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The Summerville Formation: Evidence for a Sub-Horizontal Stratigraphic Sequence below the Post-Rift Unconformity in the Middleton Place Summerville Seismic Zone

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THE SUMMERVILLE FORMATION: EVIDENCE FOR A SUB-HORIZONTAL STRATIGRAPHIC SEQUENCE BELOW THE POST-RIFT UNCONFORMITY IN THE MIDDLETON PLACE SUMMERVILLE SEISMIC ZONE

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DEDICATION

I would like to dedicate this to my grandparents and my mother, for without their support none of this would have been possible.

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I would like to give a special thanks my major advisor, Dr. Jim Knapp, for taking me on as a student and giving me guidance, and support to strive for success in all areas through my undergraduate and graduate work. I would also like to thank my committee members Dr. Camelia Knapp and Dr. Andrew Leier for their continual insight into my work. Lastly, I would like to thank the members of the Tectonics and Geophysics Laboratory and the Geophysical Exploration Laboratory for their friendship and support.

ABSTRACT

The Middleton Place Summerville Seismic Zone (MPSSZ) near Summerville, South Carolina was the site of renewed extensive investigation, beginning in the 1970's, for the source of the 1886 Charleston earthquake. Reactivation of faults associated with a putative fault-bounded Triassic rift basin through analysis of seismic reflection, seismic refraction, and well data has since become the favored interpretation for the source of MPSSZ seismicity. Critical to this interpretation is the association of continental redbed sedimentary rocks in Triassic basins throughout the North American Atlantic margin. Reanalysis of 18 seismic reflection profiles and 25 seismic refraction profiles within the MPSSZ suggests that the red beds found here are a thin, sub-horizontal, regionally extensive, generally unbroken subsurface stratigraphic sequence distinct from the sedimentary architecture observed in analog Triassic rift systems. In addition, this sequence appears to unconformably overly a structural depression (the Jedberg basin) previously interpreted as a Triassic rift basin in the vicinity of the MPSSZ. In addition to the geometries observed on seismic reflection profiles, seismic refraction velocities ranging from 4.2 to 6.1 km/s can be correlated with (1) Jurassic basalt flows, (2) the newly proposed Summerville Formation, and (3) the Basement (B) sequences, respectively. The current study maps the Summerville redbed section and its bounding reflectors. In addition to mapping the regional extent of the newly proposed Summerville Formation, refraction velocities and changes in reflection character, the lateral extent of

the basalt flows is interpreted as a more localized flow rather than a regionally extensive flow as previously thought. Reanalysis of data in the MPSSZ suggests that the area may not be part of the Triassic South Georgia Rift system due to the sub-horizontal geometry of the red bed reflections, the apparent lack of faulting, and their regional extent.

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*Following same nomenclature as previous authors

INTRODUCTION

The Middleton Place Summerville Seismic Zone has been host to many geological and geophysical studies to understand the underlying structure related to the 1886 Charleston, South Carolina earthquake. Reanalysis of seismic data obtained by previous studies provides insight into a new interpretation that changes the lithology at the prominent Jurassic horizon, which pushes back the date of potential faulting that the 1886 earthquake might have occurred on. In addition to a regional mapping of a newly proposed sedimentary sequence the new insights provide a revised extent of basaltic sills in the area.

CHAPTER 1

THE SUMMERVILLE FORMATION: EVIDENCE FOR A SUB-HORIZONTAL STRATIGRAPHIC SEQUENCE BELOW THE POST-RIFT UNCONFORMITY IN THE MIDDLETON PLACE SUMMERVILLE SEISMIC ZONE

1.1 INTRODUCTION

Historically the Middleton Place Summerville Seismic Zone, (Figure 1.1) has been identified as a Triassic rift basin, associated with the South Georgia Rift system (SGR), with earthquake focal depths ranging from 3-12 km and focal mechanisms of N60-E trend (Heffner 2013). The J reflector, the first of the two main reflections, can be seen from 600 m depth in the northwest of the study area and 750 m depth in the southeast is the contact between the Post Rift Unconformity and the Late Cretaceous coastal plain sediments. The J reflector has been previously tied to the Jurassic basalts encountered in all three of the Clubhouse Crossroads wells (Hamilton et al., 1983; Schilt et al., 1983). However it varies in its reflectivity throughout the MPSSZ, whether it is underlain by basalt, the Summerville Formation, or Basement. Instances where the J reflection is underlain by basalt the reflectivity is described as a bright two cycle reflector. An example of this can be seen in figure 4 between depths of 700-750 m throughout the profile. When the J reflection is underlain by the Summerville Formation composed of the sedimentary redbeds, it loses the nice bright reflectivity that is seen from the basalts. An example of this can be seen in Figure 6 between shot points 250 -350. The J reflection is considered to be the time marker for the hiatus of eruption and deposition of volcanic sediments in the transition period from an active to passive margin along the Atlantic coast. The second of the main reflectors, varies from 1,000 to 1,300 m depth throughout the study area, is the contact between the top of the basement (B) and the bottom of the sedimentary red beds encountered in Clubhouse Crossroads well 3. The two main reflectors are referred to as the J horizon for the Jurassic contact and B horizon for the Mesozoic basement contact, from previous studies and we will follow the same nomenclature. The newly proposed sedimentary formation, named the Summerville Formation, is noted by several sub parallel reflections that are bounded by the two prominent J and the B reflections that are composed of the sedimentary red beds encountered in the Clubhouse Crossroads well 3 core.

The B reflection was partially mapped by Schilt et al., (1983), along the four COCORP profiles but the never fully mapped throughout the MPSSZ. Behrendt et al., (1983). had previously describe the MPSSZ as being a Triassic rift basin from the Seisdata4 reflection profile, however new work suggest that it cannot be the case with the geometry of the red bed sequence being flat lying, thin, and generally unbroken. Both authors had observed the Summerville Formation, but had not mapped it fully nor recognized its significance. In the middle of the seismic reflection profile VT4 which crosses a ridge, first recognized by Ackermann, the basement drop considerably in depth. This is the only instance in the MPSSZ where the Summerville Formation might be broken due to faulting. We cannot definitely say that it is a fault with the nature of the data used in the study, however the Summerville Formation unconformably overlies the Jedburg basin.

1.2. STUDY AREA

The South Georgia Rift (SGR) is the southernmost Triassic rift system, in the Eastern North American Rift System, which trends northeast, and records the events prior to the opening of the Atlantic Ocean (Heffner, 2013). The SGR lies beneath the coastal plain sediments and extends is from Georgia, Alabama, northern Florida, to southern South Carolina. Traditionally Triassic rift basins are interpreted as asymmetric fault bounded basins with red sedimentary fill. These basin can be seen throughout Eastern North America ranging from Florida to Canada and are associated with extensional faulting from initial rifting during the breakup of Gondwana. However most of the Triassic basins seen the southeastern U.S. are similar half-graben like structures. Previous authors thought when redbeds were encountered in the Clubhouse Crossroads well 3 that the underlying structure in the MPSSZ is an asymmetric Triassic rift basin.

The three Clubhouse Crossroads wells were drilled along seismic reflection profile SC1 and penetrated approximately 700 m of coastal plain sediments before encountering the Post Rift Unconformity, which is underlain by tholeiitic basalts. Clubhouse Crossroads well 1 was drilled to total depth of 792 m in 1975 (Yantis et al. 1983) and terminated in basalt. Clubhouse Crossroads well 3 was drilled on the largest positive magnetic anomaly in the Summerville area and reached a total depth of 1,152 m. The Summerville oil well was drilled 2.5 km southwest of reflection profile VT5. The Clubhouse Crossroads well 1, 2, and the Summerville oil well bottomed in basalt and diabase, while Clubhouse Crossroads well 3 bottomed in sedimentary red beds. The Summerville oil well was an exploratory oil well while the Clubhouse Crossroads wells were drilled for understanding the lithology of the area. The redbed sedimentary section found in Clubhouse Crossroads 3 is composed of two sections. The Upper section is a fine- to very-fine grained reddish sandstone overlying red mudstones and the Lower section is composed of interbedded red mudstones, coarse grained to conglomerate arkosic red sandstones (Gohn et al., 1983).

Approximately 15 km of seismic reflection profiles were collected by the Virginia Tech Regional Geophysics Laboratory, with the U.S. Geological Survey during 1980-1981 (referred to as VT lines). Ten seismic reflection profiles, collected by the USGS, (referred to as the SC lines) were collected in 1979. Four COCORP (Consortium for Continental Reflection Profiling) seismic reflection profiles were collected with the intent of imaging deep crustal reflections in 1978 (Schilt et al., 1983). Twenty-five seismic refraction profiles were collected by Ackermann beginning in 1975, designed with enough spread to obtain a full reverse coverage of the basement horizon 600-1000 m deep and partial reverse coverage of shallower coastal plain horizons (Ackermann, 1975). The refraction profiles found varying velocities, ranging from 4.2–6.1 km/s. Velocities of 4.4 to 4.9 km/s correspond to the new Summerville Formation sedimentary section. Velocities of 5.0 to 5.5 km/s correspond to the Jurassic basalt. Typically, velocities of 6.0 to 6.1 km/s and higher were considered to be the velocities for the Mesozoic basement rocks. From Ackermann's (1975) refraction study six refraction profiles coincide with reflection profiles SC1, SC5, SC4, C3, VT5, and VT4 (Figure 1.1) and will be used to constrain depths to horizons. Figure 1.2a is Ackermann's contour map showing the depth to the Cretaceous unconformity, while figure 1.2b is the depth to the basement contour map. In figure 1.2b in the north central region of the map there is a ridge that trends N70E. On the southern end of the ridge depths to the basement range from 1200 to

2000m. On the northern side of the ridge the B reflectors drop between 900 and 1000 m into what appears to be a structural depression.

The J reflector, can be seen from 600 m depth in the northwest of the study area and 750 m depth in the southeast and is the contact between the Post Rift Unconformity and the overlying Late Cretaceous coastal plain sediments. The J reflector was previously tied to the basalts found in the Clubhouse Crossroads well (Hamilton et al., 1983; Schilt et al., 1983). The other bright reflector, the B reflector (basement), can be seen varying around 1,050 to 1,250 m (Figure 1.6). Schilt et al., 1983 were the first to recognize the B reflection along the COCORP profiles and Hamilton et al., 1983 continued to refer to the B reflector. A regional mapping of the B reflection and the Summerville Formation throughout the MPSSZ previously has not been carried out. A seismic reflection profile (SeisData 4) was collected in 1981 which trends southeast to northwest and is the only profile in South Carolina to extend from the Coast Plain into the Appalachians. Behrendt's et al., 1985 line drawing of SeisData 4 is shown in figure 1.3. The section of the profile shown is the section of SeisData 4 that coincides with the MPSSZ. The profile shown in figure 1.3 is an unmigrated section. Here Behrendt et al., 1985 has interpreted a basin between shot points 1,100 and 1,200 and has named it the Jedburg basin. However looking at the B and the J reflections in this interval there is very little evidence for a basin. Both the J and the B reflectors are marked along the profile and appear to be flat lying. Around shot point 850 the B reflection is lost. The J reflector pinches out at around shot point 300 as the profile moves seaward. Both reflectors are sub-horizontal and which is coincident with what is seen in the MPSSZ.

A simple schematic was created to show the new proposed structure in the MPSSZ. We propose from the geometry of the J and B horizons that the MPSSZ is not a fault bounded basin with the sub-parallel Summerville Fm in its respective location. On the left hand side of Figure 1.4 is the schematic representation of analog Triassic basins seen in the SGR. Clubhouse Crossroads well 3 penetrated around 650 m of coastal plain sediments before it reached the PRU. Coring conitnued until it bottomed in an asymmetric basin composed of Triassic aged sedimentary red-beds. It was assumed that when it reached the redbeds that they were deposited in a Triassic basin. On the right hand side of Figure 1.4 is our new proposed structure of the MPSSZ. From the seismic reflectoin profiles, it has been observed that the Summerville Formation is relatively flat suggesting that the red-beds underneath the PRU were not deposited in an assymetic basin, shown by the flat lying sequence underneath the basalts in figure 1.4

1.3. Observations

Tying the refraction endpoint velocities with the reflection profiles shows that the J and the B reflections are traceable over the extent of the study area (Figure 1.10). In between these two reflections are the sedimentary red beds that were encountered in Clubhouse Crossroads well 3, shown by multiple sub-parallel reflections that are seen throughout the study area.

1.3.1 Lithology of Clubhouse Crossroads well 3

For this study the focus on the lower portion of the Clubhouse Crossroads wells. Clubhouse Crossroads well 3 is the only well in the vicinity of the seismic reflection and refraction surveys that penetrated the basalt and terminated in the underlying sedimentary redbeds. The coastal plain section of Clubhouse Crossroads well 3 has a thickness of 775 m, before the basalt is encountered. A stratigraphic column of Clubhouse Crossroads well 3 is shown in Figure 1.5. The column has been modified from Schilt et al., 1983, and shows the lithology of the sediments below the basaltic layer. The sedimentary red beds were first encountered at 1,030.3 m. On the far left of Figure 1.5, is another stratigraphic column, modified from Gohn et al., 1983, that represents the last 3 m of the red bed section. In the core there are four instances where there is inverse and inverse to normal grading in the lower parts of the conglomeratic sandstones.

Basalts were encountered at 775m in Clubhouse Crossroads well 3 and have a minimum thickness of 256m. Gottfried et al., 1983 subdivided the basalt in to seven separate flows. Flows 1, 2, & 3 are very thin and vesicular flows. All three flows are aphyric and may represent flow lobes of a single eruption (Gottfried et al., 1983). The three flows range from the top of the basalt at 775m to 784.6m where coring was halted. Around 25 percent of the three flows are made up of vesicles and amygdules. The upper flow shows the most alteration of the three. The plagioclase feldspar has been altered to zeolite and some secondary chalcedony and potassium feldspar can be seen. Flow 4 is located around 921m where coring was resumed. Its thickness is around 3 m, with the base of the flow around 924m. At the base of the flow it is very fined grained and appears very similar to the sandstones found below it (Gottfried et al., 1983). At 925m, a 2m thick sequence of argillaceous sandstone is found within the basaltic section between Gottfried's flow 4 and 5. The sandstones found in the basalts, show abundant fragments of basalt, quartz, minor microcline, perthite quartz and potassium feldspar. This suggests that the source of sedimentation was not limited to the enclosing basalt (Gohn et al., 1983). It grades from black fine-grained sediments near the top to coarse-grained red sandstone at the base. In the fine-grained section near the top, angular fragments of phyric olivine basalt can be found (Gottfried et al., 1983). These sandstones may be present throughout the uncored basaltic section. In flow 5 coring was stopped around 930 m, where only four meters were recovered. The top of flow 5 is very-fine-grained texture which may suggest that the basalt may have been intruded into a sill or unconsolidated sediment (Gottfried et al., 1983). Flow 5 contains about 10-20 percent olivine phenocrysts that are spaced unevenly throughout the core. Below the very-fine-grained the sediments begin to coarsen. Coring resumed at 984 m in what Gottfried describes as Flow 6. The basalts of flow 6 is fine-grained with very few vesicles or amygdules. The base of flow 6 is at 1,021 m. in between flow 6 and 7 there is a layer of calcite, smectite, and angular basalt fragments (Gottfried et al., 1983). The base of flow 7 is the contact between the basalts and red bed section below. Basalt in flow 7 is aphyric and dark gray to black in color. There are some instances where sulfides and native copper occur but is rare (Gottfried et al., 1983).

K-Ar ages of the basalts encountered in the Clubhouse Crossroads well 1 yielded ages of 94.8 to 109 ma Theses ages are considered to be minimum ages due to the highly altered nature of the basalts (Gottfried et al. 1983). Lanphere et al., 1983 tested the basalts from Clubhouse Crossroads well 2 and found that the Ar-Ar ages to be 184 ma. While Gottfried et al. tested the same basalts from well 2 and found ages of 204, 162, and 184 ma, although the ages are out of order stratigraphically. Dates found by Lanphere and Gohn are not reliable ages because of the varying ages from the same data set. Hames et al., 2010 did an Ar/Ar dating tests on the basalts from the Clubhouse

Crossroads well 1 core. Hames laser incremental heating Ar/Ar tests were on basalt whole rock samples and plagioclase separates, that generally yielded total gas and plateau ages younger than 180 Mya. The most consistent results come from the plagioclase separates from near the top of the core for both wells. Dates for the Clubhouse Crossroads well 169.1 +- 2.0. The results found by Hames are more recent and places the age of the basalts found along the J horizon in the Middle Jurassic. The age of 170 may found by Hames is ~30 million years younger than the peak CAMP magmatism (Hames et al., 2010).

The fined-grained facies of the red bed section encountered in Clubhouse Crossroads well 3 consists of around 39 m of color mottled mudstones, siltstones, and argillaceous very-fine to medium-grained sandstones (Gohn et al., 1983). Mudstone beds found in the fine-grained facies have a thickness of around 1-4m. Within the contact zone the medium-grained sandstone occurs in irregular patches that are not vertically continuous with the main body of the present rock type at the top of the section (Gohn et al., 1983). At 1,032.4 m depth flame structures are present at the contact between the units, suggests that there was movement of water in the section. Calcite is found in irregular shaped nodules as small as 1 mm and as big as 6 cm. Mudstones in the fine-grained facies are typicllay massive, nonfissile, fine-grained rocks lacking primary stratification (Gohn et al., 1983). The rocks of the fine-grained section are mostly grayish red and pale reddish brown while he non-red rocks of the core are grayish green to grayish yellow. Color mottling of the red bed core is a secondary feature that cross-cuts the primary stratification seen (Gohn et al., 1983). From all the samples that were studied by Gohn, most of the sandstones were classified as arkosic or fledspathic wackes and the sandstones that contained locally derived mudstone and siltstone interclasts are lithic wackes (Gohn et al., 1983).

The coarse-grained facies of the red bed section has a thickness of 8.2m and consists of very poorly sorted argillaceous coarse-grained to conglomerate sandstones interbedded with mudstones. Sedimentary structures that are found in the sandstones consist of inverse or inverse-to-normal size grading (Gohn et al., 1983). Pebbles and granules occur in the center and the top of the coarse-grained section. Conglomerates found near the bottom of the section are very poor sorted and contain abundant unstable detrital rock fragments. The coarse-grained section is compositionally immature. Modal analysis performed by Gohn for the three conglomerate beds from the Clubhouse Crossroads well 3 core show that the maturity ratio is 0.4-0.16 (Gohn et al., 1983). This is very low and considered to be very immature. The greater the percentage of stable grains to unstable grains, the more compositionally mature the sediments. Shown on the right of Figure 3 is a core that was taken at 1144.7 m depth in the lower red bed sequence. The core is a part of the lower red bed section containing conglomerate arkosic sandstones. The big clast seen in the middle of the core is a basalt clast. This is lower than the basalt associated with the J horizon seen higher up the section. Initially the red bed section was considered to be Triassic in age, but finding basalt clasts in the lower section of the red bed sequence suggests that the age of the sequence may be younger than previously thought. Gohn classifies the conglomeratic sandstones as arkoses or arkosic wackes, with majority of the lithic fragments coming from granitic rocks that were composed of plagioclase, perthite, myrmekite, quartz, chlorite, epidote, while feldspar and quartz composed mostly of the single-crystal sand-sized grains. The sand-sized grains and clasts show alteration. Basaltic, microbreccia, and mylonite fragments are less common lithic fragments found in the coarse-grained section. Basalts found within the coarse-grained section indicate that there was magmatism in the MPSSZ before the Middle Jurassic when the J horizon basalts were emplaced. Basalts in the coarse-grained section might be associated with the CAMP rocks found elsewhere during rifting and then were eroded away and deposited in the coarse-grained section.

1.3.2. Seismic Analysis

Profile SC1 (Figure 1.6) has the best constraints on the data, having the three Clubhouse Crossroads wells and Ackermann's refraction profile 10 along the profile. The three Clubhouse Crossroads lie along profile SC1 at locations; 32°53'25.9871"N, 80°21'41.0333"W for well 1, 32°54'28.2000"N, 80°18'37.2000"W, for well 2, 32°54'10.7963"N, 80°18'57.0182"W for well 3. Clubhouse Crossroad well 1 penetrated 750 m of Coastal plain sediments and terminated at 792 m in the quartz normative thoeliitic basalt. Clubhouse Crossroads well 2 penetrated 750 m of Coastal Plain sediments and terminates in basalt at 907m. As mentioned previously the Clubhouse Crossroad well 3 is the only well in the vicinity to penetrate the basaltic section and terminated in the red bed sequence at 1152 m depth. SC1 profile is located in the middle of the study area and trends southwest to northeast (Figure 1.6). The bright reflector that can be seen around 750 m is the J reflector. It is sub-horizontal, (generally unbroken), and mappable throughout the profile. The brightness of the J horizon is a result of it being underlain by basalts encountered in all three wells. Beneath the J there are several sub-parallel reflections that are not multiples from the Coastal Plain sediments. These are the red bed sediments that were encountered in well 3 and the proposed Summerville

Formation. When tying the Clubhouse Crossroads well 3 to SC1, the red bed section from the well coincides with the sub-parallel reflections beneath the J horizon. Reflections of the Summerville Formation have similar geometry as those of the J refection above them. The reflections are a two cycle reflection, laterally continuous, apparently unbroken, and can be traced throughout the entire profile. The B reflection can be seen at 1050 m depth. Ackermann's refraction profile 10 with endpoints 10a and 10b have been tied to SC1 CDP 229 and 59. Velocities for the coastal plain sediments have been calculated from the sonic log by Yantis et al., 1983 and show an average velocity of 2.0km/s. Ackermann's refraction profile 10, show 5.7 km/s for endpoint 10a and 5.7 km/s for ten 10b. These velocities were used to constrain the depth to the two reflectors along SC1. In the interpreted profile shown in figure 1.6, the J horizon is marked by the black arrow and the shaded region is the Summerville Formation with its base being the B reflection. The J reflection varies very little from 750 to 776 m in depth throughout the profile. Thickness of the basaltic section along profile SC1 varies along the profile but is roughly 256m. The observed varying thickness of the J horizon is analogous to the varying topography of the top of the basement. The thickness of red bed varies along the profile around 188 m. As you move northeast along the profile the B reflection begins to thin by roughly 39 m. Towards the northeast end of the profile it begins approaching the ridge, noted by Ackermann, that trends south-southwest to north-northeast. Both the J and B reflections appear to thin as they approach the ridge in the middle of the study area.

VT5 is located in the northeast portion of the study area, trending south southwest to north northeast and sits atop a basement low first noted by Ackermann. The Summerville oil well was drilled approximately 2.5 km southwest of profile VT5, penetrated 746.8 m of coastal plain sediments and terminated at 783.3m in diabase. Ackermann's seismic refraction profile 6 endpoints are tied to VT5's CMP 67 (SW end) and 222 (NE end) (Figure 1.7). Like previously a velocity of 2.0 km/s (from Yantis et al., 1983) was used for coastal plain sediments and constrain depth for the coastal plain sediments. Velocities of 4.4 km/s, from Ackermann's refraction study, are used to determine depth for the J horizon. The reason for the low velocities is that the basalt is not present along all of the J horizon and is directly sampling from the proposed Summerville Formation.

The bright reflector that can be seen at 600-650 m is the J reflection (Figure 1.7). There is a change in reflection character in the J horizon that can be seen in the northern section of the profile. Normally when the J reflection is underlain by basalt it is observed by a bright two-cycle reflection. An example can be seen at 600 m between CDPs 1 and 115 on VT5. From CDP 125 to 1800 the spacing between reflectors of the J reflection begins to widen as you move northward. The change in reflection character can be seen on multiple profiles throughout the study area. The B reflection along VT5 has dropped considerably in depth, possibly due to the growth of the Summerville Formation sediments or caused by faulting as evidenced on VT4 which crosses the ridge that is located in the middle of the study area. There are several diffractions seen between CDPs 100 and 190. These diffractions are below the B reflection and are therefore interpreted to be in basement. Diffractions in the basement are most likely caused by faulting. The faulting in the basement along profile may be related to the ridge in the middle of the MPSSZ, but is still unknown. As you move northward throughout the MPSSZ, the J reflection begins to shallow from 750 m to approximately 600 m. Reflections of the

Summerville Formation along the southern end of VT5 share the same characteristics of those found along SC1 which are laterally continuous and sub parallel.

Profile SC4 is the southernmost reflection profile that is in the MPSSZ and trends southwest to northeast (Figure 1.8). The J reflection can be seen around 750-800 m. B reflection can be seen around 2000-2100 m. Both reflections have a slight dip towards the SE. The profile has two (17 and 22) of Ackermann's seismic refraction profiles associated with it. For the coastal plain sediments, like on profiles SC1 and VT5, a velocity of 2.0 km/s was used for both refraction profiles. On the western end of the profile, refraction profile 17 (marked by end points 17a and 17b) have velocities of 5.5 km/s for the basalt. Seismic Refraction profile 22 (marked by endpoints 22a and 22b) has velocities of 5.4 km/s for the basalt. Previous work has shown that there was a "zone of missing J" on SC4, (Figure 1.8) that was seen on the southeastern section of the profile between CDPs 244-368. We suggest, like on VT5 (Figure 1.7), which the J reflection can still be traced along the profile but the basalts do not underlie the PRU which effects the reflectivity of the J. The bright J reflector that is seen in the western part of the profile can be traced through to the SE section even though the reflector loses its reflectivity. This suggests that the prominent reflections that are seen around 1340-1410 m and in between CDPs 500 and 735 are the new proposed Summerville Formation. In-between CDP's 500 to 735 and between 2000-2100 m of the profile the Summerville formation begins to thin from 2100 to 1900 m as the profile moves seaward. The basalts can be seen between CDPs 1 to 488. On profile SC4 (Figure 1.8) we see a seaward dipping trend in the reflections which is consistent with previous author's interpretations.

Profile VT4 is located in the middle of the study area and trends NNW to SSE. The un-interpreted and interpreted profiles of VT4 are shown in Figure 1.9. The northern section of VT4 and the whole profile VT5 appear to be located in a basement low. The reflection profile is important because it is the only line to cross over the basement ridge that can be seen in Ackermann's depth to basement map (Figure 1.2b) and in Figure1.10b. On the northwestern portion of the profile Ackermann's seismic refraction profile with endpoints 4a and 4b that are tied to CDPs 375 and 305. Again velocities of 2.0 km/s were used for the coastal plain sediments. Ackermann's refraction velocities found 5.4 km/s for the basalts. These velocity calculations were used to determine the depths to each horizon on VT4. The Summerville Formation on the southeastern portion of the profile is noted by the sub parallel reflections that underlie the bright J horizon that can be seen between CDPs 50 to 180 (Figure 1.9). The B reflection seen at 1290 m depth. In the northwestern end of the profile, in the vicinity of the Ackermann profile 4, the B reflection drops to about 2490 m. This is similar to what is seen on profile VT5. Between CDPs 301 to 425 the data is very well constrained with Ackermann's refraction velocities.

The change in depth of the B reflector could be due to many possibilities. One possible cause would be a faulting that parallels the ridge which VT4 crosses and that was shown in Ackermann's contour map (Figure 1.2b). In figure 7a between CDPs 180 and 200 there is prominent faulting of the B horizon and the J horizon. On VT4, like SC4, has multiple instances along the profile where there is a change in the reflection character along the J reflection. From Ackermann's depth to basement contour map, the depth to the basement is at 2490 m in the northern part of the section just past the ridge.

1.4. Depositional Environments of redbeds

1.4.1 Fine-grained facies

The depositional environment of the upper section of the red bed sequence consisting of fine-grained facies is generally thought to be low energy because of the immaturity, moderate sorting of grains, and small amplitudes of cross stratification (Gohn et al., 1983). There was rapid deposition in the fine-grained facies shown by deposition of sediments on unstable water saturated substrates, shown by the intermixed lithologies (Gohn et al., 1983). The sandstones contain interclasts of mudstones which shows that there were moments with high enough energy to erode partially consolidated, stable substrates (Gohn et al., 1983). The sandstones are lacking body fossils and biogenic structures suggesting that deposition occurred in an environment that was lacking in abundant fauna. Sedimentary structures that were found in the Clubhouse Crossroads well 3 are very similar to the exposed Jurassic/Triassic sequences that are considered to be floodplain deposits. However Gohn describes the deposits found in the Clubhouse Crossroads well 3 as not having the typical features that fluvial floodplain deposits would normally have such as; climbing-ripple laminations in sandstones, horizontal laminations in the mudstones, and channel-sand deposits that are an integral part of fluvial systems. Gohn suggest that in the Clubhouse Crossroads well 3 core that the rocks near 1,035.5 m and the top of the core might represent one or more truncated, relatively fine-grained, channel-bar deposits which might represent the channel-sand deposits. Gohn suggests due to the dominance of mudstone and the vertical sedimentary sequences typical of fluvial channel systems, the deposits in the MPSSZ bears a resemblance to sedimentary sequences in the semi-arid Basin and Range, which was deposited on a floor of a dry closed basin. A dry basin floor is topographically flat, generally elongate axial part of a sediment-filled closed basin, flanked by alluvial fans or pediments and exclusive of the parts of the basin occupied by lakes or playas (Gohn et al., 1983). Sediments typically found in dry basin floors are transported episodically from distal parts of adjacent alluvial fans by streams during floods, mainly by slurries, and less commonly mudflows. In particular, bimodal sorting into massive mudstones beds (lacking horizontal lamination) and thinner lenses of sand or gravel is diagnostic of dry-basin-floor sediments (Gohn et al., 1983). The sedimentary features found in Clubhouse Crossroads well 3 core are very similar to those found in dry closed basins, which might be the environment of deposition for the fine-grained facies of the Summerville Fm. Calcite nodules that are found within the fine-grained section resemble those in found in the upper Paleozoic and Mesozoic continental rocks, usually interpreted to represent pedogenic carbonate deposits or caliche. These are typically found in dry-basin floors of the Southwestern United States and are interpreted to be areas that have long periods of subaerial exposure during depositional events with little to no erosion (Gohn et al., 1983). The red color of the Summerville formation could possibly come from the oxidation of the rocks in a reducing environment that was produced by the calcification process or maintained from the presence of plant material.

1.4.2 Coarse-grained facies

The coarse-grained facies in the lower section of the red beds show deposition by debris flows rather than a water-gravity flow. Mudstones seen in the lower portion of the red bed sequence show primary features that indicate that a mudflow moved in a similar manner to the debris flow and could be similar to the mudflows seen in the upper fine-grained facies. The poor sorting, inverse bedding, and lack of boulders are indicators for deposition in a semi-arid environment, on a medial to distal part of an ancient alluvial fan. The inverse bedding is also an indicator that the deposition environment was higher in energy than the depositional environment of the fine-grained facies above. The granitic clasts that are found in the conglomerate section of the red-bed core, most likely are locally derived sediments from local granitic plutons, which exposed areas of the basement might be the sediment source. The basalt clasts shows that there was periodic magmatism in the MPSSZ prior to the event that deposited the Jurassic aged basalts.

1.5. Discussion and Conclusions

The relatively flat-lying nature of the Summerville Formation reflections, seen throughout the study area, suggests that the MPSSZ is distinct from analogous Triassic rift basins seen in Eastern North America. Mapping the J and B horizons throughout the MPSSZ in a traditional Triassic rift basin, one would expect Mesozoic strata beneath the J horizon to be dipping in an asymmetric basin. After careful reanalysis of seismic reflection and seismic refraction data, the Summerville Formation, it is noted by several sub parallel reflections that underlie the J reflection and the basalt that correspond to the red bed sequence found in Clubhouse Crossroads well 3. It has an estimated thickness around 200 m below the ridge and north of it around 700m.

Hames et al., 2010 test of the Clubhouse Crossroads well 1 suggests that the new ages for the J horizon basalts indicates that they are too young to be a part of the CAMP event but many be from the same source. It brings into the question of the age of both the Jurassic basalt and the newly recognized Summerville Fm. Basalt tested from Clubhouse Crossroads well 2 in two separate studies and found varying ages. The whole rock K-Ar and Ar-Ar dating found age values of possible Early Jurassic, but had varying ranges of ages. Hames however has more recently tested the basalt from the Clubhouse Crossroads wells and found an age of 160 Mya. The depositional environment for the conglomeratic sandstones was of higher energy than those above it, which can be seen by the size of the sediments in the core from that section. Presence of basalt clasts, found at 1,447.7 m depth in the Clubhouse Crossroads well 3, in the Summerville Formation suggest that there was an earlier magmatic event that was deposited and eroded prior to the deposition of the red beds. This suggests that there was a magmatic event before the event where the Jurassic aged basalt was emplaced. Finding basalt clasts in the Summerville Formation indicates that the redbeds might be younger than previously thought. There has been no age dating of the redbeds or the basalt clast from the Clubhouse Crossroads well 3 core hence ages placed on the Summerville Formation are relative.

Figure 1.10 displays two structural maps created in Petrel. Figure 1.10a is the surface of the J horizon. The surface gently slopes southward. The J surface is a relatively continuous surface with no dominate lows or highs. The continuous nature of the J surface map suggests that there has been very little vertical movement since the Late Cretaceous, suggesting that the faulting associated with the 1886 Charleston, SC earthquake must be older. Figure 1.10b is the surface of the B horizon. Similarly, Ackermann’s depth to the basement map, there is structural depression bounded by a ridge that trend SSW to NNE in the middle of the map. North of the ridge the B reflection is offset from around 1050 to 1300 m, where profile VT5 is located. VT4 is the only reflection profile that crosses the ridge and joins VT5 in the basement low. Due to the quality of the data it is not clear what exactly is causing the offset of the B reflection.

Figure 1.12 is an isochore map that was also generated in Petrel, and shows the true vertical thickness of the Summerville Formation. The isochore shows the growth of strata in the vicinity of the Jedburg basin. The thickest part of the Summerville lies just across the ridge that Ackermann first noticed, and is around 700 m thick. Since there is no direct well control near the Jedburg basin (across the ridge) it is unclear whether or not the growth strata is completely the Summerville Formation, or possibly a combination of that and older sediments. Its thickness south of the ridge is somewhat uniform, with a general thickness of 200-225 m

One effect of mapping the Summerville Formation throughout the MPSSZ is that the extent of the basalt flows can be revised to a more localized extent. Reflection character changes seen in many of the reflection profiles show that the basalt is not as laterally extensive, but both the J and the B horizons are mappable throughout the study area. Basalt can be partially seen on profiles VT4, VT5, SC4, SC10, and SC6. All of these profiles have the reflection character changes that were mentioned previously. Along with evidence from the seismic sections Ackermann's refraction velocities were used to determine where the basalt occurs. Velocities of 5.0 to 5.7 km/s correspond to the presence of basalt. Mapping the reflection character changes along with velocity changes, seen in the seismic sections, estimated extent of the Jurassic basalt sills seen in the MPSSZ can be changed to a more localized extent (Figure 1.11). However, despite areas where the Summerville Formation underlies the PRU, the J reflection is traceable throughout the study area. The areas were we see velocities of 4.0 to 4.7 km/s is where the Summerville Fm is in contact with the PRU. A "zone of missing J," between CDPs 475 and 735 (on the eastern end of the profile), was reported being seen on profile SC4, where we suggest is the best evidence of where the basalt is not present. Normally the contact would be between the PRU and underlying basalt but in the "zone of missing J" the contact would be between the PRU and the upper fine grained sediments of the Summerville Fm. The change in reflection character of the J horizon can been seen on VT5 and several other profiles. On VT5 there is reflection character change in the northeast portion of the profile. The reflector that usually identify the J horizon change geometry.

Re-characterization of the J horizon is needed after careful reanalysis of the seismic reflection and refraction data from the MPSSZ. Normally has been characterized by a bright two-cycle reflector with basalts underlain and was the contact between the PRU and the Jurassic aged basalt. However the basalts are not as regionally prevalent regionally as once thought and in areas the J horizon is underlain by the Summerville Formation and even basement. Areas where basalt is not present have been indicated by reflector character changes seen along seismic reflection profiles and areas where seismic refraction velocities of 4.2- 4.9 km/s and 6.0-6.1 km/s. In areas where the Summerville Formation directly underlies the J reflector, it loses its bright reflectivity and the flat lying stratigraphy of the Summerville Formation becomes more apparent. Basalt coverage attenuated the reflections of the Summerville Formation due to an inverse in the velocities as you move down section. Unfortunately in areas where the basement is in contact with the PRU there is only seismic refraction surveys to constrain our analysis. A velocity model was made in ARCMap (Figure 1.13), that shows the lateral velocity changes in the MPSSZ. In the velocity model there is an area with low velocities that extends from the southern end of the map all the way up to the north central, which is where the Summerville Formation is in direct contact with the PRU. Comparing the Basaltic Extent map (Figure 1.11) and the Velocity model (Figure 1.13) areas of 5.0-5.8 km/s, which correspond to basalt, match up nicely. Seeing lateral variations in the J Horizon, due to lithologic changes at the boundary, the J horizon can be changed from the boundary between the PRU and basalt, to the PRU and the overlying Late Cretaceous coastal plain sediments.

Reanalysis of the data from the MPSSZ has shown that there is a new sedimentary lithologic unit that has many impacts on our understanding of the area surrounding Summerville, SC. The Summerville Formation is a sub-horizontal unit that in some areas is in direct contact with the PRU. A consequence of this is that the basaltic extent can be revised to a more localized flow. The J horizon can also be reclassified from being the contact between the PRU and the Jurassic aged basalts to the contact of the PRU and the overlying Late Cretaceous coastal plain sediments. Having the both the J and the Summerville Formation both being flat lying sequences it pushes back the timing of faulting in the MPSSZ, since there are no offsets in them. However work needs to be continued on getting better age constraints on the Summerville Formation and possibly dating the basalt clast found in the redbed section.

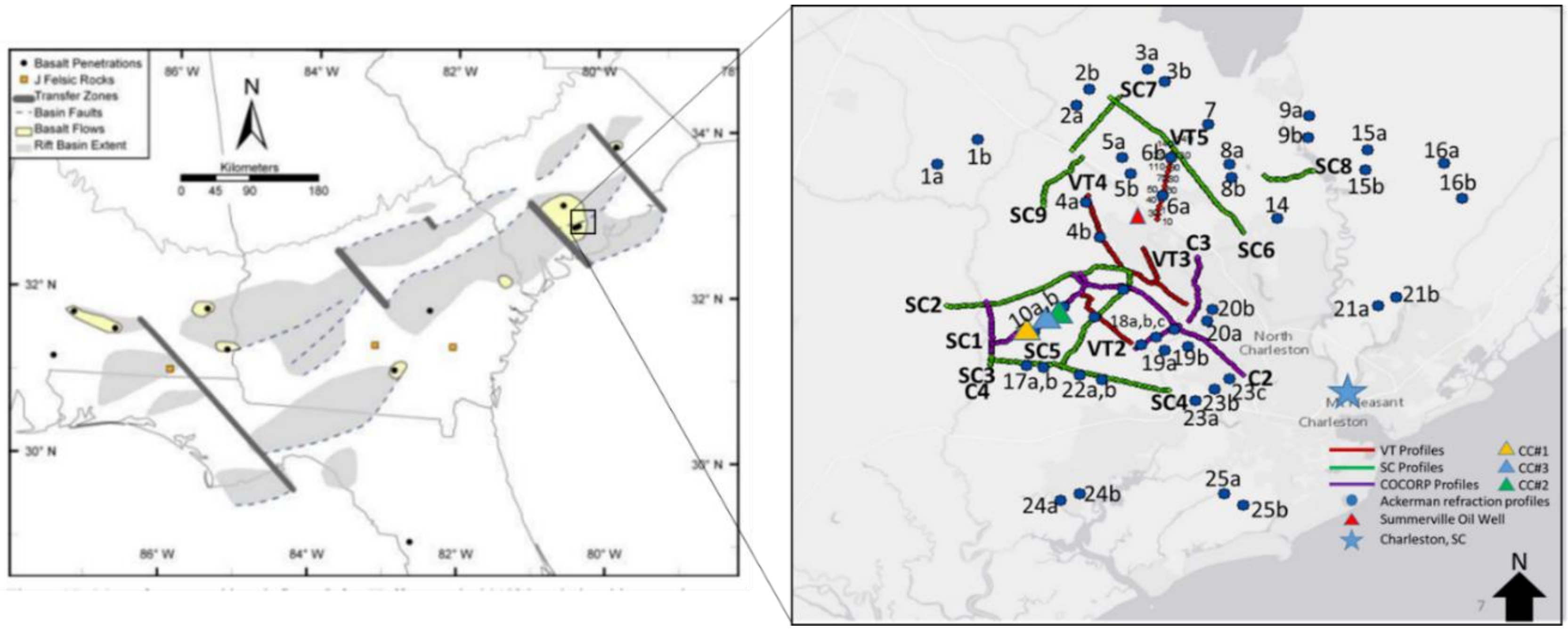

Figure 1.1: Left: Modified from Heffner et al., 2013, map of SGR in the southeastern United States. Right: zoomed in map of study area. Star is the location of Charleston, South Carolina. The Middleton Place Summerville Seismic Zone is the area around 25 km out outside of Summerville, SC where it is thought that the 1886 Charleston, SC earthquake occurred and where recent seismic activity has taken place. The seismic reflection and refractions surveys were collected here to investigate the structure underlying Summerville and the cause of the recent seismicity. Red lines refer to the Virginia Tech reflection profiles (VT), Green lines refer to the South Carolina/USGS (SC) reflection profiles, and Purple lines refer to the COCORP (C) reflections lines. Blue dots refer to the endpoints of Ackermann's refraction profiles. Triangles refer to the three Clubhouse Crossroads wells drilled along SC1 and the Summerville oil well.

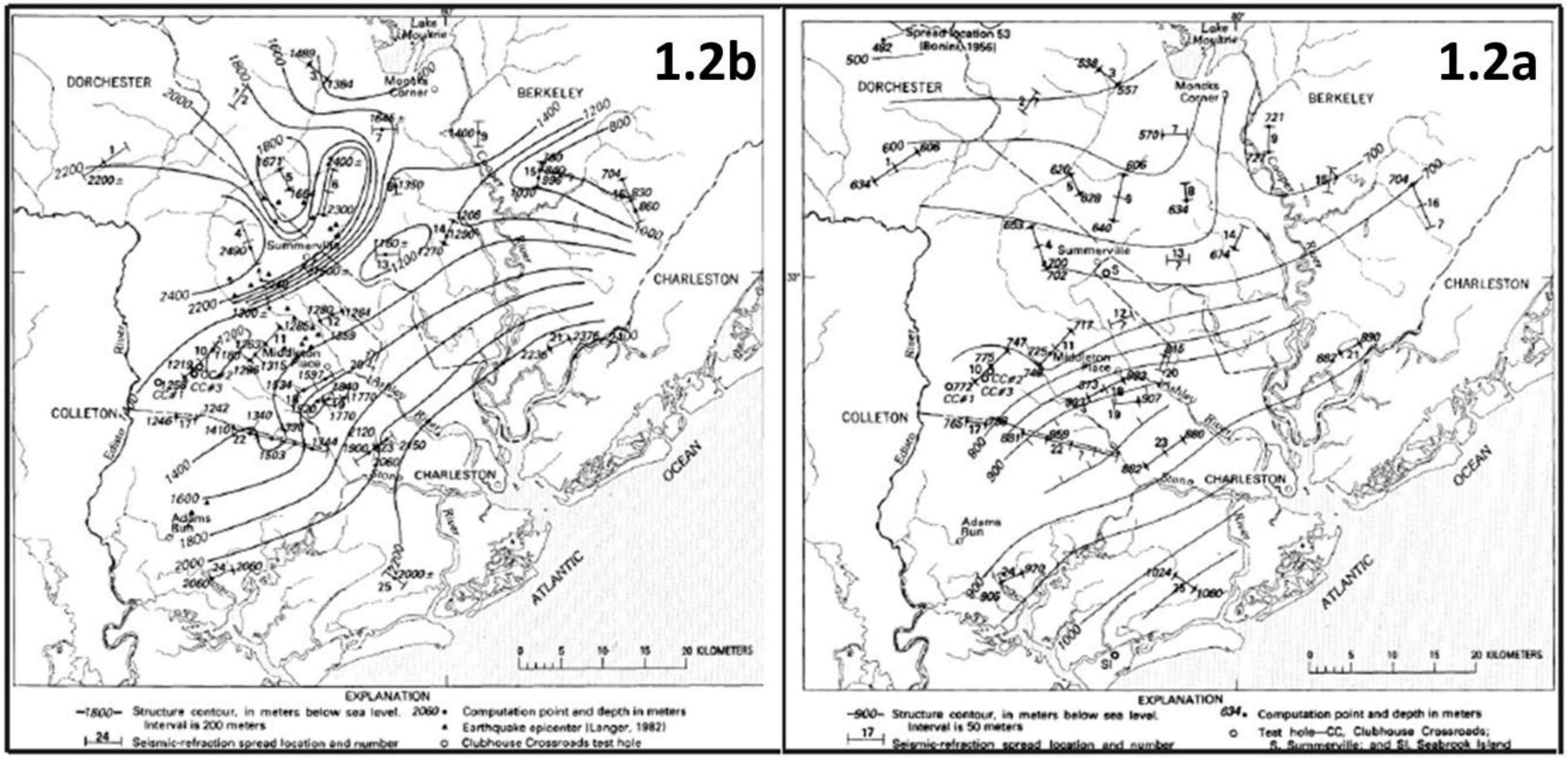

Figure 1.2: Taken from Ackermann 1983. Refraction spreads are shown by their number and depths that were calculated. The figure on the right (1.2a) is a contour map of the depth of the pre-Cretaceous surface that was interpreted from the seismic refraction data. The figure on the left (1.2b) is a contour map of the 6.0 to 6.4 km/s layer as interpreted from the refraction data.

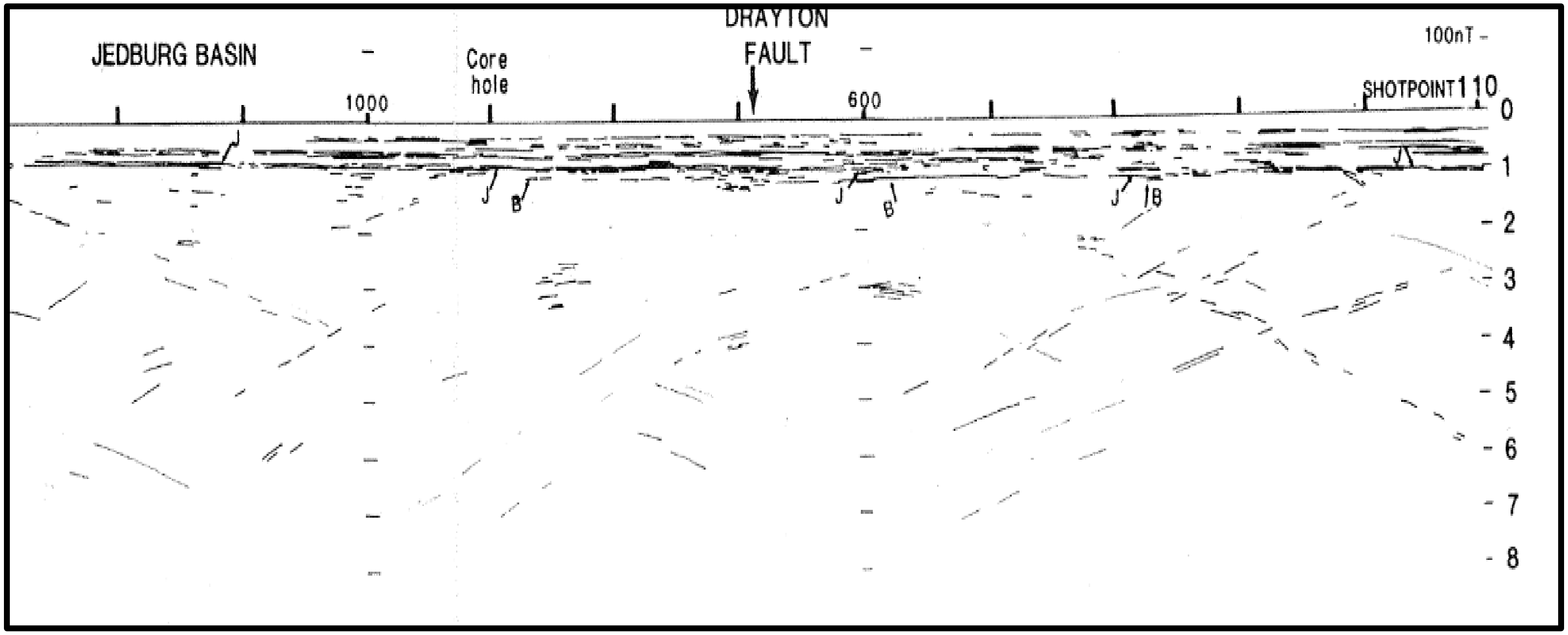

Figure 1.3: A line drawing of the SeisData 4 Profile between shot points 110 and 1300 which maps in the MPSSZ. It is a n un-migrated section that was collected in 1981. Behrendt had interpreted the Jedburg basin in-between shot points 1100 and 1200. The J and B horizons have been partially mapped throughout the profile. Both horizons are relatively flat lying. The J horizon pinches out around SP 300 as the profile moves seaward.

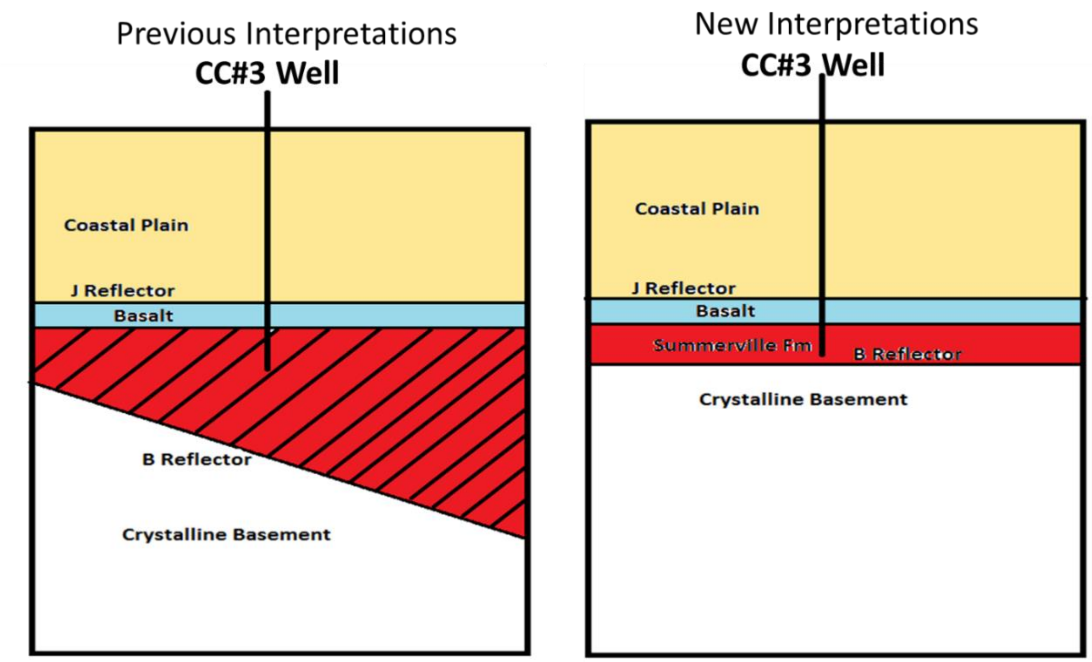

Figure 1.4: 10a (left) is a schematic representation of previous interpretation of the structure underlying the MPSSZ. 10b is the schematic representation of the new proposed structure underlying the MPSSZ. From mapping the Summerville Formation's bounding reflections, it can be said that the new proposed sedimentary stratigraphic sequence is relatively thin, flat lying section that is distinct from other analogous Triassic rift systems seen in Eastern North America.

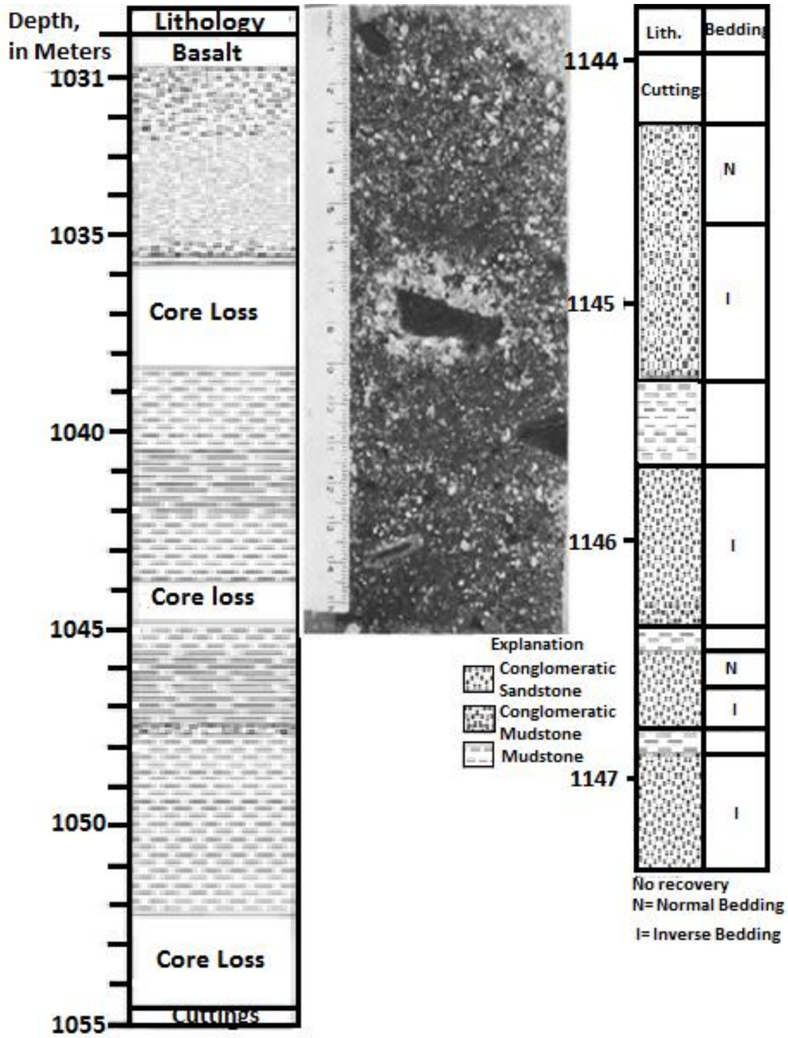

Figure 1.5: Modified from Schilt et al., 1983. Left is a stratigraphic column of Clubhouse Crossroads well 3. Middle right is a core from the Clubhouse Crossroads well 3 that was taken from 1144.7 m in the red bed sequence. The dark clast in the center of the core is a basalt clast. Large gray clasts in upper right-hand corner is a granite clast. Far right is a stratigraphic column that represents the red bed section from 1144 to 1147 meters. The stratigraphic column shows the inverse and inverse to normal grading of sandstones that are interbedded with mudstones.

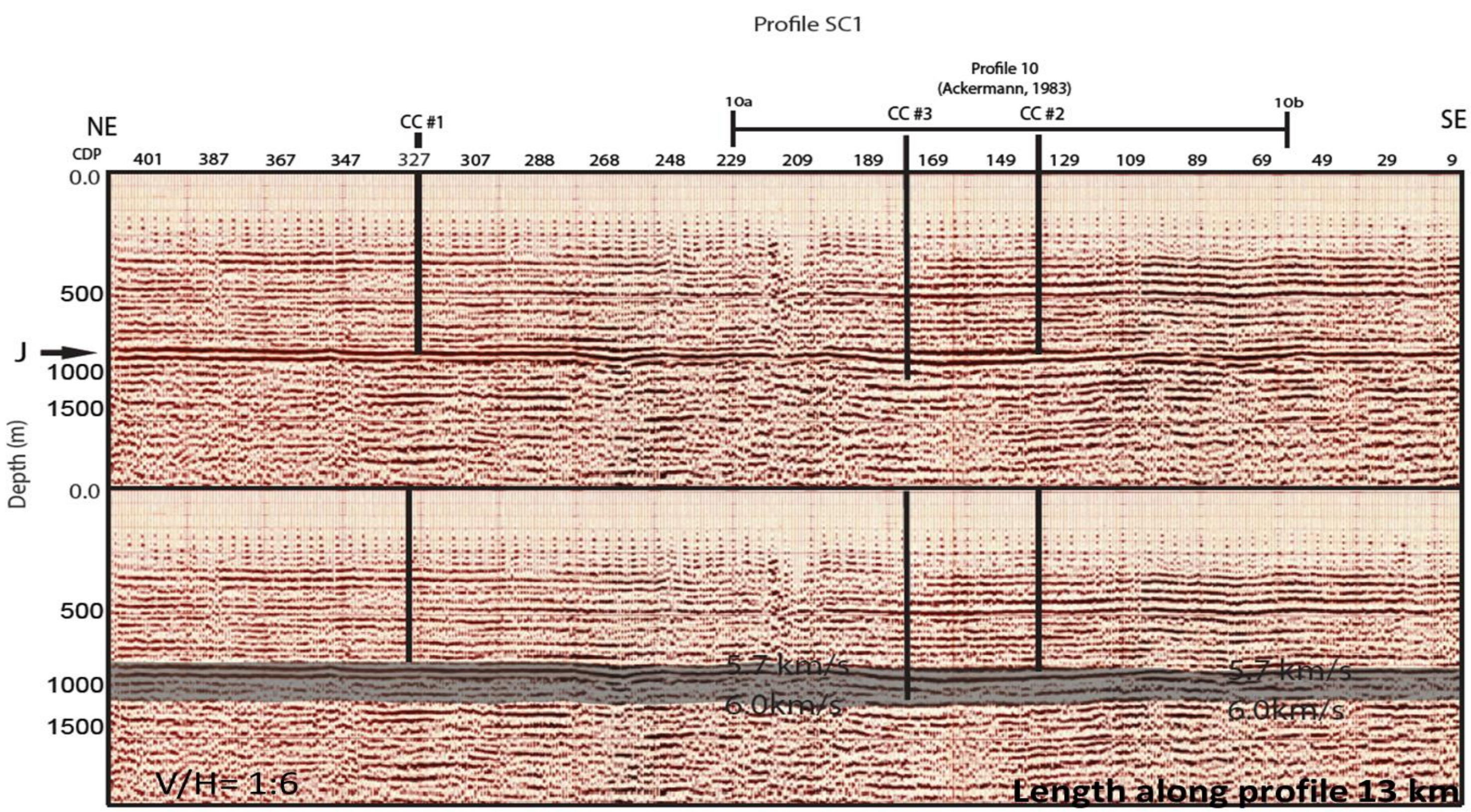

Figure 1.6: Un-interpreted (top) and Interpreted (bottom) reflection profile SC 1. Three wells penetrated 750m of Coastal Plain sediments. Wells 1 and 2 terminated in basalt/diabase. Well 3 terminated in sedimentary red beds. Ackermann's refraction profile endpoints are located at CDP 113 and 60.

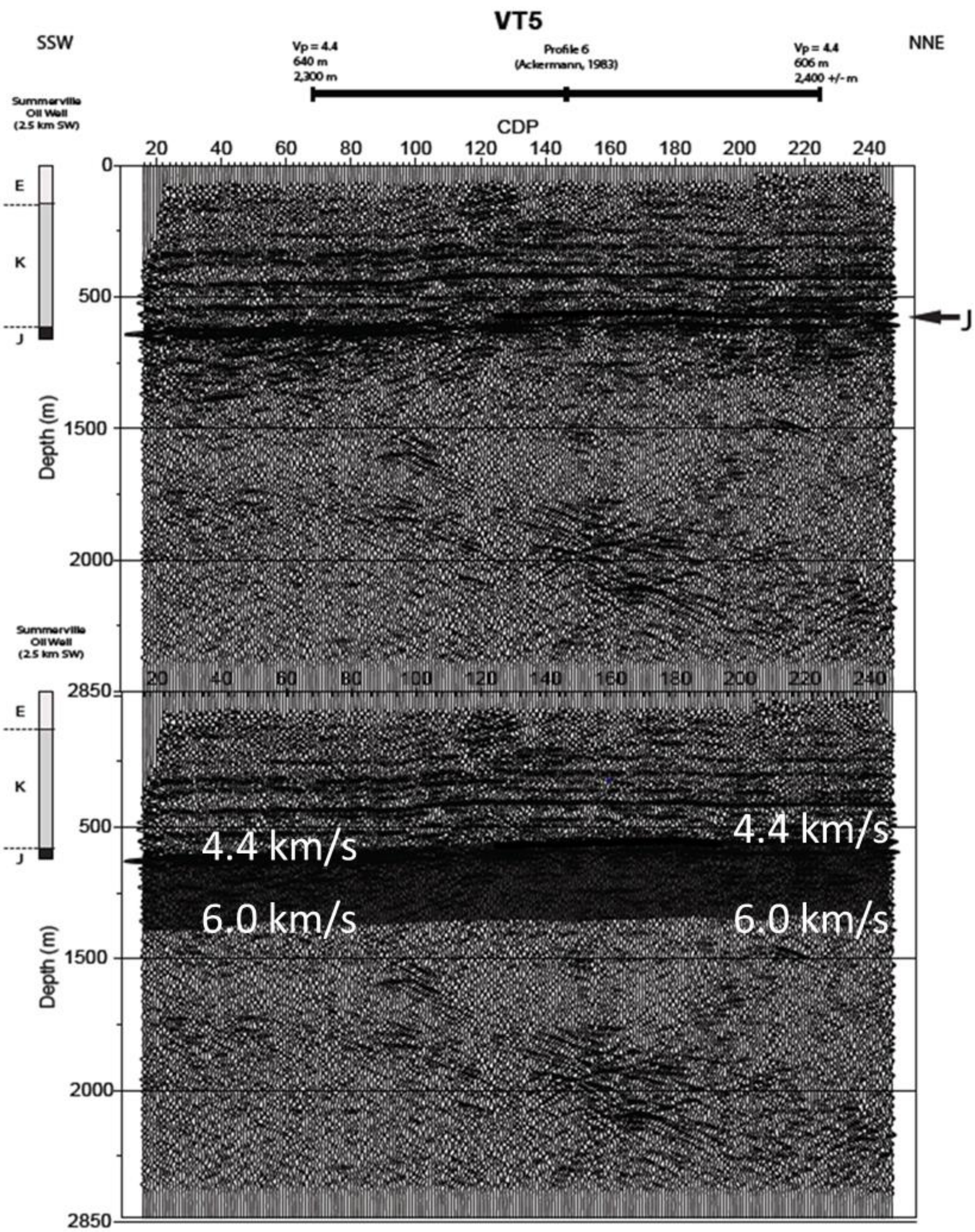

Figure 1.7: Un-interpreted (top) and interpreted (bottom) reflection profiles VT5. 2.5 km to the southwest is the Summerville oil well. The well terminated in diabase at 783.3 m. The J reflection can be seen around 600-650 m depth along the profile. Ackermann's refraction profile 6 shows velocities of 4.4 km/s which corresponds to the presence of the Summerville Formation at the J horizon PRU contact.

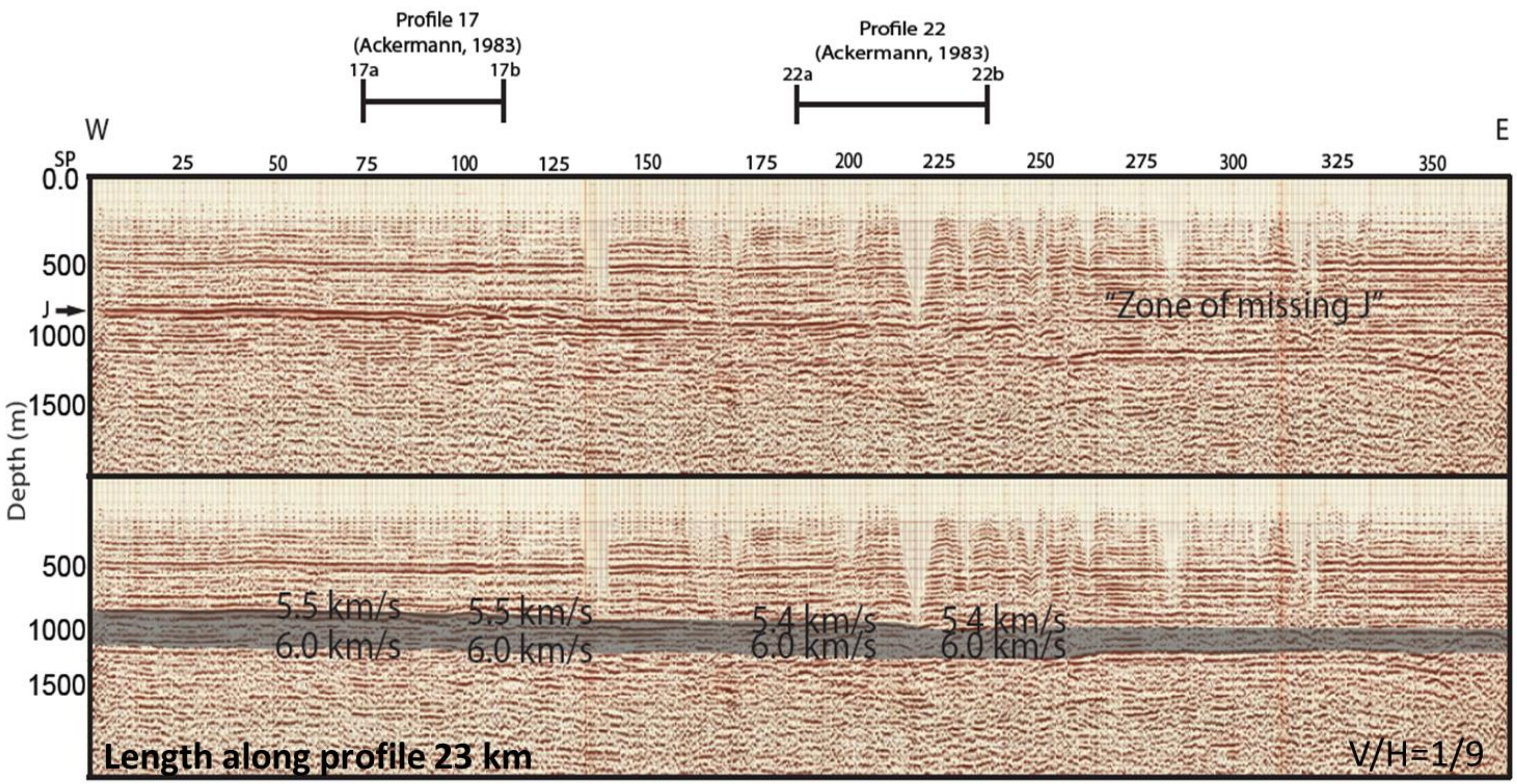

Figure 1.8: Profile SC4. Top, un-interpreted profile. Bottom: interpreted profile with corresponding Ackermann velocities. Ackermann's refraction profile endpoints are marked on both the un-interpreted and interpreted sections

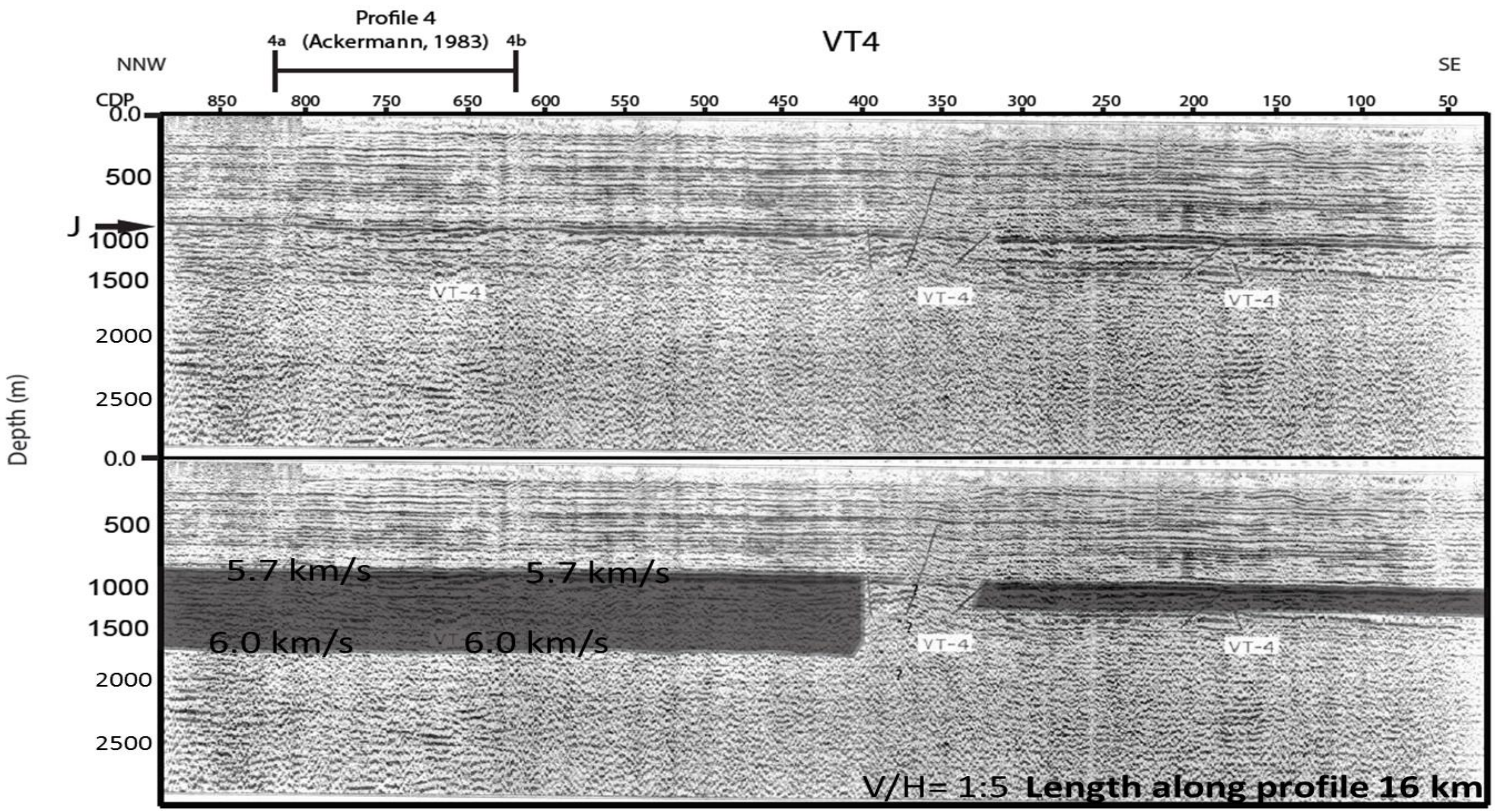

Figure 1.9: Is an un-interpreted and interpreted profile of VT4. The interpretation is the J horizon seen at 0.75 s TWTT. There is a shift in depth of the B horizon, from 0.9 s to 1.5 s TWTT that occurs around CDP 325 Refraction profile four is located in the NW portion of the profile with endpoints 4a and 4b.

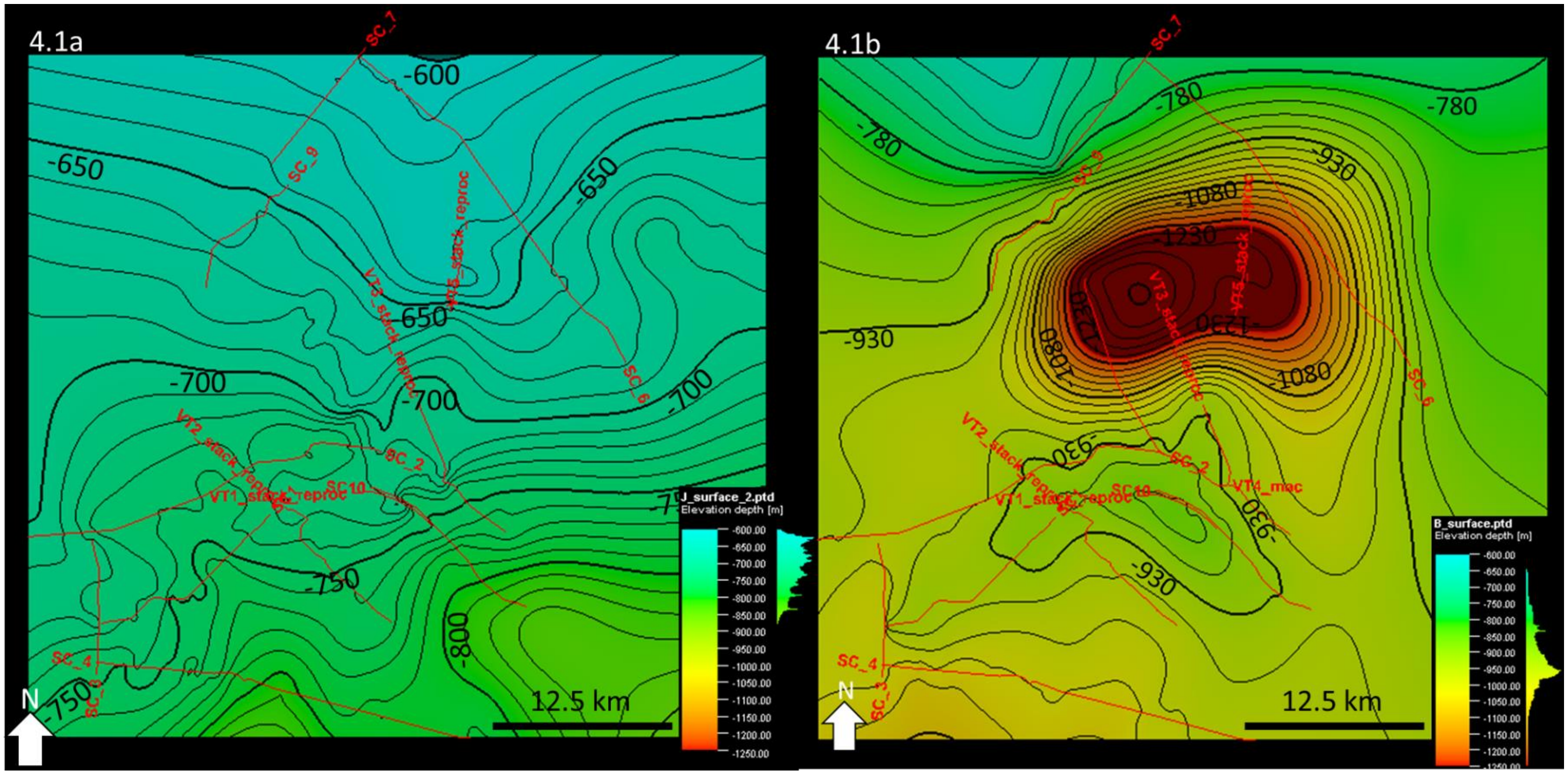

Figure 1.10: 4.1a (left) is a structure map of the J horizon is the MPSSZ. Figure 4.1b (right) is a structure map of the B horizon in the MPSSZ. Both maps were generated in PETREL.

Lateral Extent of Basalt in the MPSSZ

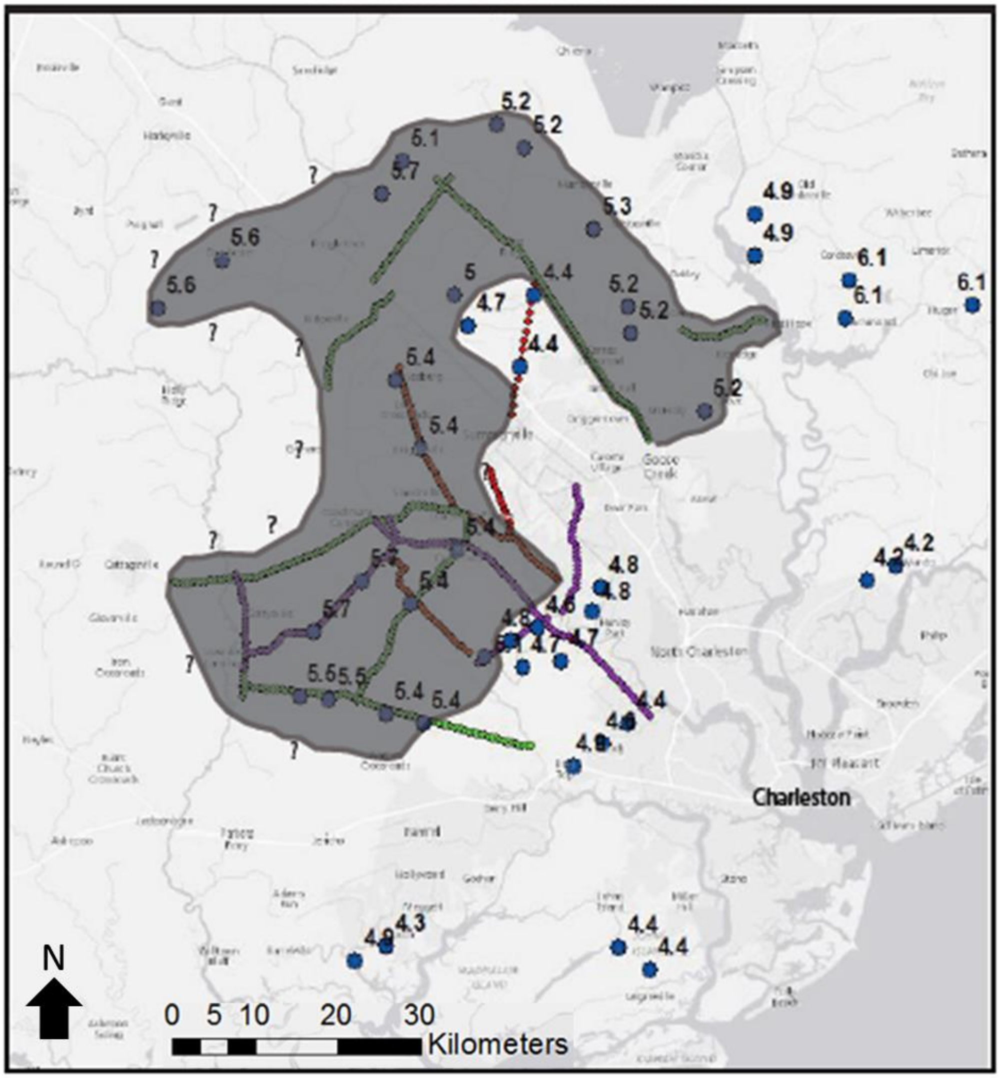

Figure 1.11: Proposed extent of basalt in the Summerville area based on refraction velocities and refection geometry. The western side of the basalt flows are poorly constrained by seismic reflection and seismic refraction surveys and may extend farther westward.

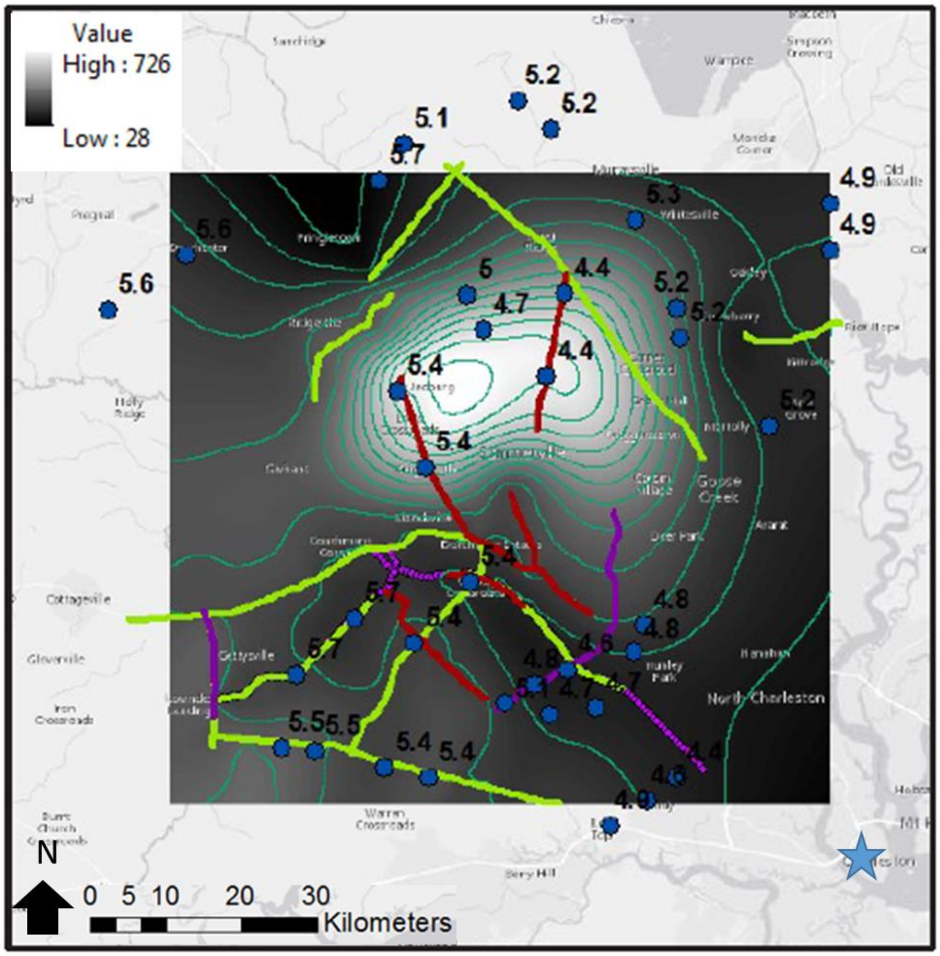

Figure 1.12: Is an isochore, generated in PETREL, between the J and B horizons or the Summerville Formation. Contour intervals: 50 m. Average thickness of sediments is around 200-225m. Thickest sediments are north of the ridge in the Jedburg basin.

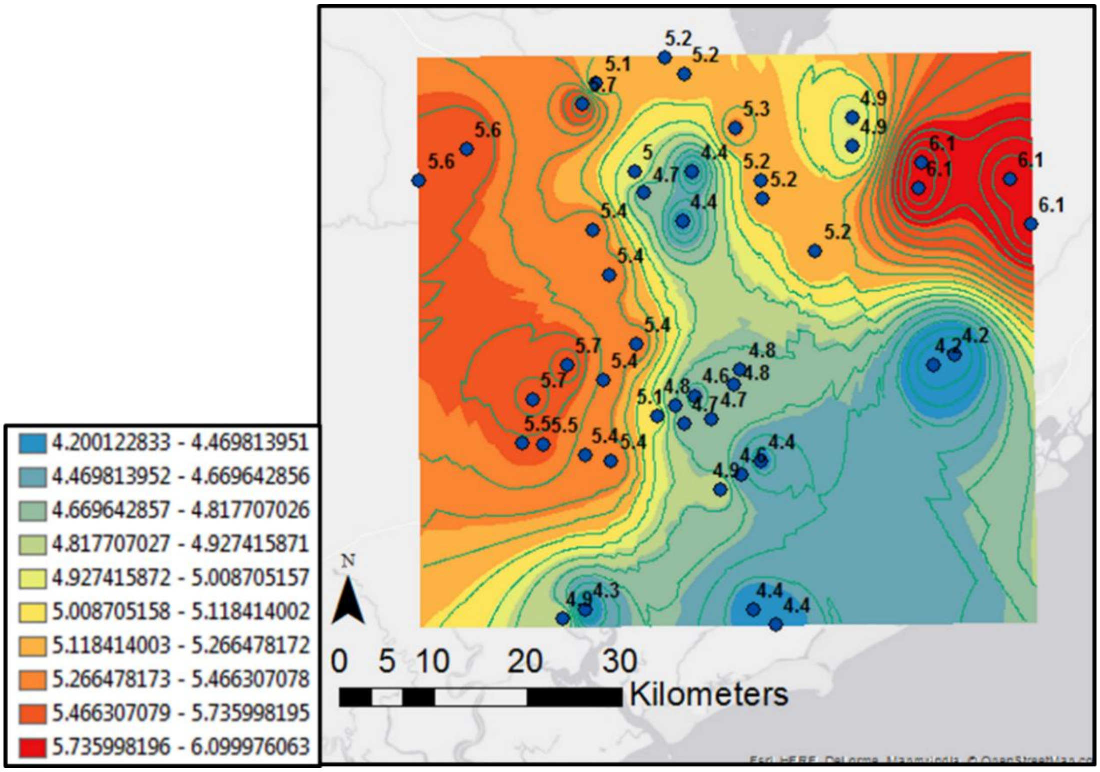

Figure 1.13: Velocity Contour map of the MPSSZ based on Ackermann's refraction velocities at the survey's endpoints. The map was created in ArcMap. The map shows the lateral velocity changes throughout the MPSSZ. The warm colors correspond to higher velocities and the cool colors correspond to low velocities. There is a zone of low velocities shown in blue where the basalts are not present based on the seismic refraction velocities.

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