Geophysical Investigation of the Geothermal System in Pagosa Springs, Colorado

2018 Geophysics Field Camp
Abstract

This report describes the results and interpretation of geophysical data acquired in Pagosa Springs, Colorado during the Colorado School of Mines 2018 Geophysics Field Camp. Pagosa Springs is home to a number of hot springs fed by the central Mother Spring, which is located downtown. The objective of this investigation was to characterize the geologic structure of northern Pagosa Springs to better understand the fluid flow in the area, and to ultimately determine the source and underlying mechanism of the Mother Spring. Geologic investigations and geophysical surveys were performed at various locations in Pagosa Springs from May 13th through May 24th. Among these locations were two main lines along County Road 200 and County Road 411, which run roughly parallel to one another north of town. There were also multiple Reconnaissance Sites examined and selected by students to perform additional surveys. These were located in downtown Pagosa Springs on a plot of land near the Mother Spring, on Reservoir Hill, and near Pagosa Springs High School. Geophysical methods used at these sites included deep seismic, gravity, DC resistivity, self potential, magnetotellurics, time domain electromagnetics, hammer seismic, and ground penetrating radar. The data acquired was then processed and interpreted at the Colorado School of Mines from May 29th through June 7th, the results of which are summarized in this document and in a final presentation, given on June 8th. Our findings indicate significant faulting along CR200, some of which reaches down into the Precambrian Basement. This faulting is a probable conduit for fluid, and is deep enough that water could be heated to the temperature at which it emerges from the Mother Spring. Other faulting confirms the hypothesis that fluid is carried to surrounding areas through fracture networks in formations like the Dakota Sandstone. Overall, the results of this investigation provide a more complete understanding of the geologic structure surrounding Pagosa Springs, along with the fluid flow systems and potential mechanism heating the Mother Spring.
Disclaimer

This report and its contents are derived from a summer field camp for undergraduate students in the Department of Geophysical Engineering at the Colorado School of Mines. The primary objective of this field camp is education, focusing on the instruction of applied field geophysics. All data contained in this report was acquired, processed, and interpreted primarily by students from the Colorado School of Mines. Therefore, all results and conclusions should be regarded appropriately. The Colorado School of Mines and its Geophysics Department do not guarantee the validity of the information or results contained in the remainder of this report.
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Introduction

Field Camp Background

The Colorado School of Mines Geophysics Field Camp is a required course taken by undergraduate students during the summer between their junior and senior year. Unlike a traditional summer course, a portion of the Field Camp takes place off-campus, providing a unique opportunity for undergraduate students, graduate student instructors, faculty, local personnel, and industry specialists to collaborate. Students enrolled in the course engage in all aspects of geophysical data acquisition and processing, applying the skills and knowledge obtained during their previous geophysics courses at CSM. The first two weeks of Field Camp are spent off-campus at a predetermined location where students, with the aid of academic and industry experts, collect geologic and geophysical data in an attempt to characterize the underlying structure of the area. Once data is collected, students return to the CSM campus to process and interpret the data collected in the field. The deliverables of the camp are a final report and presentation summarizing the results and conclusions from the investigation, both of which are made available to the public. For decades, the Geophysics Field Camp has been successfully preparing CSM students for upcoming careers as industry and academic professionals, while cultivating effective communicators, leaders, and problem solvers.

What is Geophysics?

Geophysics involves the integration of physics and geology with the goal of studying various characteristics of the Earth. The general approach consists of measuring fields and physical responses at the Earth’s surface to create a model of material properties and geologic structure of the subsurface. There are a variety of commercial and academic applications of geophysics, some of which include resource exploration, Earth hazard mitigation, and hydrology. The different geophysical applications require different methods depending on the target subsurface property. For instance, subsurface density can be modeled using gravity measurements and electrical conductivity can be modeled using DC resistivity. Other methods include deep and near-surface seismic, magnetotellurics, self potential, time domain and frequency domain electromagnetics, and ground penetrating radar. A typical geophysics work flow is as follows: determine objective, assess survey site, set survey parameters, acquire data, process data, interpret results, and, finally, make final conclusions and recommendations. Therefore, a successful geophysicist is a
“jack-of-all-trades” of sorts, possessing knowledge of survey equipment, physics, geology, math, and computer science.

**Pagosa Springs: History and Location**

**Brief History**
Revered for its beauty and abundance of natural resources, it is no surprise that Pagosa Springs has such a rich and dynamic history. Located in Archuleta County in southwest Colorado, Pagosa Springs is part of the four corners region, nestled within the San Juan Mountains and National Forest. The town is home to various hot springs, with the main Mother Spring located downtown. Numerous groups of people settled and moved through Pagosa Springs. Ten thousand years ago nomadic hunter-gatherers inhabited the area, followed by various Native American tribes. In fact, the name Pah-Gosa, meaning “water that has a bad smell,” comes from the Ute Indians who were ancient settlers of the area. More recently, the translation has shifted to “healing waters” which is likely due to the widespread belief in the healing powers of the springs and modern advertising [1]. Following an influx of explorers, trappers, and prospectors to the area, the Fort Lewis Army post was erected along the West Bank of the San Juan in 1878, due to increasing tensions between Anglos and Native Americans. The fort played an integral role in the development of Pagosa Springs along with the introduction of a railroad and Wolf Creek Pass, opening the San Juan Basin to greater economic development and commerce [2]. Today, though there are remnants of the past lumber and mining industries, the economy in Pagosa Springs is primarily based on tourism. Three spas in town make use of the hot, healing waters of the springs and attract thousands of people each year. Recreation is not the only use of the springs, however. Portions of the town are heated using geothermal systems funded by the Department of Energy, and the Geothermal Greenhouse Partnership owns local greenhouses heated by the water of the hot springs.

**Location of Main Line Sites**
Two main lines were chosen for the 2018 Geophysics Field Camp investigation in Pagosa Springs. In past years, the main lines in the area have run to the east, south, and southwest of the downtown area. This year, it was determined that the main lines should run to the north of town. Therefore, two County Roads, CR411 and CR200, running roughly parallel to the north were chosen (see Figure 1). The combined length of the main lines resulted in about 14km of data coverage. The main purpose of orienting our lines to the north was to combine the understanding of the geologic structure of Pagosa Springs with what has been studied in past Field Camps. Additionally, the decision to have two main lines was made so that a more comprehensive picture of the geology to the north could be obtained, potentially indicating any structural discontinuities between the two lines.

**Location of Reconnaissance Sites**
In addition to the mainline survey sites, three Reconnaissance (Recon) Sites were scouted and assessed by students based on the objectives of the 2018 Field Camp and work that has been done in Pagosa Springs during past Field Camps. The Reservoir Hill Recon Site is located on the north edge of the hill near the water tanks. The High School Recon Site is located in a large open space west of Pagosa Springs High School and east of CR500. The Mother Spring Recon Site is located to the southwest of the Mother Spring on an undeveloped commercial lot due east of Reservoir Hill, situated in a large bend of the San Juan River (see Figure 1). The Mother Spring and Reservoir Hill Recon sites have both been previously investigated by past Field Camps, however, the 2018 Field Camp extended these investigations by performing more extensive surveys at the two sites. The purpose for obtaining data at the High School Recon Site was to investigate the anisotropy of the Dakota Sandstone and there is a large outcrop at this site.
Figure 1: Overall map of the survey sites in Pagosa Springs, Colorado. CR200 goes northeast and CR411 goes northwest. The three Reconnaissance sites are situated on Reservoir Hill, near the Mother Springs, and near the local high school.
Results of Past Field Camps

For seven years, CSM students have performed geophysical surveys targeting different areas of Pagosa Springs in order to create a more complete geologic picture of the area. In 2012, students discovered a few previously unknown faults located due east and northwest of the Mother Spring that could explain the flow of heated water from the basement rock to the observable surface expressions. The 2013 Field Camp built off of the initial observations seen in 2012 and continued to characterize these series of faults west and southwest of the Mother Spring. Their results indicated the presence of a saturated zone in the Dakota sandstone, which may act as a recharge zone for the spring system. With the integration of geochemical observations, the 2013 group also suggested that the spring system originates as rain water on Wolf Creek Pass, permeates down to the Precambrian crystalline basement, travels laterally until reaching these faults, and finally reaches the fracture system, emerging at the surface. In 2014, Field Camp students further investigated this theory, applying it to Stinking Springs as well as tying in the whole geothermal system with surveys to the south in Chromo, Colorado. The 2015 group conducted more surveys in Chromo, characterizing the region and how it ties into Pagosa Springs. Specifically, they studied the Chormo Anticline and how it connects to faults found both in Chromo and in Pagosa Springs from previous years. Students in 2016 went back to Pagosa Springs and conducted surveys to the east of the town to investigate fluid flow. Self Potential data pointed towards an intrusive dike that might have been disrupting fluid flow but was not confirmed. They also found evidence for a fault in this area that could provide a conduit for fluid flow. The last group of students in 2017 conducted surveys back in Chromo and along Reservoir Hill in Pagosa Springs in an attempt to connect the surveys in Chromo and Pagosa Springs from previous years. They did not find a saturated zone in Chromo that they predicted; however, they did find a fracture in the basement in Chromo that could explain fluid flow and also found a fault-like structure underlying Reservoir Hill in Pagosa Springs.

Objectives and Overview

The primary objective of the 2018 Geophysics Field Camp is to further the education of undergraduate geophysics students at CSM. Students gain valuable experience working with geophysical equipment, performing surveys, processing data, and interpreting results. With that being said, there is also a hope of providing potentially useful information to the communities in which Field Camp takes place. Having conducted Field Camp in Pagosa Springs for seven years, the hope is to integrate data from each camp to provide a comprehensive description of the characteristics of the geology of the area, and to ultimately describe the mechanism of the geothermal system. Many of the results from previous Field Camps in Pagosa Springs help build a more complete picture of the geologic structure and advance our understanding of the fluid flow in the area. Though these conclusions are useful, the real questions about the geology of Pagosa Springs remain: What is the mechanism by which the water of the Mother Spring is heated, and what underlying structure enables the hot water to emerge in Pagosa Springs? These questions are what motivated the 2018 Geophysics Field Camp. Therefore, in addition to further characterizing the overall geology of the area by looking north of downtown Pagosa Springs along CR411 and CR200 and at the Reservoir Hill and High School Recon Sites, much of the efforts involved getting geophysical surveys as close to the Mother Spring as possible at the Mother Spring Recon Site. This report provides a comprehensive view of all of the data acquired, processed and analyzed over the course of the 2018 Geophysics Field Camp. Each geophysical method and its findings are presented, followed by an integrated analysis of the results, and concluded with overall interpretations and recommendations. A final presentation will be given to the public summarizing these results at CSM on June 8th.
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1. Geology

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1.1 Introduction and Structure

![Map showing geologic features and cross sections.]

Figure 1.1: The 3 lines colored pink, blue, and red are labeled on the map above as CR200, CR411, and RH (Reservoir Hill) Cross Sections respectively. The cross sections were constructed through previous knowledge from the wells as well as dip information from the outcrops seen around Pagosa Springs and can be seen in the figures 1.11 and 1.12. The RH cross section goes through the Mother Spring Recon Site. The Fluvial and Terrace deposits were similar enough to the RH Recon Site. There was no initial cross section made for the High School Recon Site.
Pagosa Springs is located on the northeastern edge of the San Juan Basin. The San Juan Basin is a structural basin that formed between the late Cretaceous to early Paleogene due to the Laramide Orogeny. The basin is located along the Colorado-New Mexico border and is bordered to the east by the Archuleta Anticlinorium and the Nacimiento Uplift, to the west by the Defiance uplift, to the south by the Zuni Uplift, and to the north by the San Juan Mountains.
The sedimentary units found in the San Juan Basin and surrounding areas were deposited in an ancient sedimentary basin. The San Juan Basin was formed in conjunction with the Archuleta Anticlinorium, San Juan Sag, and Chama Basin due to a combination of loading and subsidence of the basins and compressional forces during the Laramide Orogeny.

The Archuleta Anticlinorium is an uplift located on the northeast corner of the San Juan Basin. The Archuleta Anticlinorium is a northwest-trending, asymmetric anticline that divides the San Juan Basin from the Chama Basin to the west and the San Juan Sag to the northeast. There is a large, vertical fault on the west end if the anticline that extends from the Precambrian Basement to the Cutler-Entrada contact. The Cutler Formation and other Paleozoic sediments truncate at the fault, indicating that those formations were deposited either before or during the faulting. The uplifted sediments were eroded, creating a contact between the Entrada Sandstone and Precambrian Basement that continues into the San Juan Sag. The anticline and surrounding basins were formed in conjunction during the Laramide Orogeny. Large, vertical displacements at this time also created a series of horsts and grabens. The stratigraphic uplifts (e.g. the Archuleta Anticlinorium and the Nacimiento uplift) formed over the horsts, while the basins such as the San Juan Basin and Chama Basin formed in the grabens.

The Archuleta Anticlinorium contains a multitude of normal faults. These faults trend either north or northwest and can have vertical displacements of up to 180m. The most prominent of these faults is the Eight Mile fault, which runs southwest of the Pagosa Springs. These normal faults were caused by tensional forces in the rock layers as a result of uplifting and folding.
Figure 1.3: Large scale cross section of the Archuleta Anticlinorium. The cross-section trends from the San Juan Basin in the southwest to the San Juan Sag in the northeast. Pagosa Springs is located where the P-1 well is marked. Modified from Brister and Chapin, 1994.
1.2 Depositional History

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Figure 1.4: Type stratigraphic column for the Pagosa Springs area. Upper units are described using observations from outcrop and prior geological studies. Thicknesses shown are relative and change in the immediate area. Rock units below the Mancos are described from the P-1 well near the Mother Spring. Depositional environment for each unit is described in further detail below.
1.2 Depositional History

1.2.1 Precambrian

The Precambrian basement contains rocks that were deposited in the Proterozoic eon and the Archean eon. Not much is known about the depositional environment.

1.2.2 Paleozoic Era

In the Paleozoic era, Pagosa Springs and the surrounding area rested on a stratigraphic low. Pagosa Springs experienced a series of transgressions and regressions in the Cambrian, Devonian, Mississippian, Pennsylvanian, and Permian Periods, which deposited a sequence of marine sediments over the region. The first major structural event occurred in the Pennsylvanian period with the formation of the Ancestral Rocky Mountains. During the formation of the Ancestral Rockies, the Archuleta Anticlinorium and regions to the east were lifted above sea level and were subjected to erosional forces, erasing the Paleozoic units from the region [3].

1.2.3 Mesozoic Era

During the Triassic period, the uplifted regions were still above sea level as indicated by the lack Triassic deposits. In the basins a regression of an ancient sea resulted in the deposition of shallow marine rock units, collectively called the Moenkopi Formation. Deposition of the lowlands transitioned into a fluvial environment where the Cutler Formation was deposited. The rock material for these fluvial deposits derived from the Ancestral Rocky Mountains. The combination of deposition in the lowlands and in the highlands resulted in the region returning to an area of low relief [Beaumont:2018].

The oldest non-basement rock units found in the Archuleta Anticlinorium were deposited during the Jurassic period. During this time the Pagosa Springs area was covered in sand dunes, creating eolian sandstone deposits called the Entrada Sandstone. Adhesion ripples in the Entrada Sandstone indicate that the interdune environment was damp. The dune fields were then submerged by a transgression of the Sundance Sea from the north. The Sundance Sea in the area contained brackish still water, allowing the formation of evaporite layers known as the Wanakah Evaporites. The regression of the Sundance Sea created a fluvial environment. The Morrison Formation encompasses the regression and subsequent fluvial environment. Like the Cutler Formation beforehand, the fluvial deposits of the Morrison Formation originated in the Ancestral Rocky Mountains.

During the Cretaceous period the Western Interior Seaway covered most of the interior United States. Pagosa Springs experienced four to five major transgressions and regressions, as well as many minor transgressions and regressions during this time [Molenaar:1997]. The first transgression deposited the Dakota Sandstone, the lower Mancos Shale, and the Greenhorn Limestone. The Dakota Sandstone was deposited during the transition from a shallow marine to a deep marine environment, and the lower Mancos Shale and Greenhorn Limestone were deposited during a deep marine environment. The Greenhorn Limestone marks the maximum extent of the transgression. Two more transgressions and regressions formed the rest of the Mancos Shale. An extensive regression of the Western Interior Seaway deposited a sequence of marine and non-marine sandstones called the Mesa Verde Sandstones. The final transgression of the Inner Cretaceous Seaway deposited the Lewis Shale and the final regression of the Western Interior Seaway deposited the Pictured Cliffs Sandstone. After the Western Interior Seaway retreated, the Pagosa Springs area was covered in swamps and floodplains. The swamps and floodplains deposited the shale and coal beds of the Fruitland and Kirkland Formations. The late Cretaceous period marks the start of the Laramide Orogeny. It is during this orogeny that the Archuleta Anticlinorium and the surrounding basins were formed. During the Cretaceous period, the lower part of the Animas Formation was deposited.
1.2.4 Cenozoic Era

The Laramide Orogeny continued from the late Cretaceous Period to the Paleogene Period. The Laramide deposits from the Paleogene period are the upper part of the Animas Formation and the Blanco Basin Formation. The Animas and Blanco Basin Formations follow the same fold as the Archuleta Anticlinorium, indicating that the anticlinorium was still forming during the Eocene epoch of the Paleogene period [4]. During the Oligocene epoch there were several volcanic centers in the San Juan Mountains. These volcanoes formed intrusive, igneous dikes throughout Pagosa Springs. The volcanoes were also responsible for depositing ash-flow tuffs and lava flows called the San Juan Volcanics.

After the deposition of the San Juan Volcanics, the last major event Pagosa Springs experienced was glaciation from the ice age during the Pleistocene epoch of the Quaternary period. The resulting glaciers eroded the sediments near Pagosa Springs, erasing the Cenozoic units from the Pagosa Springs area. The glaciers brought rock fragments from the San Juan Volcanics to the valley floor where they formed resistive layers which would eventually become the tops of the hills in the region. Since the end of the ice age, the predominant driver of erosion and deposition has been the San Juan River.

1.3 Local Geologic Units

1.3.1 Precambrian Basement

Not much is known about the Precambrian Basement. The basement is 45% granitic rock, 30% gneiss and schist, 15% quartzite and phyllite, and 10% greenstone. The schist and gneiss are Archean in age, while the granitic rock, greenstone, quartzite, and phyllite are Proterozoic in age.

1.3.2 Entrada Sandstone

The Entrada Sandstone is an eolian sandstone that was formed in the Jurassic Period and sits unconformably atop the Precambrian Basement. The Entrada Sandstone consists of sub-rounded to well-rounded quartz grains and is mostly massive with some low angle cross-bedding and planar lamination present.

1.3.3 Wanakah Evaporites

The Wanakah Evaporites were formed by a transgression of the Sundance Sea from the north during the Jurassic period and sit conformably above the Entrada Sandstone. The Wanakah Evaporites consist of alternating layers of limestone and gypsum and ranges from 3-30m thick.

1.3.4 Morrison Formation

The Morrison Formation was formed in the Jurassic period and sits conformably above the Wanakah Evaporites. The Morrison is separated into 3 members: the Basal Member, the Middle Member, and the Brushy Basin Shale Member. The Lower Member and the Middle Member are 60-120m thick and 18-36m thick, respectively. Both the Lower Member and Middle Member contain cross-bedded sandstone deposited in river channels, and layers of finer grained sandstone and shale deposited in floodplains. The Brushy Basin Shale Member is 13-26m deep and contains shales and claystones with very little sandstone.

1.3.5 Dakota Sandstone

The Dakota Sandstone was deposited in the late Cretaceous, sits unconformably above the Morrison Formation, and is 122m thick. The Dakota Sandstone contains fine to coarse grained sandstones that display both parallel bedding and cross bedding. The Dakota Sandstone lies above the Morrison Formation on an erosional unconformity. The Dakota Sandstone in the
Pagosa Springs area is silicified, giving the unit a sparkling appearance. The silicification was caused by ground water flowing through the Dakota, and as a result, the Dakota Sandstone is not very porous; however, due to extensive fracturing in the formation, groundwater is able to flow through the rock. The fractures in the Dakota are parallel to the strike of the rock.

Figure 1.5: Dakota Sandstone outcrop near the transfer station to the south of Pagosa Springs town. Easily seen is the relatively flat lying sandstone on the cliff approximately 150ft above the shale beds. The blocks of sandstone stacked together are not monolithic and have many fractures. This sandstone is seen to be uplifted through the Eight-Mile Mesa fault.

1.3.6 Mancos Shale

The Mancos Shale dominates the surface geology in the Pagosa Springs area. The Mancos formed due to a series of transgressions and regressions from the Western Interior Seaway. At its maximum extent, the Mancos is 2000m thick. Due to erosion the shale is thinner in the Pagosa Springs area. The Mancos is heterogenous and contains multiple evaporite layers, the most prominent of which is the Greenhorn Limestone Member. Marine bivalve fossils, such as those from the inoceramus genus, can be found certain layers of the Mancos Shale. The Mancos Shale is easily eroded, erasing surface evidence of structural features such as faults.
1.3.7 Greenhorn Limestone

The Greenhorn Limestone is a member of the Mancos Shale. The limestone ranges from 12-21m thick and located about 18m above the Mancos-Dakota contact in the Pagosa Springs area. The Greenhorn Limestone consists of alternating beds of limestone and calcareous shale. The Greenhorn Limestone represents the furthest extent of the transgression of the Western Interior Seaway.
1.3 Local Geologic Units

1.3.8 Mesa Verde Sandstone

A regression of the Western Interior Seaway deposited the Mesa Verde Sandstone. The Mesa Verde thins in the Pagosa Springs area and truncates east of Pagosa Springs.

1.3.9 Lewis Shale

The Lewis Shale is a continuation of the Mancos Shale above the Mesa Verde Sandstone. The Lewis Shale was deposited during another transgression of the Western Interior Seaway. In places without Mesa Verde deposits, there is no distinction between the Mancos Shale and the Lewis Shale.

1.3.10 Pictured Cliffs

The Pictured Cliffs were formed by the final regression of the Western Interior Seaway in Late Cretaceous. The Pictured Cliffs are 122m thick but outcrop to the west of Pagosa Springs. Most of the Pictured Cliffs' sandstone was eroded in the Cenezoic time by glaciers and the San Juan River.

1.3.11 Kirkland and Fruitland Shale

The Kirkland and Fruitland Shales were deposited during the Laramide Orogeny. They are identifiable by their coal beds.
1.3.12 **Animos and Blanco Basin Formation.**

The Animos and Blanco Basin consists of conglomerates, arkoses, and siltstones. These rocks are late Cretaceous to early Paleogene in age. These rocks are not observed in the Pagosa Springs area due to erosion but are observed in the San Juan Basin.

1.3.13 **San Juan Volcanics**

The San Juan Volcanics were deposited in the late Paleogene about 28 million years ago. The rocks were deposited by previous volcanism in the surrounding area. While San Juan Volcanics do not outcrop in Pagosa Springs, fragments of the San Juan Volcanics carried by an ancient river form resistive caps on the tops of the hills in Pagosa Springs.

1.3.14 **Travertine**

Travertine is a sedimentary carbonate rock formed when carbon-dioxide laden water cools and deposits carbonates when it reaches the surface. Travertine is a direct indicator of geothermal activity as hot water facilitates the creation of decarbonated limestone. Travertine is deposited in layers on the surface around hot springs. The travertine deposits near the Mother Spring are between 4-10m thick and typically less than 1,000 years old [5].
### 1.3.15 Rock Properties

<table>
<thead>
<tr>
<th>Depth (m)</th>
<th>Formation</th>
<th>Gamma (API)</th>
<th>Resistivity (Ohm m)</th>
<th>Density (g/cc)</th>
<th>Porosity (%)</th>
<th>$V_p$ (ft/s)</th>
<th>$V_s$ (ft/s)</th>
<th>Reflection Coefficient</th>
<th>Amplitude</th>
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<td>2</td>
<td>22,000</td>
<td>11,000</td>
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</tr>
</tbody>
</table>

Figure 1.8: Stratigraphic column detailing all of the rocks that have been deposited near Pagosa Springs. The rock thicknesses of the Dakota Sandstone and below are based off of the P-1 well log, while rocks above the Dakota used literature to estimate their thicknesses. The rocks above the lower Mancos do not appear in Pagosa Springs due to erosion.

An integrated geophysical approach to the Mother Spring problem requires consistent assumptions of the physical properties of rocks encountered by the methods used in this study. Representative rock properties for the units encountered in the Mother Spring area are shown in Figure 1.8. These values were taken from the TG-1 well about 50m northwest of Mother Spring and were chosen as representative values for each formation. The Mancos Shale, Dakota Sanstone, and Morrison Formation are very heterogeneous and could produce results very different from those recorded in Figure 1.8. The Morrison was subdivided into the Brushy Basin Shale Member, Middle Member, and Lower Member to provide a better idea of the conditions found at the Dakota-Morrison contact and the Morrison-Wanakah contact. The thicknesses of the formations also differ throughout the area. However, these average values were used for method-specific corrections (such as gravity terrain correction) and for integrated geological interpretation between methods.
Chapter 1. Geology

The Dakota Sandstone is distinguishable from the Mancos Shale because it is a more resistive rock with faster P-wave and S-wave velocities. The top of the Morrison is hard to determine, as the contact between the Brushy Basin Shale Member and the Middle Member of the Morrison Formation appear similar to the contact between the Dakota Sandstone and the Morrison Formation. The Wanakah Evaporites act as a good datum for geophysical methods that could image it, due to the boundary between the Morrison Formation and the Wanakah Evaporites having a drastic increase in resistivity, P-wave velocity, and S-wave velocity. The Wanakah should produce the most prominent reflection in the seismic data.

1.4 Geothermal System

1.4.1 Heat Flow

The groundwater of the hot springs is significantly heated within the subsurface before reaching the surface, with water temperatures as high as $60^\circ C$ at the Mother Spring. Some possible mechanisms by which this could occur are a batholith in the subsurface or a high regional thermal gradient. There are multiple dikes around Pagosa Springs but no evidence of the presence of a batholith that is capable of heating the groundwater to the degree of the Mother Spring. According to Galloway, there is a heat flow increase from east to west and groundwater temperatures that increase towards downtown Pagosa Springs, shown in Figure 1.9. The heat flow map was later revised by the Colorado Geological Survey (CGS) to have the high groundwater temperatures centered on the Mother Spring instead of downtown Pagosa Springs, shown in Figure 1.10. Based on the geothermal gradients shown in the maps, the groundwater must travel at a depth of 2-3km to be heated enough by the basement rock for it to reach the Mother Spring temperature at the surface [Reference CGS presentation]. Therefore, the basement is most likely the primary geothermal heat source for the process.

1.4.2 Hydrology

The people of Pagosa Springs and surrounding farms and ranches rely heavily on well water. These wells are generally drilled into aquifers within the Mancos and the Dakota Formations. Water from the Mancos aquifer contains high amounts of sodium, calcium, iron, and sulfate [6]. This results in generally poor water quality. Water flow through the Mancos is primarily due to fractures and intergranular porosity. Much of the water produced from the Dakota Formation aquifer is similar to that of the water from the aquifer in the Mancos. Sometimes, however, the water is lower in dissolved salts and meets the drinking water standards. Thus it is probable that there are two aquifers within the Dakota that are separated by black shale sequences [6]. Water flow in this aquifer is due to fracture porosity and is confined within the formation.

There are multiple interpretations as to how these aquifers are recharging. One interpretation by Galloway is that the aquifers are recharging from precipitation on outcrops and from stream-channel loss as streams cross the outcrops. Recharge from precipitation will only occur after the near-surface demands for moisture are met by the water that does not run off and a residual amount of water is able to reach the zone of saturation in the aquifer [7]. These near-surface demands include evaporation, transpiration, and sublimation. Paul Morgan with CGS interprets that the aquifers are recharging from the San Juan Mountains due to the hydraulic gradient from the large hydraulic head in the San Juan Mountains to the low hydraulic head in Pagosa Springs. The groundwater movement across the hydraulic gradient follows an almost semicircular path in which it travels down through the Precambrian (2-3km depth from surface) before emerging in Pagosa Springs. This path through the Precambrian is supported by the very hot temperature of the spring water. Additionally, oxygen 16/18 isotopes in the water that suggest it is of meteoric origin.

Common areas of discharge for aquifers include springs, seeps in topographically low parts of the outcrop, aquifer outcrop to stream channels, fault planes, fractures, intrusive dikes, aquifer movement across a less permeable unit, wells, and mining operations. This suggests that the
Figure 1.9: This map shows a heat flow that increases from east to west, ranging from 3.0-4.5 heat flow units. The groundwater temperature increases from 30°C to 50°C, centered on and increasing towards downtown Pagosa Springs. This map was originally presented in Galloway’s report [6].
Figure 1.10: This map is an edited version of Galloway’s map such that the groundwater temperature increases are centered on the Mother Spring (Big Spring) and range from about 52°C to 75°C. It was originally used in a presentation by Paul Morgan with CGS.
two major, natural areas of discharge for the aquifers are the hot springs in Pagosa Springs, and that in areas south of town, the discharge occurs along the San Juan river. However, the Mancos Shale at the Mother Spring allows groundwater to flow primarily through fractures. This suggests that there may be a type of fracture network from the aquifer up to the surface to allow groundwater to flow. The fracture network could be due to an intersection of faults or intrusive dikes near the spring. An intersection of faults is a reasonable approach because rivers commonly flow along fault lines and the Mother Spring is at a sharp bend in the San Juan River, suggesting that there may be two faults intersecting at the Mother Spring. Intrusive dikes commonly result in groundwater discharge and there are many dikes in the Pagosa Springs area, so they are another probable cause for a fracture network in the Mancos [7].

1.5 Cross Sections

1.5.1 CR200

![Cross Section Diagram]

Figure 1.11: The cross section extends north from the Mother Spring (A), up CR200, to the HR Macht #1 Well (A'). The sinclinal appearance of the rock layers is not a geologic structure but an artifact of how the line bends with the road. The Greenhorn Limestone is not plotted on the cross section because it would be too small.
Figure 1.12: The cross section extends from south of the Eightmile Fault (B’), through the Mother Spring, and to the northern end of CR411 (B). The bend in section is located at the Mother Spring. Above the Mancos Formation near the bend, is a thin layer of alluvium (10m thick), which is covered by a thin layer of travertine. Because of how thin these layers are compared to the formations, they were not included in the cross section.
1.5.3 Recon Sites

Figure 1.13: The cross section extends from the west side of the Mancos outcrop across the river (A) to the east side of the 4H club, following Mill Creek Road (A'). This cross section shows the placement of the Mother Spring and a predicted area of the Victoire fault, which could be shifted a few meters toward Reservoir hill as debates continue around the exact location. The deposits seen, such as travertine and fluvial deposits around the Recon Sites, are shown in the figure below.
Figure 1.14: The travertine and fluvial deposits are seen to vary as a thin layer beneath the Mother Spring Recon Site, while the fluvial and terrace deposits are present on Reservoir Hill itself.
2. Geophysical Methods

2.1 GPS

2.1.1 Introduction

Several geophysical methods depend on location and elevation measurements for their survey locations. Global Positioning System (GPS) data is taken at those locations and we can utilize the geospatial data sets for processing. Precise GPS measurements can be crucial to certain methods, such as gravity. There are 3 main components to the gravity method: the gravity value, position, and height; making it important to get accurate GPS measurements. We used 2 different methods to obtain GPS data. We started with a hand-held GPS system, the Garmin-eTrex 30X Hand-held GPS, to get data points at all flag locations. Then, we went through with the Trimble R10 GNSS system to take differential GPS (DGPS) measurements. The Trimble instrument gives us more accuracy, and we use the hand-held as a back-up or in places that the Trimble could not be used. The collected GPS measurements are used to locate survey lines and make terrain based corrections during processing for various geophysical methods.
2.1.2 **Theory**

2.1.2.1 **Differential GPS (DGPS)**

Orbiting the Earth is a network of satellites that emit signals. These signals are then received by a base station at the surface of the Earth which includes the exact position and time that the signal was transmitted. The base station, or stationary receiver, records the exact time a signal is received. The base station also records the difference between the time the signal was transmitted and the time the signal was received. This difference in time is called the travel time. We know that the signal propagates at the speed of light, so the travel time can be used to calculate the distance between the satellite and the base station. Since the base station could be positioned anywhere, that distance is unspecific. Therefore, a second satellite is used to allow the base station to create a second sphere, and the intersection of those spheres creates the circular region of space where the coordinates of the base station are located.

A third satellite then reduces the region to two potential points that the base station could be located. More satellites are then used to resolve the location of the base station. If the base station has more time to triangulate, accuracy improves and allows the system to correct any errors. Once the base station has a known location, the rovers can begin their survey. The shot between in the base station and the rover is called the long static shot. The base station obtains corrections by taking a reading of the location and comparing that to its known location from the long static shot for a more accurate shot, and then sends the difference between those two locations to the rover. In areas of high topographic variation, the base station may need to be moved if it cannot communicate with the roving receiver. A roaming antenna may also be necessary in larger survey areas to extend the range of the DGPS [8].

![Figure 2.1: Visual representation of how the differential GPS system works.](image)
2.1.2.2 **Hand-held GPS**

The hand-held GPS also reads signals from a network of GPS satellites in order to get spatial positioning points. At least 4 satellites must be in range for the hand-held unit to work. The satellites send signals with position and time information. Similar to the DGPS, the difference between signal sent and received allows the distance from the satellite to be determined. By using the distance and signals sent and received, the hand-held GPS can determine its location. Unfortunately, a hand-held GPS records GPS points at a much less accurate rate than the DGPS. This is why methods that need accurate elevation and positioning should not use measurements from the hand-held units if there is more accurate geospatial data available [9].

2.1.3 **Objectives**

2. Process collected spatial coordinates into a usable and consistent format: easting, northing, and elevation, for use in other methods.
3. Use GPS data to create maps, using ArcGIS, for the different geophysical methods.

2.1.4 **Equipment and Survey Procedure**

2.1.4.1 **Equipment List**

- Trimble DGPS system:
  - Base station
  - Three R10 GNSS Roving receivers
  - Two hand-held Trimble Data consoles: TSC3 and TSC1
  - Car Battery
- Multiple Garmin eTrex hand-held GPS

2.1.4.2 **Data Acquisition**

First, the locations at which measurements are to be taken on the main lines had to be determined. The flagging crew decided on a 10 meter spacing for the separation of the flags along the lines. The initial flagging line for CR411 was flag number 4000 on the South end, just across from the cemetery, to the end of the road at flag number 4481. Each flag number had an increment of 1, so there was a 10 meter spacing between flag numbers 4000 and 4001. The CR200 line had flag number 2000 as its initial south-most flag extending north to flag number 2900. The convention for flagging was to have all even numbers as green flags, odd numbers as orange, a pink flag every 100 meters (or every 10 flags), and yellow flags at every 1000 meters (or every 100 flags). Both lines were extended south along their lines later in the week. CR411 was extended to flag number 3822 and CR200 was extended south to flag number 1968 (note that the flag numbering for flags 1968-2000 was irregular). This was done in order to get additional measurements for gravity and deep seismic. Specific methods that moved into the Mother Spring Recon Site flagged where they took measurements, and the GPS crew then came in and took GPS measurements using the Trimble DGPS.

The Garmin hand-held GPS devices were positioned at determined locations and GPS data was collected. The EM groups used the Garmin to get the coordinates of the Transmitter loop and receiver locations. MT used the Garmin on top of the ADU to get location information. GPR used it to define the location of their lines and grids. Hammer seismic also used it to define their lines and grids. SP used the Garmin to define their grid. In regards to the DGPS, the base station was initially set up on top of a hill on a property on the CR400 line, a county road directly between our two main lines. The base station was draining the car batteries and the solar panel’s power supply. We then decided to move the base station to a location that was halfway down CR411 at flag number 4240. The base station tripod was setup on the hill over a marked location that uses a laser for accuracy. Unfortunately, control points were never taken at the new location. One of the R10 receivers was attached at the top, as well as a car battery for power.
The rovers can be set up following the completion of the setup for the base station. Each rover is used with either the TSC3 or TSC1 hand-held consoles. The TSC3 is then set up to take general surveys as an open job with an input of the job name allowing us to take a set and auto store points, number of measurements, and occupation time. The parameters included: the units being taken in meters, the coordinate system to 13N UTM WGS1984, and the rover stand set to the \(2\)m mark. Once set up, measurements are ready to be taken. The rover must be leveled over the flag location, with confirmation of the leveling from the TSC-1 consoles. Once leveling is complete, the measure button can be pressed, and after waiting for the selected observation time, the console acquires the GPS coordinates. There was a wide range of observation times at different locations, from 3 seconds to greater than 30 seconds. In order to increase efficiency, each rover collected measurements for different flags, with one rover taking points at even-numbered flags and the other rover taking points at odd-numbered flags.

2.1.4.3 Procedure

1. Set up base station
2. Set up roving receiver(s)
3. Set up TSC1 or TSC3 handheld consoles
4. Move to location and level the roving receiver
5. Measure

2.1.5 Results

2.1.5.1 Processing

The first task for the GPS processing team was to combine the various data files from the Garmin and Trimble data. The largest part of the process was combining the even flag data with the odd flag data. Some files were in latitude/longitude (in decimal degrees) coordinates and some were in UTM coordinates (WGS1984 13N), so we had to do some conversions to get master lists of everything in the same coordinate system. We created 3 master files, one for GPS on CR200, one for GPS on CR411, and one for GPS at the Recon Sites. We included the data with both latitude/longitude (in decimal degrees) coordinates and UTM coordinates, but asked the rest of the processing groups to use the UTM coordinates if their method allowed in order to keep consistency throughout the groups. For the method specific Garmin GPS data, we separated the GPS files by method and by day in their own spreadsheets. After compiling the GPS data, we used the rest of our processing time to create maps for every method, at each location. Our main goal with this was to create consistent maps that could be used for correlation and integration.

2.1.5.2 Error and Uncertainties

The GPS method has both human and instrument errors associated with it. There are a number of factors that decrease the accuracy of the devices. The ionosphere and troposphere cause the signals to slow as they pass through the atmosphere, causing delays in receiving the signal. Errors in travel time can also occur due to the signal reflecting off of nearby objects. The receiver’s clock could also have timing errors as it is not as accurate as the satellites’ clocks. Another error that could decrease accuracy is the orbital error, where the position of satellite was recorded inaccurately. The number of satellites visible affects the accuracy as fewer satellites mean a less accurate position. All of these affect both the hand-held and the DGPS.

To get the highest accuracy, the roving receiver must be held exactly level for the entirety of the GPS location calculation. If not held level, the x, y, and z components will be calculated incorrectly. The hand-held console shows an image of the bubble level and it will only accept certain levels at which the rover can be off. Even slight changes in wind can cause an error in the measurement. Similarly, the total base station must also be leveled. Additional errors are terrain changes, vegetation, and tree cover, all reducing accuracy as the clear line of view to the total station is compromised. This could be especially prevalent for the data points collected on the Reservoir Hill Recon Site as that area is heavily forested.
2.1 GPS

More human-based error also could have occurred during acquisition. Most groups used the leap-frog method for collecting data, and if a flag was missed or the wrong flag was collected and the hand-held console was set to auto-increment, the data could be off and we would have no idea. If the hand-held console was not set to auto-increment, then a flag could have been mislabeled, and in the data it could just look like a duplicate point and would be erased. The overall accuracy of the position measurements could be affected as the accuracy of the measurements are relative to each other through the day, with slight variability when comparing each days data. This error is minimal and should not be an issue for any of the methods relying on location information.

2.1.6 Conclusion

We collected DGPS data for the entirety of the main lines, CR200 and CR411, and the Mother Spring Recon Site. Hand-held GPS data was used by individual methods in the locations that they surveyed, including along the main lines and the Recon Sites. During processing, we were then able to compile datasets for CR200, CR411, the Recon Sites, and individual method survey locations. We then took this data during processing to create survey location maps. Our recommendation for future surveys is to have a consistent format for GPS collection so that time does not need to be wasted compiling the data into a consistent coordinate systems.
2.2 Deep Seismic

Figure 2.2: Total survey area for deep seismic on CR411 and CR200
2.2 Deep Seismic

2.2.1 Introduction

Deep seismic is a geophysical method used to image the subsurface through the generation and measurement of seismic waves. It is used to gain an understanding of the properties and structure of the subsurface, and it is often used in the petroleum industry to identify possible oil or hydrocarbon-bearing formations. It has a myriad of other applications, one of which is imaging crustal and lithospheric development to better understand geomorphology and tectonics [5]. Information from seismic data, particularly common midpoint gathers, can be used to calculate the velocity of the material through which acoustic waves propagate. This is helpful in conjunction with knowledge of the area’s geology because velocities can either reinforce or challenge geologic interpretations. Seismic allows geologists to extrapolate surface features into the subsurface and better understand geologic history.

The seismic method was employed in Pagosa Springs, Colorado in an attempt to locate the source of the geothermally heated water that emerges at the Mother Spring in the downtown area. The source is currently unknown, so seismic was used to investigate if the rock formations underlying the town indicate a possible movement path of the spring water. It is likely that water must travel deep beneath the surface where relative proximity to the Earth’s mantle provides a sufficient heat source before rising once again to the surface. However, there are certain low-permeability formations present in Pagosa Springs that inhibit fluid flow, such as the Mancos Shale. There should be a traceable path in the subsurface that allows the water to rise, even through low-permeability structures, and seismic could be helpful in imaging that path. Seismic data from Pagosa Springs also helps refine interpretation of data taken through other geophysical methods, such as gravity.

2.2.2 Theory

Seismic surveys are generally used to produce detailed images of the survey area and the different rock types beneath the Earth’s surface. This is usually done by deep seismic acquisition in which seismic waves propagate into the subsurface from a source near or at the surface. These seismic waves reflect off the underground contrasting rock layers, traveling back to the surface where the surface ground motions resulting from these reflections are recorded by geophones. Analyzing the time that seismic waves take to return to the surface yields useful information about the underground formations. A depiction of this process is shown in Figure 2.3.

![Figure 2.3: An overview of the deep seismic method illustrating a deep seismic survey setup. The relative orientation of the seismic source, geophones, and recording location for a typical seismic survey are shown.](image-url)
2.2.3 Seismic Sources

The type of source used in seismic surveys depends on the desired acquisition location and survey setting, which can be marine or land environments. In marine acquisition acoustic energy is produced by air guns. Marine seismic vessels use a combination of cables and seismic sources with attached hydrophones, which capture the returning waves. Land seismic acquisition uses specialized vibrator trucks or explosives (shown in Figure 2.4) to generate seismic signals which are captured by geophones at the Earth’s surface.

Figure 2.4: Seismic sources for land acquisitions. Vibrators (a) have low energy density, but they are very heavy and large. Explosives (b) are used in areas inaccessible to vibrator trucks.

Seismic surveys were acquired on CR200, CR411, and the Mother Spring Recon Site in Pagosa Springs using a vibrator truck since it could easily access these survey locations. The truck carries a heavy plate that is vibrated on the surface and shakes the ground according to the chosen sweep parameters and specific frequency range, which are specified in Table 2.1. The frequencies change with the duration of the sweep, going from low to high frequency for an up-sweep or from high to low frequency for a down-sweep. Up-sweeps are typically used for land acquisition surveys as they cause less stress on the vibroseis. The sweeps are also broken down into either a linear or non-linear regime. Non-linear sweeps are used to either put more high or low frequency energy into the subsurface, depending on the depth and scale of the features of interest.

2.2.4 Seismic Waves

There are two main types of waves generated in seismic surveys: body waves, which can travel through the Earth’s subsurface, and surface waves, which only travel through the Earth’s crust. Therefore, the most important waves for deep seismic are body waves, which correspond to P-waves (primary or compressional waves). P-waves are the fastest seismic waves, and they propagate in the same direction as the energy transport. S-waves (secondary or shear waves) are slower than P-waves, and their energy moves perpendicular to the direction of propagation.

The velocity of P- and S-waves are given by:

\[ V_p = \sqrt{\frac{K + \frac{4G}{3}}{\rho}} \]  \hspace{1cm} (2.1)

and

\[ V_s = \sqrt{\frac{G}{\rho}} \]  \hspace{1cm} (2.2)

where \( K \) is the bulk modulus, \( G \) is the rigidity modulus, and \( \rho \) is the density. For fluids, \( G = 0 \),
meaning S-waves cannot travel through fluids, as demonstrated by the surface wave velocity equation above.

In multicomponent seismic data acquisition, both P- and S-waves are recorded. However, for this study the seismic acquisition equipment and data collection techniques were able to provide only single component data, which did not record S-waves.

Surface waves travel slower than body waves and their amplitudes decrease with depth into the Earth; however, they can be more energetic than body waves. This energy is recorded by geophones in land acquisitions, adding coherent noise to the data. This noise is known as ground roll, and must be filtered during data processing.

2.2.5 Reflections and Refractions

During a seismic survey, controlled sources of energy produce short period wave trains (pulses) that propagate through the subsurface. A pulse creates a wavefront that propagates in all directions, and each point of the wavefront can be modeled as a source of secondary wavelets according to the Huygens principle.

When a seismic wave propagating in the subsurface reaches a boundary between two material layers with distinct physical properties, the wave velocity changes and the wave energy is divided. Some of the wave energy is transmitted to lower layers (transmitted wave) and the other part is reflected back towards the surface (reflected wave). This energy partitioning process is repeated with each new interface, until the energy of the propagated wave is completely dispersed. The ratio between the transmitted and reflected energies depends on the velocity and density of the layers and on the angle of incidence.

Reflected waves have the same speed and frequency as the waves that originated them, but they travel in a different direction. The angle of reflection is equal to the angle of incidence. The reflection coefficient, \( R \), of a normally incident P-wave is given by:

\[
R = \frac{Z_2 - Z_1}{Z_2 + Z_1},
\]

where \( Z_n \) is the acoustic impedance of the layer \( n \). The acoustic impedance is the product of the rock density (\( \rho \)) and the P-wave velocity (\( V_p \)), such that:

\[
Z = \rho \cdot V_p.
\]

The interface between two geologic formations is referred to as a reflector or seismic boundary. A large reflection can be produced by a large contrast in the impedance of two consecutive layers, which can be generated by changes in lithology, diagenesis, porosity or fluid saturation.

The transmitted event generated by a P-wave obliquely incident at an interface is known as a refraction. Refraction involves a change in the wave propagation direction and velocity, and can be described by Snell’s law:

\[
\frac{\sin \theta_i}{V_{p1}} = \frac{\sin \theta_r}{V_{p2}},
\]

where \( \theta_i \) and \( \theta_r \) are the incident and refracted/transmitted angles, respectively. Figure 2.5 shows a sketch of the relationship between incident, reflected and refracted angles.

Additionally, part of the P-wave energy is converted into shear energy, which generates reflected and refracted S-waves. For a given incidence angle \( \theta_i \), the refracted angle \( \theta_r \) will be equal to 90°, i.e., the refracted wave travels along the interface between two media with the velocity of the lower medium. In this case, the process corresponds to a critical refraction and \( \theta_i \) is called the critical angle, \( \theta_c \). In this case, Snell’s law becomes:

\[
\sin \theta_c = \frac{V_{p1}}{V_{p2}},
\]

where \( \sin \theta_c \leq 1 \), \( V_{p2} \) must be greater than \( V_{p1} \), and \( V_{p2} \neq 0 \). Therefore, observing seismic refractions is only possible when seismic velocities of layers increase with depth. From the Huygens
Chapter 2. Geophysical Methods

Figure 2.5: A geometric depiction the incident, reflected, and refracted angles. The angle of incidence is equal to the angle of reflection, while the relationship between the incident and refracted angles is governed by Snell’s law. In the geometry shown, material 1 and material 2 have different velocities, where \( v_1 < v_2 \) [10].

principle, it is expected that some energy from the critical refraction of the shallow layers returns to the surface. This energy can be recorded by geophones, and thus, information about subsurface velocities can be extracted from refractions.

2.2.6 Objectives

This study aims to find the source of underground water that feeds the hot springs in the town of Pagosa Springs, Colorado. The primary interest is determining the source of the hot water that comes from the main Mother Spring, which is rumored to be the deepest hot spring on Earth. Similar studies with these purposes have been conducted in past Field Camps in Pagosa Springs.

In addition to our main objective, there are particular objectives that we hope to accomplish after processing and interpreting the seismic data. The goals of the deep seismic method for this study are the following:

- Process the data collected along the two main lines (CR200 and CR411) using SeisSpace ProMax software, which consists of denoising the data, applying corrections (elevation, velocity, etc), and creating a depth section for both lines.
- Interpret the results to make a connection to the local geology.
- Integrate the data with other methods to compare how well the datasets conform with one another.
- Find the underground stream path that provides hot water to the Mother Spring and other springs in the town once data integration with other methods is complete.
- Provide geophysics students at the Colorado School of Mines with experience in processing and interpreting deep seismic data as well as getting comfortable using the SeisSpace ProMax software.

2.2.7 Equipment and Survey Setup

2.2.7.1 Equipment List

Land seismic surveys were performed along two main survey lines, CR411 and CR200. A smaller survey was also performed at the Mother Spring Recon Site. The energy source was a seismic vibrator truck, which uses a vibrating plate to generate seismic waves in the subsurface. The receivers were placed along the main lines in order to record the returned seismic energy.
The equipment, including the processing software packages associated with this land seismic survey, are listed below.

- **Sercel SG-10 Geophones with attached cables:**
  to record returned seismic energy for data acquisition and to send the signals to the doghouse via a field digitizer unit (Figure 2.6a).

- **Field Digitizer Unit (FDU) Sercel SN408XL:**
  to convert analog signals from the geophones into digital signals which can be monitored and processed by computers in the doghouse (Figure 2.6b).

- **Doghouse:**
  to act as a communication center for all field camp deep seismic operations and check if all geophones work properly in real time. The station (located in a portable trailer) records all seismic data on the main lines and actively communicates with the seismic crew to do roll-alongs. The processing units inside are capable of checking noise and errors on the survey lines and report all malfunctions to fix the lines immediately.

- **AHV-IV Commander (PLS-364) Vibrator Truck:**
  to provide the source of acoustic energy, with a peak force of 61,800lbs and a frequency range of $< 1Hz$ to $250Hz$.

- **Geotechnical Technology Inc. (GTI) NuSeismic NRU Wireless Seismic Nodes:**
  to record returned seismic energy for data acquisition without using wires.

- **Ground Pounder:**
  to create a hole for installing the wireless nodes.

- **Measuring Tape:**
  for $10m$ spacing between the two flags.

- **Land Acquisition Unit Cross (LAUX-428):**
  to connect multiple FDU cables and manage to send all signals to the doghouse for active monitoring.

- **Land Acquisition Unit Land (LAUL-428):**
  to connect between the two FDU cables (usually placed every $40m$) and to serve as the power sources for the geophones.

- **Line Control Interface (LCI-428):**
  to manage the seismic line of up to 10,000 channels and serve as the main interface connecting a seismic line to the computers.

- **Sercel e-428 Software:**
  to control the seismic line and perform stacks and correlations prior to recording data.

- **SeisSpace ProMax 2D Software:**
  to perform several corrections, migrations, stacking to seismic data from shot records to cross-sections for both CR200 and CR411 lines.

- **SeiSee SEGD-2-SEGY:**
  to visualize the seismic data obtained from the doghouse.
2.2.7.2 Location

Throughout the course of Field Camp, three seismic lines were constructed. These lines were located along CR411, CR200, and the Mother Spring Recon Site (Figure 2.2).
2.2 Deep Seismic

**Figure 2.7**: An aerial map showing the seismic lines. CR200 is shown in blue to the east of CR411, which is shown in white. The Mother Spring Recon Site is shown in green on the southern region of the map.

**CR411 Line**
The first survey performed was along CR411. Data was collected with Sercel geophones and GTI nodes along the line which ran from flag numbers 3940-4480, making the total length of the line just over 5km. Refer to Figure 2.8

**Mother Spring Recon Site**
After acquiring permission to access the land west of the Mother Spring at the Recon Site, GTI's wireless nodes were deployed as an extension of the CR411 line. These nodes went through town, across the San Juan River, and through the Recon Site, passing the Mother Spring. This line in total was 1km long, going from flag numbers 3822-3920.
Figure 2.8: Map of the CR411 seismic survey line with flag numbers in Pagosa Springs and crossing the San Juan River to where the Mother Spring Recon Site was located in green towards the southern portion of the map.

**CR200 Line**
The last line to be collected was CR200. Only the Sercel geophones were used for acquisition at this location, as time and man power was running short toward the end of the camp. This line went from flag number 2000-2700, covering 7km in length.
2.2.7.3 Survey Parameters

When designing a deep seismic survey, it is important to consider the parameters that are being chosen. Geophone/node spacing and sweep parameters are equally important in ensuring quality data collection. The target and background knowledge of the underlying geologic structure must be considered to determine what these parameters should be. Factors such as time, cost, and source limitations are also important to consider when designing a seismic survey.

Geophone Parameters
In order to use the Sercel SG-10 geophones, it was decided that the 10m cable, which held 6 geophones, would start in the center of two flags, where it was connected to the next cable and an FDU. When placing the geophones in the ground, they need to be stomped in in order to achieve optimal coupling with a vertical orientation to provide the most accurate recordings (Figure 2.10). Due to a limited number of geophones, there was a pickup and layout crew moving the seismic line throughout the day. Once the laid down geophones were out of the range of the vibrator the pickup crew collected the geophones and moved them to the front of the line. The lay out crew then re-deployed the nodes so that the seismic line could continue.

**Node Parameters**

In order to deploy the wireless nodes provided by GTI, a ground pounder (also provided by GTI) was used. The ground pounder creates a hole the size of the node where the node can be inserted to help create a better coupling between the node and the ground. These nodes each have their own power source and GPS unit built inside of them, making the nodes almost invisible to those who encounter them. These nodes were placed at the center of two flags (5m away from each flag) with a distance of 10m between nodes. Some locations had to be skipped due to pavement where a node could not be deployed. The wireless aspect of the nodes proved to be very helpful, allowing us to setup a seismic line across the student site near the Mother Spring. Additionally, they proved to be valuable since wired geophones were not able to be run across the river and through the town, as was possible with the GTI provided nodes. Therefore, as stated before, an extension of 1km the CR411 line was made, connecting this road to the Mother Spring Recon Site (Figure 2.8).

**Sweep Parameters**

All sweep parameters must be defined prior to land seismic data acquisition of any kind. Before the actual data collection, several sweep tests are performed in order to have some idea of how the signals behave in response to unique geologic features of the desired survey area. Such parameters should be tested independently by changing one parameter at a time for multiple values. The final sweep parameters are chosen by comparing the results of each test. Based on the results of the tests, the parameters shown in Table 2.1 proved to be the optimal parameters to determine subsurface geological features along our seismic line.
Table 2.1: Seismic sweep parameters used on 2018 main lines (both CR200 and CR411).

<table>
<thead>
<tr>
<th>Source</th>
<th>AHV-IV Commander (PLS-364) Vibrator Truck</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sweep Type</td>
<td>Non-linear Upsweep</td>
</tr>
<tr>
<td>Frequency Range</td>
<td>$4\text{Hz} - 120\text{Hz}$</td>
</tr>
<tr>
<td>Sweep Length</td>
<td>$8\text{s}$</td>
</tr>
<tr>
<td>Listening Time</td>
<td>$2\text{s}$</td>
</tr>
<tr>
<td>Total Time per Station</td>
<td>$40\text{s}$</td>
</tr>
<tr>
<td>Shot Spacing</td>
<td>$10\text{m}$</td>
</tr>
<tr>
<td>Number of Sweeps</td>
<td>4 sweeps* (6 sweeps at the beginning of CR200 until hitting the first sharp right turn)</td>
</tr>
</tbody>
</table>

All sweep parameters are picked based upon how well the reflections can be recorded and shown on the shot records. The goal is to try to capture as much high-frequency signal as possible, while maintaining low-frequency signal in order to avoid Gibb's phenomena. Since most of the energy for frequencies larger than $120\text{Hz}$ is attenuated, there is no point of wasting time on producing higher frequencies. Better signal is also observed when spending more time on higher frequencies. Therefore, the non-linear up-sweep is beneficial for obtaining clean signals at higher frequencies. Due to time constraints, the vibrator truck used 4 $8\text{s}$ sweeps with a $2\text{s}$ listening time, accumulating to $40\text{s}$ per station.

Throughout this survey, only one vibrator truck was used courtesy of Dawson Geophysical. However, in industry seismic acquisition, it is standard to have more than one vibrator truck as the seismic source. To conduct our survey, we drove the vibrator truck along our chosen seismic line where it would stop every $10\text{m}$, or every flag, and conduct 4 sweeps. Some stations had to be skipped as the vibrator truck cannot vibrate the ground within $300\text{ft}$ of any buildings/structures. Other obstacles we had to skip were underground pipelines, electrical conduits, and other possible infrastructure that could be damaged due to the vibrations.

2.2.7.4 Procedure

**CR200**

Seismic data were collected along CR200 using Sercel geophones. As outlined above, a string of six geophones was oriented around each flag so that there were three phones on either side of the flag, with 2-meter spacing between each phone (see Figure 2.10). Each string of six was connected to an FDU, and the FDUs were connected down the line by orange cables. The vibroseis was provided and overseen by Dawson, with students driving some of the time. The doghouse was operated by Alba Guerrero from Sercel, with students spending time in there and learning how to program works as well. The vibroseis was driven so that the vibrating plate approximately lined up with each flag. The vibroseis operator then signaled the doghouse, where the doghouse operator began the sweep. Once the sweep was finished, the vibroseis was driven $10\text{m}$ up to the next flag, and the process repeated all the way down the line. The survey began at the south end of CR200 and worked north. Once the geophones on the southern end were out of range of the source, the phones and cables were picked up and moved to the north end of the line so that the line could keep progressing.

**CR411/Recon Site**

Seismic data collection on CR411 was similar to collection on CR200, with the addition of GTI wireless nodes and data collection moving from north to south. Nodes were deployed approximately halfway between each flag down the line. The nodes were advantageous because they could be placed where the geophones could not, such as in driveways and through the small section of town at the south end of the line. The process of data collection worked the same way, with the vibroseis and the doghouse working together and advancing down the line.
Exploratory geophysical activities include data acquisition, processing, and interpretation. Seismic processing aims to create an informative model of the subsurface from the acquired data, which can then be interpreted and used to inform decisions. During the processing flow of land data, there are steps that must be followed in order to produce such a model.

- **Geometry:**
  each recorded seismic trace must be associated to the coordinates of its source and receiver, along with a common midpoint (CMP) and its offset.

- **Static corrections:**
  these corrections cause a time shift in the seismic trace. There are two main types of static corrections. The first attempts to remove the topographic effect due to different elevations of sources and receivers in relation to an established datum. The second seeks to deal with the presence of a weather zone in the near surface, known as the low velocity zone (LBZ), where the seismic waves propagate with low velocities.

- **Ground roll attenuation:**
  the coherent noise known as ground roll is characterized by high amplitudes and low frequencies in the seismic data. Therefore, it can obfuscate important information, namely the reflections in the data. There are many filtering techniques that can be used in order to attenuate the ground roll.

- **Velocity analysis and normal moveout (NMO) correction:**
  this correction attempts to remove the effect of different offsets on the arrival time of reflections in a CMP gather. Assuming a flat Earth, a reflection arrives first at the receiver that is closest the source. Thus, for a far offset, the reflection arrival time will be delayed. The NMO correction corresponds to the difference between the traveltime, $T_x$, for a offset $x$ and the traveltime, $T_0$, which corresponds to a zero offset, such that:

  \[
  T_x^2 = T_0^2 + \frac{x^2}{V_{sta}^2},
  \]

  where the stacking velocity $V_{sta}$ (also referred to as $V_{nmo}$) represents the velocity that makes hyperbolic events appear horizontal, flattening the reflections. Therefore, a velocity analysis must be done in order to determine $V_{sta}$. A representation of the NMO correction step is showed in Figure 2.11.
2.2 Deep Seismic

Figure 2.11: The theory behind an NMO correction. The NMO correction maps the data in a CMP gather using the fact that reflections recorded from a horizontally layered earth will show up as hyperbolic events in time for different offsets. $X_n R_n$ represents a source-receiver pair. After the NMO correction, every reflection is flat and ready to be stacked [11].

- CMP Stacking:
  after the NMO correction, all of the traces of a CMP gather represent samples of the same reflection. Therefore, these samples can be stacked, which significantly increases the signal to noise ratio. The data is then reduced to a seismic section, which consists of a single trace per midpoint location.
- Migration:
  this step aims to move dipping events to their true subsurface locations. Once this imaging process is completed, the migrated seismic section can be interpreted.

2.2.8.2 Errors and Uncertainties

Cultural Noise
Cultural noise is anything related to human activity that might cause noise or error in the data acquisition. Sources of cultural noises that we experienced include:

- Power Lines
  Power lines in the Pagosa Springs area have a 60 Hz frequency that adds noise in the seismic shot record. This must be filtered out when processing data.
- Inclement Weather
  The geophones used to acquire seismic data are extremely sensitive. This means that any rain drops or wind can move the magnet that is suspended inside the coil of wire. This creates a signal that is not due to seismic waves.
- Traffic On The Road
  This includes any cars, trucks, bikes, and even people. Anything moving along the survey
line will create their own seismic signals and create noise in the data.

- **Other Surveys Being Conducted**
  Other survey crews moving around will create their own seismic signals. Additionally, methods that use electrical current, as D.C., create noise as they induce current into the seismic cables.

**Field Operation Errors**
This source of error encompasses noise caused by survey design, the equipment used, and the crew's use of the equipment. Sources of field operation errors include:

- **Survey Design**
  When creating the survey there was a lot of room for error. For instance, flags could be placed in a non-parallel orientation to the seismic line, causing a disparity in the correct distance between flags. Additionally, the flags are not perfectly parallel to the line of geophones. This means the GPS data taken at the flag is not a perfect representation of the geophones. Furthermore, geophones are not placed at a perfect $2m$ spacing from each other, and the geophone next to the flag is not a perfect $1m$ away from the flag.

- **Geophone Placement**
  In order for the geophones to work properly, they must be placed completely level and straight up. This is nearly impossible while working in the field because efficiency calls for a quick placement and stomping. This creates error in the acquired data.

- **Inaccessible Areas**
  This error is caused by the inability to conduct parts of the survey in certain locations. This results from being unable to place geophones on paved roads, use the vibe truck due to proximity to buildings, and more.

**Processing and Interpretation Errors**
This issue stems from uncertainty in the processing stage that arises since each student can select their own corrections based on their own interpretations. Types of processing and interpretation errors are as follows:

- **First Break and Velocity Picks**
  Each student selects their own first break and velocity picks for the denoising process, potentially creating inconsistency in processing results. This is done in order to decrease ground roll attenuations.

- **Correct Denoising**
  If filters are too strong during denoising, the quality of good data can be decreased.

- **Interpreters Variance**
  All interpreters are different, and therefore all final results will be different.

- **Assumptions**
  For processing purposes we are assuming a flat, homogeneous, and isotropic Earth.

### 2.2.9 Results

### 2.2.10 Processing-SeisSpace ProMax
Seismic data processing can involve an indefinite number of steps depending on the job and time constraints, such as our two weeks to compile this report. Some datasets have processors working on jobs over a span of multiple years. SeisSpace ProMax 2D from Halliburton Landmark Enterprise Solutions was the software used to carry out all of the processing needs for deep seismic. The software is a comprehensive seismic processing software that can be used for marine and land processing on 2D and 3D datasets. SeisSpace ProMax enhanced the final seismic images through the use of tools to remove noise and make data corrections. Noise was filtered out by limiting the recorded bandwidth. Corrections were made to fit assumptions of a flat, homogeneous, and isotropic Earth. The processing flow began with quality control followed by a crooked line geometry correction, statics corrections, bandwidth noise filtering, surface wave noise attenuation (SWNA), NMO velocity corrections, residual statics, and time to depth migrations. The first flow used in SeisSpace ProMax was the SEG-D (industry standard
field data format) to SEG-Y (standard processing data format) converter. The processing flow is described on Figure 2.12.

**Figure 2.12**: The general workflow model for seismic processing in SeisSpace ProMax. The flow goes from left to right, and with like colors grouping together with their processing flows, e.g., SWNA Test and SWNA Apply. Grey rectangles indicate where stacks were created and used for quality control. The color scheme was random, meaning one shade of red does not correspond to a different shade of red.

**Crooked line geometry**

The acquisition constraints of the vibroseis led to winding survey lines following CR200 and CR411, making it difficult to create a 2D plot without the Crooked Line Geometry Spreadsheet tool. This tool should be applied when turns in the line are greater than $5^\circ$ [12]. The advantage of a straight line geometry is that it places the CMPs along the survey line. In this case, the CMPs are offset from the survey line, decreasing the total folds per receiver and increasing the amount of the subsurface sampled. This adds uncertainty to the structures that are imaged. Crooked Line Geometry Spreadsheet tool used the imported $xyz$ dataset as the input to calculate and display the CMPs relative to the shot and receiver points. Using the Crooked Binning Grid tool, the bin size and maximum offset were determined from the CMP image (shown in green/blue) and is to be used after the track is made, seen in Figure 2.13. Each bin contains a number of CMPs that are then associated with the bin’s center-point in order to make a new processing line (often called the slalom line) comprised of multiple straight segments. This can occasionally cause the data to appear wavy instead of straight, and can also result in some loss of reflection signal.
Figure 2.13: A depiction of the source, and midpoint locations. The top of the figure is Northing. 2.13a displays the binning grid used to generalize the midpoint locations to improve fold number along the new processing line for CR200. 2.13b displays the CMP gathers used as constraints for line picking on CR411.

Elevation (datum) statics
Datum statics are primarily used for land-acquired data to fit the assumption of a flat Earth. The purpose of this is to correct travel time changes due to the topography affecting the apparent velocity. This works by setting a datum as a reference point, which is typically flat, to come up with a static replacement velocity. The Datum Statics Calculation tool was applied by setting the maximum elevation to $2300\text{ m}$ and a replacement velocity of $3200\text{ m/s}$ for CR200 and CR411. As a part of quality control, the elevation plot must be checked to get maximum elevation and to ensure correctness of the data. For example, from this set it was found that each dataset had some missing elevation, Easting, and Northing values. Datum Statics Apply is used for applying the calculations made from the Datum Statics Calculation algorithm. This method is useful for testing multiple parameters without having to recreate flows and output results into separate datasets.

Brute stack
A brute stack was produced in order to give a first look at the time-space data of the subsurface. Brute stacks were produced from CMP trace gathers and typically have minimal corrections and filters applied, and so are primarily used for quality control purposes rather than interpretation. Final static and NMO corrections will be added throughout processing to produce a final space-depth model. The more traces there are per CMP, the higher the signal to noise ratio and number of traces (fold number). Figure 2.14 shows the brute stack section for CR411.
First break picking

First break picking, sometimes referred to as first arrivals, is used to determine a LBZ statics model \textit{Gaviotti:2013}. SeisSpace ProMax uses a machine learning algorithm called the stabilized power ratio picker. In order to check the validity of the program, the results also produce a confusion matrix reporting correct and incorrect picks. A dataset was made from various shot gathers with a time gate where first arrivals were used as testing parameters. Time gates were used to limit the the total area the program scans over in order to save time processing. For more complex geologic structures, multiple time gates may be needed to obtain the desired accuracy and precision; however, only one time gate was necessary for both CR200 and CR411. The automated first break picker did an exceptional job highlighting the first arrivals from the testing data. There were also instances where it struggled due to high levels of noise in certain shot gathers. Average first break time results were stored into trace headers and applied using Header Statics \cite{13}. Figure 2.15 shows a panel representing this step.
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Figure 2.15: An example of the first break algorithm after the first reflection was outlined in red by the machine learning algorithm. Blue lines represent time gates set by the user, while green lines represent time gates chosen by the program. The area located at channel number 196 and 400 ms represents noise that caused the program to make a missed pick.

Refraction statics

Refracted waves occur at an interface between a low and much higher velocity medium, such as that between a weathered layer and bedrock [4]. Refraction statics help distinguish the reflections from the delayed refractions, which also aids in performing NMO corrections. The LBZ thickness can be smaller than the geophone and node spacing, making the short wavelength variations indistinguishable in the data [cite]. Using refraction statics tools, new filters for static time shifts for the near surface heterogeneous layer can be applied.

SWNA

This tool is used to limit noise generated from ground roll by investigating signal amplitude, frequency, and dip angle in addition to the previously applied bandpass filter. The data was converted from the time-space domain to the frequency-space domain and was stored in low-frequency arrays Gaviotti:2013. Frequencies outside the determined cutoff range were interpreted as noise and removed from the data, and the same was done with the two investigated parameters. The dip angle cutoff range was determined by the user from comparing shot gathers with potential ground roll velocities eliminated from the gather. Figure 2.16 shows a panel with traces corrected with different denoising velocities. For CR200, the ground roll velocity was chosen equal to 1600 m/s, while for CR400 1500 m/s was used.
Velocity analysis and NMO correction

Velocity analysis is performed using SeisSpace ProMax for the NMO corrections. It is based on the assumption that reflections are hyperbolic in the time-space domain Gaviotti:2013. Equation 2.7 is used to correct for offset in the NMO correction. Using SeisSpace ProMax, the velocities were chosen by the user with respect to time. The user is assisted in making decisions through the use of semblance plots, CDP gathers, and stacks with different displayed stacking velocities (Figure 2.17). The heat map used for the semblance plot displays the most frequent velocity at that time in red. The CDP gather can also be used to ensure best picks are made by checking that the traces line up close to horizontal for each velocity pick, obtaining a zero-offset. A velocity pick is too low if the inflection is upward, and too high of a velocity if the inflection point is downward. The velocity function stacks depict the raw stacks for a static velocity value.
Residual statics
Residual statics were used to adjust the CMP gathers to better fit a hyperbolic shape with the traces described by NMO formula in Equation 2.7. This was applied to pre-stack gathers to further correct for time shifts in the data from topography, dipping geology, and crooked line geometry. After the flow was performed on a dataset, shot gathers were then run through a number of iterations to best fit the NMO equation. When seismic processing is performed on an industry dataset, velocity analysis is repeated to improve velocity picks to get closer to a zero-offset with the NMO correction [14].

Time and depth migration
The time and depth migrations were some of the final processing steps performed on the data. The migrations were derived from the velocity analysis and NMO corrections prior to this step. Through the use of velocity picking for various points with respect to time, the data can be adjusted by the velocity chosen for that specific area. First, the time migration was run, followed by a depth migration. Depth migration is considered to be the more useful of the two corrections, producing more accurate interpretations and integrations with other methods (e.g., geology, or other geophysical methods). The migrations were performed twice, once using NMO stacking velocities, and a second time using velocities determined from the well data gathered from the P-1 Well in the Pagosa Springs area south of both survey lines. Using measured velocities shifted the depth of the reflectors by about 100m from the user-picked velocities. To use the measured well velocities, bedding horizons were user-picked to distinguish between each interface before applying the measured velocities for each layer. This assumes each layer is homogeneous and isotropic.
2.2 Deep Seismic

2.2.11 Interpretation and Conclusion
2.2.11.1 Interpretation

The deep seismic data collected along CR200 and CR411 (including the Mother Spring Recon Site extension) were processed using both NMO velocities and velocities of geologic units taken from well data in the area. For our interpretation, the NMO velocity processed sections were evaluated, but the well velocity sections can be seen in Appendix D. Comparing both the CR200 and CR411 sections (Figures 2.19a and 2.21), there are a few different horizons that are easily identifiable in both seismic sections. Based on geologic knowledge of the area (but before analyzing the velocities and depths of known units), we can make a preliminary interpretation of where the geologic units lie along CR200 and CR411. The clearest reflector for both lines is toward the bottom of each section, and likely represents the change from upper units to the basement. There are also features in both that could represent faults; however, due to the crooked line geometry, these interpretations should be corroborated by other methods. More in-depth initial interpretations for each survey line will be presented in this section.
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Figure 2.19: Images showing post-processing stacks using NMO velocities for a comparison between geophone data (2.19a) and node data (2.19b) collected along CR411. 2.19b also contains the data shot at the Mother Spring Recon Site, which is outlined in yellow.
2.2 Deep Seismic

Since both nodes and geophones were used to record data on CR411, a comparison between the two was attempted, which is shown in Figures 2.19a and 2.19b. This comparison was not one-to-one, however, since the layout parameters were different between the two. The nodes were typically spaced every $10m$ with built-in GPS, whereas the geophones were spaced every $2m$, with FDUs connected every $10m$ and DGPS measurements taken at flags (refer to Figure 2.10). This could be the cause of the geophone data appearing less noisy, and showing some better reflections in Figure 2.19a. The node data has more artifacts shown with the reflections, making the interpretations less straightforward for Figure 2.19b. The left portion (south end) of the node section shows the seismic data shot and recorded at the Mother Spring Recon Site. The basement reflection can still be seen in this portion of the data; however, it is difficult to distinguish distinct features above the basement due to the lack of vibe points needed to provide the necessary number of folds for better data resolution. The approximate depth to basement estimates are also different between the two. The basement reflector produced by the geophones with NMO velocity is at approximately $575m$, which is generally consistent with the reflectors shown in the node data. The biggest inconsistencies between the two depth sections is the thickness of some of the reflectors. The reflectors from the node data are slightly thicker than those from the geophone data. Overall, geophone data provides a clearer image of the subsurface structure along the CR411 line, and also helps maintain consistency with CR200, since node data was not collected there. The interpretation of the geologic units along CR411 using the geophone data is shown in Figure 2.20.

It is also evident in the sections from CR411 that interpretation of seismic sections alone can be tenuous. The CR411 line was processed multiple ways: using both NMO velocity and velocity information from the P-1 well with each dataset (nodes and geophones). The resulting depth sections from each processing result are similar, with similar shapes to the reflectors. They contain many of the same features, suggesting that those features are legitimate and not simply artifacts of processing. However, the main reflectors are at slightly different depths in each: the basement reflector produced by the geophones with NMO is at approximately $575m$ seen in Figure 2.20, which was shallow relative to the well velocities migrations. These approximations can be consolidated into a better depth value through integration with other methods.

![Figure 2.20: The horizon interpretations for the CR411 seismic line displaying potential fault locations reaching into the basement that could influence water flow in the region.](image)
CR200 was processed with both the NMO velocities and well velocities. The NMO velocities were used for the interpretation of geologic horizons and potential faults. The original depth migration is shown in Figure 2.21. Figure 2.22 shows the interpreted horizons and faults along CR200. The faulting toward the middle of the line is an area of geologic interest. There are some potential bends in the geometry of the seismic line causing these fault structures, but there appears to be enough unconformity for faulting or truncating bedding layers. This could potentially be a feature that affects the regional water flow and can be further investigated and compared with other geophysical methods. Since the section shown in Figure 2.21 represents NMO velocity corrected data, the interpreted depths differed slightly from expected depths based on information gathered from the nearby wells; however, the NMO velocities were determined to be more reliable.

Figure 2.21: Depth migrated section for the survey conducted along CR200 using NMO seismic velocities.
2.2 Deep Seismic

Figure 2.22: The horizon interpretations for the CR200 seismic line displaying potential fault locations reaching into the basement that could influence water flow in the region.

Considering the available geologic information, there are many different lithological units, i.e., geologic formations, in Pagosa Springs. As aforementioned, impedance contrasts can be generated by changes in lithology, such as consecutive layers of rocks with varying physical properties like density and velocity. Therefore, we can expect that the strong reflections presented in the migrated seismic sections are related to the interface between two layers with different impedances. The integration provided by geologic interpretations and other geophysical surveys performed in the area, such as gravity, will either confirm our propositions or not. Knowledge of the subsurface structure of geologic units and their respective properties is required. In Chapter 3, a cohesive interpretation for each survey location (CR200, CR411, and the Mother Spring Recon Site) will be discussed, and integrated images of the seismic sections will be presented.

2.2.11.2 Conclusion and Recommendations

After completing a processing flow and interpretation, the data acquired during Field Camp at Pagosa Springs provides information about the geological units in the subsurface. In the field, two main lines of deep seismic reflection surveys were conducted on CR200 and CR411 using a vibrator truck, along with a shorter line at the Mother Spring Recon Site. The vibrator truck generated seismic signals at 10m intervals along the lines, with approximately 13km of data collected in total. Some stations along the line were skipped due to proximity to buildings, gas pipes, or inaccessible areas. Students set up the equipment and assisted in data collection, while professionals were responsible for preliminary data quality control.

Back in Golden, an intense work flow was conducted over the course of eight days in order to use the seismic data to characterize the subsurface geologic structures of Pagosa Springs. Eight students were involved in the deep seismic data processing, and they had the supervision of two industry professionals. Jeremy Zimmerman from Chevron provided explanations of the main concepts related to the method and data processing while Robert Basker led the group in processing using SeisSpace ProMax software.

The depth migrated sections, which were the final product of the seismic processing, were used to do a structural and stratigraphical interpretation of the subsurface. By analyzing those sections, we were able to identify the main lithologic units presented in the Pagosa Spring geology, as well as some geologic structures, such as faults. The faulting seen in the southern sections of the CR200 and CR411 could potentially be directing regional water flow. Through integration with other methods, the faults can be confirmed and add to the subsurface geology in the region.
Based on the processing results as well as the permitting we required during the 2018 Field Camp, our recommendation for following Field Camps is to conduct a 3D seismic survey at the Mother Spring Recon Site. What was done this year is the closest that the Geophysics Field Camp program has ever gotten to recording seismic data near the Mother Spring itself. However, due to time constraints, extensive seismic surveys could not be carried out at this site. As a result, extensive interpretations about the origin and mechanism of the Mother Spring could not be made based on the seismic sections collected at this site during the 2018 Field Camp.

Additionally, based on information from locals in Pagosa Springs, it is very possible that the area will be developed in the coming years, which would make it very difficult for us to conduct geophysical surveys there in the future. It was also highlighted by Marvin Johnson that if a 3D survey was conducted at this site, some of the shot parameters would need to be changed due to the proximity of the surrounding infrastructure. To combat this issue, the vibrator truck could reduce its overall force down from 70% (which was used during the 2018 Field Camp) to around 30-40% when close to buildings. The sweep parameters could also be changed to a random sweep, as it would help reduce the ground roll and shaking of the nearby buildings. Lastly, if the Mother Spring Recon Site is a possible survey site in coming years, it would be encouraged for the seismic crews to communicate with industry professionals to see if it would be feasible to process a 3D seismic survey in the time allotted by Geophysics Field Camp. A second option for a 3D seismic survey is to connect the CR411 and CR200 lines, keeping the same parameters we used for the survey as it produced quality data this year. This option would provide a better and more complete understanding of the subsurface, showing how the geologic structure evolves between the CR200 and CR411 lines. Since the CR411 and CR200 data was already processed during this Field Camp, it might be more feasible to process additional lines into a 3D survey. Doing either one of these recommendations would be extremely useful, as it would be the first time we would have 3D seismic data in the Pagosa Springs area, providing a more comprehensive understanding of the geologic structure of the area.
2.3 Gravity

Figure 2.23: Total survey area for gravity on CR411, CR200, and the Mother Springs Recon Site
Chapter 2. Geophysical Methods

2.3.1 Introduction

A relative gravity survey uses a gravity meter or ‘gravimeter’ to record lateral density contrasts in the subsurface. Variations in lithology and subsurface features directly below the meter cause varying degrees of gravitational acceleration at the measurement point. After multiple measurements along a survey line, the compilation of points creates a picture of lateral variations in density contrast in the lithology. These density contrasts are useful in modeling the geometry of geologic layers and serves to confirm findings from other methods, such as deep seismic.

Land gravity surveying requires a single instrument, which makes it a highly mobile method that can be used in almost any location in the world. However, many modern gravimeters measure gravitational acceleration on the order of microgals, making this method very susceptible to urban noise such as vehicles and foot traffic that can produce noise three orders of magnitude greater than the acceleration from lithologic changes. Therefore, data quality is highest in areas of little cultural noise. Gravity surveys provide useful information for mineral and reservoir exploration but for this project added to our understanding of the geology of Pagosa Springs, Colorado, specifically its geothermal systems.

In previous years students have conducted surveys east, south, and west of Pagosa Springs; in the area of Chromo, a town to the south; and on Reservoir Hill near downtown Pagosa Springs. These surveys provided geologic context to Pagosa Springs and will aid in large-scale interpretation of the area. In addition 3D gravity data of the area surrounding the mother spring will be compared against data from our Downtown Recon site, which was in the same location.

This year students conducted surveys along two county roads north of Pagosa Springs CR411 and CR200, and on a Downtown Recon site, an area adjacent to the hot springs in downtown Pagosa Springs. The primary objective was to characterize the geology north of town and to connect the results from the various geophysical surveys next to the spring to the large scale geology around Pagosa Springs.

2.3.2 Theory

A gravity survey operates on the principle of Newton’s Law of Universal Gravitation:

\[ F = \frac{G m_1 m_2}{r^2} \]  \hspace{1cm} (2.8)

which states that every particle is attracted to one another with force \( F \) (in Newtons) proportional to the product of the two masses \( m_1 \) and \( m_2 \) (in kg) divided by the square of the distance between their centers \( r \) (in meters). \( G \) is the gravitational constant. The CG-5 meter chosen for this survey uses a mass attached to a spring to calculate the gravitational acceleration (see Figure 2.24). If the mass attached to the spring and the force pulling down on it is known, it is trivial to calculate acceleration from Newtons Second Law

\[ F = ma \]  \hspace{1cm} (2.9)

which relates force \( F \) (in Newtons) to the product of mass \( m \) (in kg) and acceleration \( a \) (in m/s\(^2\)). Mass is dependent on both density and volume, so the forward model needs to constrain both properties to accurately create a model of the subsurface. The CG-5 automatically rejects data points in its survey outside a certain standard deviation, replacing them with additional points as necessary and never listing these points (referred to in this paper as rejections). These rejections serve as a useful proxy to understand the overall quality of the data points at that location, allowing the operator to take more measurements as necessary.
Figure 2.24: General diagram of a CG5-like gravimeter. In the case of the CG5, all inputs are digital. [15]

Intrinsic in these equations are the problems associated with gravity data. Since the force of gravity is inversely proportional to the square of the distance between the center of two objects, the gravity reading decreases exponentially as the CG-5 gets farther away from Earth’s center due to topography. This is why uncorrected gravity data inversely mirrors topography and needs to be corrected for topographic changes using very accurate GPS measurements.

Throughout the day gravitational acceleration changes due to both instrument and tidal drift. Tidal drift is variations in the positions of the sun and moon relative to the earth and the effect their own gravity has on the meter. Instrument drift is due to temperature fluctuations within the CG-5, spring fatigue, and other factors. To correct for this, a location is chosen at which a measurement is taken every 2 hours. This allows for comparison of changes in readings at the same location over time.

Although it is possible to create a numerical model and perform inversion on gravity data, the technique was not used for this data set. Instead, a forward model was built using information from local geology, well bore data, and seismic profiles to constrain the parameters of the model, density and geometry.

### 2.3.3 Objectives

1. Gather gravity data along CR200 and CR411 in Pagosa Springs, CO and conduct a 3D survey grid at the Downtown Recon site next to the Mother Spring
2. Perform data corrections on all data including drift, free air, latitude, and total Bouguer corrections
3. Generate a model of the geologic subsurface north of Pagosa Springs
4. Integrate the geologic model into past years' models
5. Create a 3D model of water flow and geology next to Mother Spring
6. Compare the 3D model with the one generated in 2012 and evaluate changes

2.3.4 Equipment and Survey Setup

2.3.4.1 Equipment List

- Scintrex CG-5 Gravity Meter
- Scintrex leveling stand
- Soft Shell carrying case
- Umbrella: *to shield the meter from wind*

![Image of Scintrex CG-5 gravimeter on the leveling plate](a)
![Image of top view of the screen](b)

*Figure 2.25: The Scintrex CG-5 gravimeter on the leveling plate (a) and a top view of the screen (b).*

2.3.4.2 Location

Relative survey lines were conducted along two roads, CR411 and CR200. A 3D grid was also conducted next to the Mother Spring downtown. This site was termed the Downtown Recon site. Another line was completed from the south end of the CR411 survey line through town terminating at the Downtown Recon site. A map of where each site is located is shown in Figure 2.23.

2.3.4.3 Survey Parameters

- Read time: 20 seconds
- Cycles: 1
- Start Delay: 3 seconds
- Measurements per Station: minimum of 3
- Variable station spacing: See each line section for specific spacings
- Other parameters: No ‘Tidal Correction’, no ‘Terrain Correction’, no ‘Seismic Filtering’ in the setup menu. Set ‘Continuous Tilt Correction’ and ‘Auto Reject’ to ‘Yes’.
- Survey lines were set to ‘1’ and ‘2’ based on meters 1 and 2, not survey line names. This aided in combining datasets later.

The parameters here are finalized survey parameters. Initially a denser survey was designed and implemented, but time constraints and input from Dr. Richard Krahenbuhl led to a less dense model that would still have sufficient resolution but be completed sooner. CR200 had 40m spacing between measurements from flag 1969 to flag 2000. All other spacings on CR200 and on CR411 were 80m. Further into town a denser spacing was utilized to capture a higher
resolution of the area surrounding the Mother Spring and the San Juan River (CR411 extension and Recon Site). 40 meter spacing was chosen because, due to the nature of gravity, all physical features at all points would affect all data points. Thus all but very localized anomalous bodies can be imaged with the 80m spacing. Such localized anomalies were not anticipated on the mainlines.

2.3.4.4 Procedure and Acquisition

Surveyors completed the survey lines north of town using a 'leapfrog' technique. One CG-5 gravimeter was assigned to odd flag numbers and one to even. To begin data acquisition each day, a base station reading was taken. Measurements were then taken along the line with surveyors returning to the base station within three hours to account for tidal and instrument drift. For the CR411 line the base station for the entire line was flag 4000. For the CR200 line it was flag 2200. For each reading, a minimum of 20 seconds was used to take at least three readings per station. In the case of strong winds, cultural noise, or otherwise excessive standard deviations or sample rejections, additional readings were taken. The value with the best combination of low standard deviations and rejections was used in processing. Ideal standard deviations were below 0.01 mgals. Ideal rejections were below 6.

When taking a reading, the surveyor placed the stand on relatively level ground then pressed down with body weight. The CG-5 was then placed on the stand and leveled manually before measurements were taken. A painted mark showed where the center of the base should sit. It was important to reuse this mark each time as the meters are accurate enough to changes in elevation down to 3cm. Each measurement was recorded both on the instrument and by hand. The notebook values recorded the gravity value, the standard deviation, station number, time, and comments about that data point.

2.3.5 Processing

Because surveyors took multiple measurements at each station for accuracy, lower-quality records needed to be trimmed so that only the best record for that point remained. After downloading each day's collected data and importing into Microsoft Excel, one record from each station was chosen based on median value or the combination of best rejections and standard deviation. Once the index contained only unique records, each point was corrected for instrument and tidal drift using the following equation:

$$\Delta g_D = g_i - \frac{g_{i+1} - g_i}{t_{i+1} - t_i} (t - t_i) - g_1 \text{ mGal}$$

(2.10)

where $g_D$ is drift-corrected gravity, $g_i$ is the raw gravity value, $g_1$ and $g_{i+1}$ are the base station observations at times $t_i$ and $t_{i+1}$ respectively, and $t_i$ is the time of the raw gravity measurement. The data were then plotted as a preliminary quality check to assess any major issues, such as large amounts of missing or outlying data.

The rest of processing took place at the Colorado School of Mines campus and began with tying data from both CG-5 units together. Each meter recorded gravity that is offset from the other. One CG-5 records gravity in the low-4,000 mGal range, the other in the low-3,000 mGal range. This manifested itself as small, high frequency offsets that may have resulted in misinterpretation. To correct for this, one meter was level-shifted to be in alignment with the other based on a single data point recorded each day by both meters and compared.

As gravitational force changes inversely with distance from center of mass (Earth in this case), a free-air correction accounted for our elevation above sea level. The free-air gradient equation uses Earth’s radius and gravity at sea level but can be expressed by the scalar multiple -0.3086 times elevation above sea level (in meters):

$$\Delta g_{FA} = -\frac{2h}{R} g_0 \Rightarrow -0.3086h \text{ mGal}$$

(2.11)

It is typical to apply this correction in conjunction with a simple Bouguer correction, which corrects for the gravitational pull of additional mass above sea level. A simple Bouguer correction
simplifies the underlying geology to a horizontal slab of averaged density with a thickness equal to the depth of the measurement point to sea level. This equation can be expressed as the product of the constant 0.04191, the desired density $\rho_B$ in g/cm$^3$, and height above sea level in meters:

$$\Delta g_S = -2\pi\gamma \rho_B h \Rightarrow 0.04191h \text{ mGal} \quad (2.12)$$

A latitude correction accounts for differences in gravitational acceleration with respect to the equator. As Earth is not a perfect sphere and wider at the equator, gravitational acceleration there is lower than at Earth’s poles. This effect creates a discrepancy of approximately 0.8 mGal/km when moving north or south. This effect is calculated with the equation

$$\Delta g_L = g_e (1 + \alpha \sin^2 \phi + \beta \sin^4 \phi) \text{ mGal} \quad (2.13)$$

where $g_e$ is gravity at the equator, $\alpha$ and $\beta$ are constants, and $\phi$ is latitude in degrees. However, for a small survey requiring only a moderate degree of accuracy, this equation can be generalized to the simpler

$$\Delta g_L = 0.001626 \sin \phi \cos \phi \Delta y \text{ mGal} \quad (2.14)$$

where $\Delta y$ is meters north of a reference point (the base station in our case).

Finally, a terrain correction is applied. The terrain correction and simple Bouguer correction together make up the total Bouguer correction. This total correction deals with the excess or deficient mass unaccounted for in the simple Bouguer correction, which treated the earth as simple slabs without terrain features like hills and valleys. This is done through software by way of integration

$$\Delta g_T = -\gamma \rho_B \int \int |h_0 - h(x',y')|\frac{h'}{((x' - x)^2 + (y' - y)^2 + h'^2)^{3/2}} dh'dx'dy' \quad (2.15)$$

where $h$ is surface elevation and $h_0$ is elevation of the observation point to be corrected. While a spreadsheet program performs most of the above data processing, the full Bouguer correction requires more calculation and was performed in GM-SYS in Oasis Montaj. An illustration of the total Bouguer correction process can be seen in Figure 2.26.

![Figure 2.26: Contributions of mass above sea level and terrain on a gravity measurement and corrections for each](image)

The next step in processing was to create a model for each survey line in GM-SYS, a software extension of Oasis montaj. This model took as input our knowledge of local geology, well logs, and seismic data and simulated a gravity response representative of those geometries and densities. The modeling process began with creating a simplified section with basement rock and an overlaid sediment layer representing all other layers. This allowed for a first order match to the data. The model was then fine-tuned by adding in each of the other layers and varying their thicknesses between the known points as necessary. The generated response was then compared to actual data, and the two were studied for correlations paying particular attention.
to discrepancies in the two responses. As our simulated geologic profile is only generalized using well bores, actual geometry very likely varies in between the bores and includes features like faults, which may provide information about transport of geothermal fluids.

2.3.6 Error/Uncertainty

Sources of error in gravity data begin with the equipment. Like other gravity meters, the CG-5 is extremely sensitive by design. Improper handling can cause calibration issues. Extreme temperature changes or even a bumpy car ride can introduce errors into subsequent measurements until the unit is able to recalibrate. Our survey lines included two long stretches of county road that made driving a necessity, and the machines were not always able to settle before measuring. The meters must also sit level in order to take an accurate reading of only gravity's z-directional component. If at any time the unit was sitting at an angle, the measurement was less accurate. Significant mass movement or other vibration like a passing car can affect or even ruin a measurement. A related source of vibrations on the meter was wind. Even wind on a bush or tree near the meter can cause noise that could be transferred to the data. Error from this was prevented by shrouding the CG-5 from the wind using a large umbrella. However, winds grew stronger over the course of data collection from flags 2252 to 2296 on CR200, and one meter’s measurements had to be adjusted to be more in line with the meter, which was better shielded. Another significant source of error during processing is the limitation of our processing data, GM-SYS in Oasis Montaj, in that it can only effectively model a two dimensional survey line. Given that both lines, especially that along CR200, have very large turns, significant artifacts of this would remain in the corrected data such that we can’t effectively correct. The further a given area strays from a straight line, the greater this artifact. Much of our final model’s calculated error would arise from this source.
2.3.7 Results

2.3.7.1 CR200 Line

The data for the CR200 Line shows a gentle dip in gravitational response moving north along the survey line (left to right in the figure). Below the line is an overlay of the geological cross-section developed for the area for reference. The large spike midway through the plot is likely attributed to equipment error and is discussed in the error section below.

Figure 2.27: CR200 Line gravity profile with data points in black dots, model fit in black line, and error in red
2.3 Gravity

2.3.7.2 CR411 Line

The CR411 line in Figure 2.28 should show less of the dip seen in the CR200 line as it runs more along geologic strike. The gravity model corroborates this conclusion, showing a gentle dip and a less-pronounced increase in Mancos Shale. Eight Mile Fault is displayed on the far left of the model as well.

![CR411 Line gravity profile with data points in black dots, model fit in black line, and error in red](image)

**Figure 2.28: CR411 Line gravity profile with data points in black dots, model fit in black line, and error in red**

The CR411 line in Figure 2.28 should show less of the dip seen in the CR200 line as it runs more along geologic strike. The gravity model corroborates this conclusion, showing a gentle dip and a less-pronounced increase in Mancos Shale. Eight Mile Fault is displayed on the far left of the model as well.

2.3.7.3 Student Site

At the Downtown Recon site a 3D gravity grid was created. Shown in Figure 2.29 is the fully corrected grid. There is a consistent gradient running North-East with the relative gravity increasing by about 0.3 mGal per 100m with few anomalies. Further integration with other methods is needed to determine the cause of this gradient. It is not related to any topography.
2.3.8 Interpretation and Conclusion

2.3.8.1 Interpretation

The initial geologic profile of the Pagosa Springs region showed a gentle (below 5 degree) dip to the northeast. The gravity data profiles support this, but there is a slight syncline-like structure in both. In both cases this is likely an artifact of curves in the line following the roads surveyed. Overlaid in Figure 2.27 is the preliminary geologic profile, showing turns in the profile with dotted lines. These correspond roughly to where the gravity model deviates from the preliminary column. In general the gravity model corresponds to a gently dipping stratigraphic area with a thickening layer of less-dense Mancos Shale at the surface and a deepening basement boundary.
Faults and other subsurface changes are not modeled here but become possible if matched to other data such as magnetotelluric or seismic imaging. These methods were also used to fine-tune the models to better fit the data with a precision not possible with gravity alone.

2.3.8.2 Conclusion

Surveys were conducted to characterize the geology north of Pagosa Springs and around the Mother Spring. Collected data can be correlated with data from past years as well as seismic imaging of the same line, confirming the geology with some accuracy. However, a 3D water model near the spring would require further data and other methods to differentiate between water flow and travertine deposits immediately adjacent to the Mother Spring. It is recommended that further surveys be conducted around the Mother Spring and to conduct linear gravity surveys in straight segments processed separately so as to remove three-dimensional artifacts.
2.4 DC Resistivity and Self Potential

Figure 2.30: Total survey area for DC and SP on CR411 and CR200
2.4 DC Resistivity and Self Potential

2.4.1 Introduction

The direct current (DC) resistivity method is a geophysical method used to understand the structure of the subsurface based on the formation’s electrical properties such as impedance or resistivity. These electrical properties determine how electrical current flow reacts to a material. DC resistivity is an active geophysical method, which means the surveyor applies a controlled direct current into the ground and measures the potential difference along the survey area. The data collected can be used to analyze the subsurface response due to electrical current flow. To make it easier to interpret the collected data, the surveyors use the measured potential differences to calculate the apparent resistivity values of the subsurface.

The self potential (SP), otherwise called spontaneous potential, method is very similar to the DC resistivity method; the main difference between the two methods is the fact that SP is a passive method, which means that the surveyors measure naturally occurring electric potential differences instead of injecting a controlled electric current into the ground.

DC Resistivity method is typically used to estimate depth of water table and bedrock, detect and map geologic features, and outline aggregate deposits. Likewise, SP method is generally used to find massive ore bodies near the surface and underground water flow.

2.4.2 Theory

2.4.2.1 DC Resistivity

DC resistivity is an active source electric geophysical method that measures the change in electric potential caused by injection of current into the subsurface. The current moves through conductive bodies which creates a change in voltage that depends on the resistivity of the formations and conductive bodies. Using Ohm’s law, electric current (I) is controlled, voltage (V) is measured, and electrical resistance (R) is solved for.

\[ V = IR \]  
(2.16)

However, the values initially obtained are only apparent resistivity. As current flows through a half space (the subsurface), the value obtained is simply the average resistivity of that area, meaning local differences in resistivity will affect the value at each data point. The equation for apparent resistivity is as shown:

\[ \rho_a = \frac{V}{I} \frac{2\pi k}{\pi} \]  
(2.17)

where \( \rho_a \) is apparent resistivity, \( V \) is voltage, \( I \) is electrical current, and \( k \) is general geometric factor. It is also important to note that resistivity is inversely related to conductivity (\( \sigma \)) and thus can be used interchangeably.

\[ \sigma = \frac{1}{\rho} \]  
(2.18)

Current is injected into the ground through electrodes and flows through the subsurface from the transmitter electrode (A) to the receiver electrode (B) while the voltage difference is measured across two separate electrodes (M and N). DC surveys can be set up in various configurations as electrodes are staked into the ground along a line and connected to a cable that current is run through. The cable is plugged into an instrument that outputs the current, reads voltage differences, and controls the electrode configuration. Which electrodes transmit, receive, and measure can be modified to fit the needs of the survey. These configurations of electrodes are known as arrays; some array types include Dipole-Dipole, Schlumberger, and Wenner, which was used in all surveys.
The geometric factor, $k$, comes from the array type along with the assumption that current is flowing through a half space which has the geometry of a half sphere. The base equation for the geometric factor is shown below where $a$ is electrode spacing. In a Wenner array, four electrodes are used in one measurement. The outer two electrodes are the transmitter and receiver (A and B) while the inner two measure the voltage difference (M and N), the spacing between every electrode is constant and is referred to as “a”. The four electrodes used can be changed to get data points over a distance and their spacing can be increased in order to record a voltage deeper in the subsurface. The spacing between electrodes staked into the ground does not change; however, electrodes can be skipped in order to increase the spacing. The geometric factor for a Wenner array is:

$$k = \frac{1}{2\pi a}$$

(2.19)

The current emitted in a DC survey comes in the form of a square wave with alternating polarization; meaning current will flow, stop, then oppositely polarized current will flow and then stop again. This is done in order to avoid charge buildup within the subsurface. This prevents the reading in of the charge-ability of the electrodes instead of the apparent resistivity of the subsurface.
2.4 DC Resistivity and Self Potential

While apparent resistivity provides useful information in order to give a general idea of the subsurface, as stated previously, the values are not the true resistance at each point. Furthermore, as station spacing increases, the distance between electrodes is not the actual depth of investigation. However, a true resistance model can be generated through inversion.

2.4.2.2 Self Potential

The SP method is a passive geophysical method that measures the naturally occurring potential difference between two points on the surface caused by naturally occurring electrical current flow in the subsurface. The electrical current flow is the result of electrochemical reactions in the subsurface, generally caused by movement of ions in fluid, buried metals or metallic ore bodies, and electrons’ shift during induction. Since one of the causes of naturally occurring electrical current flow is the movement of ions in fluid, SP is a valuable method for finding underground water flow. Ore bodies interacting with groundwater create redox reactions, leading to the movement of ions and essentially creating natural batteries. The movement of fluid in the ground, specifically groundwater, or in this case spring water, creates electro-kinetic potential. The fluid carries electrolytes and ions through the subsurface, and the moving charges create potential differences that can be measured on the surface. The electro-kinetic potential generated by the ends of a capillary passage is given by the equation:

$$E_k = \frac{\left(\epsilon \rho C_E \Delta P\right)}{4\pi \eta}$$

(2.20)

where $\epsilon$ is the dielectric permittivity of pore fluid, $\rho$ is the electrical resistivity of pore fluid, $C_E$ is the electro-filtration coupling coefficient, $\Delta P$ is pressure difference, and $\eta$ is the dynamic viscosity of pore fluid.

This interaction allows us to measure the voltage difference in different areas of the surface, usually on the scale of millivolts (mV), and create a voltage contour map of the survey area. This voltage contour map can potentially reveal the path of groundwater in the subsurface: that is why SP is such a valuable method.
2.4.3 Objectives

1. To gain experience setting up and running DC resistivity and SP surveys methods in the field, as well as processing the data.
2. Verify the validity of geological interpretations by comparing results from DC, SP, and other methods.
3. Identify any traces of water flowing to and from the Mother Spring with the DC/SP method.

2.4.4 DC Equipment and Survey Setup

2.4.4.1 Equipment List

- ABEM control unit [16]
- 7 ABEM cable connectors
- 8 ABEM electrode cables
- 64 electrode stakes
- Electrode cables:
  Connects the electrodes to the ABEM electrode cables
- Switch Box:
  Connects the two lines of ABEM electrode cables
- 12V Car Battery:
  Power source of the ABEM
- Hammers:
  To hammer in electrodes
- Saltwater:
  For failed electrodes during testing
- Road guards:
  For cables in driveway

Figure 2.33: Image of the ABEM control unity used in the field for the DC Resistivity method.
2.4.2 Location

The extent of the DC resistivity surveys can be seen in Figure 2.30. It ran along both main lines on CR200 and CR411.

2.4.3 Survey Parameters

Both DC resistivity surveys utilized the same setup with Wenner arrays. After changing the mode to "resistivity" and creating a new data file, specifications can be made to the survey parameters. These include: station spacing set to 20m, power line frequency set to 60Hz, midpoint set to 0, array type set to "Wenner 64 XL", link direction set to up, square wave current set to 200mA, acquisition delay and time set to 0.3s and 0.5s, minimum amount of stacks set to 2 and maximum set to 5, error limit set to 2.5%, and random error set to "Ignore". Stacks indicate the amount of times to take a measurement at a specific location, in which the standard deviation is calculated. If the standard deviation is less than the error limit, the data is accepted. If not, the ABEM continues until the max stack value (set to 5) is reached.

2.4.4 Procedure

To set up the DC resistivity survey, the 8 ABEM electrode cables were initially spaced out 160m (16 flags) apart, 64 electrodes were planted at 20m spacing, and electrodes were connected to the ABEM electrode cable. The cable connectors link the ABEM electrode cables with the ABEM and switch box, which are located at the center of the survey line for simplicity. The ABEM should be connected to two cables at the center of the survey (between cables 4 and 5). After making all of the necessary connections, powering on the ABEM using the car battery allows for the selection of survey parameter specifications.

After setting up the ABEM with the desired parameters, testing the electrodes was the next step in completing our survey. To run this test and troubleshoot electrodes the ABEM sends currents to pairs of electrodes down the line. If it comes to an electrode that failed, the ABEM will continue to test other electrodes and send current from the good electrodes to the failed electrode(s) for validation. These electrodes will come up as failed until fixed. They can be fixed by hammering the electrodes deeper into the ground, pouring saltwater in the immediate area, and checking for disconnections. We ignored electrode locations on driveways (invasive to landowners) as well as electrodes we could not fix, which is reflected in the resulting pseudosection. The survey could then be performed after troubleshooting electrodes.

The first data collection on a line usually took the longest because we were performing a roll along. This means that after the initial line is surveyed, the first two ABEM electrode cables are disconnected and added to the front of the line. For example, cables 1 and 2 are added after cables 7 and 8. The ABEM is then shifted up the line to the center of the survey line, and is run again. This time, since the ABEM uses the previous data, the ABEM only needs to get apparent resistivity values for the new combinations with the added cables. This extends the horizontal length of the pseudosection created with the original line locations.

2.4.5 SP Equipment and Survey Setup

2.4.5.1 Equipment

- Non Polarizing Electrodes [17]
- Connector wires
- Voltmeter:
  - To measure the voltage difference in the ground
- Rock hammer:
  - To create holes with sufficient ground contact
- Flags:
  - To mark survey grid
- Measuring tape:
  - To create survey grid
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- Saltwater:
  Same reason as DC

![Image of the non-polarizing electrode and voltmeter used in the field.]

2.4.5.2 Location

Below is the Bank and Spring SP surveys performed at the Mother Spring Recon Site. Both surveys were located at this site to determine the location of any water that is running underground, possibly water that is running to and from the Mother Spring.

![Figure 2.35: This map shows the GPS coordinates for the SP Mother Spring Recon Site.]

![Figure 2.36: This map shows the GPS coordinates for the SP site south of the Mother Spring Recon Site.]

2.4.5.3 Survey Parameters

The northern SP survey had a grid spacing of $10m$ and dimensions of $80m \times 100m$, while the southern SP survey had a grid spacing of $2m$ and dimensions of $16m \times 16m$. The southern SP survey was not a complete grid because of the marsh located in the immediate area. These areas were avoided, and were assigned a value of 0 when processing so the data in this area is not extrapolated from the collected data.

2.4.5.4 Procedure

SP is a quick and inexpensive geophysical method used to find water underground and involves utilizing two non-polarizing electrodes connected to a multimeter. SP is a passive method, and uses natural occurring electric fields to measure potential difference. It is important that we use non-polarizing electrodes, this way the voltage difference in the ground can be measured rather than the voltage difference created in the electrodes.

Picking a base point is the first step in performing an SP survey. The survey grid can then be created by making a $16m \times 16m$ grid with $2m$ spacing (creating a 9 by 9 data grid). Before doing anything else, SP requires that a tip to tip measurement is taken between electrodes to account for instrumental drift. Record this voltage reading from the voltmeter by hand for later use, and bury the reference electrode at the base point. Connect the longer wire from the reference electrode and the roaming electrode to the voltmeter. Dig small holes with the rock hammer to expose the dirt underneath at each point in question (to ensure good contact) and measure the potential difference in the ground with the roaming electrode. Since the voltage value rises and falls, wait for about $10s$ and choose a value within the range of voltages shown to record.

2.4.6 DC Processing

2.4.6.1 Procedure

DC resistivity data was first preprocessed by downloading data for both lines from the ABEM. The raw data files were converted with an SAS4000 converter tool, resulting in two processed .dat files which contained three columns of data: “A” electrode positions, electrode spacings, and apparent resistivity values. This format is accepted by certain inversion programs such as Res2Dinv, but it is not useful for other inversion programs. A script was written in Python to extrapolate all electrode positions and elevations from these .dat files by correlating the electrode positions with the GPS coordinates of the corresponding flags. Additionally, measurements with unreasonable apparent resistivity values (such as measurements with very large resistivity values in comparison to surrounding points) were also removed in preprocessing.

Once the data was transferred into a more usable file format, it was inverted with a modified 2.5D DC inversion program from SimPEG [18]. In this context, 2.5 dimensions is used to imply model invariance in the direction perpendicular to the survey line. The Python script modifications allowed for a custom “tree” discretization of the model space, with finer spacing between nodes near the surface and coarser spacing between nodes near the bottom of the model where the data is nearly invariant [19]. The modifications also accounted for topography in the discretization as well as accounted for the elevation of the electrodes when running the inversion scheme. The inversion script used a process of beta cooling (beta being a variable describing certainty in the model prior to incorporating new data) to find the optimal point where both data and model misfits were minimized. By doing this, prior information about the conductivity model from apparent resistivity values is balanced with the observed data.

Significant difficulty was encountered when first attempting to perform the DC inversions on both lines using SimPEG. The code does not natively support Wenner arrays, so initially pseudosections for our data could not be plotted. Another difficulty we encountered was properly incorporating elevation and topography into the inversions. At first, the model did not properly follow the incorporated topography, leading to a ghost image in the inverted model which was not indicative of geologic changes in the subsurface. Both of these issues were corrected by a TA, and if possible, next year’s DC group should reuse his code base now that these bugs have been ironed out.
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2.4.6.2 Errors/Noise

One of the assumptions we make when running a DC resistivity survey is that we are working in a half-space, which means that the topography we are working on is presumed to be flat. Thus, hills create this space above the electrodes and make the data falsely reflect conductive bodies. In this half-space we are making a 2D profile and our winding survey lines (along CR411 and CR200) are assumed to be straight. This is misleading because the information we are getting is not part of the same plane, and instead is part of a couple of different planes at best. Another error that appears with 2D profiling is the fact that conductive bodies that exist on the sides of the survey will appear in the results (leading to fake anomalies). Other errors that we see in our data can be due to electrode failures that cause missing data points along with water pipes or creeks that flow below our survey lines.

2.4.7 SP Processing

2.4.7.1 Procedure

Processing the SP data began with formatting the data we collected from the field into a grid form that Surfer could accept. For points where data could not be taken (hard rock or water) zeros were added. Most of the data on the northern Mother Spring Recon Site was good, however a lot of the survey for the marsh site by City Hall has missing data and is shown in Figure 2.41. After the zeros were added, drift and shift corrections were performed. The drift correction accounts for instrument drift that occurs throughout the day. It is a linear correction that makes the data collected later in the day align with the data collected in the morning. This is calculated by conducting multiple tip-to-tip measurements of the electrodes. The amount of change is then subtracted from the data normalizing it. Data from the site near City Hall only needed a drift correction because it was all done in one day, but data from the Mother Spring Recon Site needed a drift and a shift correction. The shift correction links data taken on to different days. There is often a repeat line taken, and the difference between the first days data and the new data is added to the new set.

2.4.7.2 Errors/Noise

One source of error for SP data is that if the electrodes do not have a strong enough contact with the ground, there will be too much contact resistance and an accurate measurement will not be able to be taken. Another error that would affect the data is if current is being put into the ground from a DC survey nearby or power lines are in the area.
Figure 2.37: The base line at the bank site plotted with error bars. The typical error for this site was 2.44mV.

Figure 2.38: The J line at the mother spring site plotted with error bars. The typical error for this site was 9.30mV.

Figures 2.37 and 2.38 show the uncertainty calculated for both sites. During the survey the students retook measurements of a specific line on the survey site. This allows for repeatability in the measurements as well as error calculation. The error was calculated by taking the standard deviations at each point on the repeated lines. They were then averaged and divided by the square root of the number of repeated measurements.
2.4.8 Results

2.4.8.1 DC

The inverted data for CR200 is close to what we were expecting the geology to look like with the majority of the area being covered by the Mancos Shale. There are some hyperbolic features that can be seen in the data which is due to the fact that we conducted a 2-D inversion over a curved line. Ideally a 3-D inversion would be completed on the data to eliminate this error but the software is not readily available. If this were to be completed we would expect the more resistive layer to be consistently flat as this is most likely the Dakota sandstone.

The data collected for CR411 is somewhat what we expected but has much more noise due to
the amount of curves in the road. If we look beyond this however, a layered structure is hidden underneath. Near the north end of the line we see large resistive anomalies which were not expected.
Figure 2.41: Voltage contours at the southern end of the Mother Spring Recon Site in the marshy area near City Hall and the police station.
As shown in Figures 2.41 and 2.42, the SP sites conducted near the Mother Spring contain a wide range of voltage contours within the areas. Large negative voltage values represent water flowing upwards in the subsurface while positive values represent water flowing downwards. High voltage values, positive or negative, represent water flow due to the ions carried in the water create current in the subsurface which can then be measured through voltage values at
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Notable areas of interest within the plots are areas of voltage change along with the area in the 2.42 near the mother spring of high negative voltage value.

2.4.9 Interpretation and Conclusion

2.4.9.1 DC Resistivity Interpretation

Based on the geology of Pagosa Springs and the depth of investigation of the DC surveys, the expected data for both CR200 and CR411 should show a less resistive layer above a more resistive layer, marking the boundary between the Mancos Shale and the Dakota Sandstone. However, the general trend on the CR411 resistivity data shows instead a lateral change from south to north, with the majority of the subsurface becoming more resistive as the survey extended to the north. The CR200 data is closer to what we would expect, as the dip of the geologic layers leads to the Dakota Sandstone falling below the depth of investigation as the line moves north, leaving only the conductive Mancos Shale. The CR200 data does become more conductive as the line moves north, but the shift from resistive media to conductive media occurs somewhat drastically around 2250 meters along the line, in contrast to the gentle dip of the geology.

The inverted resistivity model also features many tight parabolic features which are likely artifacts from the various bends in the road, rather than actual geologic features in the subsurface. The inversion scheme we used assumed a straight line when performing the inversion, but because both CR200 and CR411 bend, our survey line is not straight. CR411 in particular has sharp bends around where the high log resistivity values of $4 \Omega m$ (These artifacts could be corrected by running the data through a proper 3D inversion rather than a 2.5D inversion; however, such processing is outside the scope of what we could accomplish during the two weeks we had to process the data and run the inversions.

2.4.9.2 Self Potential Interpretation

As stated above, the SP surveys performed in the two locations will indicate the presence of water flow as either large positive or negative voltage values. The marsh site (Figure 2.41) contains mostly areas of negative voltage with some areas of positive values. However, none of these values are of enough significant value to be interpreted as anything beyond background voltage for the area. The distant location from the Mother Spring would explain this lack of activity. While the marsh site does not provide any useful insight into the hydrothermal activity of the area, it does inform future groups that further investigation of the site is not necessary.

Compared to the bank site, the spring site (Figure 2.42) contains multiple areas of interest, notably the two areas of high negative voltage in the northwest corner and the southern region. Since both of the two points are much higher in value compared to the rest of the data in both surveys, these two areas are two spots in which water is moving upward through the travertine, possibly towards the Mother Spring. Further investigation of this area may provide more results as to how water in the subsurface behaves locally near the Mother Spring.

2.4.9.3 Conclusion

In conclusion our DC and SP surveys in Pagosa Springs were successful in giving us a better understanding of the geology in the area. For the most part, the data was what we expected, showing the conductive Mancos Shale above the more resistive Dakota Sandstone. We successfully gained knowledge in the implementation of both DC and SP surveys, as evidenced by the quality data that was gathered in both methods. In terms of our overall goal to determine water flow to the Mother Spring, our DC surveys were less helpful than we were hoping them to be, showing no apparent conductive anomalies. Our SP surveys were more successful in that regard, showing water flow towards the Mother Spring in areas with known crevasses, suggesting a possible method of travel. If possible, in the future we suggest trying to get as much data as possible near the Mother Spring, as this is where the spring system is the shallowest. We also suggest begging the department to buy you a 3D inversion software because this would greatly increase the quality of our results.
Figure 2.43: Total survey area for MT in Pagosa Springs
2.5.1 Introduction

The magnetotelluric method (MT) is a passive electromagnetic survey method which uses naturally occurring electromagnetic waves from the Earth’s atmosphere to image the conductivity properties of the subsurface. This method alone can be used to derive layered conductivity models, which can identify areas of anomalously high conductivities, outline possible faults, and supply information about the layering structure of the subsurface.

2.5.2 Theory

As a passive method, MT relies on naturally time-varying electric and magnetic fields to act as a source for EM induction. EM waves propagate from the atmosphere to the subsurface in a planar wave field over a wide band of frequencies. Higher frequencies are produced by thunderstorms in the tropics while lower frequencies come from solar storms, radiation, and general solar interaction with the ionosphere [20].

The creation of a magnetic field from moving charges (the situation of a thunder or lightning storm) is possible via

\[
\nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t}
\]

(2.21)

\[
\nabla \times \mathbf{B} = \mu_0 \mathbf{J} + \mu_0 \epsilon_0 \frac{\partial \mathbf{E}}{\partial t}
\]

(2.22)

Where \( \mathbf{E} \) is the electric field, and \( \mathbf{B} \) is the magnetic field, \( \mu \) is the magnetic permeability (H/m), and \( \epsilon \) is the dielectric permittivity (F/m). These equations show that the magnetic and electric fields are coupled, and thus a change in one will invoke a change in the other.

The relationship between the electric and magnetic fields describes impedance (Z). Since we measure both of these fields, impedance is our mathematical gateway to discovering information about the subsurface resistivity. Physically, it describes the effective resistance of an electric circuit (here the Earth is our resistor). Impedance is represented by a four-component tensor

\[
Z(\omega) = \begin{bmatrix}
Z_{xx} & Z_{xy} \\
Z_{yx} & Z_{yy}
\end{bmatrix}
\]

where the individual components are described by

\[
Z_{ij}(\omega) = \frac{\mu E_i(\omega)}{B_j(\omega)}
\]

(2.23)

where \( i,j = \{x,y\} \).

We can represent the electric and magnetic fields in the frequency domain in terms of conductivity, depth and magnetic permeability.

\[
E_i(\omega) = E_i(0) \exp(-\sqrt{i\omega\mu\sigma z})
\]

(2.24)

\[
B_j(\omega) = B_j(0) \exp(-\sqrt{i\omega\mu\sigma z})
\]

(2.25)

which when substituted into equation 2.23 becomes

\[
Z_{i,j}(\omega) = \sqrt{\frac{i\omega\mu}{\sigma}}
\]

(2.26)

Further,

\[
\rho = \frac{1}{\sigma}
\]

(2.27)

so by using equation 2.27 to rearrange equation 2.26, the apparent resistivity can be solved for as in equation 2.28

\[
\rho_a(\omega) = \frac{|Z_{ij}(\omega)|^2}{\omega\mu}
\]

(2.28)
Additionally, since the impedance is a complex value, the phase (angle between the real and imaginary parts, $\phi$) of the impedance must be calculated.

$$\phi(w) = \arctan \left( \frac{\text{Im}(Z_{12}(w))}{\text{Re}(Z_{12}(w))} \right)$$

(2.29)

As EM waves of different frequencies propagate into the Earth, they will produce resistivity changes for the geologic layers’ different depths. For example, higher frequencies will give resistivity information about nearer-surface layers while low frequencies will be useful for deeper layers. This is predictable following the equation for skin depth ($\delta$):

$$\delta = \sqrt{\frac{2}{w\mu\sigma}}$$

The signals received from the sun and lightning storms will contribute different frequencies. Since neither of these sources create signals at all frequencies, there is a frequency band for which we have less information. This range of values for which fewer frequency signals exist is called the dead-band. Due the the existence of the dead-band, there will inevitably be unreliable data coherency for some frequencies that will contribute a small source of error to the overall measurement.

### 2.5.3 Objectives

Similar to previous years’ attempts at locating the geothermal source in Pagosa Springs, groups using MT worked to:

- **Derive a conductivity model of the subsurface of the Earth using inversion software to locate areas of high conductivity which may be tied to the source of the Mother Spring in Pagosa Springs.**
- **Use 1D inversion models to calculate the depth to basement at each site location.**
- **Use 2D inversion models to locate areas of high conductivity/resistivity.**
- **Use a combination of 1D and 2D inversion models to locate possible faulted areas.**

### 2.5.4 Equipment and Survey Setup

#### 2.5.4.1 Equipment List

- **Metronix ADU-07e system (ADU):** Analog/Digital Unit converter that records and stores the electric and magnetic field time-series.
- **4 copper sulfate non-polarizing electrodes:** Electrodes that are stored in bentonite clay and buried in each cardinal direction to collect electric field time-series as coupled pairs.
- **3 MFS-07e induction coil magnetometers:** Magnetometers are buried horizontally in north-south and east-west directions, and sometimes a third is buried vertically in the z-direction to measure each component of the magnetic field.
- **1 stainless steel grounding electrode:** The grounding electrode connects to the ADU and is used to ensure that charges do not accumulate on the internal hardware of the ADU.
- **8 50 meter cables:** Four of these cables are used to connect the electrodes to the ADU, and extras are brought in case there were any issues with the original cables.
- **4 10 meter cables:** Depending on how many magnetometers are used in a particular survey, either two or three of these cables are used to connect the magnetometers to the ADU. Extras are brought in case there are any issues with the original cables.
• 2 12 volt car batteries:
The car battery is used to power the ADU system as well as the laptop. An extra is brought in case there are issues with one car battery.
• Field laptop:
The laptop is connected to the ADU and used to run the MT surveys, as well as set parameters and look at test data in the field to ensure all components of the survey are working properly.
• Mobile GPS:
The GPS collects coordinates of the field site and can be used for time drift corrections applied to the data during processing. The GPS system that we used connects to the ADU.
• 100 meter measuring tape:
Measuring tapes are used to ensure that each electrode is 50 meters away from the ADU system located at the center of the survey.
• Compass, shovel and leveler:
The compass is used to make sure that all components are oriented correctly, the shovel is used to bury the electrodes and magnetometers and the leveler is used to make sure that the magnetometers are completely horizontal.
• Salt water:
The salt water is used to make sure that the ground is wet and conductive when the electrodes are buried.

2.5.4.2 Location
MT surveys were conducted along the forest service road at the end of CR200 as most of these areas were located at least 500 meters away from power lines and large metal objects. The closer the MT sites are to urban areas, like Site 7 for example, the more likely it is that noise will have a more prominent effect on the data. These site locations also continue along the path of CR200, which allows the MT data to be extended to areas where other geophysical method surveys were conducted. A map of where each survey was located is seen in Figure 2.43.

2.5.4.3 Survey Parameters
2.5.4.4 Procedure
To begin acquiring MT data, survey sites must first be picked. Survey sites should be located at least 500 meters away from power lines and human activity. In an ideal case, the center point of the survey should have at least 100 square meters of clearing surrounding it, but obstacles such as trees can be avoided. After establishing the location of a site, the ADU system can be placed in the center of the survey, and a compass can be used to orient the survey in either the direction of true north or magnetic north. Once the cardinal directions are found, a measuring tape can be used to place electrodes 50 meters from the ADU, and the compass can again be used to ensure that each electrode is perpendicular to its neighboring electrode as well as the ADU. Holes can then be dug to place electrodes in. These holes should be approximately 6-8 inches deep and can have a small amount of salt water poured into them before burying the electrode. Next, magnetometers can be buried in the north-south and east-west directions to measure the x-component and y-component of the magnetic field, respectively. A leveler can be used to ensure that the magnetometers are completely horizontal before they are buried. The 10 meter cables can be used to connect the magnetometers to the ADU. A third magnetometer can be buried vertically to measure the z-component of the magnetic field, but this is not necessary and only occurred at Site 3, see Figure 2.43. The laptop, GPS, and car battery can then be connected to the ADU system and the GPS can be synced in order to achieve accurate timing data. For a complete image of the site set up parameters see Figure 2.44. On the laptop, a web page can be opened and the IP address of the ADU can be entered. "ADU General" can be selected to run a general job, or "ADU 286" can be selected to open the machine specific page. A self-test should be performed to ensure that all components are working properly. If all the components are working correctly then the survey is ready to be run.
2.5 Magnetotellurics

2.5.5 Processing

While MT is a very useful method, it is not very useful without further data processing. This is because MT is sensitive to electromagnetic waves emanating from sources up to 1 kilometer from the survey site. These external waves generate noise within the collected data due to their non-planar shape (further expansion in the Error / Noise section). This noise creates spikes within the time series of each data set. These spikes are extreme outliers within the time domain data and can skew results, therefore these spikes must be removed so that the data is only comprised of signal. Such edits can be made within the ProcMT software. To further process the data, in the case that the resistivity curve has significant jumps, computer code can be used to further process (Python was used in this study). The code generates plots of frequency. These plots can be used to locate frequencies that generated extreme outliers in the data. These frequencies can then be removed to result in plots which have no extreme outliers and only signal. These processing efforts improve the data coherency. Data coherency is a statistical value that determines how trustworthy the data is. In the 2D inversion, the terrain must be accounted for otherwise incorrect anomalies will be displayed. The following processing steps were used to process the MT data for the 2018 field session in order to remove noise from the collected data due to external forces not associated with the natural magnetic and electric fields.

To begin processing, we first downloaded the program ProcMT from Metronix. To run the program, we selected the "ProcMTGui" file from the downloaded files. To create a new file, we selected "Create Project" under the file menu. In the file folders that are located in the ProcMT files, we created an empty folder called "Processing" and selected this folder in the application. This will prompt multiple folders to populate inside the "Processing" folder which will contain information and results for processing. Next, we created a new site by selecting "Create Site" under the file menu in the application. In the file explorer, we moved the measurement files

Figure 2.44: Example of the general survey setup that was followed for the MT surveys during the 2018 field camp. This figure was taken from the 2016 Geophysics Field Camp report [21].
that were downloaded from the ADU to the appropriate site folders. The appropriate site folders can be found by selecting the "Processing" and then "ts" folders under the ProcMT files. After opening the zipped files and copying the file within them, this file was pasted in the same site folder as the zipped file and delete the zipped file. The remaining file was a measurement file with a naming convention similar to the following: "meas_2018-05-19_22-30-00." After uploading the measurement files, in ProcMT we selected the down arrow next to the site to view the file making sure the appropriate data was uploaded to each site, Figure 2.45.

![Figure 2.45: Example of ProcMT user interface with measurement data uploaded to site files.](image)

To prepare the data for processing, it must be down-sampled. This can be done by selecting a site in ProcMT, right clicking on the measurement file below it, and selecting "Filter." A new window appeared, then we selected "4x" and ran it, see Figure 2.46. A new measurement file was generated beneath the old file with a sampling rate that is \( \frac{1}{4} \)th of the original file. This process was repeated three more times to create files with sampling rates of 256 Hz, 64 Hz, 16 Hz, 4 Hz, and 1 Hz. The data was then ready to run simple processing.
To begin the simple processing, we selected the appropriate site, selected a processing filter \texttt{mt\_auto\_smooth}, \texttt{mt\_auto\_sharp}, or \texttt{mt\_auto\_med} from the processing window, and ran the job. Each site needed results from each of the processing filters. These results could be found in the "Processing" folder under "edi". To review these results, instead of re-running the program, we opened the EdiPlotter and dragged and dropped the .edi files into the application. After each site has been run through simple processing, results were reviewed using the EdiPlotter, and we choose which processing filter formulated the best curves. For the purpose of the 2018 field session, the processing filter that best fit the gathered MT data was \texttt{mt\_auto\_smooth}. Curves that appear messy or have large jumps will require further processing.

To begin further processing, we began by using the EdiPlotter to plot the results from the chosen processing filter. When looking at the plots for each site, we categorized them into good, OK, and poor results. The good results could be classified as having apparent resistivity and phase curves with no large jumps. This data was ready to be prepared for inversion, see Figure 2.47. The OK results could be classified as having apparent resistivity and phase curves with only a few jumpy sections, and the poor results contain many jumps in the curves (see Figures 2.48 and 2.49). The OK and poor results would require more processing before they were ready to be prepared for inversion.

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{fastfilter_window.png}
\caption{Image of "fastfilter" window with down-sampled file locations and parameters.}
\end{figure}
Figure 2.47: Example of "good" data plotted in the ediplotter application in ProcMT after down-sampling.
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Figure 2.48: Example of "OK" data plotted in the ediplotter application in ProcMT after down-sampling.
To further process the OK results, we viewed the time series for a given frequency and under the settings tab selected mouse selects. To speed up the process, set the window length to 8192 or 16384 for larger files. We used the mouse to mark unusual areas of the data; large spikes or odd variations that occurred in one channel but not in others. See Figure 2.51 for examples. When finished, we saved the selections. This process was done for each input frequency in the site folder. After all of the time series have been corrected, in the ProcMT program we opened the mt_auto_smooth processing for editing. Under the command line options we changed "auto bandwidth" to 8, "auto parzen" to 16, set "reject coherency less than in advance" to 0.5, used the drop-down to set "dump various to "on" and "dump raw transfer function" to "on". We turned off mt_processing_median but left _stackall and _ct checked. Under mt_processing_ct, we set the lower threshold to 0.6. We saved this edited processing with a new file name. See Figure 2.50 to visualize changes. Finally, we ran the newly created processing filter on the sites which have undergone the time series corrections. When this generated plots with smooth apparent resistivity and phase curves, the files were ready for inversion; however, if this was not the case further processing steps were taken.
Figure 2.50: Parameters used to generate new smooth processing filter.
To further process the poor results, we began by following the same steps as those for the OK results. If this did not generate smooth curves, two Jupyter/Python notebook programs were used for further editing. The first program, "Read Multiple Files," was used to convert .edi files into Excel spreadsheets. First, we transferred the most recent stack all .edi files to the folder where the Jupyter/Python notebooks were saved. The filenames resembled the following: "2.mt_auto_smooth_mt_processing_stack_all_1.edi." Next, we opened the "Read Multiple Files" Jupyter/Python notebook and typed out the file name in the second code box after "ls =." Then, in the seventh code box we named the Excel spreadsheet that would be output by typing the file name within the parentheses of "writer = pd.ExcelWriter()." being sure to include the file extension. Under the cell tab, we selected "Run All." An Excel spreadsheet of the data, as pictured in 2.52, was output in the same folder as the Jupyter/Python notebooks were stored. This spreadsheet was then uploaded into the Jupyter/Python notebook "Plotting frequencies" by typing the filename after "df = pd.read_excel()" in the second code box. Again, we selected "Run All." This generated plots for Zxx real, Zxx imaginary, Zxy real, and Zxy imaginary against frequency. Using these generated plots, we removed 2-4 outliers from the excel spreadsheet. To see these changes we simply re-ran the program with the saved spreadsheet data. This generated more usable curves, and the data was then ready to prepare for inversion.
To prepare the data for inversion, we began by using the "Read Multiple Files" Jupyter/Python notebook to generate Excel spreadsheets for sites that did not have them yet. After these files were created, several calculations needed to be run within them to calculate the square root of the period, apparent resistivity, error in the apparent resistivity, phase, error in the phase, and the log of apparent resistivity. These calculations needed to be done for both the XY and YX components. The equations necessary for these calculations are found below, and an example file can be viewed in 2.53.

To calculate the square root of the period the following equation was used:

$$ r = \sqrt{\frac{T}{f}} \tag{2.30} $$

where $f$ corresponded to the frequency.

To calculate the apparent resistivity of the XY components, the following equation was used:

$$ p_a = \frac{0.2}{f} \sqrt{(Z_{xyr})^2 + (Z_{xyi})^2} \tag{2.31} $$

where $f$ is again equal to the frequency, $Z_{xyr}$ is equal to the real XY component, and $Z_{xyi}$ is equal to the imaginary XY component.

To calculate the error in the apparent resistivity for the XY components the following equation was used:

$$ p_a(error) = 1 - Coh_{xy} \tag{2.32} $$

where Coh_{xy} is the coherency value for the XY components. *Note: this is not the only way to calculate error but the general idea is to characterize the quality of each data point.

To calculate the phase for the XY components the following equation can be used:

$$ \phi = \arctan \left( \frac{Z_{xyi}}{Z_{xyr}} \right) \tag{2.33} $$

To calculate the phase error for the XY components the following equation was used:

$$ \phi_{error} = 10 \times p_a(error) \tag{2.34} $$

where $p_a(error)$ is equivalent to the calculated error in apparent resistivity. *Note: this is not the only way to calculate error but the general idea is to characterize the quality of each data point.
To calculate the log of apparent resistivity the following equation was used:

$$p_{al} = \log_{10}(p_a)$$

(2.35)

where $p_a$ is equivalent to the apparent resistivity calculated for the XY components.

### Figure 2.53: Excel spreadsheet format generated after preforming calculations for the square root of the period, apparent resistivity, error in the apparent resistivity, phase, error in the phase, and the log of apparent resistivity for the XY components of the Z tensor.

After completing the calculations for the XY components, the same calculations were run for the YX components making sure to use the appropriate YX values in place of the XY values in the above equations. Once these calculations we performed and saved for each data, the data was manipulated into the appropriate file types for 1D and 2D inversions.

### 1D Inversion

The previous processing steps ultimately produced values for each component of the Z(w) tensor shown in Equation 2.23, apparent resistivity, phase and period. Once these values were calculated, it was possible to create a model of the subsurface through inversion. The goal of inversion was to create a picture of what the subsurface looks like using both the collected data and programming. The program first creates a “guess” of what the subsurface might look like. Then, features were added to this model. For each feature added, the program simulated what kind of data would be produced by such a structure. By comparing the simulated data with the actual collected data, the program refined its model through an iterative process until a result was produced that lay within a specified tolerance range.

Even though the Z(w) tensor has four components, it was possible that not all of these components changed from site to site. For instance, if there were only vertical variations in the subsurface (layer cake Earth model) with no lateral variations and if we assume that vertical corresponds to the y component, then we would only have changes in the $Z_{xy}$ or $Z_{yx}$ tensor component. Since there were only variations in one tensor component, a 1D inversion was performed. The final product of the 1D inversion is seen in Figure 2.60 which is a resistivity profile with depth which would aid in the identification of depth to basement.

To create the 1D inversion, the program IPI2win was used. The first step was to correctly format all data files for each site that will be inverted. It was easiest to copy the teste1.MT file from IPI2win mt directory and edit it for each site’s data in notepad or VIM. The appropriate format for this data can be seen below in Figure 2.54.
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The first six lines of this file did not need to be edited. Line 7 represents the number of data lines (unique frequencies) that will be inputted. Line 8 and on contain the data. Each data line should either have 3 (if not using error bars) or 5 (if using error bars) columns. The columns were ordered:

- square root of period, apparent resistivity, resistivity error, phase, phase error

This file was saved as a .mt file by selecting "save as", "All File Types" and typing .mt at the end of the file name.

To begin running the inversion, IPI2win was opened, and we selected file → open and select the .mt file to be inverted, which generated an image similar to Figure 2.55.
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In Figure 2.55, the blue line is representative of the model (layer resistivity and depth). The black boxes are the error bars. If error bars were not being used, the data appears as a black line. The red line is the calculated curves (simulated data). Note that these figures have depth on the x-axis and resistivity on the y-axis. By clicking and dragging the blue line, it was possible to adjust the model to make the red line match the black. The program can also run automatic inversions. These inversions could be run with respect to resistivity (yellow lightning bolt), phase (blue lightning bolt) or both ($\rho$ and $\Phi$ button). The table on the right side of the screen depicts the numerical format of the calculated curves. To edit a field, we double clicked and typed. This could be used if there were known resistivity values and depths of geologic layers in the survey area. The number of layers could be specified by selecting options → new model → min. layers number → okay. We started with a low number of layers (3 or 4) and gradually increased if needed to improve the model. To begin the 1D inversion process, we selected the $\rho\Phi$ button to preform an automatic inversion, then manually adjusted the blue line. If the phase and resistivity models were not complimentary, we inverted only with respect to $\rho$. Also, it was more important to focus on fitting the higher frequency information than the low frequencies because the lower frequencies were more prone to noise. It was important to note that IPI2win outputs depth in a log scale. In order to get a geologic model that was comparable to normal depth, the layers and their respective depths were inputted and plotted in Excel. To do this, we made a note of the apparent resistivity and depth for each "corner" of the geologic model and plotted those values in Excel and created a graph. This was an important step because when the MT data was being integrated with the other methods, the depth could not be in a log scale since other methods use linear depth, so the two datasets would not be comparable.
2D Inversion

For an Earth that is perceived to vary laterally as well as in depth, 2D inversion was essential for a more accurate representation of the subsurface. A south to north line was created in order to linearly connect the survey sites. This line orientation was justified because it lies within 150 m of the Easting and Northing components for each site. The topographic profile was then created by connecting the nodes of the site locations and their elevations. The profile was then extended south to incorporate the Mother Spring and north to incorporate Eagle Mountain. This was done to account for the changing topography of the line. To create the model, the open-source software MARE2DEM was used along with complimentary Matlab 2013b-compatible codes. The MARE2DEM inversion program was setup on Mio, the Colorado School of Mines super computer, and run with a bash file. The Matlab codes were used to produce the models prior to running MARE2DEM and view the outputs from MARE2DEM.

Much like 1D MT inversion, 2D inversion uses the apparent resistivity and phase determined from the \( Z(w) \) tensor for both the \( Z_{xy} \) and \( Z_{yx} \) components. These values along with the frequencies and site information for each site can then be organized into a single .emdata file, see Figure 2.56.
With the .emdata file set up, a model needed to be made with Mamba2D.m in Matlab 2013b. Within Mamba, a boundary of the survey area that envelopes all the sites and estimated depth of investigation is the initial step to creating the model. Typically the default range is large enough. Next is the topographic elevation profile which can be imported from several file types. Then we set the free and fixed resistivity parameter; air was set at 1e9 resistivity with 0 for free parameter, and subsurface area was set to 1 resistivity with 1 for free parameter. This told MARE2DEM to only invert for the subsurface area, which is where the data was (See Figure 2.57).

This was a good saving point so that this could be the base model of a half-space. This was where nodes and segments were used to make smaller boundary areas within the subsurface that were of more interest for inversion. These smaller boundary areas could be used with triangles to make even smaller boundary areas that would be inverted in MARE2DEM. These should be fairly close to the surface and more dense where the sites are along the topographic profile.
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Figure 2.57: This is the initial resistivity model created in Mamba2D.m prior to inversion. The blue area is the air as a fixed parameter and the orange area is the subsurface.

Lastly, before the files could be written, the root of the files had to be named, and the .emdata file had to be defined. Penalty values were changed along with the upper and lower bounds of resistivity, but these were not changed for this inversion. The files were written by clicking the large box in the lower right-hand corner.
Mamba2D.m outputted 4 files: root.poly, root.0.resistivity, root.penalty, and root.mamba2d. All of these were required to run MARE2DEM along with the .emdata file and a mare2dem.settings file, which was obtained from the examples on the MARE2DEM website. The example bash file was required when running on Mio, which could be obtained from within the MARE2DM directory in Mio.

![Figure 2.58](image)

To run MARE2DEM, we followed the directions on the MARE2DEM tutorial and training PDF. Once MARE2DEM produced a new iteration of root.*.resistivity, it was viewed with plotMARE2DEM.m in Matlab2013b. For a more in depth explanation of this process see the Appendix C.

### 2.5.5.1 Errors/ Uncertainties

There are several factors which can contribute errors and uncertainties in processed MT data. One of the important assumptions in MT is that source waves are assumed to be planar as they emanate far away from the survey location. Therefore, any type of non-planar EM wave will cause interference. Such noise can be contributed by power lines, cultural activities and nearby lightning storms. These events can create large spikes in the time series data. Errors will also result from incorrectly labeled misaligned magnetometers or poor ground contact with the electrodes. There will also be poorer information for frequencies within the dead-band range.

Aside from errors and uncertainty associated with the theory surrounding MT, there are also many site specific errors (see Figure 2.43). Site 1 was located near a stream, which could have caused shallow interference. Additionally, the electrodes had to be re-placed to ensure good ground contact. This site was also recording during a lightning storm. Site 2 was located near a more traveled part of the forest service road, and thus some noise could have been due to cars...
driving by. This site was picked up just before a lightning storm occurred. Additionally, the crew did walk over the electrodes with cell phones to demonstrate noise in the data right after data collection began. At Site 3 electrodes had extreme corrosion on their connection ports. The corrosion was removed, and then the survey was re-started. This site was also running during a lightning storm. Site 4 had no nearby cultural interference except for the crews’ cell phones. Site 5 was located about 200m from a waterfall and stream system in an area of uneven ground. The magnetometers may not have been exactly leveled at this site. Additionally, a rain storm occurred during data collection. Site 6 had no major errors beyond initial port connection failures that were remedied before data collection began. Site 7 was located in an extremely marshy area surrounded by irrigation ditches. The terrain was hilly and a fence was located 200m away from the survey.

The goal of processing was to decrease the amount of noise in the data. However, errors were made during the processing portion. During the time series correction phase, there was a lack of consistency between team members about what qualified as a spike and what was acceptable as signal. This led to different interpretations between the three crew members removing noise. When working with Python, there was initially error in understanding the mechanics of the "Read Multiple Files" and "Plotting frequencies" codes. This led to a misinterpretation of generated plots, and frequencies may have been removed from the excel sheets that should have been included in the data. Additionally, correctly coding for apparent resistivity, error and phase was difficult. It was noted that in all data sets, the coherency decreases substantially with depth, and therefore our data are less reliable at greater depths. During the 1D inversion phase, the goal was to create a calculated curve that would pass through as many error bars as possible. However, none of the data sets resulted in a perfect match, which meant that the accuracy of the model was not high. For many of the sites this occurred because the ground had substantial 2D variations, which were unable to be captured by a 1D model. Few of the data sets were able to create a curve that successfully passed through the high and low frequencies. Thus the model accuracy also decreases with depth. Additionally, 1D and 2D inversions were originally done with depth represented on a logarithmic scale for the 1D plots. These depth values had to be recalculated and re-plotted on a linear scale and thus might have slight variations from actual depth. The 2D inversion will have inherent errors due to the limited number of iterations that were able to be done. The model will not be completely accurate because our data sets are too misfit in some locations in order to produce an exact model of the subsurface.
2.5.6 Results

Figure 2.60: Results of 1D inversion at Site 2 Station A created in IPI2win.MT. The geologic variation primarily occurs vertically in this area, and therefore it is well captured by the 1D inversion. This is confirmed because the calculated apparent resistivity (red) matches the majority of the data boxes (black boxes denoting the error on the real data). The image shows resistivity on the x-axis and increasing depth on the y-axis. The model shows a depth to basement at approximately .45 km. This interpretation is further discussed in the following interpretation section.
Figure 2.61: Results of 1D inversion at Site 7 Station A IPI2win.MT. Here, the geologic variation occurs laterally and vertically. This is because the original resistivity plots are divergent. Since this data is 2D in nature, trying to fit it to a 1 dimensional inversion produces poor, unreliable results. The model (blue) could not be trusted because there is low correspondence between the real data (black boxes) and the calculated apparent resistivity (red). This model shows a depth to basement at approximately .8 km, which is further discussed in the following Interpretation section.
Figure 2.62: Results of the 2D inversion created using Mare2Dem. The model is a cross sectional view of the station line. Air is represented by gray color, with the model reflecting the topographical profile of the area. Resistivity is denoted by the color scale in which blue is high resistivity and red is low resistivity. Depth is on the y axis given as negative elevation, and the x-axis run south to north using UTM coordinates. Each of the triangles at the top of the model represent a data collection site. The sites used, ordered left to right, were 7,6,2,4,1 and 3. These sites were chosen because of their proximity to the line of best fit between all sites. Site 5, see Figure 2.43, was not used as it was not located in close proximity to the other sites and thus was not useful for the profile. There is a general trend of increasing resistivity with depth. This makes sense for the survey area because basement rock is predicted to be one of the last geologic layers in the area, which will show high resistivity. In addition to vertical changes, the 2D inversion shows lateral rock layer changes in resistivity. This data show an area in between -2 and -1 with significantly lower resistivity than the surrounding sections.
The 1D inversion plots depicted in Figures 2.60 and 2.61 show the changes in geologic layers by plotting apparent resistivity against depth. Different layers are composed of different materials and thus will not have the same rock properties. Therefore, it is possible possible to infer the depth of geologic units by looking for changes in apparent resistivity. By combining data from all of the sites, the 2D plot shows vertical and lateral changes in conductivity over the entire survey area, seen in Figure 2.62. The 1D and 2D models, when combined, should match in areas of pure vertical change and slightly disagree in areas of both lateral and vertical change, seen in Figure 2.63. 1D inversions for all sites were produced and can be found in Appendix B.
2.5.7 Interpretation and Conclusion

2.5.7.1 Interpretation

Figure 2.64: Results of 1D inversion at Site 2 Station A created in IPI2win.MT. The geologic variation primarily occurs vertically in this area, and therefore it is well captured by the 1D inversion. This is confirmed because the calculated apparent resistivity (red) matches the majority of the data boxes (black boxes denoting the error on the real data). The image shows resistivity on the x-axis and increasing depth on the y-axis. The model shows a depth to basement at approximately 0.45 km. This interpretation is further discussed in the following interpretation section.
Figure 2.65: Results of 1D inversion at Site 7 Station A IPI2win.MT. Here the geologic variation occurs laterally and vertically. This is because the original resistivity plots are divergent. Since this data is 2D in nature, trying to fit it to a 1 dimensional inversion produces poor, unreliable results. The model (blue) could not be trusted because there is low correspondence between the real data (black boxes) and the calculated apparent resistivity (red). This model shows a depth to basement at approximately .8 km, which is further discussed in the following Interpretation section.
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Figure 2.66: Results of the 2D inversion created using Mare2Dem. The model is a cross sectional view of the station line. Air is represented by gray color, with the model reflecting the topographical profile of the area. Resistivity is denoted by the color scale in which blue is high resistivity and red is low resistivity. Depth is on the y-axis given as negative elevation, and the x-axis run south to north using UTM coordinates. Each of the triangles at the top of the model represent a data collection site. The sites used, ordered left to right, were 7,6,2,4,1 and 3. These sites were chosen because of their proximity to the line of best fit between all sites. Site 5, see Figure 2.43, was not used as it was not located in close proximity to the other sites and thus was not useful for the profile. There is a general trend of increasing resistivity with depth. This makes sense for the survey area because basement rock is predicted to be one of the last geologic layers in the area, which will show high resistivity. In addition to vertical changes, the 2D inversion shows lateral rock layer changes in resistivity. This data show an area in between -2 and -1 with significantly lower resistivity than the surrounding sections.
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Figure 2.67: In this figure, the 1D inversion models are layered over the 2D model at the site where they were recorded. By combining both data sets, it is possible to see where the Earth has true 1 and 2 dimensional variations. The 1D models are shown with black lines. By using the models from the 1D inversions and the resistivity changes in the 2D model, the basement depth was plotted in pink. Dashed lines show areas that were not crossed by our survey sites and thus have less confidence. Basement was determined by correlating the areas where the 1D and 2D models showed a sharp increase in resistivity. The general basement trend shows an increase towards the Northing end of the survey. This is also a useful model for integration with other methods since it clearly defines where basement occurs.

The 1D inversion plots depicted in Figures 2.64 and 2.65 show the changes in geologic layers by plotting apparent resistivity against depth. Different layers are composed of different materials and thus will not have the same rock properties. Therefore, it is possible possible to infer the depth of geologic units by looking for changes in apparent resistivity. By combining data from all of the sites, the 2D plot shows vertical and lateral changes in conductivity over the entire survey area, seen in Figure 2.66. The 1D and 2D models, when combined, should match in areas of pure vertical change and slightly disagree in areas of both lateral and vertical change, seen in Figure 2.67. 1D inversions for all sites were produced and can be found in Appendix B.

2.5.7.2 Conclusion

Overall, depths to basement were calculated via the 1D inversion software and the 2D model. Overlaying the two inversion sets enabled a complete profile of the ground conductivity and mapping of depth to basement. The results show a moderate correlation between the two data sets where there is only major variation in one direction. In places with a great deal of lateral change, the 2D results are more accurate.

In future years, it is recommended that the survey sites be planned in as best of a straight line as possible. This way all data collected can be used in the 2D resistivity model. Future years should also plan to spend more time correcting the 2D inversion than the 1D inversions as 2D is more representative of a 3D Earth. This data set was also ultimately more helpful when integrating data with other geophysical data sets. Now that there is an example of how to work with ProcMT, future years could improve the processing steps by using the boxplot option in ProcMT (export a Ztensor file as described in previous sections and choose box plot in ediplotter). This function would give a visual representation of data distribution, making it easier to remove outliers. This step could replace some Python coding in future years’ processing. These steps are outlined in detail in the future goals of ProcMT, which can be found in Appendix E.
2.6 Time Domain Electromagnetics

Figure 2.68: Total survey area for TEM in Pagosa Springs
2.6.1 Introduction

Electromagnetic (EM) methods utilize a transmitter loop carrying alternating current to transmit current into the ground, which produces a secondary magnetic field which varies in magnitude based off of the conductivity of the ground. The secondary magnetic field is measured as an induced voltage by the receiver loop. This signal can then be digitalized and processed to determine conductivity properties of the subsurface. Conductivity anomalies may represent lithological interfaces, potential fluid flow paths, and possible locations of geothermal fluids [21]. EM methods are generally divided into two categories: time-domain electromagnetics (TEM) and frequency-domain electromagnetics (FDEM).

TEM utilizes a square-wave current in the transmitter loop [22]. For this reason, TEM is used to produce vertical conductivity soundings which may be combined with results from other methods to produce a more accurate final model. TEM is an advantageous method because it images deeper than most methods, with the exception of MT and deep seismic. In previous years’ surveys, the EM-47 was used along with the EM-57 [21]. The EM-47 was not used in 2018 because it is more useful for shallow depths, which were not of interest in the 2018 survey.

In previous years, FDEM surveys were conducted in areas around the town of Pagosa Springs. FDEM applies a sinusoidally varying current at a specific frequency to a transmitter loop. The frequency is chosen based off of the desired depth of imaging. In general, FDEM is used for imaging of horizontal anomalies and does not penetrate as deeply as TEM [21]. Due to a lack of useful findings from FDEM surveys in previous years, FDEM was not used in 2018.

2.6.2 Theory

TDEM utilizes a transmitter loop with an alternating current which is shut off after some time. When the current is shut off, the associated magnetic field decays which induces a current in the ground, directly below the transmitter loop, in the opposite direction of the original current. This phenomenon is described by Amperes Law [22], which is defined as:

\[ \nabla \times \vec{B} = \mu_0 \vec{J} \]  

(2.36)

where \( \vec{B} \) is the magnetic field, \( \mu_0 \) is the magnetic permeability of free space, and \( \vec{J} \) is the current density in the transmitter loop.

These current rings are commonly referred to as smoke rings because they diffuse outwards and travel downwards into the ground (see Figure 2.69). The smoke rings reduce in magnitude over time as a result of wave attenuation. Wave attenuation affects the maximum depth that the survey can image, or the depth of investigation. Depth of investigation is reduced in more conductive media.
Faraday’s Law states that every electric field has an associated magnetic field. This equation is as follows:

$$\nabla \times \vec{E} = -\frac{d\vec{B}}{dt}$$ \hspace{1cm} (2.37)

where $\vec{B}$ is the magnetic field and $\vec{E}$ is the electric field.

As the smoke rings decay, the magnitude of the magnetic field produced by the current in these rings also decays. This change in magnetic field induces a secondary magnetic field that is stronger in more conductive anomalies. As this magnetic field decays, it induces a current in the receiver loop, as governed by Equation 2.37, which is recorded by the receiver box as an induced voltage. The measured voltage includes the voltage induced by the primary magnetic field from the transmitter loop in addition to the voltage induced by the secondary magnetic field. The primary induced voltage is known, and is removed from the recorded value by the device [22].

Ohm’s Law is defined as:

$$\vec{J} = \sigma \vec{E}$$ \hspace{1cm} (2.38)

where $\vec{J}$ is current density, $\sigma$ is conductivity, and $\vec{E}$ is electric field.

Equation 2.37 may be rewritten using Equation 2.38 to relate the induced voltage to current density and conductivity as follows:

$$\nabla \times \frac{\vec{J}}{\sigma_a} = -\frac{d\vec{B}}{dt} = -e(t)$$ \hspace{1cm} (2.39)

where $\vec{J}$ is current density, $\sigma$ is apparent conductivity, $\vec{B}$ is the secondary magnetic field measured by the receiver, and $e(t)$ is the induced voltage, as a function of time, per unit of effective area (number of loops times area of the receiver loop).

Equation 2.39 may be further simplified as follows, under the assumption of a homogeneous Earth:

$$e(t) = \frac{\delta B}{\delta t} = \frac{1}{20\pi^2} \frac{\delta \mu_a}{\delta t} \frac{1}{t^{\frac{5}{2}}}$$ \hspace{1cm} (2.40)
where \( e(t) \) is the induced voltage, as a function of time, per unit of effective area (number of loops times area of the receiver loop), \( B \) is the magnetic field, \( I \) is the current in the transmitter loop, \( \sigma_a \) is the apparent conductivity, \( \mu_0 \) is the magnetic permeability of free space, \( a \) is the length of one side of the transmitter loop (in some cases, \( a^2 \) should be multiplied by the number of loops in transmitter loop), and \( t \) is the time after transmitter is shut off (modified from 2016 Field Camp Report).

Equation 2.40 may be rearranged as follows to solve for apparent conductivity, which may be used to determine areas of anomalous conductivity.

\[
\sigma_a = \left( \frac{20\pi^2 e(t) t^2}{I\mu_0 a^2} \right)^{\frac{1}{2}}
\]

(2.41)

where \( e(t) \) is the induced voltage, as a function of time, per unit of effective area (number of loops times area of the receiver loop), \( B \) is the magnetic field, \( I \) is the current in the transmitter loop, \( \sigma_a \) is the apparent conductivity, \( \mu_0 \) is the magnetic permeability of free space, \( a \) is the length of one side of the transmitter loop (in some cases, \( a^2 \) should be multiplied by the number of loops in transmitter loop), and \( t \) is the time after transmitter is shut off. Note that Equation 2.41 assumes a homogeneous Earth, and that inversion must be used to produce a model for a system that varies three-dimensionally.

### 2.6.3 Objectives

The objectives of the TEM surveys are as follows:

1. Imaging of vertical changes in apparent conductivity for use in determining depths and thicknesses of lithological units, specifically the Dakota Sandstone;
2. Creation of an inverse model of conductivity versus depth;
3. Identification of more resistive areas which may indicate flow paths for groundwater towards the Mother Spring;
4. Identification of more conductive areas which may indicate the presence of geothermal fluids; and
5. Correlation of results from CR200 lines with those produced by MT and deep seismic surveys.

### 2.6.4 Equipment and Survey Setup

#### 2.6.4.1 Equipment List

1. Geonics EM-57 transmitter:
   - Provides and controls alternating current for transmitter loop (see Figure 2.70).
2. 400 m of cable:
   - Serves as a transmitter loop.
3. Geonics PROTEM 57 receiver box and coil:
   - Measures and digitalizes secondary magnetic field (see Figure 2.70).
4. Generator:
   - Used as a power supply for the transmitter (Maximum output of 22 A).
5. Synchronization cable:
   - Used for initial synchronization of transmitter and receiver.
6. Tape measures:
   - Used in setting up the transmitter loop.
7. Plastic stakes:
   - Outlined transmitter loop before laying down cable.
8. Garmin eTrex 30 handheld GPS:
   - Used for setting up transmitter loop and recording location data.
Surveys were conducted at four locations along CR200, two in the Mother Spring Recon Site, and one on the Reservoir Hill Recon Site as shown in Figure 2.68. All surveys measured only the z-component of the secondary magnetic field. Sites were chosen based on permission from landowners, proximity to MT and seismic surveys for data correlation, and distance from power lines and other sources of noise. Some survey sites were located close to power lines as a result of limited site availability. These sites are described under the Error and Noise section.

Survey 1

Survey 1 was conducted on May 17, 2018 on the Eoff property along CR200 (see Figure 2.68). The transmitter loop was a square with 100 m sides. This survey was experimental for use in determining the best parameters to apply to later surveys. Line 1 used 11 A, high frequency (30 Hz), and a turn-off time of 39 \( \mu \)s. Line 2 used 11.8 A, low frequency (3 Hz), and a turn-off time of 62 \( \mu \)s. Line 3 used high 20.4 A, low frequency (3 Hz), and a turn-off time of 100 \( \mu \)s. A gain of 5 was used by the receiver for high frequencies, and 7 was used for low frequencies.

Survey 2

Survey 2 was conducted on May 18, 2018 on the Eoff property along CR200 (see Figure 2.68). The transmitter loop was a square with 100 m sides. Both Lines 1 and 2 used a current of 11 A and a turn-off time of 39 \( \mu \)s. Line 1 stations collected on a 300 x 300 m grid with 100 m spacing. High frequency was used at all station locations, with the exception of Station 6. Line 2 occupied the southwest corner of the station grid for Line 1. One high frequency measurement and one low frequency measurement were taken at the center of the transmitter loop. A gain of 5 was used by the receiver for high frequencies, and 7 was used for low frequencies.

Survey 3
Survey 3 was conducted on May 19, 2018 on the Reservoir Hill Recon Site (see Figure 2.68). The transmitter loop was a square with 100 m sides. Only one line was surveyed, using a current of 11 A for transmission. Stations 1 and 2 were in the center of the transmitter loop using high and low frequency respectively. All stations, with the exception of Station 2, used high frequency transmission. A gain of 6 was used by the receiver for high frequencies, and 7 was used for low frequencies along with a turn-off time of 38 $\mu$s.

Survey 4

Survey 4 was conducted on May 20, 2018 on the Hershey property along CR200 (see Figure 2.68). The transmitter loop was a square with 100 m sides with an applied current of 11 A. Stations 1 and 2 were taken in the center of the loop using high and low frequencies respectively. A gain of 4 was used by the receiver for high frequencies, and 7 was used for low frequencies. A turn-off time of 39 $\mu$s was used by the receiver.

Survey 5

Survey 5 was conducted on May 21, 2018 at the Mother Spring Recon Site (see Figure 2.68). The transmitter loop was a square with 50 m sides (two loops in the cable) with an applied current of 22 A. Line 1 included high (Station 1) and low (Station 2) frequencies, both at the center of the transmitter loop. Line 2’s eastern edge was the western edge of Line 1. One high frequency measurement was taken at the center of the transmitter loop. Line 3’s southern edge was the northern edge of Line 2. One high frequency measurement was taken at the center of the transmitter loop. A gain of 2 was used by the receiver for high frequencies, and 7 was used for low frequencies along with a turn-off time of 65 $\mu$s.

Survey 6

Survey 6 was conducted on May 22, 2018 at the floodplain on the Mother Spring Recon Site (see Figure 2.68). Line 1 used a current of 22 A, while Line 2 used 11 A. The transmitter loop for Line 1 was a square with 50 m sides (two loops in the cable). Station 1 was in the center of the transmitter loop, using high frequency. Line 2 used a square transmitter loop with sides of length 100 m. Stations 1 and 2 were in the center of the transmitter loop, using high and low frequencies respectively. A gain of 2 was used by the receiver for high frequencies, and 7 was used for low frequencies along with a turn-off time of 65 $\mu$s.

Survey 7

Survey 7 was conducted on May 23, 2018 in a clearing approximately 400m from the Forest Service Road (see Figure 2.68). The transmitter loop was a square with 100 m sides with an applied current of 11 A. Stations 1 and 2 were in the center of the transmitter loop, using high and low frequencies respectively. A gain of 4 was used by the receiver for high frequencies, and 7 was used for low frequencies. A turn-off time of 39 $\mu$s was used by the receiver.

2.6.4.4 Procedure

During each survey, the transmitter loop was laid out first using a tape measure, plastic stakes and a handheld GPS. The transmitter loop was laid out with sides oriented parallel to the cardinal compass directions. The cable was then laid out and connected to the EM-57 transmitter box. After inputting survey parameters and initial synchronization of the transmitter with the receiver, the PROTEM receiver was placed and leveled at various station locations. Most measurements were taken using high frequency, and an additional low frequency measurement was taken at the center of most transmitter loops.
2.6.5 Processing

2.6.5.1 Procedure

Multiple measurements were taken at each station to decrease the uncertainty in the data. For each station, the average of all of the recorded measurements was used with GPS data to produce contour plots of time-slices using Python program written by Joseph Capriotti. Data known to be extremely noisy or erroneous were removed before averaging. Each time slice plot shows the horizontal voltage distribution with respect to time. Comparing the time-slices indicated voltage decay over time, which is what is expected physically. Time slices were used to determine whether or not each dataset was useful, and to observe the amount of noise in each dataset.

Inversion was then used to create 1D inverse models of conductivity versus depth using a Python script written by Joseph Capriotti. The inversion code works by iterating through possible conductivity values and choosing those which best fit the measured data. These profiles were used to compare the TEM data to geologic, MT, and seismic data collected in close proximity to TEM survey sites through overlaying the profiles on cross-sections. Modeled conductivity values produced from the TEM data were also compared to the resistivity values for each geologic layer (see Figure 1.8), and to the DC resistivity experimental conductivity values (see Figure 2.39).

2.6.5.2 Error/Noise

Potential sources of error include power lines, conductive fences, changes in the Earth’s magnetic field, and error in setting up the transmitter loop as a result of imprecise equipment. Power lines create a secondary source of magnetic field, which can produce noisy results. Fences appear as conductive anomalies in the data, which may be falsely interpreted as a subsurface conductive anomaly. While changes in the Earth’s magnetic field typically occur on a larger time scale, they can introduce a tertiary magnetic field to be accounted for during data processing. Error in setting up the transmitter loop was minimized to the extent possible, but may still produce small variations in the apparent results following processing.

Surveys 1 and 2 took measurements at stations close to power lines. The centers of each transmitter loop, however, were located at least 100 m from the nearest power line. Only center-line soundings were processed using inversion; therefore, noise from power lines may exist in the data, but is likely small compared to the data itself.

Another source of low quality data is the conductive Mancos Shale (see Figure 1.8). EM waves attenuate faster in more conductive media; therefore, the surveys over the Mancos Shale have a reduced depth of investigation.

2.6.6 Results

Surveys 1 and 2: CR200

Figure 2.71 shows the inverted results from Survey 1. Due to shallow depth of investigation, the data only shows 150 m of useful information. At about 30 m depth, an increase in conductivity occurs with a magnitude of 0.085 S/m, or a resistivity ($\rho$) of about 11.8 Ohm m.

Figure 2.72 shows the inverted results from Survey 2. Wave attenuation caused by high conductivity values reduced the depth of investigation of Survey 2 to about 220 m. Line 1 shows a single conductive anomaly at about 30 m with a magnitude of about 0.85 S/m ($\rho = 1.2$ Ohm m). Line 2 shows two separate conductive anomalies: one at about 40 m depth with a magnitude of about 0.075 S/m ($\rho = 13.3$ Ohm m), and another at about 100 m depth with a conductivity of about 0.1 S/m ($\rho = 10$ Ohm m).
Figure 2.71: Survey 1 results. **Left:** Observed data averaged over all time gates (red) plotted with data used to produce model (blue) for center-line stations. This plot is used to visualize how well the data fits the model. **Right:** Conductivity versus depth profile produced from inversion.
Figure 2.72: Survey 2 results. **Top-left:** Observed data averaged over all time gates (red) plotted with data used to produce model (blue) for center-line stations for Line 1. **Bottom-left:** Observed data averaged over all time gates (red) plotted with data used to produce model (blue) for center-line stations for Line 2. These plots are used to visualize how well the data fits the model. **Top-right:** Conductivity versus depth profile produced from inversion for Line 1. **Bottom-right:** Conductivity versus depth profile produced from inversion for Line 2.
Surveys 4 and 7: Forest Service Road (North of CR200)

Figure 2.73 shows the inverted results from Survey 4. Wave attenuation caused by high conductivity values reduced the depth of investigation of Survey 4 to about 200 m. Starting at about 40 m depth, a conductive anomaly occurs with a magnitude of 0.1 S/m ($\rho = 10\Omega m$).

Figure 2.74 shows the inverted results from Survey 7, which appears to have a greater depth of investigation than Survey 4. At about 30 m depth, a conductive anomaly occurs with a magnitude of 0.1 S/m ($\rho = 10\Omega m$). A more resistive anomaly appears at roughly 80 m with a magnitude of 0.07 S/m ($\rho = 15\Omega m$). The model also suggests a conductive anomaly of approximately 0.1 S/m ($\rho = 10\Omega m$) starting at about 130 m.

![Figure 2.73: Survey 4 results. Left: Observed data averaged over all time gates (red) plotted with data used to produce model (blue) for center-line stations. This plot is used to visualize how well the data fits the model. Right: Conductivity versus depth profile produced from inversion.](image-url)
Figure 2.74: Survey 7 results. **Left:** Observed data averaged over all time gates (red) plotted with data used to produce model (blue) for center-line stations. This plot is used to visualize how well the data fits the model. **Right:** Conductivity versus depth profile produced from inversion.

**Survey 3: Reservoir Hill Recon Sites**

Figure 2.75 shows the inverted results from Survey 3. A discontinuity exists at a depth of roughly 30m with a magnitude near 0.013S/m ($\rho = 77\, \text{Ohm}m$), followed by a conductive anomaly at a depth of about 60m with a magnitude of approximately 0.06S/m ($\rho = 17\, \text{Ohm}m$). The conductive anomaly is followed by a more resistive anomaly at about 125m with a magnitude of about 0.05S/m ($\rho = 20\, \text{Ohm}m$), proceeded by an increase in conductivity at a depth of around 200m to 0.08S/m ($\rho = 12.5\, \text{Ohm}m$). The profile then reaches its depth of investigation and is no longer interpretable.
Figure 2.75: Survey 3 results. **Left:** Observed data averaged over all time gates (red) plotted with data used to produce model (blue) for center-line stations. This plot is used to visualize how well the data fits the model. **Right:** Conductivity versus depth profile produced from inversion.

Surveys 5 and 6: Mother Spring Recon Site

Figure 2.76 shows the inverted results from Survey 5. In Line 1, a conductive anomaly occurs at roughly 5 m with a magnitude of approximately $0.035 \text{S/m} \ (\rho = 28 \text{Ohm m})$, followed by a more resistive anomaly around beginning near $70 \text{m}$ with a magnitude of about $0.012 \text{S/m} \ (\rho = 83 \text{Ohm m})$. These anomalies are followed by another conductive anomaly at starting about $150 \text{m}$ with a magnitude of roughly $0.05 \text{S/m} \ (\rho = 25 \text{Ohm m})$ proceeded by uninterpretable data at the depth of investigation.

Line 2 results suggest a conductive anomaly at about $5 \text{ m}$ with a magnitude of approximately $0.08 \text{ S/m} \ (\rho = 12 \text{ Ohm m})$. This conductive anomaly is proceeded by a more resistive anomaly at a depth of roughly $50 \text{ m}$ with a magnitude of $0.008 \text{ S/m} \ (\rho = 125 \text{ Ohm m})$ which is underlain by another conductive anomaly of an uninterpretable magnitude (the survey reached its depth of investigation).

The results from Line 3 show a conductive anomaly at about $10 \text{ m}$ with a magnitude of approximately $0.055 \text{S/m} \ (\rho = 20 \text{Ohmm})$, followed by a more resistive anomaly starting near $70 \text{m}$ with a magnitude of roughly $0.004 \text{S/m} \ (\rho = 250 \text{Ohmm})$. The modeled conductivity then increases to an uninterpretable magnitude before reaching depth of investigation.

Figure 2.77 shows the inverted results from Survey 6. The conductivity versus depth profile for line 1 suggests a conductive anomaly at a depth of roughly $30 \text{m}$ with a magnitude of $0.053 \text{S/m} \ (\rho = 280 \text{Ohmm})$, proceeded by a resistive anomaly at approximately $90 \text{m}$ with a magnitude of about $0.025 \text{S/m} \ (\rho = 40 \text{Ohmm})$. 
The conductivity versus depth profile for Line 2 shows a conductive anomaly at a depth starting near 10m with a magnitude of approximately 0.06 S/m (ρ = 17 Ohmm), followed by a more resistive anomaly at roughly 70m with a magnitude of about 0.03 S/m (ρ = 33 Ohmm).
Figure 2.76: Survey 5 results. **Top-left**: Observed data averaged over all time gates (red) plotted with data used to produce model (blue) for center-line stations for Line 1. **Center-left**: Observed data averaged over all time gates (red) plotted with data used to produce model (blue) for center-line stations for Line 2. **Bottom-left**: Observed data averaged over all time gates (red) plotted with data used to produce model (blue) for center-line stations for Line 3. **Top-right**: Conductivity versus depth profile produced from inversion for Line 1. **Center-left**: Conductivity versus depth profile produced from inversion for Line 3. **Bottom-right**: Conductivity versus depth profile produced from inversion for Line 3.
Figure 2.77: Survey 6 results. **Top-left:** Observed data averaged over all time gates (red) plotted with data used to produce model (blue) for center-line stations for Line 1. **Bottom-left:** Observed data averaged over all time gates (red) plotted with data used to produce model (blue) for center-line stations for Line 2. These plots are used to visualize how well the data fits the model. **Top-right:** Conductivity versus depth profile produced from inversion for Line 1. **Bottom-right:** Conductivity versus depth profile produced from inversion for Line 2.
2.6 Time Domain Electromagnetics

2.6.7 Interpretation and Conclusion

2.6.7.1 Interpretation

Surveys 1 and 2: CR200

In the results from Survey 1 (Figure 2.78), the conductive anomaly at about 30m depth has a magnitude of 0.085 S/m, \(\rho = 11.8 \text{Ohmm}\), which is about half the value listed for the resistivity of Mancos Shale in Figure 1.8. The survey field was extremely saturated, so it is likely that the higher conductivity values are a result of the saturated shale close to the surface.

The conductive anomaly at roughly 50m in Line 1 of Survey 2 (Figure 2.79) has a magnitude of about 0.85 S/m \(\rho = 1.2 \text{Ohmm}\) is likely evidence of the Mancos Shale despite the very low resistivity value compared to the value listed for the resistivity of Mancos Shale in Figure 1.8. In the results for Line 2, the first, more resistive anomaly at about 40m depth has a magnitude of about 0.075 S/m \(\rho = 13.3 \text{Ohmm}\). The second, more conductive anomaly at roughly 100m depth has a magnitude of about 0.15 S/m \(\rho = 10 \text{Ohmm}\). These two separate conductivity anomalies are interpreted as variations in the Mancos Shale. Again, the survey field was saturated, likely causing lower resistivity values than expected.

Despite field saturation, limited depth of investigation, and potential noise in the data, it may be concluded from Surveys 1 and 2 that the Mancos Shale is overlain by roughly 30 – 40m of topsoil, and that there are slight lateral variations in the conductivity properties of the Mancos Shale along CR200. The variations in the Mancos Shale could be a result of varying historical depositional environments, or differences in saturation due to varying rock permeability.

The CR200 data is fairly noisy as displayed by the plots comparing observed data to the data used to produce the model (See Figures 2.78 and 2.79). Separation between the observed data and model data is apparent, especially in the lower half of the data. Noise is greater in Survey 2 than in Survey 1. The noise in these datasets is likely caused by overhead electrical lines and flowing water.
Figure 2.78: Survey 1 interpreted results. **Left**: Observed data averaged over all time gates (red) plotted with data used to produce model (blue) for center-line stations. This plot is used to visualize how well the data fits the model. **Right**: Conductivity versus depth profile produced from inversion with inferred formation tops and conductivity values labeled.
Surveys 4 and 7: Forest Service Road (North of CR200)

Survey 4 (Figure 2.80) suggests a conductive anomaly exists at a depth of about 40m depth with a magnitude of $0.1 S/m$, $\rho = 100\Omega m$. This is relatively low compared to the value for Man-
cos Shale listed in Figure 1.8. This is likely an artifact of the reduced depth of investigation caused by the conductive Mancos Shale, but could also be evidence of the Greenhorn Formation, a more resistive limestone located below the Mancos Shale in areas north of Pagosa Springs.

The results from Survey 7 (Figure 2.81) show a conductive anomaly at a depth of about 30m depth with a magnitude of $0.1 S/m$ ($\rho = 10\text{Ohmm}$). This is relatively low compared to the value for Mancos Shale listed in Figure 1.8. The lower conductivity value is likely a result of the underlying Greenhorn Formation, which may be observed through the more resistive anomaly at about 80m with a magnitude of $0.07 S/m$ ($\rho = 15\text{Ohmm}$). The conductivity spike of about $0.15 S/m$ ($\rho = 10\text{Ohmm}$) starting at about 130m is presumably the Dakota Sandstone which is imaged for about 120m before reaching the depth of investigation. According to Figure 1.8, the Dakota Formation has an average resistivity of $100\text{Ohmm}$, which aligns with the results.

The results of Surveys 4 and 7 imply that the Mancos Shale has a thickness of about 40 – 50m along the Forest Service Road, is overlain by roughly 30 – 40m of topsoil, and is underlain by about 40m of the Greenhorn Formation. The Dakota Sandstone, which underlies the Greenhorn Formation, has a thickness greater than 120m and is more conductive closer to the surface, possibly indicating that the upper portion of the Dakota Sandstone is more silicified than the lower portion. This could also be an indicator of fresh water in the lower portion of the formation.

![Figure 2.80: Survey 4 interpreted results. Left: Observed data averaged over all time gates (red) plotted with data used to produce model (blue) for center-line stations. This plot is used to visualize how well the data fits the model. Right: Conductivity versus depth profile produced from inversion with inferred formation tops and conductivity values labeled.](image-url)
Surveys 3: Reservoir Hill Recon Sites

The inverted model produce from Survey 3 (Figure 2.82) depicts a thin discontinuity in conductivity at a depth of about 30m with a magnitude near $0.013 \text{S/m} \ (\rho = 77 \text{Ohm m})$ which is likely fine to coarse grain alluvium deposited by the river that historically flowed through the area. This discontinuity is followed by a conductive anomaly at a depth of about 60m with a magnitude of about $0.06 \text{S/m} \ (\rho = 17 \text{Ohm m})$. The second anomaly is presumably the Mancos Shale. The conductive anomaly is followed by a reduction in conductivity at about 125m with a magnitude of approximately $0.05 \text{S/m} \ (\rho = 200 \text{Ohm m})$, proceeded by an increase in conductivity at a depth of around 200m to $0.08 \text{S/m} \ (\rho = 12.5 \text{Ohm m})$. The more resistive section is probably a result of variations in the Mancos Shale, and the proceeding increase in conductivity is assumed to be a continuation of the Mancos Shale.

Survey 3 suggests that the Mancos Shale on top of Reservoir Hill is overlain by roughly 60m of alluvium varying from fine to coarse grained. The Reservoir Hill Recon Site data is fairly noisy as shown by the plots comparing observed data to the data used to produce the model (See Figure 2.82). Separation between the observed data and model data is notable, especially in the uppermost and lowermost portions of the data. The noise in this dataset is likely caused by underground electrical lines.
Surveys 5 and 6: Mother Spring Recon Site

Survey 5 results (Figure 2.83) from Line 1 show a conductive anomaly at about 5 m with a magnitude of approximately 0.035 S/m ($\rho = 28 \text{Ohmm}$), followed by a more resistive anomaly around 70 m with a magnitude of approximately 0.012 S/m ($\rho = 83 \text{Ohmm}$). This section is assumed to be the Mancos Shale on top of the Dakota Sandstone. This section is followed by another conductive anomaly at about 150 m with a magnitude of roughly 0.05 S/m ($\rho = 25 \text{Ohmm}$). This is presumably the Morrison Formation.

Line 2 results suggest a conductive anomaly at about 5 m with a magnitude of approximately 0.08 S/m ($\rho = 12 \text{Ohmm}$). This value is slightly below the resistivity value for the Mancos Shale listed in Figure 1.8, which may indicate the presence of briney water. The conductive anomaly is proceeded by a more resistive anomaly at a depth of roughly 50 m with a magnitude of 0.008 S/m ($\rho = 125 \text{Ohmm}$). This resistivity value is slightly higher than the resistivity value listed for Dakota Sandstone (Figure 1.8). This could be a result of fresh water, or it could be a result of noise in the data. The conductive anomaly underlying the resistive anomaly starting at about 300 m is assumed to be the start of the Morrison Formation.

The results from Line 3 show a conductive anomaly at about 7 m with a magnitude of approximately 0.05 S/m ($\rho = 20 \text{Ohmm}$). As in previous lines, this is inferred to be the Mancos Shale. The conductive anomaly is followed by a more resistive anomaly near 70 m with a magnitude of roughly 0.004 S/m ($\rho = 250 \text{Ohmm}$). This value is very high compared to the value listed in Figure 1.8 for Dakota Sandstone, potentially indicating the presence of fresh water. The modeled conductivity then increases before reaching depth of investigation, presumably showing the start of the Morrison Formation.

The inverted results from Survey 6 (Figure 2.84) suggest a conductive anomaly at a depth of
roughly 20 m with a magnitude of 0.053 S/m ($\rho = 28 \text{Ohm}\cdot\text{m}$), assumed to be the Mancos Shale. The conductive anomaly is preceded by a resistive anomaly at approximately 90 m with a magnitude of about 0.025 S/m ($\rho = 40 \text{Ohm}\cdot\text{m}$). This anomaly is assumed to be the Dakota Sandstone, although the resistivity value is very low compared to the value listed in Figure 1.8. This difference could either be a result of brine water in the Dakota Sandstone, an artifact caused by the thick layer of conductive Morrison below the Dakota, or noise in the data.

Line 2’s conductivity versus depth profile shows a conductive anomaly at a depth near 10 m with a magnitude of approximately 0.06 S/m ($\rho = 17 \text{Ohm}\cdot\text{m}$), which is assumed to be the Mancos Shale despite the lower resistivity value compared to that listed in Figure 1.8. This conductive anomaly is followed by a more resistive anomaly at roughly 70 m with a magnitude of about 0.03 S/m ($\rho = 33 \text{Ohm}\cdot\text{m}$). This anomaly is assumed to be the Dakota Sandstone despite the very low resistivity value. This difference could either be a result of brine water in the Dakota Sandstone, an artifact caused by the thick layer of conductive Morrison below the Dakota, or noise in the data.

Results from Surveys 5 and 6 imply that the Mancos Shale in the Mother Spring Recon Site has a thickness between 60 and 70 m, and is overlain by 5 – 7 m of travertine in most areas. The travertine may be as thick as 30 m in the southwestern portion of the Mother Spring Recon Site. The Dakota Sandstone, which underlies the Mancos Shale, appears to be approximately 90 – 250 m thick in the Mother Spring Recon Site, but is likely thicker in reality. Additionally, the results imply that the underlying Morrison Formation is at least twice as thick as the Dakota Sandstone.

As stated previously, the Mother Spring Recon Site Data is fairly noisy, especially that from Survey 6. Noise in this survey site is caused by closed proximity to the town of Pagosa Springs, which inherently introduces electrical noise. The noise is observable in the plots comparing observed data to data used to produce the model (See Figure 2.84). Separation between the observed data and model data is visible, especially in the lower half of the data.
Figure 2.83: Survey 5 interpreted results. **Top-left:** Observed data averaged over all time gates (red) plotted with data used to produce model (blue) for center-line stations for Line 1. **Center-left:** Observed data averaged over all time gates (red) plotted with data used to produce model (blue) for center-line stations for Line 2. **Bottom-left:** Observed data averaged over all time gates (red) plotted with data used to produce model (blue) for center-line stations for Line 3. These plots are used to visualize how well the data fits the model. **Top-right:** Conductivity versus depth profile produced from inversion for Line 1 with inferred formation tops and conductivity values. **Center-right:** Conductivity versus depth profile produced from inversion for Line 3 with inferred formation tops and conductivity values. **Bottom-right:** Conductivity versus depth profile produced from inversion for Line 3 with inferred formation tops and conductivity values labeled.
2.6.7.2 Conclusion

TEM surveys, useful for detecting subsurface conductive anomalies, were executed at seven sites in and north of Pagosa Springs. Data were processed, inverted, and interpreted. TEM results generally align with the geologic cross sections for CR200 and the Mother Spring site. Relative conductivities closely align with values provided through well logging data, although error
and noise cause variations in the observed conductivity values. The depth information matches closely with predicted values with the exception of the Reservoir Hill Recon Site where TEM data suggests a deeper Mancos shale layer than that presented in the cross section. Additionally, TEM surveys identified probable geothermal water in the Dakota Sandstone underlying the eastern portion of the Mother Spring Recon Site, and probable fresh water in the Dakota Sandstone underlying the western portion of the Mother Spring Recon Site. Due to the depth of investigation restrictions and a limited number of site sites, an accurate prediction of the depths and thicknesses of each geological unit cannot be made from TEM data alone. TEM data is integrated with other geophysical datasets collected in the area in a later section.
2.7 Hammer Seismic

Figure 2.85: Total survey area for Hammer Seismic near downtown Pagosa Springs
2.7.1 Introduction

Hammer seismic uses acoustic waves to image impedance contrasts in the subsurface. It is used to determine velocities of layers and depths of interfaces in the first tens of meters. This near-surface seismic method allows us to use a controlled source to view Earth’s subsurface on a much smaller scale than a deep seismic method. Therefore, it can be applied in various locations that deep seismic sources cannot normally reach with a vibroseis truck.

2.7.2 Theory

Since this is a seismic method, it shares a lot of the same theory as deep seismic. The source is a sledge hammer hitting an aluminum plate. This creates seismic waves in the subsurface which propagate along or reflect off of layer interfaces. The frequency of these waves is typically around 100Hz but can reach up to 250Hz. Geophones measure the seismic waves as they travel back to the surface from the source.

In the area of investigation we assume a simple, two-layer Earth model with a slow layer of alluvium or travertine overlaying a faster layer of Mancos Shale. Seismic waves propagate directly through the slow layer to geophones along the surface, creating arrivals that follow a linear slope. Waves also travel through the slow layer to the Mancos Shale, where it travels along the interface at the speed of the lower layer. These waves travel back up to geophones and are recorded at a sooner time than the direct waves. These arrivals also create a linear trend of arrival times, but with a shallower slope. Figure 2.86 shows such a stack where the initial arrival has two distinct slopes. The first arrival represents the first velocity, \( V_1 \), while the second arrival represents the second velocity, \( V_2 \). The intercept of \( V_2 \) at zero offset is \( t_i \).

The equation to solve for the thickness of the top layer is:

\[
h_1 = \frac{t_i}{2} \frac{V_2 V_1}{(V_2^2 - V_1^2)^{1/2}}. \tag{2.42}
\]

where \( V_1 \) is the velocity of the first arrival, \( V_2 \) is the velocity of the second arrival, \( t_i \) is the intercept of \( V_2 \) at zero offset, and \( h_1 \) is the resulting thickness [24]. The thicknesses at each end of a line can be used to determine dips using the following equation:

\[
\alpha = \arctan\left(\frac{h_2 - h_1}{d}\right) \tag{2.43}
\]

By combining the layer thicknesses and dip angle, we can create geological models. We can use these geological models to determine regional trends in thicknesses and dips, which helps identify subsurface structures such as river channels or faults.
2.7.3 Objectives

1. Determine local dips and layer characteristics for each survey line.
2. Determine regional dip trends.

2.7.4 Equipment and Survey Setup

2.7.4.1 Equipment List

- Sledge hammer and aluminum plate:
  Acts as our controlled seismic source
- Trigger cable:
  Attached to hammer, tells geophones when to start recording data
- Geode:
  Box that converts analog data to digital data, sends data to laptop
- Laptop:
  Contains Seismodule Controller software to look at shots in real time
- 2 Geophone cables:
  Each contains 24 geophones, connects them to Geode
- 48 Sercel geophones:
  Measures vertical ground displacement
- Yellow cable:
  Connects geophone cables to Geode
- Garmin handheld GPS:
  Maps end points of survey lines
- Measuring tape:
  Helps set up survey line and measure out locations for geophones

2.7.4.2 Location

The first site was chosen based on a previous Field Camp’s data on Reservoir Hill, in which they suggested the presence of a fault. The presence of an ancient stream channel and the relatively thin remaining alluvial deposits were motivating factors in choosing additional sites on
Reservoir Hill. The Mother Spring Recon Site was also chosen as a location for hammer seismic, as there is a relatively thin layer of travertine deposits overlying a deeper lithologic unit with a higher velocity. Several other geophysical methods with shallow depths of investigation were used at the Mother Spring Recon Site, such as ground penetrating radar and self potential, which provided an opportunity for data integration. These locations are shown in Figure 2.85.

2.7.4.3 Survey Parameters

The parameters for each survey were dependent upon their main objectives. Some parameters such as number of shots the survey line length/orientation varied, while listening time and sampling rate remained the same. Survey length was dependent upon the orientation of the two geophone cables. Several surveys performed lines with just one cable, measuring a total of 48m. Other surveys connected the two lines to measure a total length of 96m. Some surveys were also conducted with two perpendicular lines, where each line contained one geophone cable. This perpendicular cable setup allowed for data collection even when the lines were in the same direction as geological dip. The sampling rate was chosen based on the Nyquist frequency. Therefore, each survey sampled at 2000Hz to avoid aliasing within the data. The listening time was 1s for each survey, providing a long enough time to collect all possible data from each shot.

2.7.4.4 Procedure

To acquire data, the aluminum plate is placed at specific locations along the geophone cable line. These points lie either a half spacing off the end or in between two geophones. Then the sledgehammer hits the plate, pausing in between hits, for at least 3 shots per location. If poor data is recorded for one trace, more stacks are added. The geophones collect the ground movement at the surface and sends this information through the cables to the Geode, where it is digitized. Listening time for one shot is 1 second.

2.7.5 Processing

2.7.5.1 Procedure

The stacked shot gathers for each end of the line were displayed and visually inspected. The velocity of the deeper layer was determined by measuring the slope of the first arrival at far offsets. This was done by finding a linear approximation of these first arrivals in the far offset interval. The rate of change between time and displacement was used for the velocity. The linear approximation was extended to zero offset, and this intercept was used for \( t_i \). At the farthest trace that no longer fit the line, a second line was drawn from that first arrival to zero time and zero offset. The slope of this line was used to find the velocity of the upper subsurface. These three values were then used to determine depths at each end-point.

Shot gathers from the center of the survey line were used to determine dip direction and approximate magnitude. Changes in the speed seismic waves propagate on either end related to the amount of slow alluvial material that overlaid the Mancos Shale.

Variations in the far offset line were used to characterize the shape of the interface. Arrivals that appeared to come before or after the expected time were indicated to represent undulations. Using this, along with the depths at either end, cross sections were constructed. Regional contour maps were also created to determine large scale dips and trends in the interface elevation and alluvial depths.

2.7.5.2 Errors/Noise

The primary source of error in the data is poor connections between the geophone and ground. This leads to lower amplitudes and missed arrivals in the data. Wind blowing on the geophones can cause added noise, as there is extra movement that is not caused by subsurface reflections. The survey locations were relatively active with several people walking by throughout the day. The Mother Spring Recon Site was particularly active, as there were several other groups doing surveys in the area. Walking causes extra seismic sources which can be picked up in the data and lead to added noise. Surveys on May 21st occurred between rain showers, which can lead
to variable velocities in the upper subsurface. The added water increases velocity, as the air that once filled pore spaces of subsurface material is replaced with a faster material.

2.7.6 Reservoir Hill Recon Site Results

Geologic cross sections were built using data that showed undulations along the survey line. Locations that failed to show features are included in determining regional dip trends.

2.7.6.1 5/18

*Figure 2.87: A model of alluvial deposit dip angle of 0.003 degrees with a thickness of 0.30m.*

The survey line on Reservoir Hill performed on May 18th (Figure 2.87) contains a very slight eastward dip and a small alluvial deposit thickness. It is believed that there is a small channel running beneath the surface into the Mancos Shale. This could be left over from a river channel that ran over the top of Reservoir Hill.
2.7.6.2 5/19

Figure 2.88: A model of alluvial deposit dip angle of 0.005 degrees with a thickness of 0.45m along Survey Line 1.

The first survey line on Reservoir Hill performed on May 19th (Figure 2.88) shows a topography with layers dipping at a larger angle than the previous line. The alluvial deposit thickness is also slightly larger. The river channel into the Mancos Shale is still present, however, its shape has changed slightly. This feature is aligned with the one seen in 5/18.

Figure 2.89: A model of alluvial deposit dip angle of 0.060 degrees with a thickness of 5.94m along Survey Line 2.

The second survey line on Reservoir Hill performed on May 19th (Figure 2.89) has a slightly larger dip angle with a much greater alluvial deposit thickness. The channel is not present in the stack. This is likely due to the high angle between this survey line and the connection of the channel feature between the two days.
2.7.6.3 5/23

Figure 2.90: A model of alluvial deposit dip angle of 0.020 degrees with a thickness of 0.95 m taken along Survey Line 1 created by calculating layer depths.

The first survey line on Reservoir Hill performed on May 23rd (Figure 2.90) has the smallest dip, with a thickness that rests in between the other days’ measurements. The river channel is not present in this line, and the small thickness indicates that this area was farther away from the river. This is due to the smaller amounts of alluvial deposit from river erosion.

2.7.6.4 Regional Trends

Figure 2.91: A model of alluvium deposit thickness for all areas on Reservoir Hill Recon Site.
The regional thickness trend on top of Reservoir Hill shows an area of thick deposit of alluviunm on the far east side of the survey area. Depth to the Mancos Shale in this area is up to 7\text{m}. The thickness decreases moving west on the hill, and reaches its lowest thickness, less than 2\text{m}.

*Figure 2.92: A model of the elevation of the Mancos Shale / alluvium interface.*
The area in the northeast corner shows a trend where thickness increases to the south, corresponding to uphill topographically. The maximum thickness was found to be 7.4 m, and decreases to 1.5 m at the northern end. At the southern point, there are two data points which have significant differences between them (7.4 m versus 4.7 m).

Figure 2.93: A model of alluvium thicknesses (in meters) for far east corner.
Elevation of the top of the Mancos Shale was found by subtracting alluvial deposit thickness from topographic elevation. The main change in elevation for this interface runs from a high point in the southwest to a relative low in the middle of the survey area and rises again to the east side. The scale of this change is on the order of tens of meters. The dip of the alluvium/Mancos Shale for this area is eastward.
The trend in alluvium thickness shows an increase moving towards the south and east. The magnitude of these changes range from 4.4\text{m} in the east to 2.3\text{m} in the north.
Figure 2.96: A proposed model of the elevation of the Mancos Shale / alluvium for area near pavillion and water tower.

The top of the Mancos Shale shows an elevated feature running south west to north east. There is a steep dip to the west of this and a shallow dip to the east.
2.7.7 Mother Spring Recon Site

Figure 2.97: A model of alluvium thicknesses for Mother Spring Recon Site.

The thickness of travertine deposits shows a thinning in the middle of the survey area. The east and west ends have thicknesses ranging from 4\,m to 7\,m. The area in the middle have smaller values of below 3\,m thick.
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2.7.8 Interpretation and Conclusion

2.7.8.1 Interpretation

Since the elevation in the Mother Spring Recon Site is relatively flat, the elevation of the top Mancos closely follows the inverse of the travertine thickness. There is a general dip to the south and east.

The channel feature seen on the east end Reservoir Hill does not show the sharp characteristics indicative of a fault. It is likely that this is a broader feature like a river channel.

The regional dip trends seen in Figure 2.92 are strongly influenced by the surface topography. Elevation changes of the interface are much larger than the changes in thickness for the area. The continuous area of thick alluvium deposits in Figure 2.91 running east of the pavilion is a promising indicator of an ancient river channel. The interval elevation for this area does not show a syncline feature that would indicate a river bed. The thickness and elevation decrease to the northwest, so it is likely this thick deposit is a bank of the un-imaged channel. The data for the Reservoir Hill Recon Site is sparse, so any interpretation of areas between survey locations is unreliable.

The data from the Mother Spring Recon Site shows a highly variable interface elevation that is inversely related to the travertine thickness. This suggests a previously undulating terrain that was covered with flows from the Mother Spring.

2.7.8.2 Conclusion

Hammer seismic provides an effective method for imaging the shallow subsurface. Survey locations on Reservoir Hill provided information on the top Mancos elevation and alluvium thickness and suggested the features seen in previous years are not likely to be faults. Data from the Mother Spring Recon Site showed a highly undulating subsurface interface that was filled with travertine to produce the observable flat surface.
Recommendations for future surveys include expanding the Reservoir Hill Recon Site to the north and west in an attempt to image a syncline river channel feature and conducting more surveys in the current location to provide better regional dip interpretation. More survey locations should also be added at the Mother Spring Recon Site to provide a more holistic view of regional dip and travertine thickness. Locations should be added to the north by the bend in the San Juan River. This can be integrated with ground penetrating radar and self potential which conducted surveys in the same area.
Figure 2.99: Total survey area for GPR in Pagosa Springs
2.8.1 Introduction

Ground penetrating radar (GPR) uses electromagnetic (EM) waves to detect changes in electrical permittivity and conductivity in rocks. It is specifically used for detecting changes in subsurface EM properties. The transmitter sends EM waves into the ground at certain frequencies, and then the receiver picks up the reflected signals. This is important to us because subsurface changes in permittivity indicate the presence of groundwater and possibly geothermal fluid [25].

GPR and seismic methods are very similar because both include wave propagation in the subsurface, analysis of how waves interact with buried reflectors, and two-way travel time calculations.

In the Pagosa Springs surveys, GPR was an experimental method conducted more for learning purposes than for its contribution to the overall field camp objectives. The method has not performed well in past classroom exercises because of the conductive soils in Golden, Colorado. Therefore, field camp served as the first major opportunity for students to interpret GPR data, which they also collected.

2.8.2 Theory

GPR utilizes electromagnetic waves to image the subsurface. The paths these waves take are governed by the 2D electromagnetic wave equation [26]:

\[ \nabla^2 E = \mu \sigma \frac{dE}{dt} + \mu \epsilon \frac{d^2 E}{dt^2}, \tag{2.44} \]

where \( \mu \) is the permeability, \( \sigma \) is the conductivity, \( \epsilon \) is the permittivity, \( E \) is the electric field, and \( t \) is time.

Permeability is the measure of a material’s ability to sustain an internal magnetic field in the presence of an applied field. In isotropic materials, it is represented as a scalar. For anisotropic materials the value becomes a tensor [27]. Conductivity is the measure of a material’s ability to conduct an electric current. The value is dependent on the geometry and temperature of the material. For highly conductive materials such as the Mancos Shale in Pagosa Springs, the first term in equation 2.44 dominates and the signal becomes quickly attenuated, preventing anything below that material from being imaged.

Permittivity is the measure of how easily a material to become aligned with an external electromagnetic field [28]. Since permeability and conductivity values for the earth materials imaged in the field are very small, the permittivity is the main control on impedance contrasts and reflections. Permittivity is a complex value with the real component relating to the potential energy stored while rotating to align with the external field [29]. Therefore, permittivity is frequency dependent as after a certain frequency the molecule cannot fully rotate, and the potential energy decreases.

Different materials in the earth will have different permittivities for the same current. When two materials are touching, their different permittivities cause an impedance contrast between two layers or a contrast in effective resistance for the alternating current (AC) that is traveling from one layer to the other. This contrast creates a reflection of the radar wave, which travels back up to the receiving antenna. The amplitude and phase of this reflected wave is determined from the relative differences in electromagnetic properties, and the two-way travel time is calculated using the following equation [30]:

\[ t = \sqrt{\frac{x^2 + 4z^2}{V^2}}, \tag{2.45} \]

where \( x \) is the offset between antennas, \( z \) is the depth of the interface causing reflections, and \( V \) is the velocity of the subsurface above that interface. This velocity is determined using a common midpoint gather (CMP).

CMPs are a data acquisition method that involves moving a transmitting and receiving antenna away from a fixed midpoint at constant intervals. The travel-time curve obtained from a
CMP can qualitatively tell us about the velocity of the subsurface; flatter reflection curves correspond to a faster velocity and vice versa. We can also quantitatively solve for the velocity from the CMP plot. At far antenna offsets, reflections become linear, and the slope of their linear segments can be used to determine subsurface velocity using the equation:

$$V = \sqrt{\frac{1}{m}}, \quad (2.46)$$

where $m$ is the slope of the reflection.

### 2.8.3 Objectives

1. Image the shallow subsurface of the Dakota Sandstone and travertine deposits located west of the Mother Spring.
2. Measure anisotropy within the Dakota Sandstone.
3. Produce 3D data distributions of the Dakota Sandstone to identify lateral continuity of large, homogeneous zones where no signal was reflected in data collected early on.
4. Identify subterranean water flow near the Mother Spring.
5. Locate and map possible infrastructure west of the Mother Spring.

### 2.8.4 Equipment and Survey Setup

#### 2.8.4.1 Equipment List

- **SPIDAR multichannel system**: NIC box, software, sensors, and WiFi antenna for recording data.
- **100 MHz antennae (unshielded)**: One antenna to transmit EM waves into the ground and one antenna to record them.
- **500 MHz antennae (shielded)**: One antenna to transmit EM waves into the ground and one antenna to record them.
- **Laptop**: To see data in real time during the survey.
- **Garmin hand held GPS**: To obtain coordinates of the survey line end points.
- **Measuring tape**: To set up survey lines.
- **GPR cart**: To carry GPR equipment and maintain a constant antennae spacing.

#### 2.8.4.2 Location

Locations of all the GPR surveys conducted in Pagosa Springs is found in Figure 2.99 with specific sites shown below.
2.8.4.3 Survey Parameters

Throughout the field camp in Pagosa Springs, different GPR groups performed one or more of the following surveys: common offset profile, 3D volume, azimuth, and common midpoint gather. These methods are briefly explained as follows:

- **Common offset profiles** take several traces at given locations and combine them to create a 2D cross section. The separation between the transmitter and receiver remains fixed, and the lateral placement of each trace is dictated by the odometer wheel. To prevent aliasing, traces were placed a quarter wavelength from each other. The velocity was estimated to be $0.1 m/ns$, and frequencies produced by the transmitter can be up to twice as much as the central frequency. For the $500 MHz$ antennas, the sample interval was determined to be $2.5 cm$, and for the $100 MHz$ antennas the sample interval was $10 cm$. Several 2D profiles were recorded at sites across Pagosa Springs. Locations include an outcrop of Dakota Sandstone southeast of the high school and at the Mother Spring Recon Site.

- **3D grids** are set up as a series of parallel common offset profiles. $500 MHz$ antennas were used for the acquisition because they provide better resolution. The parameters used for the grids are similar to those used for the 2D cross sections, with line spacing being $25 cm$ apart. Two grids were acquired, one near the high school and one at the Mother Spring Recon Site.

- **Azimuth testing** measures the anisotropy of a particular location. It is performed using $100 MHz$ antennas arranged $6 m$ apart, centered on a common midpoint. A trace is gathered at a starting orientation, and then the antennas are rotated around the midpoint by 10 degrees. This is repeated for either 180 degrees or until a full circular profile is recorded, depending on time constraints.

- **CMPs** utilize two $500 MHz$ antennas that are centered at a common midpoint. One trace is taken per offset, and then the antennas are moved $2 cm$ away from the midpoint and another trace recorded. This is repeated until the total offset is $4 m$ away. CMPs are taken either on or near a common offset profile to ensure the geology is similar to that seen in the cross section.
2.8.4.4 Procedure

To begin a survey the laptop and NIC are connected via WiFi. All cables are then connected to the NIC with the battery being connected last. Survey line names and parameters are set using the laptop interface. Before a line is acquired, the delay time between the transmitter and receiver is set. The beginning of the signal or ‘first break’ of a trace is lined up to where it comes after 10% of the total listening time. A start button is pressed on the laptop to begin the survey. A real-time cross section is built on the screen as the line is recorded with gain and dewow filter being applied. The data for one day of acquisition is stored in a compressed file, which contains the data and header files for each line.

2.8.5 Processing

2.8.5.1 Procedure

Before we could interpret the data collected in the field, we had to make several corrections to the data. In all cases the first to be applied was the time-zero correction. This correction accounts for the delay between the time that the transmitter is triggered and the time the first arrival is received and is done by shifting the traces back in time until the first arrival is at time zero.

Next we applied a dewow filter to the data. The dewow filter removes low-frequency background noise resulting from the inductive coupling of the GPR transmitter with the ground surface. This inductive coupling creates a large amplitude, low frequency, secondary diffusive current into the ground that is similar to the smoke-ring effect in a TEM experiment. This secondary current dominates GPR data at smaller offsets and becomes less prevalent at larger offsets. The dewow filter acts as a high-pass filter, removing the effect of the secondary current and allowing the remaining data to be enhanced.

For much of the data that was collected, a gain correction in the form of an Automatic Gain Control (AGC) was necessary to amplify weak signals that are especially common at later times in the data. AGC uses a moving window to scale the amplitudes within that window and create a more uniform signal throughout the dataset. The window size and amplification magnitude could be uniquely set for specific data sets to provide the best compensation between amplifying reflected signal and noise.

For the 3D datasets, it was necessary to take the envelope of the signal amplitudes before plotting depth slices. Also called the instantaneous phase, the envelope of a signal effectively creates a new signal by fitting a curve to the positive peaks of the original signal. The amplitudes of this new signal are easier to compare than the original because they are all positive.

2.8.5.2 Errors/Noise

The main sources of noise which we encountered in the field were other electromagnetic sources such as the TEM surveys, power lines, and the radios we all wore in the field. Additionally, we also encountered many objects above ground which were very conductive, either because they were metallic (like cars), or because they hold a lot of water (like trees or people). These additional sources and conductors caused interference in our data and created reflectors and other artifacts in the data.

There were also sources of human error which affected the data. Most of this data was collected over uneven ground, which hindered our ability to create survey lines which were straight, of the exact desired length, and constantly spaced. This led to a reduced signal-to-noise ratio in the data and affected the accuracy of the travel times we saw in our data.

Additionally, the uneven ground at the survey locations also hindered our ability to maintain good contact with the ground, causing the first arrival time for that particular trace to happen later than it would with good contact. Since our time-zero correction is the same for all traces, this causes the travel-time and resulting depth information to be inconsistent for traces where good contact was achieved and traces where poor contact was achieved.
2.8 GPR

2.8.6 Results

The subsections that follow detail the GPR results that were obtained in Pagosa Springs from May 16 through May 23. The data for May 16 through May 20 was collected south of Pagosa Springs High School, and the data for May 20 through May 23 was collected near the Mother Spring at the Mother Spring Recon Site.

2.8.6.1 5/16

Five surveys were conducted on May 16. These included three common offset profiles along approximately 180 m lines using both the 500 and 100 MHz antennas, two CMP gathers with both sets of antennas, and one 100 MHz anisotropy test. All lines were positioned on a hillside at approximately the same location.

![Figure 2.102: Line 1 common offset profile collected with the 500 MHz antennae.](image)

In Line 1, which was collected in the northeast direction, there are vertical discontinuities in the early arrivals at distances of 80 m and 120 m. These are due to poor coupling of the transmitter with the ground as discussed in the Sources of Error and Noise section. On the right half of the profile, the signal seems to disappear after 10 ns.

The signal penetrates much further on the first half of the profile than on the right half, which can be explained by a transition from the more resistive Dakota Sandstone to the more conductive Mancos Shale as we went down the line.
In Line 2 the signal penetrates much further on one half of the line than the other. Since the data were collected in a direction opposing the direction Line 1 was collected in, we see the signal penetrating further on the right half.

Figure 2.103: Line 2 common offset profile collected with the 500MHz antennae.
Figure 2.104: Line 3 common offset profile collected with the 100 MHz antennae.

Line 3 shows a very heterogeneous subsurface. There are several layers of reflections at 25, 40, and 55 ns. The signal maintains a high amplitude for a relatively long listening time. The inconsistent signals seen at early times are again likely an artifact of processing.
The signal from 0 to 20\text{ns} is noise and is likely an artifact of processing. From 30 to 50\text{ns} there is an almost horizontal layer, but it is very complex in content at distances from 40\text{m} to 80\text{m}. The signal is bending and curving in shape, which indicates that there are significant spatial contrasts in permittivity. Additionally, at 40 and 100\text{ns} from 0\text{m} to 30\text{m}, there are at least 2 slightly dipping layers. As distance increases from left to right, the signal vanishes, possibly due to conductive soil.

2.8.6.2 5/17

The May 17 surveys consisted of one 500\text{MHz} and one 100\text{MHz} common offset profile along a 96\text{m} line running parallel to Trujillo Road, a CMP gather for both sets of antennas, and a 100\text{MHz} azimuth test.
In the first dataset above, there appears to be a vertical spike at an offset of 13m. We can conclude that this spike is synthetic and is likely due to someone transmitting a signal with his or her radio. There seems to be a boundary between two distinct sediment deposits at 30m because the signal barely penetrates deeper than 5ns on the left half, whereas the signal on the right half penetrates far deeper. Shapes of sediment boundaries at early arrivals seem to be fairly horizontal, whereas late arrivals reveal that sediment from deeper layers seems to have very discontinuous and tilting boundaries.
In the second dataset we see the same features as in the first including flat sediment layers at the top of the profile, a vertical sediment boundary (this time at 60m), and discontinuous and tilting boundaries deeper down in the profile. This time the signal penetrates deeper on the right side of the profile, but this is because data were collected in the opposite direction that it was in the previous profile.
Figure 2.108: Results of the azimuth test conducted with 100 MHz antennas.

Figure 2.108 shows the results of the azimuth test that was conducted in order to study the anisotropy of the Dakota Sandstone at the High School Recon Site. The scattered points resemble a sinusoidal pattern with the peak and trough falling between the fracture alignment. Velocities are higher at the blue marker and lower at the red. These correspond to high velocities parallel to the fractures and low velocities perpendicular to the fractures. This is to be expected since the EM waves traveling along a fracture likely go through void space filled with air and do not experience travel time delays due to the absorption and re-emission of the waves by the rock.

2.8.6.3 5/18

The May 18 surveys were conducted further north at the high school site than the previous days’ surveys but remained largely over the exposed Dakota outcrop. These surveys consisted of one 500 MHz and one 100 MHz common offset profile along a 100m long line, a CMP gather for both sets of antennas, and a 100 MHz azimuth test. The azimuth test used 10 degree increments for 180 degrees.

Data from 0 to 5 ns have good conformity and show that there are 2 almost horizontal layers. Data below are diffusive, thus we are not able to extract information that is of our interest. In this plot there are one or more regions of “dead space” where no reflections occurred, indicating homogeneous areas where fluid flow could occur.
In the profile above, we see multiple areas of "dead space" where no reflections occurred. These regions indicate regions that are homogeneous, and could be fluvial sand deposits. The leftmost region of dead space, centered at an offset of 20m and bounded above by the flat reflection at 13ns, attenuates the signal. Therefore, it is likely conductive and is a potential aquifer.
In the profile above there appear to be three bumpy reflectors at 25\text{ns}, 45\text{ns}, and 65\text{ns}. These could be periodic fluvial deposits, but it is difficult to tell.

**2.8.6.4 5/19**

The May 19 surveys consisted of one 500\text{MHz} and one 100\text{MHz} common offset profile along a 100m long line, a CMP gather for both sets of antennas, and a 100\text{MHz} azimuth test. The azimuth test used 10m increments for 360 degrees, and a 6m offset.

Velocity analysis of the 500\text{MHz} CMP gather returned an average velocity for the Dakota Sandstone in the area of 0.094\text{m/ns}, and analysis of the 100\text{MHz} CMP gather returned an average velocity of 0.091\text{m/ns}.
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Figure 2.111: Results of the azimuth test collected with 100 MHz antennas.

The azimuth test results were especially clean for this day as they demonstrated a clear sinusoidal pattern of high velocities parallel to the fractures and low velocities perpendicular to the fractures.
The profile above presents us with a series of reflectors from 0\textit{ns} to 100\textit{ns}. A spike at about 72\textit{m} is synthetic and was likely caused by someone using his or her radio. Additionally, on the left side prominent hyperbolic curves starting from 100\textit{ns} might be from power lines to the west of the line, while the shallow, hyperbolic features near 350\textit{ns} are presumably from a tree, underground water, or any large metallic object that is some distance away from our survey site.
In the profile above there is a region of “dead space” at an offset of 90 to 115 m, bounded on top by a reflector at 7 ns. Signal is able to penetrate this region, so it is likely a homogeneous region that does not contain water.

2.8.6.5 5/20

The data from the previous days motivated a 3D survey to be conducted over the Dakota outcrop on May 30 in the hopes that the homogeneous features visible in Figure 2.113 would be laterally continuous and therefore visible in a slice plot of 3D data. We collected data for 60 lines, which ran from north to south, were each 60 m long, and had a spacing of 25 cm. The CMP was 4 m long and used an offset interval of 2 cm. Velocity analysis of the CMP gather returned an average velocity of 0.10 m/ns.

A slice plot was created for this 3D volume and is shown in figure 2.114. The 0.5 m depth slice shows a heterogeneous surface with a sliver of low amplitudes on the southern-most part of the slice. This is likely were the Mancos Shale begins in the area. The 1.5 m depth slice - and the 1 m depth slice to a lesser extent - is dominated by low amplitude signals, revealing a conductive, homogeneous region that is likely Mancos. The 2 m depth slice shows high-amplitude pockets throughout the section, potentially where fluid flow has eroded the overlying rock material, creating a heterogeneous surface where much of the transmitted signal is being reflected.
2.8.6.6 5/21

The May 21 surveys were the first to be conducted at the Mother Spring Recon Site. These consisted of one $100 MHz$ CMP gather and $500 MHz$ common offset profiles along five lines of varying orientations and lengths, where $100 MHz$ antennas were used at every line and $500 MHz$ antennas were used at the first line as well.
Figure 2.115: Line 1 common offset profile collected with the 100MHz antennas.
Line 1 was aligned east to west, beginning near the Springs Resort parking lot and ending by the river. The data collected with different antennas both show a dipping interface between 50 and 100m and a gently dipping interface at larger distances. The square-shaped areas of low signal propagation are not aligned between the two figures.
Line 2 runs perpendicular to the first, starting in the south and running north. The data show an undulating interface between 50 and 100 ns. There is an area of low propagation at 150 m where the travertine thickness is at a maximum.
Line 3 is located at the far north of the Mother Spring Recon Site and is orientated east/west. The data show a strong reflector between 40 and 60 ns that dips to the east. There are two areas in the first half of the common offset gather that show reduced amplitudes after 50 ns. Between these are a few traces with similar amplitudes to the rest of the cross section.
Line 4 runs along the San Juan River from north to south. It shows several layers of signal down to 80\(\text{ns}\) where the amplitudes are diminished. The reflections are relatively flat with small undulations in the first 100\(m\).
Line 5 was aligned parallel to Line 1 and ran west to east. There is a similar dipping interface that abruptly ends at 100 m.

2.8.6.7 5/22

On May 22, a 100 MHz 3D survey and a 100 MHz CMP gather were done at the Mother Spring Recon Site. The 3D survey consisted of 110 lines running east to west with a length of 30 m and a spacing of 10 cm. CMP velocity analysis revealed that the average velocity of the travertine is 0.09 m/s.

Figure 2.121 shows the depth slices that were taken from the 3D data volume that was collected and processed. The lack of signal propagation through the travertine confines the depth slices to the first meter. Linear areas of high amplitude in the upper right corner appear to be continuous in the top two depth slices. The obloid feature in the bottom left is also continuous through the 0.43 m and 0.64 m slices.
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2.8.6.8 5/23

The 3D survey conducted on May 23rd was inspired by a groundwater pipe buried at the Mother Spring Recon Site that has outcrops at the surface in multiple places. The composition of this pipe is variable, changing from PVC near the Mother Spring to metallic by the San Juan River to the west.

The 3D survey consisted of a 40m by 20m grid with 41 parallel lines spaced 1m apart running...
from the northwest to the southwest and 3 parallel lines running from the northeast to the southwest and spaced approximately 10 m apart. The 41 lines were positioned such that they were centered above the supposed location of the pipe, and the center line of the 3 additional lines was meant to run along the pipe. Velocity analysis of the CMP gather that was conducted at this site returned an average velocity of 0.085 m/ns, which is consistent with the travertine velocity that was calculated on the previous day.

The following figures show the common offset profiles collected for select lines, and a 3D model of the pipe location that was constructed from the May 23 dataset.

![Figure 2.122: Line 2 common offset profile collected with the 500 MHz antennas](image)

The black lines were added in post-processing to denote an area where anomalously high-amplitude reflections indicate that the soil has been disturbed. Since this region is approximately halfway down the line, and the line is supposed to be centered over the pipe, it is reasonable to conclude that this area was dug up to bury the pipe. This response is consistent with a PVC pipe, since plastic is not conductive and reflectors are still apparent beneath the region where soil disturbance is visible.
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Figure 2.123: Line 24 common offset profile collected with the 500 MHz antennas

The attenuation seen in Line 24 and bounded by the black lines is similar to the feature seen in Line 4 with a moderate lack of signal. There are also reflections under where the pipe is hypothesized to be, indicating some signal is penetrating the pipe and propagating underneath. This is consistent with a PVC pipe that has lower conductivity that a metallic one. The surface reflection is non-linear, which could be from the digging up of soil to insert the pipe.
The vertical area with no amplitude corresponds to a metallic pipe, which attenuates the signal much more than a PVC pipe. This prevents any energy from penetrating below the object, producing the lack of signal. This area is surrounded by a black box.
When the common offset profiles are aligned with the survey grid, the area of attenuation is linearly aligned across each profile and maintains a constant depth. This supports the hypothesis that the cause is a pipe. By analyzing the amount of attenuation caused by the pipe, it is possible to determine the location at which the composition of the pipe changes from PVC to metal. This change occurs between $28\,m$ and $32\,m$ along the survey grid.

### 2.8.7 Interpretation and Conclusion

CMGs were gathered for each location, and velocities were determined. Depth migrations were not performed for all of the lines because interval velocities could not be determined. The last day’s data were migrated to depth using the CMP velocity to provide an estimate of depths of the travertine.

#### 2.8.7.1 High School Recon Site Interpretation

There are several homogeneous features seen in the data gathered from the High School Recon Site. The data in figure 2.107 show two main reflectors at $7\,ns$ and $15\,ns$ with an area of low amplitudes in between. The homogeneous area for the next day seen in figure 2.110 is much larger, with a bottom reflector at $25\,ns$. 5/19 data in figure 2.112 have a similar shape in the homogeneous area and are bounded on the lower end by a reflector at $15 – 20\,ns$. The 3D grid in figure 2.114 shows no evidence of a continuous feature of low amplitude. The data from this day and from 5/17 are located in the same area, whereas the other two days’ data are located farther east. It is likely this feature was not captured by the 3D survey but exists in the area between the two surveys that captured it. The depositional environment for the Dakota Sandstone is a beach environment, so it is unlikely this feature is fluvial.

#### 2.8.7.2 Mother Spring Recon Site Interpretation

Figures 2.115 and 2.120 show a dipping interface that is similarly shaped. This corresponds to a change from travertine on the surface to vegetation. Other lines collected for that day do not provide much data for larger depths, indicating a highly conductive travertine layer. The upper reflections show undulating interfaces, which can also be seen in the 3D data in figure 2.121. There appear to be pockets of high amplitude response at $0.43\,m$ and $0.64\,m$. These could possibly be low spots in the old terrain that were filled in by flows from the Mother Spring. Data collected on 5/23 identified a subsurface pipe that moved water from near the Mother Spring to the San Juan River. Figure 2.125 shows the location of this pipe in relation to the survey lines. It is
possibly to determine the composition of this pipe by the amount of attenuation caused. Areas with high attenuation correspond to a metallic pipe, and areas with more signal are indicative of a plastic PVC pipe. The depth of the travertine was found to be $2 - 3 \text{m}$. This confirms the results of the 2012 field session, which found the travertine thickness to also be $2 \text{m}$. Apparent dips seen in the common offset profiles correspond to the change from travertine to vegetation and soil. The conductive soil is responsible for the lack of signal propagation. The dips could be a result of elevation change relative to the subsurface layer.

### 2.8.7.3 Conclusion

Ground Penetrating radar (GPR) is a significant geophysical tool that has evolved into a sophisticated technique capable of providing us with high-resolution pseudo imagines of the near-subsurface. Its ability to detect changes in conductivity and permittivity GPR make GPR optimum for detecting soil, bedrock, groundwater, and sediment boundaries as these differ in conductivity compared to their background. In the field we implemented azimuth survey, common offset profile survey, common midpoint gather survey, combination of a series of common offset profile results in 3D volume profile. Most results are of excellent resolution. For future GPR surveys, a higher degree of filtering should be utilized.
3. Joint Interpretation and Final Results

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3.1 Results and Interpretation

3.1.1 Introduction

Upon completion of processing, data from each method were integrated in order to generate a comprehensive overview of the lithology beneath Pagosa Springs. This process involved layering the datasets and looking for points of agreement or disparity. Data were correlated along CR200, CR411, the Mother Spring Recon Site, and the Reservoir Hill Recon Site using geology, deep seismic, SP, GPR, hammer seismic, MT, and TEM datasets. DC resistivity data is not included because the 3D artifacts from the bends in the road were too strong to allow integration with other methods. Gravity data was not included in integration because the data did not contribute to the objectives of the investigation. This was likely a result of off-axis 3D effects caused by curves in the roads.

3.1.2 Objectives

- Correlate TEM, MT, deep seismic, gravity, SP, hammer seismic, and GPR results in order to reduce uncertainty in the final models produced for CR200, CR411, and the Mother Spring and Reservoir Hill Recon Sites.
- Draw conclusions about the sources and potential flow paths of water towards the Mother Spring.
3.1 Results and Interpretation

3.1.3 CR411

3.1.3.1 Geology and Deep Seismic

A deep seismic survey was conducted along CR411. These datasets, along with geologic information including well logs, are integrated to form a more complete interpretation of the subsurface north of Pagosa Springs.

As with integration of CR200, the deep seismic team worked closely with the geology team to choose appropriate velocities for building a velocity model to use during the migration. NMO velocities using CMP gathers proved to be more useful, producing depth estimates that better corresponded to local well logs as geology at those points was known absolutely. Therefore, NMO velocities were selected to create images that were more closely representative of known geology. From here the geology was interpreted from the deep seismic profile based on the preliminary geology profiles.

![Figure 3.1: Integrated deep seismic and geology data for CR411 with interpreted geologic structure overlain.](image)

The smooth line in 3.1 corresponds to the modeled data considering the information in the plot on the bottom, which corresponds to a final geological interpretation of the subsurface. During processing, the deep seismic data were simplified into straight segments. Therefore, the integration shown above cannot corroborate the data, and we cannot make significant conclusions regarding the depth migrated cross-section with the interpreted geology of the subsurface along CR411.

3.1.3.2 DC, Seismic, and Geology

Despite the DC resistivity data being quite noisy, we attempted to fit the data to both the initial geologic cross section and the cross section modified by the seismic data.
Figure 3.2: Integrated DC resistivity and geology data for CR411.

In Figure 3.2, the 2D DC resistivity inverse model is overlaid on the geology cross section for CR411. As the geologic layers are mostly flat, the changes in resistivity across the DC line are likely not due to large changes in lithology. It is more likely that the anomalies seen in the DC data are pure noise, or the anomalies are caused by smaller-scale geologic features, such as calcite deposits seen on the line.
3.1 Results and Interpretation

3.1.4 CR200

3.1.4.1 MT, TEM, and Geology

MT data images show changes in apparent resistivity, which correspond with different geologic layers. This is especially useful for imaging to greater depths and identifying depth to basement. TEM images vertical variations in conductivity at shallower depths. 2D MT contour images are compared to 1D TEM conductivity profiles in an attempt to correlate the datasets as a means of reducing overall interpretation uncertainty. The two data sets are comparable because TEM measures conductivity, which is the inverse of what MT measures (resistivity).

Four TEM stations and seven MT stations were recorded at various locations along the CR200 line. All of the TEM stations fell within the range of the geologic cross section. However, only two MT stations fell within this range. Relating the TEM values to those of MT may confirm general trends in relative conductivity values in the northern section of the CR200 cross section.

In conclusion, while the integration of the DC resistivity data with geology and seismic data did not refine our understanding of CR411, it did help confirm that the DC resistivity data on this line was heavily corrupted by noise and that we should not attempt to interpret any of the apparent anomalies on the line.

Figure 3.3: Integrated DC resistivity, seismic and geology data for CR411.

In figure 3.3, the 2D DC resistivity inverse model is overlaid on the geology cross section for CR411 that includes the new features determined by the seismic data. While the DC resistivity data still mostly appears as noise, the fact that it was performed over a fractured subsurface may have also contributed to the appearance of the DC resistivity data.

In conclusion, while the integration of the DC resistivity data with geology and seismic data did not refine our understanding of CR411, it did help confirm that the DC resistivity data on this line was heavily corrupted by noise and that we should not attempt to interpret any of the apparent anomalies on the line.
Figure 3.4 displays the TEM data, represented in blue and centered at $T$, overlain on 2D MT data on CR200. While providing more data in shallow earth, the TEM data only reaches an interpretable depth of around $150-350m$ as a result of wave attenuation caused by the conductive Mancos Shale. When comparing the relative conductivity values, MT and TEM conductivity value trends correlate well in the upper section of the graph. These values are then referenced against the geologic cross section to evaluate the accuracy of the model, as well as the data.

Figure 3.4: 1D-inverted TEM data (blue lines) with station locations (purple T’s), overlain on 2D MT inversion for northern portion of CR200. Color bar shows relative values because integration uses a relative scale.

Figure 3.5 represents TEM and MT data overlain on the geologic cross-section for CR200. The TEM data aligns with the data in the cross-section, although topsoil is not depicted by the cross-section. While the 2D MT data does not correlate well with the data in the cross-section, both the MT and geological data suggest the depth to basement is greater around the $5000-6000m$ area than it is around the $9000-10000m$ area on the cross section (see Figure 3.5).

The integration of these datasets suggests that there is some uncertainty in the true depth to basement along CR200. However, it is uncertain which dataset should be given greater credibility because of the relative lack of well data in the area north of CR200.
3.1.4.2 Deep Seismic and Geology

Three well logs along the CR200 line provided information about formation depths and thicknesses of geologic units, which represented known values with which other datasets should likely agree. Initial geologic cross sections were constructed using this information along with information obtained during geologic investigations of the area. Early deep seismic images used velocities generated from well data as initial estimates for layer velocities. However, inspection of these images against known formation depths did not agree, and thus NMO velocity values were used to produce new images until these datasets agreed. The new velocities produced an image with more accurate depths, which was labeled with geologic units by the geology team. Through the use of a trusted image from the deep seismic team as well as well log information, the overall geometries became more apparent. Figure 3.6 shows an integration of deep seismic datasets with a geologic interpretation. The bends in the road create lateral variations that are not accounted for when the data are forced into a 2D line during processing.
3.1.4.3 Deep Seismic and MT

In Figure 3.7, the 2D MT inverse model is overlaid on the deep seismic line for CR200. Along with the MT model showing a more resistive region at a depth of around a kilometer, deep seismic data can assist in confidently interpreting the fault zone in the area. This fault zone likely contains fresh water as the MT model suggests since the resistivity change with depth is not abrupt and covers a large area intersecting with the interpreted location of the faulting. Around Flag 2600 a less resistive feature is observable. This is a result of the site being located on a ridge with a thicker layer of Mancos Shale near the surface compared to the rest of the line. The absence of resistive media here is also due to the instrument not recording as many low frequency data points at this location. Thus inversion at depth is as accurate as at other sites.
3.1.4.4 Geology and DC

To better understand our DC resistivity data, we placed it over our initial geologic cross section.

With the DC resistivity data overlaid on the geologic cross section, we can better understand the general trend of resistivity. The more resistive Dakota and Morrison formations are closer to the surface near the south portion of the cross section, contributing to the higher resistivities seen in the DC resistivity. As we move north and the Mancos shale thickens, the DC resistivity data becomes less resistive, which agrees with the geology.
Unfortunately, because the DC resistivity data is quite noisy due to the crooked line geometry of our line, it would difficult to integrate the DC resistivity data with other methods’ data or to refine the geologic cross section based on the DC resistivity. However, this simple data integration is a good method to better understand our DC resistivity data and to ensure that it agrees with the regional geology.

3.1.4.5 Final Integrated Model for CR200

Figure 3.9 shows the final integrated model for CR200 including TEM 1D inversions, an MT 1D inversion, deep seismic data, and geologic interpretation. The TEM data suggest a topsoil layer of approximately 30m, which is plausible based on the deep seismic and MT data. The geologic interpretation suggests a relatively large fault centered at about 2.5km. The MT data show a spike in resistivity at the depth of the fault, which suggests that the fault may act as a flow path for fresh water. The large resistivity value could instead be indicative of the top of the basement. However, the conductivity values and the shape of the anomaly in the 2D MT profile (Figure 3.7) suggest that this anomaly is water.

![Figure 3.9: Final integrated model with TEM, MT, deep seismic, and geologic data for CR200. Integrated model with TEM 1D inversions, MT 1D inversion, deep seismic data, and geologic interpretation.](image)

3.1.5 Mother Spring Recon Site

Several grids were set up on the Mother Spring Recon Site for use in gravity, SP, GPR, and hammer seismic surveys. As a result of the close proximity of the survey grids to each other and imaging of similar depths, the data sets are able to be correlated, allowing more accurate conclusions to be drawn about the shallow subsurface.

3.1.5.1 SP and Gravity

Although SP and gravity methods measure very different properties, SP data were integrated with gravity data in an attempt to correlate anomalies in both datasets (see Figure 3.10). The datasets show that two anomalous areas align. The low-voltage area in the upper right section of
the SP lines up with the variation in the gravity trend which runs horizontally along the middle of the grid. This indicates the potential for radial water flow from the Mother Spring. SP clearly indicates a large area of near-surface water flow in the anomalous area, explaining the anomaly in the gravity data. The marginally larger gravity reading is likely caused from relative saturation of pore space and crevices compared the surrounding ground. This saturation seems to extend radially, however the direction cannot be concluded from the available data.

Figure 3.10: SP overlain on Gravity data from student site. Diamonds are Gravity points and crosses are SP points. Data is plotted along Easting and Northing.

3.1.5.2 GPR and Hammer Seismic

GPR and hammer seismic surveys overlap with the edge of the hammer seismic area running along Line 1 collected on May 21. Both methods are sensitive to the first few meters and are able to determine depths of lithology changes. The GPR line in figure 2.99 running east to west shows a deep reflection depicting the travertine base starting at 75m and 100ns. Using velocity determined from the common midpoint gather, the depth of this reflection is 4.5m. This corresponds to the top left point in figure 2.85, which has a depth of 4.75m. The hammer seismic
data point at 321550, 4126020 is located 75 m along the GPR line. The depth at this point was found to be 2.2 m using hammer seismic. The depth using GPR is found to be 1.8 m.

(a) Common offset profile using 100MHz antennas

(b) Travertine thickness determined using hammer seismic. The common offset profile is highlighted in red
3.1 Results and Interpretation

3.1.6 Reservoir Hill Recon Site Data Integrated With Previous Years’ Data

3.1.6.1 Reservoir Hill Recon Site

Hammer seismic data from the 2017 Field Camp was able to be used to build on data collected at the Reservoir Hill Recon Site in 2018. The previous year’s data is located along the top of the hill in the north east section as well as in the south east. The additional data show an increase in alluvium thickness in the area between the northern most data collected this year. Thickness consistently decreases southward among both years of data sets. The points at 322460, 4126220 overlap between years, with the difference in depths between the two points being nearly two meters. This is likely due to errors in processing as two overlapping point from this year show similar differences in depth.

3.1.6.2 2016 Student Line Hammer Seismic and 2016 Time Domain EM Data with 2018 CR411 Deep Seismic Data

Results from the hammer seismic and TEM data collected along the 2016 Field Camp Student Line were a key factor in determining the area of investigation for the 2018 Field Camp. The 2016 data suggests a fault or fault zone crossing CR411, which is further supported by the 2018 seismic data from CR200. The anomalous points from the 2016 data were plotted with those in the 2018 data and extrapolated (see Figure 3.13. The integrated dataset concludes that there is a very large fault zone crossing both CR411 and CR200 which could serve as a preferential flow path for fluids, potentially towards the Mother Spring.
Figure 3.13: Interpreted fault zone extending across CR411 and CR200. This
3.1 Results and Interpretation

### 3.1.7 Overall Interpretation

Using the information collected from the results from all the methods, it may be inferred that there is water flowing up through the faults shown in the CR200 section and likely the CR411 section as well as supported by 2016 data. This is likely evidence of the source of the water that feeds the Mother Spring and the other springs in the town of Pagosa Springs. The water is probably meteoric, meaning that it is sourced from precipitation and likely travels south from the north through the Precambrian basement. High temperatures and pressure in the basement push the water upwards towards the surface though fault zones and fractures to more permeable layers, such as the Dakota Sandstone. Figures 3.15 and 3.14 show the interpreted fluid flow paths on the cross-sections for CR200 and CR411. It is believed that a large portion of the water feeding the Mother Spring flows horizontally in the Dakota Sandstone. The remainder of the water continues horizontally through the basement until it is forced upwards at the location of the Mother Spring.

![Figure 3.14: Final interpreted cross section for CR200, including inferred fluid flow paths.](image)
3.1.8 Final Results

After processing all of the data, the results from each method were integrated to understand the lithology of Pagosa Springs as well as the faulting and potential flow paths of water in the area.

Along CR200, MT, seismic, TEM, and geologic data were integrated. Geologic interpretation of the deep seismic data identified a fault zone around 2.5 km on the line and the MT data shows a spike in resistivity at the depth of the fault zone. This fault zone, as supported by 2016 data, extends across the CR411 line as well. It may be concluded from integration that the fault zone serves as a conduit for water traveling up from the Precambrian basement to more permeable layers such as the Dakota Sandstone. The water, sourced from precipitation, flows from the north through the basement until the high pressure pushes the water towards surface through the identified fault zone in addition to other fault zones in the area surrounding Pagosa Springs.

Much of the data did not fit the geologic model very well. This problem existed in the deep seismic, gravity, and DC resistivity data and was attributed to the curvature within the line. While processing, the datasets were simplified into straight segments, which ignores the curves along the road. This made integration problematic; therefore, much of the data could not be corroborated.

In the Mother Spring Recon Site, SP and gravity both show an anomaly in the same position indicating water flow from the Mother Spring. GPR and hammer seismic, both sensitive to shallow depths, concluded the depth of the travertine to be between 1.8 and 2.2 m.
3.2 Conclusion

The 2018 Colorado School of Mines Field Camp was conducted between May 13 and June 8th with the intention of using a variety of geophysical methods to understand the subterranean hot water flow surrounding the Mother Hot Spring. The field camp was broken into two parts: the first half was in Pagosa Springs collecting data and the rest of the time was spent processing the data at the Colorado School of Mines Campus with the help of industry and academic professionals. This report represents the culmination of the students’ investigation of the subsurface and their critical findings concerning Pagosa’s Springs geothermal system.

Previous field camps have conducted surveys to the west, south, and east of Pagosa Springs, leaving the area north of town to be investigated. Data acquisition was conducted along two county roads north of town, County Road 411 called the McCabe line and County Road 200 called the Snowball Line. In addition, the area directly west of the Mother Spring was chosen as the student site in which students controlled all the survey parameters. This area was previously explored in 2012 and was revisited in order to better understand the mechanisms supplying hot water to the Mother Spring.

Along the CR411 line, DC resistivity, deep seismic, and gravity surveys were conducted, analyzed individually, then integrated to create an overall geologic interpretation. DC resistivity found that there is a general resistivity increase towards the northern end of the line indicating a greater presence of shallow Dakota Sandstone, a geologic layer known to be a pathway for water. Furthermore, deep seismic identified significant faulting at the southern section of the road, which could potentially direct regional water flow. From the gravity survey along CR411, a general geologic dip of 5° was confirmed.

CR200 was surveyed by DC resistivity, deep seismic, gravity, MT, and TEM. Like CR411 the individual method teams collected and analyzed their own data and then came together for an overall interpretation. Similar to their findings on CR411, DC resistivity confirmed that Mancos Shale is on top of Dakota sandstone until the northern end of the line. However, they did discover a dramatic shift in conductivity (at 2250m along the line), which contrasts the gently dipping geology. Deep seismic analysis showed faulting at the Southern end of the line, similar to that on CR411. Gravity data analysis confirmed the initial geologic profile of the area by supporting the existence of a 5° dip. However, their analysis also suggested the presence of a syncline along this line. MT surveys showed a depth to basement which has a general increase northward. The TEM results for subsurface resistivity confirm the geologic cross section, which closely aligned with well log information.

This year, the student site was the Mother Spring Recon Site, and GPR, gravity, hammer seismic, and TEM surveys were conducted to locate the subterranean water flow around the Mother Spring. GPR was able to refine the thickness of the travertine layer to 2-3 m thickness. To further map the travertine layer, several hammer seismic surveys were conducted and were able to identify a variable travertine thickness that is inversely related to elevation, suggesting that the area had a previously undulating terrain which was later covered by hot water flows. A gravity grid was set up close to the Mother Spring. However, its only major conclusion was to confirm a general geologic dip of 5° in the area. TEM analysis was able to identify fresh water on the far east and west sides of the site.

This year’s field camp had overarching goals to map the pathway of water flow to the Mother Spring. During the final integration process, deep seismic, TEM, and MT were correlated to show faulting along the southern portion of CR200. The identified faults could be a pathway for water flow. Water is believed to flow horizontally through the Dakota Sandstone. However, none of the methods definitively identified a distinct water flow pattern.

Recommendations for following years’ field camps include expanding surveys near the Mother Spring with emphasis on 3D data collection. This would be extremely useful for understanding the mechanics that allow hot water to reach the surface at the Mother Spring location.
3.3 Recommendations For Future Surveys

We believe a viable recommendation is to further investigate the Mother Spring Recon Site. Our objective was to determine where the water from the Mother Spring is coming from. Even with the data that was collected this year, we believe it is still valuable to return to get more information. This area is likely to be developed in the coming years, which limits our window to get additional surveys surrounding the Mother Spring. The only information that we have on this area is from the 2012 Geophysics Field Camp and the this year’s Geophysics Field Camp. This year was the closest that this program has ever gotten to recording seismic data near the Mother Spring itself. Unfortunately, an extensive survey was not able to be carried out due to time constraints. As a result, extensive interpretations about the origin and mechanism of the Mother Spring could not be made based on the seismic sections collected at this site during the 2018 Field Camp.

Conducting a 3D seismic survey in the area near the Mother Spring is our first recommendation. The Mother Spring Recon Site has surrounding infrastructure so certain survey parameters would need to be altered. The vibrator truck would need to reduce its overall force from 70% to 30-40% in areas that are near buildings. To mitigate ground roll and shaking of nearby buildings, the sweep parameters could be changed to a random sweep. The use of a weight drop is also an option in this area, but would likely be slower compared to using the vibroseis truck, and likely just as noisy. A weight drop could still be used in areas that the vibroseis truck would have to skip. Other methods, such as gravity, DC, and SP, would greatly benefit from 3D surveys in this area.

One issue we foresee is the limited time allotted for field session. This time frame may not be feasible for processing a 3D seismic survey. We encourage future years to reach out and communicate with industry professionals to see if it is still feasible to process the 3D seismic survey. Another option is for a senior design group to model a survey in this area to estimate the feasibility of completing a 3D survey for seismic.

Other options for a 3D survey would be to connect the CR411 and CR200 lines. Since those main lines were processed during this year’s Field Camp, additional lines between would provide useful information. Another viable recommendation would be a further investigation of the Reservoir Hill Recon Site. Surveys could give us more information about a better regional dip interpretation, syncline river channel features, and more insight into the faulting that we believe exists in this area. If all of these recommendations are not attainable, there are 2 roads in the Pagosa Springs area that we believe would provide useful information. CR500 is to the south, and is an area with significant faulting. FR629 is a quiet road and has the ability for all methods to complete acquisition along it.

In addition to recommendations for possible survey sites, based on difficulties experienced during data processing, we have additional recommendations. For processing, the recommendation is to become familiar with the software you will be using before field camp. If this is not a possibility, be sure to read the sections of past papers, as they will have information on the challenges that were faced during the processing portion of the field camp. A final recommendation is to keep the data acquired during field portion organized and make backups onto external hard drives and USBs.

Additionally, this year’s field camp created a Precambrian Basement elevation surface plot based on well and seismic data collected along CR200 and CR411. The final recommendation is to collect more data between CR200 and CR411, as well as around the town of Pagosa Springs, in order to gather more points of the basement elevation. Methods that are useful for this are deep seismic, DC resistivity, and MT.
4.1 Elevation of Precambrian Basement

The students compiled depth data from seismic, MT, and well logs. The depth and location information from the wells were taken from the well logs on the COGCC website. The MT depths were taken from the final processed images. The data from the seismic lines were picked by hand from the final images based on individual flag numbers. Exact locations of each point were taken with DGPS. Easting, northing, and elevation were all recorded; The depths at all points were subtracted from their respective elevations to calculate the elevation of the Precambrian basement.

The elevation of the basement was compiled into an excel sheet with easting, northing, and elevation in meters. The final compilation of the data was imported into Surfer 14. The area between the data points are interpreted by the software and are most likey not accurate as there is some drastic topography and distance between the two seismic lines. Integration with additional data points in the future may yield more accurate results.

4.1.1 Figures
Figure 4.1: Contour map of the elevation of the basement derived from well data as well as MT and seismic data collected by the students.
Figure 4.2: 3d surface of the elevation of the basement derived from well data as well as MT and seismic data collected by the students.
4.2 MT 1D Inversions: All Sites
Figure 4.3: 1D inversion model of MT data collected at site 1 station A. This image shows a profile of apparent resistivity changes with depth and thus is only useful for identifying vertical geologic layers. Here, the calculated apparent resistivity (red) matches well within the real data error (black boxes). Since we were able to match the inversion model to the data, we can assume that there are primarily vertical geologic changes. Each geologic formation will have a consistent resistivity, and places where the resistivity changes represent layer changes. We can also identify basement, since basement is characterized by highly resistive rocks. Basement depth is calculated to be .75km for this site (calculated via ipi2win numerical output).
Figure 4.4: 1D inversion model of MT data collected at site 1 station B. This image shows a profile of apparent resistivity changes with depth and thus is only useful for identifying vertical geologic layers. Here, the calculated apparent resistivity (red) does not match well with in the real data error (black boxes). Since we were not able to match the inversion model to the data, we can assume that there are both vertical and lateral geologic changes. Thus, trying to fit these 2D changes to a 1D model does not produce a reliable model. Each geologic formation will have a consistent resistivity, and places where the resistivity changes represent layer changes. We can also identify basement, since basement is characterized by highly resistive rocks. Basement depth is calculated to be .2km for this site (calculated via ipi2win numerical output).
Figure 4.5: 1D inversion model of MT data collected at site 1 station C. This image shows a profile of apparent resistivity changes with depth and thus is only useful for identifying vertical geologic layers. Here, the calculated apparent resistivity (red) matches well with in the real data error (black boxes). Since we were able to match the inversion model to the data, we can assume that there are primarily vertical geologic changes. Each geologic formation will have a consistent resistivity, and places where the resistivity changes represent layer changes. We can also identify basement, since basement is characterized by highly resistive rocks. Basement depth is calculated to be .8km for this site (calculated via ipi2win numerical output).
Figure 4.6: 1D inversion model of MT data collected at site 3 station A. This image shows a profile of apparent resistivity changes with depth and thus is only useful for identifying vertical geologic layers. Here, the calculated apparent resistivity (red) matches well with in the real data error (black boxes). Since we were able to match the inversion model to the data, we can assume that there are primarily vertical geologic changes. Each geologic formation will have a consistent resistivity, and places where the resistivity changes represent layer changes. We can also identify basement, since basement is characterized by highly resistive rocks. Basement depth is calculated to be .63km for this site (calculated via ipi2win numerical output).
Figure 4.7: 1D inversion model of MT data collected at site 4 station A. This image shows a profile of apparent resistivity changes with depth and thus is only useful for identifying vertical geologic layers. Here, the calculated apparent resistivity (red) does not match well with the real data error (black boxes). Since we were not able to match the inversion model to the data, we can assume that there are both vertical and lateral geologic changes. Thus, trying to fit these 2D changes to a 1D model does not produce a reliable model. Each geologic formation will have a consistent resistivity, and places where the resistivity changes represent layer changes. We can also identify basement, since basement is characterized by highly resistive rocks. Basement depth is calculated to be .15km for this site (calculated via ipi2win numerical output).
Figure 4.8: 1D inversion model of MT data collected at site 7 station A. This image shows a profile of apparent resistivity changes with depth and thus is only useful for identifying vertical geologic layers. Here, the calculated apparent resistivity (red) does not match well with the real data error (black boxes). Since we were not able to match the inversion model to the data, we can assume that there are both vertical and lateral geologic changes. Thus, trying to fit these 2D changes to a 1D model does not produce a reliable model. Each geologic formation will have a consistent resistivity, and places where the resistivity changes represent layer changes. We can also identify basement, since basement is characterized by highly resistive rocks. Basement depth is calculated to be .8km for this site (calculated via ipi2win numerical output).
4.3 MARE2DEM Manual: Colorado School of Mines

4.3.1 Introduction

This is an instructional guide to be able create a beautiful 2D inversion created by an undergraduate group that has “used” the software for about 7 days at the time of writing. Thus, this will be more of the steps we followed to make a meaningful model that represents our data.

MARE2DEM is an open-source magnetotellurics (MT) inversion code that anyone can download and work on located at this site: http://mare2dem.ucsd.edu/. It comes with Source Codes, Matlab Codes, Example data sets, and a File Formats pdf. For the purposes of those at the Colorado School of Mines, the Source Codes and Examples are already installed on Mio, the Mines super computer, and we will explain how to get access to this exceptional piece of technology in the Mio section. So, all you will need to start is stated below.

4.3.2 Program Needs

- MARE2DEM: Matlab codes and Examples
- Matlab 2013b
- Vim, or other text editor
- PuTTY, for Windows users
- Command Prompt Window
- ProcMT
- Excel
- Python, Processing Codes

4.3.3 Data Processing

4.3.3.1 ProcMT

You just got back from the field and are super hyped to take all that data and throw it at a code and wait for the figure of your dreams to pop up. Well, it’s not quite that easy, but it’s actually not too bad!

First, you will want ProcMT via https://geo-metronix.de/mtxcl/index.php/s/B9cLYq9MVwj7Y5F?path=%2FLatest%2Fprocmt_win64 where you need to download procmt.zip, qt_dll.zip, and mingw_dll.zip.

You will first want to unzip procmt into a folder that you are comfortable using as more or less your initial base for all your MT processing, with all the data you wish to process. Next, unzip the other two zips into the procmt folder you just unzipped. Within procmt, there might be another procmt folder; You want to copy everything in that 2nd procmt into the main procmt folder.

To run the ProcMT, simply select the "ProcMTGui" file from the downloaded files. To create a new file, select "Create Project" under the file menu. In the file folders that are located in the ProcMT files, create an empty folder called "Processing" and select this folder in the application. This will prompt multiple folders to populate inside the "Processing" folder, which will contain information and results for processing. Next, create a new site by selecting "Create Site" under the file menu in the application. In the file explorer, move the measurement files that were downloaded from the ADU to the appropriate site folders. The appropriate site folders can be found by selecting the "Processing" and then "ts" folders under the ProcMT files. Open the zipped files and copy the file within them. Then paste this file in the same site folder as the zipped file, and delete the zipped file. The remaining file should be a measurement file with a naming convention similar to the following: "meas.2018-05-19_22-30-00." After uploading the measurement files, in ProcMT select the down arrow next to the site to view the file, make sure the appropriate data is uploaded to each site, Figure 2.45.
To prepare the data for processing, it must be down-sampled. This can be done by selecting a site in ProcMT, right clicking on the measurement file below it, and selecting “Filter.” A new window will appear, select “$4x$” and run, see Figure 4.10. A new measurement file will be generated beneath the old file with a sampling rate that is $\frac{1}{4}$th of the original file. Repeat this process three more times to create files with sampling rates of $256\,Hz$, $64\,Hz$, $16\,Hz$, $4\,Hz$, and $1\,Hz$. The data is now ready to run simple processing.
To begin the simple processing, select the appropriate site, select a processing filter `mt_auto_smooth`, `mt_auto_sharp`, or `mt_auto_med` from the processing window, and run the job. Each site will need results from each of the processing filters. These results can be found in the “Processing” folder under “edi”. To review these results, instead of re-running the program, simply open the EdiPlotter and drag and drop the `.edi` files into the application. After each site has been run through simple processing, review the results using the EdiPlotter and choose which processing filter formulates the best curves. For the purpose of the 2018 field session, the processing filter that best fit the gathered MT data was `mt_auto_smooth`. Curves that appear messy or have large jumps will require further processing.

To begin further processing, begin by using the EdiPlotter to plot the results from the chosen processing filter. When looking at the plots for each site categorize them into good, OK, and poor results. The good results can be classified as having apparent resistivity and phase curves with no large jumps; this data is ready to be prepared for inversion, see Figure 4.11. The OK results can be classified as having apparent resistivity and phase curves with only a few jumpy sections and the poor results contain many jumps in the curves, see Figures 4.12 and 4.13. The OK and poor results will require more processing before they are ready to be prepared for inversion.
Figure 4.11: Example of "good" data plotted in the ediplotter application in ProcMT after down-sampling.
Figure 4.12: Example of "OK" data plotted in the ediplotter application in ProcMT after down-sampling.
Figure 4.13: Example of "poor" data plotted in the ediplotter application in ProcMT after down-sampling.

To further process procedure the OK results, view the time series for a given frequency and under the settings tab select mouse selects. To speed up the process, set the window length to 8192 or 16384 for larger files. Use the mouse to mark unusual areas of the data; large spikes or odd variations that occur in one channel but not in others, see Figure 4.15 for examples. When finished, save the selections. This process must be done for each input frequency in the site folder. After all of the time series have been corrected, in the ProcMT program open the mt_auto_smooth processing for editing. Under the command line options change "auto bandwidth" to 8, "auto parzen" to 16, set "reject coherency less than in advance" to 0.5, use the drop-down to set "dump various to "on" and "dump raw transfer function" to "on". Turn off mt_processing_median but leave _stackall and _ct checked. Under mt_processing_ct, set the lower threshold to 0.6. Save this edited processing with a new file name, see Figure 4.14 to visualize changes. Finally, run the newly created processing filter on the sites which have undergone the time series corrections. If this generates plots with smooth apparent resistivity and phase curves, the files are ready for inversion; however, if this is not the case further processing steps will need to be taken.
Figure 4.14: Parameters used to generate new smooth processing filter.
4.3.3.2 Additional Python Corrections

To further process the poor results, begin by following the same steps as those for the OK results. If this does not generate smooth curves, two Jupyter/Python notebook programs can be used for further editing. The first program, "Read Multiple Files," can be used to convert .edi files into Excel spreadsheets. First, transfer the most recent stack all .edi files to the folder where the Jupyter/Python notebooks are saved, the filenames should resemble the following: "2_mt_auto_smooth_mt_processing_stack_all_1.edi." Next, open the "Read Multiple Files" Jupyter/Python notebook and type out the file name in the second code box after "ls =." Then, in the seventh code box name the Excel spreadsheet that will be outputted by typing the file name within the parentheses of "writer = pd.ExcelWriter()," be sure to include the file extension. Under the cell tab, select "Run All." An Excel spreadsheet of the data, as pictured in 2.52, will be outputted in the same folder as the Jupyter/Python notebooks are stored. This spreadsheet can then be uploaded into the Jupyter/Python notebook "Plotting frequencies" by typing the filename after "df = pd.read_excel()" in the second code box. Again, select "Run All." This will generate plots for Zxx real, Zxx imaginary, Zxy real, and Zxy imaginary against frequency. Using these generated plots, remove 2-4 outliers from the excel spreadsheet. To see these changes simply re-run the program with the saved spreadsheet data. This should generate more usable curves and the data should be ready to prepare for inversion.
4.3.3 Excel and Calculations

To prepare the data for inversion, begin by using the "Read Multiple Files" Jupyter/Python notebook to generate Excel spreadsheets for sites that do not have them yet. After these files have been created, several calculations will need to be run within them to the apparent resistivity, phase, and the log of apparent resistivity. These calculations will need to be done for both the XY and YX components. The equations necessary for these calculations can be found below and an example file can be viewed in 4.17.

To calculate the apparent resistivity of the XY components the following equation can be used:

\[ p_a = 0.2 \frac{f}{(Z_{xyr})^2 + (Z_{xyi})^2} \]  

(4.1)

where \( f \) is again equal to the frequency, \( Z_{xyr} \) is equal to the real XY component, and \( Z_{xyi} \) is equal to the imaginary XY component.

To calculate the phase for the XY components the following equation can be used:

\[ \phi = \arctan\left(\frac{Z_{xyi}}{Z_{xyr}}\right) \]  

(4.2)

To calculate the log of apparent resistivity the following equation can be used:

\[ p_{al} = \log_{10}(p_a) \]  

(4.3)

where \( p_a \) is equivalent to the apparent resistivity calculated for the XY components.
Figure 4.17: Excel spreadsheet format generated after performing calculations for the apparent resistivity, phase, and the log of apparent resistivity for the XY and YX components of the Z tensor.

After completing the calculations for the XY components, the same calculations can be run for the YX components making sure to use the appropriate YX values in place of the XY values in the above equations. Once these calculations have been performed and saved for each site, the data can be manipulated into the appropriate file formats for 2D inversion.
4.3.4 EM Data File

Now that you've done all of the work you would have done anyway if you were just doing 1D (hint hint do that too), it's time to invert, right? Nope, we've got 3 more sections to get through before you can do that. Well, let's continue.

4.3.4.1 Initial Setup

The base data file that you will need is a .emdata file. A correctly formated file with that extension can be found in the directory path Examples/inversion_MT/DemoSynthMT.emdata file. Using your now processed data nicely organized by frequency and in column form, copy-paste it into the .emdata file using that format with help of the File Formats file. Refer back to the Demo file to check for formating errors, too.

We recommend to start with just two sites at an arbitrary distance apart with their respective data and used frequencies. This will allow you play with how Mamba2D and MARE2DEM work with your data. However, you can make your full .emdata in down time while that is running and what you may need to change for the final .emdata file.

4.3.4.2 Receiver Setup

One important note and change to make to your receivers is that you should make your best fit line of receivers. Then translate your sites to the line. Depending on the orientation of your line, i.e. not south-north or west-east, additional steps are needed to set up your file, which we will get to at the end of this section.

So, say you have made our line changing in only northing or easting, nice! It's simpler. Leave all the 'X' values at 0 and have the Easting/Northing change in 'Y'. Easting/Northing must be relative to a point, this was done by averaging them in excel and making that the '0' point. This is just how PlotMARE2DEM.m likes it based on how we setup the Mamba2D model.

Your 'Z' values are your elevations. This will need to be actually just above the surface that you will make in Mamba2D, so depending on how you do that, you can change this as needed. Putting them like 0.01 meters above the surface in the fixed area is crucial for the inversion. You can skip to last .emdata figure

Okay, you decided to actually make a best fit line that isn't south/north or west/east. We can give you a few instructions, but you'll most likely need to fiddle with it to make it work.

We still recommend to make a relative point on your line to be the 0N and 0E point on your model. Next, you will want to change 2 things:

Format: EMData_2.2
UTM of x,y origin (UTM zone, N, E, 2D strike): 0 0 0 0 0

Figure 4.18: You will want to change the 2D strike to the strike of your line.
Figure 4.19: You will also want to change your Theta angle. This will be the same as your strike of your line if you took measurements aligned with North and East. This will tell MARE2DEM to rotate your xy data from measurement angle to strike of line angle as you could do with the $Z(w)$ tensor.

### 4.3.4.3 Final .emdata File

You should end up with something like this

```
MT Receivers: 6

<table>
<thead>
<tr>
<th></th>
<th>X</th>
<th>Y</th>
<th>Z</th>
<th>Theta</th>
<th>Alpha</th>
<th>Beta</th>
<th>Length</th>
<th>SolveStatic</th>
<th>Name</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>1538</td>
<td>-2373.01</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>MT01</td>
<td></td>
</tr>
<tr>
<td>0</td>
<td>2</td>
<td>-2332.01</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>MT02</td>
<td></td>
</tr>
<tr>
<td>0</td>
<td>2900</td>
<td>-2396.01</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>MT03</td>
<td></td>
</tr>
<tr>
<td>0</td>
<td>810</td>
<td>-2356.01</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>MT04</td>
<td></td>
</tr>
<tr>
<td>0</td>
<td>-4697</td>
<td>-2230.01</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>MT05</td>
<td></td>
</tr>
<tr>
<td>0</td>
<td>-1547</td>
<td>-2323.01</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>MT06</td>
<td></td>
</tr>
</tbody>
</table>
```
Figure 4.20: This example file is edited for format purposes.
4.3.5  Mamba2D

Woo, you got yourself a compatible data file now! Next, let’s make model. This is the point at which we remind you that you need Matlab, but not just any version of Matlab... but the 2013b version of Matlab! As far as we could tell from first using the 2018 then 2014 versions, Mamba2D.m only properly works with 2013b since that was when the code was initially created. Don’t fret, it is possible to obtain said version from CCIT, hopefully, and a code to authenticate it as well, at least for 60 days. Once you have Matlab 2013b downloaded and installed, you can now open Mamba2D.m with confidence it should work and it won’t be Matlab’s fault if it doesn’t. Remember to add all pathways with all the Matlab codes to be able to run the codes.

4.3.5.1  Running Mamba2D.m

First, you will create the boundary of your model:

Figure 4.21: Click Create with the boundary you prefer, but the default should be good (it’s in meters).

Next, you want to define a topographic boundary. This can be done with importing a file, by drawing the points out yourself (remember to connect to the boundary), or simply draw a horizontal line using the “horiz.” button under “Segment”. We will do the latter in the next figure:
Figure 4.22: Click "horiz." button under "Segments" (highlighted in green to the right) and enter the depth you want the line at. We use 0 for simplicity, but your’s might be an elevation. (Remember in meters)

Next, you want to set values for your fixed and free parameters, i.e. the air and the subsurface. Click on "set values" and click the top half-space, this will be the air set at "1e9", log10(app. resistivity), and 0 for free parameter. This area will stay constant in the inversion.
Figure 4.23: Setting the air to a constant resistivity.
Next, you will set the bottom half-space, your subsurface, to the default "1" resistivity since it will change anyway when you set the free parameter also to "1" so that MARE2DEM will know to invert this space.

![Image: Setting the subsurface to be a free parameter.]

Figure 4.24: Setting the subsurface to be a free parameter.

Now we can start effectively making your model. We will be making a very simple model in this example, but I will also show a complicated one we used for Summer Field Session in 2018.

**HOWEVER, SAVE THIS**

figure as Matlab figure somewhere, we saved mine in the a_util folder in the Matlab codes directory. This will allow you to comeback to this initial setup of your model, especially if you want to keep the same elevation profile.
4.3.5.2 Making the Mesh Grid

Start by zooming in a bit to where your sites are. This also may be a good time to remind you that this is where those relative points come in handy. Click the "rectangle" button under "Segments" and draw a rectangle encompassing our site location with a little bit of space on both lateral sides.

Figure 4.25: We draw a rectangle of based on what we believe is the depth of investigation and around the imaginary 5 receivers that we put nodes at. You do not have to put nodes at your receiver locations for the programs to work.

You will want to now delete the nodes in the air as they don't serve your purpose. Use "delete" under "Nodes" and click on the nodes in the air. This will leave you with your nodes on the topography and a rectangle just in the subsurface. You can continue this process to have more elaborate rectangles by moving the nodes around and making more rectangles.
4.3.5.3 Triangles

You should be ready to make your mesh of triangles. Click "triangles" under "Grid". The "Min Angle" is for truncations; if you have an angle less than 25 degrees anywhere on our model, then MARE2DEM will not invert and tell you what to exactly to fix.

Now click inside your subsurface rectangle and it will pop up with a gui to input your desired triangle length.

Figure 4.26: We choose 150 meters because that seems to be a good number to make triangles in the area of the rectangle.

It will think for a second and return with a confirmation prompt for the number of triangles of that length will produce in your enclosed area.

Figure 4.27: It returned 6877 triangles, and that may be alright for what I’m doing for this example. This will depend on how dense you want your triangles and what you are looking for and where. Use intuition for this, less triangles means less quality but also less time inverting. More triangles equals better quality, more time inverting and greater possibility of crashing MARE2DEM.
Now confirm that and it will draw your triangles.

*Figure 4.28: All the triangles.*

Next you will want to fill out the rest of the space that you don’t care much about in the subsurface because your measurements actually can’t “see” that far. You will click “triangles” again and click on the rest of the space that you haven’t set yet and set the distance to “-1”. This will tell Mamba to make as big as possible triangles to fill the space.
Now, here is an example of what was a model for what I used in Summer 2018.
Figure 4.31: Summer 2018 model. Used 4 main rectangles to get the best density of triangles for the depth of investigation and for MARE2DEM to work.

Now, as you may see in the previous the "Output" section is filled in. You can name your root however you want, but it will be the root of this inversion files, there will be four of them. Also you will need to name your Data.emdata the same, with the extension, that you named it previously. Then, click "write MARE2DEM Files".
Figure 4.32: This is the Output section for my example Mamba2D model. You are able to change the Penalty, the Target Misfit, and the Rho bounds, but for your first inversion, probably don’t touch them.

This will give you four files of: root.0.resistivity, root.poly, root.penalty, and root.mamba2d in your folder where you have Mamba open. This is also a good time to pull mamba2dem.settings from the Examples folder. You shouldn’t need to change anything with it, but it’s straight-forward what it does if you open it in a text editor.

4.3.6 Mio

Now that you have all of your files, let’s get it to a place where you can actually invert it, Mio. First, to get access to Mio, you will need to contact a member of CCIT. Timothy Kaiser was our contact for Summer 2018, who can give you access. They will give you a bit of information but you will PuTTY if on Windows or a ssh-friendly command prompt such as Linux or OSX. Mark run Windows 10 on his laptop so we will continue to reference use with PuTTY.

You will need to get onto Mio via PuTTY, or ssh-ing, and create a few directories that the CCIT person should give you directions for but basically we created the pathway /u/au/sa/*username*/scratch/scripps then we proceeded to add directories from there for organizational purposes, but this is the least you need. Now for Windows users, you need to open a command prompt to pass on your files using pscp, which should have come with your PuTTY download. You will use the command:

```
pscp *directory-to-file-on-pc*/root.ext *directory-path-in-Mio*
```

Then click enter. You will enter your Mio password and if everything exists and your password is right, it will transfer the file. This will automatically overwrite a file with the same name and extension if present in the destination directory. To transfer files back, follow the same format, just switch the directory pathways.

Now that you have transferred all the files you need it is finally time to edit some more files before you invert...
4.3.7 MARE2DEM

First, you will need the example bash file that is housed within Mio which you can copy to your current directory using

```
cp /opt/mare2dem/example .
```

This will put the bash file in your current directory. Open this with your favorite text editor, Vim for me, and go down a bit in the file until you see similar extensions to your files. Change the root of those files to match your file names. mare2dem.settings should be left alone name wise. Save and quit out of the editor and you are actually finally ready to invert!! Your command is now if your directory similar to this:

```
sbatch example
```

![Figure 4.33](image)

This will start a job in Mio, creating a directory with the number of the job Mio assigns. Change into that directory for a new copy of all your files and a couple of outputs from MARE2DEM. The key output file you want to pay attention to is "output.*job#*.out". This will show you how MARE2DEM is running. You can either open this in your favorite text editor or use the command "tail -f output.*job#*.out" and this will update the file as it updates from MARE2DEM if it is still running.

If this has nothing in it, then there is something wrong with your example bash prior to getting to that step. This can be viewed in the directory that you original ran the sbatch under the name of "slurm-*job#*-out".

However, if you are lucky enough to get everything right and the output file is updating as you tail it, you should eventually see additional versions of your root.0.resistivity file pop up when you check the contents of the job directory with increasing number values for the number of iterations MARE2DEM has inverted your data. This process can take minutes or hours depending on how busy Mio is. Physics really likes to start running their stuff in the early afternoon during field session, btw.

Once MARE2DEM stops, the output file will show that it has shut down or has been stuck on a line for more than a couple minutes. This hopefully means that there are multiple iterations of inversion MARE2DEM has done. Now we can take these back to where you can plot them, Matlab.
4.3.8 PlotMARE2DEM

You are now almost able to see your inversions! First, transfer your root.#.resistivity file back over to where you originally made the files with Mamba2D. MARE2DEM does not change any of the existing files and only makes root.#.resistivity and root.#.resp files. Now, open Matlab 2013b and open PlotMARE2DEM.m. This will prompt you to open a .resistivity file so choose the one you want to see.

![Image of Matlab interface](Image)

*Figure 4.34*
BOOM! It should load and now you can mess with the zoom and the color bar to make your figure all nice and interpretable. This will also require some figure editing for the final product for UTM tick marks and elevation.

![Figure 4.35: This is the final figure for the Summer Field Session 2018 MT 2D inversion. (ignore the negative elevation, was fixed for actual final figure)](image)

**4.3.9 Conclusion and Last Remarks**

Hopefully, this guide provided you with some insight and progress in developing your own 2D inversions much faster than we did. This took us about 4 days of troubleshooting with all of the steps past processing to be able to just make a figure, much less get a figure of the data. For further troubleshooting, consult the next sections or you can email Mark directly at markjeska10@gmail.com.
4.3.10 Frequently Encountered Problems/Why does this not work?

- Got to have the 2013b version of Matlab.
- Call the right files that are in the same directory in Mio in the example bash
- Adding multiple nodes in Mamba then editing them apparently does not work well, so you have to add and edit one at a time.
- Make sure you have semi-colons in the .emdata where you need those semi-colons.
- Do not change .emdata file while an inversion is running if you want to view the inversion properly. Wait or make a new copy of the .emdata file.
- Do not make too many triangles in the model; we figured out it crashes MARE2DEM in some capacity/it will take forever to do the inversion if there's over like 30,000 triangles. Use them wisely.

4.3.11 Complementary & Professional Resources

- MARE2DEM: Tutorial and Training - This presentation by Kerry Key was a huge help in figuring out Mamba2d.m and how MARE2DEM will work while it is running. Link to it uploaded in Google drive: https://drive.google.com/open?id=1pt3P0rFnKYOy6W-u3q9396bSykOTi_Gf.
Seismic Depth Migrated Images Using Well Velocities

The location of the reflectors in the well velocity corrected depth migrated stacks seen in Figures 4.36, 4.37, and 4.38 are shifted from the NMO velocities used for interpretation. Some of the uncertainty could come from the methods used for obtaining the lithologic velocity data. One cause of this may come from taking measurements on samples that are not in the native environment where the confining stress and temperatures has been changed. This is one factor that could change the rock physics. The data reveals features with their relative location, since the absolute locations cannot be inferred without accurate velocity models.

Looking at the well velocity migrated data in Figure 4.36, the location of the basement reflector starts around a depth at $800\text{m}$ at the south end, then slopes down around $1100\text{m}$ at the north end. The features are nearly identical to the interpretations in earlier sections, although the depth locations have changed significantly for the CR200 seismic line and are about $100\text{m}$ deeper. The motivation for not interpreting the well data was that the locations of the interpreted bed horizons was not matching well with the well data and the geologic cross sections made. For instance, the Dakota Sandstone was found at a depth of $652\text{m}$ at the Holly Oil Macht 1 well located east of the seismic line at about flag 2524. We found this location on our depth migrated figures and began to interpret the rest of the rock beds. The area of most interest in Figure 4.36 is where there is some unconformity in the reflections seen near the middle of the line where the reflection events are not connecting clearly across the acquired seismic line. There is also another smaller unconformity slightly north of the middle of the line shot.
4.4 Seismic Depth Migrated Images Using Well Velocities

Comparing the two final depth migrated stacks, the locations of the occurrences of the reflection events fit better with the geology for the node data in Figure 4.38 than the geophone data in the Figure 4.37 when using the well velocity data; however, this was not the case for the NMO velocities used to generate the final figures in the report. Overall, the resolution of the reflection events is better shown in the geophone data, most likely due to the difference in the receiver spacing between the 2 lines (approximately $2\text{m}$ for geophones versus approximately $10\text{m}$ for nodes). One of the interesting differences is an unconformity in the deepest reflection in the node data in Figure 4.38 located around flag 4050, which is not apparent in the geophone data. Both the datasets agree about the unconformity around flag 3970. Some of the differences in the data could come from the uncertainty when making user picks throughout the processing, such
Chapter 4. Appendix

4.5 MT ProcMT Expansion Manual

Above is an initial run through of the southernmost site. Some things we can see are that there are unreasonably high resistivities in the lower frequencies. But, the upper most frequencies show a nice clear pattern with the rise in resistivity coming in around 10Hz.

In order to improve the lower frequencies if I take the Ztensor output and examine it a little more I can see some issues figure 2 shows a boxplot of the data. This is just a way of representing the distribution of values at each frequency; narrow boxes mean a close distribution. It is clear here that as frequency approaches 1 Hz and lower our distribution gets spread. If we examine the distribution closer by using a histograms like in figure 3 we can see what is happening. We see a clear concentration at lower magnitudes of the Zxy values, but some extreme outliers. These outliers will skew the final calculations. For a quick fix we might choose to limit the upper Rho values in ProcMT processings. I did this and got the result in figure 4. Although a bit jumpy still, the overall pattern is much more coherent and reasonable, with resistivities rising around 10 Hz and leveling out around 1Hz to 0.02Hz.

To even further improve the overall shape of the curve more statistics could be performed using the Ztensor input.

One idea for example:

1. search for clusters of Z tensor components
2. determine from surrounding frequencies what is noise vs. signal
3. delete the values determined as noise.
4. calculate apparent resistivity curves from adjusted distribution
Figure 2: Boxplot view of Rhoxy distribution

Figure 3: Histogram view of Zxy magnitude for multiple frequencies. Horizontal axis is Zxy magnitude, vertical is how many values calculated at that magnitude. Clearly see that there are some huge outliers from main concentration.
Figure 4: Southernmost site run with limit to upper Rho


