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Seismic Characterization of the J-Reflector Near the Meizoseismal Area of the 1886 Charleston Earthquake for Lithologic Constraint

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by

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DEDICATION

This work is dedicated to my parents and brother, who have never questioned my ability to accomplish anything I’ve set out to do, and to my friends and acquaintances, which have, and will continue too, provide help and guidance along this life’s journey.

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ABSTRACT

Investigations into the relationship between geologic structure and seismicity in and around the meizoseismal area of the 1886 Charleston earthquake have been ongoing since the 1970s. Seismic reflection profiles collected in this area display a prominent, laterally continuous, high amplitude, low frequency, two cycle reflection at ~0.7-1.2 s TWT, termed the “J” reflector , which has been correlated with Lower to Middle Jurassic tholeiitic basalt flows encountered in the Clubhouse Crossroads wells. The “J” reflector was also extended offshore onto the continental shelf. Recent reevaluation of sub Coastal Plain wells within the South Georgia Rift (SGR) Basin, including wells around the meizoseismal area of the 1886 Charleston earthquake, has shown most do not encounter basalt rising suspicions as to the true lithology of the “J”-reflector. Moreover, this same reflector has been interpreted to be the unconformity at the base of the Cretaceous-age Coastal Plain sediments. In order to define the regional extent of the Clubhouse Crossroads basalt, seismic inversion and attribute analysis were performed on two recently acquired reflection profiles, SCO2-1 and SCO2-5. Beginning in December 2010 through February 2011, seven 2D reflection profiles: SCO2-1 – SCO2-7 (total length 240 km) were acquired to the immediate west and northwest of the Charleston meizoseismal zone and legacy seismic data as part of DOE Award DE-FE0001965: Geologic Characterization of the South Georgia Rift Basin for Source Proximal $C0_2$ Storage project. The first profile, SCO2-1, intersects Norris Lightsey #1 and Rizer #1, two wells that never encountered basalt at the base of coastal plain. SCO2-5 intersects Dorchester 211, a well that bottomed into basalt at the base of the coastal plain. Variations in seismic attributes provide evidence for a western termination of the clubhouse crossroads basalt flow on SCO2-1 and key support for visible amplitude variations

at the contact between coastal plain-unconformity and coastal plain-basalt. Amplitude variations were then used to reinterpret the extent of the clubhouse crossroads basalt flow on vintage seismic profiles. Given new interpretations, the clubhouse crossroads basalt flow is much smaller in extent than previously estimated, covering approximately 20.4×10^5 km^2

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1.1 Introduction

In the 1970's and early 1980's, investigations began into the relationship between geologic structure and seismicity in and around the meizoseismal area of the 1886 Charleston earthquake. Data contributing to these studies included three continuously cored drill holes at Clubhouse Crossroads (Gohn et al. 1977, 1978; Gohn, 1983) and seismic reflection profiles by Yantis and others (1983), Schilt and others (1983), Hamilton and others (1983), and Coruh and others (1981). This data added to other geophysical surveys of the Charleston area, including seismic refraction (Bonini and Woolard, 1960; Ackermann, 1977, 1983; Talwani, 1977), magnetic (Popenoe and Zietz, 1977; Phillips, 1977; Daniels and others, 1983), gravity (Long and Champion, 1977) and vertical electrical soundings (Campbell, 1977).

The most prominent reflector, referred to as the J horizon, was found nearly universally across all 270 km of reflection profiles (Yantis, 1978, Schilt et al., 1983; Hamilton et al., 1983; McBride et al., 1989). Reflection profiles passing the Clubhouse Crossroads corehole correlated this high amplitude, low frequency, two cycle reflection at ~0.7 s TWT to the Cretaceous Coastal Plain-basalt Contact (Yantis 1978, Schilt et al., 1983; Hamilton et al., 1983). A similarly strong, two cycle reflector has been found offshore (Dillon et al., 1979, 1983; Behrendt et al., 1983; Austin et al., 1990; Oh et al., 1995) and throughout the seismic reflection profiles in southwestern and southeastern Georgia (McBride et al., 1989).

Basalt encountered in the Clubhouse Crossroad coreholes has been dated at 184 ± 3 Ma (Lanphere, 1983) and is believed to be part of the Central Atlantic Magmatic Province (CAMP)(Daniels et al., 1983; Gohn 1983; Olsen et al., 2003; McBride et al., 1989). Ties

between the Clubhouse Crossroad basalt, the onshore J-reflector found throughout the South Georgia Rift (SGR) basin, offshore seaward dipping reflectors (SDR), and CAMP have been used to link CAMP to the opening of the Atlantic (Austin et al., 1990; Oh et al., 1995, Olsen et al., 2003) and suggest a diachronous rift-drift transition of eastern North America (Withjack et al. 1998; Schilische et al., 2003). Recent reevaluation of sub Coastal Plain wells within the SGR basin has shown most do not encounter basalt (Heffner et al., 2012) rising suspicions as to the true lithology of the J-reflector. In this paper, we will demonstrate variations along the J-reflector on two new seismic profiles, SCO2-5 and SCO2-1. The first profile, SCO2-1, passes Norris Lightsey #1 and Rizer #1, two wells that never encountered basalt at the base of coastal plain. The fifth profile, SCO2-5, passes Dorchester 211, a well that bottomed into basalt at the base of the coastal plain. Seismic inversion is performed to produce estimates of the J-reflections acoustic impedance, in addition to seismic attribute analysis including phase, envelope, and instantaneous frequency.

1.2 Background

In 1975, the first of 3 continuously cored Clubhouse Crossroad test holes were drilled 40 km west-northwest of Charleston, S.C. (Figure 1) in support of a U.S. Geological Survey investigation into the cause of seismicity in the Coastal Plain near Charleston, S.C. (Gohn et al. 1977). Clubhouse Crossroads #1 (CC#1) was drilled to a total depth of 792 m where it bottomed into basalt dated to the Jurassic-Triassic boundary (Olsen, 1997; Marzoli et al., 1999; Hames et al., 2000; McHone, 2000; Olsen et al., 2003; Nomade et al., 2007).

The stratigraphy of those core holes is described by Gohn et al. (1977, 1978, 1983) and discussed below:

The tertiary section (244 m) can be broken into four named formations. The Oligocene to Eocene Cooper formation (64 m) consisting of impure limestone, the Eocene Santee Limestone

(56 m), the Eocene to Paleocene Black Mingo Formation (67 m) and the Paleocene Beaufort formation (52 m). All tertiary formation boundaries contain unconformities.

The Cretaceous section (506 m) can also be broken into four named formations. The PeeDee formation (164 m), the upper cretaceous Black Creek (159 m), the Middendorf Formation (124 m) and the Cape Fear formation (59 m). The basal unit of the Cape Fear formation is muddy conglomeratic sand which overlies basalt at 750 m. Contacts between cretaceous formations are not as pronounced as in the tertiary section.

Clubhouse Crossroads corehole #1 bottomed in 42 m of weathered, amygdaloidal, massive basalt. Two distinct flows were identified, an upper 34.7 m thick flow and a lower 7 meter flow. The upper flow consists of 4.6 m of mottled clay displaying a relict amygdaloidal texture, 4.2 m of grading-upward weathered basalt, 22.9 m of fresh amygdaloidal basalt, and 3 m of fractured basalt. The lower flow contains 5.2 m of basalt displaying an upward increase in size and abundance of amygdules with a lower 1.8 m of considerably altered finely fractured basalt.

Two subsequent coreholes were also drilled at the clubhouse crossroads location, adeptly named Clubhouse Crossroads corehole #2 (CC#2) and Clubhouse Crossroads corehole #3 (CC#3). Similar lithology was encountered and is summarized below. Clubhouse Crossroads #2 was drilled to a total depth of 907 m, encountering Tertiary sediments to 239 m, and Cretaceous sediments to 776 m before bottoming in 131 m of basalt. Three flows were distinguished in CC#2. Flow 1 begins at 776 m and is 6 m thick, highly vesicular and moderately altered. A 4-cm layer of smectite, zeolite, and calcite separate flow 1 from flow 2. Flow 2 begins at 782 m and is 89 m thick. The upper 8 m is sheeted horizontal layers that are highly vesicular, overlying 30 m of massive flow with few vesicles, under which a 1 m thick highly vesicular horizontal sheet can be found. From 830 to 850 m highly fractured basalt can be found, becoming massive again to a total depth of 871 m. Flow 2 and flow 3 are separated by a 5-cm thick layer of calcite and zeolite. The upper 24 m of flow 3 is highly amygdaloidal with vesicles increasing with depth. At 895 m the flow becomes massive with less vesicles and an overall fresher appearance. Horizontal

vesicle sheets can be found from 904 m to the bottom of the well at 907 m. Clubhouse Crossroads #3 was drilled to a total depth of 1152 m, encountering Tertiary sediments down to 240 m, Cretaceous sediments to 775 m, basalt to 1031 m before bottoming in 121 m of Triassic redbeds. Seven flows were recognized in CC#3 (Gottfried et al., 1983). As coring was sporadic throughout the 256 m thick basalt section, these flows will not be summarized. A 2-m thick red sandstone was cored at a depth of 925 m, indicating that other sedimentary beds may exist within the basalt, remaining undetected due to uncored sections from 784.6-921 m and 930-984 m. Beginning at 1031 m Triassic redbeds were encountered. The redbed consist of red-colored mudstone and smaller amounts of siltstone and fine grained sandstone transitioning into courser grained facies at an approximate depth of 1070 m to the bottom of the corehole at 1152 m.

In the summer of 1974 three short seismic reflection lines (total length 7 km) were collected by the U.S. Geological Survey (Figure 1) with a record length of 1.5 seconds two-way travel time (Yantis, 1978). This study was a joint effort by Virginia Polytechnic Institute and State University (VPI&SU) and the U.S. Geological Survey (USGS) and was the first to target subsurface structure in the Charleston area. The three lines were designated Interstate, Clubhouse Crossroads, and Middleton Place with a respective length of 1.0, 1.7, and 4.3 km**.** The Clubhouse Crossroad line is of particular importance. In combination with a continuous velocity log (CVL) acquired in the Clubhouse Crossroads corehole #1 (CC #1), Yantis (1978) correlated the brightest reflector at 0.71s to the basalt encountered in CC#1 at 750 meters. Other distinct arrivals correlated on this line include a reflector at 0.13s corresponding to the Santee Limestone-Black Mingo contact, a reflector at 0.20 sec corresponding to the Black Mingo-Beaufort contact, and a reflection at 0.27s which corresponds to a lithologic change within the top portion of the PeeDee formation as indicated by a large acoustic velocity change shown in the CVL. Other reflectors between 0.27s and 0.71s were associated with lithologic changes throughout the lower cretaceous section, with reflectors at 0.43s and 0.55s corresponding to changes near the top and bottom of the Black Creek formation (Yantis, 1978).

The Consortium for Continental Reflection Profiling (COCORP) surveyed four lines (Figure 1): C1-C4 (total length 72km) with a record length of 20s in 1978. The reflection survey was designed to image deep extensional structures and consequently did not image reflections shallower than 0.4s. The results of this study were presented by Schilt et al. (1983). Schilt et al. (1983) adopted some nomenclature for reflections or group of reflections seen on all four seismic profiles. These include the "K" reflector at about 0.45s-0.55s representing the lithologic changes within the Cretaceous Black Creek formation and the "J" reflector at 0.7s TWT on C1, corresponding to the Jurassic basalt found in CC#1 which was correlated to the same TWT reflector by Yantis (1978). The last group, the "B" reflectors at 0.85s to 1.05s, has an inferred correlation to the contact between Triassic sediment and crystalline basement. We will adopt the same nomenclature in this study.

In 1979 the USGS contracted ten seismic reflection profiles (Figure 1): SC1-SC10 (total length 140km) with a record length of 3s. The purpose of these seismic lines was to continue the investigation into the relationship between seismicity and geologic structure. The results of these profiles were presented by Hamilton et al. (1983). Unsurprisingly, K, J, and B reflectors were noted on all lines.

An additional 5 reflection profiles (Figure 1): VT1-VT5 (total length 51 km) with a record length ranging from 21-39s were collected in 1980 and 1981 by VPI&SU. These seismic profiles were discussed by Coruh et al. (1981) and provided the highest resolution data of all lines at that time.

The most prominent reflector, found nearly universally on all of these lines, is the "J" reflector, a high-amplitude, low frequency, two-cycle reflection (Schilt et al., 1983; Hamilton et al., 1983; Yantis, 1978). Seismic lines CC, C1, and SC1 passed CC#1 (Figure 1) and allowed the correlation of this bright reflector at ~0.7s to the Cretaceous-basalt contact. Correlations of

the J reflection were then made across all other profiles in the Charleston area, indicating this reflector is laterally continuous. A similarly strong, two cycle reflector has been found offshore beneath the continental shelf (Behrendt et al., 1983; Dillon et al., 1983) and throughout the seismic reflection profiles in southwestern and southeastern Georgia (McBride et al., 1989). In Georgia, this reflector was correlated to diabase in the Horace Parker #1 well (McBride et al., 1989) leading to the conclusion that flood basalt covers the SGR. Reanalysis of well and seismic data by Heffner et al. (2012) shows numerous wells within the SGR do not encounter basalt nor diabase; suggesting the J-reflector corresponds with the base of the Coastal Plain irrespective of basalt.

Beginning in December 2010 through February 2011, seven 2D reflection profiles: SCO2-1 – SCO2-7 (total length 240 km) were acquired to the immediate west and northwest of the Charleston meizoseismal zone and legacy seismic data (Figure 1) as part of DOE Award DE-FE0001965: Geologic Characterization of the South Georgia Rift Basin for Source Proximal CO_2 Storage project. The first profile, SCO2-1, passes Norris Lightsey #1 and Rizer #1, two wells that never encountered basalt at the base of coastal plain. The fifth profile, SCO2-5, passes Dorchester 211, a well that bottomed into basalt at the base of the coastal plain.

1.3 SEISMIC INVERSION

Seismic inversion produces an estimation of Rock density (ρ), P-wave velocity (V_p), and S-wave velocity (V_s) from physical rock properties like compressibility, rigidity, and bulk density could be calculated, providing information on lithology, porosity, and pore fluid. Acoustic Impedance ($AI = V_p * \rho$), Shear Impedance ($SI = V_s * \rho$), and V_p/V_s ratio (=AI/SI) are all common properties used to differentiate rock lithologies. De Vincenzi et al. (2002) reported high acoustic impedance could be used to identify some basalt varieties from seismic data. Klarner and Klarner (2012) reported the use of V_p versus ρ, V_p versus V_s, and AI versus V_p/V_s ratio for discriminating

volcanic lithologies. The ratio of V_p to V_s appear comparable to limestones, diverging from the empiric Greensberg-Castagna trend for carbonates only at very high velocities. With an anomalously high V_p/V_s ratio, basalt layers usually show amplitude strengthening with offset.

Theory of inversion

Russell and Hampson (2006) described seismic inversion as follows. Stacked seismic traces can be modeled as the convolution of the earth's reflectivity and a band limited seismic wavelet written as

$$S_t = w_t * r_t \qquad (1)$$

where s_t is the seismic trace, w_t is the seismic wavelet, * is the convolution operator, and r_t is the reflectivity. In turn, the reflectivity is related to the acoustic impedance of the earth by

$$r_{pi} = \frac{\quad}{\quad} \qquad (2)$$

where r_{pi} is the zero offset P-wave reflection coefficient at the i^{th} interface of a stack of N layers and $Z_{pi} = \rho i V_{Pi}$ is the i^{th} ρ-impedance of the i^{th} layer, ρ is density, and V_p is P-wave velocity. Lindseth (1979) showed that if we assume the recorded seismic signal is as given in equation (2), inverting this equation will recover the P-impedance given by

$$\frac{\quad}{\quad} \qquad (3)$$

Applying equation (3) to a seismic trace, we effectively invert the seismic reflection data to P-impedance. By working with pre-stack data, seismic inversion is no longer limited to only P-impedance (Acoustic Impedance, AI). Aki and Richards (2002) were able to show a linearized version of the Zoeppritz equations that could be written for the reflected P-wave in which the response was divided into three weighted values of changes in P-wave velocity, S-wave velocity,

and density. Fatti et al. (1994) re-formulated the Aki-Richards equation as a function of zero-offset P-wave reflectivity R_{P0}, zero-offset S-wave reflectivity R_{S0} and density R_D in the form

$$R_{PP}(\theta) = c_1 R_{P0} + c_2 R_{S0} + c_3 R_D \qquad (4)$$

Where

$c_1 = 1+\tan^2\theta$, $c_2 = -8\gamma^2\tan^2\theta$, $\gamma = V_s / V_p$, $c_3 = -0.5\tan^2\theta + 2\gamma^2\sin^2\theta$, $R_{P0} = - \text{—} \quad \text{—}$,

$R_{S0} = - \text{—} \quad \text{—}$, and $R_D = \text{—}$. Using equation (4), a least-squares procedure can extract the three reflectivity terms from the pre-stack seismic data. Once the three reflectivity terms are known, they can be inverted using the post-stack inversion method described in equation (3).

1.4 DATA

In order to evaluate the J reflector in South Carolina, we have processed, inverted, and calculated seismic attributes on reflection profiles SCO2-1 and SCO2-5. The first profile (SCO2-1) is 60 km long oriented NW-SE and passes the Norris-Lightsey #1 and Rizer #1 well. The Norris-Lightsey #1 well (COL-241) located in Colleton County, South Carolina is a deep oil test well ~55 km west of CC#1 that never encountered basalt. The well penetrated the coastal plain at ~610 m before reaching a total depth of ~4115 m. Two thin ~3 m diabase layers were encountered at 1200 and 1227 m with thicker diabase layers at 1410 m and below. Geophysical logs including acoustic velocity (DT) logs from 35- 630 m; 922 m to base, and gamma-gamma density (RHOB) from 922-2366 m were acquired. The second well, Rizer #1, also located in Colleton County, South Carolina is a scientific well ~3 km southwest of Norris-Lightsey #1. Rizer #1 penetrated the coastal plain at ~601 m before bottoming in diabase at a total depth of ~1890 m. Two thin ~3 m diabase layers were also encountered at ~1094 m and ~1114 m. Sonic (DTCO) and density (RHOZ) geophysical logs were acquired in this well.

The fifth profile (SCO2-5) is 29 km long oriented NE-SW and passes the Dorchester 211 well. The Dorchester 211 well (DOR-211) located in Dorchester County, South Carolina is ~34 km NW of CC#1 and ~42 km to the NE of Norris Lightsey #1. The well penetrated the coastal plain at ~ 599 m before bottoming in ~32 m of basalt at a total depth of ~631 m (Reid et al. 1986). Geophysical logs including DT and RHOB were acquired in the uncased well.

Seismic acquisition and processing parameters for SCO2-1 and SCO2-5 are shown in Tables 1 and 2, respectively. Data processing steps include preprocessing trace edits, static correction, bandpass filtering, velocity analysis, normal moveout correction, and CDP stacking. Pre-stack seismic inversion requires the preservation of the true reflection amplitudes and, therefore, minimum processing was done. SCO2-5 contained out of plane reflections and strong 60Hz noise (Figure 2), SCO2-1 contained strong 60Hz noise, but did not display any noticeable out of plane reflections (Figure 3). These were best addressed with a top mute and 60Hz notch bandpass in accordance with the minimal processing goal. Shot gather frequency varied greatly in both SCO2-5 (Figure 4) and SCO2-1 (Figure 5), but became consistent after stacking (Figure 6).

1.5 RESULTS

Geophysical well log data quality varies greatly (Figure 7). Dorchester 211 p-wave and density logs most closely reflect values expected in the coastal plain with p-wave velocities ranging from ~3500 m/s in the shallow Cooper/Santee Limestone to ~1400 m/s in the silty/sandy clay units of the cretaceous (Figure 7, Track 7). Density values are also realistic at ~2.5 g/cc in the Cooper/Santee limestone with average for the cretaceous section at ~2.2 g/cc (Figure 7, Track 9). Where Dorchester 211 bottomed into basalt, p-wave velocities are ~4800 m/s with a density of ~2.8 g/cc. Norris Lightsey p-wave log data for the coastal plain is unrealistic, with values upwards of 1000 m/s. At lowest, p-wave velocities are ~3600 m/s. Norris Lightsey was not used during seismic inversion. Rizer #1 sonic log for the coastal plain was acquired through casing ,

with velocities of ~6700 m/s (Figure 7, Track 8), these velocities do not display near the inconsistencies seen in Norris Lightsey #1, and have been bulk shifted closer to velocities expected within the coastal plain (Figure 7, Track 8). After shifting, Rizer #1 sonic log within the coastal plain is consistently higher then values seen in Dorchester 211 (Figure 7, Track 5).   Rizer #1 density values of the coastal plain appear realistic, ranging from ~1.9 g/cc to ~2.4 g/cc. From ~491 to ~730 m, the density log displays occasional spikes up to 3.4 g/cc. From ~730 to ~808 m is the edge of the casing, causing invalid density values. Densities from ~730 to ~808 m were shifted ~1.4 g/cc to reduce error during inversion (Figure 7, Track 10).

With minimal processing (see Table 2), final stacked reflection profiles for SCO2-1 (Figure 8) and SCO2-5 (Figure 9) display expected reflections at the base of the coastal plain. Reflection profile SCO2-5 was reduced from the original 29 km long profile to ~12 km using only CDP's 735-1331. This was done to remove coherent noise produced by cement plants at the north end of the profile without further processing. The J-reflector is found at ~600 ms across the entire profile with minor variations in amplitude and character. Discontinuous reflectors within the coastal plain can be seen at ~200 ms and ~400 ms (Figure 10). On SCO2-1, the J-reflector can be found with inconsistent amplitudes and character dipping from ~500 ms at the NW to ~760 ms at the SE (Figure 11). Reflectors within the coastal plain are overall more continuous then within SCO2-5.

Non-NMO corrected CDP gathers for SCO2-1 and SCO2-5 were imported into Hampson-Russell Suite for pre-stack inversion. A velocity model was chosen then applied to calculate angle gathers from 0 to 23 and 0 to 32 degrees, respectively. Amplitude variability on angle traces, at the reflector of interest for a given CDP, is too large to accurately compute an AVO analysis at, or near, the well locations on both SCO2-1 (Figure 12) and SCO2-5.

Post-stack profiles for SCO2-1 and SCO2-5 were then imported into Hampson-Russell suite for post-stack inversion. The results of the P-impedance inversion show impedance values ranging from 3550 to 28567 (ft/s)*(g/cc) for SC02_5 (Figure 13) and 2599 to 14783 (ft/s)*(g/cc) for SC02_1 (Figure 14). At the reflector of interest, p-impedance values vary from 9936 to 25840 (ft/s)*(g/cc) at Dorchester 211 (Figure 15) and 4693 to 6820 (ft/s)*(g/cc) at Rizer #1 (Figure 16).

Seismic attributes of Phase, Instantaneous Frequency, and Envelope were calculated. Seismic phase is independent of amplitude and highlights continuity of events. Phase displays the J-reflector as a continuous event on SCO2-5 (Figure 17) and on most of SCO2-1 (Figure 18). On SCO2-1 between CDPs 1040-1820 the reflection is less coherent but present, appearing lower in amplitude. From CDPs 1820-1860 and 2400-2440 the reflection is not present (Figure 18). Instantaneous frequency is the time derivative of phase and represents the mean amplitude of the wavelet. Instantaneous frequency varies dramatically across the J-reflector on both SCO2-5 (Figure 19) and SCO2-1 (Figure 21). At Dorchester 211, instantaneous frequency of the J-reflector is ~28-32 Hz. This same frequency is seen in a unique feature at CDP 1060-1107. From CDP 1107-1269, instantaneous frequency of the reflector becomes much more variable with considerably higher frequencies ranging from 34-59Hz being more prominent (Figure 20). On SCO2-1 at Rizer #1, instantaneous frequency of the J-reflector is ~10-26Hz. From CDPs 1880-2407, and 2443-2493, instantaneous frequency of the J-reflector varies from ~29-35 Hz (Figure 22). Envelope is the envelope of the seismic signal representing the instantaneous energy of the signal and is proportional in its magnitude to the reflection coefficient. Envelope is continuous and highlights a strong reflection at the J-horizon on SCO2-5, varying slightly in strength between CDP 1100-1160 and 1280-1313 (Figure 23). Envelope is also strong at the J-horizon on SCO2-1, becoming slightly less continuous and weaker between CDPs 1040-1750 and drastically changing from CDPs 1750-1900, 2400-2440, and 2490-2553. (Figure 24).

1.6 Discussion and Conclusions

Seismic attributes highlight variations in continuity, mean amplitude, and magnitude of the reflection coefficient along the J-reflection on both SCO2-1 and SCO2-5.

Accurate estimates of zero-offset P-wave reflectivity R_{P0} and zero-offset S-wave reflectivity R_{S0} would not be obtained due to strong variations of amplitudes on angle traces. This renders pre-stack inversion an implausible method for lithologic constraint on seismic data. At Rizer #1, SCO2-1's envelope displays less energy at both the J-horizon and a semi-continuous reflector directly above the J-horizon at ~500 ms (Figure 24). This decrease in energy highlights an area of poorer seismic data quality and may drive the large variations in amplitudes at the well location. This is demonstrated between CDPs 1820-1860 and 2400-2440 where a strong loss in energy seen on the envelope coincide with otherwise continuous reflectors in the phase domain becoming discontinuous.

Results from p-impedance inversion indicate a coastal plain impedance variation of ~3000 (ft/s)*(g/cc) between inverted SCO2-1 and SCO2-5 profiles. This variation is likely strongly driven by incorrect Rizer #1 sonic log values. Furthermore, the p-impedance model of SCO2-1 pushes the coastal plain down to 750ms at Rizer #1, below both the J-horizon and the synthetic tie. Incorrect sonic log values as well as an invalid density log at the casing are influencing the model to extend the coastal plain. Both the initial model and final inverted log reflect a deviation from the original log (Figure 25) at 700-800 ms. Given the poor correlation of the coastal plain between SCO2-1 and SCO2-5 models, and a modeled deeper coastal plain on SCO2-1, comparisons of impedance values of the unconformity encountered at Rizer #1 and basalt encountered at Dorchester 211 cannot be made.

Seismic phase of SCO2-1 provides further support the correct reflector was picked for the base of the coastal plain. This reflector separates sub-parallel continuous events in the

shallow section from less continuous events below. This reinforces the invalidity of a deeper coastal plain seen in the p-impendence SCO2-1 model (Figure 18, 14). At Rizer#1, the disruption in energy seen with the envelope is not reflected in phase, indicating the presence of a geologic interface. The weaker envelope between CDP 1040-1750 could be highlighting an actual change in the reflection coefficient of the J-horizon, representing the unconformity at the base of the coastal plain. From CDP 1880-2493, instantaneous frequency is ~29-35Hz, similar to the J-reflector frequency at Dorchester 211 on SCO2-5. Areas within this region where the frequency is different, including CDPs 2407-2443 and 2493-2553 coincide with poor data quality. Furthermore, a simple evaluation of amplitudes across the J-horizon shows large variations between CDPs 1040-1750 before becoming relatively consistent from CDP 1880-2493. We therefore interpret the western termination of the clubhouse crossroads basalt flow can be seen on SCO2-1 at CDP 1880.

The J-reflector on SCO2-5 displays a continuous and consistent phase and envelope. Between CDPs 960 and 1070 loss of data from heavy top muting can be seen. This top muting was done to address out of plane noise. Out of plane noise may be contributing to disruptions in instantaneous frequency, phase, and envelope over this same interval. A weaker envelope between CDP 1100-1160 coincides with a higher, more variable, instantaneous frequency seen from CDP 1107-1269. An explanation for this is lacking, as a higher frequency is counterintuitive to a loss in energy at the J-reflector. At minimum, amplitudes appear consistent across the entire line, supporting a similar coastal plain-basalt interface over the entire processed SCO2-5 profile.

Similar evaluations of amplitudes were performed on the vintage seismic profiles to the east-southeast of the SCO2 profiles. Seismic profiles VT1, VT2, VT4, SC1, SC2, SC3, SC5, SC7, and SC9 (Figure 26) all display consistent amplitudes across the entire J-reflection. Furthermore, VT-5 displays an amplitude change at CMP 140, VT3 at CMP 270, SC10 at CMP 160, and SC4 at CMP 180 (Figure 27) providing a constraint on the coastal plain-basalt interface

to the northeast, east, and southeast of clubhouse crossroads. Given this interpretation, we propose a clubhouse crossroad basalt flow extent (Figure 28) of approximately 20.4 x 10^5 km^2.

1.7 FIGURES

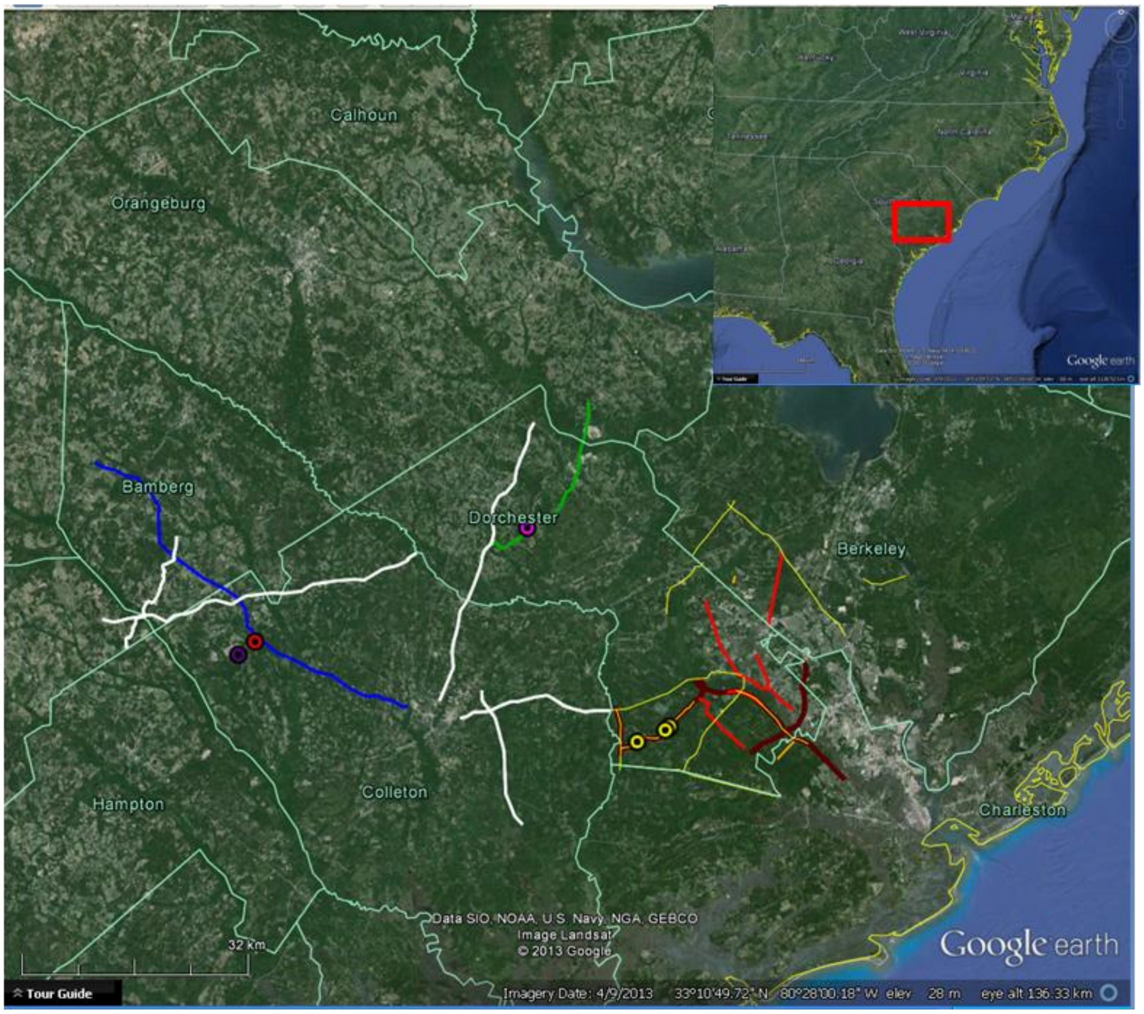

Figure 1.1. Location map of study. Yellow dots are Clubhouse Crossroads Coreholes (CCC1, CCC2, CCC3). Pink, Red, and Purple dots are Dorchester 211, Norris Lightsey #1, and Rizer #1 wells, respectively. Yantis et al. 1978 profiles in orange, COCORP (C1-C4) in brown (Hamilton et al. 1983), SC1-10 in yellow (Schilt et al. 1983), VT1-5 in red (Coruh et al. 1981), SC02_1-2-4,6-7 in white, and SC02_1 in blue and SC02_5 in green.

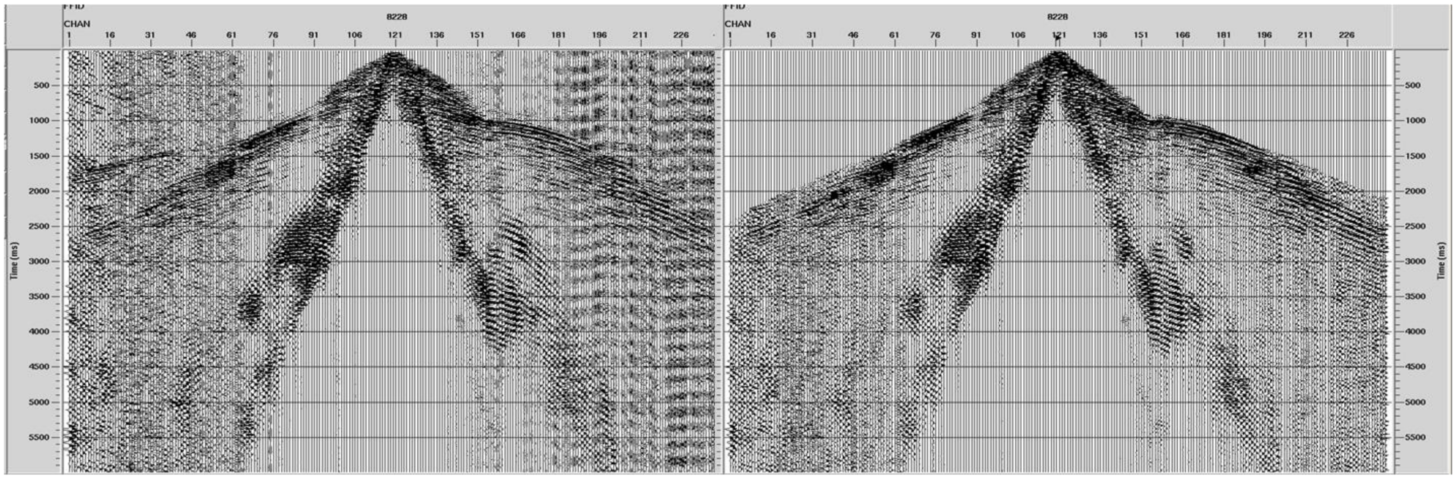

Figure 1.2. (Left) Raw shot gather of SC02_5 at FFID 8228. Strong 60Hz noise is apparent on the right side of the gather. Out of plane reflections can be seen ~channel 151. (Right) Trace edits, Topmute and 60Hz bandpass applied.

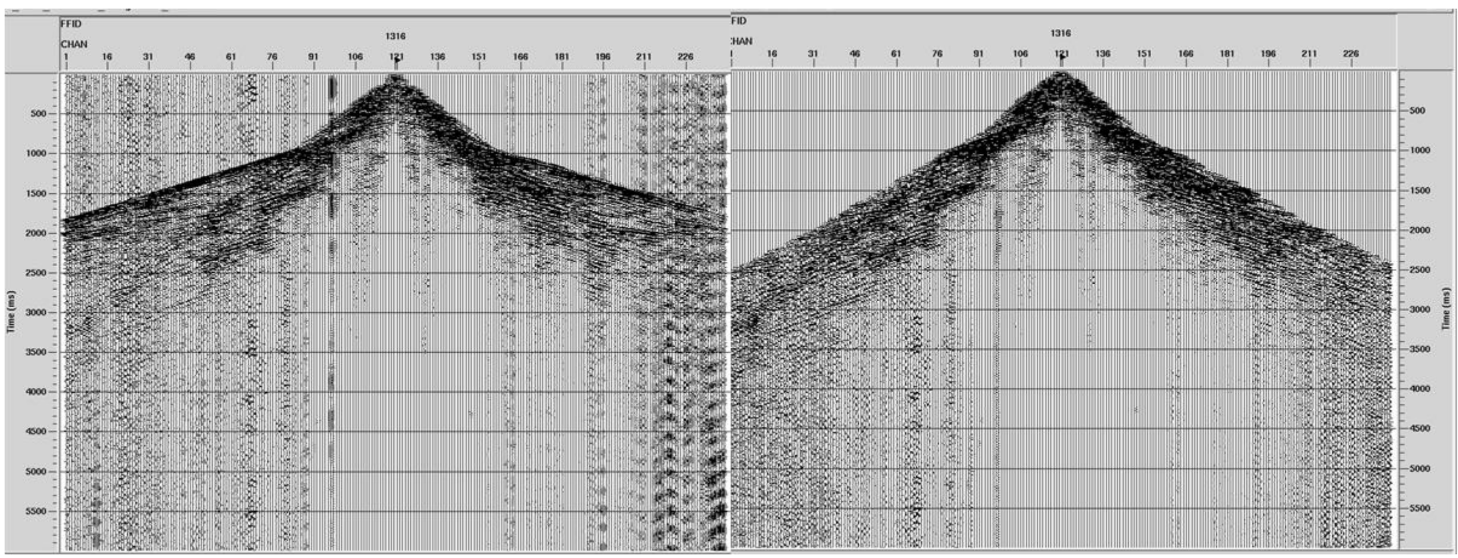

Figure 1.3. (Left) Raw shot gather of SC02_1 at FFID 1316. 60Hz noise is apparent on the right side of the gather, with no noticeable out of plane noise. (Right) Trace edits, Topmute, and 60Hz bandpass applied.

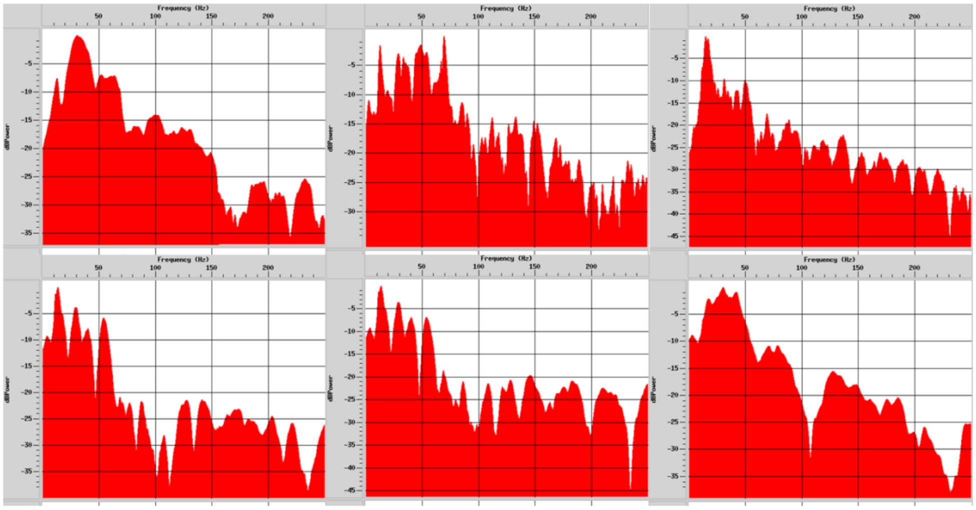

Figure 1.4. Raw shot gather frequency on SC02_5 at FFID 8170, 8174, 8226, 8228, 8230, and 8232. Notice the large variability in frequency content between adjacent shots.

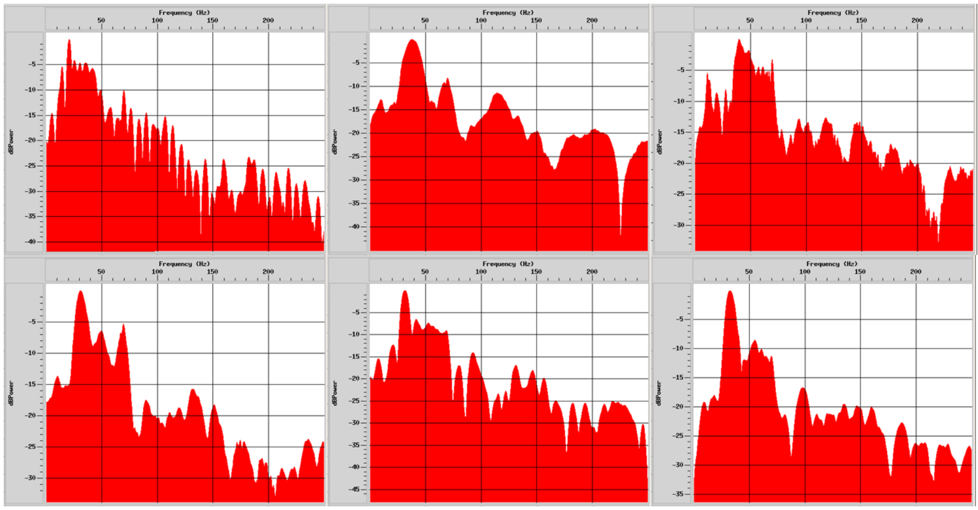

Figure 1.5. Raw shot gather frequency on SC02_1 at FFID 1256, 1306, 1310, 1314, 1318, and 1322. Note the large variability in the power spectrum between adjacent shots.

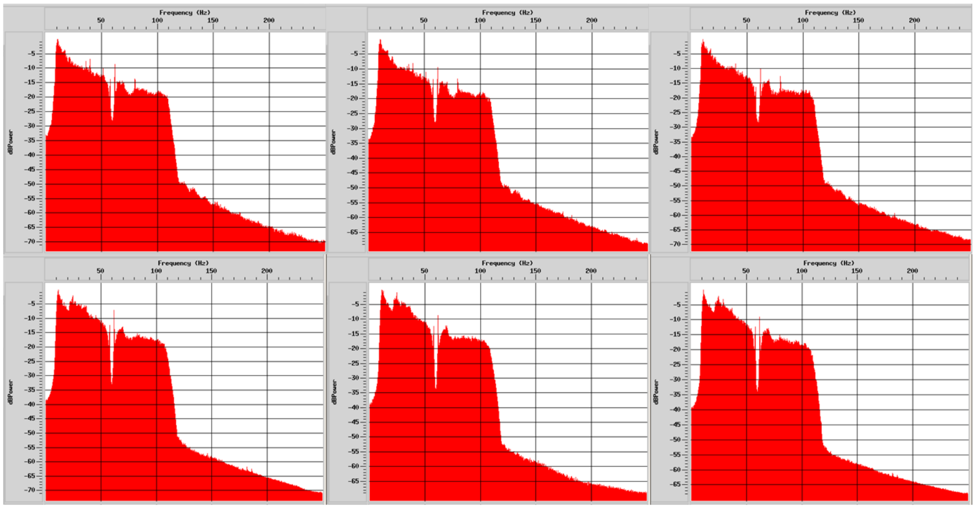

Figure 1.6. Stacked frequency content with bandpass on SC02_5 at CDPs 920,925, and 930 (Top) and SC02_1 at CDPs 1480, 1486, and 1490 (Bottom). Note the consistent power spectrum between CDPs.

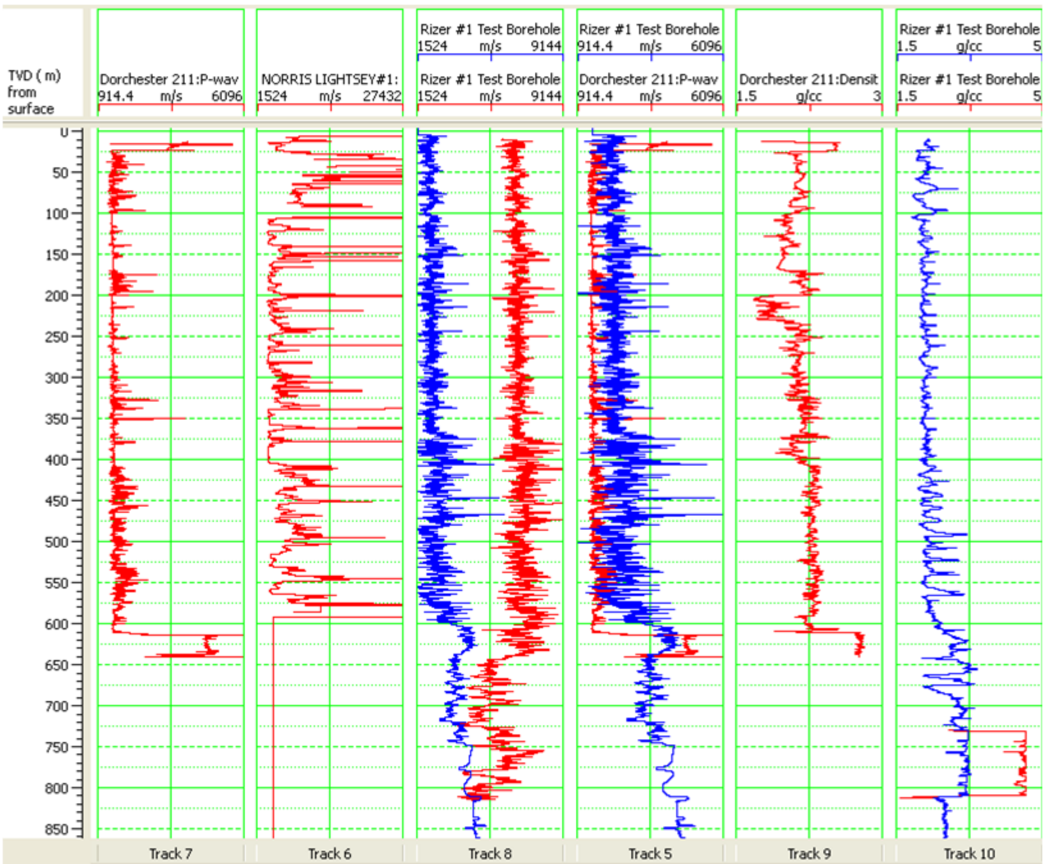

Figure 1.7. Sonic and Density logs used in this study. Dorchester 211 sonic log can be seen in Track 7. Norris Lightsey #1 sonic log can be seen in Track 6. Note values are excessively fast for coastal plain sediment. Rizer #1 sonic log (red) can be seen in Track 8 along with bulk shifted (blue) log. Track 5 demonstrates variation between Rizer #1 shifted sonic log and Dorchester 211 sonic log. Dorchester 211 density log can be seen in Track 9. Rizer #1 density log (red) and edited (blue) can be seen in Track 10.

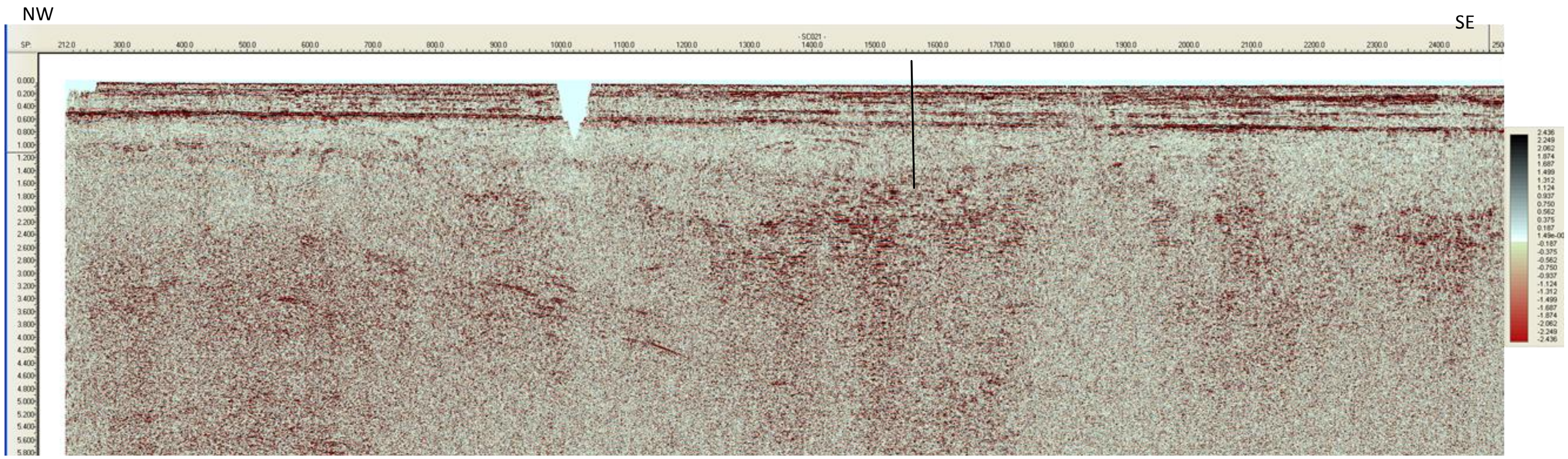

Figure 1.8. SC02_1 final stacked reflection profile. The J reflection is apparent dipping from ~500 MS at the NW to ~760 at the SE. Rizer #1 is displayed at CDP 1486.

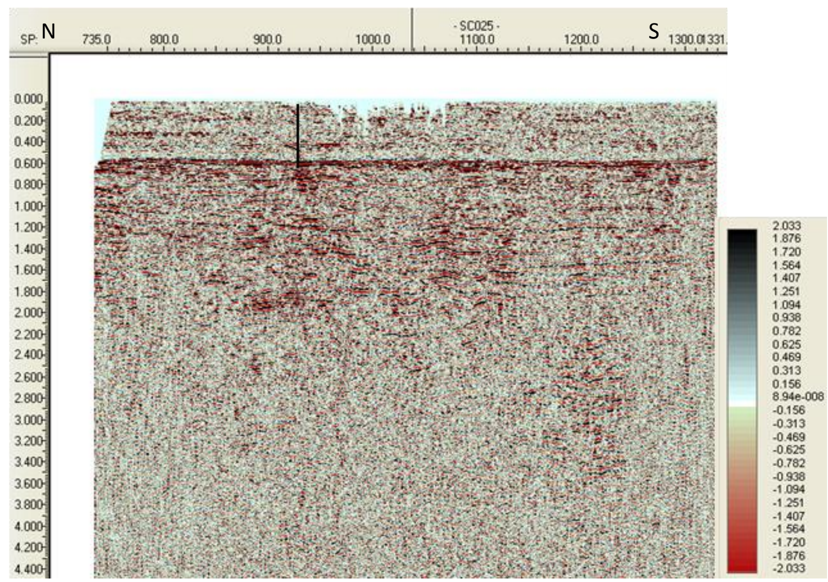

Figure 1.9. SC02_5 final stacked reflection profile. The J reflection is apparent at ~600 ms across the entire profile. Dorchester 211 is displayed at CDP 925.

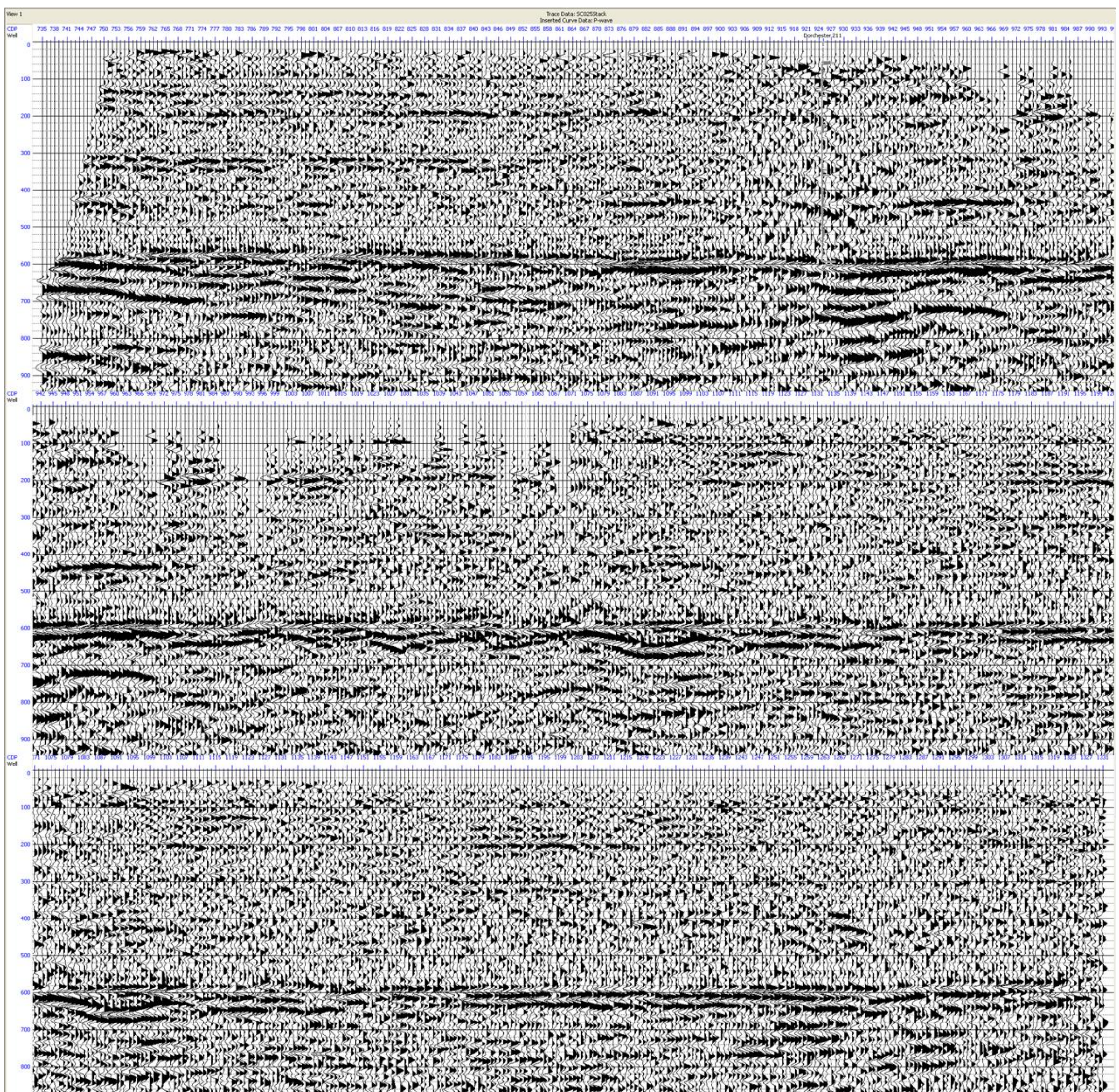

Figure 1.10. Wiggle display of final stacked SC02_5. The J-reflector can be seen at ~600 ms across the entire profile. Reflectors at ~200 and ~400 ms are discontinuous. Heavy top muting, and disruptions in the J-reflection can be seen from CDP 960-1070.

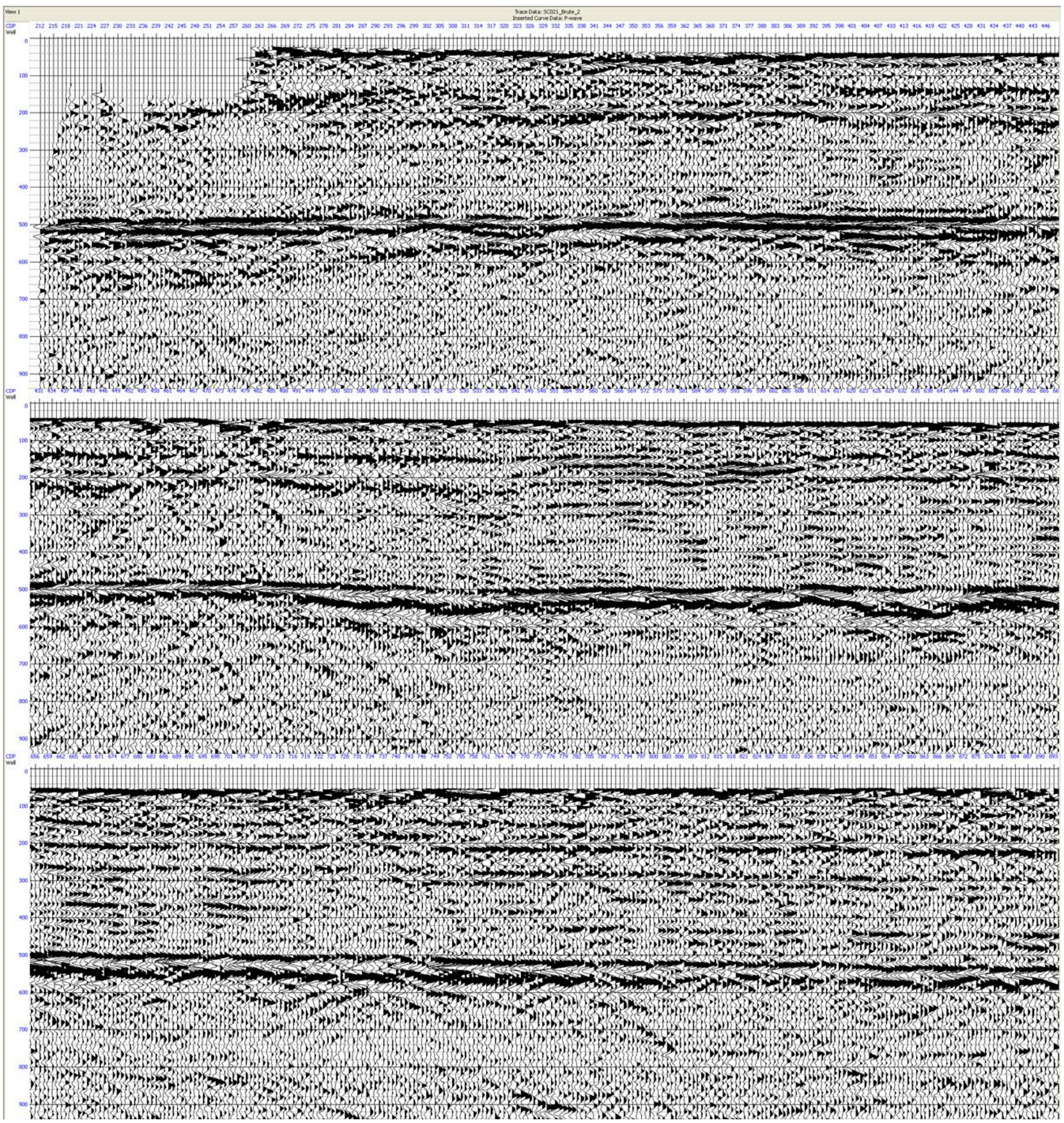

Figure 1.11.1 Wiggle display of final stack SC02_1 from CDP 212-893. A high amplitude J-reflection can be seen at ~500 ms. coherent reflections at ~200 ms can also be seen.

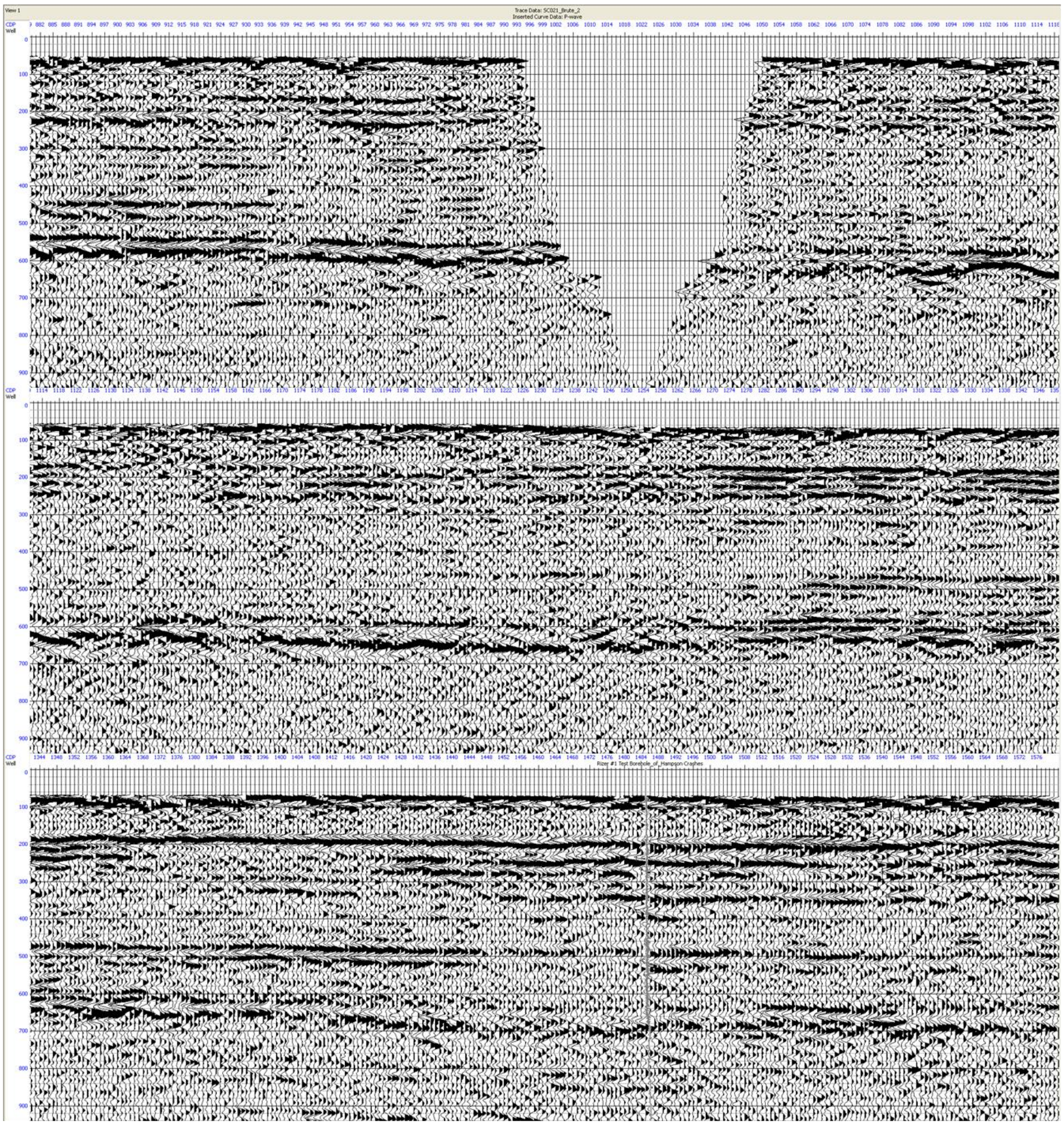

Figure 1.11.2 Wiggle display of final SC02_1 stack from CDPs 882-1582. The J-reflection can be seen from ~550-650 ms with drastic changes in amplitude character. Rizer #1 is displayed at CDP 1486.

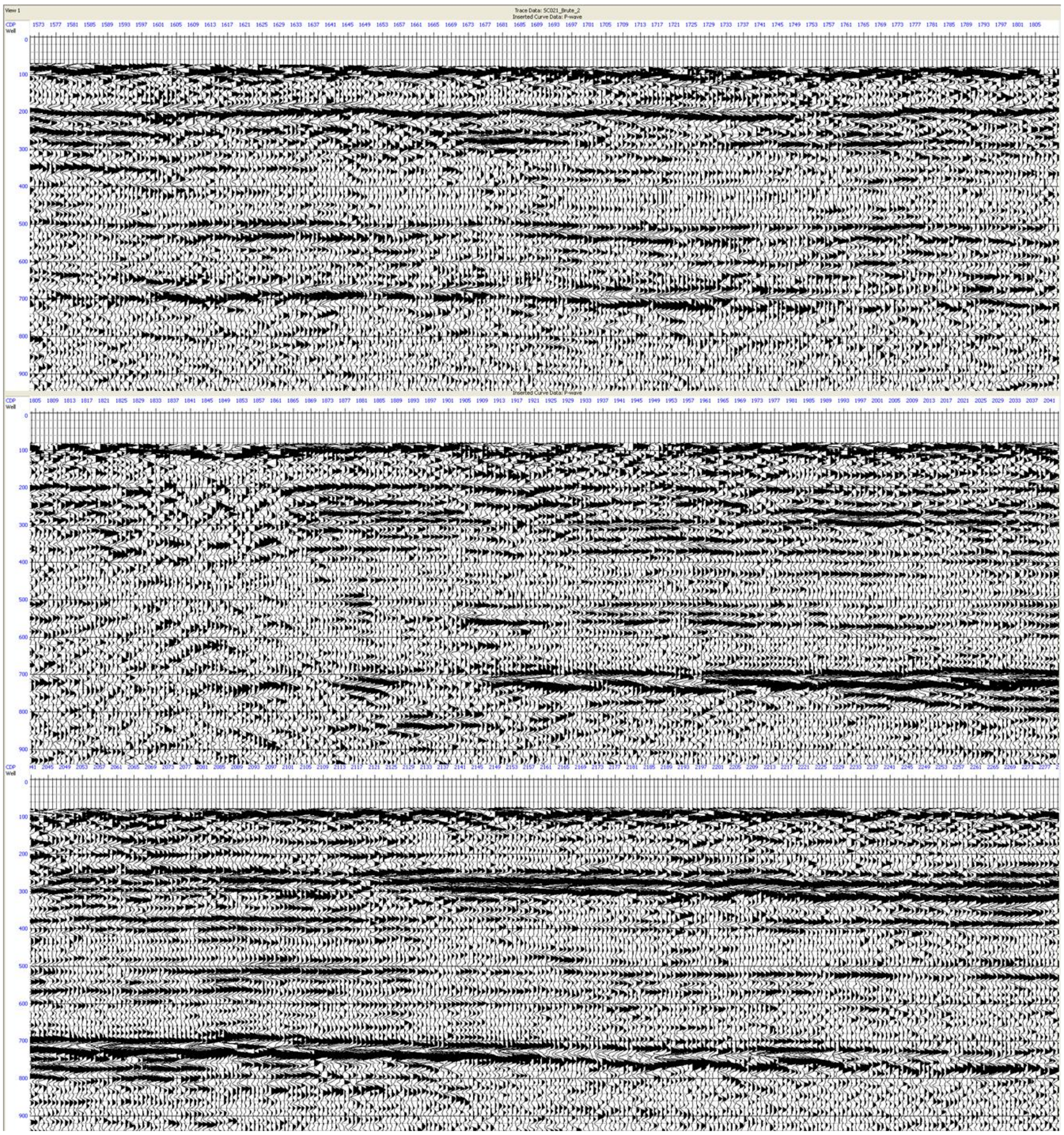

Figure 1.11.3 Wiggle display of final SC02_1 stack from CDP 1571 to 2280. The J-reflection can be seen from ~700-750 ms with drastic changes in amplitude.

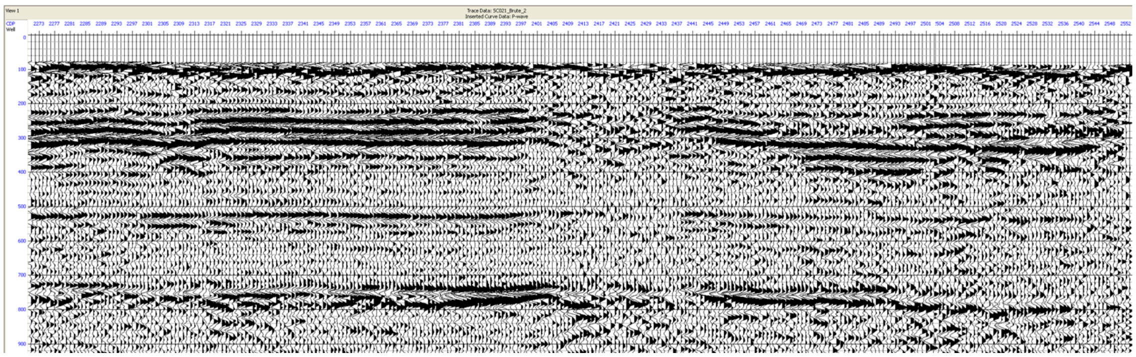

Figure 1.11.4 Wiggle display of final SC02_1 stack from CDP 2271-2553. The J-reflection can be seen at ~750ms with some variation in amplitude. Areas with the most change correspond to poor data quality.

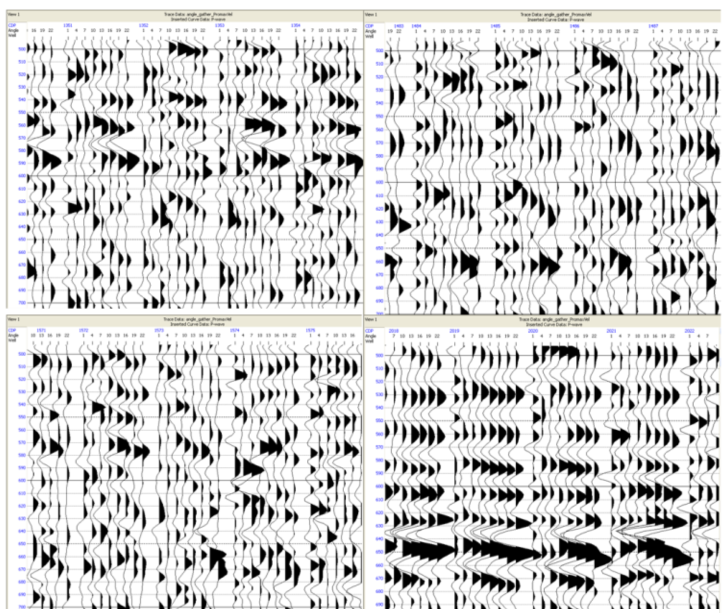

Figure 1.12. Angle gathers for SC02_1 at a variety of CDPs. Note the large amplitude variability in the 500-700 ms window. At CDP 2018-2022 amplitude vs offset can be seen (Bottom right). This is far removed from Rizer #1 well control.

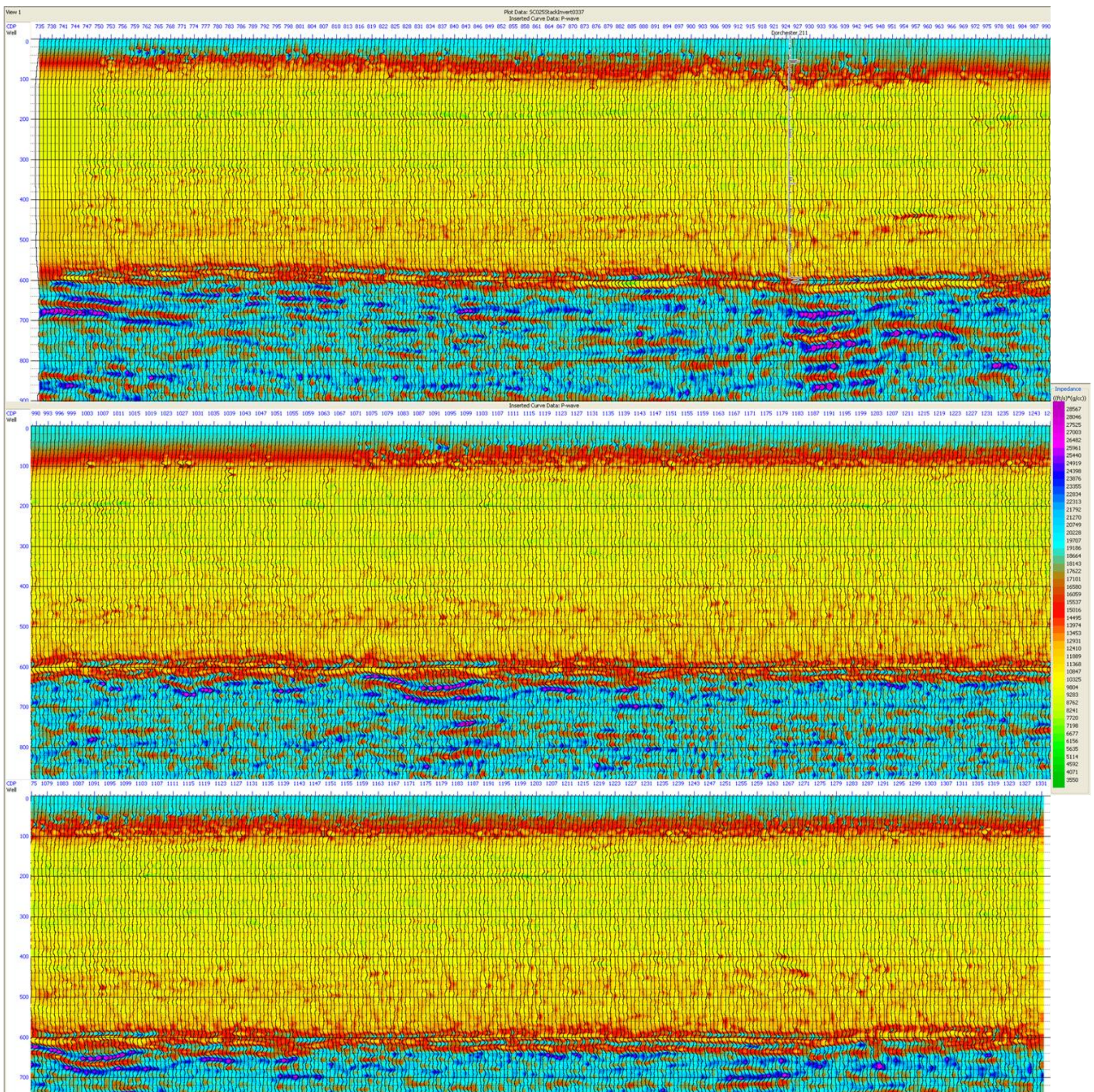

Figure 1.13. P-impedance inversion of SC02_5 with Dorchester 211 being displayed at CDP 925. The violet color represents higher impedance values whereas the green color represents low impedance.

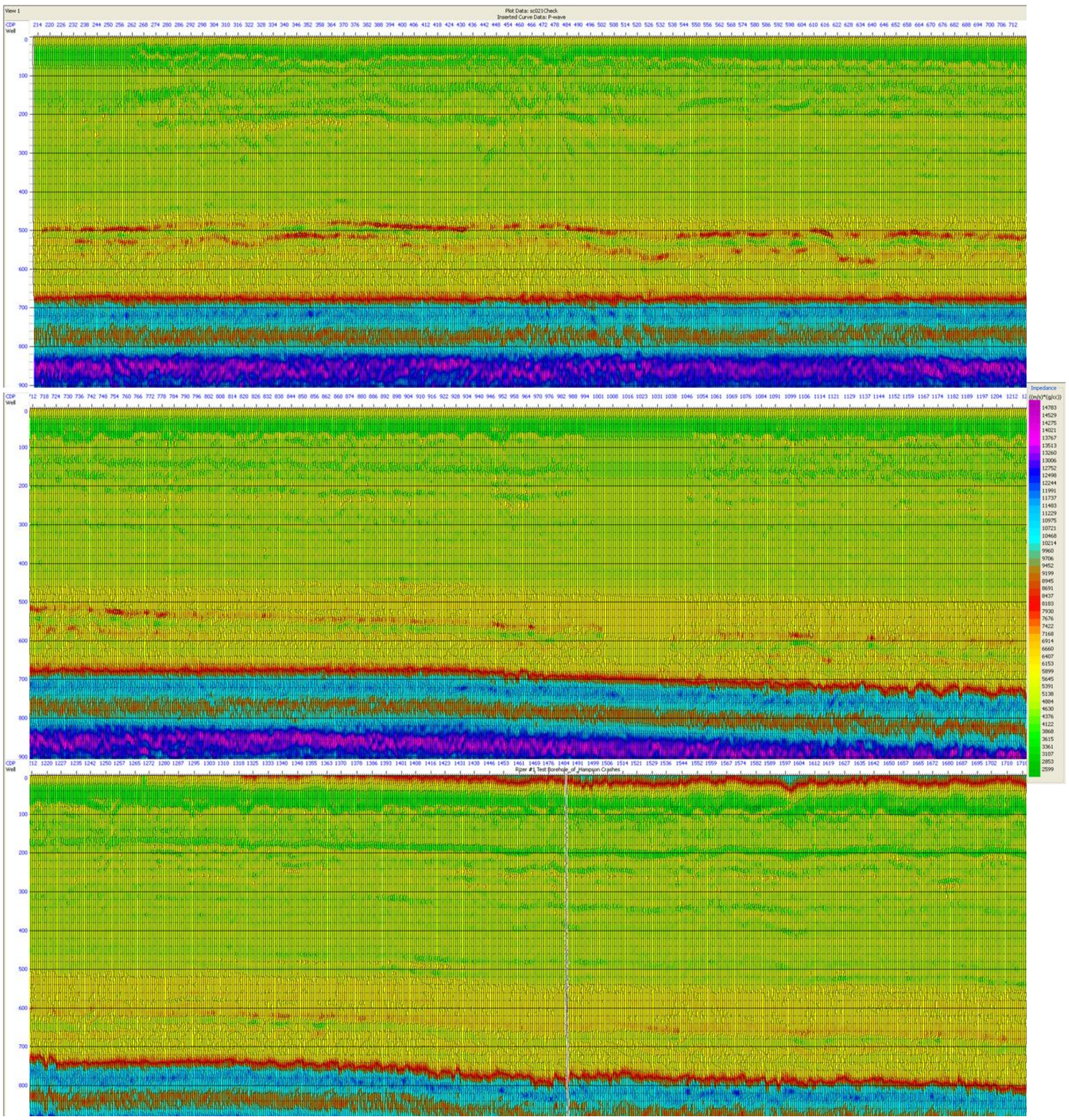

Figure 1.14.1 P-impedance inversion of SC02_1 from CDP 212-1718 with Rizer #1 being displayed at CDP 1486. The The violet color represents higher impedance values whereas the green color represents low impedance.

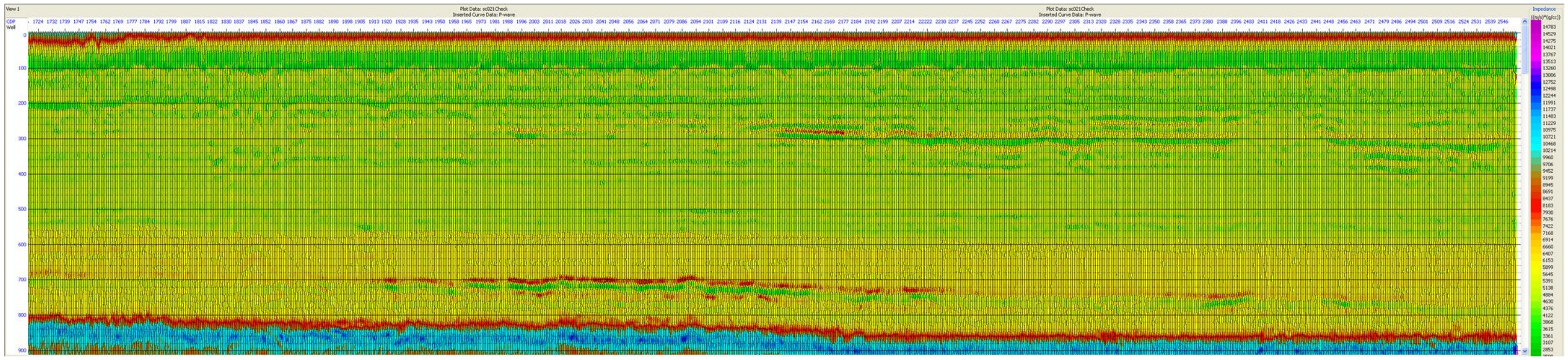

Figure 1.14.2 P-impedance inversion of SC02_1 from CDP 1719-2553. The violet color represents higher impedance values whereas the green color represents low impedance.

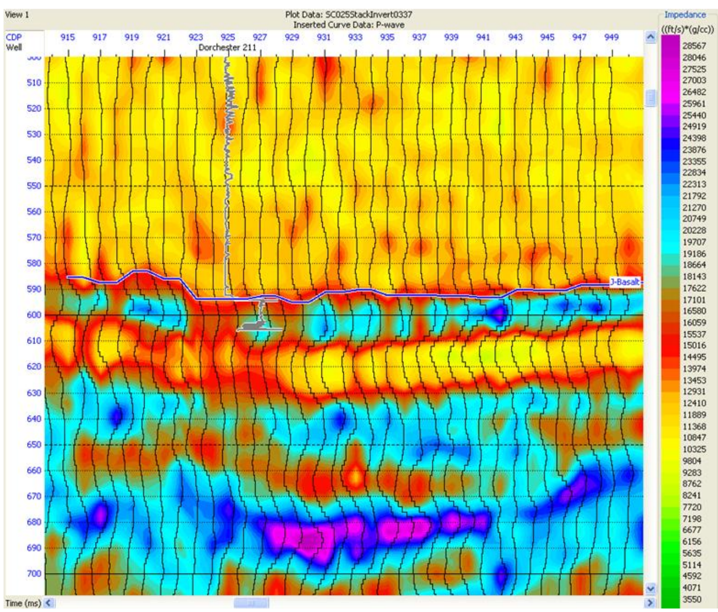

Figure 1.15. P-impedance inversion of SC02_5 from CDP 914-949, P-impedance values range from 9936 to 25840 (ft/s)*(g/cc) along the J-reflector near Dorchester 211.

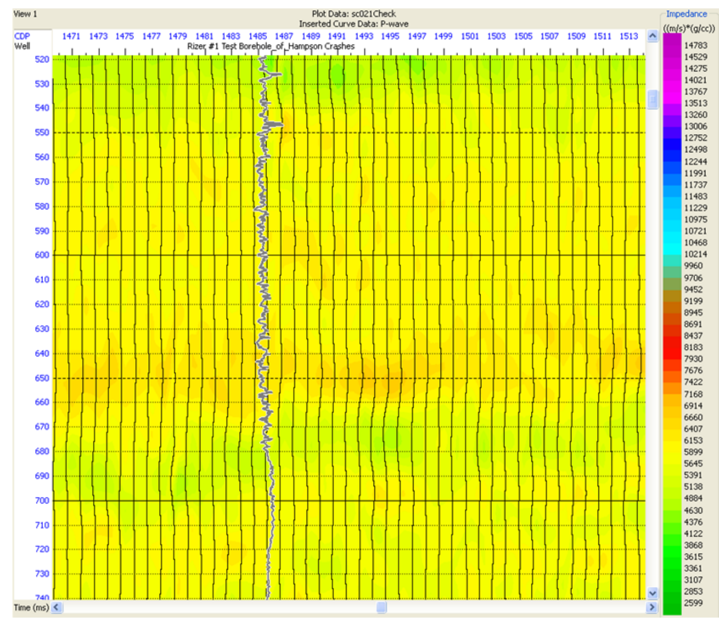

Figure 1.16. P-impedance inversion of SC02_1 from CDP 1470-1514, P-impedance values range from 4693 to 6820 (ft/s)*(g/cc) along the J-reflector near Rizer #1

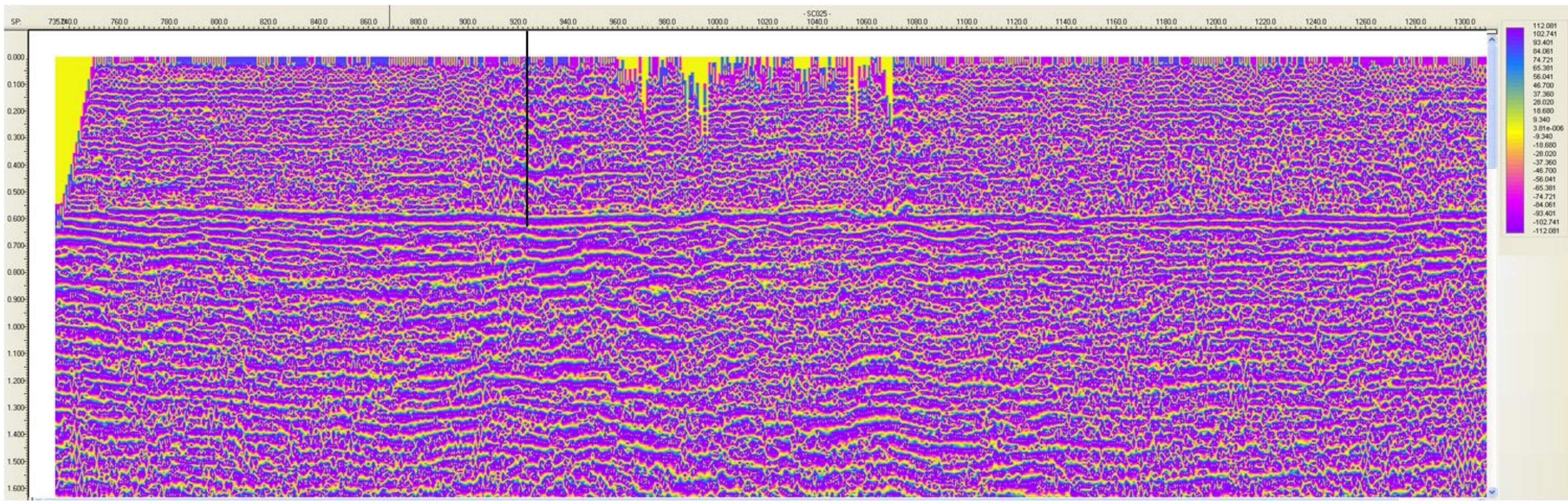

Figure 1.17 Seismic phase of SC02_5. Dorchester 211 is displayed at CDP 925.

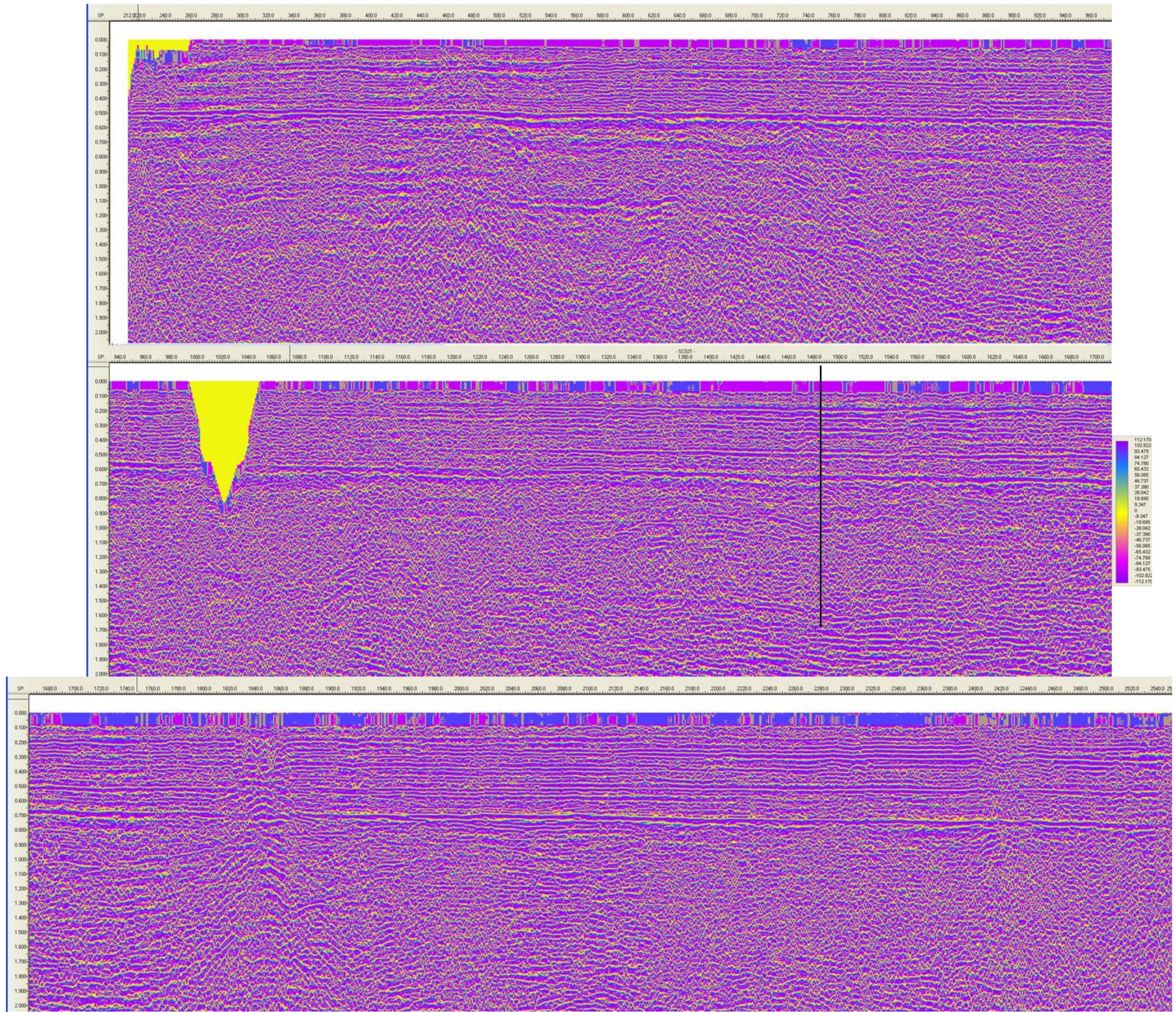

Figure 1.18 Seismic phase of SC02_1. Rizer #1 is displayed at CDP 1486.

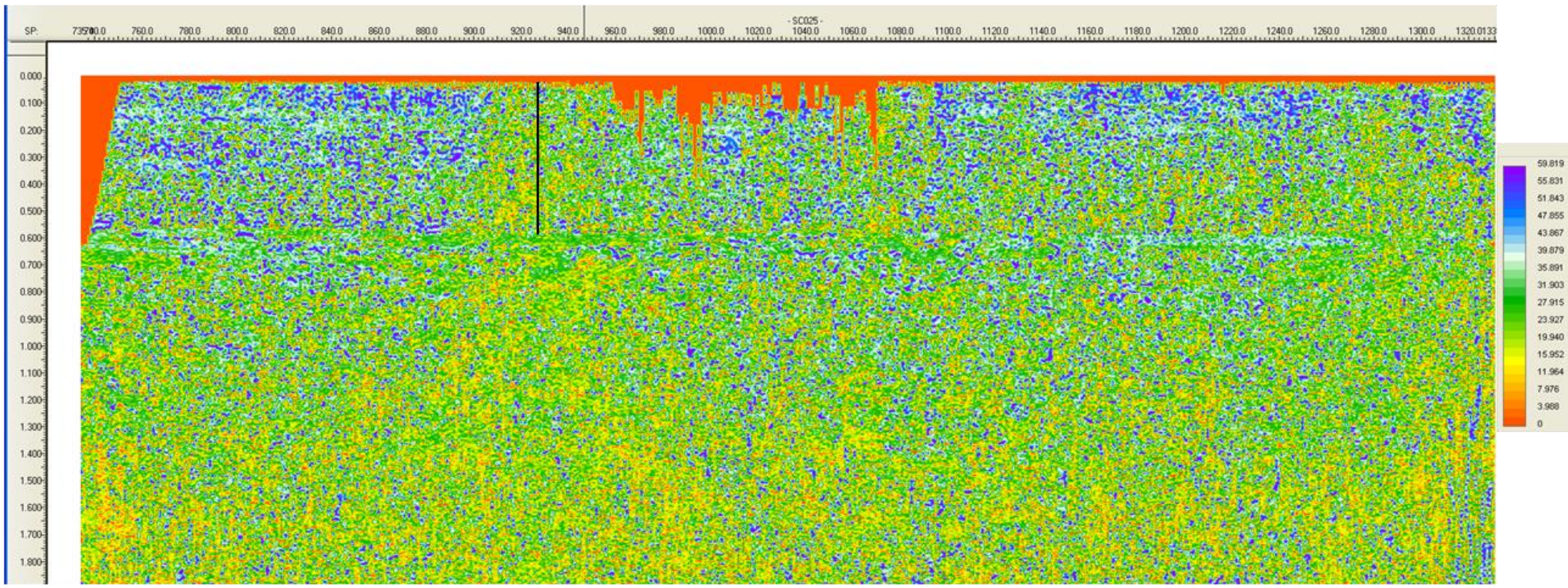

Figure 1.19 Instantaneous Frequency of SC02_5. Dorchester 211 is displayed at CDP 925. Higher frequencies can be seen in violet with lower frequencies in red.

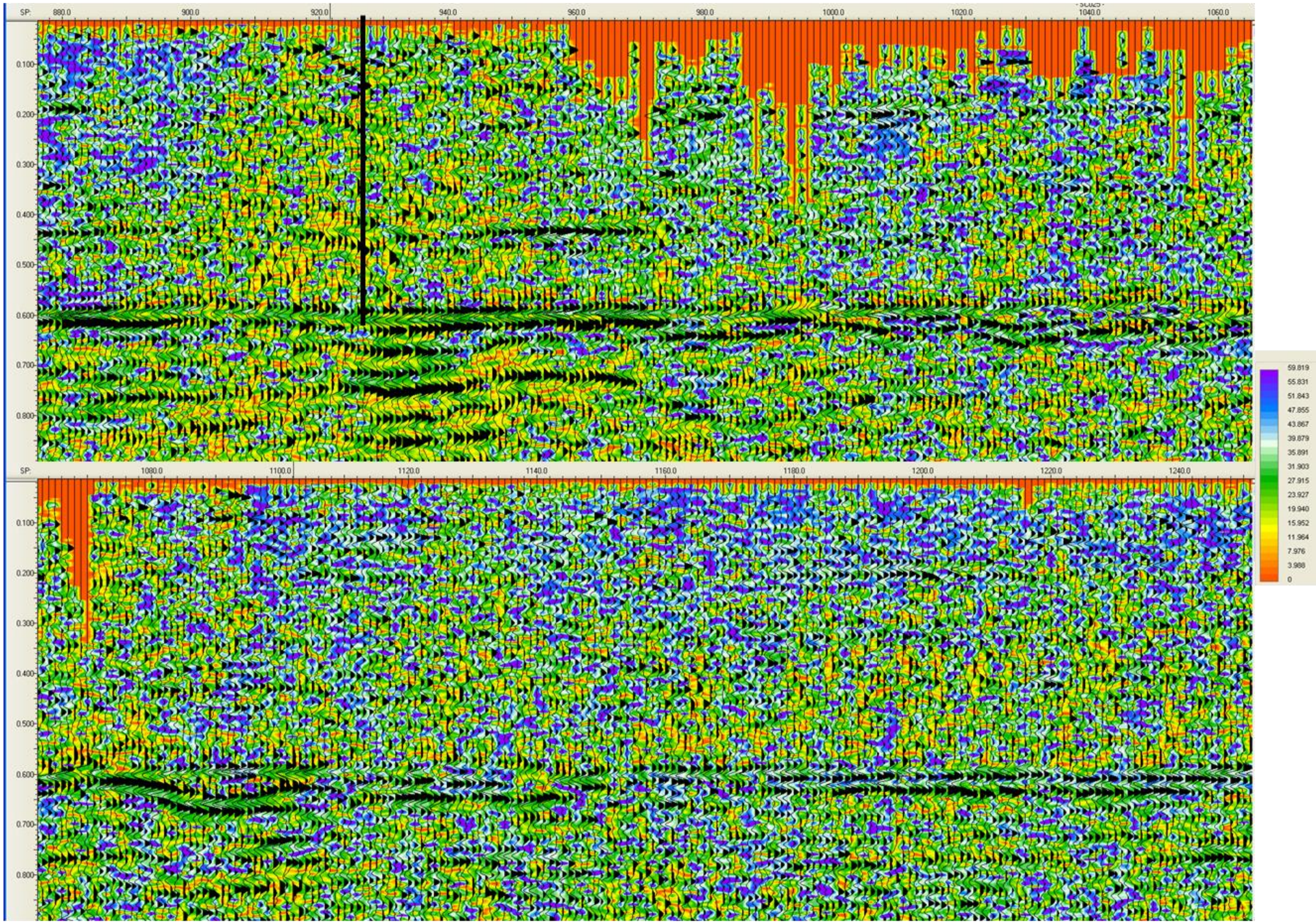

Figure 1.20. Instantaneous frequency of SC02_5 from CDPs 877-1065 (Top) and CDPs 1063-1251 (Bottom). Dorchester 211 is displayed at CDP 925. Higher frequencies are in violet with lower frequencies in red.

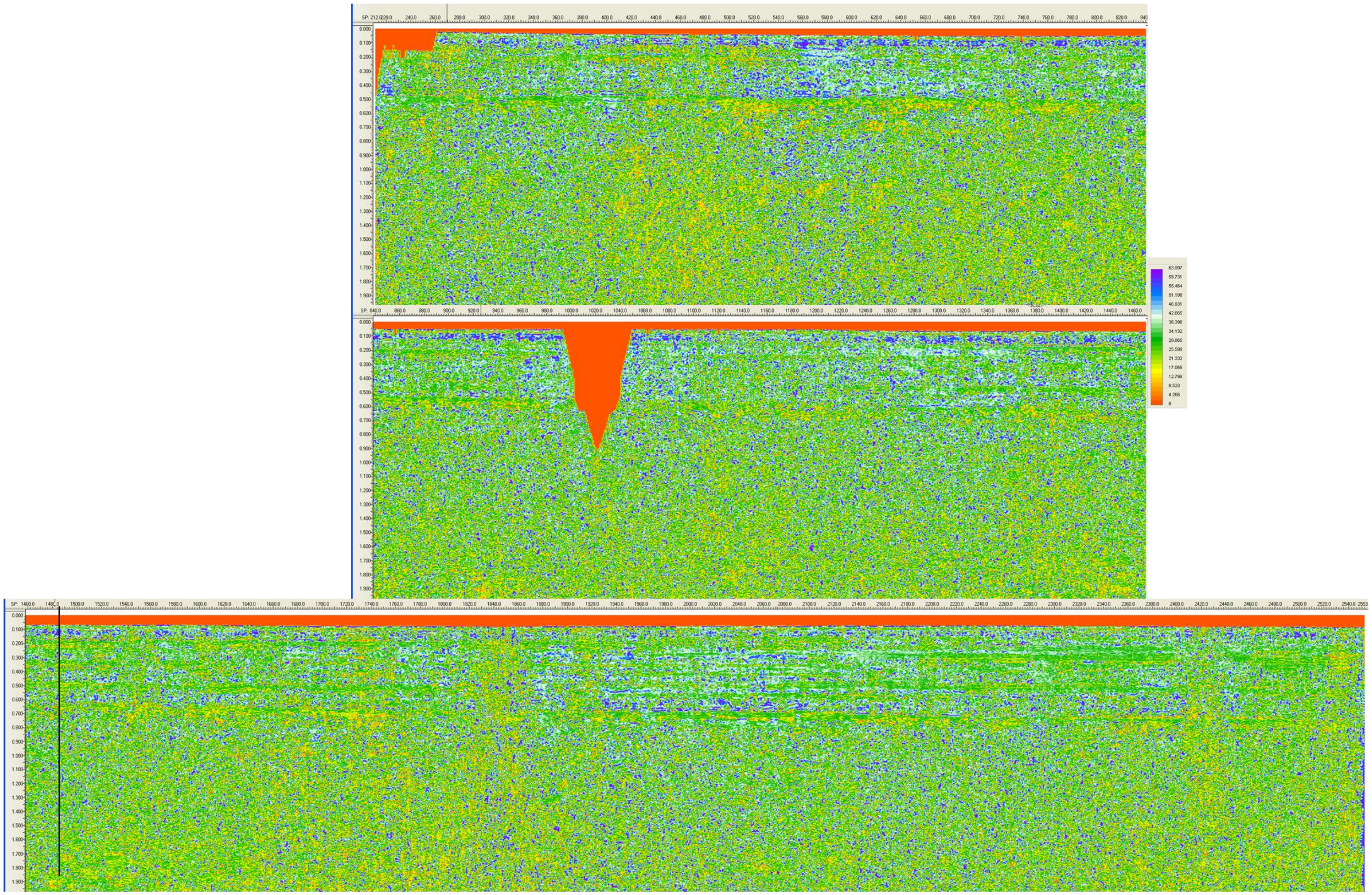

Figure 1.21. Instantaneous frequency of SC02_1. Rizer #1 is displayed at CDP 1486. Higher frequencies can be seen in violet with lower frequencies in red.

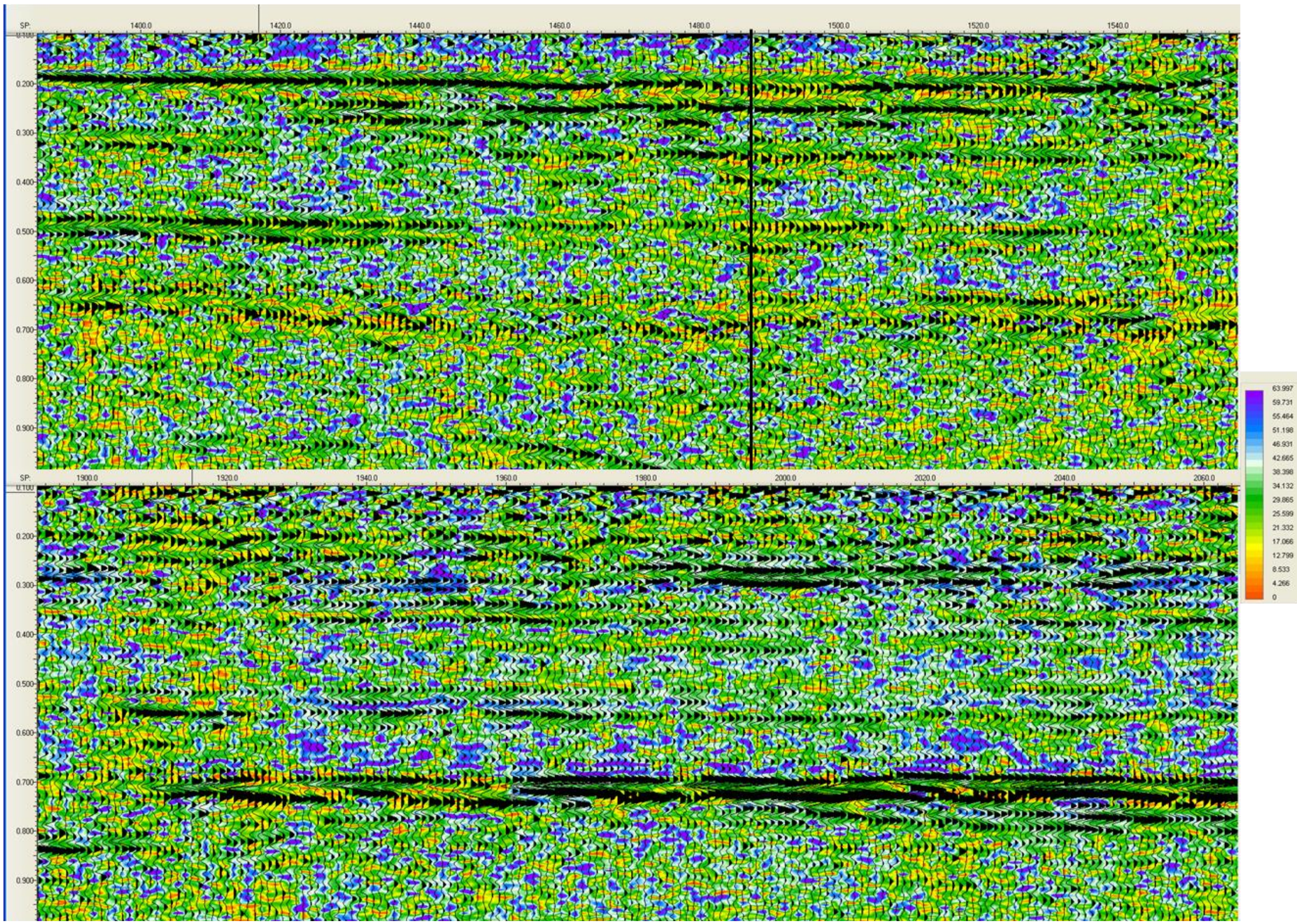

Figure 1.22. Instantaneous frequency of SC02_1 from CDP 1385-1557 (Top) and CDPs 1892-2064 (Bottom). Rizer #1 is shown at CDP 1486. Higher frequencies can be seen in violet with lower frequencies in red.

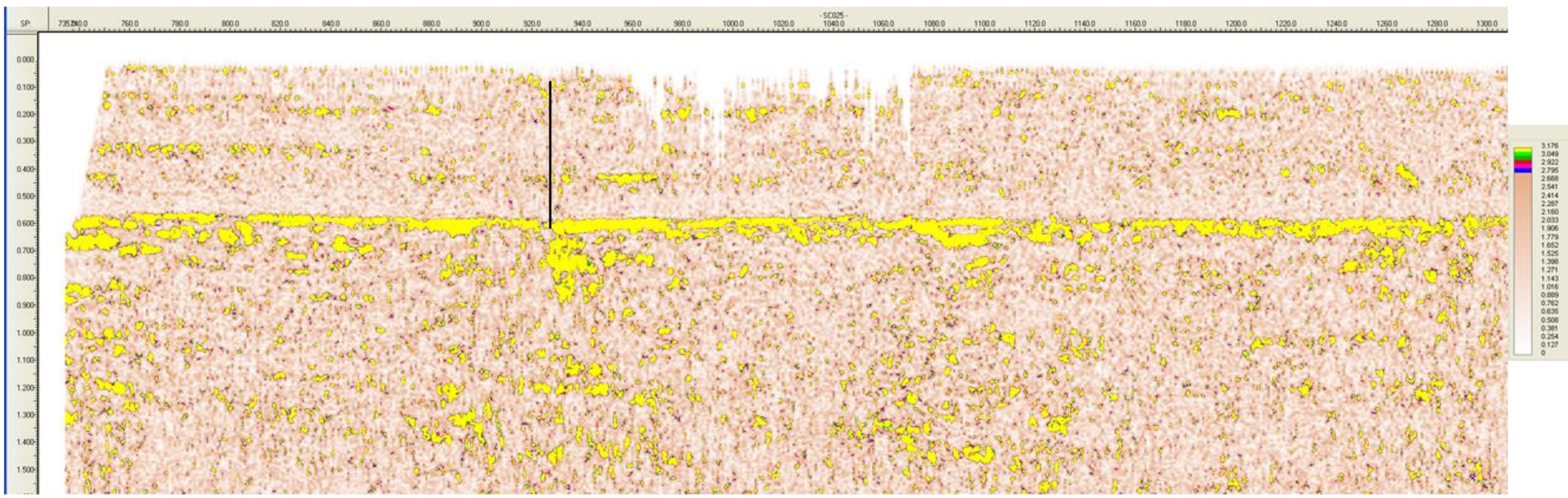

Figure 1.23. Envelope of SC02_5. Dorchester 211 is displayed at CDP 925. Higher energy can be seen in yellow with lower energy in white.

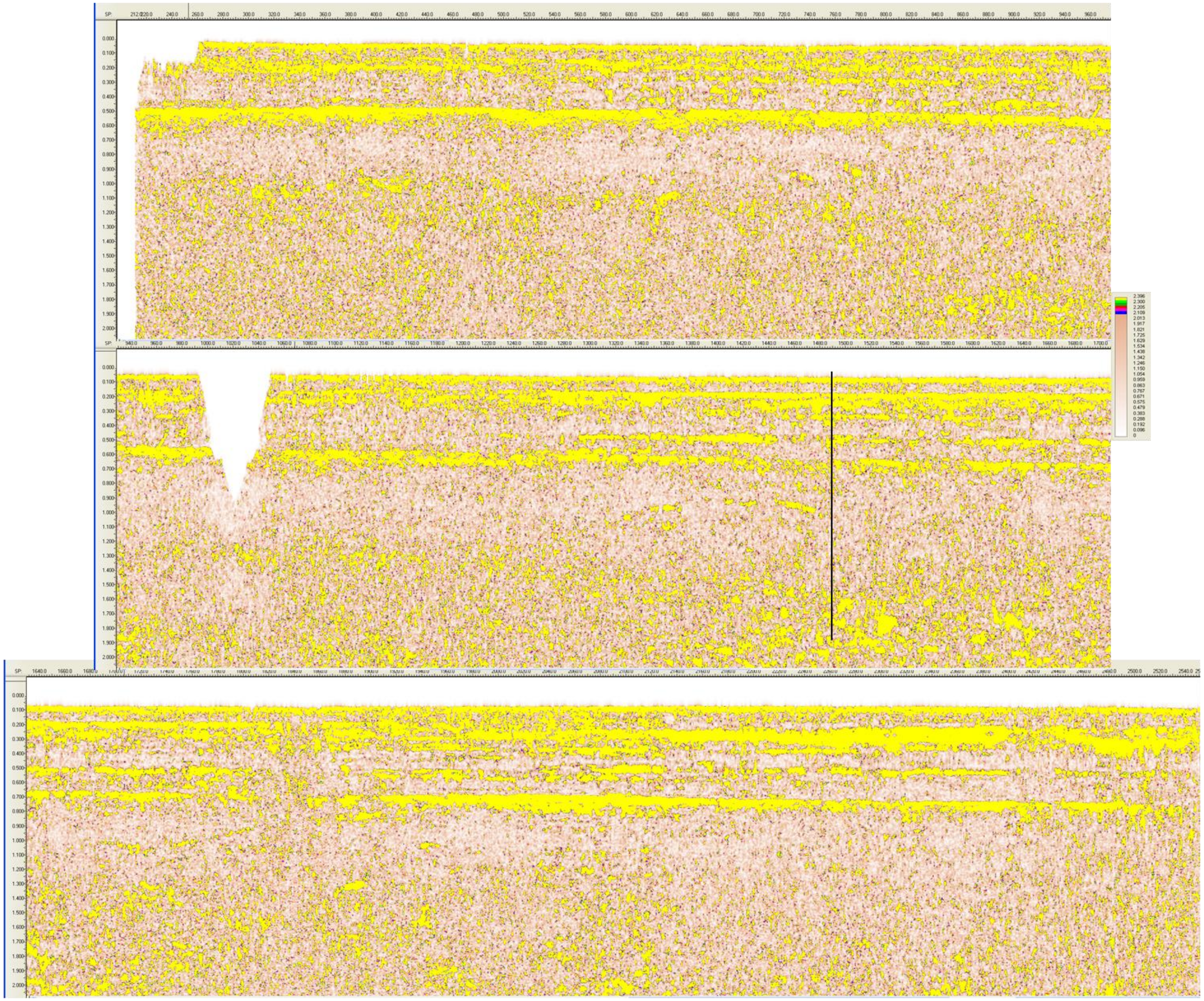

Figure 1.24. Envelope of SC02_1. Rizer #1 is displayed at CDP 1486. Higher energy is in yellow with lower energy in white.

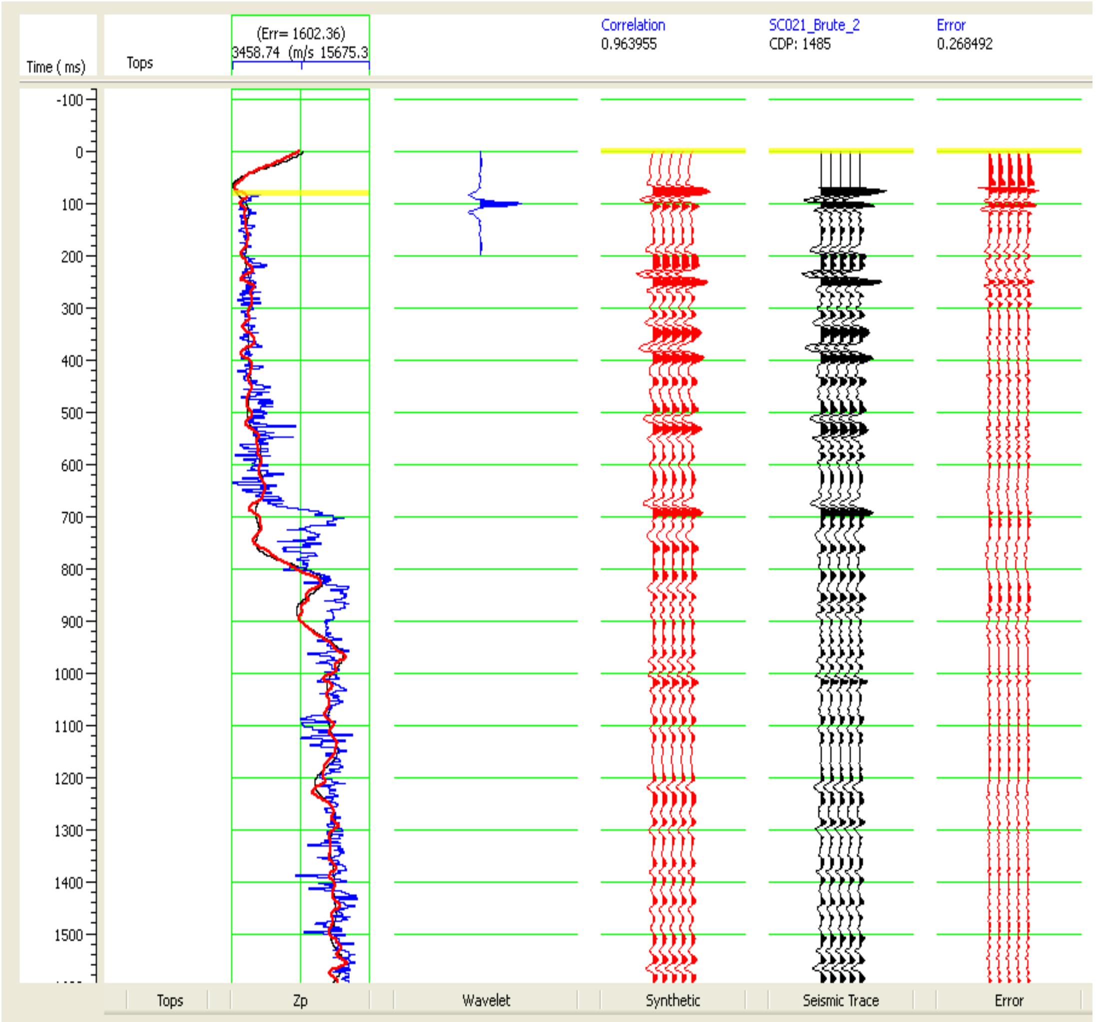

Figure 1.25. Rizer #1 acoustic impedance log (Zp) used to generate inversion model. Blue is original log, black is the initial model, and red is the final inverted log.

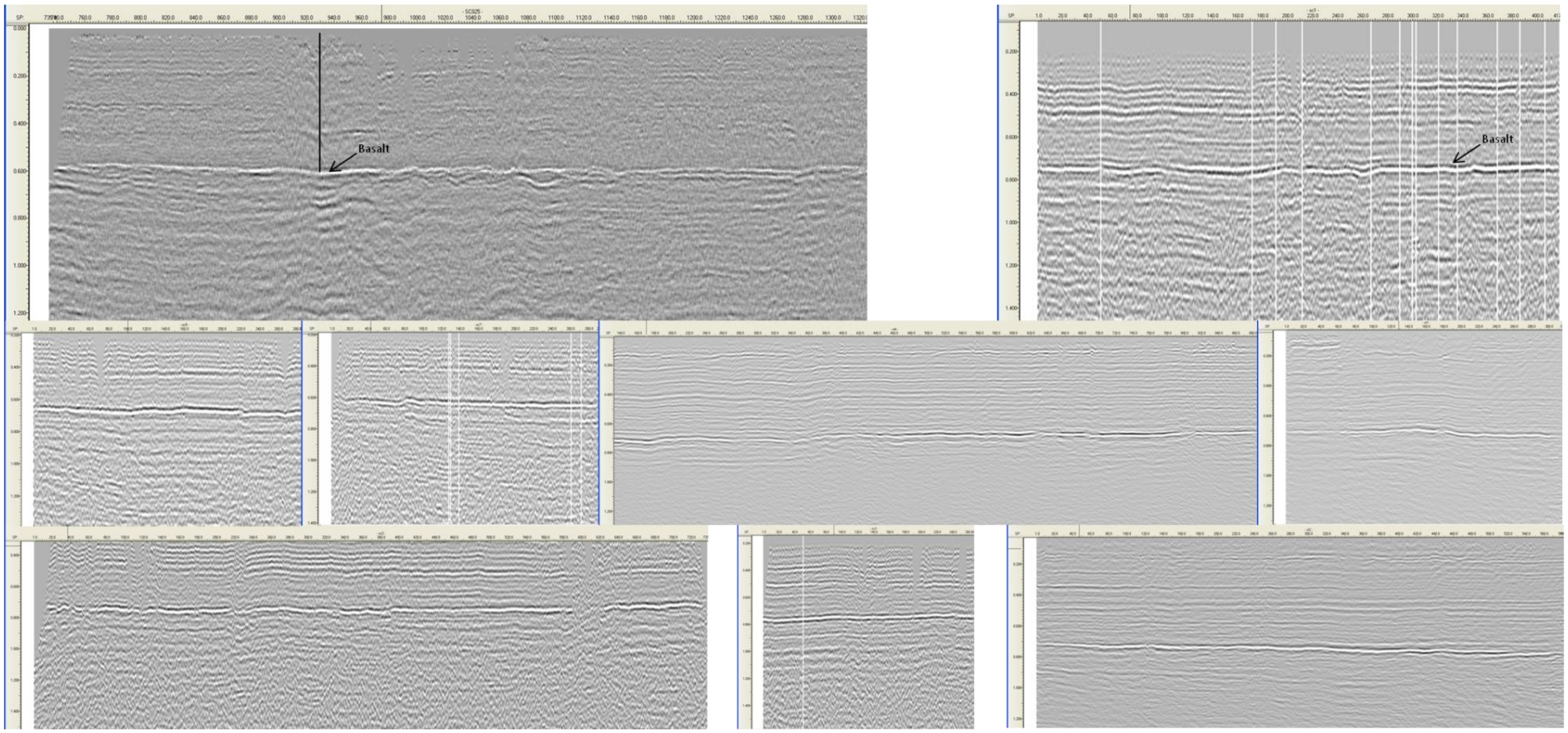

Figure 1.26 Seismic reflection profiles SC02_5, SC1, SC9, SC7, VT4, VT1, SC2, SC3, and VT2 with plot gain fixed using maximum amplitudes. Basalt was encountered in Dorchester 211 and Clubhouse Crossroads. Amplitude character of J-reflector appear consistent across all profiles.

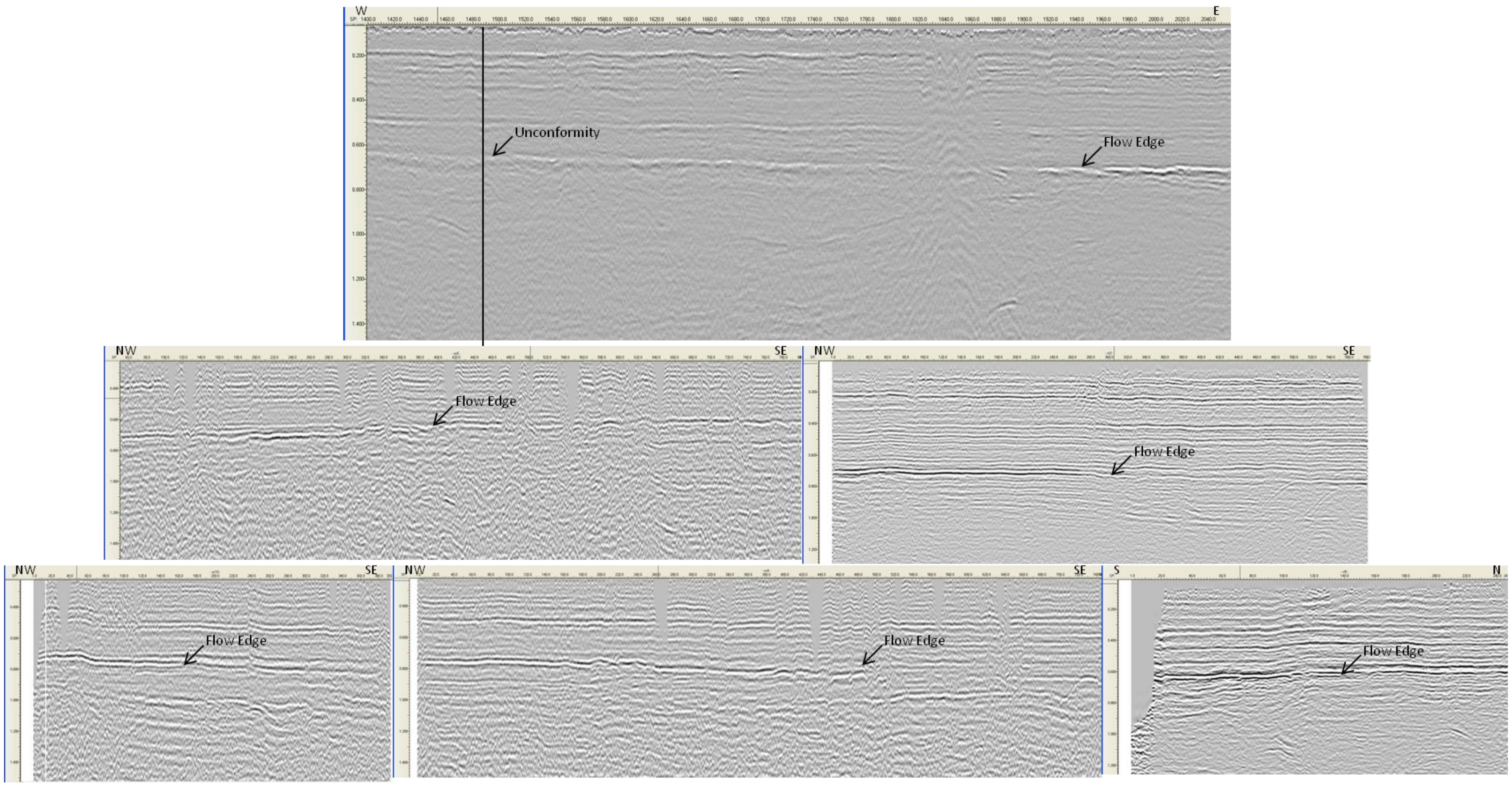

Figure 1.27. Seismic reflection profiles SC02_1, SC6, VT3, SC10, SC4 and VT5 with plot gain fixed using maximum amplitudes. No basalt at the base of the coastal plain was encountered in Rizer #1. Edge of basalt flow is marked by a significant change in amplitude character of the J-reflector.

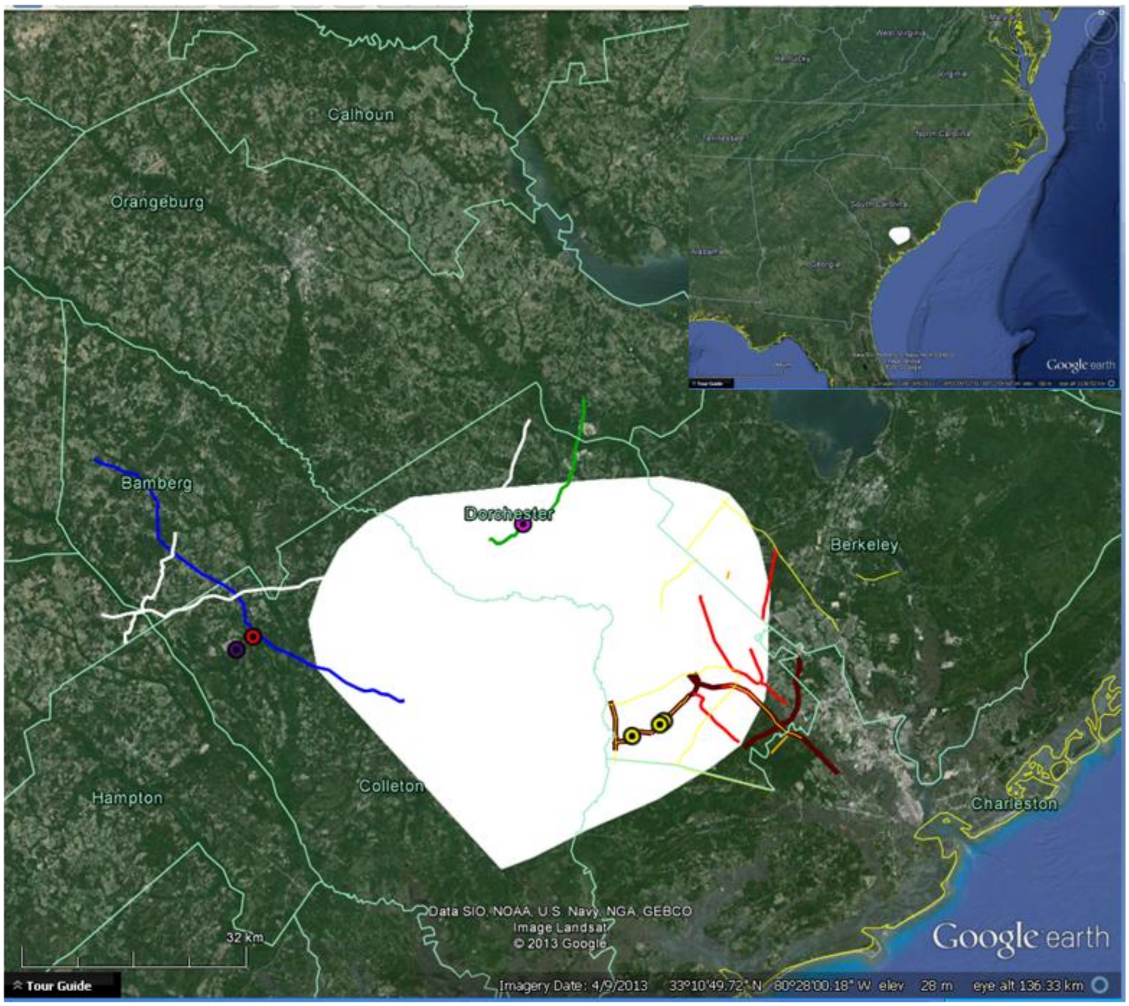

Figure 1.28. Map of preserved clubhouse crossroads basalt flow as seen on seismic reflection profiles. Yellow dots are Clubhouse Crossroads Coreholes (CCC1, CCC2, CCC3). Pink, Red, and Purple dots are Dorchester 211, Norris Lightsey #1, and Rizer #1 wells, respectively. Yantis et al. 1978 profiles in orange, COCORP (C1-C4) in brown (Hamilton et al. 1983), SC1-10 in yellow (Schilt et al. 1983), VT1-5 in red (Coruh et al. 1981), SC02_1-2-4,6-7 in white, and SC02_5 in green.

1.8 TABLES

Table 1.1. Seismic Acquisition parameters for SC02_1 and SC02_5.

NUMBER OF CHANNELS	240 CHANNELS
GROUP INTERVAL	52 METERS
SOURCE INTERVAL	52 METERS
SPREAD	SYMMETRICAL SPLIT SPREAD MAXIMUM OFFSET 6,240 METERS
SOURCE	3 IVI LITTON 315 SYSTEM VIBRATORS (42,000 FORCE LBS WITH ADVANCE TORQUE AMP CONTROL SYSTEM)
SWEEP PARAMETERS	10 HZ TO 72 HZ, 8 EACH-8 SECOND SWEEPS
RECORD LENGTH SAMPLE RATE GEOPHONE ARRAY	6 SECONDS 2 MS 12 (EACH) OYO GEOSPACE GEOPHONES- 10 HZ OVER 52 METERS

Table 1.2. Example processing flow used on SC02_1 and SC02_5.

GEOMETRY
TRACE EDITS, TOP MUTE
ELEVATION STATICS
BANDPASS FILTER (8-10-100-120 HZ) WITH 4 MS WIDTH 60HZ NOTCH
VELOCITY ANALYSIS
NORMAL MOVEOUT CORRECTION
CDP STACK

REFERENCE

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Appendix A - Acquisition Parameters for Legacy Reflection Profiles

Table A.1 Acquisition parameters for reflection profiles in the meizoseismal area of the 1886 Charleston earthquake.

		Data type	Station spacing	# channels	Profile length	Shotpoin t spacing	Source	Sample rate	Record length	Year of acquisition	References	Notes
Yantis et al Profiles		Reflection					Dynamite			1974 (summer)	Yantis, B. R., 1978, A reflection seismic study near Charleston, South Carolina: Blacksburg, Virginia Polytechnic Institute and State University, M.S. thesis.	Recorded analog, and digitized @ 2 ms. Shot depth 1-3m, size 1lb
	Clubhouse Crossroads		15.2	24	1.7 km	30.5	"	2 ms	1.5 s			
	Interstate		15.2	24	1.0 km	30.5	"	2 ms	1.5 s			
	Middleton Place		15.2	24	4.3 km	30.5	"	2 ms	1.5 s			
U.S.G.S. Profiles		Reflection			140 km		3 Vibrators				Hamilton, R.M., Behrendt, J.C., and Ackermann, H.D., 1983, Land multichannel seismic-reflection evidence for tectonic features near Charleston, South Carolina, in Gohn, G.S., ed., Studies related to the Charleston, South Carolina, earthquake of 1886—Tectonics and seismicity: U.S. Geological Survey Professional Paper 1313, p. I1–I18.	split spread, 120m geophone group offset, 7s sweep 10-60hz at alternate geophone groups, 15 sweeps at each vib point, trucks moved up ~3 m between sweeps
	SC 1		60 m	48	~12.94	120	"	4 ms	3 s	1979		
	SC 2		60 m	48	~23.9	120	"	4 ms	3s	1979		
	SC 3		60 m	48	~8.57	120	"	4 ms	3 s	1979		
	SC 4		60 m	48	~22.88	120	"	4 ms	3 s	1979		
	SC 5		60 m	48	~16.38	120	"	4 ms	3 s	1979		
	SC 6		60 m	48	~25	120	"	4 ms	3 s	1979		
	SC 7		60 m	48	~9.55	120	"	4 ms	3 s	1979		
	SC 8		60 m	48	~6.38	120	"	4 ms	3 s	1979		
	SC 9		60 m	48	~9.75	120	"	4 ms	3 s	1979		
	SC 10		60 m	48	~12.87	120	"	4 ms	3 s	1979		

		Data type	Station spacing	# channels	Profile length	Shotpoin t spacing	Source	Sample rate	Record length	Year of acquisition	References	Notes
COCORP Profiles		Reflection			72 km		5 Vibrators 23 m apart				Schilt, F.S., Brown, L.D., Oliver, J.E., and Kaufman, S., 1983, Subsurface structure near Charleston, South Carolina Results of COCORP reflection profiling in the Atlantic Coastal Plain, in Gohn, G.S., ed., Studies related to the Charleston, South Carolina, earthquake of 1886—Tectonics and seismicity: U.S. Geological Survey Professional Paper 1313, p. H1–H19.	vibrators 23 m apart, 8-32 hz upsweep, distance to nearest station 469 m, receiver array length 6,370 m
	COCORP 1		67 m	96	~17.47	?	"	8 ms	20	1978		sta 41-199 24 fold sta 948-41 16 fold
	COCORP 2		67 m	96	~26.64	?	"	8 ms	20	1978		24 fold
	COCORP 3		67 m	96	~17.14	?	"	8 ms	20	1978		24 fold
	COCORP 4		67 m	96	~7.05	?	"	8 ms	20	1978		16 fold
VT profiles		Reflection									Chapman, M., Beale, J., On the Geologic Structure at the Epicenter of the 1886 Charleston, South Carolina, Earthquake., Bulletin of the Seismological Society of America, V. 100 N. 3 p. 1010-1030, June 2010, doi: 10.1785/0120090231	
	VT1		34.5	48	~5.5	34.5	Single Vibrator	2	21	1980	Coruh_et_al_1982 unpublished (Rift Basin Library)	off-end, 80-10hz sweep, 19 s sweep length
	VT2		34.5	48	~10.5	34.5	"	2	21	1980	Coruh, C., Costain, J. K., Behrendt, J. C., and Hamilton, R. M., 1981, New reflection seismic evidence for deformation of Mesozoic sediments near Charleston, S. C. [abs]: Geological Society of America Abstracts with Programs, v. 13, no. 7, p. 431	off-end, 80-10hz sweep, 19 s sweep length
	VT3		34.5	48	~10.1	34.5	"	2	21	1980		off-end, 80-10hz sweep, 19 s sweep length
	VT4		34.5	48	~15.84	34.5	"	2	21	1981		off-end, 80-10hz sweep, 17 s sweep length
	VT5		69	48	~10.21	34.5	"	2	39	1981		Split, 80-10hz sweep, 25 s sweep length
SCO2 Profiles		Reflection					3 Vibrators					
	SCO2_1		52	240	61.2	52		2 ms	6 s	2011		10-72hz
	SCO2_2		52	240	20.9	52		2 ms	6 s	2011		10-72hz
	SCO2_3		52	240	48.2	52		2 ms	6 s	2011		10-72hz
	SCO2_4		52	240	25.9	52		2 ms	6 s	2011		8-72hz
	SCO2_5		52	240	29.3	52		2 ms	6 s	2011		8-72hz
	SCO2_6		52	240	22.3	52		2 ms	6 s	2011		8-72hz
	SCO2_7		52	240	20.5	52		2 ms	6 s	2011		8-72hz

Appendix B - Directory of Projects and Tips for Hampson-Russell Inversion

All projects used are located on the tg(e)l seismic server jupiter.seis.sc.edu within Projects/Craig/craigc.

Each inversion was done in an independent project. Post-stack seismic with Geometry, 60Hz Bandpass, & NMO/Stack only are referred to as “SC021Stack” “SC025Stack” and “SC021_Brute_2”. Pre-stack seismic is referred to as “SC021CDP” and “SC025CDP”. Kimmy McCormack’s fully processed version of SCO2-1 is also present, referred to as “stack_sc021”.

An overview of what each project contains is as follows:

- Project Line 1 contains Prestack and Angle Gather information for SC02-1, and well information for Rizer #1 and Norris Lightsey #1.
- Project Line 1 Check contains post stack seismic for SCO2-1 and the final AI model for SCO2-1.
- Project Line 1 Processed Coastal Shift contains Kimmy McCormack’s processed SCO2-1 “stack_sc021” along with a poststack inverted dataset. This was used to compare AI results between fully processed and minimal processed post stack seismic.
- Line 1 Rizer Shift to Dor contains post stack seismic for SC02-1 “SC021Stack” and an initial inverted AI model. This project was used during the initial coastal plain well editing of Rizer to values closer to those seen in Dorchester 211.
- Line 5 contains post stack seismic for SCO2-5 and the final AI model for SCO2-5.
- Line 5 Prestack contains prestack and angle gather information for SCO2-5, and well information for Dorchester 211
- Project Hampson Crashes contains all pre and post stack seismic.
- Wells contains all well information
- Seismic vol’s and segy’s can be found within Hampson_Russel_Seismic_Input

Some helpful tips:

- CGG has great information on their website. I'm providing two hyperlinks to useful information. "Post-Stack Inversion Demo" is a great place to start. http://www.cgg.com/default.aspx?cid=4729&lang=1 and http://www.cgg.com/data//1/rec_docs/1918_LithoSI.pdf
- Geoview will crash if you try to run a second inversion in a given project. This is why there are separate projects. When running the inversion, if the program crashes upon trying to build a model, you likely have negative values in your depth-time table. Along the top, select "Data Explorer", from the dropdown window Display "Well Data Explorer", click the blue arrow on whichever Well you are using, then select the blue arrow again for whichever depth-time table you are trying to build the model with. Find the negative value or time reversal in the table and correct. Also, if the density log units are not g/cc the program will crash.
- All seismic profiles may be pointing to a SGR Basalt database. This database is found in craigc/Hampson_Russel_Project2. There was an initial project before "Hampson Crashes", however this project became corrupted during a problem with Jupiter.
- Within craigc folder, are folders labeled by the Well name. These contain log files and other relevant information. There is also a folder for Clubhouse Crossroads, which contains pdf files of the clubhouse crossroads logs. They can be digitized in Kingdom. A How-To on digitizing logs in Kingdom can be found in the craigc folder labeled "Digitizing Instructions"
- I recommend doing any Well edits in a project independent of your inversion project, then import copying

Open Geoview.

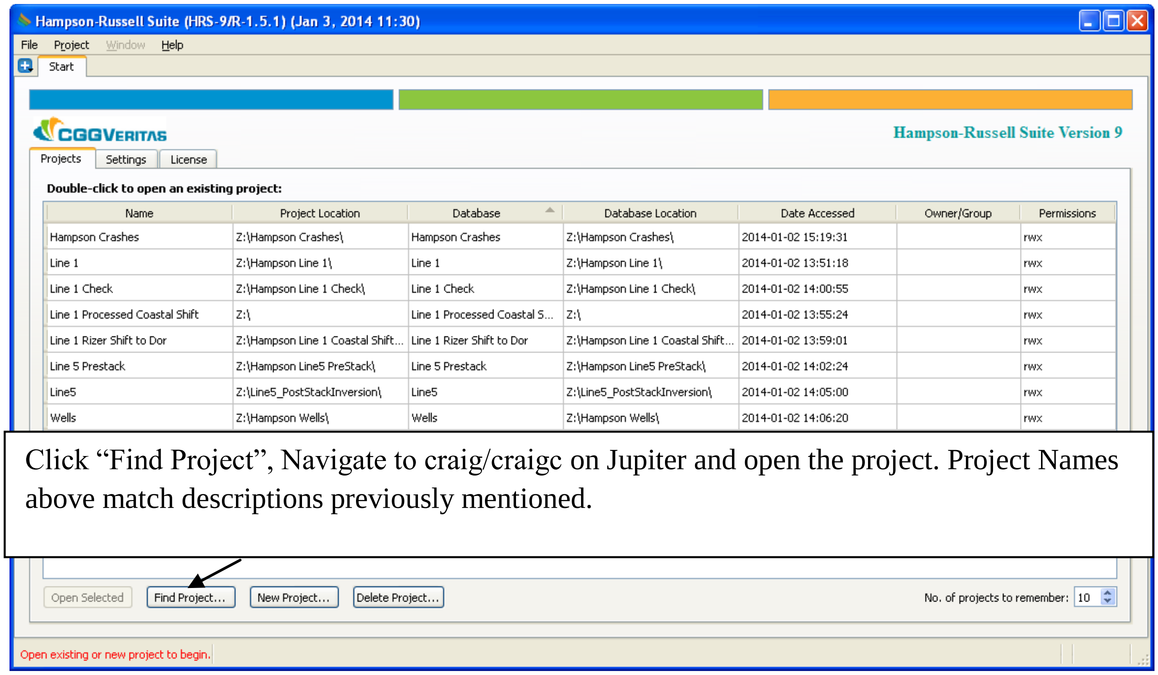

Figure B.1 Opening Geoview

Key points for Navigation.

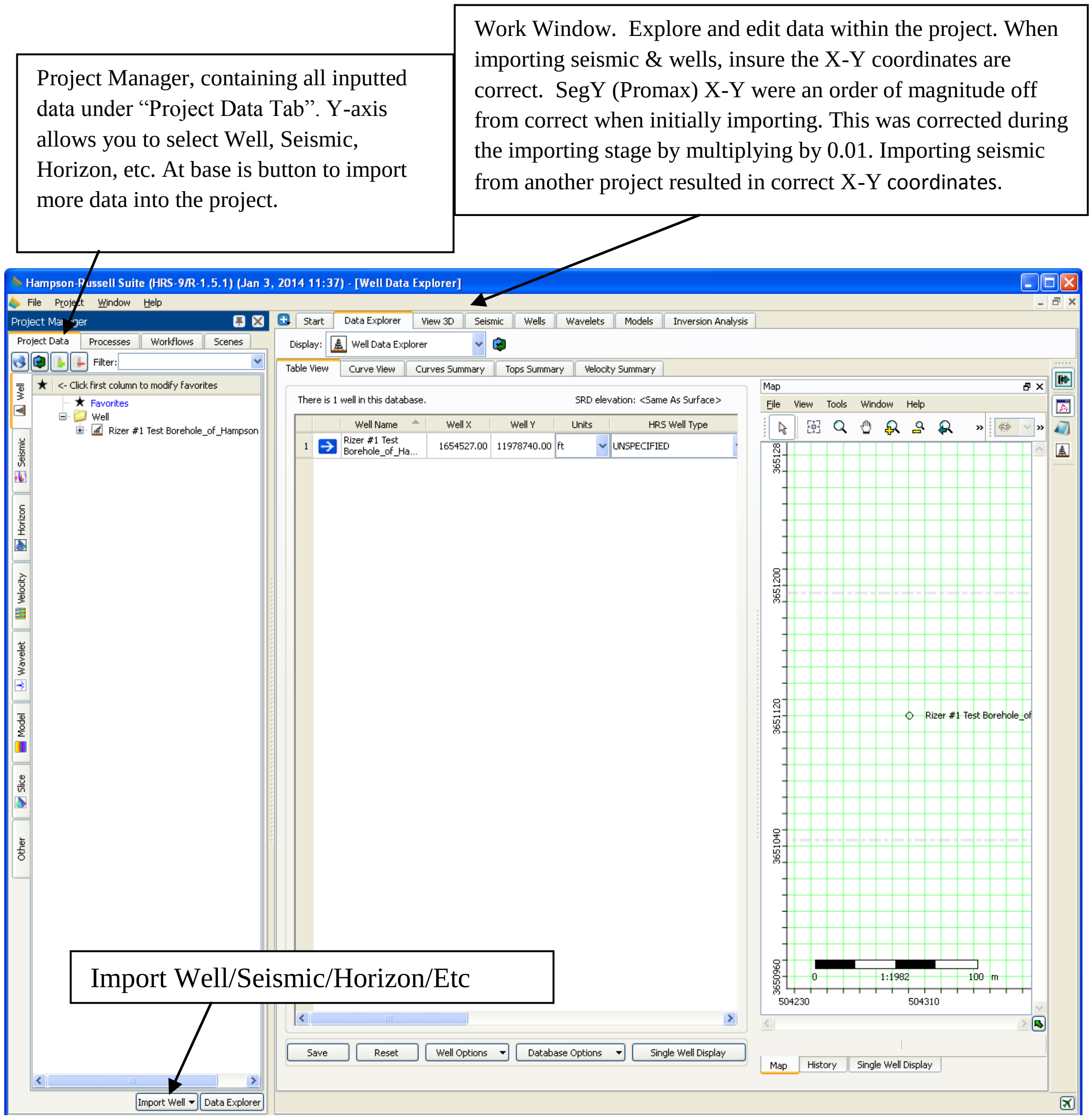

Figure B.2 Geoview Navigation

Click “Workflows” under project manager. Select “Post Stack Inversion” and follow suggested workflow.

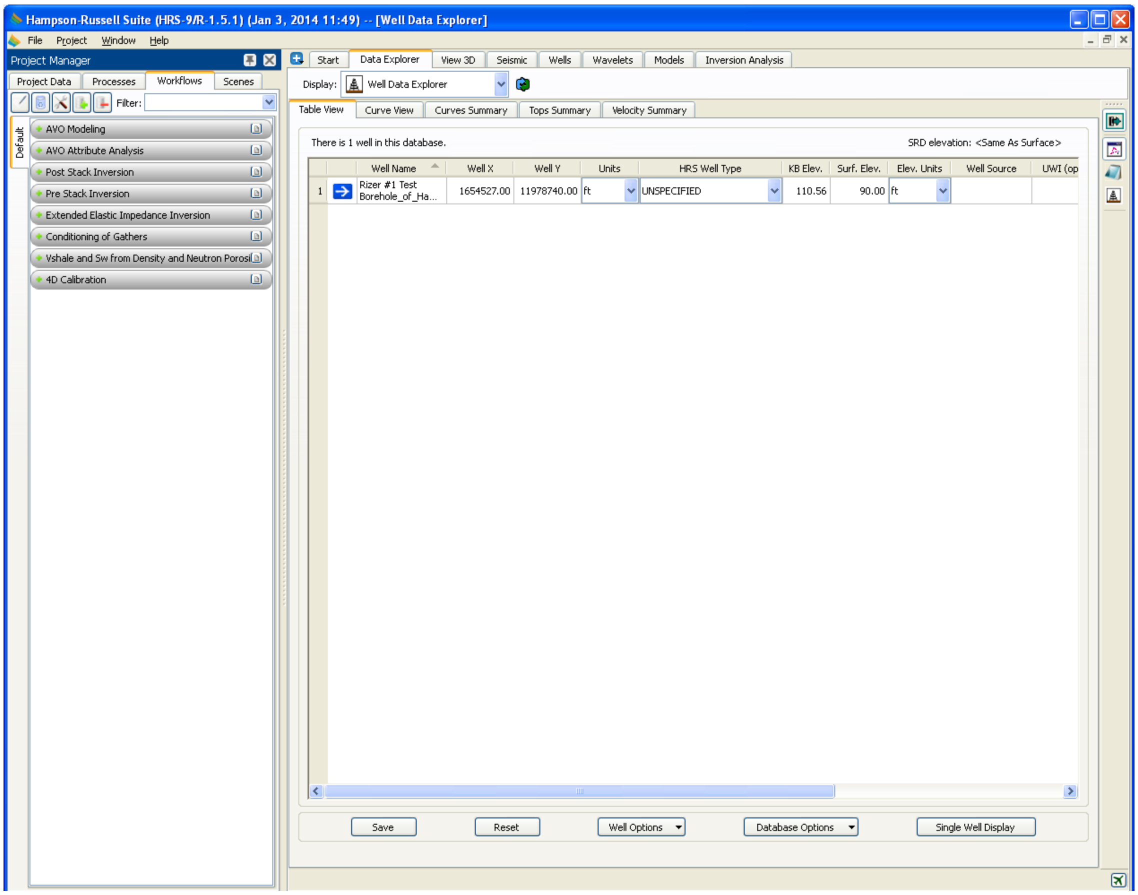

Figure B.3 Log Editing Geoview

Log Edits can be done using “Log Processing” found under the “Processes” tab of the Project Manager (One tab left of the workflow tab). You can also copy a well, rename it, and edit X-Y coordinates. To do this, click “Import Well” at the bottom of the Project Manager -> “Copy Wells from another database”. Once the well is imported, go to “Data Explorer” tab, select “Well Data Explorer” from the drop down display bar, and edit the X-Y coordinates