SEISMIC REFLECTION AS A DIRECT DETECTOR OF GOLD MINERALISATION IN THE CARLIN DISTRICT, USA

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DEPARTMENT OF EXPLORATION GEOPHYSICS

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This thesis is dedicated to my mother, Rhonda Barrett-Smith, and father, Dennis Smith, whose love and support has allowed me to achieve my goals.

Thank you
Abstract

The Carlin district of Nevada, USA, is responsible for some of the world’s most lucrative gold production. Within the Carlin district, significant gold mineralisation occurs along a number of highly prospective and well mapped “trends” through the process of hydrothermal alteration within carbonate lithologies. This fluid interaction has been observed to create ore bodies characterised by heavy decalcification and silicification, which often host economically viable concentrations of gold mineralisation. Within these trends, however, are numerous zones characterised by thick pediment sections, which inhibit the effectiveness of traditional electromagnetic and potential field approaches to mineral detection. In addition to this, geochemical signatures are substantially masked and hold little substance for interpretation of deep-lying prospects. Seismic reflection offers the depth of penetration and spatial resolution to image both regional and local geological structure over these areas. Furthermore, the alteration style and intensity, as well as the nature of mineralisation within the Carlin district, suggest that significant impedance contrasts will be apparent within prospective decalcified and silicified zones, creating ideal seismic targets.

Petrophysical measurements have shown a reliable inverse-linear relationship between the apparent porosity and acoustic impedance of a suite of samples, representative of the local Cortez lithologies. This relationship indicates that seismic reflectivity is likely to provide information not only on lithological unit interfaces, but also on the porosity of rock units, and indirectly, provide possible inferences as to where hydrothermal fluid migration and activity is likely to have occurred.
Full elastic modelling of geological sections representative of typical Carlin lithologies in the presence of decalcified and silicified lenses, has shown that for realistic and critically inferred petrophysical attributes for altered ore bodies, and measured petrophysical averages for local lithologies, seismic reflection is able to clearly delineate heavily decalcified lenses from adjacent formation boundaries. This response is reliable for modelled lens thicknesses of 5, 10 and 20 metres, where increasing thickness is matched with increases in amplitude of reflections. All models are characterised by lens thicknesses that are less than ¼ of the dominant wavelength within the geological setting and hence, due to tuning limits, image as single reflection events, as opposed to individual responses from tops and bottoms of the ore bodies.

Inputting realistic attributes, simulating silicification of the lenses, returned results far less obvious than in the case of decalcification. For all lens thicknesses (5, 10 and 20 metres), reflectivity over the anomalous zones was insignificant, and under real-life circumstances, would more than likely be masked by intrinsic noise and lack of signal to noise ratio that is apparent in practical hard-rock seismic data.

Synthetic responses for decalcified lenses show comparative characteristics to some areas observed in true field data, in which high reflectivity horizons can be tied to spikes in gold mineralisation as measured with borehole fire assays. These horizons, however, are also interpretable as pediment/bedrock interfaces and hence further research is required to identify the degree of influence that possible alteration has had on reflection strength.
The results have indicated that seismic reflection technology holds significant potential in detecting zones of heavy decalcification within the Carlin district over areas in which traditional hard-rock mineral exploration techniques are inapplicable.
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First and foremost I would like to thank my parents, Rhonda Barrett-Smith and Dennis Smith, for their loving guidance throughout my life, and in particular, my time at University. I would never have been able to achieve my goals without the emotional and financial support that they have provided through the good times and the bad. I am more grateful than you could know.

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1 Introduction

The motivation behind this research stems from the characteristic nature of Carlin-type Au mineralisation within the Carlin District of Nevada, USA, and the highly prospective nature of the province with respect to gold production and extraction. The known and well understood presence of mineralisation “trends” within the Carlin district outline succinct zones of highly prospective terrain. Within these mineralisation trends are many areas characterised by thick pediment cover, of which modern geophysical methodology, in particular electromagnetic and potential field approaches, are ineffective at imaging subsurface ore bodies. In addition to this, geochemical signatures are strongly masked and lack analytical substance for exploration purposes. The seismic method holds the potential to achieve the spatial resolution required to image both regional and local structures, and can adequately penetrate these thick pediment units. In addition to this, it is typical for extensive alteration to produce heavily decalcified or alternatively, silicified ore units that are often rich in Au mineralisation. This decalcification and silification process leaves Au rich host rocks with suggestively strong impedance contrasts due to altered density and velocity characteristics, justifying the seismic approach to isolating these zones.

1.1 Seismic Reflection in Complex Hard Rock Environments

The application of seismic reflection as a geophysical method has, for the most part, been constrained to exploration and reservoir classification involved with oil and gas production. In recent years, with the value of rare and economical minerals increasing consistently, hard rock geophysical methodology has inevitably converged
with methods used predominantly for oil and gas exploration, in order to provide a broader geophysical toolbox for use in hard rock exploration and mineral detection.

Seismic reflection is best known for its ability to discern subsurface reflections, produced by a wavelet travelling across media interfaces of contrasting impedances. With impedance being directly related to elastic attributes of a medium, the effectiveness of seismic reflection in hard rock environments, where media is characterised by dense, consolidated rock sequences, is questionable. This is more so the case when considering reflection techniques for direct isolation and delineation of mineralisation or depositional zones, as opposed to the porosity, permeability and density contrasts seen in fluid-saturated reservoir environments related to oil and gas applications.

High resolution reflection seismology introduces a new approach to hard rock exploration and analysis, but is currently restricted by poor signal to noise ratios. The lateral resolution and depth of investigation attainable by modern seismic surveys is unmatched by most geophysical techniques, and in many cases, offers an informative snapshot of the geological setting and subsurface structure, invaluable to the study of stress orientation and deformations of a study area. For areas, such as those seen in the Carlin District, where both regional and local geological structure is a key determinant of localised mineralisation and fluid genesis, a highly resolved seismic approach has potential to be extremely valuable.

1.2 Hydrothermal Alteration as a Seismic Target

The geological methods by which we understand hydrothermal alteration and subsequent mineralisation to occur, present theoretical openings that suit the application of seismic reflection techniques. Rock alteration, by definition, outlines
the change in mineralogy of a rock as a result of some variation in depositional properties. This can be due to changes in temperature, pressure or chemical conditions, or any combination of the above. With regards to hydrothermal rock alteration, significant mineralogical alteration is due to interaction with hot fluids originating from nearby igneous intrusions or adjacent rock leaching. The interaction with such fluids causes the introduction or removal of isolated minerals, altering the physical properties of the rock.

Seismic reflection as a geophysical tool, fundamentally acts on variations in physical rock characteristics, in particular, the seismic impedance of a rock. As we know, seismic impedance is a product of both velocity and density of a medium, so it is feasible to expect that, due to the nature of hydrothermal alteration and the resultant manipulation of the physical structure, an impedance contrast will occur between zones of altered rock and the surrounding rock bodies. The resulting petrophysical attributes of hydrothermally altered rock units is, however, ambiguous and highly dependent on the nature and age of fluid interaction. This variation adds complexities to seismic responses and amplitude analysis.

1.3 Seismic Reflection for Direct Detection of Mineralisation

Seismic reflection techniques as an avenue for direct detection of mineralisation, is an ambitious and experimental study, holding significant prospects if proven feasible. The resolution attainable by modern 2D and 3D seismic systems, particularly when calibration with proximal borehole logging and check shots is involved, is of the order of tens of metres. Data of such resolution, in conjunction with seismic inversions, analysis of Amplitude Variations with Offset (AVO) and a thorough understanding of the survey area’s petrophysical attributes, provide
sufficient information to make justifiable predictions of direct locations of hydrothermally altered mineralisation zones on a sub-seismic scale.

In the case of the Carlin style Au deposits of hydrothermal genesis, is it acceptable to assume that, in many cases, significant deformation and material break-down has occurred within carbonate units that have undergone alteration. Tying this material deformation to petrophysical properties, in particular, apparent porosity, density and compressional velocity, and resultant variations in seismic impedance, allows us to indirectly take seismic reflectivity as an indicator of plausible alteration intensity and zones of likely fluid interaction.
2 Nevada, USA

Production reports from 2008 valued gold production in the state of Nevada at greater than five billion U.S. dollars, 76% of the U.S. total. Nevada was independently responsible for eight percent of the world’s gold production for 2008, with only Australia, China and South Africa producing more gold than the individual state (Price, 2009). With such lucrative historical standing with respect to gold mining, extensive exploration and extraction projects are undertaken throughout the state each year.

A set of highly anomalous mineral deposit trends found within Nevada were originally defined by the alignment of diverse mineral deposit types (Ordovician and Devonian Sedex barite, Jurassic/Cretaceous/Tertiary porphyry Cu-Mo-W-Au, and epithermal Ag-Au) along regional structural fabrics and igneous intrusions, thought to be controlled by deep basement faults (Emsob et al., 2006). Emsob et al. (2006) explains that, with subsequent discovery of Carlin-type mineralisation, these trends became synonymous with more recently defined bands of giant gold deposits in the Carlin, Battle Mountain-Eureka, Getchell, Jerritt Canyon and Alligator ridge trends.
Figure 2.1: State map of Nevada, USA. Carlin and Cortez areas of interest marked in the North-East of Nevada (accessed http://go.hrw.com/atlas/norm_htm/nevada.htm).
2.1 Carlin-type Gold Mineralisation

Carlin-type mineralisation has only recently been thoroughly defined, encapsulating gold mineralisation styles that replicate those seen in the Carlin Mine, which began operation in 1965 in the Lynn district of Eureka Country, Nevada, USA. This style of gold mineralisation predominately occurs within sedimentary host rocks, in particular, those containing carbonates. Various concentrations of Carlin-type Au deposits have been discovered across the globe, with the largest being those in the state of Nevada, USA and China.

A major defining factor of the Carlin-type deposit is the presence of “invisible gold”, undetectable in its native form by the human eye (Castor and Ferdock, 2004). Investigation into the geologic constraints and determinants of the Carlin-type Au deposits have been numerous, with hypotheses of the genesis of such deposits being related to possible connections to igneous activity at depth, to complex evolution of tectono-thermal events, to inherent host rock permeabilities, to evolved meteoric fluids, oil brines, or orogenic fluids, and many other factor (Peters, 2004). As the focus of this thesis is those Carlin-type Au deposits within the state of Nevada, isolated depositional characteristics for this environment will be developed on throughout.

Gold found in deposits along known mineralisation trends throughout the state of Nevada, particularly those along the Carlin trend, occur as submicron particles (50-200Å) within the lattices of pyrite and arsenian pyrite primarily (Hausen and Kerr, 1968; Radtke, 1985; Bakken, 1990; Arehart et al, 1993a; Sha, 1993). Fluid inclusion studies have been carried out by Kuehn (1989) in the Carlin deposit, Hofstra and by others in the adjacent Jerrit Canyon district, of which results suggest that gold was
transported as a hydrogen bisulfide complex. As fluid inclusion analysis shows consistent low salinities (1-7% NaCl equivalent) and enrichment in both H$_2$S and CO$_2$, gold-bearing fluids that have formed the Carlin trend deposits are interpreted as an evolved fluid chemistry, being the result of mixed meteoric-magmatic fluids origin. This follows that enriched H$_2$S concentration in the ore fluid resulted in sulfidation of reactive iron in the host rock to precipitate gold-bearing arsenian pyrite (Teal and Jackson, 2002)

2.2 Structural Controls of Carlin-type Gold Deposits

The various trends of gold mineralisation throughout north-east Nevada have not been related to a manifestation of any singular fault zone, but rather a combination of structural features in a zone of crustal weakness and sustained high heat flow, as indicated by multiple periods of intrusive activity. Teal and Jackson (2002) explain, with reference to the famous Carlin trend of Au deposits, that this environment created a setting conducive to prolific gold mineralisation. Furthermore, while structural influences differ between deposits on a regional scale, common features include:

- High-angle, northwest-striking fault sets that served as primary fluid conduits and are commonly filled by lamprophyric and monzonitic dikes;
- High-angle northeast-striking faults that served as secondary conduits, particularly at structural intersections with northwest faults;
- Broad to moderate amplitude anticlinal folds in autochthonous carbonate rocks; and
- High-angle and stratabound, premineral stage, collapse breccia bodies.
2.3 Alteration Styles and Theoretical Responses

Teal and Jackson (2002) report that numerous papers describing wall-rock alteration of the Carlin trend deposits have been produced, in particular Hausen and Kerr (1968), Radtke (1985), Kuehn (1989), and Bakken (1990). Such documentation entails that the pervasiveness and intensity of alteration varies both within and between gold deposits, depending on the magnitude of mineralising system, nature of the host rock, and density of structural conduits (Teal and Jackson, 2002).

Furthermore, Cuffney and Mallette (1992) summarised the dominant features that characterised Carlin-type deposits to be:

- Carbonate dissolution;
- Silicification, particularly within structural conduits;
- Argillic alteration of primary silicate minerals;
- Gold-enriched sulfidation of reactive iron in host rocks, to form gold-bearing sulphide minerals (pyrite, arsenical pyrite, marcasites, arsenical marcasites);
- Multi-phase fluid inclusions, characterised by low salinity (0.5-7 wt % NaCl equiv.), variable amounts of CO₂ and low homogenisation temperatures (120-250°C).

In the styles of alteration mentioned above, it is important to note that the physical contrasts suggested by carbonate dissolution and unit silicification are most appropriate for seismic forward modelling, and will be the focus of this study.

2.3.1 Carbonate Dissolution

Teal and Jackson (2002) explain that the removal of carbonate as a process of decalcification (calcite removal), and the more advanced decarbonisation (calcite/dolomite removal), to be the most omnipresent style of alteration observed...
within the Carlin trend deposits. Teal and Jackson (2002) provide a comprehensive analysis of alteration styles across the Carlin trend of Au deposits and will be discussed herein.

The extent of dissolution of carbonate is controlled to some degree, by the composition of the original host rock. Deposits hosted within or above dense, biosparatic, limestone protolith are reported to have decalcification restricted to zones around high-angle paleo-fluid conduits and laterally along abrupt compositional changes in strata. In addition to this, deposits such as Carlin have seen decalcification intensified and more pervasive in nature due to the original porosity and permeability of the host rock.

Studies by Kuehn (1989) and Bakken (1990) have proposed, with respect to the Carlin deposits that acidic, hydrothermal fluid channelling along high-angle structural conduits and favourable stratigraphic horizons has resulted in pre-ore stage decalcification, loss in density, and an increase in porosity and permeability of the host rock. Furthermore, the intensity of carbonate removal and degrees of decalcification ranges widely between mineralising systems, and does not always exhibit a clear zonal relationship with gold deposition.

### 2.3.2 Silicification

Although high levels of variation with respect to the degree of silicification and nature of alteration are expected across individual Au deposits, there are a number of loose relationships that have been established for silicification mineralisation along known Au depositional trends within Nevada. I will discuss the Carlin trend deposits with reference to literature published by Teal and Jackson (2002) herein.
Similar to carbonate removal, silicification as an alteration product is partially controlled by the composition of the host rock involved. Teal and Jackson (1997; 2002) use examples of the Meikle and Deep Star Au deposits that exhibit northwest structural controls in the Carlin trend, to suggest that in deposits hosted by dense, biosparatic limestones or calc-silicate protolith, fluid permeability is more restricted to high-angle, structural conduits. Due to these constraints, silicification is locally intensified and is generally spatially associated with gold mineralisation.

The fore-mentioned Meikle deposit has been dissected into five stages of silicification documented by Volk et al. (1995), which follows:

1. **Early pre-ore** metamorphic quartz veins associated with the emplacement of Jurassic intrusive rocks
2. **Late pre-ore** silica replacement associated with early stage carbonate dissolution
3. **Main stage ore** silicification occurring as episodic pulses, open-space fillings and veinlets associated with precipitation of fine grain pyrite and gold
4. **Post-ore** chalcedonic vug fillings and coatings and,
5. **Very late stage**, outwardly zoned quartz veinlets in siliciclastic rocks of the Vinini formation that form a non-mineralised cap above the deposit

For deposits such as Carlin, West Leeville, Hardie Footwall and Screamer, along the Carlin trend, stratigraphy acts as a dominant control of the extent of alteration. In such situations, it has been observed that fluid migration is more passive in nature and ore zone silicification is less significant. Furthermore, silicification is focused
along bioclastic debris horizons and closely situated to fluid conduits, where it is peripheral to the main ore zone.

Studies by Keuhn and Rose (1992) have shown a linear relationship between carbonate dissolution (CO₂ removal) and an increase in SiO₂. This suggests that the intensity of silica addition, beyond isochemical enrichment (~67%SiO₂), is more prevalent in dense carbonate hosted deposits, or as isolated replacement in calcite-rich and permeable bioclastic debris flow beds, due to their originally higher composition of calcite (Teal and Jackson, 1997).
3 Petrophysical Attributes

A thorough understanding of the relationships between specific petrophysical attributes is a key process involved with investigating the feasibility of seismic methodology in carbonates, as seen in the Carlin-type deposits of Cortez and more broadly, Nevada.

Petrophysical measurements were taken on various core samples by Barrick Gold in 2010. The suite of rock samples being analysed included a broad range of characteristic rock types, representative of typical Carlin lithologies. Data collected includes dry, saturated and submerged mass, as well as bulk volume, apparent porosity, magnetic susceptibility, grain density and both wet and dry compressional wave velocity.

For further processing and simulation of synthetic modelling, accurate representations of compressional velocities and density are paramount to producing realistically devised geological models.

3.1 Porosity and Permeability Background

Porosity and permeability are critical characteristics when considering alteration as a result of hydrothermal fluid interaction. The importance for fluid transport and mobility within the Carlin area is paramount, and an in-depth understanding of a rocks potential to interact with hydrothermal fluids for the area, provides much insight as to where Au deposition may be located.

The porosity of a given material is an expression of the ratio of void volume to a measurable total volume of the material. As a ratio, it is typically represented as a fraction of the total volume between 0 and 1 or alternatively, as a percentage.
PETROPHYSICAL ATTRIBUTES

\[ \phi = \frac{V_v}{V_T} \]

Where \( \phi \) = Porosity

\( V_v = \text{Volume of void space (cubic metres)} \)

\( V_T = \text{Volume of total space (cubic metres)} \)

Figure 3.1: Typical apparent porosity values for various rock types (Emerson, 1990)

3.1.1 Fluid Mobility and Seismic Velocity

Emerson (1990) explains the variations in rock porosity such that total porosity (\( P_T \)) represents total void volume comprising both occluded and interconnected pore space, given as the excess of bulk volume (\( V_B \)), over grain volume (\( V_g \)). Apparent porosity (\( P_A \)) represents the interconnected pore space comprising: (1) flow pores – channels that permit significant fluid flow – also given as the effective porosity constituting the permeable framework of the medium; and (2) diffusion pores –
lateral, dead-end and fine pores that do not contribute to significant fluid flow, but in which aqueous species may be transported by diffusion. In relation to prior definitions, apparent porosity is the excess of bulk volume over grain and occluded pore volumes.

Emerson states that some general relationships between effective porosity and permeability of material groups can be inferred for many situations. Specifically, for soft, highly porous rocks, the effective porosity approaches the apparent porosity in most cases. For tightly bound rocks, however, effective porosity is best taken as only a small fraction of apparent porosity.

This assumption is adequately fitting as a primitive generalisation for the Carlin district carbonates, particularly in those cases in which active decalcification alterations have occurred. Units of elevated porosity and permeability are expected to present with noticeable drops in compressional velocity as a result of wave travel through pore and void space, predominantly inhabited by fluid or air.

3.2 Porosity Implications

The relationship between apparent porosity and acoustic impedance is critical to linking seismic reflection to fluid characteristics. Any direct relationship that can be tied between the porosity of a rock unit, and its reflectivity, indicates that the application of seismic reflectivity surveys can indirectly provide information regarding porosity and permeability of a geological environment.

In the case of Carlin style hydrothermal alteration, porosity and permeability, and more directly, fluid mobility and welling, are indicators of potential zones of hydrothermal activity and resultantly, possible mineralisation.
Figure 3.2 shows the relationship between apparent porosity and acoustic impedance, as measured from the Cortez petrophysical rock suite. It can be seen that a fairly strong, inverse-linear relationship is apparent, such that rocks with apparent porosity approaching and exceeding 4-5%, are characterised by markedly lower impedances, particularly within the Wenban unit. This relationship however, must be considered carefully, as porosity measurements represent both primary and secondary porosities within the sample. It is important to note that primary porosity within carbonates can be highly differential, with some sandstones being characterised by up to 30% apparent porosity (Emmerson, 1990). For this area, however, cases of high primary porosity (10% and more) are rare, as carbonate formations are typically well consolidated in the absence of dissolution processes.

The presence of the regional, low angle Abyss thrust fault has caused significant deformation in the lower plate carbonate package, introducing antiformal fold structures in the hanging wall. The presence of smaller scale imbricate, high angle thrust faulting has intensified the deformation in these zones. Structural influences as such, can act as a possible origin of secondary porosity and influence the potential for secondary fluid conduits to form within fractured and deformed rock units.

Figure 3.3 shows the relationship between apparent porosity as a percentage of total volume and measured wet compressional velocity (metres per second). It can be seen that a linear relationship holds constant across the Cortez suite of rock samples with a dense packing of samples with moderate velocities, between 5000 and 6000 m/s, being characterised by porosities of <3%. This relationship, with velocity being a
contributing factor to seismic impedance, has strong influence on the ability to infer porosity information from seismic reflectivity data.

Individual formation plots can be seen in Appendix A, for comparison of density, porosity, velocity and impedance across Horse Canyon, Devonian Wenban and Silurian Roberts Mountain formations, as well as intrusive samples that were measured.
Figure 3.2: Apparent porosity with respect to seismic impedance plot for the Cortez petrophysical rock suite. Data indicates a relatively strong inverse-linear relationship for all units.
Figure 3.3: Apparent porosity with respect to compressional velocity (P-Wave velocity) plot for the Cortez petrophysical rock suite. Inverse-linear relationship is visible across all rock units.
3.3 Density

Significant density variations between hydrothermally altered carbonates and their adjacent, unaltered carbonate hosts have been observed throughout the Carlin and Cortez district. Decalcification processes leaving altered zones heavily deformed, brittle and lacking consolidation gives theoretical emphasis to the thought that seismic reflection may be a plausible option to image such contrasts.

Unfortunately, due to the often extreme alteration that occurs within samples, it is particularly difficult for decalcified core samples to be extracted intact. Due to the brittle nature, having had significant dissolution occur and calcium removal from the structure, samples tend to fracture and crumble once relieved of in-situ stresses. This inability to maintain intact samples representative of decalcified, and often mineralised units, make petrophysical measurements unattainable and hence, critical density and velocity inferences had to be made based on geological knowledge and experience with these types of samples.

The nature of decalcification can be seen in Figures 3.4 and 3.5, such that it becomes seemingly obvious that contrasts between altered and unaltered samples are quite dramatic. In the case of decalcified rock units, density values of 2.3 g/cc have been inferred for modelling purposes, which is believed to be conservative based on the appearance and physical fragility of such units. In the case of silicification modelling, density has been inferred as 2.6g/cc based on field assumptions made by Curtin/HiSeis staff and Barrick Gold.
Density Characteristics (m/s)

<table>
<thead>
<tr>
<th>Formation</th>
<th>Average Density (g/cm³)</th>
<th>Standard Deviation</th>
<th>Number of Samples</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wenban</td>
<td>2.50</td>
<td>0.03</td>
<td>60</td>
</tr>
<tr>
<td>Roberts Mountain</td>
<td>2.53</td>
<td>0.04</td>
<td>17</td>
</tr>
<tr>
<td>Horse Canyon</td>
<td>2.46</td>
<td>0.03</td>
<td>2</td>
</tr>
<tr>
<td>Intrusion</td>
<td>2.37</td>
<td>0.07</td>
<td>13</td>
</tr>
<tr>
<td>Inferred Decalcified Unit</td>
<td>2.30</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Inferred Silicified Unit</td>
<td>2.60</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 3.1: Average density, standard deviation and sample volumes as measured from petrophysical rock suite from the Cortez area. Inferred density for decalcified (2.3 g/cc) and silicified (2.6 g/cc) rock units.

Figure 3.4: Heavily decalcified and mineralised rock sample. Represents suitable mineralisation zones with strong economical prospect.
Figure 3.5: Decalcified core sample (left), showing lack of consolidation and brittle nature, compared to unaltered core sample (right), heavily consolidated and strong formation.

Figure 3.6: Density relative to impedance of the Cortez petrophysical rock suite. Intrusive samples are shown to be characterised by lower densities, and hence lower impedances, which separate them from the remaining petrophysical samples.
Figure 3.6 represents the relationship between sample wet density and acoustic impedance. Density spread across the data set is quite tight, with Wenban, RMT and Horse Canyon samples ranging between 2.4 and 2.6g/cc. Intrusive samples, however, are characterised by markedly lower densities, and resultantly, lower impedances. These intrusive samples appear to plot with reasonably tight packing.

Petrophysical measurements did not encompass wet density values, so values were calculated as follows:

\[
W\text{etDensity} (\rho_w) = [(1 - \phi_{ap}) \times \rho_g] + (\phi_{ap} \times \rho_w)
\]

\[
\phi_{ap} = \text{apparentPorosity}
\]

\[
\rho_g = \text{grain density (g/cm}^3\text{)}
\]

\[
\rho_w = \text{density of water} = 0.998 \text{ g/cm}^3
\]

3.4 Sonic Velocity

Velocity measurements were made using a James VC9900 velocity meter across clean core samples. Wet samples were left soaking for several days and set to dry for one day before readings were taken. This method provides a thoroughly saturated sample, while eliminating surface moisture that can affect the measurements. No vacuum was used during measurements, but the accompanied error is believed to be negligible.

Wet compressional velocities were measured and provided courtesy of Barrick Gold for major lithological rock units. This included a working dataset of approximately 100 velocity measurements across Devonian Wenban, Roberts Mountain, Horse Canyon and various intrusive units. This data, along with measured density information, was fundamental in defining unit properties for elastic modelling. Full
velocity measurements across rock units can be seen in Appendix A. For modelling purposes, an average was taken over the data set for each individual rock unit. These can be seen in Table 3.2.

### Compressional Sonic Velocity Characteristics (m/s)

<table>
<thead>
<tr>
<th>Formation</th>
<th>Average Velocity (Wet)</th>
<th>Standard Deviation</th>
<th>Average Velocity (Dry)</th>
<th>Standard Deviation</th>
<th>Number of Samples</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wenban</td>
<td>5150</td>
<td>650</td>
<td>4860</td>
<td>810</td>
<td>60</td>
</tr>
<tr>
<td>Roberts Mountain</td>
<td>5160</td>
<td>590</td>
<td>5030</td>
<td>740</td>
<td>17</td>
</tr>
<tr>
<td>Horse Canyon</td>
<td>4320</td>
<td>420</td>
<td>4150</td>
<td>340</td>
<td>2</td>
</tr>
<tr>
<td>Intrusion</td>
<td>4250</td>
<td>490</td>
<td>4080</td>
<td>660</td>
<td>13</td>
</tr>
<tr>
<td>Inferred Decalcified Unit</td>
<td>3650</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Inferred Silicified Unit</td>
<td>5300</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 3.2: Compression sonic velocity characteristics based on petrophysical data from the Cortez rock suite. Inferred velocities for decalcified (3650 m/s) and silicified (5300 m/s) rock units.

In the case of theoretical, heavily decalcified mineralisation zones, a major target for exploration due to the often economically viable volumes of microscopic Au throughout the unit, representative compressional velocities were inferred from geological expectations and input from experienced geophysicists from Curtin University and Barrick Gold, who have had hands-on experience with core samples from such altered samples. Instrumental measurements for velocity and density were unattainable due to the brittle nature and tendency for samples to crumble and fracture as previously discussed.

The contrast between heavily decalcified carbonate and unaltered Wenban and Roberts Mountain rock units is both visually and physically obvious, primarily with respect to densities, however, for modelling purposes, these lenses were assigned a
compressional velocity of 3600 m/s which, due to the soft and brittle nature, is again, considered a conservative approach.

Figure 3.7: Example of heavily decalcified core sample for purpose of density approximations

3.5 Mineralisation Intensity

In order to make strong assumptions as to whether seismic reflectivity can directly identify zones of mineralisation, as opposed to porosity information, petrophysical samples were correlated with geological logging, for which decalcification and silicification intensities have been recorded, to investigate alteration intensity relative to porosity and impedance. It should be noted that intensity of decalcification and silicification is a subjective observation made by logging geologists and hence has variation between each interpreter.
Figure 3.8: Decalcification intensity relative to apparent porosity and acoustic impedance

Figure 3.9: Silicification intensity relative to apparent porosity and acoustic impedance
Plotting intensity of decalcification relative to apparent porosity and acoustic impedance of the Cortez petrophysics samples (as seen in Figure 3.7) has shown that there is a slight correlation between increased porosity and elevated levels of decalcification, however, the number of data points representing decalcified samples is limited. A fairly even spread of weakly decalcified samples is present across both high and low impedances, as well as both upper and lower bounds of porosity. Ideally we would expect strongly decalcified units to plot with elevated apparent porosity and reduced acoustic impedance, however, it appears that strongly decalcified samples are apparent in both high and low porosities, as well as low to moderate impedance values.

The introduction of silica post Au deposition typically causes rock units to become harder and porosity to be reduced due to the crystallisation of silica within effective pore space. Silicification observations were made on only six samples but, of these, heavily silicified samples plotted quite consistently in zones of reduced porosity and moderate to high acoustic impedance, as expected. All weakly silicified samples were characterised by apparent porosities greater than six percent, and transition from weak, to moderate, to strong silicification intensity correlated consistently with decreasing porosity (see Figure 3.8).

3.6 Summary of Petrophysics

Acquisition of localised petrophysical data, representing Cortez (Carlin-type) lithologies has provided information on the elastic characteristics of representative units, in particular the Horse Canyon, Devonian Wenban and Silurian Roberts Mountain formations, as well as a number of intrusive samples. Petrophysical measurements provided information on wet and dry compressional sonic velocity,
magnetic susceptibility, wet, dry and submerged mass, wet and dry density, grain density and apparent porosity.

Noticeable inverse-linear relationships were observed between apparent porosity and impedance of the samples with highly porous samples being characterised by relatively low impedances. This relationship is as expected with increasing pore-space representing possible influx of fluid presence or void-space encapsulating air pockets, both of which reduce velocity within the medium, and subsequently, reduce impedance. The strength of this relationship, in essence, reinforces the idea that seismic reflection in the Carlin district not only images lithological interfaces between zones of varying host-rock characteristics, but can also tie zones of elevated reflectivity to possible increases in porosity.

It is important to note that, for the study area, although the majority of gold mineralisation requires hydrothermal activity and alteration to have occurred, not all hydrothermally altered carbonates contain gold mineralisation. This is enforced in plots of impedance versus porosity, with incorporated decalcification and silicification intensities being represented. Geological logging saw a small number of samples represent varying degrees of decalcification and silicification intensity, ranging between null, weak, moderate and strong degrees of alteration. The representative data set of samples with logged alteration is too scarce to make strong assumptions, however, a general trend of silicification intensity with increasing impedance was weakly present, having heavily silicified samples plotting with higher values of impedance, and lower porosities, than those with moderate to weak silicification.
Previous seismic application in this area has been focused on delineating structural boundaries and lithological interfaces, as opposed to relating reflectivity to petrophysical attributes. The petrophysical findings have demonstrated that the contrast between Devonian Wenban and Silurian Roberts Mountain samples, are less dominant than previously expected, with averaged impedances across both formations differing by less than 2%. This is, however, a vast generalisation across the entire petrophysical suite and it is understood that within major units, significant variation occurs in somewhat sequential layering. The lack of significant contrast between formations does however suggest that strong seismic reflectivity along interfaces may be attributed to petrophysical characteristics, particularly porosity, as opposed to primarily assumed lithological boundaries.
4 Forward Modelling and Synthetic Seismic

4.1 Introduction

This chapter details the process behind production of realistic, synthetic seismic reflection data, representative of the study area.

Focus was placed on realistic modelling of thin, decalcified and silicified mineralisation lenses within Carlin-style carbonate sequences for the production of synthetic seismic data.

Full elastic modelling of a realistic representation of typical Gold Acres geological setting, based on petrophysical attributes taken from the Cortez rock suite was the major aim of the study. Petrophysical data from the Cortez rock suite, was used to establish primary unit velocity and density values, and inferred velocities and densities were used to simulate decalcified and silicified lenses, as discussed in Chapter 3. Lens thickness was simulated at thicknesses of 20m, 10m and 5m to investigate the variation in reflection amplitudes and ability to discern unit boundaries, as well as the limitations for imaging the structural tops and bottoms of alteration zones.

4.2 Full Nevada Mineralisation Modelling

The production of a realistic geological model for synthetic data analysis is imperative, and thus, importance is placed on the accuracy and realism of input parameters. In this case, models have been designed with strong correlation to geological interpretations made from seismic surveys conducted in the past, for the purpose of regional structural unit mapping. Barrick Gold Exploration Inc. provided an interpreted geological cross-section, representative of the Gold Acres exploration
area, derived from previous seismic and drill-hole data, which is the major contributor into the regional structure of the synthetic model.

The geological section that has been replicated for modelling is shown below in Figure 4.2 and has been validated by its similar orientation to Curtin University/Hiseis seismic lines acquired in 2009. This orientation provides a representative section of the overall structural architecture of the Gold Acres area, with particular emphasis on regional, antiformal, rollover folding occurring in the hanging wall of the low angle Abyss thrust fault.

For the purpose of this study, modelling will incorporate local lithological units with elastic parameters predicted from previously mentioned Cortez rock suite petrophysical measurements for wet density and sonic velocity. This includes units representative of Devonian Horse Canyon, Devonian Wenban, Silurian Roberts Mountains and Ordovician Horse Canyon formations, as well as a deliberate geological contact representative of the Abyss Fault interface. It should be noted however, true petrophysics were acquired only on the upper three units, being the Devonian Horse Canyon, Devonian Wenban and the Silurian Roberts Mountain. All subsequent formations have been assigned theoretical parameters in accordance with assumptions and expectations. An example of the model used can be seen in Figure 4.1.
Figure 4.1: Synthetic geological model with thin lenses representing alteration zones.
Figure 4.2: Geological cross section interpreted based on previous seismic surveys and borehole measurements. East-West Orientation over low angle Abyss thrust fault. (Leonardson, 2009)


4.3 Survey Design

The synthetic survey design was intended to represent suitable field techniques that are applicable to real-life seismic acquisition. For these reasons, synthetic data was modelled with survey parameters similar to those used in field acquisition by HiSeis in 2009. This involved a 6 kilometre geological model, of which the primary zones of interest (two individual alteration zones) were situated within the central 3 kilometres. Data was collected over 150 source shots, modelled at 20 metre intervals across the central 3 kilometre zone of interest, with a 50 Hz Ricker wavelet input as the dominant source frequency. Source positioning replicated rolling split-spread acquisition, such that 300 active receivers were split in the centre by the source at all shot points. Receivers were spaced at 10 metre intervals, which provided 1500 metres of offset, each side of the source, at each shot point.

It should be noted that this survey design replicated previous acquisition parameters, of which regional structural mapping of lithological units and boundaries was the priority. True seismic data, acquired primarily to isolate zones of alteration, has not been performed or made available, so a theoretical survey design for focussed exploration of these altered rock units will be discussed in later chapters.
4.4 Null Model

An initial null model was created to highlight the responses from lithological boundaries across the Gold Acres geological model, in the absence of alteration zones. Petrophysical data, for the purpose of modelling was limited to the Horse Canyon, Devonian Wenban and Silurian Roberts Mountain formations, as mentioned previously, and hence responses at these interfaces hold greater practical truth than those for which values have been inferred. Represented units within the null model seismic response can be seen in Figure 4.3.
Figure 4.3: Significant rock formations being modelled by synthetics, overlaying null model response.

Figure 4.4: Seismic response of representative geological model in the absence of alteration zones.
4.5 Modelling Impedance Contrasts Due to Decalcification

Seismic response resulting from contrasting impedances, due to heavy alteration and subsequent decalcification was the dominant motivation behind this study. Thin lenses were placed at two individual locations within the representative geological model; the first of these theoretical ore bodies was situated between the Devonian Wenban and Silurian Roberts Mountain units in a flat-lying orientation. The second zone of alteration represents fluid trap zones situated at the peak of a regionally occurring anticlinal fold system overlying the low angle Abyss thrust fault.

Representative decalcified ore zones have been assigned compressional wave velocities of 3650 m/s, shear wave velocities of 2020 m/s and density of 2.3 g/cc as discussed in Chapter 3.

Full elastic modelling of this scenario, indicates quite strongly, the presence of high reflectivity events that correlate directly to the location of theoretically decalcified ore bodies. The presence of these reflectivity bright spots is obvious at all modelled lens thicknesses, with amplitude increases being the primary variation with increasing ore body thickness.

The presence of flat-lying alteration zones at the Wenban/Roberts Mountain unit boundary responds with reflectivity amplitudes that can be clearly delineated from the unit interface reflections, due to the significant contrast in amplitudes. This is similarly the case for the modelled ore body situated at the apex of the regional antiform.

For hard-rock environments, we expect velocities within rock formations to be seemingly high. Due to this high velocity environment, we can calculate dominant
wavelength as a function of unit velocity and source frequency as a rough approximation. This follows:

\[ \lambda = \frac{v}{f} \]

\[ \lambda = \text{dominant wavelength} \times m \]

\[ v = \text{velocity within medium} \times s^{-1} = 5200 \times m/s^{-1} \]

\[ f = \text{dominant source frequency} \times Hz = 50 \times Hz \]

Thus,

\[ \lambda = \frac{5200}{50} = 104m \]

This value of dominant wavelength within the upper geological section provides information as to the thickness of ore body at which we can delineate tops, bottoms and structural extremities. Typical generalisations for vertical seismic resolution are that Rayleigh resolution limit, or the tuning thickness, is \( \frac{1}{4} \) of the wavelength according to the dominant frequency within the media. At such thicknesses we see constructive interference occur from reflections on the upper and lower bounds of the ore body, causing reflection of increased amplitude. Theoretically, detection limits are bound by body thicknesses approaching \( \frac{1}{25} \) – \( \frac{1}{30} \) of the dominant wavelength. In the case of the modelled data, it can be seen that ore body thicknesses as low as 5 metres are still detectable as high amplitude reflectivity events.

Modelling of lenses thinner than \( \frac{1}{30} \) of the dominant wavelength (approximately 3.5 metre thickness), may be a theoretically justifiable investigation, however for practical application and imitation of underground, minable targets, Au abundance
within such thin lenses would need to be significant to warrant economical extraction.

Figure 4.5 represents a post-stack phase-shift migrated section of the expected response from 5m decalcified ore zones within the representative geological model. This demonstrates quite clearly that the reflectivity over these heavily decalcified areas is significantly greater than those of the contrasts due to lithological interfaces.

Increasing lens thickness responses can be seen in Figure 4.6, showing the change in responses between the null model, 5m lens and 10m lens. It can be observed that increases in the thickness of alteration zone causes significant increase in amplitude and it is also notable that the presence of late time multiple, situated below the alteration zone, begins to become apparent.

Modelling alteration zones of 20m thickness is shown in Figure 4.7, with comparison to a 10m response. Again, amplitude increases are the fundamental difference, as we expect that lens thicknesses this low are still undergoing tuning effects such that tops and bottoms cannot be delineated as individual response, according to the dominant frequency of 50Hz in the model.
Figure 4.5: Synthetic seismic response over 5m thick decalcified alteration zones showing alteration as high amplitude reflectivity events.

Figure 4.6: Synthetic seismic response over null, 5m and 10m decalcification zones.
4.6 Modelling Impedance Contrasts Due to Silicification

Modelling situations representative of heavily silicified alteration zones gives an indication of possible seismic responses of common brecciated and heavily silicified ore zones within the Carlin District. Input parameters for such ore bodies have been carefully inferred based on educated geological knowledge and input from trained geophysicists with field experience of the study area. For this case, alteration zones have been given a compressional wave velocity of 5300 m/s, shear wave velocity of 3080 m/s and density of 2.6 g/cc, representing an ore body that has been heavily silicified and hardened post alteration.

Figure 4.8 shows the response of the null model in comparison to 5m and 10m silicified sections. Further to this, comparisons between thicknesses of 10m and 20m can be seen in Figure 4.9. The contrast between alteration zones and lithological interfaces in the case of silicified ore bodies is significantly less dominant than that
seen in the decalcified scenarios. We see reflection responses in all models, as small as 5 metre thicknesses, however, the amplitude of reflection, even in idealised synthetics, is far too insignificant for real-life identification. With the introduction of external noise and the realistic lack of signal to noise ratio in hard-rock environments, it is highly unlikely that responses like this will be detectable post-migration.

It should be noted that in the case of 20m silicified ore bodies, we begin to see the lens situated at the apex of the hanging wall drag fold begin to become more visible in comparison to its flat-lying equal, however, reflectivity is still subtle and likely to be masked by real-life interferences and noise.
Figure 4.8: Synthetic seismic response over null, 5m and 10m silicified zones

Figure 4.9: Synthetic seismic response over 10m and 20m silicified zones
Although the application of seismic reflection for detection of prospective Au bearing alteration zones is promising, forward modelling responses from silicified units have not imaged contrasts over ore bodies that are detectable enough to confidently warrant further exploration. This is the case for modelled scenarios, however, in reality, we may see silicification occur in a variety of structures, possibly spherical bodies of larger dimensions which may appear as more anomalous reflection events, however, the contrast in impedances is expected to remain similar to those being modelled herein.

4.7 Processing of Synthetic Data

All shot data was simulated using Tesseral-2D, full elastic modelling software. This created shot records and SEG-Y data files for each forward model to be processed more thoroughly using ProMAX.

Once SEG-Y data files were imported to ProMAX software, a focus was placed on maintaining as close to natural amplitudes as possible in order to investigate accurately, the changes caused by increasing ore zone thickness. Initial geometry was assigned to the data sets, assigning station number, shot number, receiver number, and FFIDS to all survey parameters for binning. Data was then corrected for Normal Moveout (NMO) and converted to Common Depth Point (CDP) domain for later stage stacking. NMO and stacking velocities were derived from semblance analysis on supergathers to create a realistic velocity model for the data.

Brute stacks were created using NMO corrected data, having applied band-pass filtering to remove very high frequency numerical noise, a by-product of software’s numerical approach to synthetic production. Introduction of degrees of random noise
were applied to the data to replicate realistic data quality, however the severity of practical signal-noise ratios is unlikely to be replicated accurately within software.

Post-stack phase-shift migration was then applied using converted velocity models, in order to return reflection events to their true locations in time domain.

Processing routines aimed to keep the data from being dramatically manipulated and represent as closely as possible, true amplitudes from survey acquisition.

4.7.1 Processing Issues

Forward modelling using geophysical software aims to simplify the production of seismic data and remove the external influences seen in real life. Though this is the case, the numerical approach of synthetic software is prone to intrinsic issues that are related to the idealised nature of data production.

An important attribute of the seismic application in the Carlin district, is its potential to image below thick sections of colluvium and alluvium, which currently masks modern electromagnetic and potential field geophysics, as well as geochemical responses of underlying geology and potential mineralisation targets.

Initially, the representative forward model aimed to include these thick colluvium sections to more realistically represent the target area. This created issues with synthetic modelling, however, due to the significantly large contrast in acoustic impedance between upper unconsolidated colluvium and bedrock interfaces. Computer software images this contact as a perfect “mirror-like” interface at which seismic energy is reflected back and forth with high amplitude. This ringing, or repeating, of multiple reflections causes high amplitude multiple to contaminate the shot record when source shots are proximal to these colluvium packages. To counter
this influence, all modelling was designed from the Horse Canyon formation, avoiding the inclusion of colluvium packages. This effectively removed the reverberation of reflections and allowed a much cleaner final image to be modelled.

Further issues were apparent over zones where “wedging” was apparent, even in the absence of colluvium packages. This was isolated to the areas where the Horse Canyon formation has been modelled to intersect the surface and can be seen closer in Figure 4.11.

The result of this wedging effect was contamination over 5 shot records, overlying the peak of the wedge. This is seen in Figure 4.12.
Figure 4.10: Synthetic geological model highlighting issues with wedging units

Figure 4.11: Synthetic issues with wedging units (Horse Canyon)
4.8 Amplitude Variation with Lens Thickness

As all lens thicknesses that have been modelled are below ¼ of the dominant wavelength of the geological model, we do not expect to see structural tops and bottoms of the individual ore zones. This has been proven with synthetics, as responses from 5m, 10m and 20m alteration zones are represented by visually similar reflection responses. The major variation that is apparent, when increasing alteration thickness, is the amplitude of reflection, which can be seen once stacked and migrated.

Investigation of the relationship between thickness of alteration lenses and amplitude of reflection has been undertaken, in particular, the rate at which amplitude increases for factor of 2 increases in thickness. In order to represent amplitude differences between varying lens thicknesses, responses have been focused over the anomalous numerical noise.
areas and plotted relative to each model. Variations occur between the flat-lying alteration zone and the dipping zone, and hence have been presented individually.

Figure 4.13: Isolated amplitude response over alteration zones.

Figures 4.14 and 4.15 represent the peak-to-peak amplitude response of both decalcified and silicified models, over the flat oriented alteration zones respectively. It should be noted that scaling for each case is different, and we notice that the decalcified response is significantly stronger than that over the silicified lens. Focusing on the decalcified response, we see that a factor of 2 increase (5 metre lens to 10 metre lens) in body thickness, results in a peak-to-peak amplitude increase by a factor of 1.5. Repeating this body thickness increment from 10m to 20m, shows amplitudes increasing similarly, by a factor of 1.45 (see Table 4.1).
Peak-to-peak amplitude responses over flat-lying silicified alteration zone, although significantly lower in magnitude, respond quite similarly to that seen in the decalcified scenarios. Increments of body thickness from 5m to 10m, and from 10m to 20m saw amplitude increase by a factor of 1.88, and 1.35 respectively.
Figure 4.14: Amplitude response over flat-lying, decalcified alteration.
Figure 4.15: Amplitude response over flat-lying, silicified alteration.
Table 4.1: Amplitude variations and ratios for flat-lying alteration zones (decalcified and silicified).

Figures 4.16 and 4.17 represent the peak-to-peak amplitude responses of decalcified and silicified models over dipping alteration zones situated at the apex of a regional antiform drag fold. Variations over these anomalous areas responded differently to those seen in flat-lying ore zones, particularly in the case of decalcification modelling. Increases from 5m lenses to 10m decalcified lenses saw amplitude increase by a factor of 2.71, while increases from 10m to 20m saw only 14% increases in amplitudes. With respect to silicified modelling of dipping bodies, amplitudes appreciated by factors comparable to its identically characterised flat-lying ore body. Increments from 5m to 10m thickness, and 10m to 20m thickness, saw amplitude increase by factors of 1.56 and 1.38 respectively (see Table 4.2).
Figure 4.16: Amplitude response over dipping, decalcified alteration.
Figure 4.17: Amplitude response over dipping, silicified alteration.
Forward modelling of geological environments representative of typical Carlin lithologies hosting varying thicknesses of hydrothermally altered ore bodies, was the focus of this study. The data was simulated for situations implying heavy decalcification and silicification had taken place within thin alteration zones with thicknesses varying between 5m, 10m and 20m. The data was simulated using Tesseral-2D, and processed using ProMAX geophysical software.

The results from this investigation have shown that, for the input parameters derived from local petrophysics from the Cortez area of Nevada representing dominant lithological units, and critically inferred characteristics for zones representing hydrothermal alteration and subsequent decalcification and silicification, seismic reflection, as a means of exploration, holds significant potential, particularly for the detection of decalcified zones. Forward modelling over areas representative of decalcified ore zones responded as reflectivity bright spots, for which amplitudes increased relative to thickness of the ore body. For flat-lying decalcified ore bodies, it was found that amplitude increased at a factor of 1.5, for ore body thickness increases by a factor of 2. Reflection events from the zones of interest appear to be of significantly higher amplitude than the local reflections resulting from lithological

### Peak-Peak amplitude (Dipping Ore Body)

<table>
<thead>
<tr>
<th>Thickness</th>
<th>Decalcification</th>
<th>Silicification</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>3.24</td>
<td>0.82</td>
</tr>
<tr>
<td>10</td>
<td>8.85</td>
<td>1.27</td>
</tr>
<tr>
<td>20</td>
<td>10.11</td>
<td>1.75</td>
</tr>
<tr>
<td>10:5</td>
<td>2.73</td>
<td>1.56</td>
</tr>
<tr>
<td>20:10</td>
<td>1.14</td>
<td>1.38</td>
</tr>
</tbody>
</table>

Table 4.2: Amplitude variations and ratios for dipping alteration zones (decalcified and silicified).

### 4.9 Synthetic Data Summary

Forward modelling of geological environments representative of typical Carlin lithologies hosting varying thicknesses of hydrothermally altered ore bodies, was the focus of this study. The data was simulated for situations implying heavy decalcification and silicification had taken place within thin alteration zones with thicknesses varying between 5m, 10m and 20m. The data was simulated using Tesseral-2D, and processed using ProMAX geophysical software.
boundaries between the Devonian Wenban formation and the Silurian Roberts Mountain formation, of which seismic impedance contrasts are far less dramatic than previously expected.

It should not be overlooked however, that in reality, many inter-bed variations occur within each subsequent formation, such that true field data may see many small scale reflections as a result of variations within the carbonate packages. Decalcified alteration zones however, should their elastic properties correlate to those inferred within this study, are expected to respond strongly in comparison to most lithological and structurally derived seismic reflections.

With respect to seismic responses over theoretically silicified alteration zones, identification of ore bodies as seismic reflectivity events is far less apparent. At ore body thicknesses of 20m, the largest modelled in this study, reflection events appear as only a slight contrast in comparison to responses from lithological boundaries between the Devonian Wenban and Silurian Roberts Mountain formations. Taking realistic intrinsic noise, and the issues involved with poor signal to noise ratios for hard rock seismic application, it is very possible that these events will be masked completely and be unidentifiable amongst the data.
5 Seismic Reflection Surveys

5.1 Previous Seismic Reflection Surveys

A number of 2D seismic reflection surveys have been acquired throughout the state of Nevada for exploration purposes, with strong variations in the quality of deliverables. Modern day field techniques and improvements to source energy output, however, has pushed outcomes into a more economically favourable category, emphasising the value of seismic reflection for analysis of both regional and local subsurface geological structure.

Curtin University and Hiseis Pty Ltd personnel acquired two lines, 14.8 line kilometres, of high resolution seismic data in Lander Country, Nevada, within the Pipeline-Cortez Mine Project site, for Barrick Gold Exploration Inc, in 2009. Implication of modern field techniques and the introduction of higher energy Vibroseis sources produced significant improvement to prior acquisition attempts and the results discussed herein will relate to this acquisition.

5.1.1 Survey Objectives

Surveys conducted within the area have not been designed for specific delineation of mineralisation, but rather to produce highly resolved images of the geological setting and possible identification of fluid genesis and understanding of low angle thrust systems. Previous seismic surveys (prior to 2009) have shown a number of key results:

1. The host sequence is characterised by its “higher density of occurrence” of high reflectivity events. Hence the depth, volume and geometry of the host units can be mapped by seismic.
2. The base of the Golden Acres intrusion is mapped as a high reflectivity event.

3. The Abyss low angle fault/thrust is also imaged by the seismic reflection data.

5.1.2 Survey Requirements

As previously discussed, a major issue with hard rock seismic reflection is the lack of signal to noise ratio within datasets. Combined with notoriously complex geological structure of the Cortez and Carlin areas, survey configuration for optimal signal is essential. Cox and Ruming (2004) identify the interpretable depth of the image as another critical concern for the mineral exploration industry. Shallow targets, 100-500 metres in depth are, in most cases, ideal for economical mining access. The deeper structures, over one kilometre in depth, however, are of interest with respect to crustal-scale mesothermal lode gold transportation conduits and trapping mechanisms (Harrison, 2009).

Previously, seismic surveys have aimed to image structural and lithological characteristics of the area, with little consideration for the relationships between reflectivity and rock characteristics. For these reasons, both survey design and nature of data processing, has aimed to emphasise geological structure as opposed to maintaining representative reflection amplitudes, or achieving maximum resolution at depths of only minable interest.

Typical survey design for structural mapping and boundary identification revolve around maximising depth of penetration, whilst maintaining suitable signal to noise, in order to return adequate geological response for the survey area. In modern practice, this will typically involve the mobilisation of singular, or arrays of vibroseis
sources, or alternatively, explosive shot sources to maximise amplitude and quality of source wavelet. Signal responses are often recorded over long offsets, utilising rolling-split-spread acquisition methods. This can involve receiver offsets up to 2km in each direction from the shot point, with group intervals up to 20m. This is accompanied by shot points at 20m intervals with the array recording reflection data to depths in excess of 2-3 kilometres. Although these techniques are effective for regional mapping, for the purpose of detection of zones of alteration, and more specifically, Au bearing ore bodies, the trade off between depth of penetration and increasing resolution at depths which are economically minable becomes more important. This point will be discussed in more depth in later sections.

5.1.3 Survey Outcomes

As previously mentioned, this section will be relating to seismic data acquired in 2009 for Barrick Gold. Again, it must be noted that the survey was aimed at delineating structural units and formations, and hence, maintaining true reflection amplitude was not a high priority in comparison to maximising interpretable bedding reflections and unit boundaries.

Figures 5.1 and 5.2 represent seismic reflection data over a single 2D land survey line, acquired in a similar orientation to geological cross-sections seen in Figure 4.2. We can see that seismic reflection has identified many important features representing the geological structure of the survey area. These include:

- Numerous reflections throughout what is interpreted as an upper pediment zone indicating variation in composition and possibly consolidation with depth
- Bedrock/pediment contact reflection
• Lower plate carbonate package and early indications of rollover folding and
• Low angle Abyss thrust fault contact

For the purpose of architectural mapping of subsurface geological structure, much of the processing of land seismic involves application of gain controls and filtering to improve signal to noise and delineate target structures. As amplitude of reflectivity has been found to be representative of possible ore body thickness (see Chapter 4), for comparison of synthetic seismic data to true field data, we require a more accurate representation of true amplitudes within the field data.

Figure 5.1: FK migrated post stack, converted to depth. Amplitude and gain manipulation has been applied to highlight regional structure and lithological units over the area.
Figure 5.2: FK migrated post stack, converted to depth with overlay of interpreted units.
Figure 5.3: Pre-stack depth migrated (PSDM) stack from 2009 seismic survey. A closer representation of true amplitudes of reflection. High reflectivity horizon can be seen clearly.

Figure 5.3 represents a pre-stack depth migrated section from the seismic survey acquired in 2009. This processing flow maintains a closer representation of true amplitudes than those seen in stacks created for architectural emphasis. We can see here that bright spots appear in a number of locations within the data set, which are thought to correlate strongly with pediment/bedrock interfaces, and at depth, with the Abyss fault contact. Inspecting this section while focusing on the expected reflectivity response of porous zones, and comparing these bright spots to borehole Au assay measurements, we are able to explore the correlation between Au abundance and seismic reflectivity. This will be discussed in more detail in later sections.
5.2 Borehole Assay and Reflectivity Correlation

Assay logging gives an indication of mineralisation within borehole samples. For the purpose of gold exploration, a significant indicator of mineral abundance within samples is that of Fire Assaying, which effectively separates crushed sample rock from its mineral components of interest through smelting processes. This is typically done by mixing a small, split ore sample with a mixture of lead oxide, reducing agents and fluxes, and firing in a muffle furnace. The product of this stage sees the molten lead oxide well at the bottom of a conical mould, which draws with it any gold that was present within the sample. The residual ore and flux components cool to a glassy slag which remains at the top of the mould and is easily removed. The remaining lead button is then separated from the gold constituent through a cupelling process and the remaining metallic bead represents the separated gold from within the sample. This is then weighed on a microbalance to determine the amount of gold that was extracted from the original sample. For the purpose of this study, I have focused on fire assay measurements as an indication of Au abundance within borehole measurements.

A number of assay logs have been taken over high reflectivity events that are present in the 2009 seismic data. Plotting fire assay response for Au presence relative to depth allows us to correlate any mineralisation spikes and investigate whether they tie with high reflectivity seismic responses. For confidentiality reasons, fire assay scales and borehole identifications have been censored.
Figure 5.4: Fire Assay responses for Au concentration (ounces/ton) for mineralised boreholes over high reflectivity horizon (scales removed for confidentiality).
Figure 5.5 represents three fire assay logs that indicate sufficient Au abundances to be classified as “mineralised”. For confidentiality reasons, specific values and hole identities have been censored. These measurements are located over what appears as significant bright reflection horizons within true seismic data. Scaling plots to match interpreted borehole depths (as plotted on the left hand side of Figure 5.5), we are able to see some degree of correlation between spikes of Au mineralisation and individual reflectivity horizons. The location of mineralisation spikes is difficult to relate to reflectivity due to the presence of proximal lithological boundaries, between pediment/bedrock, as well as Devonian Wenban/Silurian Roberts Mountain. Direct separation of those reflectivity responses from lithological interfaces, and those brought about from the influence of mineralisation, is beyond the scope of this research and likely involves the application of AVO and inversion techniques.
6 Conclusions and Recommendations

6.1 Conclusions

The aim of this research was to investigate the potential for seismic reflection methodology to image zones of hydrothermally altered carbonates, and subsequent Au mineralisation, based on realistic input parameters derived from petrophysical measurements.

Through the provision of approximately 100 petrophysical samples, representative of typical Carlin and Cortez lithological units, it was found that a strong relationship is present between acoustic impedance and apparent porosity of the rock suite. This relationship was apparent across Devonian Horse Canyon, Devonian Wenban and Silurian Roberts Mountain formations, as well as a number of intrusive samples. This strong inverse-linear relationship suggests that seismic reflectivity over this area, is not only a representation of lithological interfaces and geological unit transitions, but may also provide information on the fluid transmission and welling potential of the lower plate carbonates. An understanding of a rock’s potential to transport and house hydrothermally active fluid, indirectly provides information on the rock’s potential to have undergone alteration and Au deposition.

Analysis of the Cortez petrophysical rock suite saw averages taken for density, velocity and acoustic impedance which were used to classify major rock units, these being the Devonian Horse Canyon, Devonian Wenban and the Silurian Roberts Mountain formations. These averages have shown that the impedance contrast between Devonian Wenban and Silurian Roberts Mountain units is less dramatic than previously expected. The contrast was measured to be less than 2% between these
formations, whilst in reality, impedance variations up to 5% represent suitable reflectivity targets. These averages are, however, calculated over all petrophysical samples and it is understood that significant inter-unit variation is characteristic of these units. The lack of measured impedance contrast between the Devonian Wenban and Silurian Roberts Mountain, allows speculation as to the influence of rock petrophysics, in particular porosity, to the intensity of reflectivity in these areas.

Forward modelling of realistic geological models, which were designed to replicate typical structural architecture of the Gold Acres prospect, Nevada, and with unit characteristics derived from petrophysical averages, has seen that for the case of theoretically decalcified mineral lenses situated between Devonian Wenban and Silurian Roberts Mountain formations, suitable reflectivity responses are clearly present over altered zones and appear as significant bright spots, of which amplitudes of reflectivity clearly delineate alteration zones from lithological boundary reflections (Figures 4.6, 4.7). Modelling was undertaken for lens thicknesses of 5m, 10m and 20m, for both decalcified and silicified scenarios. With respect to decalcified ore bodies, the major change in response was tied to amplitude increases by a factor of approximately 1.5 in all incremental stages (i.e. from 5m to 10m, and from 10m to 20m). All modelled lenses are characterised by thicknesses less than \( \frac{1}{4} \) of the dominant wavelength of the model, and hence, are represented as a singular event, as opposed to a doublet, denoting tops and bottoms of reflectors.

Full elastic modelling of these ore bodies with attributes replicating silicification environments saw significantly smaller impedance contrasts relative to the lithological variations between major carbonate units, than those seen in the decalcified scenarios. Again, lenses of thickness 5m, 10m and 20m were imaged,
with 5m and 10m lenses responding as very weak reflectivity events, which would most definitely be masked in true application by intrinsic noises and realistic signal to noise ratios. At thicknesses of 20m, reflectivity of the target is increased, but is still seemingly low in comparison to unit reflections from the Devonian Wenban/Silurian Roberts Mountain interface. For silicified ore body thicknesses modelled in this study, I believe detection of these units in real life practice would be unlikely, unless intensity of silicification has increased rock density dramatically to create higher impedance contrasts.

Comparison of synthetic seismic responses resulting from theoretically decalcified ore bodies, with real field data acquired over the area, requires a focus be placed on maintaining as true amplitude as possible. The closest representation of this true amplitude for real data is shown as a pre-stack, depth migrated section which images zones of high reflectivity, particularly at what has been interpreted as the contact between upper pediment and bedrock. Fire assay for gold abundance has been acquired from numerous boreholes that overlie the major reflectivity target within the true data, and noticeable spikes in Au abundance correlate with zones of high reflectivity. Unfortunately, a means by which to isolate the cause of reflectivity increases, be it due to impedance contrasts between pediment and bedrock, or further related to porosity, and suggestive mineralisation, was beyond the scope of this study, but holds potential for future research.

6.2 Recommendations

Petrophysical information on the characteristic lithological units of the Cortez and surrounding areas is pivotal to understanding how fluid interaction and alteration intensity can be represented through acoustic impedances and hence through seismic
applications. To improve assumptions being made on the relationships between
decalcification and silicification intensities relative to porosity and acoustic
impedances, a larger representative data set of samples that demonstrate moderate to
strong intensities of alteration would provide a clearer image/plot and help to
identify, with more substance, whether high levels of alteration correlate with
increasing (in the case of silicification) or decreasing (in the case of decalcification)
acoustic impedances. This may be done in accordance with collection of
petrophysical measurements, so as to give a clear alteration intensity observation on
the specific sample on which measurements are being taken, as opposed to an often
thicker segment of core during logging.

Modelling undertaken in this thesis has explored responses of thin lenses
representing suitable underground minable targets at depths of approximately 270-
300 metres. For high velocity media as seen in hard-rock exploration, dominant
wavelets are characterised by wavelengths of around 100m, providing detection
thickness limits at approximately 1/30\textsuperscript{th} of the dominant wavelength (3-5 metres). It
is expected that for any bodies with thickness less than 1/4 of the dominant
wavelength (<25m), responses will appear as singular reflectivity events, as opposed
to isolated responses for tops and bottoms of the ore bodies. Modelling the responses
of thicker and structurally variable ore zones (e.g. spherical or blocky units), may
provide a more thorough reference for characteristic responses for comparison with
real seismic data.

Application of seismic methodology for direct detection of alteration zones may see
survey design be revised, with less focus being placed on imaging to depths at which
it is not economically viable to extract ore, and more emphasis being placed on
image resolution and frequency control. It is likely also, that processing routines will require addressing in order to maintain, as near as possible, a true representation of reflectivity amplitude, free of gain controls and excessive filtering. This will likely see receiver group intervals be tightened from a typical 10 metres, to 5 metres, to try and combat ground roll and increase resolution. Modelling has shown that far offset receivers (> 1km) can often provide very little information for depths less than 500m for these styles of environments. Reducing maximum offsets and receiver group intervals will see higher fold achieved at shallower, economically minable depths, and hence provide a higher resolution image over areas that host potential targets. This must be done cautiously, as long offsets can be valuable for capturing reflections from strongly dipping geology. The aim for improved signal to noise ratio will always be paramount for hard-rock seismic, and it is likely that this will be achieved by introducing vibroseis arrays, as opposed to singular sources, or possible implication of explosive sources.

As it is difficult to delineate tops and bottoms of thin ore bodies, which may still be minable targets depending on gold abundance, possible steps into identifying ore body thickness on a sub-seismic scale may be achieved through seismic impedance inversion processing. This study, however, requires very accurate petrophysical information proximal to the target body. This can require wire-line logging over anomalous zones, which can be time consuming and expensive. The benefits of such analysis may, however, be valuable for analysis of prospect value and profit estimation.
References


Appendix A: Petrophysical Attributes

Figure A1: Apparent Porosity vs Impedance of entire Cortez rock suite.

Figure A2: Density vs Impedance of entire Cortez rock suite.
Figure A3: Apparent Porosity vs Impedance of Wenban samples.

Figure A4: Apparent Porosity vs Impedance of Roberts Mountain samples.
Figure A5: Apparent Porosity vs Impedance of Intrusive samples.

Figure A6: Density vs Impedance of Wenban samples.
Figure A7: Density vs Impedance of Roberts Mountain samples.

Figure A8: Density vs Impedance of Intrusive samples.
## Wenban Density Calculations

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Table A1: Wenban samples petrophysical data.
## Roberts Mountain Density Calculations

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Table A2: Roberts Mountain samples petrophysical data.
### Intrusion Samples Density Calculations

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Table A3: Intrusive samples petrophysical data.
Appendix B: Forward Modelling and Synthetic Data

Figure B1: Numerical noise seen in five shot points overlying the extremities of wedging units.

Figure B2: Shot records of numerical noise from wedging unit effects.
Figure B3: Shot records of numerical noise from wedging unit effects.