetry data sets. Magnetic susceptibility data will be analyzed and linked to rock units. These data sets will be used to identify boundaries of lithological units and verify the interpretation through forward modeling of 2D profiles.

1.2 STUDY AREA

The area of interest lies between the coast of southwestern Nova Scotia from Pembroke to Barrington Passage, and German Bank on the continental shelf (Figure 1.1). The study focuses on German Bank, which has been investigated by the use of swath bathymetric surveys, and the onshore limits of geologic mapping. The limits of these data sets were used to define the study area.

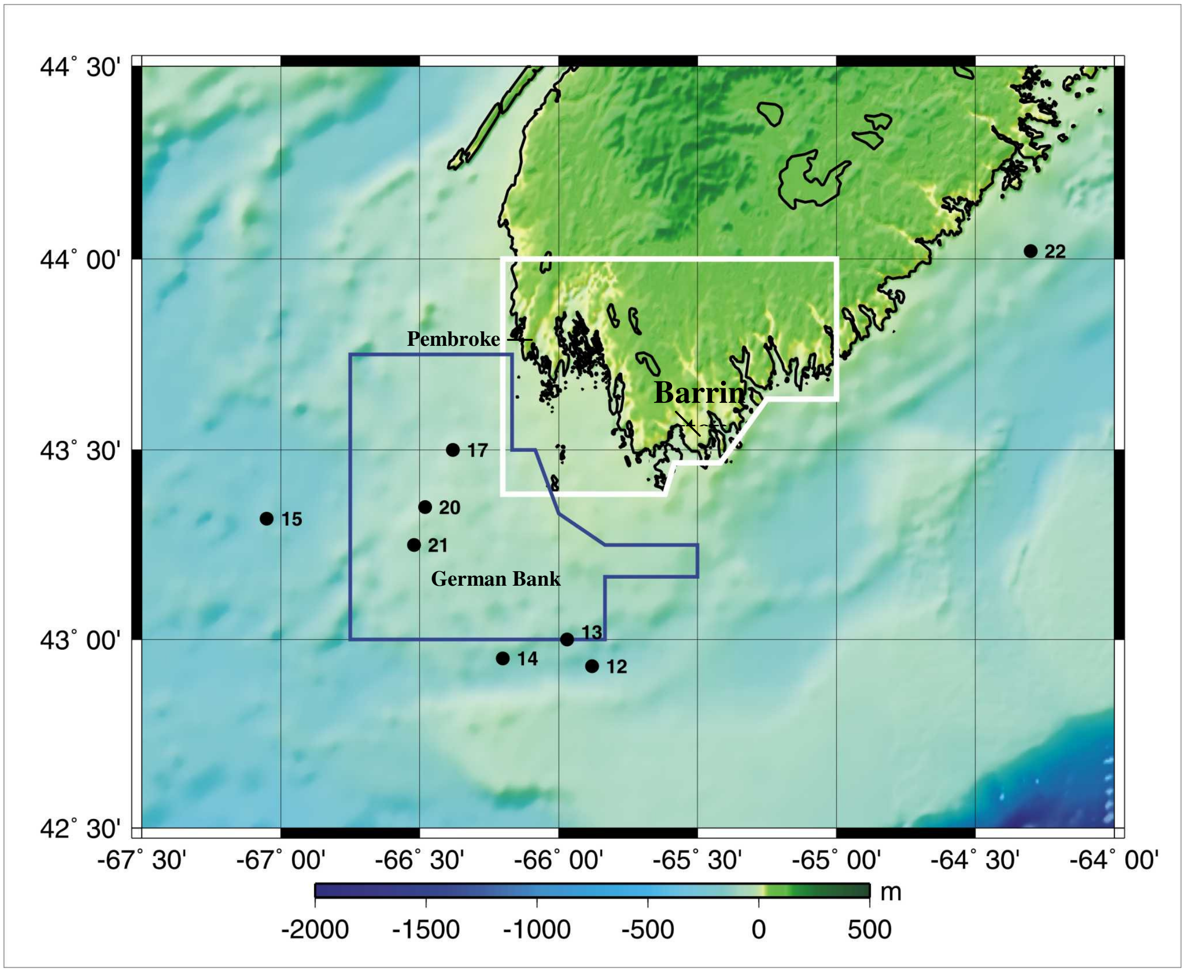

Figure 1.1: *Location map of the study area: The study area incorporates a map of onshore geology of southwestern Nova Scotia (outlined in white) provided by C. White (Nova Scotia Department of Natural Resources (NSDNR)) and swath bathymetry data on the German Bank (outlined in blue) supplied by B. Todd (Geologic Survey of Canada (GSC) Atlantic). Numbered dots indicate the core locations of Pe-Piper and Loncarevic (1989), the magnetic susceptibility values from which were used for comparison in this study. (Map from S. Dehler, GSC Atlantic).*

Three main areas were focused upon in this study:

• An onshore transect from Pembroke to Barrington Passage interpreting the intrusion of the Shelburne and Barrington Passage plutons into the Meguma terrane.

• An offshore transect near Mud and Seal Islands to determine the extent of the Seal Island Pluton in the offshore.

•A second offshore transect on the continental shelf to investigate the source of the high positive magnetic anomaly.

1.3 GEOLOGICAL BACKGROUND

The geology of southwestern Nova Scotia is dominated by the Goldenville and Halifax Formations of the Meguma Terrane. The Goldenville Formation typically consists of massive to locally laminated or cross-laminated, fine-grained metasandstone, interbedded with minor metasiltstone and slate. The conformably overlying Halifax Formation consists mainly of thinly laminated slate and metasiltstone (MacDonald et al., 2002). Additionally, the White Rock Formation outcrops in various locations throughout southwestern Nova Scotia, the lower member of which consists of quartzite, slate, conglomerate, and greywacke, with some silicic and mafic volcanic units (Ferguson, 1986). This geology has been extensively studied onshore and inferred into the offshore using geophysical techniques such as aeromagnetics and gravity. More recently, the German Bank was investigated through the use of swath bathymetry mapping by the Geologic Survey of Canada (GSC) Atlantic.

1.3.1 Onshore

Onshore geology of southwestern Nova Scotia has been re-mapped in detail from 1998 onward through an initiative by the Nova Scotia Department of Natural Resources (NSDNR). Mapping has taken place primarily in the Meguma Terrane and has resulted in a series of 1:50, 000 scale geologic maps of the area from Digby to Shelburne that interpret lithology, deformation and economic potential (White, 2003). These maps show the Meguma terrane and associated plutons of varying composition that have intruded throughout southwest Nova Scotia (Figure 1.2).

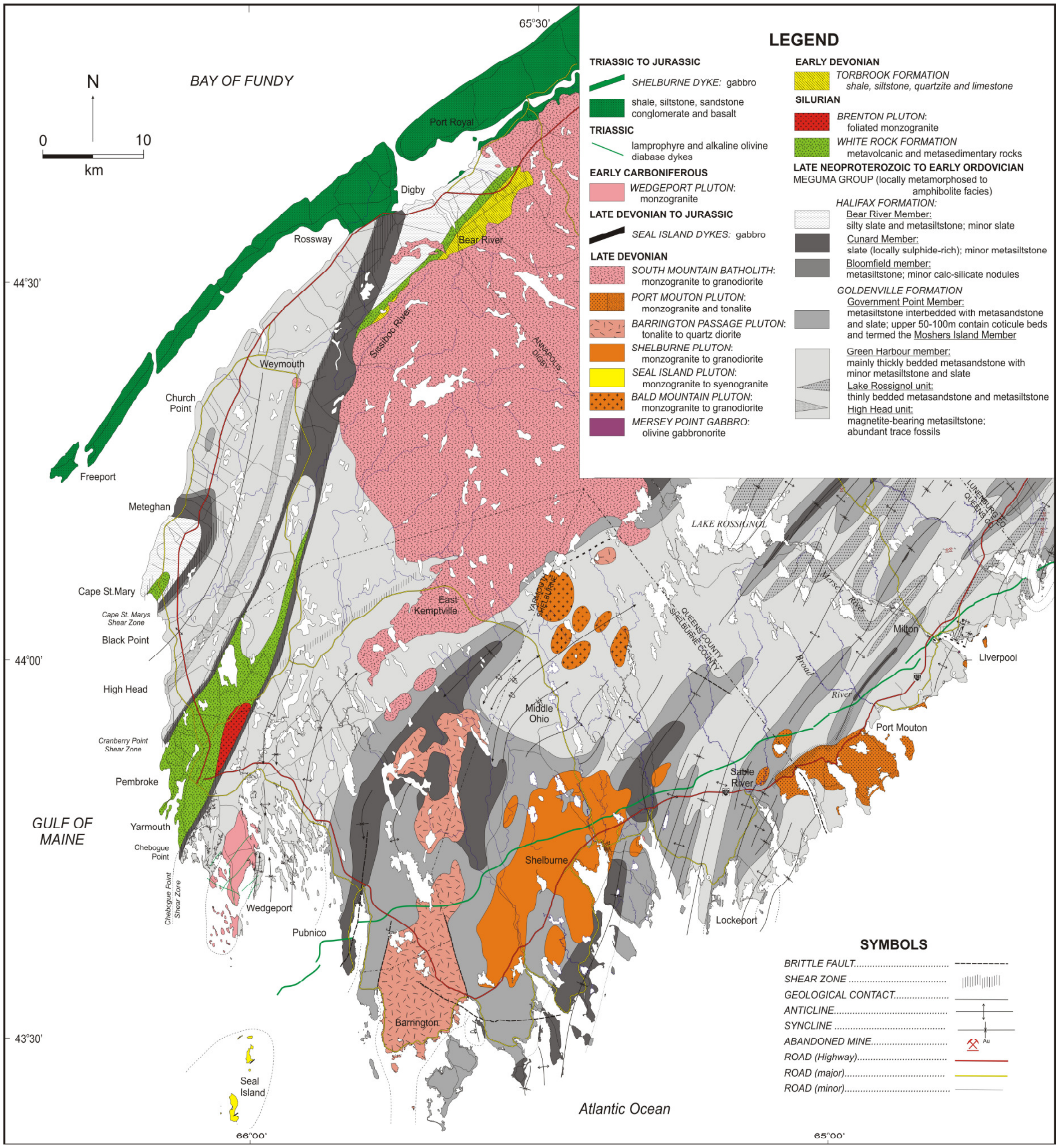

Figure 1.2: *Onshore geology of southwestern Nova Scotia: The map shows the Halifax and Goldenville Formations of the Meguma Group intruded by various plutons (corresponds to area outlined in white, Figure 1.1). Note the locations of the White Rock Formation, Barrington Passage Pluton, Shelburne Pluton, Shelburne Dyke and Mud and Seal Islands (*unpublished NSDNR image from the Southwest Nova Bedrock Mapping Project, Chris White*).*

The onshore geology map provides the most recent information on the lithology and structure of the region, showing how the Meguma Group has been affected by plutonic activity. Additionally, a database of magnetic susceptibility values has been created from measurements collected during the 2000 to 2004 mapping seasons as part of the Southwest Nova Bedrock Mapping Project (C.White, personal communication, 2005).

1.3.2 Offshore

The continental shelf southwest of Nova Scotia was investigated by the use of eight short drill cores by Pe-Piper and Loncarevic (1989). The cores range from 20 to 501 cm in length and recovered two types of granitoid rocks: ilmenite bearing granite petrographically and geochemically similar to the South Mountain Batholith (SMB); and a magnetite bearing granite that was also peraluminous, but has no exact analogue onshore (Pe-Piper and Loncarevic, 1989).

Investigation of the Seal Island Pluton has found that outcrops of the pluton have been cut by aplite dykes and quartz veins (White, 2003). The extent of the Seal Island Pluton has been speculated by previous investigations and can be further constrained due to this study.

The continental shelf has also been investigated recently by the use of swath bathymetry which is effective in displaying surficial features of the area.

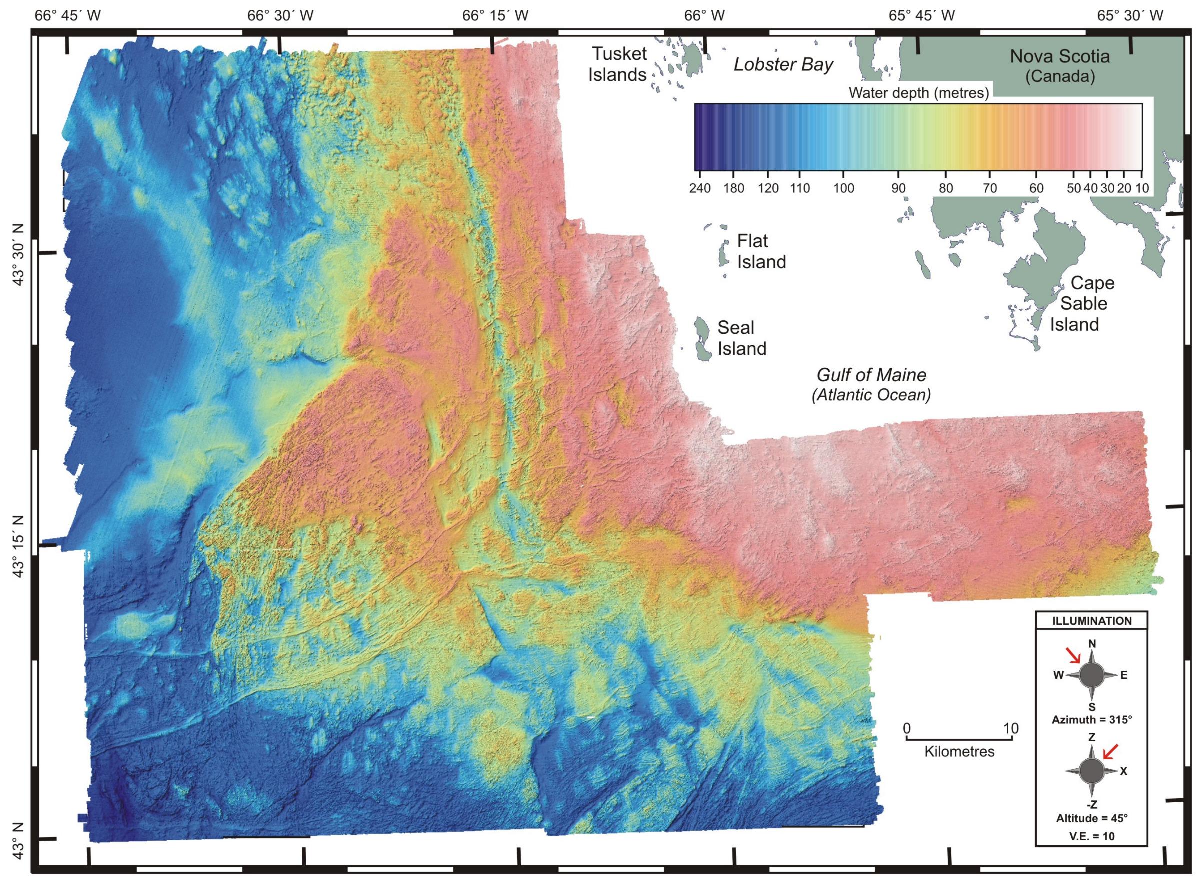

Figure 1.3: *Swath Bathymetry data set for the continental shelf of southwestern Nova Scotia (German Bank). The information put forth in this diagram corresponds to the area indicated by a blue box in figure 1.1 (digital image from B .Todd; GSC Atlantic).*

Other digital datasets available for the area include magnetic anomaly and gravity data collected from airborne and marine surveys.

CHAPTER II
Geophysical data sets

Numerous geophysical techniques have been used to extend known onshore geology into the offshore. This chapter investigates the offshore geology of southwestern Nova Scotia through analysis of magnetic anomaly, gravity anomaly and swath bathymetry data. Information extracted from the data sets has been combined with the southwest Nova magnetic susceptibility database to create 2D profiles of the region. This study combines the various interpretations in order to determine lateral extent as well as depth of units.

2.1 MAGNETIC ANOMALY

The magnetic anomaly map of southwestern Nova Scotia used in this study was provided by GSC Atlantic. The map was produced by processing and compiling several magnetic anomaly surveys to create a composite grid (Oakey & Dehler, 2004). Corrections and levelling of the various surveys were applied before the data set was obtained for this study. Anomaly data have been extracted from this data set and input into the 2D GM-SYS modeling program.

Remanent magnetization could not be incorporated into the study given that little information is available. In the absence of age, disturbance history and paleomagnetic information, the remanent magnetization was assumed to be negligible, and induced magnetization was assumed for all source bodies modeled.

The magnetic anomalies over the offshore are predominantly positive, possibly corresponding to the signature of mafic intrusive rocks (Figure 2.1). Superimposed on these positive anomalies are areas of strong lineations, that tend to curve south as they extend offshore. These have been caused by the folding of the Halifax and Goldenville Formations of the Meguma Group. These features of the magnetic anomaly map aid in the correlation between onshore and offshore by defining the boundaries of rock units and showing obvious differences between igneous and metamorphic bodies. Igneous areas are displayed as smooth features and are visible in both the onshore and offshore. However, the majority of igneous bodies in the onshore produce a negative magnetic anomaly, whereas in the offshore the magnetic anomaly is dominantly positive. Similarly, the Shelburne dyke can also be extended into the offshore, seen as a positive magnetic anomaly. In the offshore region of high positive anomaly, semi-linear features, some of which loop and close, are detected and investigated in profile 3.

A map of first vertical derivative further enhances the features of the magnetic anomaly map by accentuating the relative effects of shallow masses (Parasnis, 1997). The alternating features of the Halifax and Goldenville Formations of the Meguma group are displayed as an alternation of red and blue linear features on the map allowing for further interpretation of units into the offshore. Positive anomaly, semi-linear features are enhanced to varying degrees. The feature at the east end of the second profile and the feature cut by profile 3 are displayed as alternating red and blue linear features like the Meguma. The feature south of the east end of the third profile displays a much lower anomaly value.

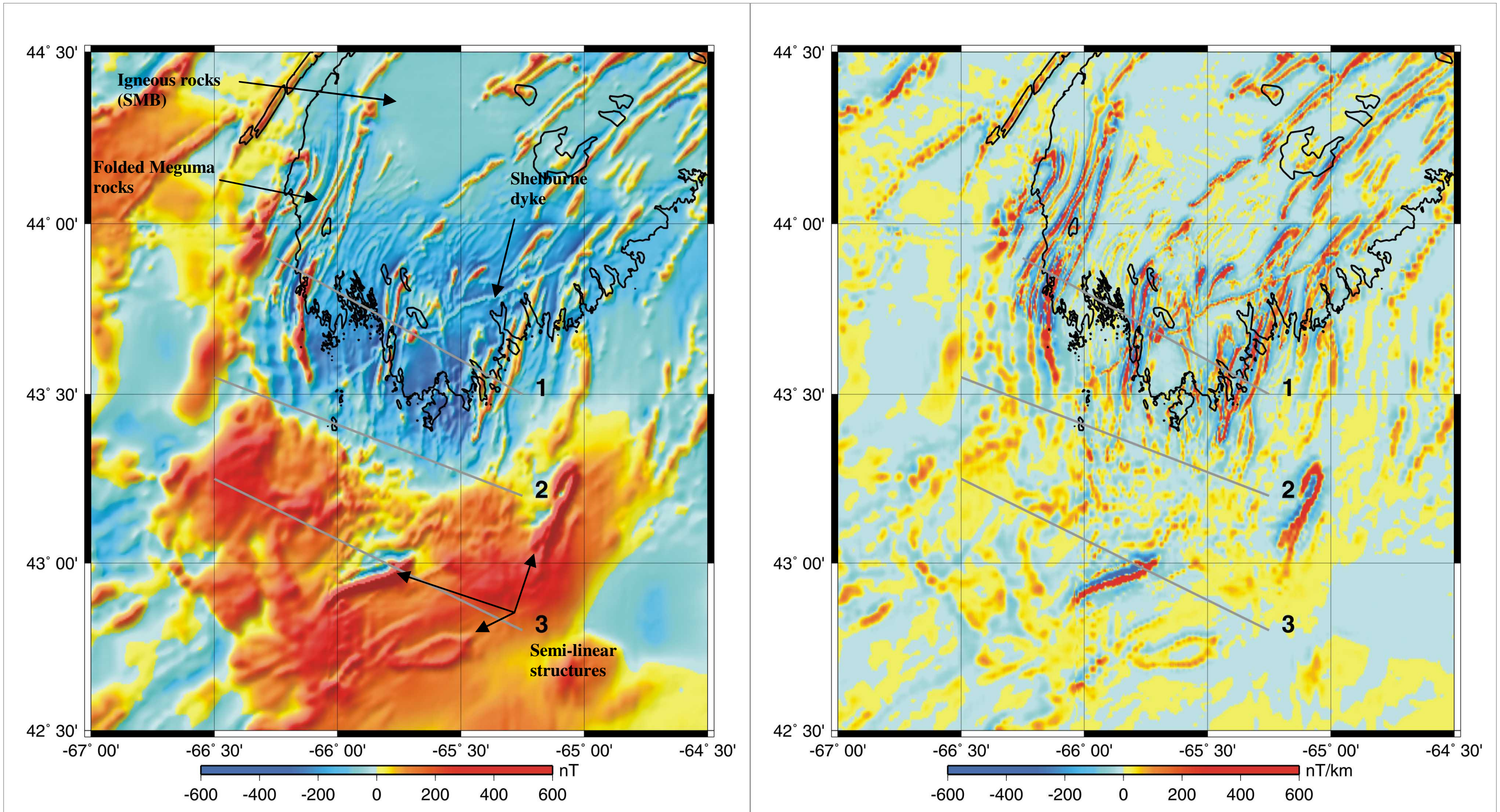

Figure 2.1: Magnetic anomaly map and its first vertical derivative(x 10^{-3}): Igneous areas are displayed as smooth features with varying anomaly signature between the onshore and offshore. The Halifax and Goldenville Formations of the Meguma Group appear to curve south as they extend offshore. Note the location of the semi-linear features in the offshore area of positive anomaly (Base map images provided by S. Dehler GSC Atlantic.

2.2 GRAVITY ANOMALY

Similar to magnetic anomaly data, the gravity data set was prepared at GSC Atlantic from numerous surveys that were corrected and gridded to form a regional data grid. A subset of the regional grid was used in this study (Dehler & Roest, 1998). The onshore data has corrected to the Bouguer anomaly for elevation – related mass effects, while the offshore data has been corrected to free air anomaly.

The gravity data set can be used to interpret changes in density related to the composition of lithologic units (Figure 2.2). The gravity anomalies in the study area were found to be highly variable. Onshore data show strong positive anomalies possibly indicating dense bodies in the Wedgeport and Pembroke areas, compared to the surrounding onshore gravity anomaly. The anomalies suggest the presence of a lower density body in the offshore bordered by more dense material on either side that partially corresponds to the area of high positive magnetic anomaly. Several data sets thus, suggest the presence of a large granite body off southwestern Nova Scotia. The presence of granitoid rock bodies in the offshore has been confirmed by drill core data of Pe-Piper and Loncarevic (1989).

The gravity data, like the magnetic anomaly data, have been extracted along the profiles and imported into the 2D modeling program GM-SYS. The gravity data will be compared with the other data sets to make the correlation between the onshore and continental shelf.

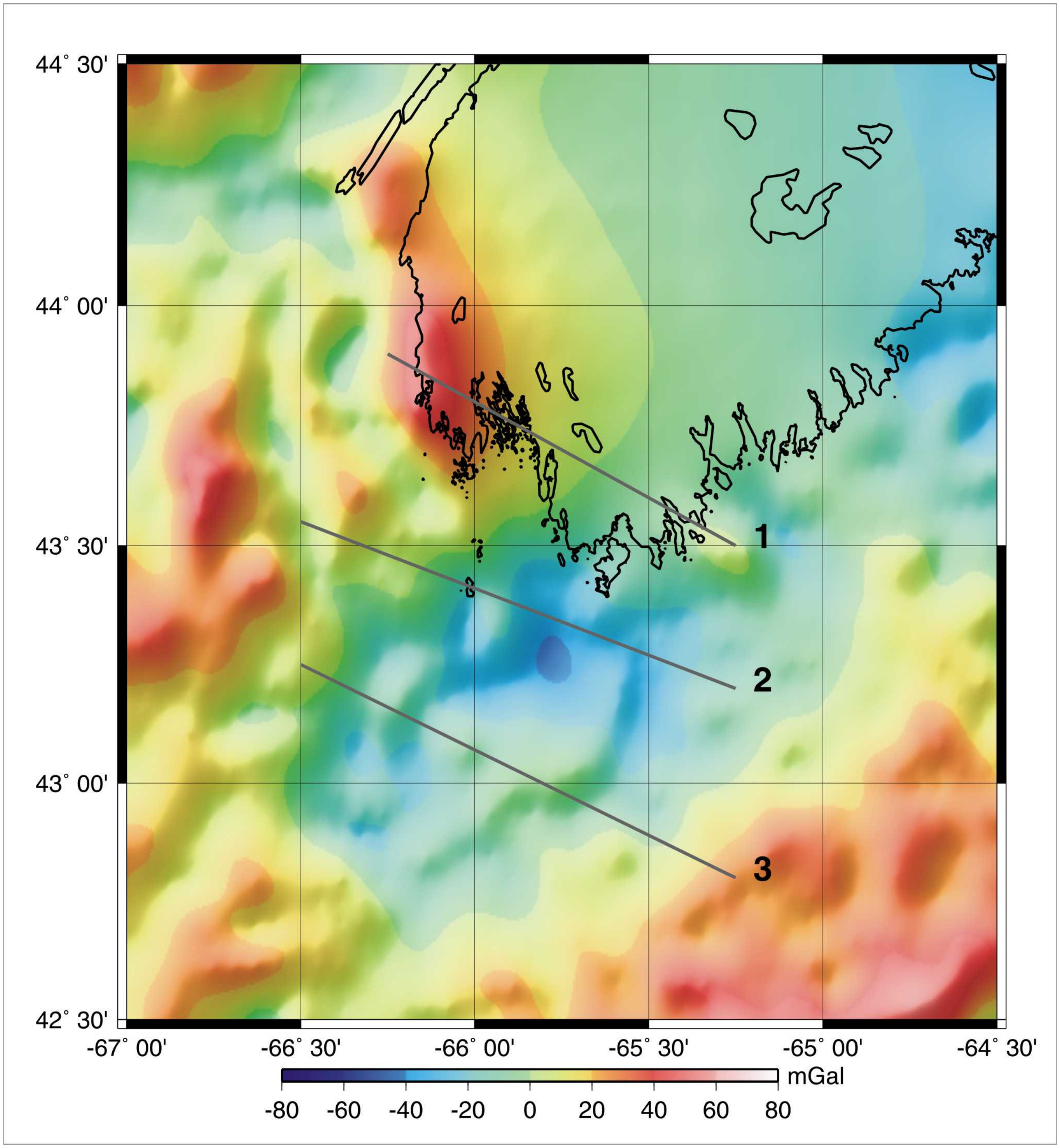

Figure 2.2: *Gravity anomaly data for southwestern Nova Scotia: The lower density area in the offshore is bordered by an area of greater density. (Digital map provided by S.Dehler, GSC Atlantic).*

2.3 SWATH BATHYMETRY

Swath bathymetry mapping involves using a fan-like array of many narrow sonar beams directed to either side of the ship's track to collect a swath image of the seafloor. Bathymetry is mapped along several parallel lines to produce a composite image of the seafloor (eg. Clarke et al., 1996). The data set used in this study was collected over two seasons of sea floor mapping by the GSC Atlantic.

The swath bathymetry data set provides the most recent information on the surficial geology of the shelf. An attempt will be made to correlate this information from the continental shelf with onshore geology.

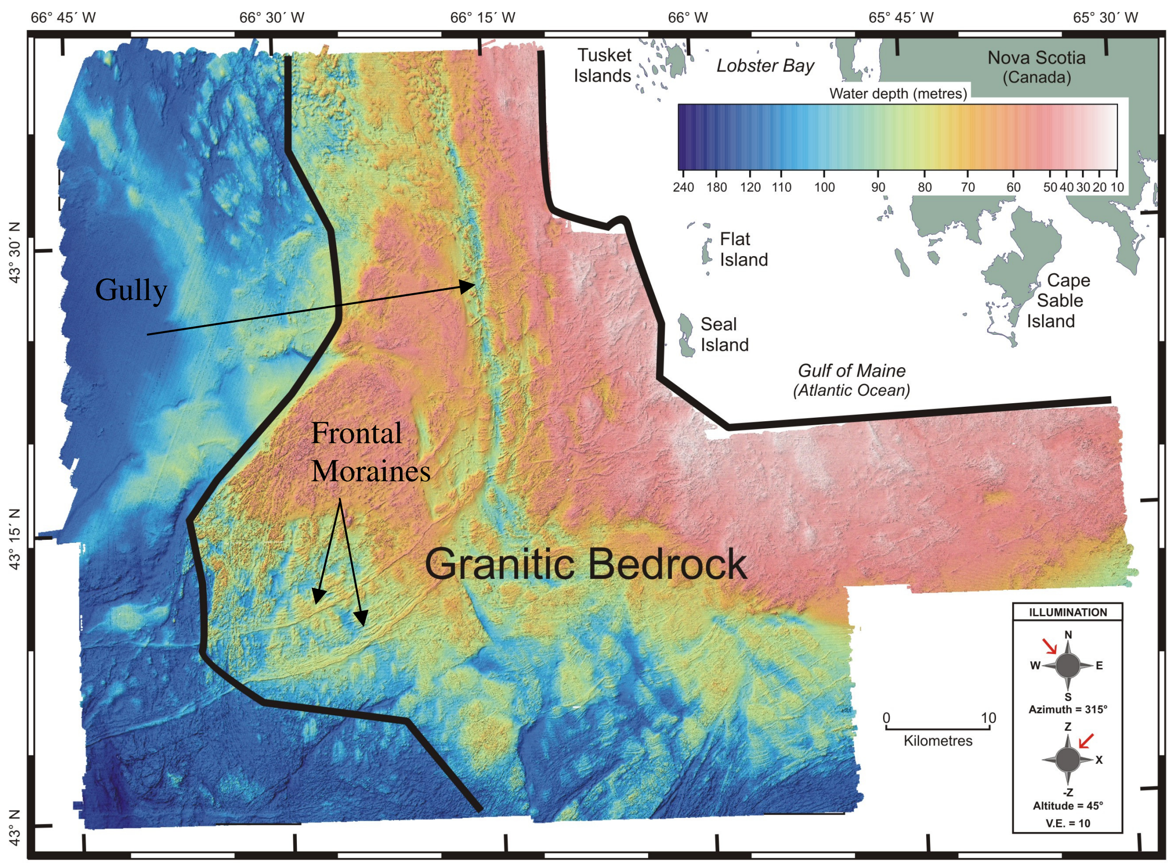

Figure 2.3*: Swath bathymetry data for the German bank on the continental shelf. Note the contrast between hard seafloor and smooth sediment – covered areas. (digital image provided by B. Todd; GSC Atlantic).*

The swath bathymetry map (Figure 2.3) shows a unit that appears to be resistant to erosion that has been interpreted by Brian Todd (personal communication, 2005) at GSC Atlantic as bedrock. The data set also shows frontal moraines that were formed during the retreat of last glaciation as well as the location of a gully that formed as a meltwater channel beneath the glacier, which has been preserved to the present.

2.4 MAGNETIC SUSCEPTIBILITY

Magnetic susceptibility refers to the ability of a rock to become temporarily magnetised while a magnetic field is applied to it. In order to determine the magnetic susceptibility of an outcrop or rock, a known magnetic field is applied to a rock sample and the increased magnetism created by the sample is measured. Since the magnetic fabric of a rock or outcrop can be variable, magnetic susceptibility is measured in perpendicular directions and averaged.

The magnetic susceptibility data used in this study were collected by Chris White (NSDNR), in the area from Yarmouth to Port Mouton and as far north as the South Mountain Batholith, using an Exploranium KT-9 Kappameter (C. White, personal communication, 2005). This particular model of magnetic susceptibility meter recorded up to 13 readings to a precision of two decimal places (SI units $x10^{-3}$), the arithmetic mean of which was calculated to determine the magnetic susceptibility value for each lithology (C. White, personal communication, 2005) .

CHAPTER III
Magnetic and Gravity Modeling

Three 2 – dimensional models were created in order to determine extent, depth of emplacement and geometry of geologic bodies at depth. Model locations were chosen in order to best sample geologic and geophysical features of interest. The models were created in the 2D modeling program GM-SYS and were constrained by magnetic and gravity anomaly profile data extracted from the previously discussed data sets, as well as magnetic susceptibility and density information. Observed surface lithologies onshore and interpreted lithologies offshore (obtained from the swath bathymetry) have been used along with the magnetic susceptibility database to create initial models. The latter are adjusted by varying the assumed densities and geometries of the various rock units to obtain the best possible agreement with observed magnetic and gravity anomalies.

3.1 METHOD

A study of regional geology was undertaken in order to determine geologic and structural information. Combining this information with the observations from the magnetic anomaly, gravity anomaly and swath bathymetry data sets, and the magnetic susceptibility database, geologic features of interest could be correlated to the geophysical data in order to determine profile locations.

The magnetic susceptibility values from the Southwest Nova Bedrock Mapping Database were plotted on a basemap in order to determine the coverage of measurements (Figure 3.1), which aided in the onshore profile location (profile 1). The log of magnetic susceptibility was then plotted versus formation to extract the average magnetic susceptibility for each formation (Figure 3.2). Additionally, density information for each lithology was compiled from a variety of geophysics text books to provide a range of density values for each rock type.

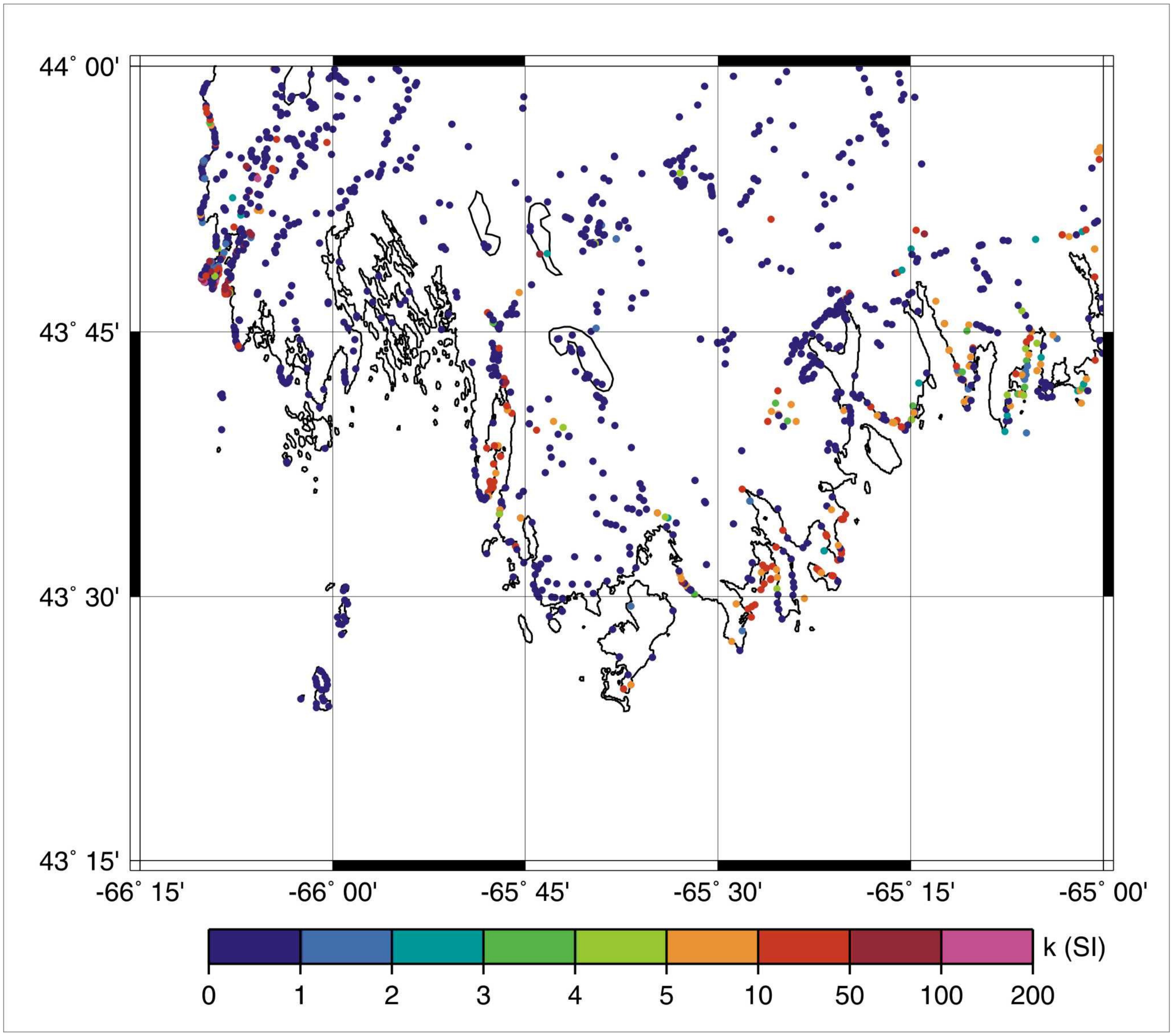

***Figure 3.1**: Plot of magnetic susceptibility values (unpublished NSDNR data from the Southwest Nova Bedrock Mapping Project, Chris White) created to determine profile 1 location (digital map from GSC Atlantic; S. Dehler)*

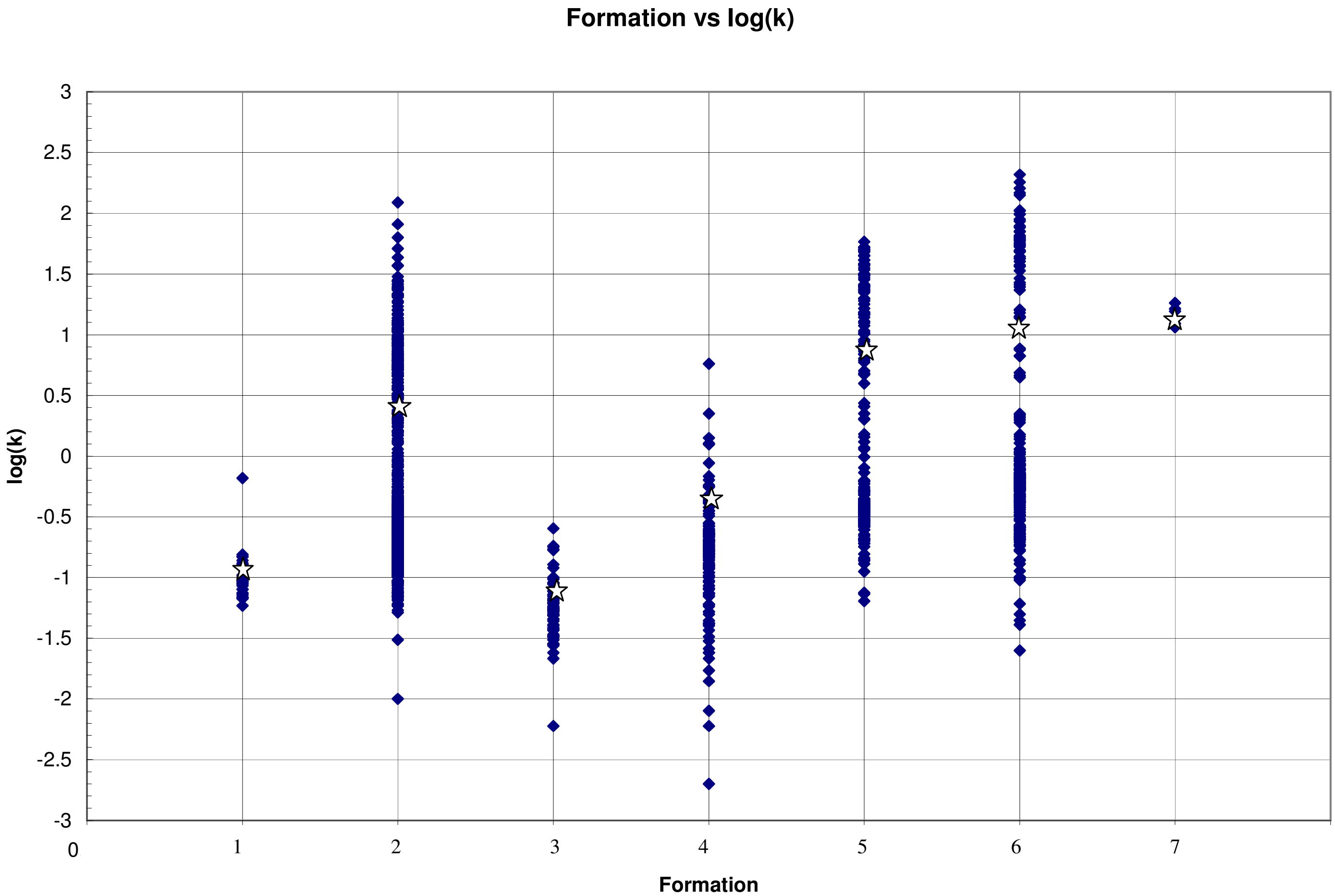

Figure 3.2: *Plot of formation versus log magnetic susceptibility. Note the high magnetic susceptibility for the White Rock and Halifax Formation as well as the Shelburne dyke. Tightly spaced clusters indicate average values; stars indicate the value input into the GM-SYS program. Formations are identified by numbers in table 3.1.*

Formation #	Formation	Lithology	Density (gm/cc)	Magnetic susceptibility (SI units x 10^{-3})
1	Seal Island Pluton	Granite	2.5-2.8	0.12
2	Goldenville Fm.	Metasandstone	2.71*	2.58
3	Shelburne Pluton	Granite	2.5-2.8	0.07
4	Barrington Passage Pluton	Tonalite	2.75	0.43
5	Halifax Fm.	Slate	2.72*	7.7
6	White Rock Fm.	Schist/Basalt	2.72	13.33†
7	Shelburne Dyke	Diorite/Basalt	2.92	14.79

***Table 3.1**: Average magnetic susceptibility values determined from the formation versus log of magnetic susceptibility plot and compiled range of density values input into the GM-SYS modeling program. Density values based on averages in Telford et al. (1990).*
*Values from Keen (1976)
† Value for the entire formation, only the quartzite member was used in modeling.

After initial interpretation of the data sets three profile locations were chosen in order to examine the regional geology of southwestern Nova Scotia and offshore (Figure 3.3). The onshore profile was chosen in order to interpret the intrusion of plutons into the Meguma Terrane and interpret the White Rock Formation as constrained by geologic mapping. The second profile location was chosen in an attempt to put constraints on the extent of the Seal Island Pluton, while the third profile aimed to investigate the area of high magnetic anomaly and the semi-linear features present in the area.

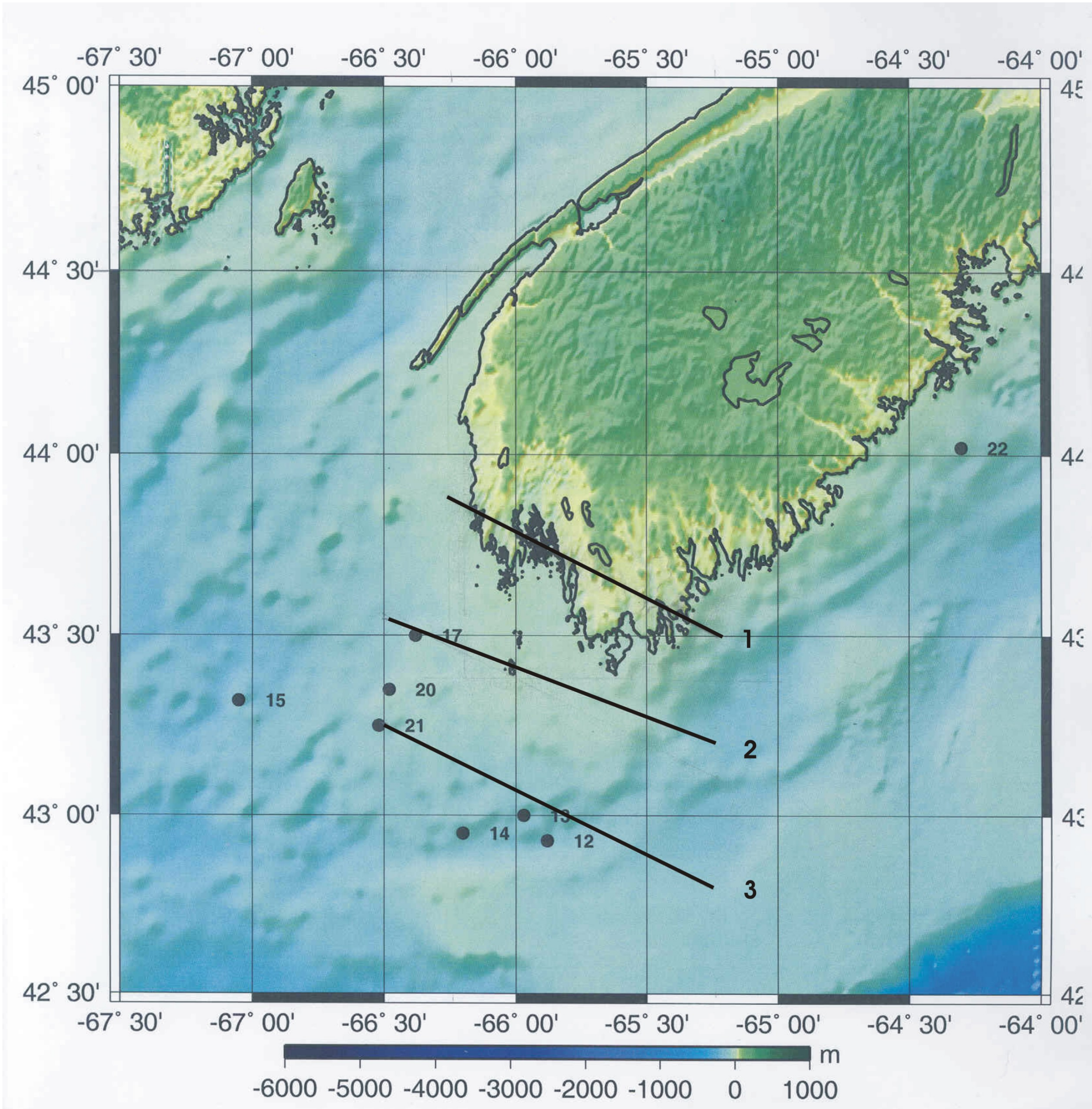

***Figure 3.3**: Profile location map. Profile 1 is located onshore and is constrained primarily by geologic mapping. Geology of profiles 2 and 3 is interpreted from swath bathymetry, gravity and magnetic anomaly data.*

In order to begin the creation of profiles, modeling limits must be input into the GM-SYS modeling program. The limits of the 2D section were dependant upon the size of the profile modeled. The three profiles had varying length dimensions (X); the Z, or depth extent of each profile was set to 5 km. A depth of 5 km was chosen assuming that most of the variation between the profiles was in the uppermost crust. There was a lack of information available to constrain deeper structure in the models. The profile azimuths were measured directly from the profile location map and ranged from 152-160°. Topography was not incorporated into profile 1 as elevations are close to sea level. The offshore profiles incorporate bathymetry data to account for the water depth. Gravity and magnetic anomaly data were extracted from digital data sets at 1 km spacing and imported into the program as text files. The following values for the Earth's magnetic field were adopted: strength = 54000.0 nT, inclination = 65°, declination = -21°.

	Cross-section limits	**Azimuth**	**Strike Angle**	**Coordinates/Endpoints Lon (E), Lat (N)**
Profile 1	0 -94 km	151°	90°	-66.25 43.90 -65.25 43.50
Profile 2	0 -112 km	160°	90°	-66.50 43.55 -65.25 43.20
Profile 3	0 -118 km	151°	90°	-66.50 43.25 -65.25 42.80

Table 3.2: *Limitations of 2D profile orientations*

3.2 PROFILE 1:

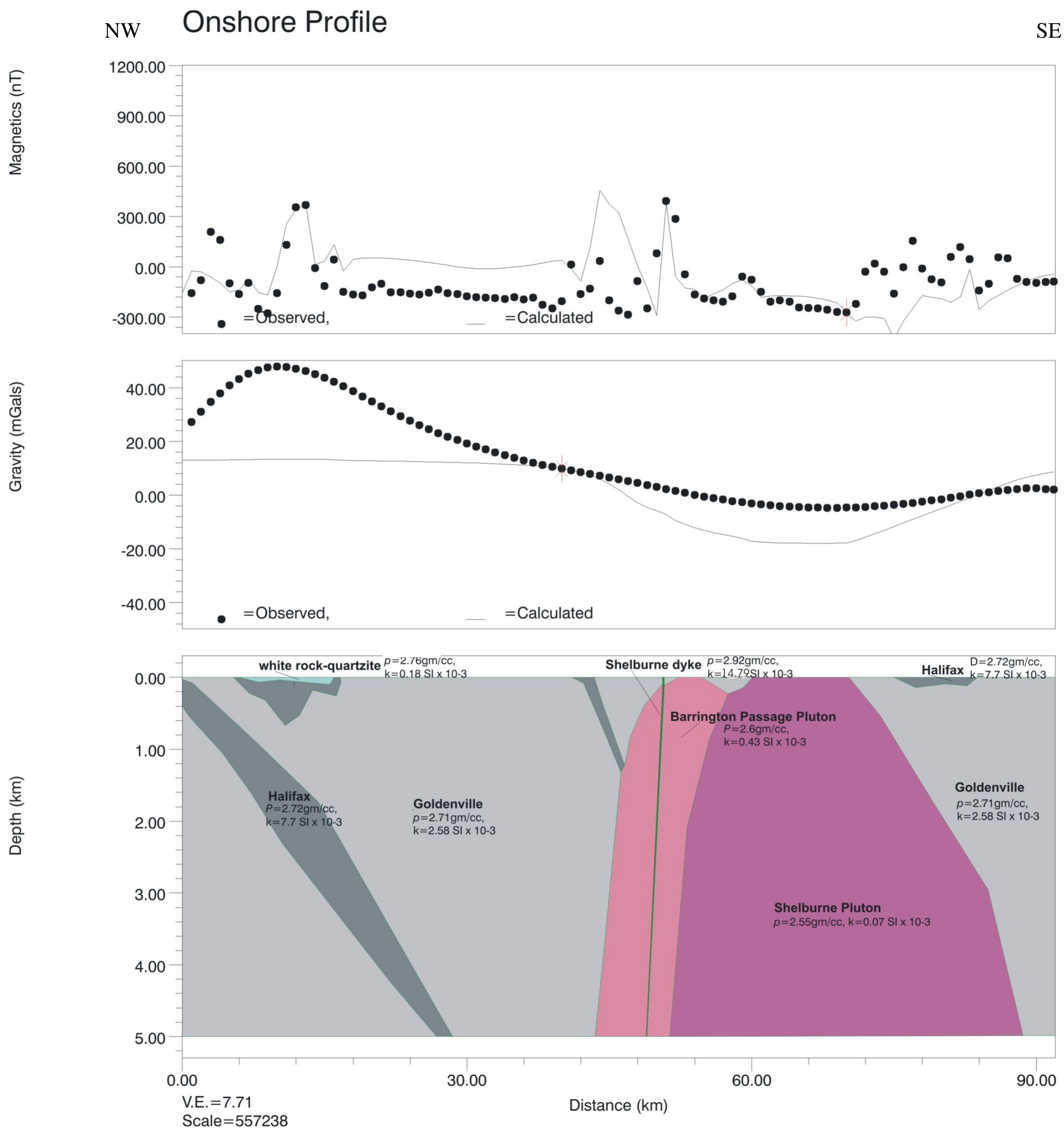

***Figure 3.4**: Model 1: Onshore model from Pembroke to Barrington Passage showing the presence of two plutons at 5 km depth intruding the Halifax and Goldenville Formations. The White Rock Formation is present in the form of a syncline.*

Profile 1 displays a relatively good fit between the calculated and observed magnetic anomaly curves. A large positive anomaly is generated by the magnetic signature of the Halifax Formation as well as the Shelburne dyke. Areas of misfit are greatest over Meguma rocks, suggesting greater complexity of the Goldenville and Halifax Formations than shown in this model.

The fit of the observed and calculated gravity anomaly curves is similar to the magnetic data in area of misfit. In the west end of the profile, the observed large positive gravity anomaly was not modeled successfully. The gravity misfit suggests that more mass is required in the model; perhaps the Goldenville Formation extends to depths greater than 5 km and the model is not homogenous below 5 km depth as the programs assumes. There is a reasonable match of observed and calculated curves over the southeastern part of the model; however, there is some degree of misfit over the Barrington Passage and Shelburne Plutons where lower densities, or thicker plutons, are suggested.

3.3 PROFILE 2:

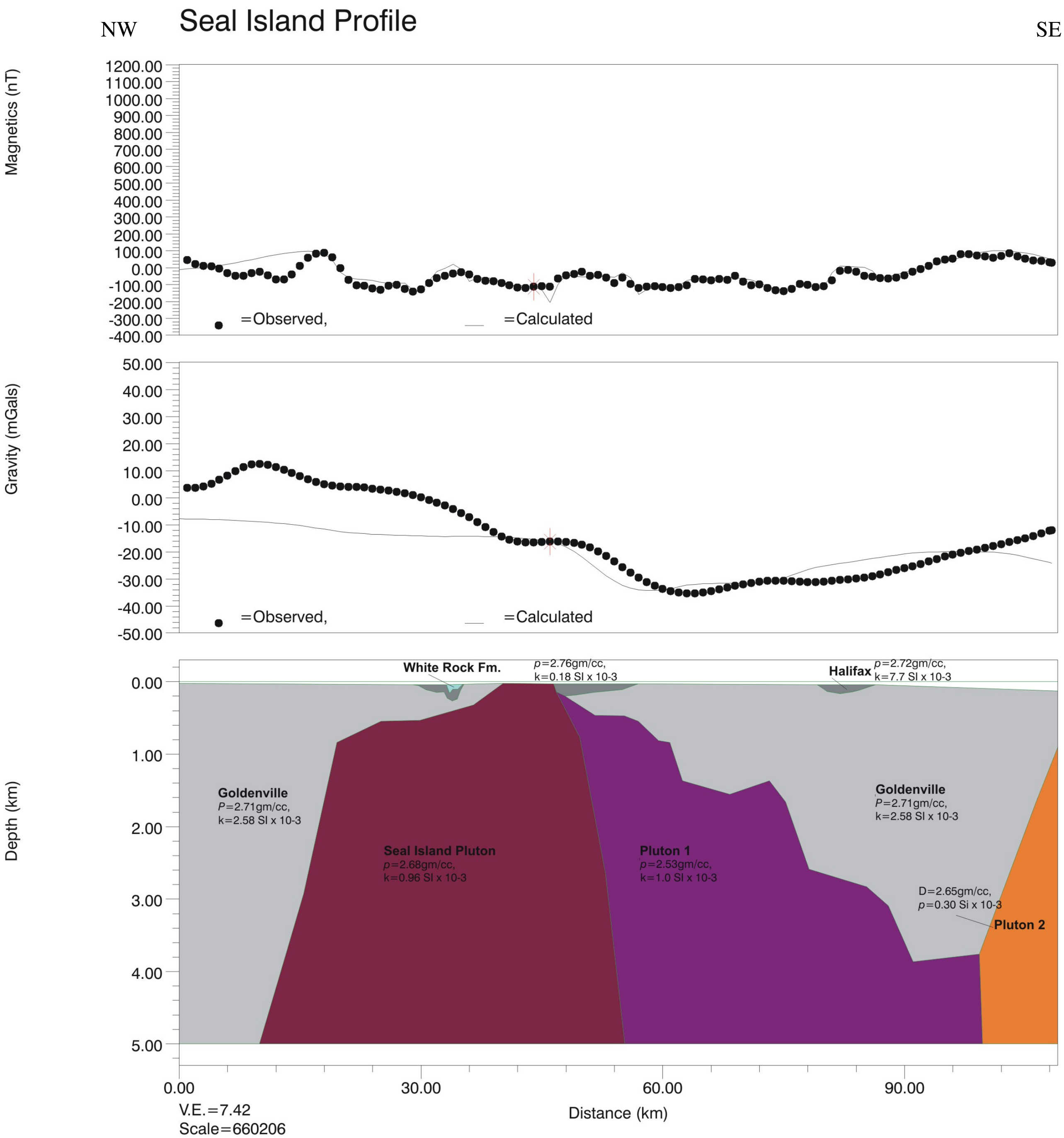

***Figure 3.5**: Model 2: Offshore model and profile south of Mud and Seal islands showing the area to be underlain by the Seal Island Pluton and Pluton 1 at depth.*

The fit of the observed and calculated magnetic anomaly data is very good with minor exceptions in the west end of the profile. In the west end there is a slight misfit over the Goldenville Formation, likely caused by a small near - surface feature not included in the model. Profile 2 features a broad, slightly negative anomaly due to the combined effect of the Seal Island Pluton and Pluton 1 that are bordered by the Goldenville Formation.

Gravity information is suitably matched between observed and calculated curves except at the west end of the profile. In this area the observed gravity is slightly higher than the calculated anomaly suggesting the Goldenville has a vertical extent of greater than 5 km in this region, or a greater density than its measured onshore expression. The observed gravity anomaly could also indicate that the Goldenville Formation overlies higher density rock.

3.4 PROFILE 3:

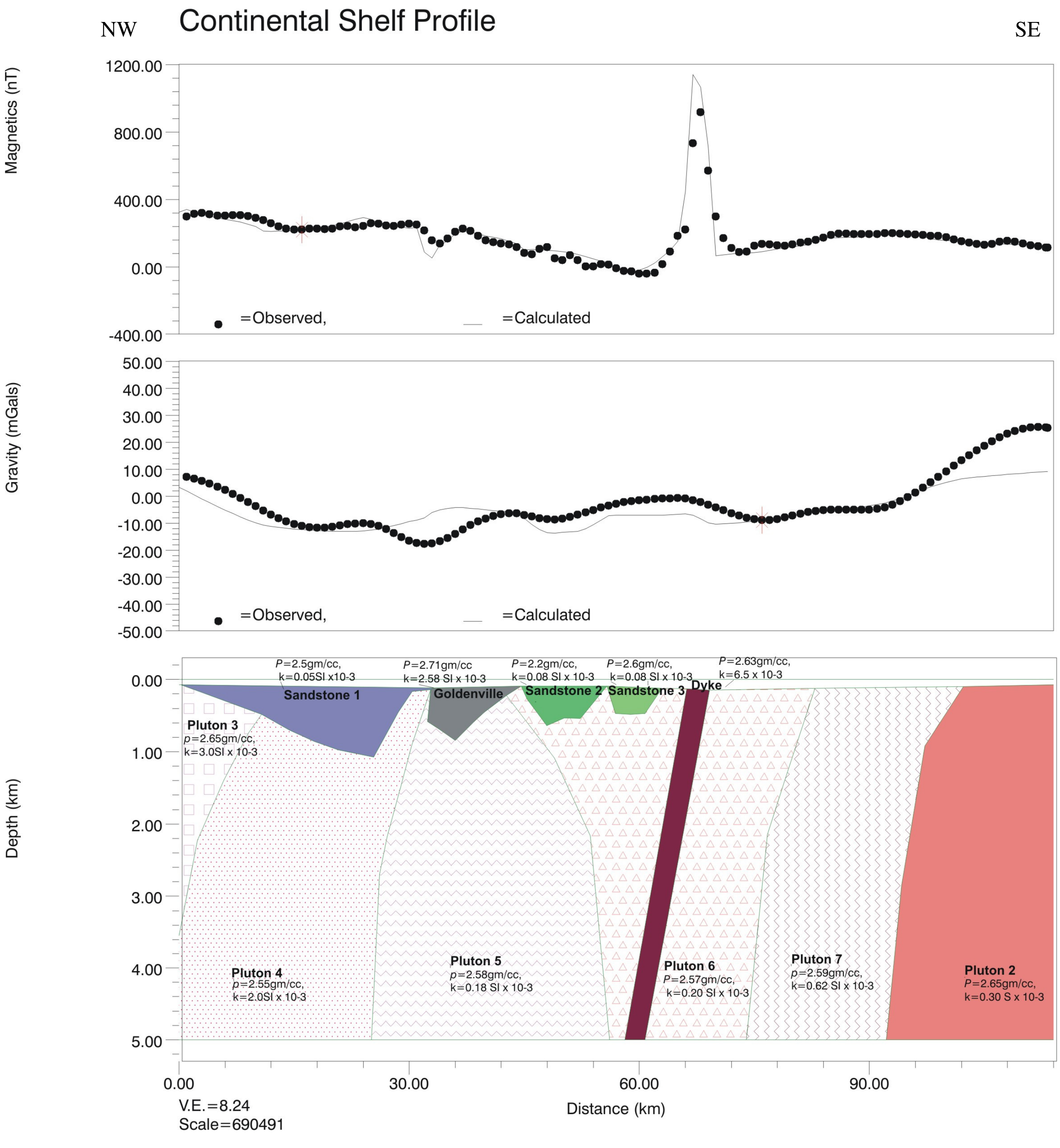

Figure 3.6*: Model 3: Continental shelf model displaying plutonic rocks overlain by sandstone and shale. Up to six plutons with similar magnetic susceptibility and density values that have been intruded by a dyke at ~60 km.*

The fit of the observed and calculated magnetic anomaly curves is quite good. The magnetic field values are consistently between 0 and 300 nT with the exception of the large positive anomaly generated over the intrusion at 66 km distance, where values are as high as 960 nT. Fit of the gravity anomaly curves is within 15 mGal with some degree of misfit at 35 km distance over Pluton 5.

OVERVIEW OF PROFILES

In general the fit of observed and calculated curves for both the magnetic and gravity anomaly is much better in profiles 2 and 3 compared to profile 1, in part because there are fewer constraints in the offshore profiles. Another key difference is the type of rocks present. Profile 2 contains less of the Halifax Formation than Profile 1, whereas the Halifax Formation is absent in the third profile. The contact between the Goldenville and Halifax Formations generates small anomalies in the calculated magnetics that are not present in the observed data, suggesting the relationship between these units is more gradational than shown in the models.

Profile 1 has an area of misfit over the Goldenville unit present from 15-40 km. In comparison to the Goldenville presence throughout the remainder of the profile the misfit from 14-40 km is an interesting feature. This may be due to a slight variance in the magnetic susceptibility throughout southwest Nova Scotia.

The combined effect of the Seal Island Pluton and Pluton 1 in the second profile generates a broad, slightly negative anomaly. This anomaly is generated by the fact that the plutons are bordered by the Goldenville Formation which is slightly more magnetic.

Profile 3 contains several low density plutons with similar magnetic susceptibility. The magnetic profile for this section is dominated by the dyke-like intrusion at ~60 km. The magnetic anomaly generated by the Shelburne Dyke was ~400 nT, the intrusion modeled in Profile 3 generated a magnetic anomaly of >950 nT. The magnetic anomaly map (Figure 2.1) suggests that this feature may be a localized intrusion, but there are no constraints on depth or composition.

CHAPTER IV
Interpretation of Models

The following interpretations have been made based on the 2D magnetic and gravity profiles of the study area. Limits to the extent of the Halifax, Goldenville, and White Rock Formations as well as plutonic activity in the region can be speculated on and correlated between models.

4.1 MODEL 1 OBSERVATIONS

The 2D section presented in profile 1 provides a cross-section of the onshore geology of southwestern Nova Scotia. The model displays the presence of the Barrington Passage and Shelburne Plutons to 5 km depth as well as the Halifax, Goldenville and White Rock Formations.

The Barrington Passage and Shelburne plutons present in the model outcrop at the surface and have known locations determined from geologic mapping. The Barrington Passage Pluton (ρ=2.6gm/cc, k=0.43 SI x 10^{-3}) intrudes the Goldenville Formation and has also been intruded by the Shelburne Pluton as well as the Shelburne dyke, which corresponds with available age information. The Shelburne dyke (ρ=2.92 gm/cc, k=14.79 SI x 10^{-3}) has been interpreted as a near vertical body based on magnetic and gravity modeling. The Shelburne Pluton (ρ=2.55gm/cc, k=0.07 SI x 10^{-3}) itself not only intrudes the Barrington Passage Pluton, but also the Goldenville Formation as determined from modeling.

The contact between the Goldenville and Halifax Formations, or the Goldenville – Halifax Transition zone (GHT), generates anomalies in the magnetic data due to metal enrichment in the zone between the formations (Zentilli et al., 1986). This zone of enrichment leads to a complex magnetic signature as observed in the model.

The White Rock Formation is present in the form of a dipping syncline in the west end of the profile, satisfying the observed and calculated magnetic anomaly curves. The modeling of the White Rock Formation as a syncline disagrees with the findings of MacDonald et al. (2002) in that the formation is divided into seven map units that appear to young from west to east. Further, the findings of MacDonald et al, were inconsistent with a previously assumed synclinal structure (MacDonald et al., 2002). Formation properties (ρ=2.76gm/cc, k=0.18 SI x 10^{-3}) used in the model represent an average of all lithologies, and the formation is assumed to conformably overlie the Halifax Formation. Using the data provided in this study, a syncline provided the best fit to the constraints.

4.2 MODEL 2 OBSERVATIONS

Model 2, the offshore profile south of Mud and Seal Islands, is similar to Model 1 in composition. Like Model 1, the Halifax, Goldenville and White Rock Formations are present and have been intruded. Three plutons are present within the model, two of which have been inferred by the gravity and magnetics. The third pluton, the Seal Island Pluton, has had its magnetic susceptibility measured directly.

A higher susceptibility value than the measured value was required in order to fit the observed and calculated magnetic susceptibility curves for the Seal Island Pluton suggesting a greater content of magnetic minerals than previously thought. The Seal Island Pluton was inferred from modeling to have a surface width of ~6 km at the seafloor.

Two of the three plutons presented in Profile 2 appear to be exposed at the surface of the seafloor. The Seal Island Pluton (ρ=2.68gm/cc. k=0.96 SI x 10^{-3}) is partially exposed on Mud and Seal Islands and is shown in this model intruding pluton 1, as well as the Halifax and Goldenville Formations. Pluton 1 (ρ=2.53gm/cc, k=1.00 SI x 10^{-3}) displays an irregular intrusion into the overlying Goldenville Formation with its depth varying from 0.3 to 5 km. The shape and position of inferred plutons is determined from matching the observed and calculated curves for magnetic and gravity anomaly.

The Halifax and Goldenville Formations are present in this model as a thin folded veneer of metasedimentary rocks covering rocks of igneous origin. The Halifax Formation does not appear to extend greater than 0.2 km depth while the Goldenville Formation appears to be the dominant lithology of the Meguma Group in this profile, extending to 5 km depth. The White Rock Formation is determined from modeling to continue from the onshore as a syncline extending to 0.16 km depth.

4.3 MODEL 3 OBSERVATIONS

Model 3 is very distinct from the first two profiles in that the Halifax Formation is not present. Instead, Model 3 displays the presence of up to 6 plutons covered by thin units similar to sedimentary sandstone and shale, plus a small exposure of the Goldenville Formation. The presence of 6 plutons and the units covering them was inferred from the match of observed and calculated magnetic and gravity information where a slight variance in properties was required to match the curves. The properties of the plutons can be found in Table 4.1, numbered 2 through 7. Plutons 2 and 3, located in the east and west ends of the profile, were found to have greater density than the surrounding plutons, corresponding to the observations from the gravity anomaly data.

Table 4.1*: Density and Magnetic Susceptibility values determined from models. Density values have been measured by Keen (1976). Measured magnetic susceptibility information is from the southwest Nova mapping project*

Geologic unit	Density (gm/cc)		Magnetic susceptibility (SI x 10^{-3})	
	Measured	Inferred	Measured	Inferred
Halifax Formation	2.72		7.7	
Goldenville Formation	2.71		2.58	
White Rock		2.76	0.18	
Barrington Passage Pluton		2.60	0.43	
Seal Island Pluton		2.68		0.96
Shelburne Pluton		2.55	0.07	
Shelburne Dyke		2.92	14.79	
Pluton 1		2.53		1.00
Pluton 2		2.65		0.30
Pluton 3		2.65		3.00
Pluton 4		2.55		2.00
Pluton 5		2.58		0.18
Pluton 6		2.57		0.20
Pluton 7		2.59		0.62
Intrusion		2.63		6.50
Sandstone 1		2.50		0.05
Sandstone 2		2.20		0.08
Sandstone 3		2.60		0.08

The profile also shows the presence of a dyke-like intrusion (ρ=2.63gm/cc, k=6.50 SI x 10^{-3}) corresponding to the semi-linear features from the magnetic anomaly and first vertical derivative maps. The magnitude of the magnetic anomaly dominates the profile and could possibly extend to greater than 5 km depth. The origin of the anomaly is unknown. The values of the Shelburne dyke were initially input for the body but were insufficient for matching the observed to the calculated curves. As a result the magnetic susceptibility and density values were inferred from modeling. The magnetic susceptibility value matches the value found by Pe-Piper and Loncarevic (1989) in Core 20 (Table 4.2), which was defined as granite, however the granite lithology is inconsistent with the dyke-like lithology. Density inferred for the intrusion suggests an igneous origin dyke that intrudes the less-dense surrounding plutons.

Core #	Rock Type	Magnetic Susceptibility (SI x 10^{-3})
12	Metavolcanic rock	22.5
13	Metapelite	15.6
14	Granite	0.18
17	Deformed granite	0.23
20	Granite	6.5
21	Granite	10.1
22	Quartzite	0.28

Table 4.2*: Core information from Pe-Piper and Loncarevic(1989). The values collected by Pe-Piper and Loncarevic are within the same range as those inferred in this study. Locations shown in Figure 1.1.*

Overlying the intrusive units of model 3 sedimentary sandstone units have been inferred. There are four distinct units, one of which could be an exposure of the metasedimentary Goldenville Formation. The other three units are interpreted as sandstones (from west to east (1) ρ=2.5gm/cc, k=0.05 SI x 10^{-3} (2) ρ= 2.2gm/cc, k=0.08 SI x 10^{-3} (3) ρ=2.6gm/cc, k=0.08 SI x 10^{-3}) present in pockets within the granitic bedrock.

Comparing the findings of this study with the drill core findings of Pe-Piper and Loncarevic (1989) correlation between granitic rock units exists. Magnetic susceptibility measurements on core samples of granite were between 0.23 and 10.1 SI x 10^{-3} (from cores 14, 17, 21, 22), which fit within the range of values determined from this study. Cores 12 and 13, which are south of profile 3, were found to be metapelites, which correspond to the Halifax Formation. This study found the Halifax Formation to be absent in profile 3, although it is located between the onshore and the core sample area. These two cores exhibit the highest magnetic susceptibility values reported by Pe-Piper and Loncarevic (1989).

CHAPTER V
Discussion

The previously discussed models and their interpretations have provided new information on the regional geology of southwestern Nova Scotia. The linking of these three profiles to the known geology of onshore Nova Scotia and the continental shelf provides insight into the igneous history of the region.

5.1 Discussion of magnetic profiles

The models generated in this study satisfy, to a first approximation, the observed gravity and magnetic anomaly data extracted from regional data sets, while taking into account measured magnetic susceptibility data and geologic mapping. The 2D models provide a geologically realistic interpretation using the given data. In using forward modeling a variety of geometries and solutions are always possible. Initial models were created to 3 km depth and later changed to 5 km in order to better fit the available data. Creating the models to 5 km depth continued to be problematic, particularly for the gravity data given that the program then assumes everything beneath 5 km depth to be uniform and data indicated density contrasts may extend to greater depth. Most of the variation in rock composition, and therefore density and magnetic properties, occurs within the upper 5 – 10 km, so it may have been necessary to extend the models to 10 km depth. However, constraints on lower structure were not available.

Model 1 was created in the onshore region as a way to groundtruth the correlation of units. In starting with a known lithologic presence at the surface of the model and attempting to extend those units laterally into the offshore, as well as to 5 km depth, a regional study of the area was undertaken. In Profile 1, as with all of the profiles, it was necessary to fit the calculated magnetic anomaly to the observed anomaly by matching peak positions and amplitudes. The magnetic anomaly data for profile 1 indicated a much more complex profile than profiles 2 and 3 due to the Goldenville - Halifax contacts, or GHT (Goldenville – Halifax Transition zone), whereas the offshore profiles were modeled to have less or, in the case of the third profile, no Halifax Formation.

Gravity anomaly data provide an indication of the symmetry or shape of geologic bodies, whereas magnetic anomaly is especially helpful in determining orientation of such bodies. Using these principles the presence of plutons was determined although many plutons did not reach the surface of the profile. The plutons were inferred while geometry and density were adjusted to fit the gravity anomaly. In a similar fashion the dip of folded bodies was determined, which found the Shelburne dyke to be roughly vertical and the White Rock formation to be a southeast dipping syncline in Models 1 & 2.

5.2 Regional Comparison

This study has been successful in interpreting the regional geology of the study area. Correlations have been made that show possible links between the onshore and the offshore, as well as relationships between plutonic bodies.

As observed in the onshore model the surface expressions of the bodies show much different geology at depth. The Halifax, Goldenville and White Rock Formations have all been folded and the Goldenville Formation appears to be the dominant lithology intruded. The surface expressions of the plutons are not indicative of their intrusion history. Many of the plutons intrude not only the metasedimentary background rocks but other plutons as well, a history of which is helpful in determining the sequence of events.

The onshore exposure of the Shelburne pluton correlates to pluton 2 of profile 2, indicating a relationship in intrusion history. A slight variance in magnetic susceptibility is shown, which could represent the evolution or change in pluton composition over time and space. A further correlation can be made between profiles 2 and 3 given that Pluton 6 is present in the east end of both profiles, having identical density and magnetic susceptibility. Profile 3 is underlain by 6 apparent plutons beneath a thin covering of sediments and sedimentary rock. The similarities in density and susceptibility of these plutons indicate that they may in fact be components of a much larger pluton with varying amounts of magnetic minerals, rather than individual plutons. These individual plutons do, however, have a similar density and susceptibility to that of the Shelburne and Barrington Plutons onshore, and link the onshore with the continental shelf (Figure 5.1).

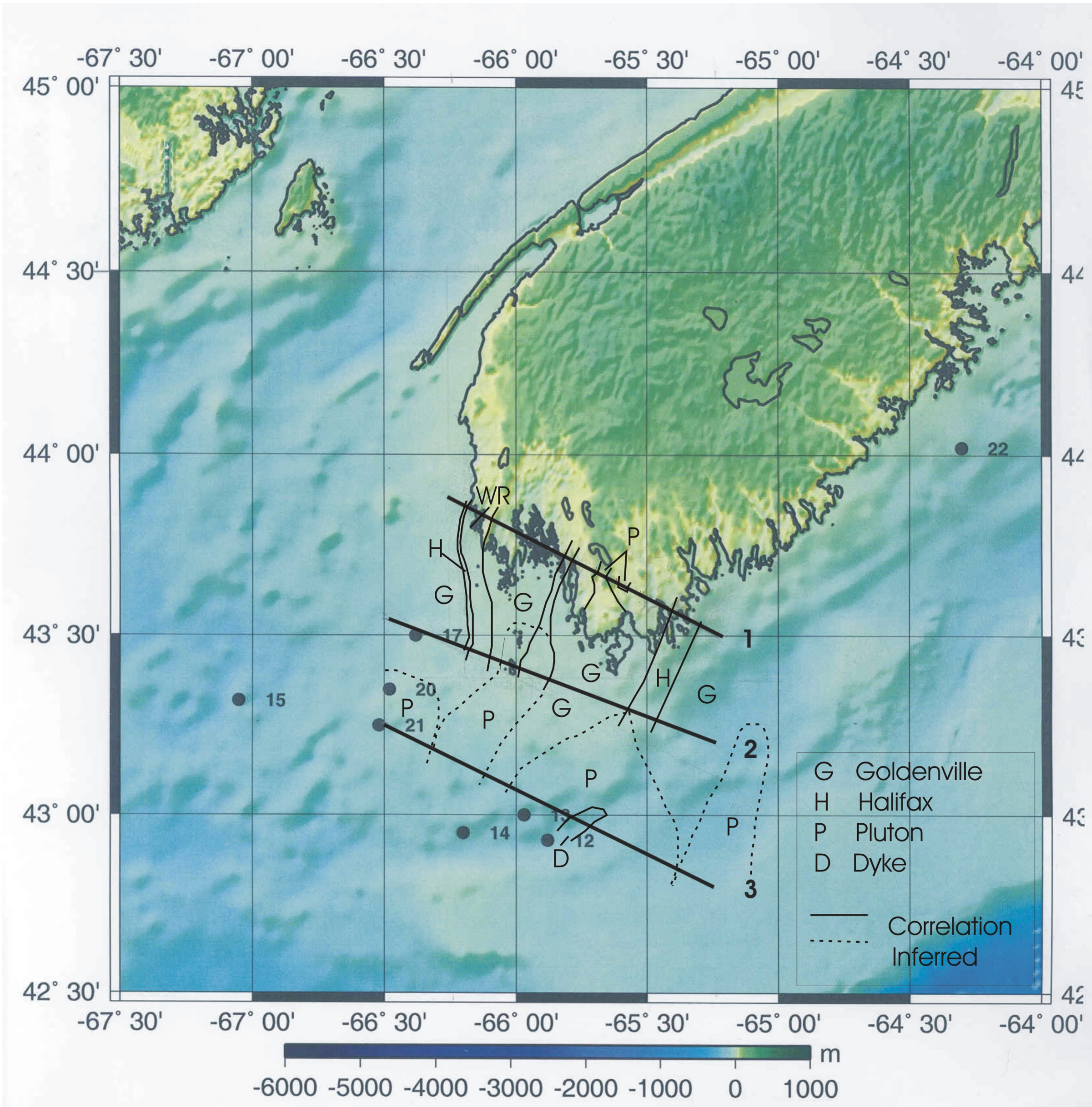

Figure 5.1: *Map of correlated and inferred geology: Correlation between Profiles 1 and 2 is fairly certain. Links between Profiles 2 and 3 were speculative given the area is mainly underlain by plutons and the Goldenville has only a minor presence in the third profile. Areas of similar plutonic units were grouped and correlated.*

5.3 Conclusions

• The Meguma Group extends into the offshore as far as the German Bank on the continental shelf. The White Rock Formation has a minor presence in Models 1 & 2, as a southeast dipping syncline as interpreted by the modeling.

• Complex magnetic anomaly signatures are generated by the contacts between the Halifax and Goldenville Formations (eg. the GHT, the Goldenville – Halifax Transition zone) due to the metal enrichment.

• Closer constraints can be placed on the extent of the Seal Island Pluton given the findings of this study. The Seal Island Pluton was found to have a near-surface exposure of ~ 6 km, and broadens considerably with depth.

• The area of positive magnetic anomaly and negative gravity anomaly that was a target in profile 3 was confirmed to be granitic bedrock as suggested by the swath bathymetry.

• The strong magnetic anomaly in the offshore was modeled as a dyke yet this feature may possibly represent a localized intrusion. The classification of this feature is difficult due to lack of constraints on depth or composition.

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