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Structure of the Moyie Anticline delineated on a grid of reflection seismic profiles in southeastern British Columbia

by

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Abstract

The Moyie anticline in southeastern British Columbia is the lowermost regional structure of the Purcell anticlinorium; it is cored by Mesoproterozoic strata of the Belt-Purcell Supergroup. Analyses of a grid of seismic reflection profiles have provided new information on the detailed structure of the anticline. In the shallow crust, four horizons were picked over a network of two-dimensional seismic reflection data to illustrate the three-dimensional structure. The resulting maps highlight the plunging structure of the Moyie anticline above the homoclinally dipping near-basement reflections. Isochron maps show variations in the thickness of the package of intruded sills as well as variations in their emplacement.

To address the deep structure of the Moyie anticline, key reflection horizons were correlated with a deep drill hole and then used as important constraints to interpret regional high isostatic gravity values. Together, these data provide new information that the anticline is likely cored by Purcell strata at depth; previous interpretations had proposed that the anticline was cored by high density basement. The detailed gravity analysis found that the large quantity of Moyie sills is sufficient to produce the observed high and thus that the core of the Moyie anticline is likely to be thickened lower Aldridge strata.

Acknowledgements

I greatly appreciate all the guidance and support from my supervisor, Fred Cook. I saw this project as a wonderful opportunity when he suggested it and have thoroughly enjoyed working on it. I would like to thank Kris Vasudevan for his help with the seismic processing and so many other aspects of the project, Frank Dostaler and Mike Thomas for their help with preparing the gravity data for modelling and the Gallagher Library staff for their consistent help. This project received funding through the Geological Survey of Canada's Targeted Geoscience Initiative (TGI3). I would have been even less efficient without the influence of my officemates, Arie van der Velden and Fred Gaidies, to keep me on track. A task that was often not aided by my friends and fellow grad students, especially Joanna Cooper, Kelley Classen and Catrina Alexandrakis, who provided helpful suggestions when things were not going smoothly and willing to celebrate all of the small victories along the way. Last but not least, I would like to thank my family for their love and patience as well as their willingness to listen.

Dedication

To resilient Patterson women, Mom and Nana, who valued education so highly; I would not be the person I am today without either of you in my life. I wish you were here to see the finished result and celebrate.

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Chapter One: Introduction

1.1 General

The objective of this study is to consider both the deep and shallow crustal structure of the Moyie anticline in southeastern British Columbia through interpretation of reflection seismic data and gravity modeling. The Moyie Anticline is the southernmost and structurally deepest of a series of north-plunging, nested anticlines in the Purcell Anticlinorium. It is cored by folded Mesoproterozoic Aldridge Formation turbidites of the Belt-Purcell Supergroup that have been intruded by syndepositional mafic Moyie Sills. The nature of the material in the deep core of the Moyie Anticline is significant for palinspastic reconstructions of the southern Canadian Cordillera and for the establishing of the pre-Cordilleran westward extent of the North American cratonic rocks, while the detailed structural trends near the surface are relevant for mineral exploration of stratigraphically controlled deposits that are found through the Purcell anticlinorium.

1.2 Regional Geology

The Purcell anticlinorium is located between the Rocky Mountain foreland thrust and fold belt on the east and generally metamorphosed Neoproterozoic and Paleozoic rocks of the Kootenay Arc on the west. Its east flank is cut by early and middle Tertiary northwest-striking extensional faults associated with the southern Rocky Mountain Trench while its west flank is characterized by moderate to steeply dipping structures associated with contraction and eastward displacement of distal North American strata and possibly accreted rocks. The anticlinorium consists of the Mesoproterozoic Belt-

Purcell Supergroup, which has been intruded by the ca. 1430-1468 Ma Moyie sills (Höy, 1993; Anderson and Parrish, 2000), the Neoproterozoic Windermere Supergroup and local Paleozoic continental margin sedimentary rocks (Figure 1-1). Regional seismic cross-sections coupled with the geological variations have demonstrated that the Moyie anticline was carried above a regional west-dipping décollement that projects eastward beneath the deformed supracrustal rocks of the foreland thrust and fold belt of the Rocky Mountains (Cook and van der Velden, 1995).

The subsurface structure of the anticline is outlined by a thick succession of Mesoproterozoic sills (ca. 1.45 Ga Moyie sills) that were intruded into the Mesoproterozoic Aldridge Formation (e.g. Cook and Jones, 1995). The position of the base of the Aldridge Formation in the anticline and the nature of the rocks in the core of the anticline are uncertain, but important for establishing the relationship between the anticline and deeper rocks to the west.

1.2.1 Regional Stratigraphy

The Belt-Purcell Supergroup is interpreted to have been deposited unconformably on basement gneiss and is in turn unconformably overlain by the Windermere Supergroup, Cambrian clastic and/or carbonate rocks (Höy, 1993). The oldest exposed rocks are the Proterozoic Aldridge Formation, which consist of deep-water shales, argillites and turbidites, have been intruded by 1430-1468 Ma gabbroic sills (Figure 1-1; Höy, 1993; Anderson and Parrish, 2000). The thickness of the Aldridge strata is unknown (Figure 1-2), as the base is not observed, but exposures with composite stratigraphic thicknesses of up to 20.4 km have been mapped in the northern United

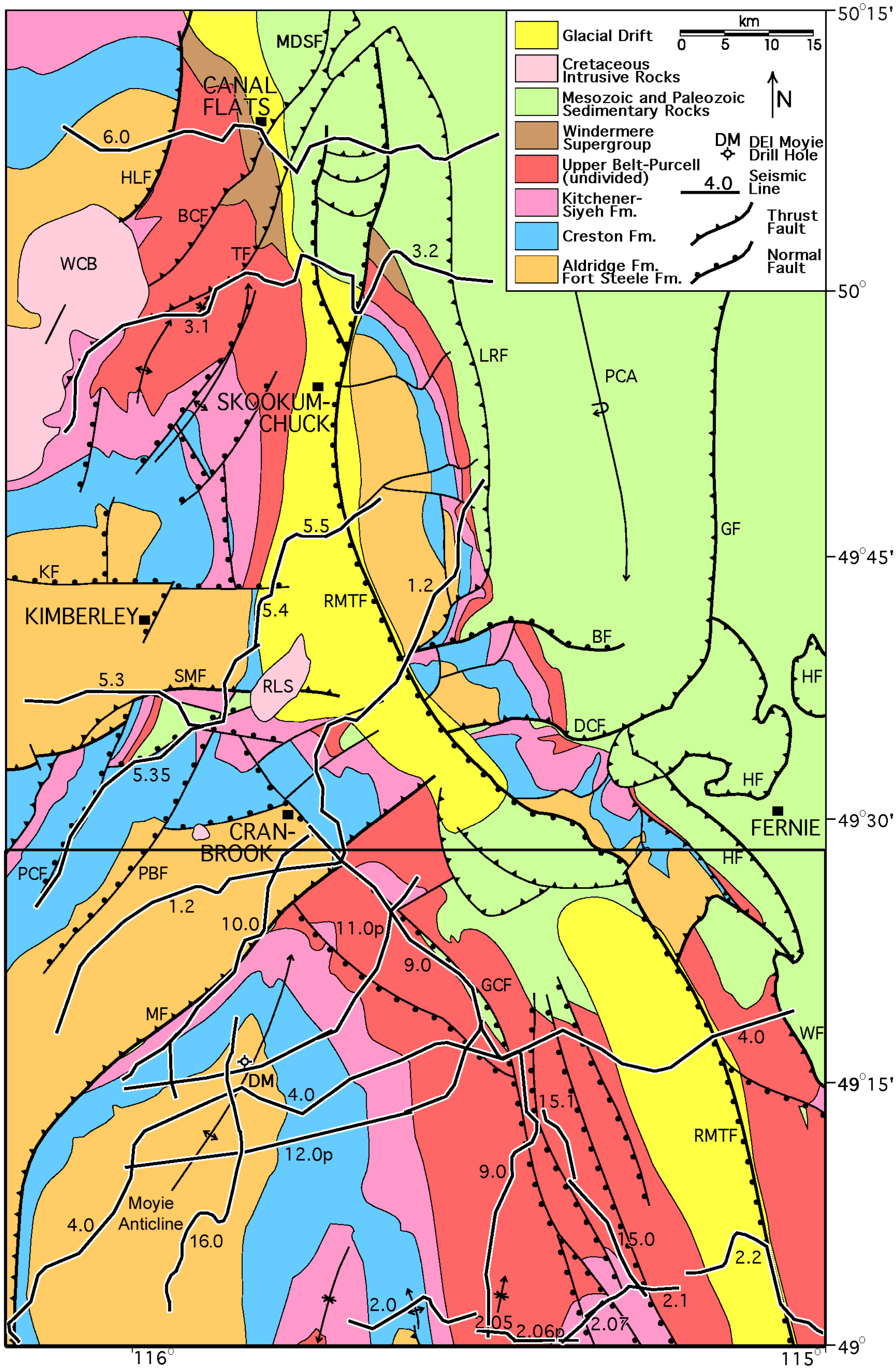

Glacial Drift
Cretaceous Intrusive Rocks
Mesozoic and Paleozoic Sedimentary Rocks
Windermere Supergroup
Upper Belt-Purcell (undivided)
Kitchener-Siyeh Fm.
Creston Fm.
Aldridge Fm. Fort Steele Fm.
km
0 5 10 15
N
DM DEI Moyie Drill Hole
4.0 Seismic Line
Thrust Fault
Normal Fault
50°15'
50°
49°45'
49°30'
49°15'
49°
116°
115°
MDSF
CANAL FLATS
6.0
HLF
BCF
TF
WCB
3.2
3.1
LRF
PCA
SKOOKUM-CHUCK
GF
5.5
KF
1.2
RMTF
5.4
KIMBERLEY
BF
HF
5.3
SMF
RLS
DCF
5.35
HF
FERNIE
CRAN-BROOK
HF
PCF
PBF
1.2
10.0
11.0p
9.0
GCF
MF
4.0
WF
DM
4.0
15.1
12.0p
RMTF
9.0
Moyie Anticline
4.0
16.0
15.0
2.2
2.1
2.0
2.05
2.06p
2.07

Figure 1-1: Geologic map of southeastern British Columbia with the locations of the majority of the seismic profiles recorded by Duncan Energy and their exploration well (DM) (modified from van der Velden and Cook, 1996). Boxed area shows the location of this study. Abbreviations used are: BCF, Buhl Creek fault, BF, Boulder fault, DCF, Dibble Creek fault, DM, DEI Moyie#1 drill hole, GCF, Gold Creek fault, GF, Gypsum fault, HF, Hosmer fault, HLF, Hall Lake fault, KF, Kimberley fault, LRF, Lussier River fault, MA, Moyie anticline, MDSF, Mount DeSmet fault, MF, Moyie fault, PBF, Palmer Bar fault, PCA, Porcupine Creek anticlinorium, PCF, Perry Creek fault, RLS, Reade Lake stock, RMBD, Rocky Mountain basal detachment, RMT, Rocky Mountain trench, RMTF, Rocky Mountain trench fault, SMF, Saint Mary fault, TF, Torrent fault, WCB, White Creek batholith, WF, Wigwam fault, WMF, Wigwam-MacDonald fault (combined). (previous page)

States (Harrison, 1972), and up to 11 km have been mapped in southeastern British Columbia (Höy, 1984).

The Aldridge Formation is typically subdivided into three members. The Lower Aldridge is dominantly comprised of rusty weathering, thin to medium-bedded, graded, fine-grained quartz wacke, siltstone and argillite, which suggests distal turbidite deposition. The Lower Aldridge is commonly intruded by a number of thick gabbroic Moyie sills (Höy, 1993). The Middle Aldridge Member is comprised of dominantly well bedded, medium to locally coarse-grained, grey weathering quartz arenite, wacke and siltstone and represents classical or proximal turbidite deposits (Höy, 1993). The Upper Aldridge is comprised of medium to dark grey siltstone, argillaceous siltstone and argillite. It is different from the other subdivisions in that it is not a turbidite deposit. Instead, the Upper Aldridge is comprised of pelagic and wind-blown material, which

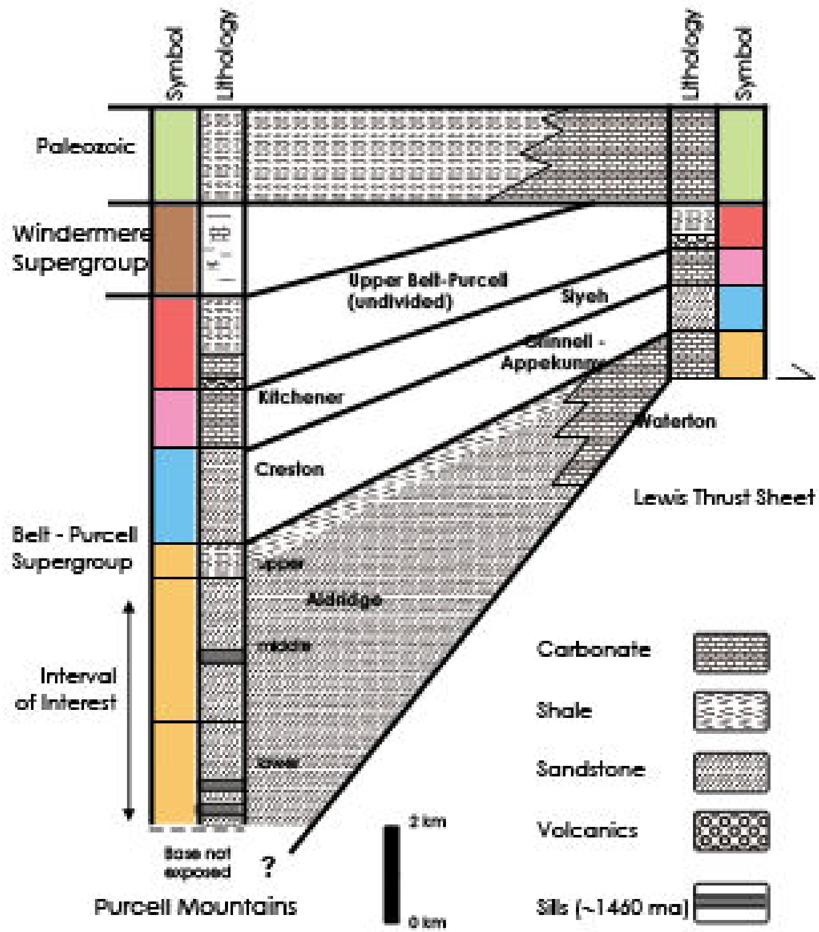


Figure 1-2: Belt-Purcell Supergroup stratigraphy (modified from van der Velden and Cook, 1996). This study concentrates on rocks in the Aldridge Formation.

infilled the Purcell basin. This suggests that the movement on growth faults that formed the basin had ceased by this time (Höy, 1993). Quartz-rich turbidites flowed dominantly from the southeast during the time of Aldridge deposition (Finch and Baldwin, 1983).

The Moyie sills are gabbroic and dioritic sills that are concentrated within the Lower and Middle Aldridge Formation (Höy, 1993). These fine-grained sills range in composition from biotite granodiorite to biotite quartz diorite with hornblende and plagioclase phenocysts dominating and a finer grained groundmass of plagioclase, quartz, hornblende, chlorite and epidote (Höy, 1993). The unusual contacts, internal structures and lack of evidence of erosion further up-section indicate that the Moyie sills intruded into the wet sediments of the Aldridge Formation 1468±3 Ma (Anderson and Parrish, 2001). Hamilton (1983) suggests that the Moyie sills, which compose approximately a quarter of the thickness of the Lower Aldridge, are genetically as well as temporally related to the post-ore alteration fluids in the vicinity of the Sullivan Deposit. Perhaps, a body of magma at intermediate depth was the source of the gabbroic and dioritic sills and drives the convective fluid flow (Hamilton, 1983). Rapid precipitation of sulfides from ascending, metal-bearing fluids flanking locally focused seafloor vents formed the Sullivan deposit as a relatively unmetamorphosed, proximal, clastic-hosted deposit which lies conformably at the top of the lower Aldridge (Hamilton, 1983).

The Aldridge Formation is overlain by the upper Belt-Purcell strata including the Creston and Kitchener-Siyeh Formations (Figure 1-2) that consist of a series dominated by carbonates and shallow water clastic rocks (e.g., Price, 1964, Höy, 1984), which produce little seismic response (Cook and van der Velden, 1995). The Kitchener Formation includes dolostone interbedded with argillite (Reesor, 1983). The Purcell Lava is thick fragmental volcanic rock unit about 60m thick (Reesor, 1983) that was deposited unconformably on the Kitchener Formation.

Within the Purcell anticlinorium, the Belt-Purcell strata are unconformably overlain by the Neoproterozoic Windermere Supergroup locally; however, these rocks are not present in the Moyie anticline, probably due to non-deposition (e.g., Lis and Price, 1976). For example, Devonian strata are found in the footwall of the Moyie fault northwest of the DEI Moyie drill hole (Figure 1-1) where they overlie the Kitchener-

Siyeh formation with angular unconformity with no intervening Windermere or Early Paleozoic rocks (Lis and Price, 1976; Höy, 1984). Thus, the Windermere strata and Lower Paleozoic strata are missing from this part of the Purcell anticloinorium (Lis and Price, 1976), although these strata are present across the northern Purcell anticlinorium.

Purcell strata were deposited west of the rifted western edge of the North American Proterozoic continental craton on a basement of tectonically attenuated continental crust (Price, 1981; 1983). Late Proterozoic block faulting associated with the Goat River orogeny caused rifting and eventually drifting such that the distal part of the westerly prograded sedimentary wedge was extended and moved westward an uncertain distance (Price, 1983).

1.2.2 Structure of the Purcell Anticlinorium

The Purcell anticlinorium is a doubly-plunging structure situated between the thrust and fold belt of the Rocky Mountains and the allochthonous North American, possibly exotic, and plutonic rocks of the Kootenay Arc and Omineca Belt (Figure 1-1). Van der Velden and Cook (1996) describe this anticlinorium as resembling an asymmetric box fold with steeply dipping limbs and a broad, flat top on which a series of chevron-like folds are superimposed. A series of northeast-trending thrust faults (Hall Lake, Saint Mary, and Moyie faults) divide the Purcell anticlinorium into a series of north-plunging anticlines the most southerly of which is the Moyie anticline. These faults are a “family” of imbricate thrust faults that formed during regional contraction (Dahlstrom, 1970); Cook and van der Velden, 1995) during the Late Jurassic to Early Cretaceous and are crosscut by mid-Cretaceous granitic plutons.

The Moyie fault correlates across the southern Rocky Mountain trench to the Dibble Creek fault and the movement along the Moyie fault is dated at between 69 and 71 Ma based on the age of the mylonites found in northern Montana (Fillipone and Yin, 1994). Regional low-grade metamorphism, folding and cleavage development before the deposition of the Windermere Supergroup and intrusive rocks dated at approximately 1300-1350 Ma are a result of the East Kootenay orogeny and associated regional contraction (McMechan and Price, 1982).

Late Proterozoic and Early Paleozoic regional extensional structures associated with the formation and development of the Cordilleran passive margin may have been reactivated later as contractional faults during the Mesozoic and Tertiary. Mesozoic and Early Tertiary contractional faults and associated large folds are carried eastward on basal décollement of the Rocky Mountain foreland thrust and fold belt (Cook and van der Velden, 1995, Höy, 1983). The southern Rocky Mountain Trench Fault is part of a series of Early and Middle Tertiary northwest-striking extensional structures. The fault bounding the east wall of the trench has little or no strike-slip component and has as much as 7 kilometres of dip slip offset (Cook and van der Velden, 1995; van der Velden and Cook, 1996).

1.3 Mineral deposits in the vicinity of the Moyie anticline

There are many historic lead-zinc deposits in this part of southeastern British Columbia. These deposits may have a similar geographic relationship in a northwest-southeast trend, but many of these are stratiform deposits (for example, Sullivan, North Star and Kootenay King; Höy, 1993), whereas some of these are vein deposits (for example, Aurora, St. Eugene and Society Girl; Höy, 1993). Therefore, the mineralization is not likely to be temporally related. The stratabound clastic-hosted deposits were formed during the deposition of the host succession, primarily the deep-water facies of the Aldridge Formation, in a tectonically active, intracratonic setting (Höy, 1993), while the carbonate-hosted deposits are replacement lead-zinc deposits and are found in the upper Purcell carbonate rocks (Höy, 1993). The vein deposits are structurally controlled and are younger than the stratabound deposits (Höy, 1993). Some vein deposits are related to intrusive activity; for example, copper veins are related to the mafic Moyie intrusions while lead-zinc veins are related to the more felsic Mesozoic intrusions (Höy, 1993). Lead-zinc veins contain variable amounts of copper, silver and gold and are composed of galena, sphalerite, pyrite and pyrrhotite as major sulphide minerals and chalcopyrite, arsenopyrite and tetrahedrite as minor sulphide minerals (Höy, 1993). Quartz is the usual gangue in these veins, though quartz-calcite and quartz-siderite are sometimes the gangue (Höy, 1993). Cerussite and pyromorphite are contained in the Society Girl veins, which are a higher level, oxidized extension of the St. Eugene vein systems (Höy, 1993).

Nearly all lead-zinc vein occurrences are within the Aldridge Formation (Höy, 1993). They are concentrated in the Middle Aldridge, which is a deep-water clastic facies with relatively high background metal values that provide the source for the metals in the veins (Höy, 1993). The Middle Aldridge rocks are commonly thick-bedded, competent and fracture readily (Höy, 1993). Though the lead isotopic ratios of the vein deposits are similar to those of the stratiform deposits, which indicate a common lead source, likely the host Aldridge succession, very few lead-zinc veins appear to be associated with the Moyie sills (Höy, 1993). The St. Eugene deposit is the largest vein deposit in the Purcell Supergroup; its total production approximately 78,846 g of gold, 182,691 kg of silver, 113,034 tonnes of lead and 14,483 tonnes of zinc from 1.47 million tones of ore over approximately twenty years (Höy, 1993). This vein system is controlled by a large fracture system that cuts across the nose of the north-plunging Moyie anticline approximately perpendicular to the axis of the anticline (Höy, 1993).

1.4 Summary

The Moyie Anticline is the southernmost anticline of the Purcell Anticlinorium in Canada. It consists of folded Mesoproterozoic Aldridge Formation rocks of the Belt-Purcell Supergroup. This formation of turbititic rocks was deposited in a rift basin setting following the early break-up of Rodinia and was intruded with synsedimentary gabbroic Moyie Sills. It is these sills that outline the structure of the Moyie Anticline in reflection seismic sections and that allow detailed interpretations of stratigraphic variations.

Chapter Two: Database and Methods

2.1 General

The project described in this thesis is multidisciplinary in nature. Accordingly, a variety of different geological and geophysical data sets were used to address the basic questions relating to the crustal structure of the southern Purcell anticlinorium. Seismic reflection data provided by Duncan Energy of Denver, Colorado provide basic geometric information of subsurface structures. Regional isostatic gravity data from the Geological Survey of Canada provide constraints on variations in mass distribution at depth, particularly when combined with the geometric information from the seismic data. Finally, a key drill hole penetrated 3.477 km of Proterozoic strata and sills and can be correlated to the seismic data in order to enhance the interpretations of both seismic reflectors and physical properties (density and mass distribution).

2.2 Seismic Reflection Data

2.2.1 Recording and Processing

More than 1000 km of seismic reflection data were recorded by Duncan Energy for petroleum exploration (Figure 1-1) in and around the Purcell Anticlinorium, and were donated to Lithoprobe in the early 1990's for scientific research. Previous studies have combined seismic lines into regional profiles that focus on crustal and upper mantle structure (e.g. Cook and van der Velden, 1995; van der Velden and Cook, 1996); however, some lines had not been processed in previous studies due to their unsuitability (for example, their lengths may have been too short or they may have been in an unfavourable orientation). Such data are, however, valuable in developing three-dimensional geometry for key structures. In addition, little effort had been previously directed to enhancing the seismic images of the near surface. However, as a component of the research described here is to address potential mineral deposits, application of techniques to improve near-surface resolution may help in delineating structures or trends that may host such deposits.

The data were acquired as part of a regional exploration survey in 1985-1986 that eventually led to the drilling of the DEI Moyie #1 hole in 1987 (located on Figure 1-1) by Duncan Energy. The objective of this exploration effort was a series of prominent reflectors observed on seismic data that were originally interpreted as Palaeozoic and/or Mesozoic strata that were overthrust by Proterozoic strata during formation of the Rocky Mountains in the late Cretaceous - early Tertiary. However, because drilling encountered Proterozoic (Middle and Lower Aldridge Formation and Moyie Sills) strata throughout the entire 3.477 km, the seismic data were provided to Lithoprobe for research purposes.

Data acquisition was primarily by the Vibroseis technique (Table 2-1), although a few profiles in the regional study were acquired using helicopter supported portable surveys with explosive sources (denoted with 'P', as in line 11.0P). They provide good 2.5-D regional coverage of the Purcell anticlinorium, and specifically of the Moyie anticline.

One of the key lines that had not been examined previously is Line 16 (Figure 2-2 and Figure 2-3), an approximately north-south profile along the axis of the Moyie anticline. Line 16.0 processing followed a normal sequence for the regional analysis (Table 2-1). Subsequently, additional processing that focused on the near surface (0.0-3.0 s) was applied to all of the data in the vicinity of the DEI Moyie #1 drill hole and

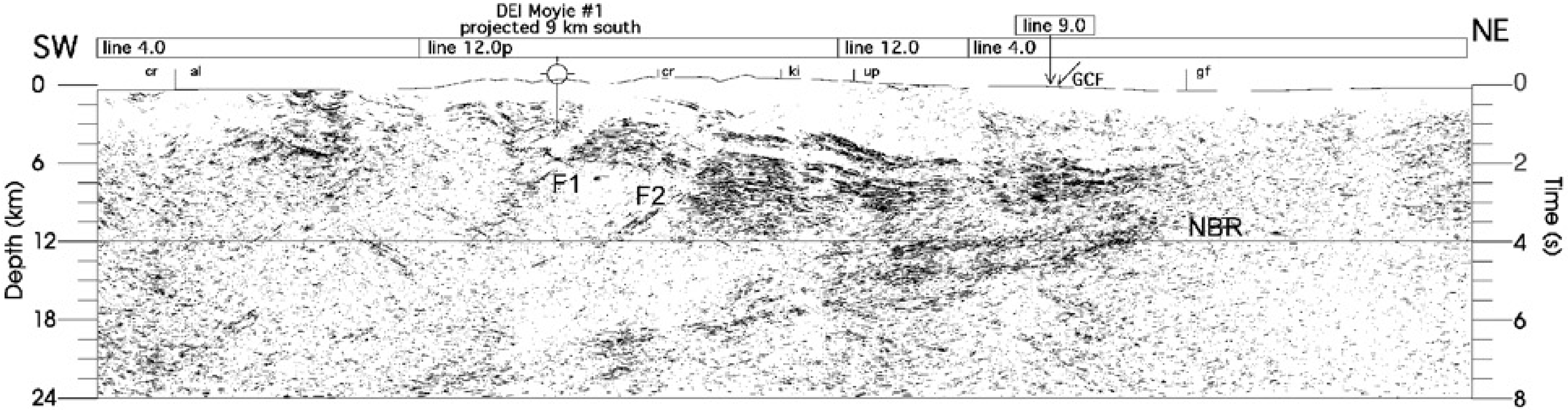


Figure 2-1: Regional data along lines 4.0, 12.0p and 12.0. The geometry of the Moyie sills and near-basement reflectors dominate the structure, though two interpreted faults are also labelled (van der Velden and Cook, 1995).

Moyie anticline. In order to enhance the near surface features, the bias window and coherency filtering aperture were adjusted to allow somewhat steeper dips and a floating datum located above the surface was used, so the reflections can be traced to the surface. Crooked line geometry was important for all of the processing, but had a significant effect on the near surface data. In addition, in order to focus the results for the near surface, residual (trim) statics were calculated using a much smaller window than for the regional processing. While the fundamental geometry did not change, the reprocessing was successful in producing substantial improvement in some key areas (e.g., Figure 2-2 and Figure 2-3). The coherency of the reflections due to the Moyie sills is greatly improved, especially the Middle Aldridge Marker (MAMa).

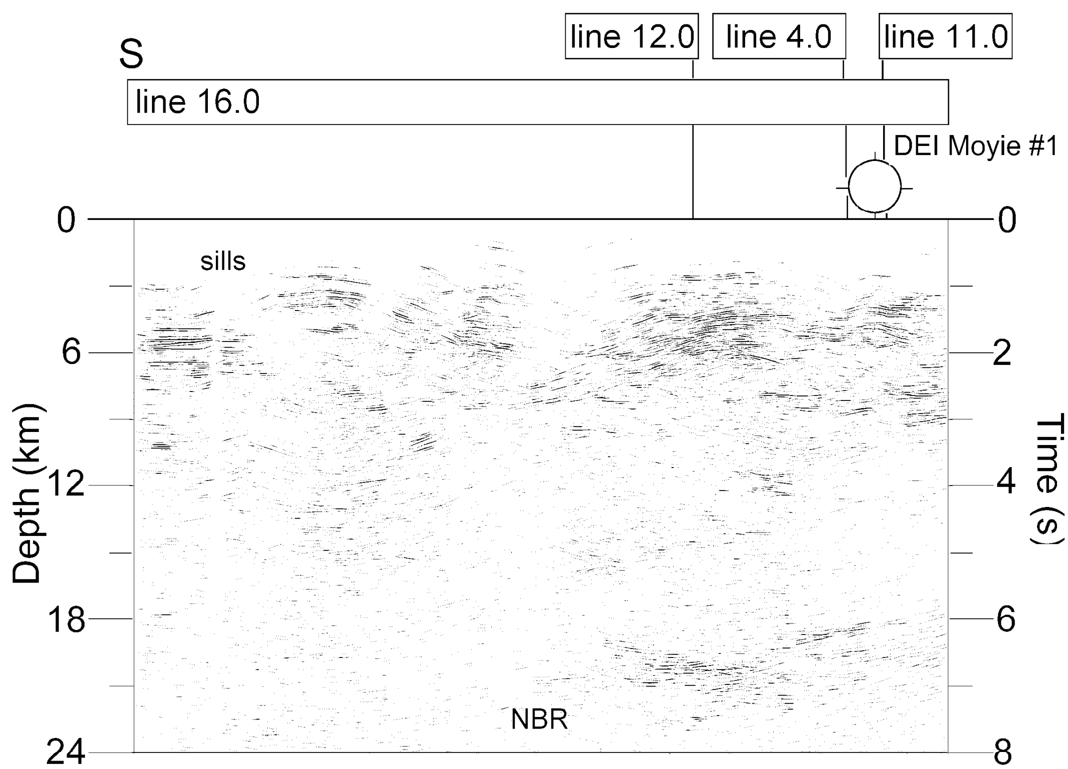


Figure 2-2: Line 16.0 processed with regional parameters to 8.0 s including migration. The deep reflections near 6-7s are the near-basement reflections and the shallow reflections are primarily from diabase sills in the Middle and Lower Aldridge formation (Cook and Jones, 1995 and Cook and van der Velden, 1995).

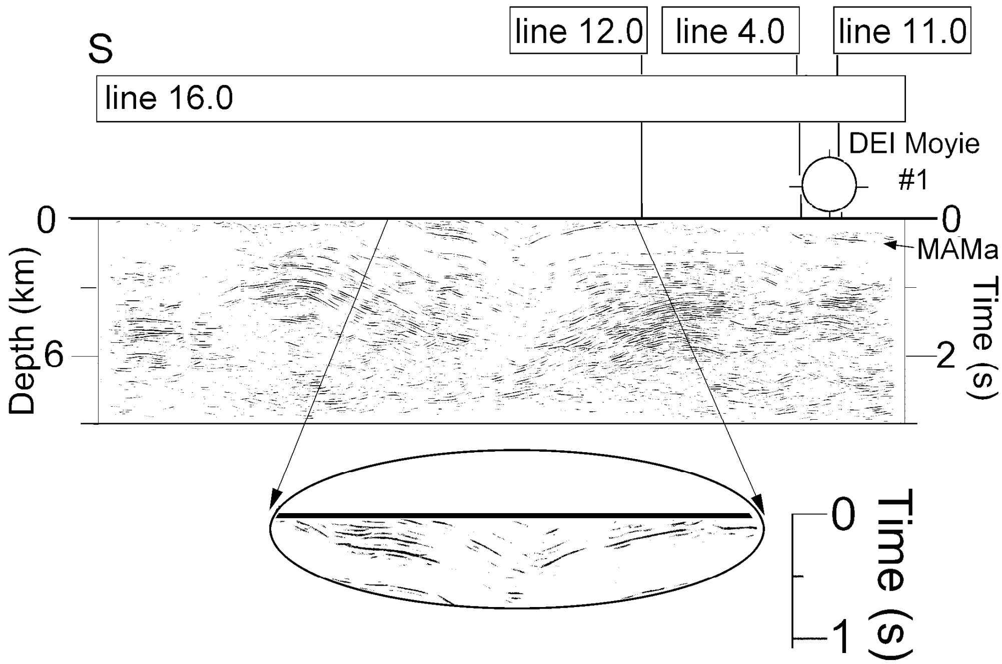


Figure 2-3: Line 16.0 reprocessed to 3.0 s in an effort to focus on the near surface data. The enlargement in the lower part of the figure illustrates some of the detail near the centre of the line where reflections rise to very near the ground surface. MAMa is the Middle Aldridge sill Marker which is visible on other lines as well.

A time-migration was applied to these newly processed sections using a similar algorithm to that of the regional studies. Some lines required trace padding to allow steeply-dipping features to be moved up-dip into their proper locations and geometries. Bias and coherency filtering were also applied before the sections were displayed.

The regional processed versions of these lines are dominated by two key reflection patterns: a narrow zone of west-dipping reflections between 4.0 and 8.0 s (labelled NBR for Near-basement Reflections) and a prominent zone of arcuate to east-dipping reflections between 0.0 and 3.0 s that, as described later, are now known to be Moyie sills (~1.45 Ga) intruded into the Aldridge Formation (Cook and Jones, 1995).

Reflections NBR are correlative with the Near Basement reflections that are interpreted to be Proterozoic and/or Palaeozoic strata sitting on Paleoproterozoic and older 'basement' rocks of the North American craton beneath the foreland thrust and fold belt (e.g., Bally et al., 1966; Cook and van der Velden, 1995).

Table 2-1: Acquisition parameters for Duncan Line 16.0

Direction	South to North
Source	4 vibrators over 50 m
Recording	IFP-MDS-10
VP interval	67 m
Sweep	10-58 Hz
No. sweeps	12
Sweep length	12 s
Record length	8 s
Geophone frequency	10 Hz
Station interval	33.5 m
Geophone pattern	20 over 33.5 m
Sample interval	4 ms

Table 2-2: Processing sequence for Duncan Line 16.0

Demultiplex	SEGB 9-track tapes to SEGY disc files
Extended correlation	Self truncating to 20 s
Geometry	17 m x 500 m bins (crooked line)
Trace edits	First breaks, trace kills, mutes
Scaling	AGC (500 ms window)
Spectral balancing	10-56 Hz
Predictive deconvolution	24 ms prediction distance; 120 ms operator
Refraction statics	Datum 1200 m; 5700 m/s replacement
Velocity analysis	Constant velocity stacks
Brute stack	
Cross-dip analysis	
Residual statics	0.30-3.0 s window; +/- 32 ms shift
Velocity analysis	Constant velocity stacks
Trim statics	0.3-3.0 s; +/- 16ms shift
Energy balance	0.0-16.0 s
Final stack	Nominal 30-fold
Migration	Phase shift with laterally varying velocity
Coherency filter	31 tr window with 6 ms/tr slowness over 17values
Plot	

2.3 Gravity Data

The gravity data used in this study were the isostatic gravity from the Canadian National database (http://gdrdap.agg.nrcan.gc.ca/geodap/index_e.html). Data were acquired by the Geological Survey of Canada and were corrected for the normal sequence of steps that are applied to gravity measurements (free air, full Bouguer, and isostatic), and were then gridded (5 km grid spacing) to provide the map shown in Figure 2-4.

The isostatic gravity anomaly is the difference between Bouguer gravity anomaly and the response of a predicted increase in crustal thickness based on the topography. When the isostatic anomalies are near zero, it is likely that any elevation above sea level

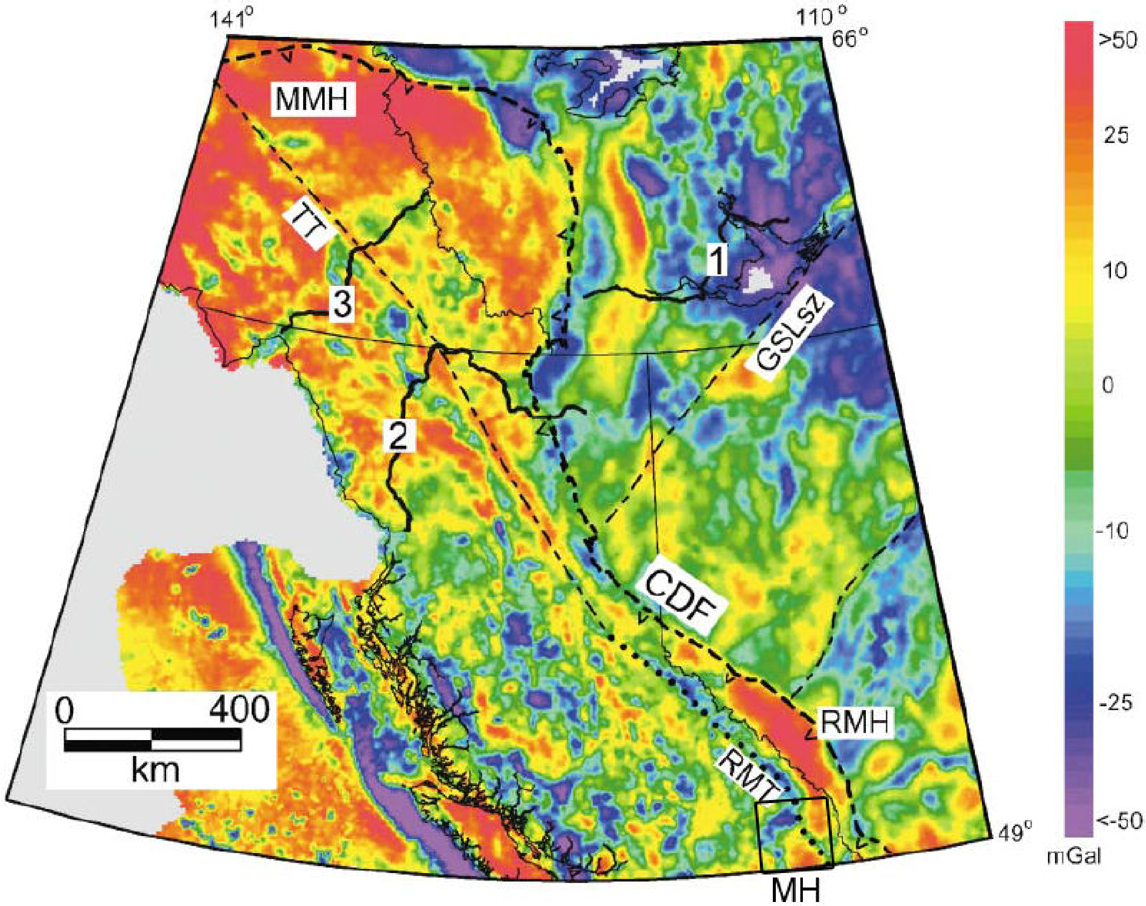


Figure 2-4: **Isostatic gravity map of western Canada south of 66°N latitude in milligals (Cook et al., 2003). There is a large regional high throughout the Mackenzie Mountains (MMH), while the values are near zero in the southern Cordillera, excluding the high in the Rocky Mountains (RMH). Locations of Lithoprobe SNORCLE seismic profiles (1, 2, and 3) are indicated in the north as well as the Great Slave Lake shear zone (GSLsz), the Cordilleran deformation front (CDF), the Rocky Mountain Trench (RMT), the Tintina Trench (TT) and the Moyie High (MH). The area around the Moyie High shown in Figure 2-5 is outlined as well.**

is compensated at depth, either by variations in Moho depth or by lateral changes in density. Deviations from zero imply either undercompensation (negative anomalies) or overcompensation (positive anomalies). Throughout the southern Cordillera, isostatic gravity anomalies are generally near zero with several small, local anomalies superimposed (Figure 2-4). However, two major gravity highs (RMH and MH in Figure 2-4) deviate from the generally low values of isostatic gravity. Anomaly RMH (Rocky Mountain High) has been interpreted by Cook and van der Velden (1995) as an effect of dynamic support of topography by relatively rigid lithosphere. Anomaly MH is associated with the Moyie anticline, and is addressed further here. Anomaly MH has a magnitude of approximately 30 mGals and spatially correlates to the Moyie anticline (Figure 2-5). It also diminishes to the north as the anticline plunges.

2.3.1 Gravity Profiles

Isostatic gravity gridded data were downloaded from the Geoscience Data Repository of the Geological Survey of Canada (GSC) (http://gdrdap.agg.nrcan.gc.ca/geodap/index_e.html). This grid was compiled from approximately 660,000 gravity observations acquired between 1944 and 2001 with an average spacing between 5 and 10 km. To address the detailed subsurface geometry of the Moyie anticline, and to compare the details to the structures observed on the seismic reflection data, nine parallel west-east profiles (Figure 2-5), each of which is 78 km long, were extracted from the gridded gravity data; the profiles are about 7 km apart. The profiles extend from the west edge of the Moyie gravity high to east of the Rocky Mountain Trench.

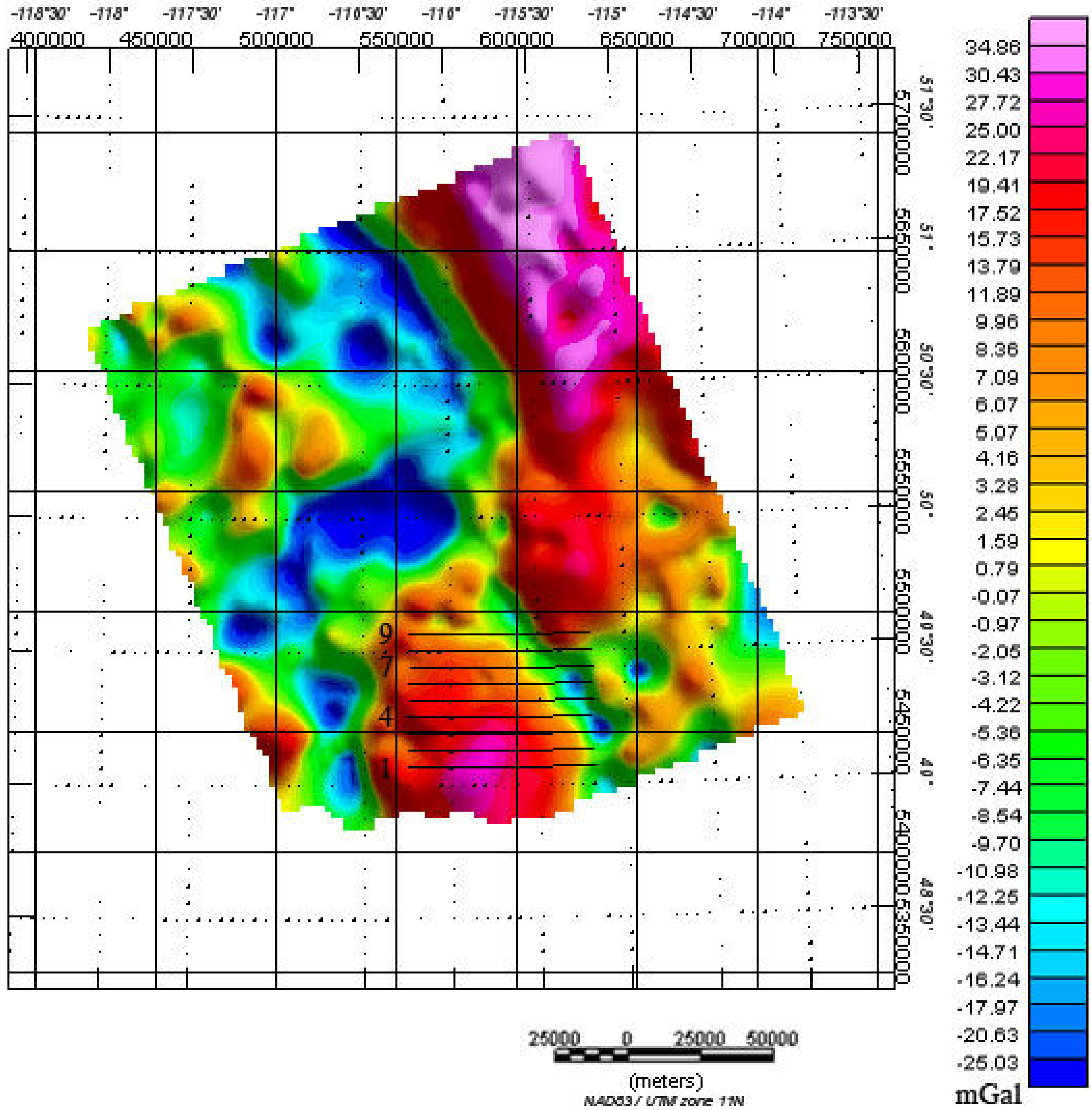


Figure 2-5: **Isostatic gravity of southeastern British Columbia in milligals plotted using Geosoft montaj. Gridded gravity data were downloaded from the GSC's Geophysical Data Repository. The gravity profiles used for modeling are numbered from south to north 1 through 9.**

Because interpretations of gravity data are critically dependent on knowledge of the subsurface geometry, the gravity profile locations were chosen to approximately follow portions of the seismic lines. For example, Duncan line 4.0 has a dogleg that trends southwest, but the majority of line trends approximately along that of gravity profile 4 (Figure 4–2). For that reason, gravity profile 4 is constrained by the seismic interpretation geometry of line 4.0. Similarly, seismic lines 11.0 and 11.0p are used to constrain profile 5 (Figure 4-3).

2.4 Drill Hole Data

The northern end of seismic line 16.0 is located about 2 km west of the DEI Moyie #1 drill hole (Figure 1-1) and provides a good tie between layers drilled and the reflectivity (Figure 2-6). To estimate a modeled seismic trace, impedance contrasts between layers in the drill hole were calculated from a series of density and velocity logs (Cook and van der Velden, 1995). The key point from this analysis for interpretation of the seismic data is that the prominent reflectivity is due to impedance contrasts between the Moyie sills and the surrounding Aldridge Formation strata (Cook and Jones, 1995). Furthermore, the excellent correlation of shallow (0.100-1.200 s) reflections on the data to shallow sills in the drill hole allows important features (e.g., MAMa in Figure 2–1, Figure 2-2 and Figure 2-3) to be followed southward along line 16.0 where they rise to the surface. This in turn provides an opportunity to locate these specific reflectors in outcrop.

In addition to the seismic impedance contrasts, the density log provided direct measurements of the densities for utilization in the gravity modelling. To accomplish this, the density log of Duncan Energy's exploration well was blocked into a series of vertical intervals, each with a representative average density. The density log shows consistent values in a step-wise fashion that alternate between a quartz-like density and higher density sills. This information was used to calculate weighted averages of density over the drilled interval. Seven sills were noted with an average density of 2.858 g/cm^3 which alternated with intervals of sedimentary rocks of an average density of 2.667 g/cm^3 (Table 4-1). The total drilled depth of the exploration well is 3477 m, of which ~39% is sills; the log shows that both the frequency and thickness of the sills increase with depth and this is consistent with the seismic data which show increasing reflectivity near the base of the drill hole.

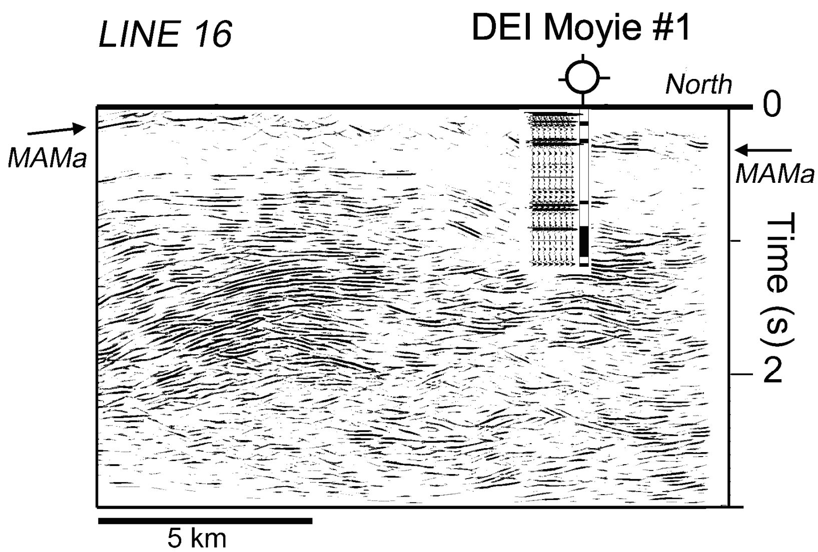


Figure 2-6: Duncan line 16.0 with a synthetic seismogram calculated from the well logs. The Duncan Energy exploration well is labelled. The Middle Aldridge Marker (MAMa) correlated to a sill intersected by the well.

Chapter Three: Seismic Interpretation

3.1 General

The reflection seismic sections are dominated by two zones of prominent reflections (Figure 2–1, Figure 2-2 and Figure 3–1). The shallow, antiformal reflections are known to be Moyie sills, whereas the deep, dominantly west-dipping zone of reflections is interpreted to be the westward continuation of the 'near-basement reflection' zone is seen beneath the Rocky Mountains (Bally et al. 1966; Cook et al., 1987; Cook and van der Velden, 1995). The dominant antiformal structure of the Moyie Anticline is obvious in the Moyie sill reflections, and is confined to the region above the basement.

In this chapter, the reflection data are interpreted by utilizing both cross-sectional images and by mapping seismic horizons. While the new results affirm the dominant structures observed previously (Cook and van der Velden, 1995; van der Velden and Cook, 1996), the added detail provides enhanced resolution with resulting potential applications for detailed mapping.

3.2 Description of Key Features

To illustrate the general features of the data, key profiles are presented here. First, two profiles, (DL 4.0, and DL 12.0 and 12.0P) are described that cross the Moyie anticline at high angles to strike (Figure 2–1 and Figure 3–1). These illustrate how the geometry of some reflectors, such as the sills, change on different cross strike sections. Subsequently, Line 16.0 will be examined to illustrate how the important reflections vary along the strike near the axis of the Moyie anticline (Figure 2-2 and Figure 2-3).

There are a few dominant features seen in the reflection seismic data. From deep to shallow, these include the following. The deepest, more or less prominent, zone of reflections dips west-southwest from ~4.0 s on the east to ~8.0 s on the west. These are known as the Near-Basement Reflections (NBR on (Figure 2–1 and Figure 2-2). Previous authors (e.g., Bally et al., 1966; Cook and van der Velden, 1995) have interpreted these as autochthonous Proterozoic and/or Palaeozoic strata sitting on Paleoproterozoic and older 'basement' rocks of the North American craton. If correct, this interpretation means that the deformation of the Moyie anticline, Purcell anticlinorium, and indeed the Rocky Mountain thrust and fold belt, was confined to the crust above this surface.

The seismic profiles above NBR are dominated by a broad arcuate zone of dipping reflections in the upper portion (0.0-3.0s) that dip towards the east-northeast (Figure 2-3). These reflections are a result of the large impedance contrast between the turbiditic Aldridge Formation and gabbroic Moyie Sills (Cook and Jones, 1995). The narrow zone of reflections above the thicker zone is labelled MAMa for the Middle Aldridge Marker. This reflection was found to correlate with a 7 m thick sill (Cook and Jones, 1995). This horizon was picked for further consideration (mapping) in this study. The top of the broad zone of reflections was also picked as a horizon in this study; it is labelled MS (Moyie Sills). This horizon marks the top of the heavily intruded zone in the Lower Aldridge and is sometimes referred to as the Lower Aldridge Marker, LAMa. The base of this broad zone of strong reflections (RLB) was also considered. This may represent the lowest extent of the intrusion of the Moyie Sills or a fault (van der Velden and Cook, 1996).

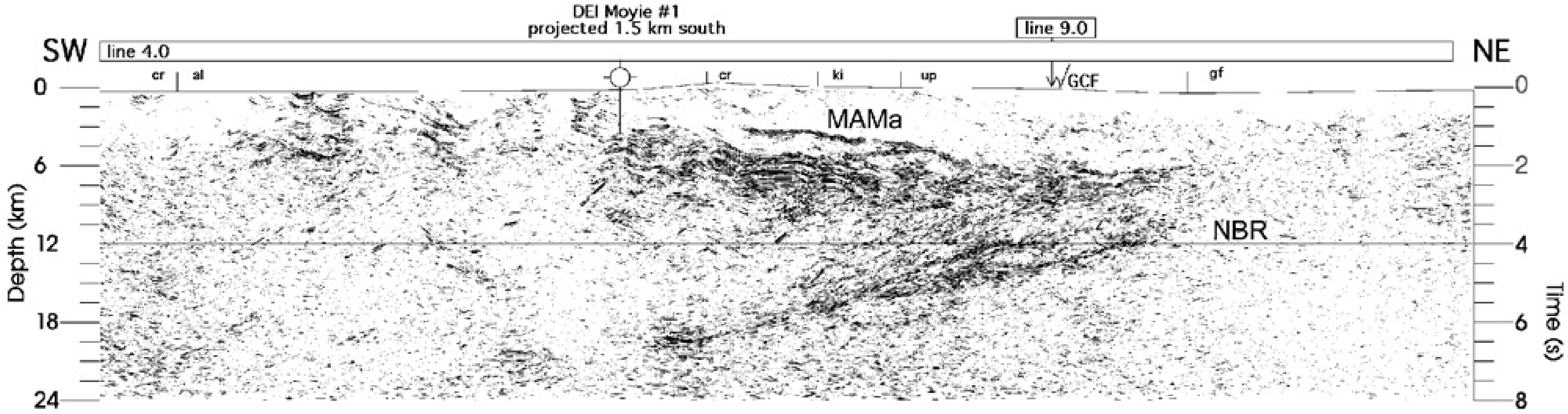


Figure 3-2: Duncan line 4.0 with NBR (Near-Basement Reflections), and MAMa (Middle Aldridge Marker) labelled as well as Duncan Energy's exploration well.

These features are seen on all sections regardless of their orientation, though there are variations. The lines that are oriented roughly across strike (e.g., DL 4.0, and DL 12.0 and 12.0p) show the near-basement reflections and intruded sills as very strong reflections. The southernmost of these profiles (DL 12.0p) (Figure 3–1) shows small offsets in the sills due to small thrust faults (van der Velden and Cook, 1996) that are not as obvious in the northern section (DL 4.0**;** Figure 2–1) and not imaged on lines further down-plunge to the north (DL 11.0 and 11.0p). These lines had been previously considered in regional studies due to their orientation across the regional strike of the structures, while lines oriented along strike had not been used. Recent processing of one of these along strike lines (DL 16.0; Figure 2-2 and Figure 2-3) along with the reprocessing of these previously considered lines provided a great deal more detailed information about the structure of the Moyie Anticline, especially of shallow structures, than previous work. Line 16.0 runs roughly along the crest of the Moyie Anticline from north to south. Though the key features of the package of intruded Moyie Sills dominate, the near-basement reflections are fainter than in the across-strike sections. The most surprising aspect of this section is the small synform (0.5s TWT) seen south of the intersection with DL 12.0p. This synform is faint between 1 s and 2 s in the 8s section (Figure 2-2), but is clearly visible in the 3s section (Figure 2-3).

3.3 Interpretations

Because the focus of this study is the three-dimensional structure of the Moyie anticline, and because there are both along- and across-strike variations observed on the two-dimensional lines as noted above, maps of key horizons were constructed. Four horizons were picked on the reflection seismic sections using Kingdom Suite interpretation software. They are the Middle Aldridge Marker (MAMa), the top of the heavily intruded package (Moyie Sills, MS) the base of the reflective layer (RLB) and the near-basement reflections (NBR). After correlating key horizons from line to line, traveltimes of each horizon are mapped along the lines. These horizons highlight the structure of the anticline shown in the pseudo-grid of seismic sections (Figure 3-2 to Figure 3-5 on pages 27 to 30).

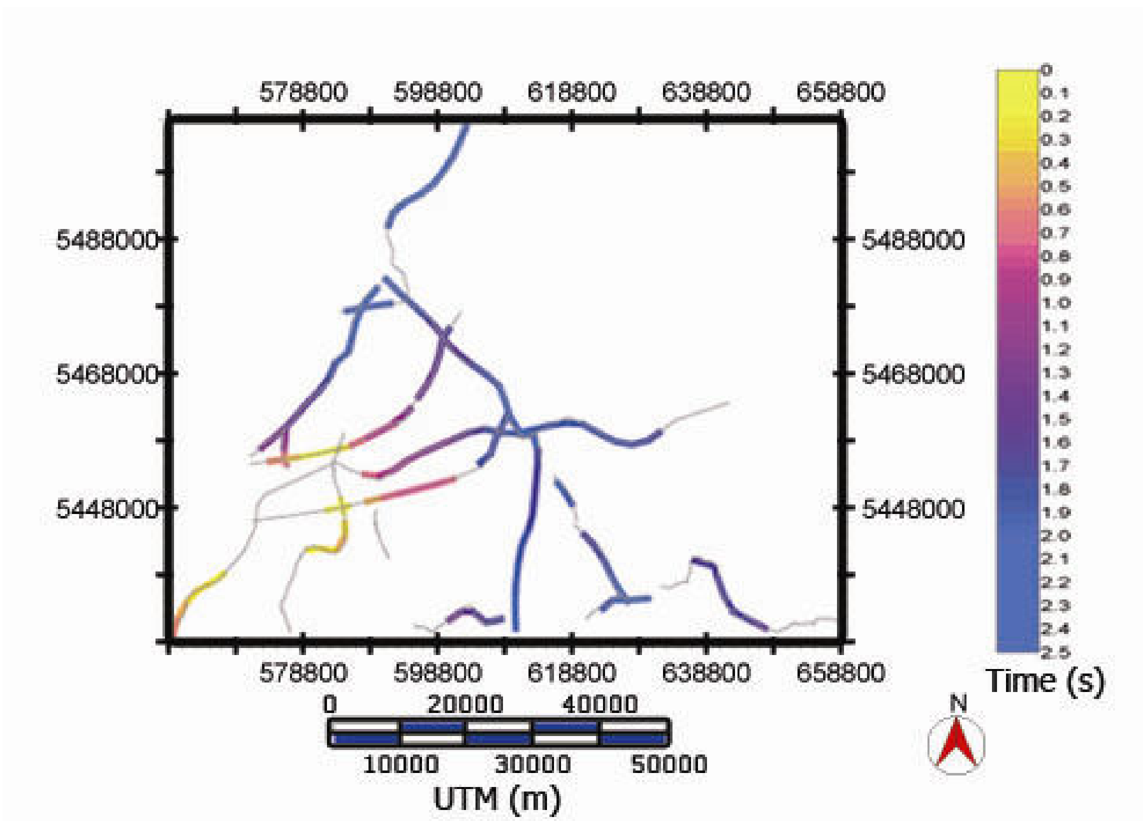


Figure 3-2: Segmented time-structure map of Middle Aldridge Marker (MAMa)

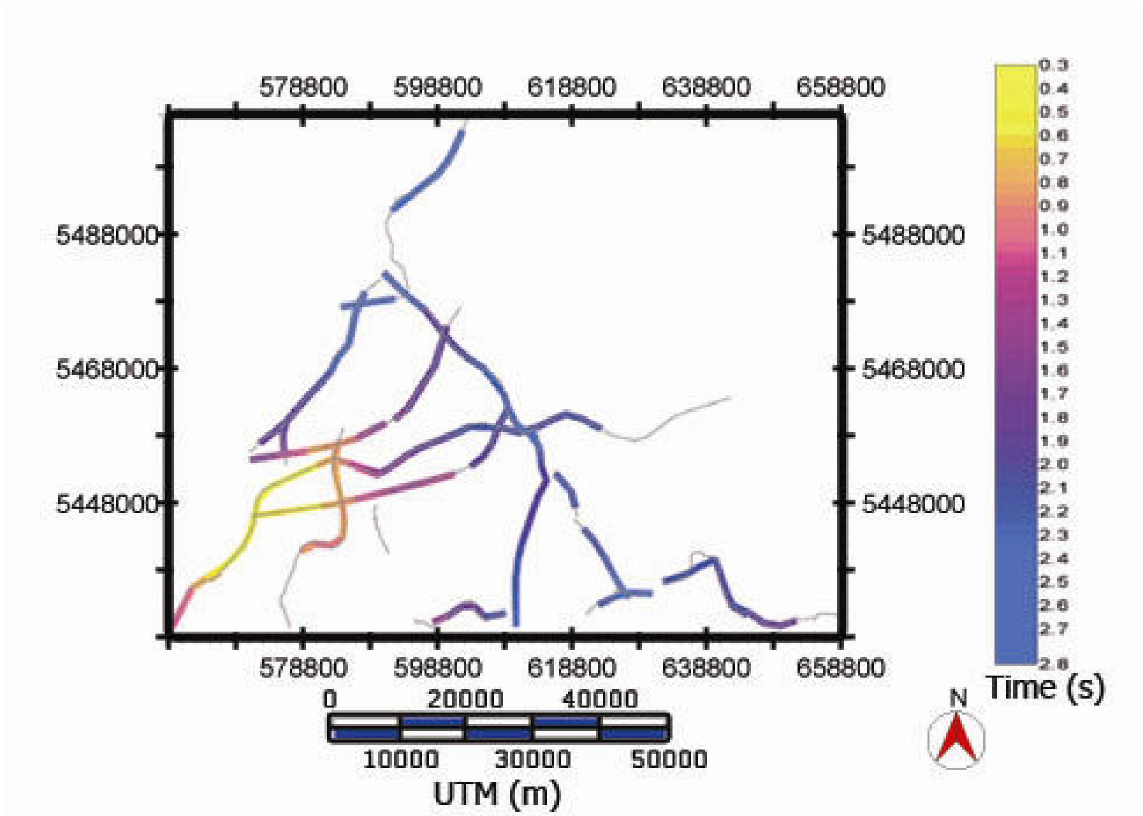


Figure 3-3: Segmented time-structure map of top of the Moyie Sills (MS).

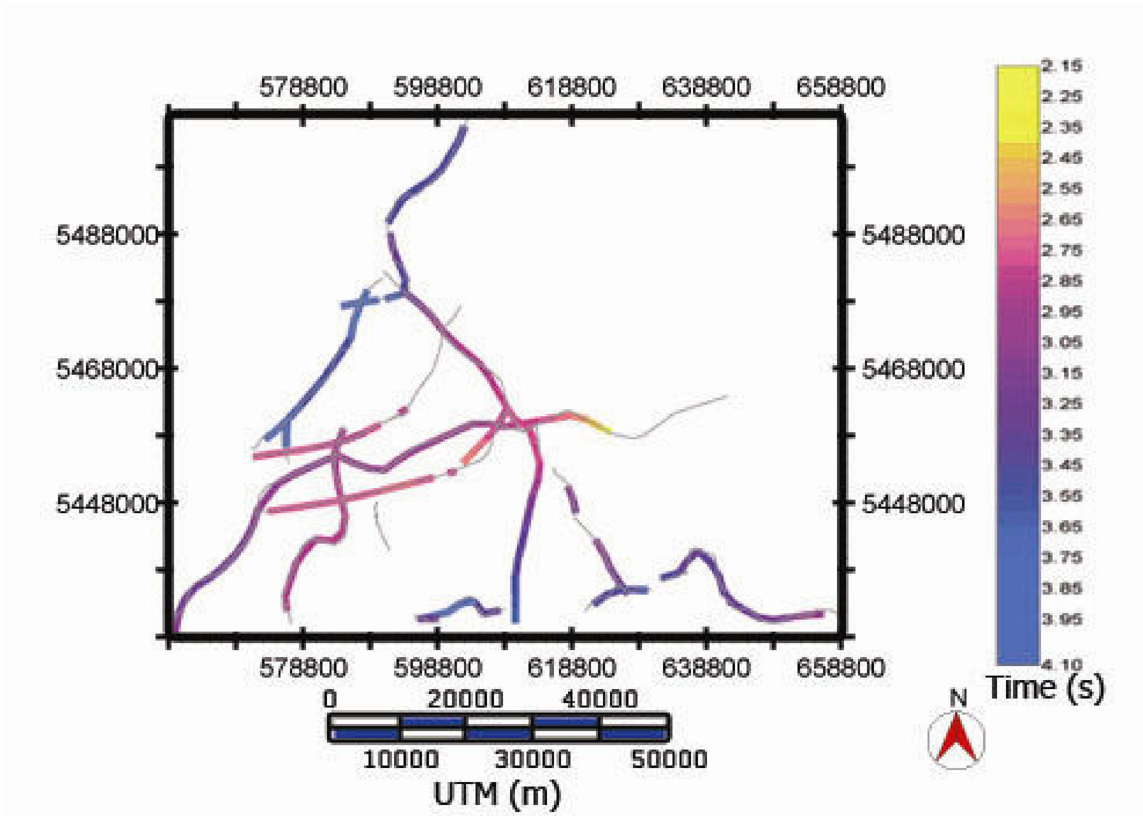


Figure 3-4: Segmented time-structure map of base of the highly reflective layer (RLB).

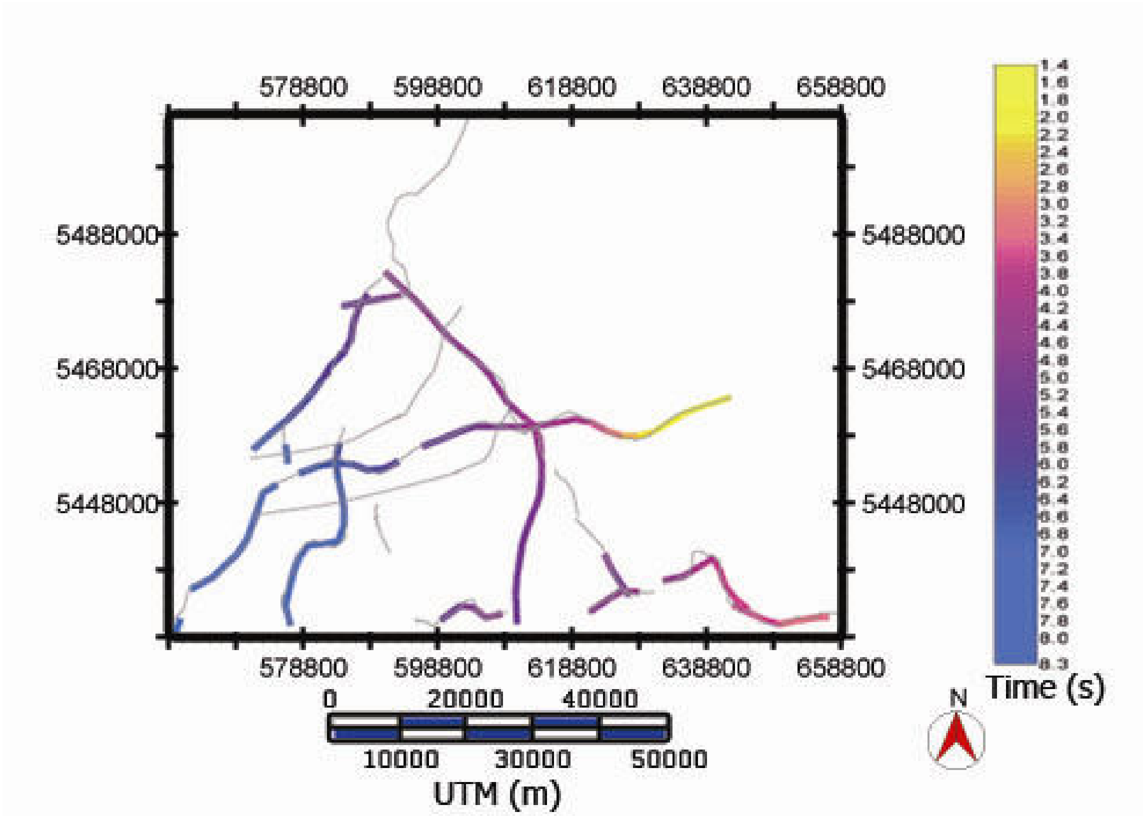


Figure 3-5: Segmented time-structure map of near-basement reflections (NBR).

A gridding algorithm was used to interpolate between the reflections seismic lines and to map each horizon. A gradient projection gridding algorithm with an inverse distance weighting power of 2 and low amount of smoothing was used to calculate the map pattern distribution of each horizon based on two-dimensional data (Figure 3-6 to Figure 3-9).

The contour map of the NBR reflection (Figure 3-9) shows the dominant west-southwest dip of the Near-Basement Reflections as noted in Cook and van der Velden (1995). In the east side of the map, near UTMs 638800 and 5438000, an apparent ridge appears as yellow contours. These are controlled by only one seismic line (DL 4.0) and may be associated with a slight thickening of the NBR reflections.

The map of the base of the layered sills (Figure 3-8) is the most problematic of the horizon maps, because the base is not well defined. This is particularly evident along DL 4.0 were there are local closed contours. It is likely that small scale variations in the base of the layers prevent detailed correlation from one seismic line to another.

Maps of the top of the Lower Aldridge sills (MS, Figure 3-7) and the Middle Aldridge marker (MAMa, Figure 3-6) are better controlled by good correlations from line to line and are similar in that they display the north-northeast plunging structure of the horizons above the near-basement reflections (Figure 3-9).

Stratigraphic thickness variations in the Middle Aldridge – Lower Aldridge transition zone are found in some areas to be locales for enhanced mineral development (e.g., Sullivan deposit; Lydon, 2000). To address whether such variations are visible on the seismic data, isochron maps were created by subtracting the higher grid from the lower one. The first of these, the total intruded package (RLB-MAMa), illustrates fairly uniformly westward increasing thickness (Figure 3-10) with local thickening in the core of the anticline. There are more distinct local variations in the thickness between MAMA and MS (Figure 3-11). This indicates variations in the thickness of the Middle and Lower Aldridge transition.

Most notable, perhaps, is a northwest-southeast thick zone that appears to correlate spatially with some important historical mineral deposits (Figure 3-12). The Middle Aldridge – Lower Aldridge transition is in the subsurface southeast of deposits such as the St. Eugene and Society Girl and has therefore not been explored.

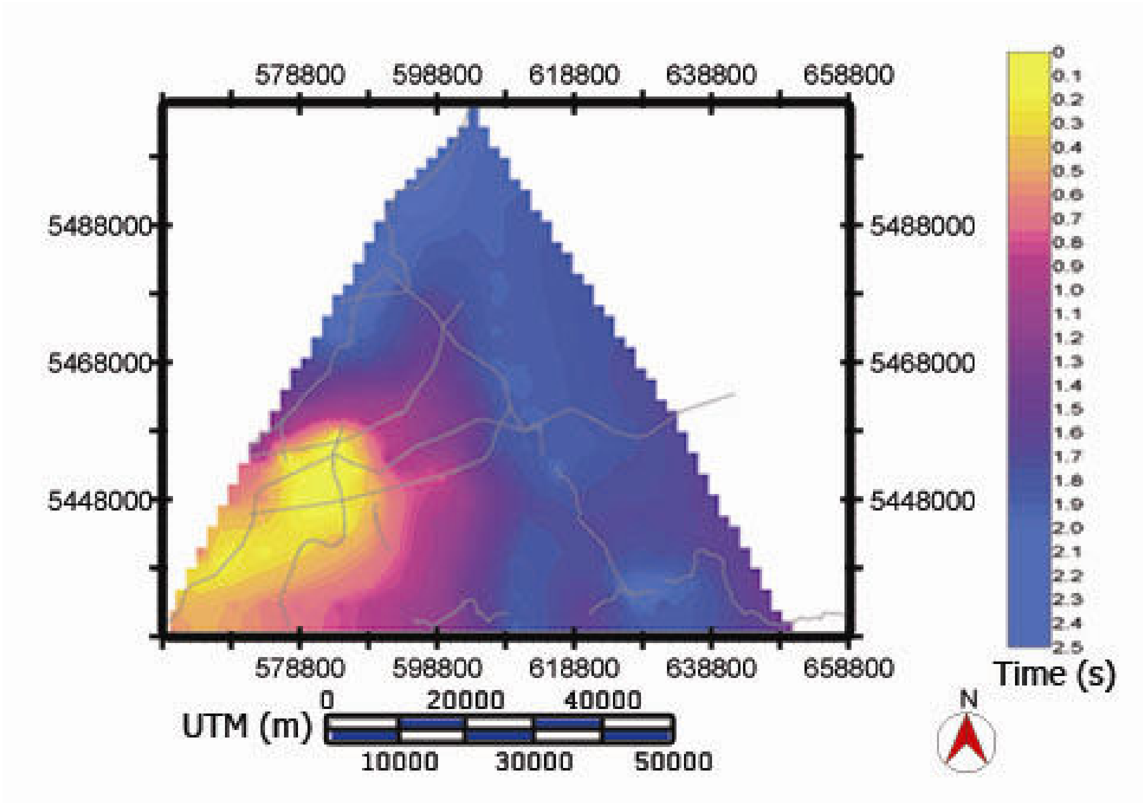


Figure 3-6: Gridded time-structure map of top of the Middle Aldridge Marker (MAMa)

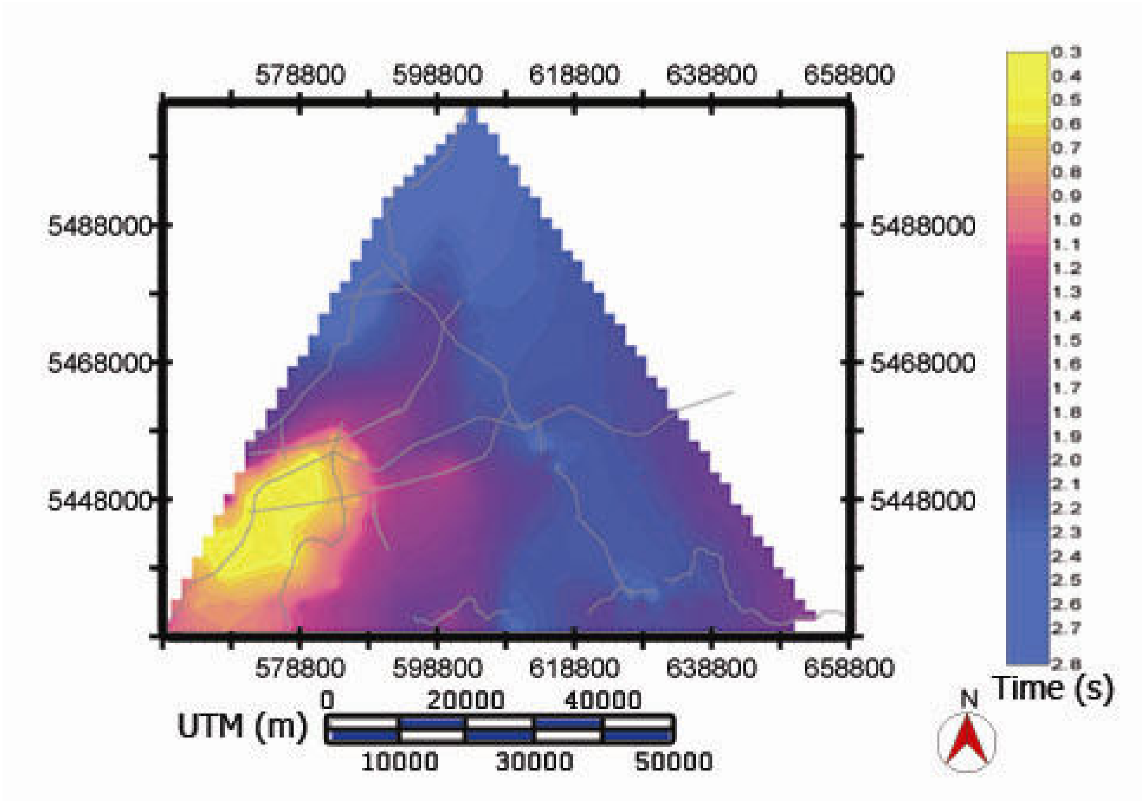


Figure 3-7: Gridded time-structure map of top of the Moyie Sills (MS)

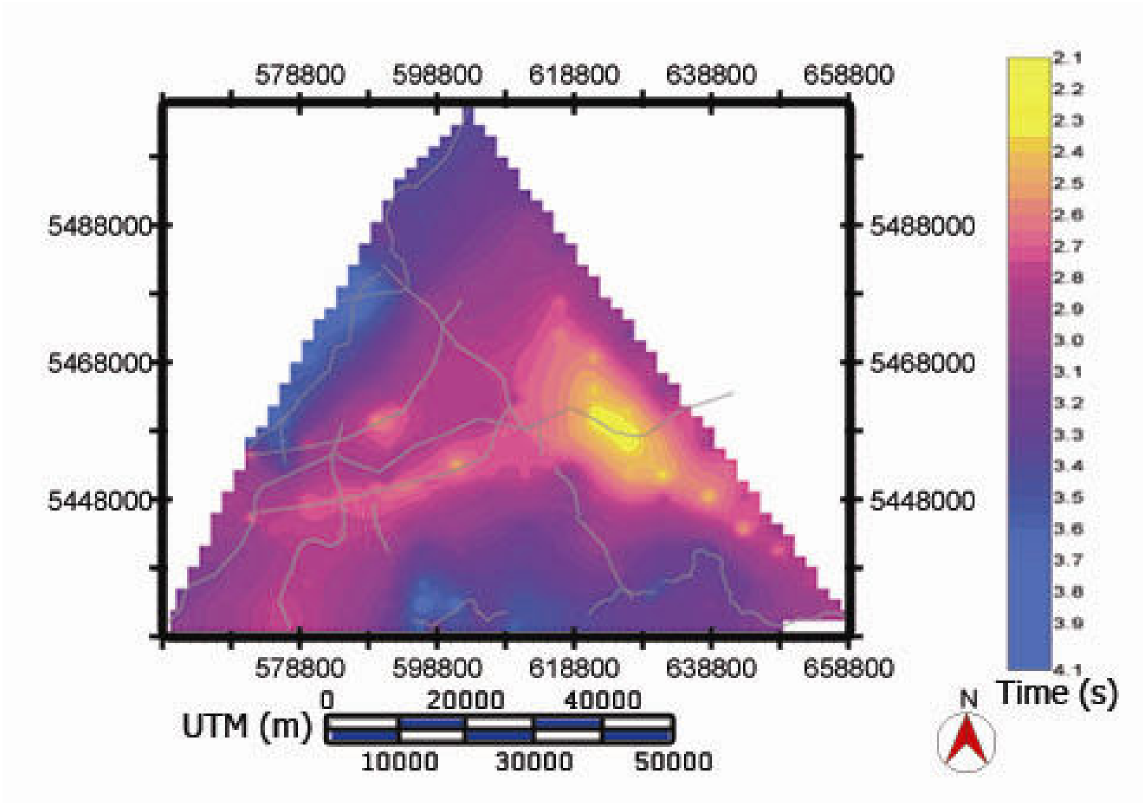


Figure 3-8: Gridded time-structure map of base of the reflective layer (RLB)

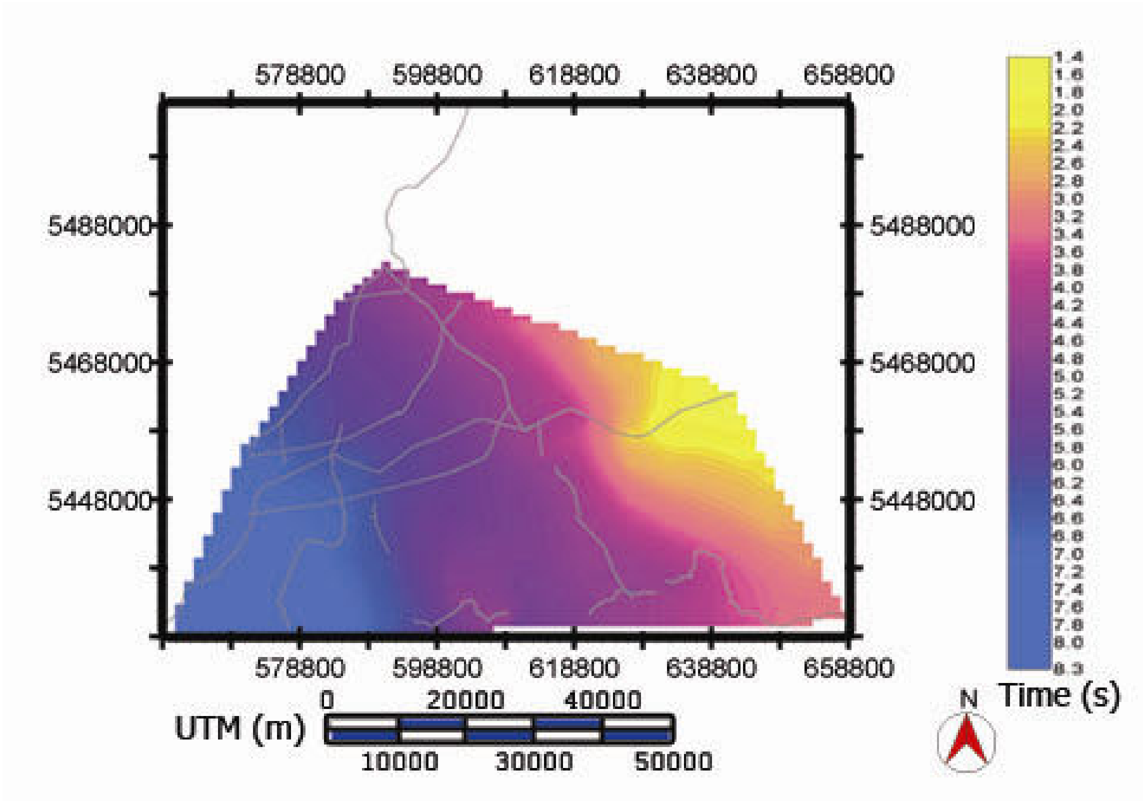


Figure 3-9: Gridded time-structure map of near-basement reflections (NBR)

3.4 Summary

The Moyie Sills are the dominant reflection features above the Near-Basement Reflections in the seismic data recorded by Duncan Energy. Analyses of the data along and across strike indicate some evidence for local variations. These are illustrated more clearly on the isochron maps where local thickening of intruded sills in the core of the anticline and slight thickening of the Lower and Middle Aldridge transition are evident.

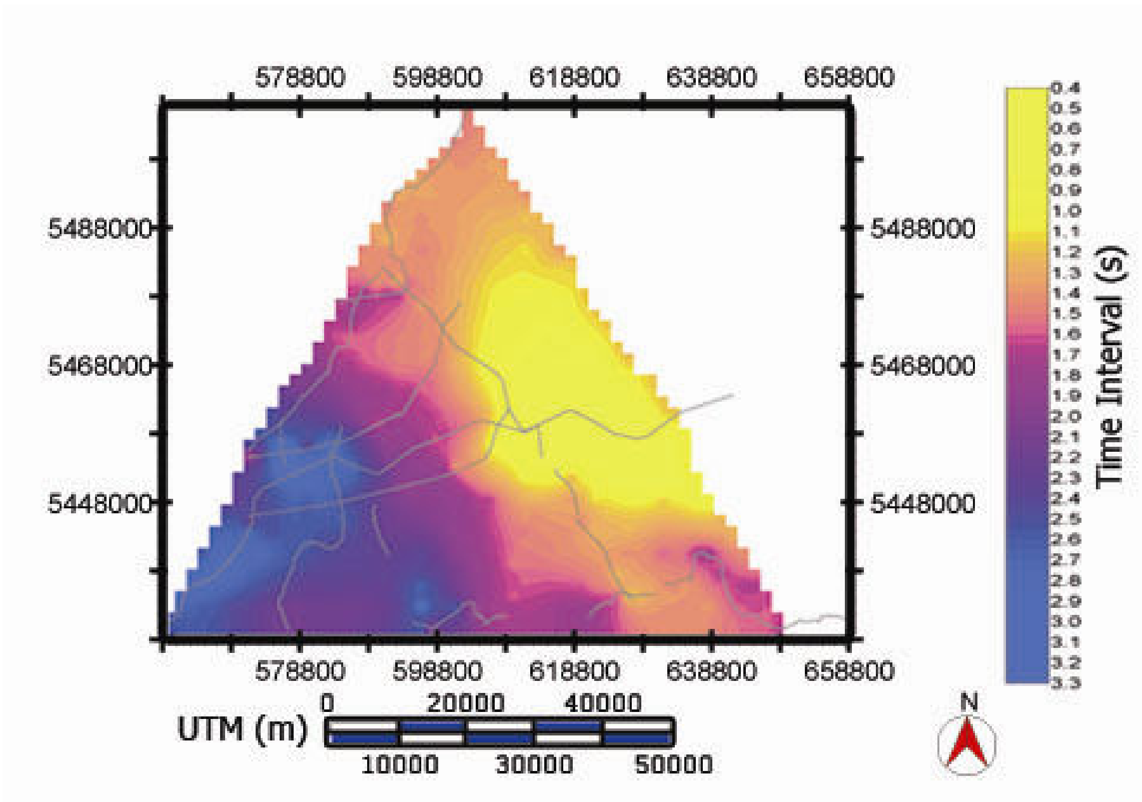


Figure 3-10: Isochron map of intruded zone (RLB-MAMa)

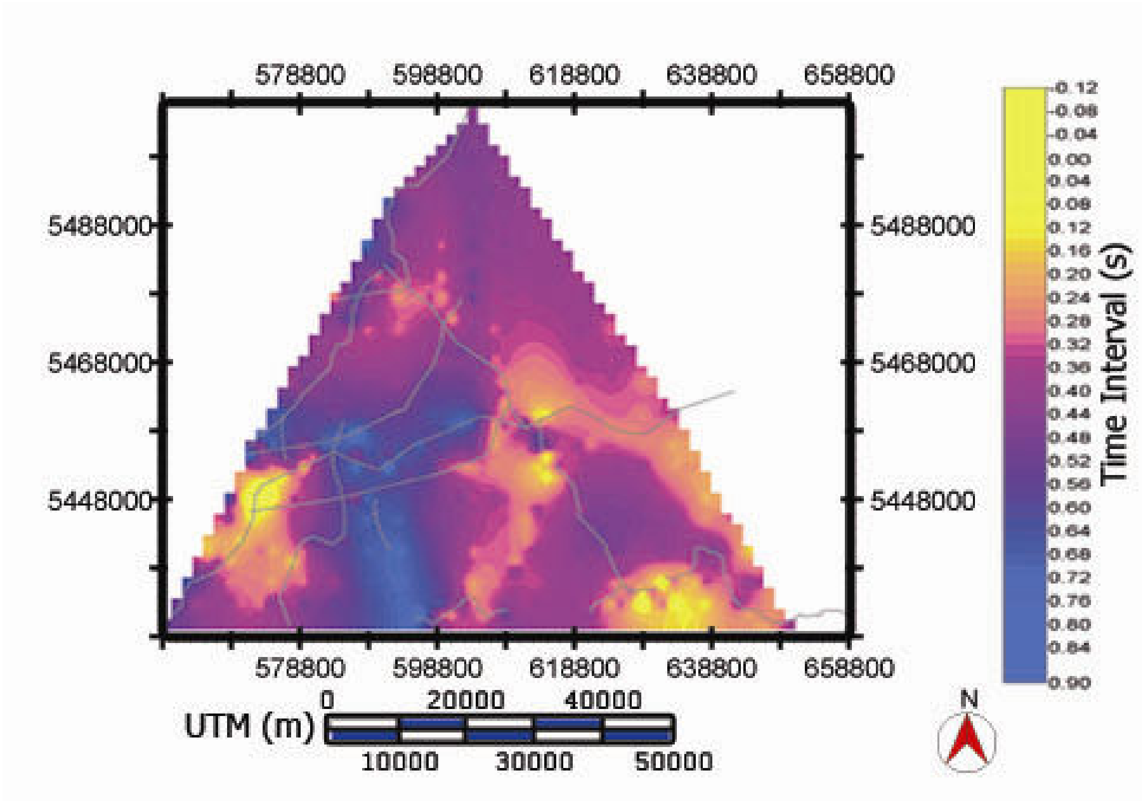


Figure 3-11: Isochron map of Middle to Lower Aldridge transition zone (MS-MAMa).

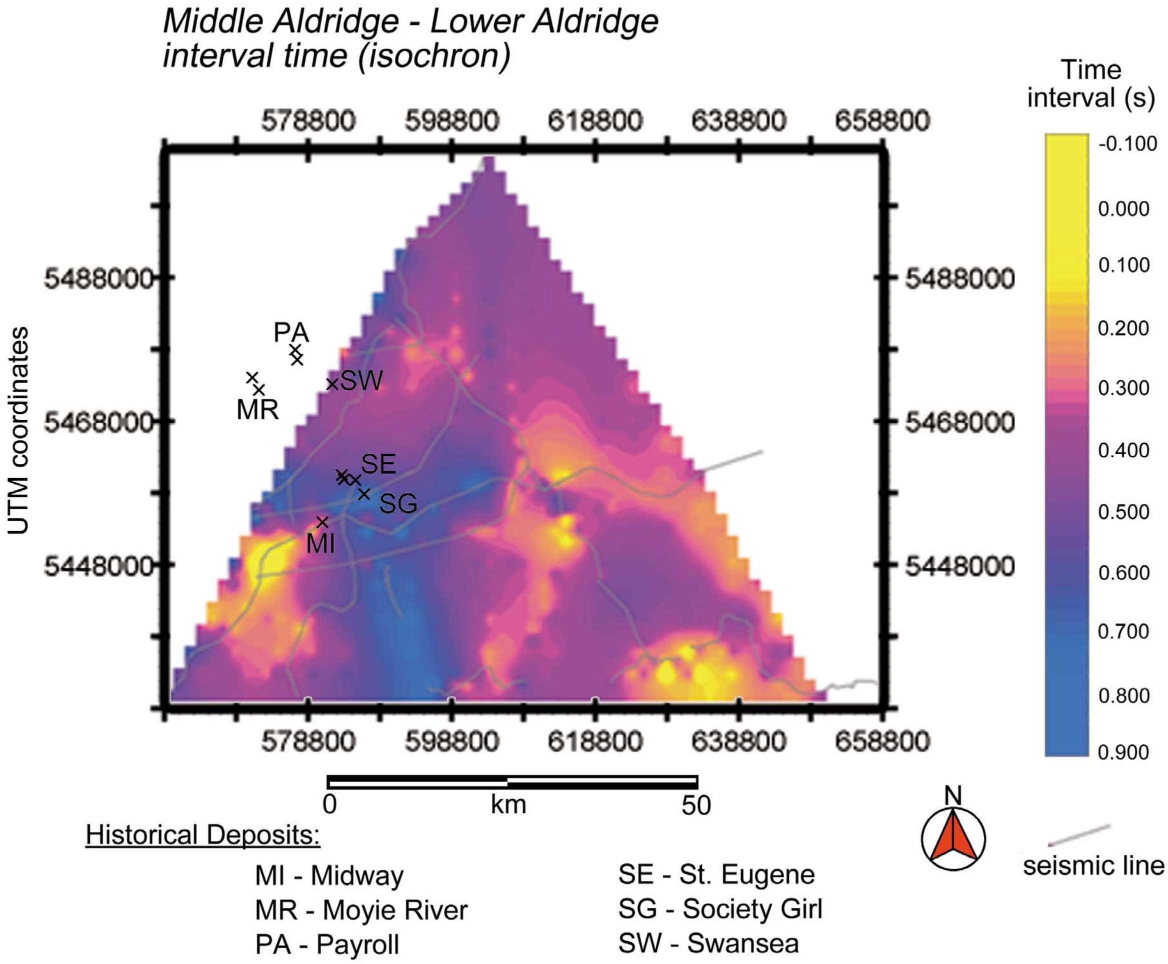


Figure 3-12: Isochron map of Middle to Lower Aldridge transition zone (MS-MAMa with historic lead-zinc mines labelled. These show a spatial correlation between the stratigraphic thickening and the mineralization seen at the north end of Moyie Lake.

Chapter Four: Gravity Modeling Study

4.1 General

The purpose of this portion of this study is to estimate, using gravity modeling in conjunction with regional seismic reflection data and drill hole information, the origin of the regional isostatic gravity anomaly in the Moyie anticline. The results are important for the nature of the Moyie anticline, because they address the question of whether the anticline is cored by high-density basement rocks or whether it is cored by lower-density metasedimentary rocks of the Belt-Purcell Supergroup.

4.2 Regional Gravity Highs

As noted previously, the isostatic gravity anomaly is the difference between Bouguer gravity anomaly and the response of a predicted increase in crustal thickness based on the topography. Throughout the southern Cordillera, isostatic gravity anomalies are generally near zero with several small, local anomalies superimposed (Figure 2-4). Within the region, however, there are two major gravity highs (RMH and MH in Figure 2-4) that deviate from the generally low values of isostatic gravity. Both of these highs indicate that the crust (and/or upper mantle) has more high density rocks than are expected from the calculated values. In this chapter, the procedure for modeling the gravity is described, the application of seismic data and drill hole results are included, and the an interpretation is provided that includes information from all of these methods.

Anomaly MH (Moyie High) has a magnitude of approximately 30 mGals above the regional values and spatially correlates to the Moyie anticline (Figure 2-5). It also diminishes to the north as the anticline plunges. Kleinkopf (1984) proposed that the gravity high associated with the Moyie anticline is a result of thrust slices of high-density Precambrian crystalline basement along a linear zone just west of the Rocky Mountain Trench. As an alternative, Cook and van der Velden (1995) also consider a large quantity of sills within the Belt-Purcell rocks as the cause of the gravity high, but prefer the interpretation of high-density basement in the core of the anticline. Because these interpretations involve density variations that are deep (for basement slices) or shallow (for uplifted sills), gravity analyses offer the possibility of distinguishing between them, particularly when combined with seismic geometry and drill hole lithologies.

4.3 Gravity Modeling Procedure

The gravity models were built in GravCadW, a two-dimensional gravity modeling program (Sherriff, 1997). It uses the Talwani algorithm to calculate the gravity anomaly over a polygon, which relies on the line integral described by Hubbert (1948). These relatively straight-forward mathematical expressions for the vertical and horizontal components of the gravitational attraction due to a two-dimensional body approximated by an n-sided polygon and their derivation in a computationally simple manner are described by Talwani et al. (1959). GravCadW allows polygons with up to 64 corners, which must be defined in a clockwise fashion, to be used to build a model. An iterative process is needed to apply the set of equations to all sides of any n-sided polygon. These can be summed further to show the response of a model constructed from a series of polygons. GravCadW calculates the response of the model which can be compared to the recorded gravity data. The corners of the polygons in the model as well as the density

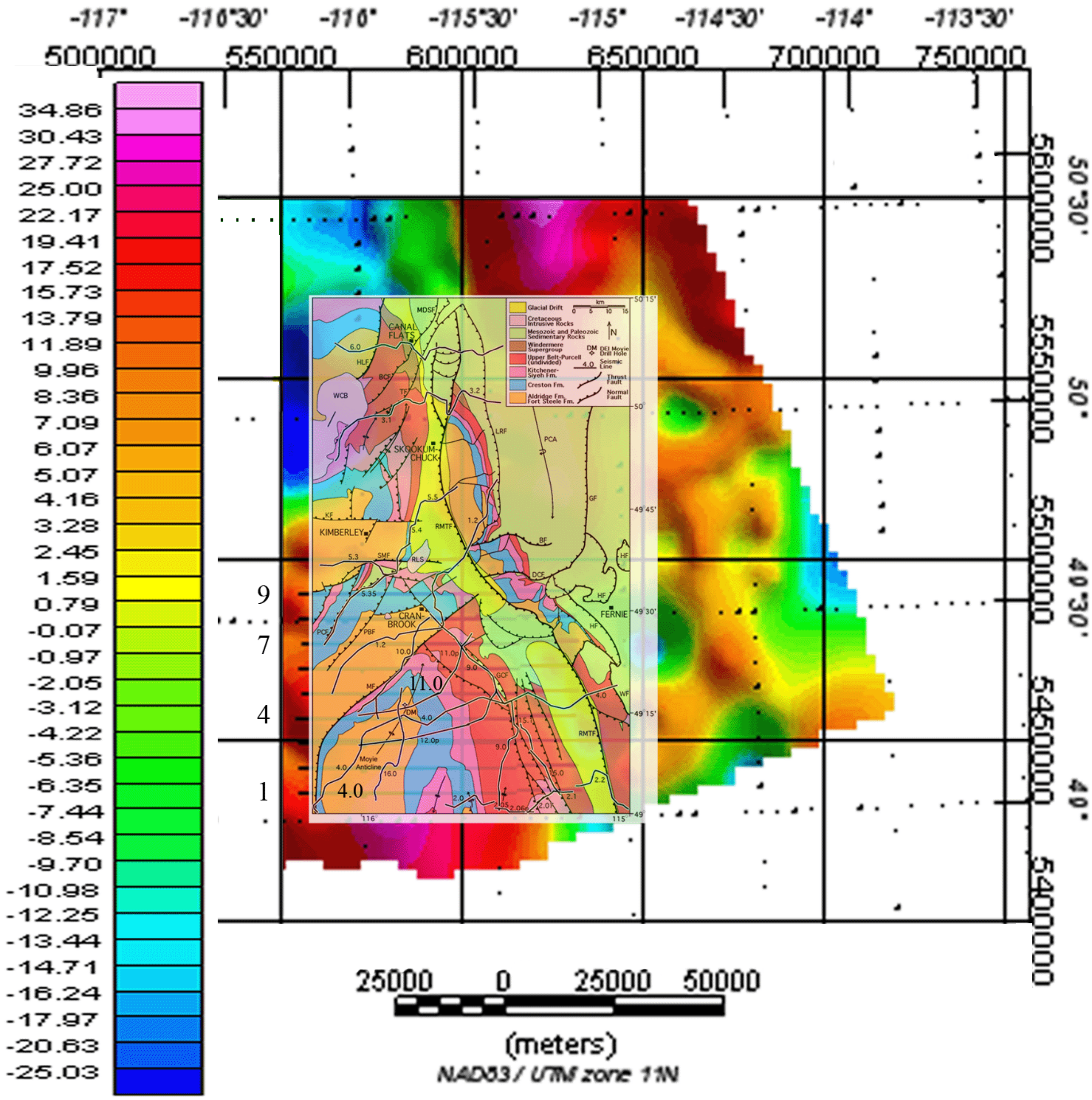


Figure 4-1: **Isostatic gravity of southeastern British Columbia in milligals plotted using Geosoft montaj underlying regional geological map.**

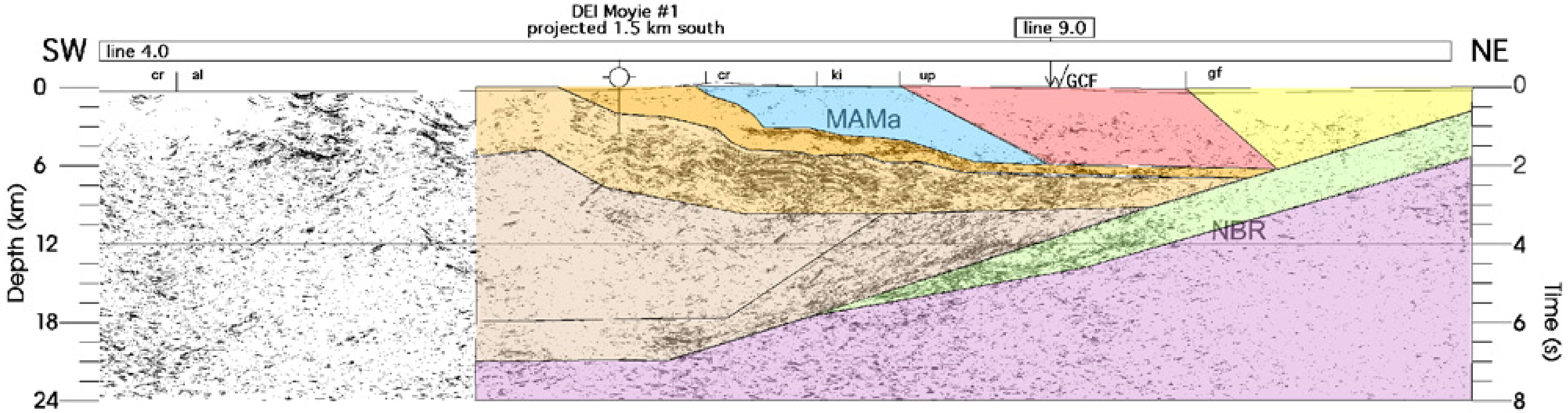


Figure 4-3: Duncan line 4.0 with an interpretation overlain on the portion of line that runs approximately east-west. This was used in building the model for profile 4. The Duncan Energy exploration well is labelled.

contrast of each polygon can be adjusted until the calculated response fits the recorded values. Models were constructed of irregular polygons whose geometry was constrained by interpretations of reflection seismic data. The lines from the Duncan Energy survey, which are approximately oriented west-southwest to east-northeast and close enough to project onto the gravity model profiles, provide limits on the general shapes and sizes of the blocks within particular models. The general characteristics were then propagated throughout the series of models. The profiles for models 4 and 5 are in a similar location to Duncan lines 4.0 and 11.0p respectively. The geometric information from the interpretations of these seismic lines was used to constrain the models to plausible geometries (Figure 4–21 and Figure 4-3).

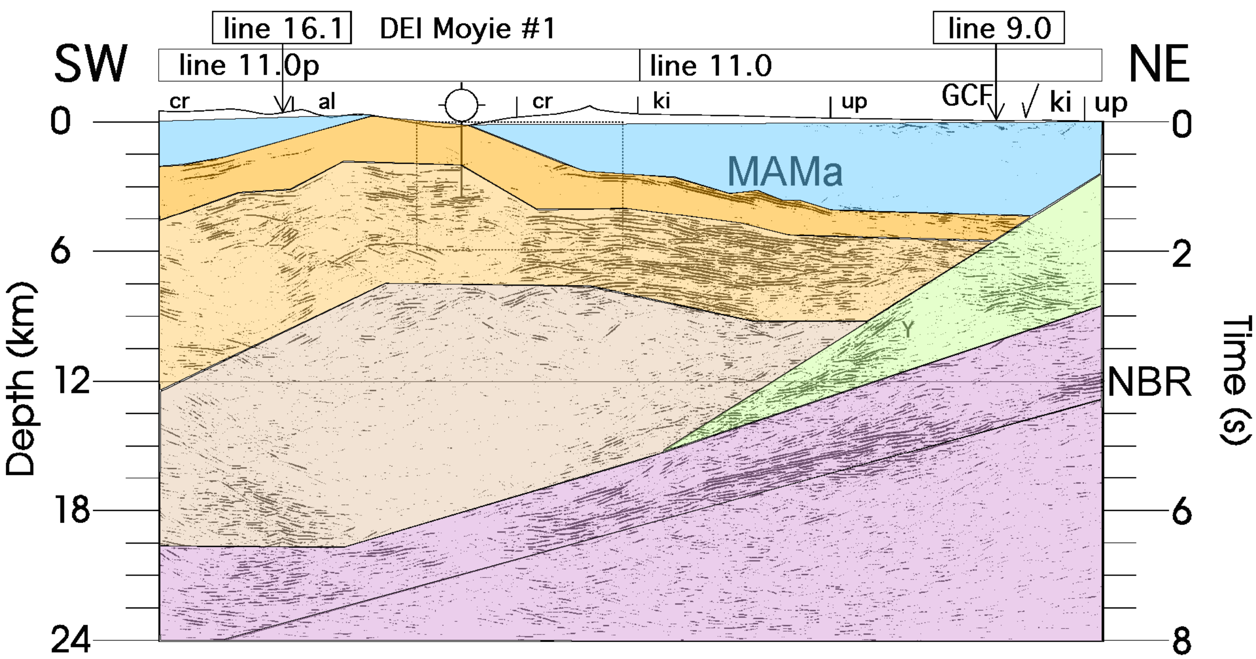


Figure 4-3: Duncan lines 11.0p and 11.0 with an interpretation. This was used in building the model for profile 5. The Duncan Energy exploration well is labelled

4.4 Incorporation of Drill hole Information

The density log of Duncan Energy's exploration well was blocked into a series of vertical intervals, each with a representative average density. The total drilled depth of the well is 3477 m, of which approximately 39% is sills; the log shows that the frequency and thicknesses of the sills increase with depth. The typical density of the sills is approximately 3.00 gm/ cm^3. However, to be useful for the gravity modeling polygons, it is necessary to calculate the average densities over appropriate intervals for the polygons.

Accordingly, the weighted average of the density in the Middle Aldridge with occasional sills was found to be 2.718 g/cm^3, while the weighted average of the density of the Lower Aldridge with many more sills was found to be 2.850 g/cm^3 (Table 4-1). If it is assumed that the regional average crustal density is equal to the Bouguer average crustal density of 2.67 g/cm^3, then the density contrast for these layers becomes 0.048 and 0.180 g/cm^3 respectively. Since the well goes through all of the Middle Aldridge, that value for the density contrast is considered representative of the whole member. The reflection seismic data indicate that the number of sills decreases with increased depth below the depth of the exploration well (Figure 2-6). Therefore, the density contrast of 0.180 g/cm^3 for the Lower Aldridge is considered to be slightly overestimated; hence, for the purposes of modeling, a value of 0.150 g/cm^3 is used instead.

Table 4-1: **Weighted Density Averages from Density Log of Duncan Energy's Moyie #1 exploration well**

drilled interval (m)		average density (kg/m3)	thickness (m)	weighted average density (kg/m3)	weighted average density (g/cm3)	density constrast relative to 2.67 (g/cm3)
0	50	2612.903	50	2718.3844	2.7184	0.0484
50	93	2612.903	43			
93	117	2741.935	24			
117	198	2661.290	81			
198	258	2806.452	60			
258	510	2709.677	252			
510	620	2822.581	110			
620	1682	2717.742	1062			
1682	1870	2822.581	188	2850.2155	2.8502	0.1802
1870	1956	2596.774	86			
1956	1993	2895.161	37			
1993	2481	2669.355	488			
2481	3330	2983.871	849			
3330	3378	2701.613	48			
3378	3463	2935.484	85			
	3477		total	2786.1844	2.7862	

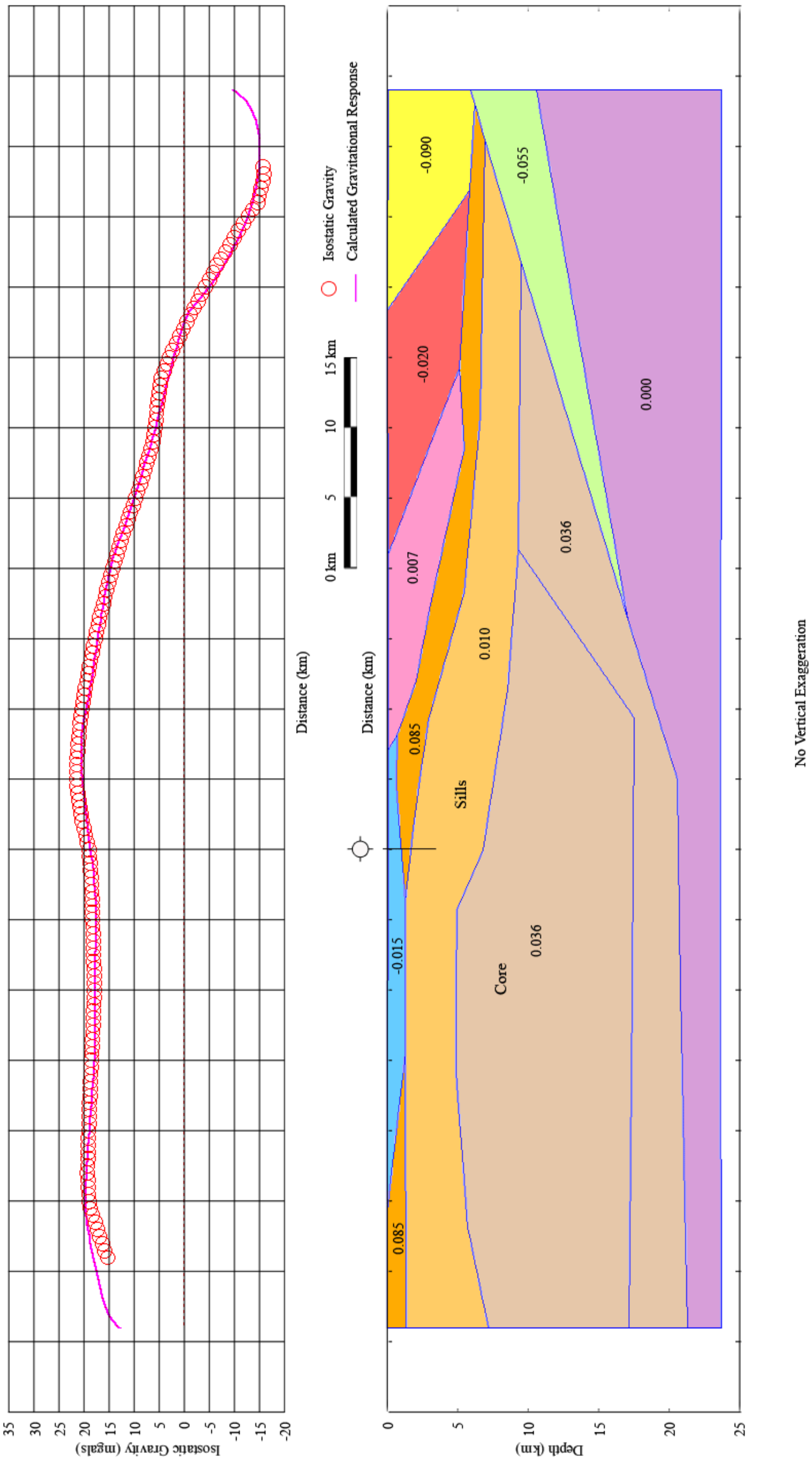
4.5 Interpretations

The ambiguity inherent in potential field inverse problems is such that any recorded response can be matched by a variety of geometries and assorted densities. However, based on regional considerations, the likely interpretations center around two possibilities: 1) that the gravity anomaly is caused by high density rocks at depth in the core of the anticline, or 2) that the gravity anomaly is caused by up-folded sills at relatively shallow depth. As a result, two types of models were constructed (Figure 4-4 and Figure 4-5).

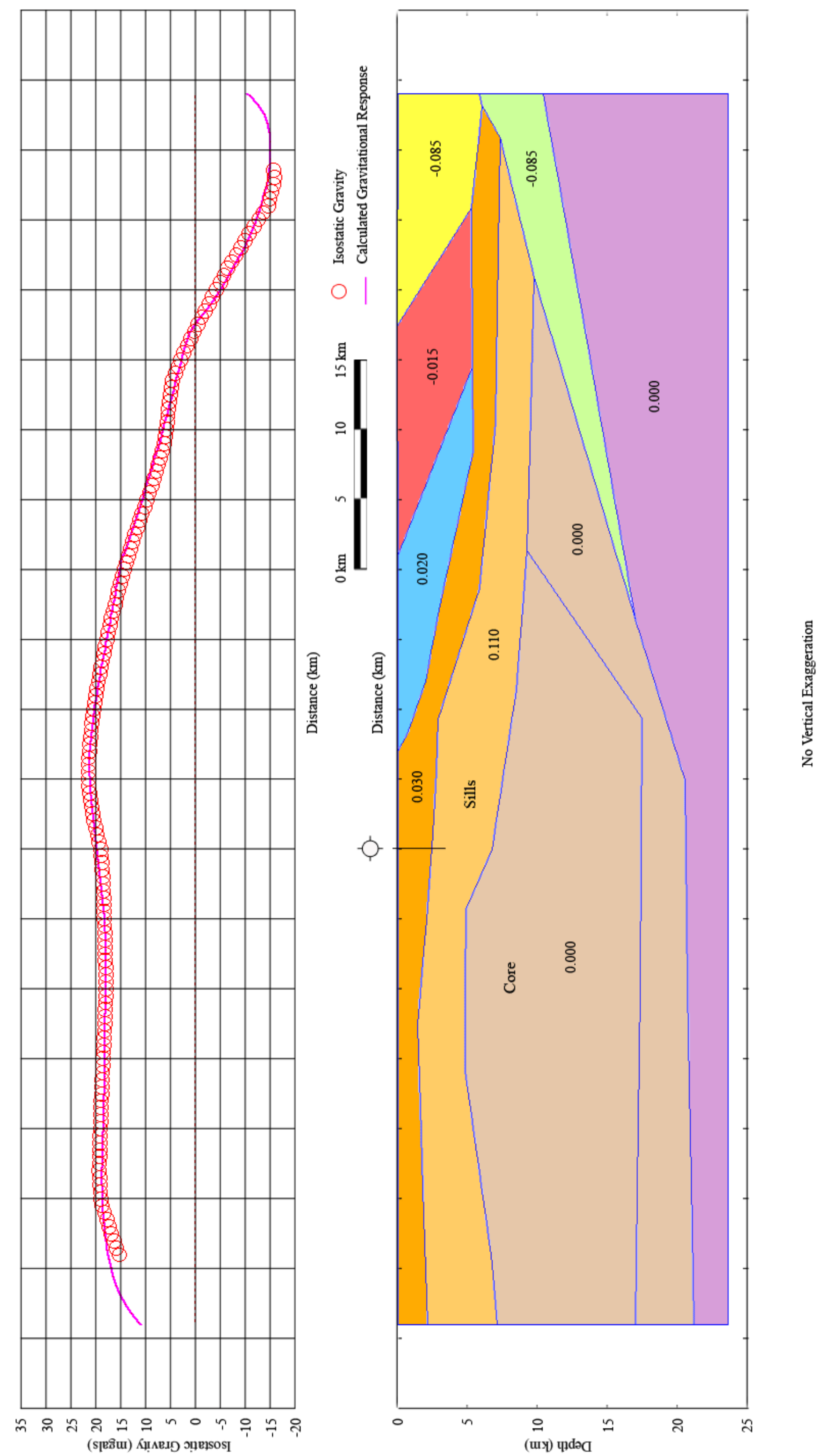
In the first type of model (Figure 4-4), the core of the Moyie Anticline is considered to be higher density than the background material. In this case, the layers with sills are considered to only have slightly higher bulk density than background, implying that the quantity (and/or densities) of the sills is small. Nevertheless, some relatively high-density material in the overlying layer on the flanks of the anticline is needed to account for relatively steep gradients in the gravity profile. Another problematic aspect of this model is that the unit overlying the sills is composed of three polygons with differing density contrasts. This is not consistent with regional geology mapping. Höy (1993) has mapped the Middle Aldridge Member outcropping in the area immediately surrounding Duncan Energy's exploration well. His map and cross-sections do not indicate that this is an isolated sliver of material at the surface; this does not support a synform or basin located above the Moyie anticline.

In the second possible type of model (Figure 4-5), the majority of the high density rocks needed to explain the gravity high is considered to be in the layers that are dominated by Moyie sills. In other words, either the sills are very high density, and/or there are many of them, such that the presence of the sills at shallow levels in the anticline is sufficient to account for the elevated gravity. The model with high-density sills (Figure 4-5) is consistent with both the regional geology and the density contrasts indicated by the weighted average of the density log. For this reason, subsequent models were built using values from the density log and high-density sills.

Figure 4-4: Gravity model for profile 4 over the Moyie anticline constrained by the interpretation of local reflection seismic sections and Duncan Energy's exploration well's density log and a high density core. (following page)



Isostatic Gravity (mgals)
35 30 25 20 15 10 5 0 -5 -10 -15 -20
Distance (km)
Isostatic Gravity
Calculated Gravitational Response
0 km 5 10 15 km
Distance (km)
Depth (km)
0 5 10 15 20 25
-0.090
-0.055
-0.020
0.000
0.007
0.036
0.010
0.085
Sills
-0.015
Core
0.036
0.085
No Vertical Exaggeration



Isostatic Gravity (mgals)
35 30 25 20 15 10 5 0 -5 -10 -15 -20
Distance (km)
Isostatic Gravity
Calculated Gravitational Response
0 km 5 10 15 km
Distance (km)
-0.085
-0.085
-0.015
0.020
0.030
0.110
0.000
0.000
0.000
Sills
Core
Depth (km)
0 5 10 15 20 25
No Vertical Exaggeration

Figure 4-5: **Gravity model for profile 4 over the Moyie anticline constrained by the interpretation of local reflection seismic and Duncan Energy's exploration well's density log with high density sills. (previous page)**

A band of high density materials in an antiform that flattens and plunges to the north and an inclined buried wedge of low density materials are required to match the general shape of the isostatic gravity. These are interpreted to be the Moyie sills and buried Palaeozoic sediments. A zone of strongly negative density contrast further pulls down the calculated response in the vicinity of the Rocky Mountain Trench. Other layers of various density contrasts are needed for the calculated response to match the recorded isostatic gravity.

The plunging anticline diminishes in amplitude to the north and the intruded layers thicken to the south. This is seen in the flattening of the folded strata while the intruded zone thins to the north. Though there are variations in the densities and specific locations of the corners of the polygons, the models are generally similar in major characteristics. To illustrate this, Figure 4–6 to Figure 4–14 show the gravity models along the nine profiles from south to north. Layers in the models are labelled with letters and numbers if two polygons are composed of the same general material and have the same density contrast (for example, Layers C1 and C2). Each polygon represents a unit with a specific density contrast; these may not directly correlate to a particular geological unit. A similar colour scheme to that of the geological map (Figure 1-1) was used because many of these polygons are spatially related to formations, even though the spatial distribution of each polygon may not show the distribution of a specific formation.

Layer A is interpreted to be Precambrian crystalline basement while Layer B is a wedge of Palaeozoic sediments. Layer C is the material in the core of the Moyie Anticline. Layer D is the zone of many intruded sills while Layer E has far fewer sills; both of these layers have density contrasts indicated by the density log. Layer I is the sediment fill associated with the Rocky Mountain Trench. Layers F, G and H are Upper Belt-Purcell rocks with varying densities representing the Creston Formation, the Kitchener-Siyeh Formation and the undivided Belt-Purcell rocks on the east side of the Moyie Anticline. Layers J, K and L are additional layers required to achieve a good match; these layers also represent the Creston Formation, the Kitchener-Siyeh Formation, the undivided Belt-Purcell rocks and Palaeozoic sedimentary rocks on the west side of the Moyie Anticline, though they usually do not have a consistent density contrast compared to the correlative layer on the east side of the anticline.

Gravity models for profiles over the Moyie anticline constrained by the interpretation of local reflection seismic and Duncan Energy's exploration well's density log. Figures 4-6 through Figure 4-14 on pages 51 to 59

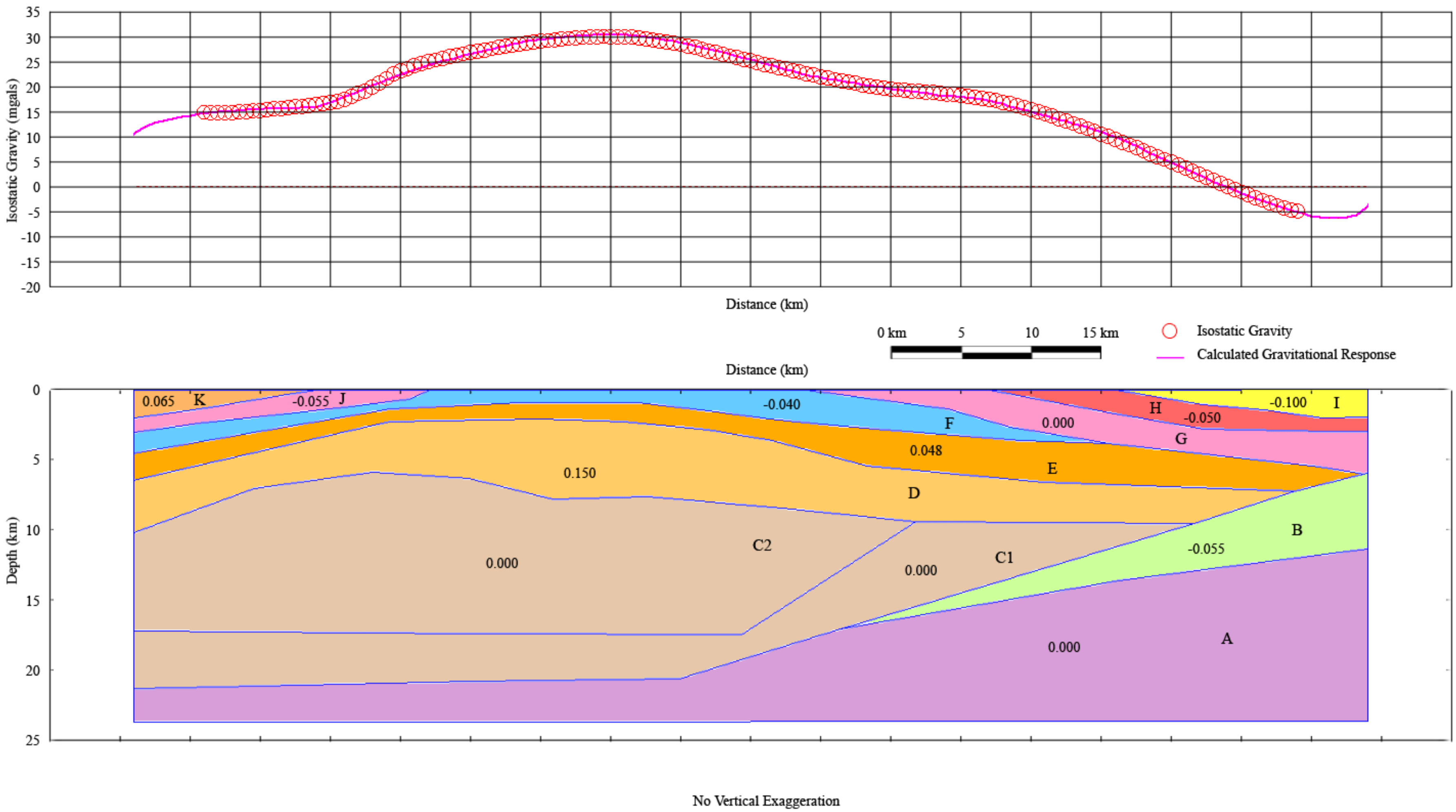
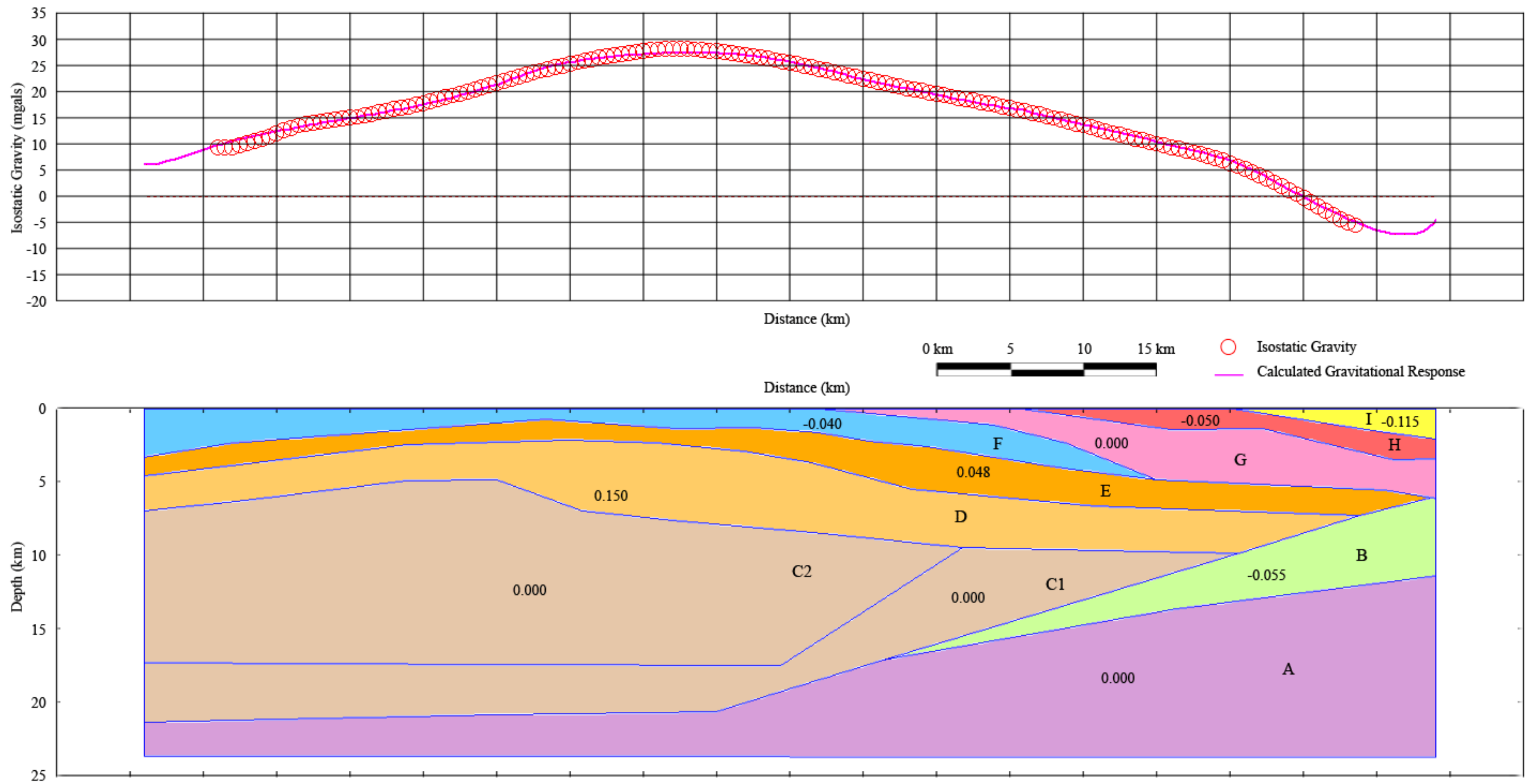


Figure 4-2: Profile 1



No Vertical Exaggeration

Figure 4-7: Profile 2

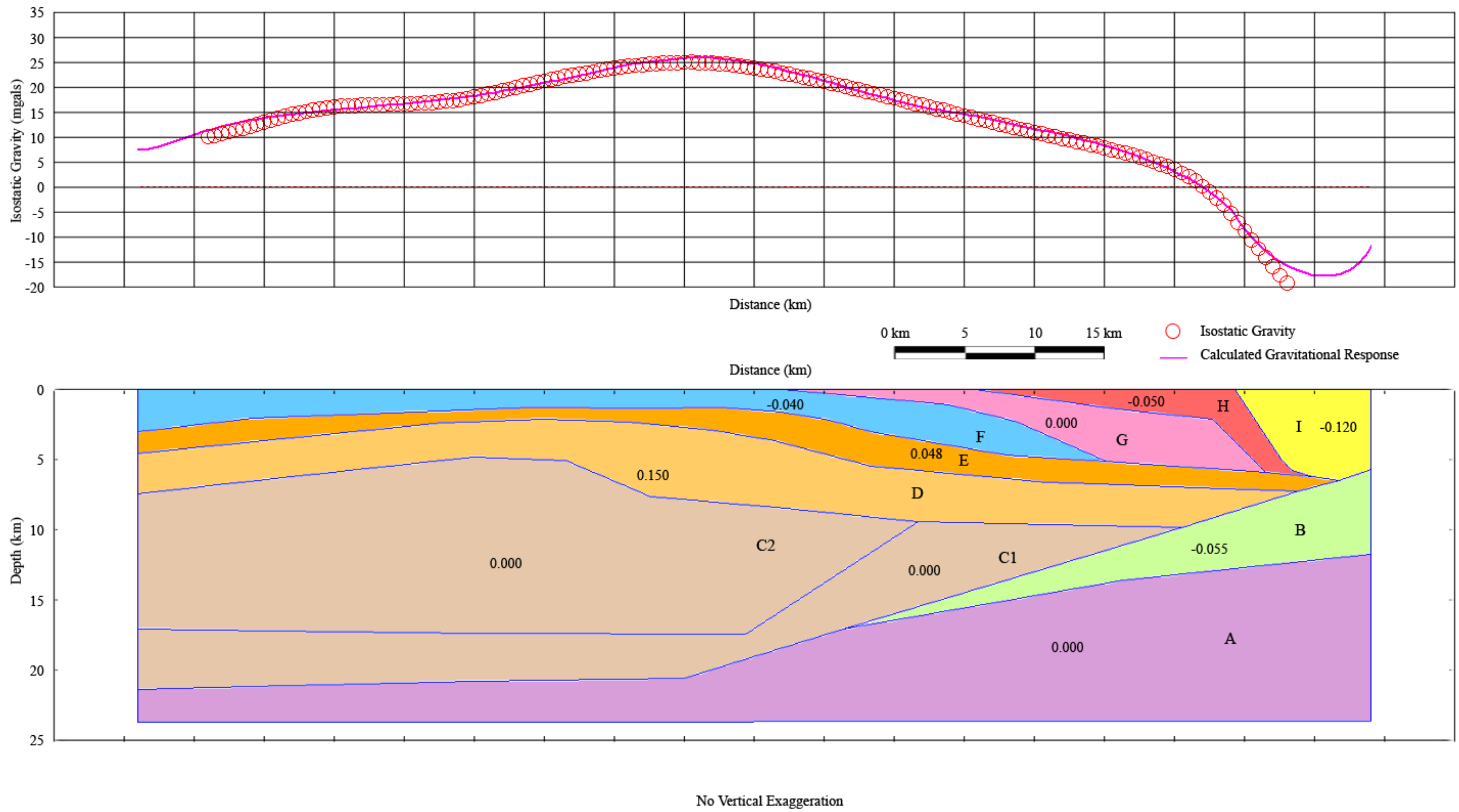


Figure 4-8: Profile 3

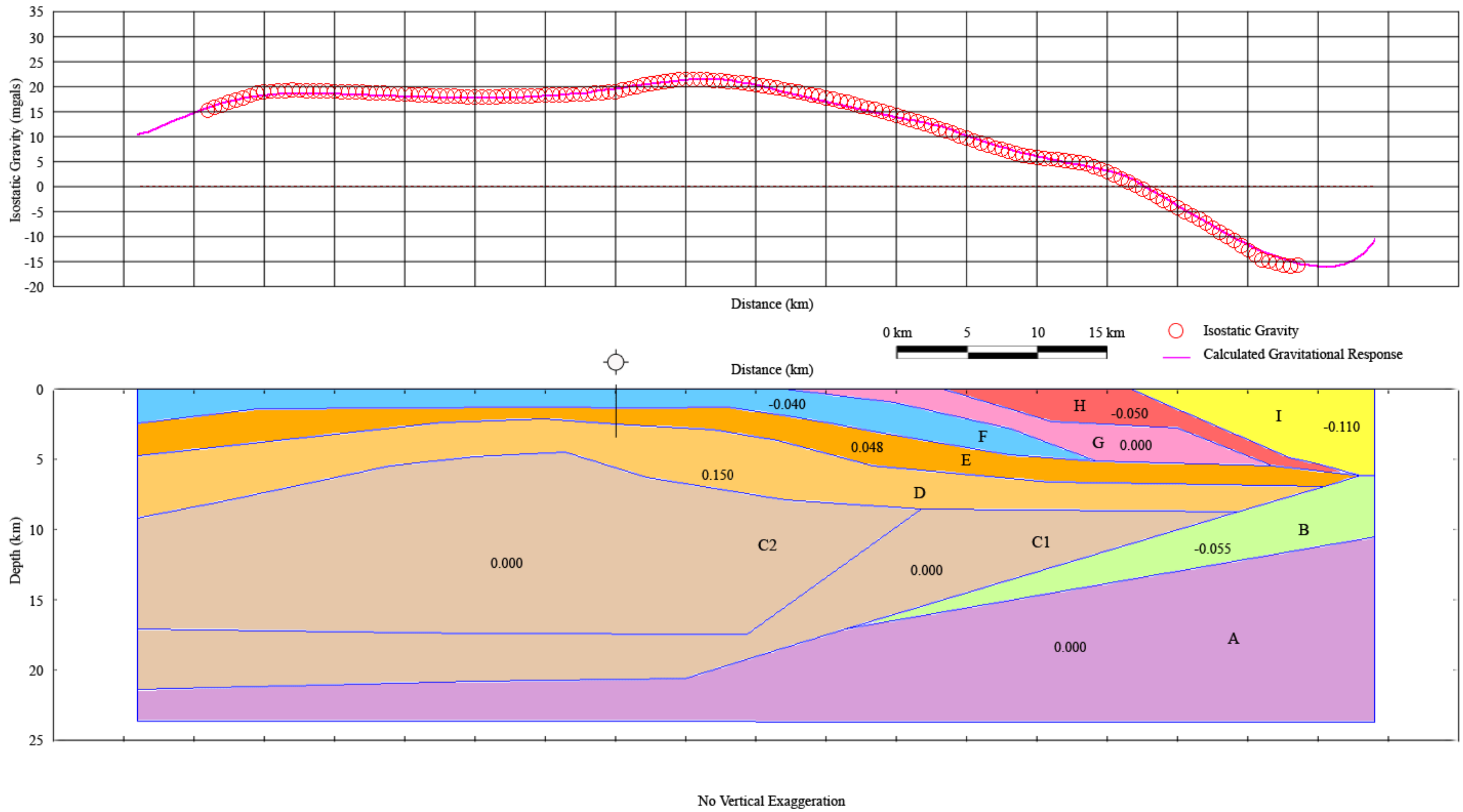


Figure 4-9: Profile 4 with the exploration well shown.

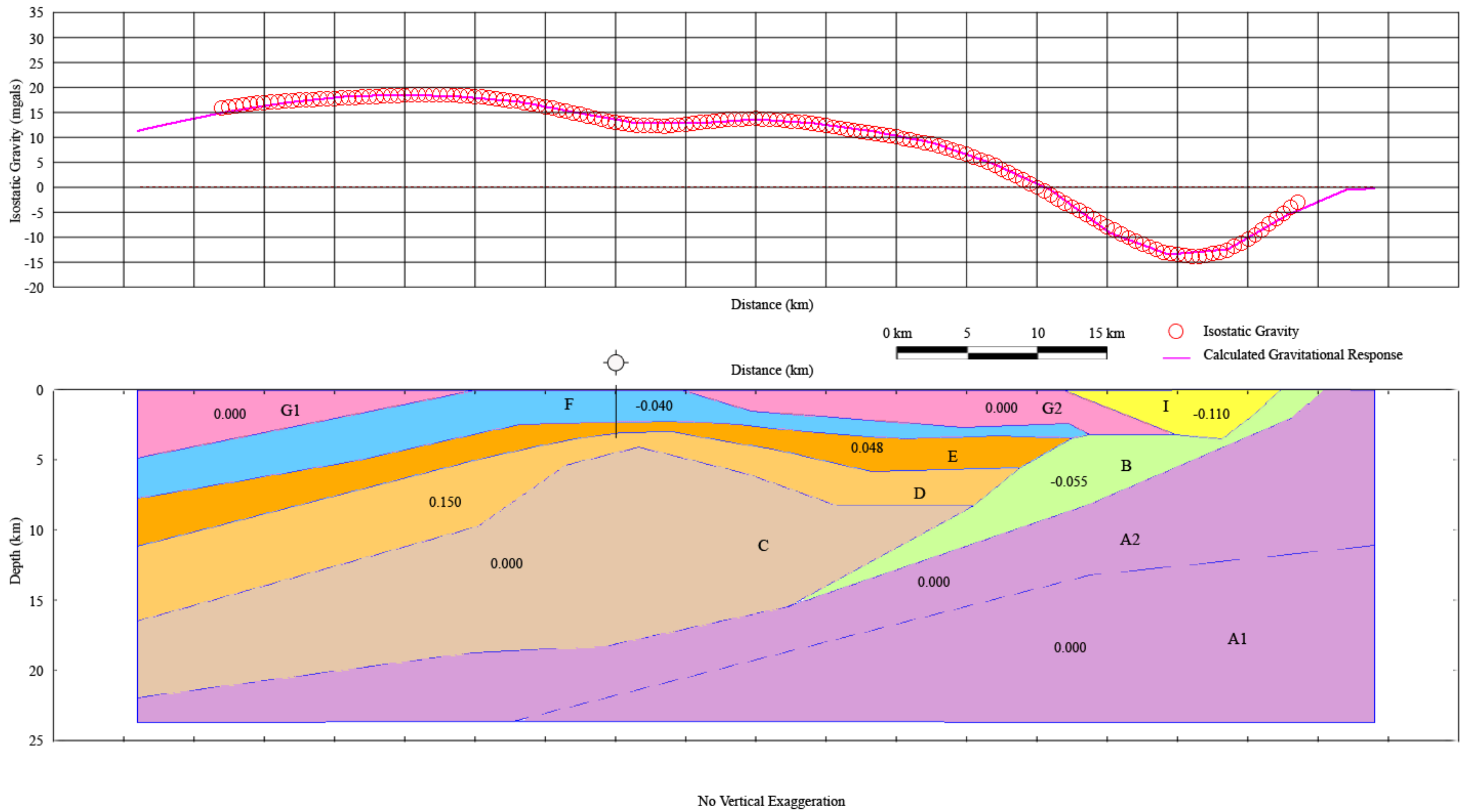


Figure 4-10: Profile 5 with the exploration well shown.

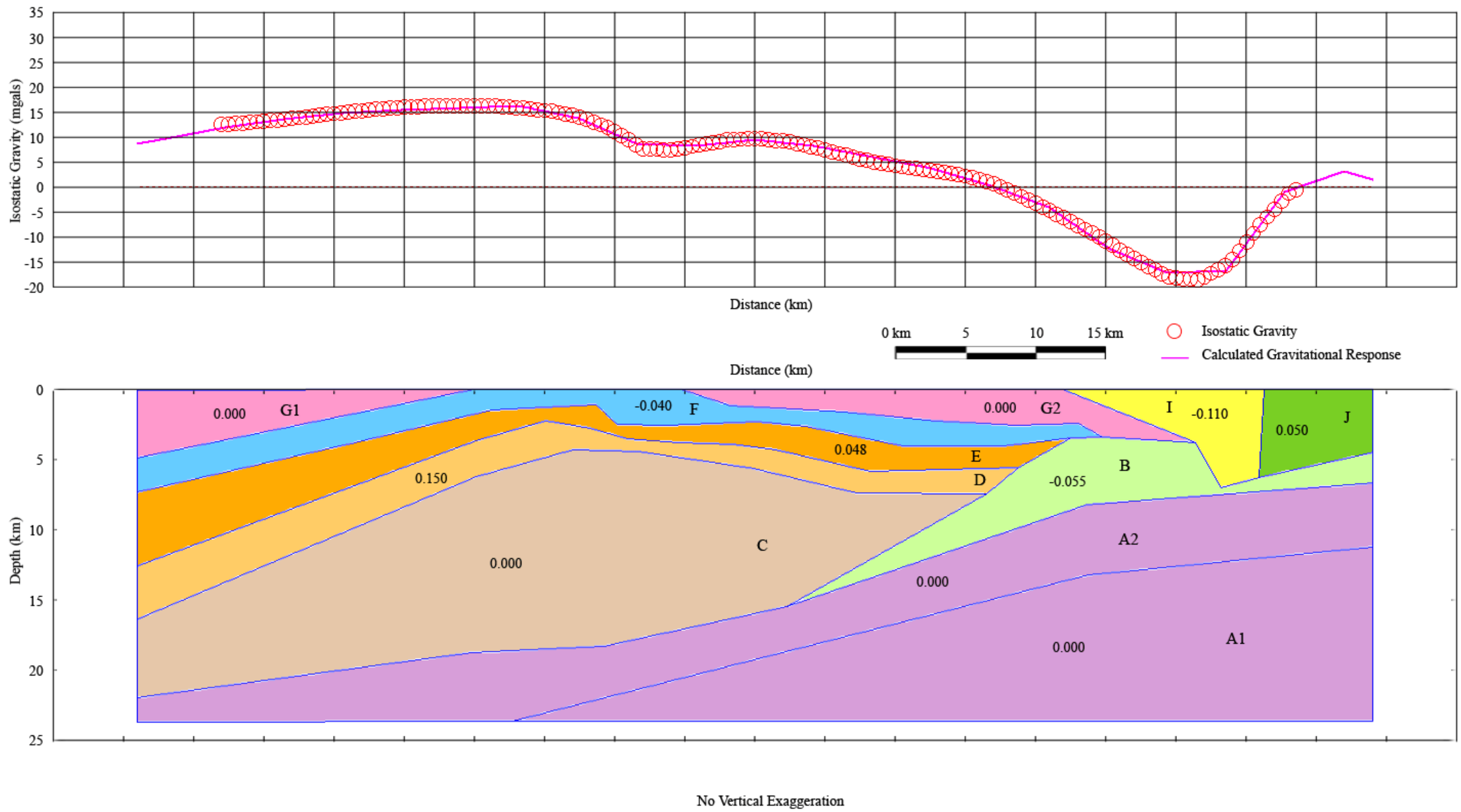


Figure 4-11: Profile 6

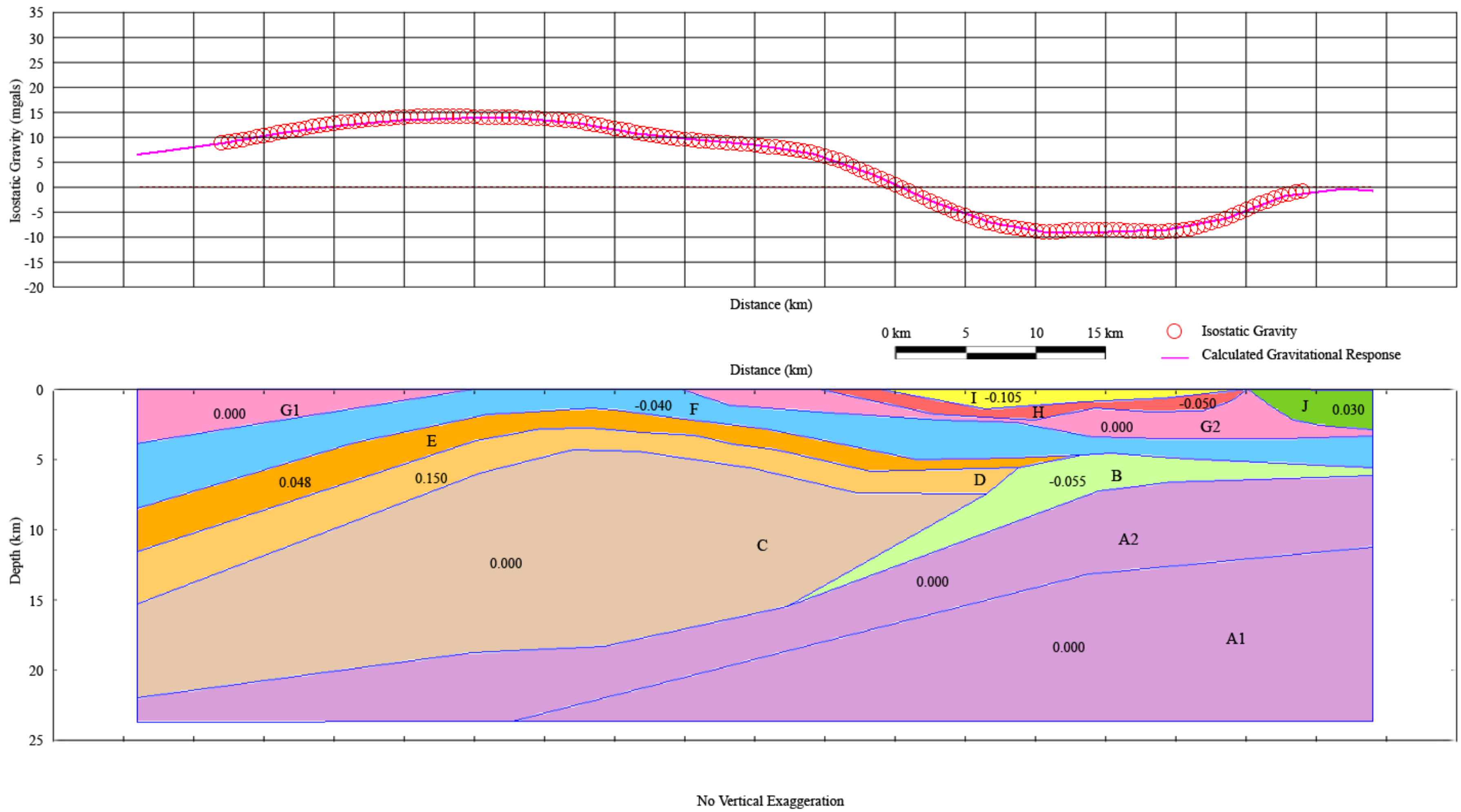


Figure 4-12: Profile 7

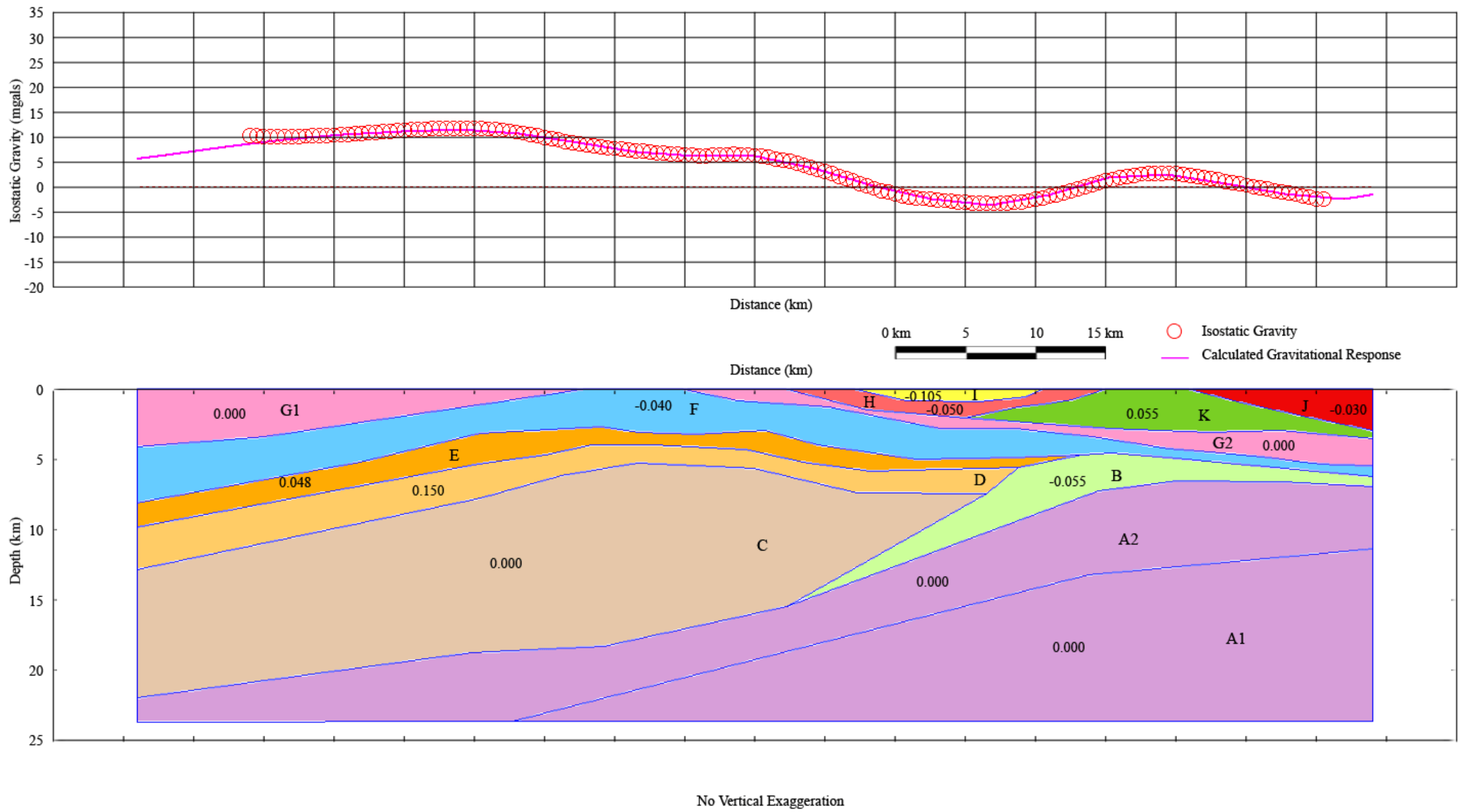


Figure 4-13: Profile 8

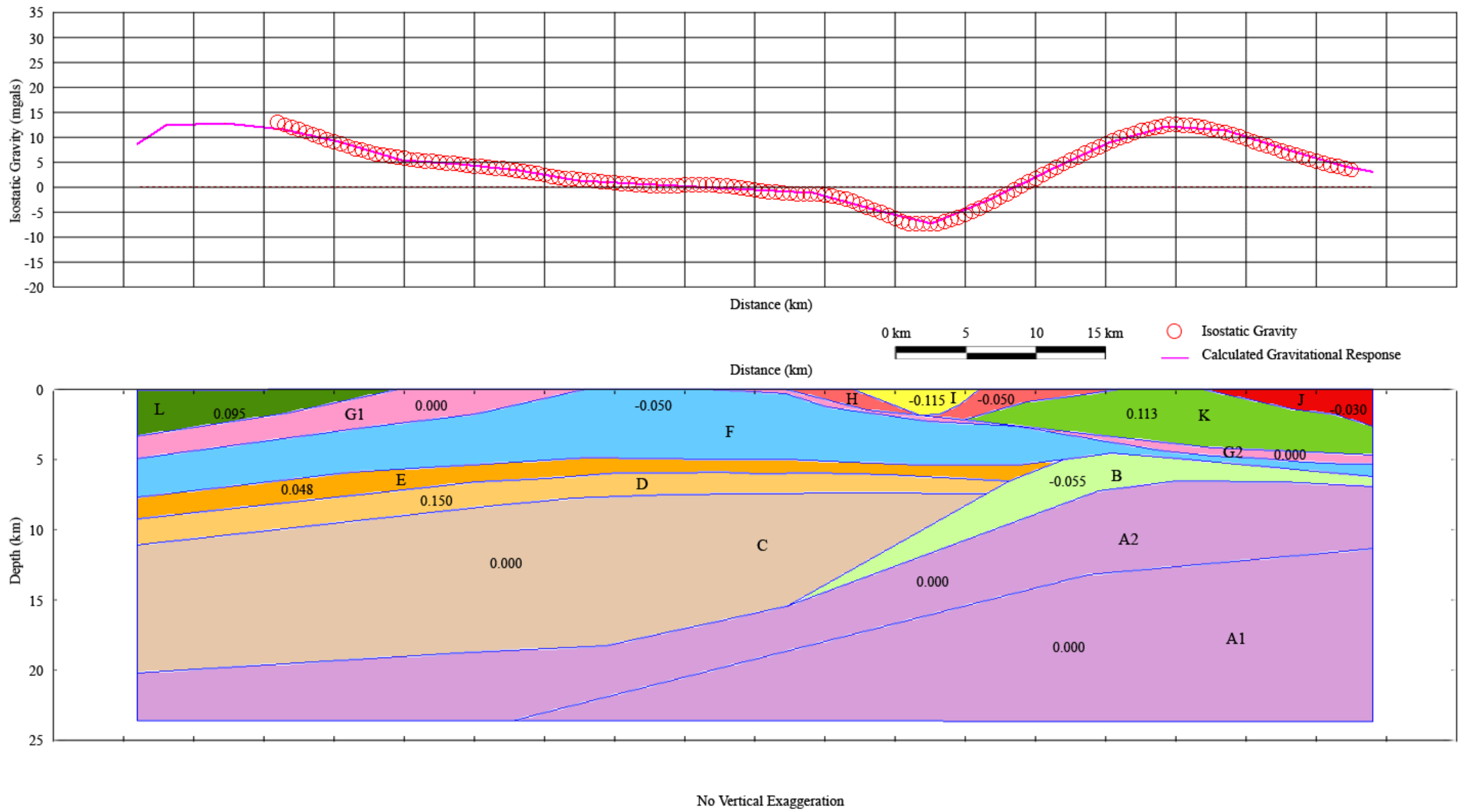


Figure 4-14: Profile 9

4.6 Summary of Results

Two-dimensional gravity modeling of the isostatic gravity of the Moyie High shows that the anomaly can be modeled by a positive density contrast either in the deep core of the anticline or in the heavily intruded zone closer to the surface. The high density and large quantity of sills in the Duncan drill hole support the latter model and can then be used to constrain the average density values throughout the modeled section. The reflection seismic data are used to constrain the regional geometry of the two-dimensional models. The series of nine models shows that the strong positive density contrast of the Moyie sills is the main contributor to the isostatic gravity high in this area; since the core of the anticline has a regional average density; it has no contribution to the positive gravity anomaly. As a result, the deep core of the Moyie anticline is not likely to be high density 'basement'. It could be anomalously low density basement material; however, it is more likely that it is thickened Proterozoic strata (Aldridge).

Chapter Five: Discussion

5.1 General

This study makes use of industry data that were recorded for hydrocarbon exploration and that have been subsequently reprocessed to highlight regional features as well as shallow or local features. Incorporating drill hole data and gravity data adds key constraints to understanding the crustal structure of the Moyie Anticline with implications for palinspastic reconstructions and our knowledge of the extent of the North American craton. Careful reprocessing of the seismic reflection profiles provides new approaches to mapping the stratigraphic changes in the vicinity of the Moyie anticline. In this chapter, some of the implications of these results are discussed.

5.2 Implications of the new results for crustal structure

By interpreting gravity modeling in conjunction with regional seismic reflection data and drill hole information, new evidence is provided for the origin of the regional isostatic gravity anomaly in the Moyie anticline. In short, it can be interpreted to be associated with thickened, high density sills rather than uplift of deep, high density basement.

Kleinkopf (1984) proposed that the gravity high is a result of thrust slices of high-density Precambrian crystalline basement along a linear zone just west of the Rocky Mountain Trench. As an alternative, Cook and van der Velden (1995) also consider a large quantity of sills within the Belt-Purcell rocks, but preferred the interpretation of high-density basement in the core of the anticline. Whether the anticline is cored by high-density basement rocks or whether it is cored by lower density metasedimentary rocks of the Belt-Purcell Supergroup will be critical to the way in which the Moyie anticline is palinspastically reconstructed. In Cook and van der Velden (1995), interpreted basement in the core of the Moyie anticline is reconstructed to deep crustal levels far to the west (see also Travis, 2006). However, if the core of the anticline is thickened Aldridge rocks with little or no deformed basement, then such reconstructions may be made with deformation confined to the supracrustal strata above westward-thinning basement.

Because the deepest thrust faults that carry the deformed rocks of the Rocky Mountains project beneath the Moyie anticline, the rocks of the anticline were transported from the west a distance that is equivalent to the combined amount of displacement on foreland faults. If the core of the Moyie anticline is primarily basement rocks, restoration indicates that those rocks came from approximately 150 km to the west based on reconstruction of the Lewis thrust sheet; (Price, 1981 and Cook and van der Velden, 1995; Price and Sears, 2000). Because these rocks would have been transported from a greater depth than their present position in the Moyie anticline, it is likely that they would have greater densities than equivalent rocks to the east. However, the gravity high appears to be caused predominantly by the intruded Moyie sills, especially where the sills are thicker and near the surface. To the north of the Moyie anticline, where the Moyie sills occur with less frequency and at greater depth, they produce a longer wavelength response of lower magnitude.

According to the results from the gravity modeling, therefore, the crystalline basement in the autochthon and the material in the core of the anticline both have approximately the same density, which is in turn equivalent to the regional average density. It is unlikely that the core of the anticline is composed completely of deep crustal basement rocks, though a thin sliver of basement that is not gravimetrically resolvable is possible. These results supports the hypothesis that the Rocky Mountain basal detachment occurs along the top of the crystalline basement and that there is a thickened section of Aldridge turbidites in the core of the Moyie anticline.

5.3 Implications of the new results for detailed structures and stratigraphic variations

The time-structure maps of the Middle Aldridge marker (MAMa) and the top of the heavily intruded zone (MS) provide three map views of the subsurface structure of the Moyie anticline. While these are generally consistent with the surface geology, they provide detail that is not easy to map from the surface alone. This is particularly evident in the isochron maps, such as the thickness of the intruded zone (RLB-MAMa; Figure 3-10) which shows some thickening in the centre of the anticline, likely due to thickening in the hinge zone. It also highlights where the Moyie Sills were intruded and where they are not present.

A second isochron map (Figure 3-11) shows how the Middle Aldridge Marker is fairly consistently spaced above the heavily intruded Lower Aldridge sill zone, but identifies variations in this transition zone between the Middle and Lower Aldridge members. Perhaps significantly, there is a local thickening of this transition zone that spatially corresponds with the location of historic lead-zinc deposits in this area. Many of these are stratiform deposits (for example, Sullivan, North Star and Kootenay King, north of the Moyie anticline), though some of these are vein deposits (for example, Aurora, St. Eugene and Society Girl; Höy, 1993).

The stratabound clastic-hosted deposits were formed during the deposition of the host succession in a tectonically active, intracratonic setting (Höy, 1993). While the carbonate-hosted deposits are replacement lead-zinc deposits found in the upper Purcell carbonate rocks, the clastic-hosted deposits are found primarily in the Aldridge Formation (Höy, 1993). The vein deposits are younger than the stratabound deposits and are structurally controlled (Höy, 1993). Some vein deposits are related to intrusive activity; for example, copper veins are related to the mafic Moyie intrusions while lead-zinc veins are related to the more felsic Mesozoic intrusions (Höy, 1993). In either case, isochron variations that delineate stratigraphic changes may be helpful in focusing exploration efforts on either structurally or stratigraphically controlled anomalous regions.

Chapter Six: Conclusions

Based on the two-dimensional gravity modeling and the interpretation of the pseudo-grid of two-dimensional reflection seismic data, the following conclusions can be made:

1) Reprocessing of the portion of the Duncan Energy dataset that geographically overlies the Moyie anticline has improved the imaging of near-surface features.

2) Identification of key mafic sill horizons in the Middle and Lower Aldridge formations provides pseudo-stratigraphic intervals that can be mapped to analyze structure and thickness variations. The maps illustrate detailed structural variations that had not been visible previously and further highlight thickness variations between horizons.

3) A particularly significant interval for mapping is the Middle Aldridge to Lower Aldridge transition, as thickness variations in this stratigraphic interval have been shown to be associated with important mineral deposits (Lydon, 2000). In the maps shown here, time-thickness variations of as much as 0.50 s are observed.

   a. These variations may be significant in exploration for stratigraphically controlled mineral deposits.

   b. As important mineral deposits in this region are associated with thickness variations (Lydon, 2001), then this approach may provide a new tool for mapping the regional extent of such variations in the subsurface of the Purcell anticlinorium and perhaps elsewhere.

4) The Moyie gravity high is an isostatic gravity anomaly that can be modeled by a positive density contrast either in the deep core of the anticline or in the heavily intruded zone closer to the surface.

a. The high density and large quantity of sills in the Duncan drill hole support the latter model and can then be used to constrain the average density values throughout the modeled section.

b. The reflection seismic data are used to constrain the regional geometry of the two-dimensional models.

5) The series of nine models shows that the strong positive density contrast of the Moyie sills is the main contributor to the isostatic gravity high in this area. Since the core of the anticline has a density that is close to the regional average, it apparently has little or no contribution to the positive gravity anomaly. As a result, the deep core of the Moyie anticline is not likely to be high density 'basement'. This is significant because the Aldridge formation sedimentary rocks in the DEI Moyie drill hole typically have a density that is lower than, or approximately the same as the regional 2670 kg/m3 that was assumed. However, if the deep core of the Moyie anticline were basement rocks brought from substantial depths (as would be necessary during contractional faulting), such rocks would be expected to have densities appropriate for lower crustal values. Accordingly, it is more likely that is the deep lithology of the Moyie anticline is thickened Proterozoic strata (Aldridge).

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