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Title: "Development of a Community Velocity Model for the Charleston, South Carolina Region"

Steven C. Jaumé and Norman S. Levine
Department of Geology and Environmental Geosciences
College of Charleston
66 George Street
Charleston, South Carolina 29424
843-953-1802; FAX: 843-953-5446; jaumes@cofc.edu

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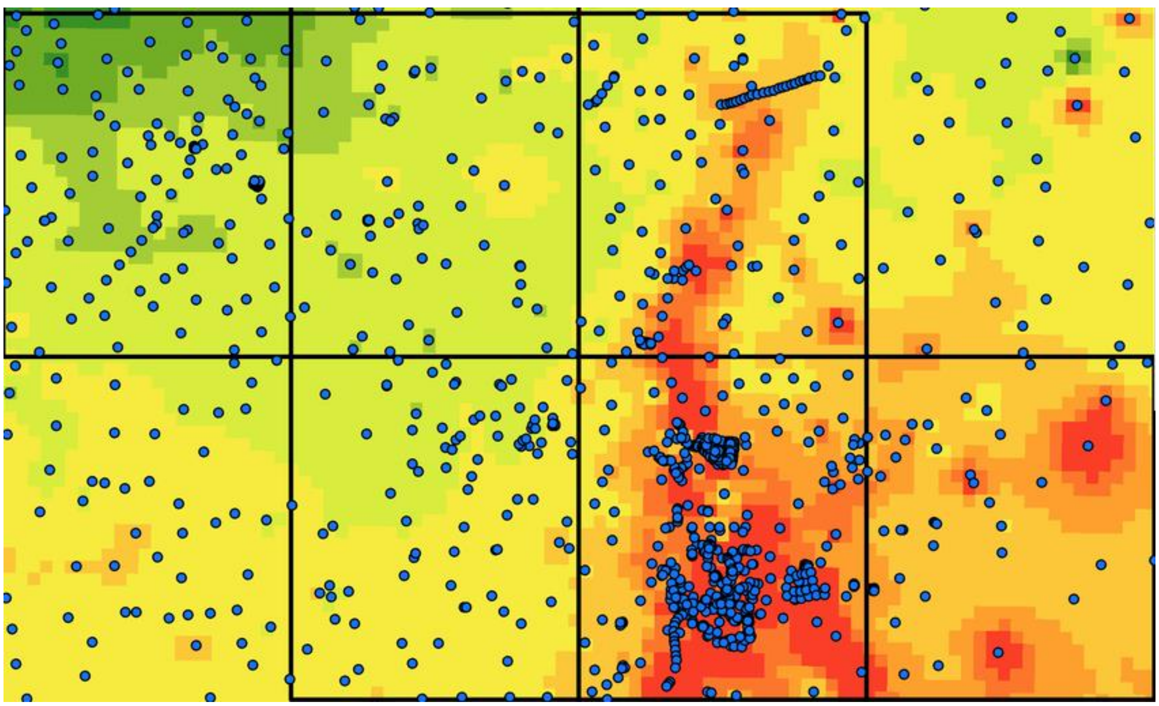

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Abstract

We have integrated seismological, geological, hydrogeological, geophysical and geotechnical data to construct a 3-dimensional shear wave velocity model of a highly populated nine quadrangle (Summerville, Mount Holly, Stallsville, Ladson, North Charleston, Johns Island, James Island, Charleston and Fort Moultrie) area of the greater Charleston, South Carolina, region. We find the semi- and unconsolidated Atlantic Coastal Plain sediments range from less than 600 to nearly 1000 meters in thickness across our study area. Shear wave velocities of geological units range from up to 900 meters/second in a high velocity layer at depth we name the Gordon High Velocity Zone to less than 180 meters/second in near surface man-made and Holocene tidal marsh deposits. We estimate the depth of three significant impedance contrast surfaces (base of coastal plain, top of Gordon High Velocity Zone and the Quaternary/Tertiary contact) and reference the thickness of 7 pre-Quaternary sedimentary velocity units to these boundaries. Our shallowest layer (Quaternary and man-made sediments) is divided into estimates of shear wave velocity (both average and linearly increasing with depth) for 18 surficial units. Downloadable GIS files and Excel tables related to this project can be found at https://arcg.is/0SafDi.

INTRODUCTION

The purpose of the Charleston Area Earthquake Hazards Project (CAEHMP) Community Velocity Model project is to define major shear wave velocity units underlying the Charleston metro area, specifically the highly populated Summerville, Mount Holly, Stallsville, Ladson, North Charleston, Johns Island, James Island, Charleston and Fort Moultrie quadrangles (Figure 1). This model will form the basis for future studies of deterministic and probabilistic strong ground motion in the CAEHMP region.

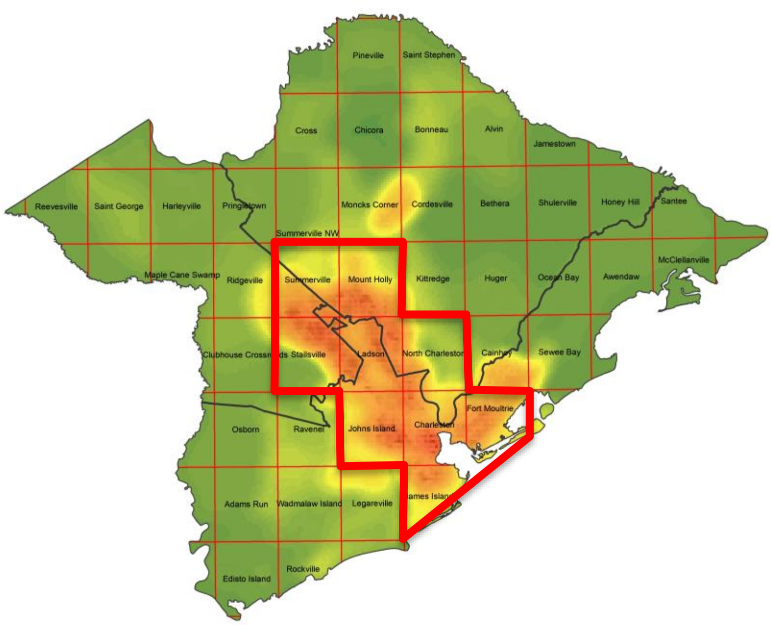

Figure 1: Population density (warmer colors represent greater density) and quadrangle locations in the Charleston metropolitan region. Our study area consists of 9 heavily populated quadrangles (outlined by thick red line).

An initial pilot study (Cramer et al., 2015) concentrated on mapping the shallow geologic and shear wave velocity structure of the Charleston quadrangle and using this model to construct both deterministic and probabilistic seismic and liquefaction hazard maps. That study showed a clear dependence of seismic hazard on both the type and thickness of the Quaternary section, and also showed that this dependence varied with frequency (i.e., increasing hazard with increased Quaternary thickness at low frequency but decreasing hazard at high frequency). The pilot study made the simplifying assumption that the total thickness of the coastal plain sediments did not change beneath the Charleston quadrangle. This is clearly not the case for the entire CAEHMP study region, so this project addresses both the thickness and shear wave velocity structure of the entire coastal plain sedimentary section.

PREVIOUS WORK

Here we briefly review some of the previous research used to define the thickness and seismic velocity of the Atlantic Coastal Plain sediments underlying the greater Charleston region. Much of the early work focused on the overall thickness and P-wave velocities of the coastal plain sediments (see Rankin, 1977; Gohn, 1983 and studies therein) but did not include information on shear wave velocities (V_S) needed for seismic hazard assessment. Wong et al. (2005; also see URS Corporation, 2001 for more detail) utilized limited borehole V_S measurements near Charleston merged with more complete information from the Savannah River Site to construct an estimated V_S profile for a Charleston Site Response category as part of a state-wide HAZUS study of seismic risk and vulnerability in South Carolina. Chapman et al. (2003) were able to make a direct estimate of the thickness and average V_S (700 m/sec) of coastal plain sediments in the epicentral area of the 1886 earthquake based mainly upon observations of converted Sp phases. Both Andrus et al. (2006) and Chapman et al. (2006) used shallow V_S profiles derived from a combination of surficial geophysical and borehole techniques to estimate site response; however, both of these studies were forced to make assumptions regarding V_S below ~110 meters owing to the lack of direct V_S measurements. Finally, Aboye et al. (2011 & 2015) had access to V_S measurements in a deeper (~240 meter) geotechnical borehole near downtown Charleston for their site response estimates. This work builds upon these previous studies primarily by merging together these results and adding additional hydrogeologic, geotechnical and geological borehole information to estimate the thickness and V_S of geological formations within the Atlantic Coastal Plain near Charleston, South Carolina.

DATA

The data used to characterize the V_S structure of the Atlantic Coastal Plain comes from a variety of sources. Here we briefly describe the general characteristics of these datasets and how they are used, saving more detailed descriptions for later sections where they are applied to define specific seismological boundaries and V_S of specific units.

Seismological Data

Previous workers have interpreted seismic refraction (Ackermann, 1983), reflection (Chapman et al., 2010) and earthquake data (Chapman et al., 2003) to estimate the depths of seismological boundaries and the seismic velocity of the coastal plain section and the underlying crustal units. We primarily use this data to define the base of the coastal plain section (which is also the base of our model), where the largest impedance contrast exists. Earthquake arrival time data of Sp phases also helps constrain the average V_S of the coastal plain sediments (Chapman et al., 2003).

Hydrogeologic and Deep Geologic Borehole Data

The majority of the deep boreholes in the Charleston region were drilled to tap the freshwater resources of the numerous aquifers in the coastal plain sedimentary section. Several of the deeper boreholes reach the base of the coastal plain, and many of them also have geophysical well logs (one or more of the following: gamma ray, resistivity, and spontaneous potential), which allow for correlation of stratigraphic units between wells. We use this data both to help define the base of the coastal plain section and also define the depths of specific geologic/seismological boundaries within the coastal plain sedimentary section. In particular we rely heavily upon the work of Colquhuon (1997) and Gellici and Lautier (2010); plus the interpretations of the Clubhouse Crossroads well stratigraphy by Gohn et al. (1977) and the Cannon Park well stratigraphy by Bybell et al. (1998).

Deep (>30 meter) Geotechnical Boreholes

In recent years the South Carolina Department of Transportation (SCDOT) has sponsored the drilling of several deep (150-250 meters) geotechnical boreholes on the Atlantic Coastal Plain. All of these geotechnical wells have continuous V_P and V_S measurements plus other geophysical well logs, which allows us to correlate significant sections with the deep hydrogeological wells. We use three of these wells (see Figure 2) to help define seismological units and their V_S characteristics at depths below ~100 meters in our model. Additional deep geotechnical wells help constrain V_S from the base of the Quaternary to ~100 meter depths.

Shallow Geotechnical Boreholes and Surface Geophysics

We use both previously collected geotechnical boreholes/surface geophysics database (Mohanan et al., 2006) plus an additional 157 geotechnical wells donated by S&ME (Ulmer and Camp, pers. comm.) to help define both the Quaternary/Tertiary boundary and the V_S of Quaternary surface units.

Geologic Auger Holes

We combine an extensive auger hole data collected by USGS researchers for geologic mapping purposes (Weems et al., 2014 and references therein) plus an additional 227 auger holes collected by D. Colquhuon and students at the University of South Carolina. The University of South Carolina auger data were in the form of paper files that were converted into digital form for use in this project. This data was primarily used to add additional detail to the nature of the Quaternary/Tertiary boundary in the study area. In addition, this data was used to set the Quaternary sediment thickness where our projected Quaternary/Tertiary surface (see below) came above the land surface. We wish here to acknowledge the vital assistance of two colleagues in the Department of Geology and Environmental Geosciences at the College of Charleston: Dr. Micheal Katuna, who saved the D. Colquhuon files from destruction and Dr. M. Scott Harris, who alerted us to the presence of this data.

Surface Geology Map and Digital Elevation Model

Tertiary units outcrop at several locations in our study area (Weems et al., 2014). In this case were able to use the location information of these outcrops plus a digital elevation model (DEM) developed at the College of Charleston's Lowcountry Hazard Center to further define the elevation of this Quaternary/Tertiary boundary.

GEOLOGICAL/SEISMOLOGICAL BOUNDARIES and UNITS

The geological/seismological boundaries and subdivision into seismological (i.e., velocity) units in our model are controlled by two factors: 1) depth location of major impedance contrasts in the Atlantic Coastal Plain sedimentary column and 2) availability of V_S measurements of stratigraphic units. In general, much more data is available for shallow geological structure and units than for deeper ones. We have chosen 3 major boundaries which we believe can be consistently defined across the study region (base of the coastal plain, top of the Gordon High Velocity Zone, top of the Cooper Group) and reference all other unit boundaries to these. Table 1 summarizes our model for the Atlantic Coast Plain in the greater Charleston region, excluding the surficial Quaternary units.

Table 1: Vs and Thickness of Pre-Quaternary Coastal Plain Sediments

Unit	V_S (m/sec)	S.D.[1]	Thickness	Uncertainty
Upper Cooper Group	422	55	Variable	5
Lower Cooper Group	624	117	37	5
Gordon High Velocity Zone	903	178	29	5
Lower Bridge Member	478	103	29	5
Rhems Formation	612	95	58	5
Pee Dee Formation	654	87	25	5
Late Cretaceous (undifferentiated)	750	100[2]	Variable	50

[1]S.D. = standard deviation of V_S based on geotechnical measurements.

[2]Assumed standard deviation (see text).

Base of Coastal Plain and Late Cretaceous sediments (excluding Pee Dee Formation)

We define the base of the coastal plain as the contact between the semi- and unconsolidated Late Cretaceous and younger sediments of the Atlantic Coastal Plain and older Jurassic basalts and consolidated Triassic sediments of the syn-rift sequence deposited during the opening of the Atlantic Ocean (Gohn et al., 1977). In the Charleston region this boundary represents a factor of 2 or more increase P-wave velocity (Yantiss et al., 1983) and with an even greater increase in V_S (Chapman et al., 2006).

The first dataset used to estimate the elevation of the base of the coastal plain are water well data in Gellici and Lautier (2010), who use the base of the coastal plain as the base of their hydrologic model. We simply covert their elevation estimate from feet to meters in the GIS shapefile included with their publication. These elevation estimates are shown as purple squares on Figure 2.

The second dataset used to define this boundary are seismic refraction estimates of the elevation of the base of the coastal plain found in Figure 8 of Ackermann (1983). This figure was scanned

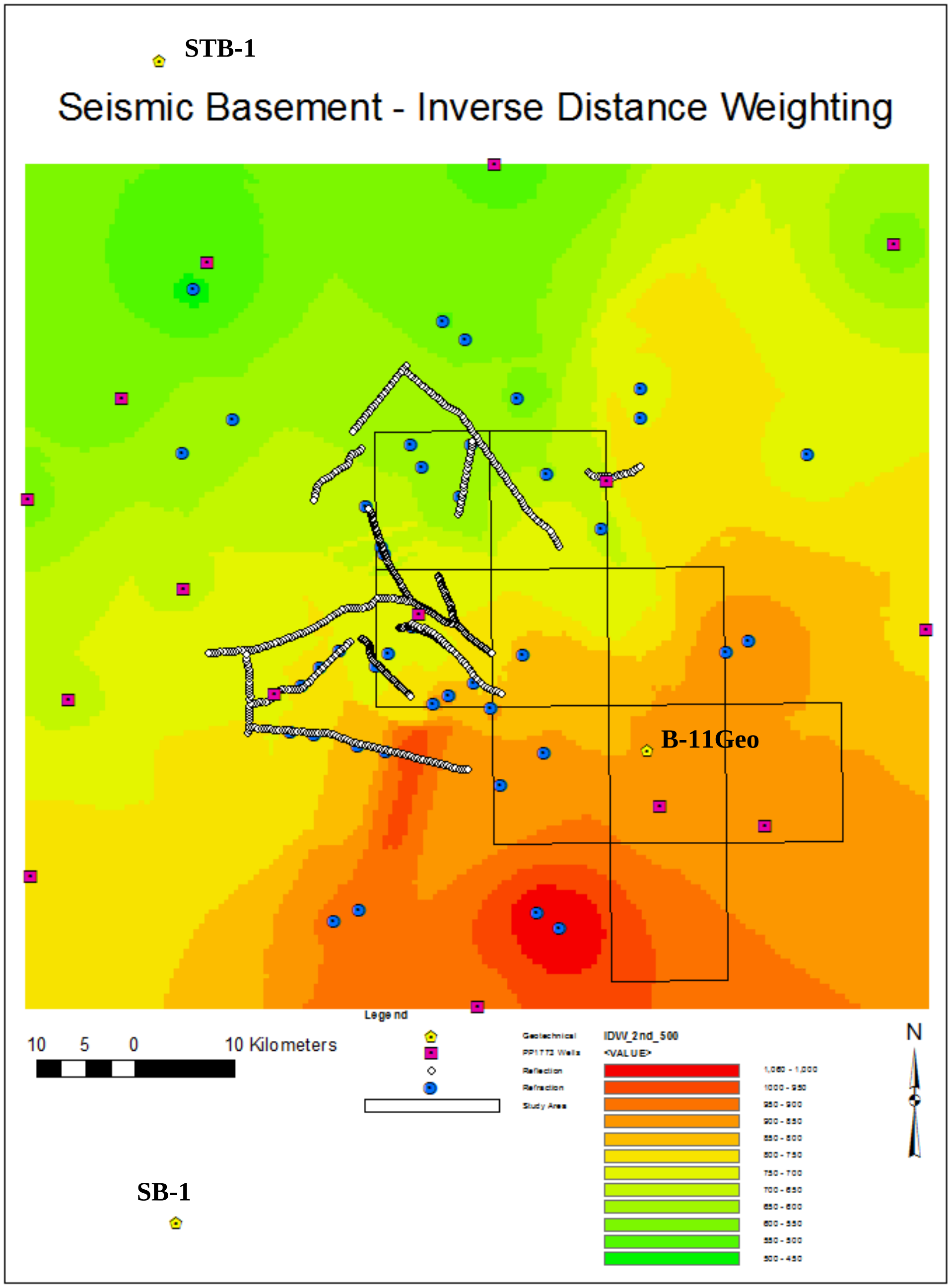

Figure 2: Location and type of depth estimate of seismic basement beneath the study area together with an Inverse Distance Weighting (IDW) extrapolation of the seismic basement surface. Depths are in meters below mean sea level (MSL). Cell size is 0.5 km x 0.5 km. Locations of 3 deep geotechnical wells with V_S estimates (see Figure 3) are also shown; note 2 of these lie outside the IDW extrapolated basement surface.

and georectified to a modern base map and the refraction elevation estimates were digitized from the figure. These elevation estimates are shown as blue circles on Figure 2.

The last dataset of elevation estimates of the base of the coastal plain are derived from seismic reflection lines collected by the U. S. Geologic Survey and Virginia Tech. SEGY files available from Chapman et al. (2010) were downloaded and displayed in JRG (Java Resource Geophysics) software (Louie, pers. comm.). We picked the highest amplitude reflector consistent with the known two-way travel time of the seismic basement reflector (Yantiss et al., 1983). One seismic line intersects the Clubhouse Crossroads deep borehole and the thickness of the coastal plain section in the borehole was used to constrain the P-wave velocity used to convert two-way travel time to sediment thickness at every 10 CMPs in each seismic reflection line. Estimated elevations at each CMP from a DEM were used to correct for elevation below mean sea level (MSL). These elevation estimates are shown as white diamonds on Figure 2.

One issue encountered during the seismic reflection interpretation was an apparent mismatch between USGS line SC10 and Virginia Tech line VT1, which overlap. The estimated two-way travel times of the seismic basement reflector on VT1 were approximately 0.02 seconds less than the corresponding reflector on SC10. Given that we were using two-way travel time estimates from line USGS line SC1 and the base of the coastal plain encountered in the Clubhouse Crossroads borehole to constrain the P-wave velocity, we decided to use the time picks from the USGS line as the standard and simply correct the time picks from the VT lines by adding 0.02. We cross-checked at several locations were USGS and VT lines nearly intersect and found our two-way travel time picks in the USGS versus Virginia Tech seismic reflection lines were in reasonable agreement.

Finally, we applied several interpolation schemes available in ArcGIS, including linear, polynomial, natural neighbor, inverse distance weighting (Figure 2) and kriging, to estimate the shape of the base of the coastal plain surface in our study area. The linear and polynomial interpolations were primarily used as a “sanity check”, to see if our data set recovered the same general trends seen in other work (e.g., Gellici and Lautier, 2010, Figure B3). We found the natural neighbor algorithm cut off part of the study area due to the distribution of points. We decided not to use the and kriging results, since kriging requires in each area that statistical “tensioning” parameters are developed which means that the results would not be as directly reproducible as the IDW results. Therefore we include only the inverse distance weighting (IDW) results in our final product.

We experimented with several grid cell sizes for interpolation and settled upon a 500 m by 500 m grid for this and the other layer boundaries in our model. The mismatch between the input basement elevation data and our model has a standard deviation of ±6.5 meters but with outliers as much -85/+40 meters. Given the sparse input dataset (Figure 2) we assign a ±50 meter uncertainty to this surface which translates into the ±50 meter uncertainty in the thickness of the undifferentiated Late Cretaceous sediments (Table 1).

There are no direct measurements of V_S of the coastal plain sediments from the base of the coastal plain to the base of the late Cretaceous Pee Dee Formation, the deepest unit for which there are direct V_S measurements. Chapman et al. (2006) estimated V_S to be 625-820 m/sec in this depth range based on the P-velocity sonic log from the Clubhouse Crossroads well, with an average V_S ~ 756 m/sec. We find V_S = 751 m/sec gives an average of V_S = 700 m/sec for our model at 33.0° North, -80.125° East; i.e., near the middle of the Chapman et al., 2003 study region. Therefore we assign V_S = 750 m/sec with an assumed standard deviation of ±100 m/sec (i.e., similar to other deeper V_S units in Table 1) for this section of our model.

Pee Dee Formation

Based upon correlation of geological and geophysical information between geotechnical and hydrogeologic boreholes, the late Cretaceous Pee Dee Formation is the deepest stratigraphic unit for which there are direct measurements of V_S. This unit is encountered in the deep geotechnical boreholes STB-1 and B-11Geo (Figures 2 and 3). V_S is measured over a 20 (STB-1) to 30 (B-11Geo) meter interval in these wells. This corresponds closely to the 26-meter interval for the Pee Dee Formation in the Cannon Park deep water well as identified by Bybell et al. (1998). Therefore we use this data to estimate V_S = 654±87 m/sec for this formation and use a thickness of 25±5 meters.

We reference the top of the Pee Dee Formation to a better-defined overlying surface (Top of Gordon HVZ – see below). In our model the top of the Pee Dee Formation lies 116 meters deeper than the Top of the Gordon HVZ.

Rhems Formation

Like the Pee Dee Formation, the Rhems Formation is encountered in geotechnical wells STB-1 and B-11Geo and the Cannon Park deep water well. Katuna (2005) interprets this formation to lie between depths of 450 and 500 feet (137-152 meters) in B-11Geo (note that Katuna, 2005, did not have access to samples from deeper levels in the borehole) and Bybell et al. (1998) interpret it to lie between 500 and 745 feet (152-227 meters) in the Cannon Park well.

For our purposes the Rhems Formation extends from the top of the Pee Dee Formation to base of a low velocity zone overlapping the Lower Bridge Member of the Williamsburg Formation. We assume the top of the Rhems Formation is where V_S stays consistently below 600 m/sec. In well B-11Geo this zone is ~60 meters thick and in well STB-1 it is ~56 meters thick (Figure 3). In our model we make the Rhems Formation 58±5 meters thick with its top lying 58 meters below the Top of Gordon HVZ boundary. From the measurements in B-11Geo and STB-1 it has V_S = 612±95 m/sec.

Lower Bridge Member of the Williamsburg Formation

As for the two formations defined above, the Lower Bridge Member of the Williamsburg Formation is encountered in wells STB-1, B-11Geo and Cannon Park. Katuna (2005) interprets this formation to lie between depths of 395 and 450 feet (120-137 meters) in B-11Geo and Bybell et al. (1998) interpret it to lie between 430 and 500 feet (131-152 meters) in the Cannon Park well.

In both STB-1 and B-11Geo there is a low velocity zone (LVZ) that substantially overlaps with this stratigraphic horizon. Using a 600 m/sec cutoff to define this zone, it is ~30 meters thick in B-11Geo and ~28 meters thick in STB-1. In our model we make the Lower Bridge LVZ 29±5 meters thick with its top lying 29 meters below the Top of Gordon HVZ boundary. From the measurements in B-11Geo and STB-1 it has V_S = 478±103 m/sec.

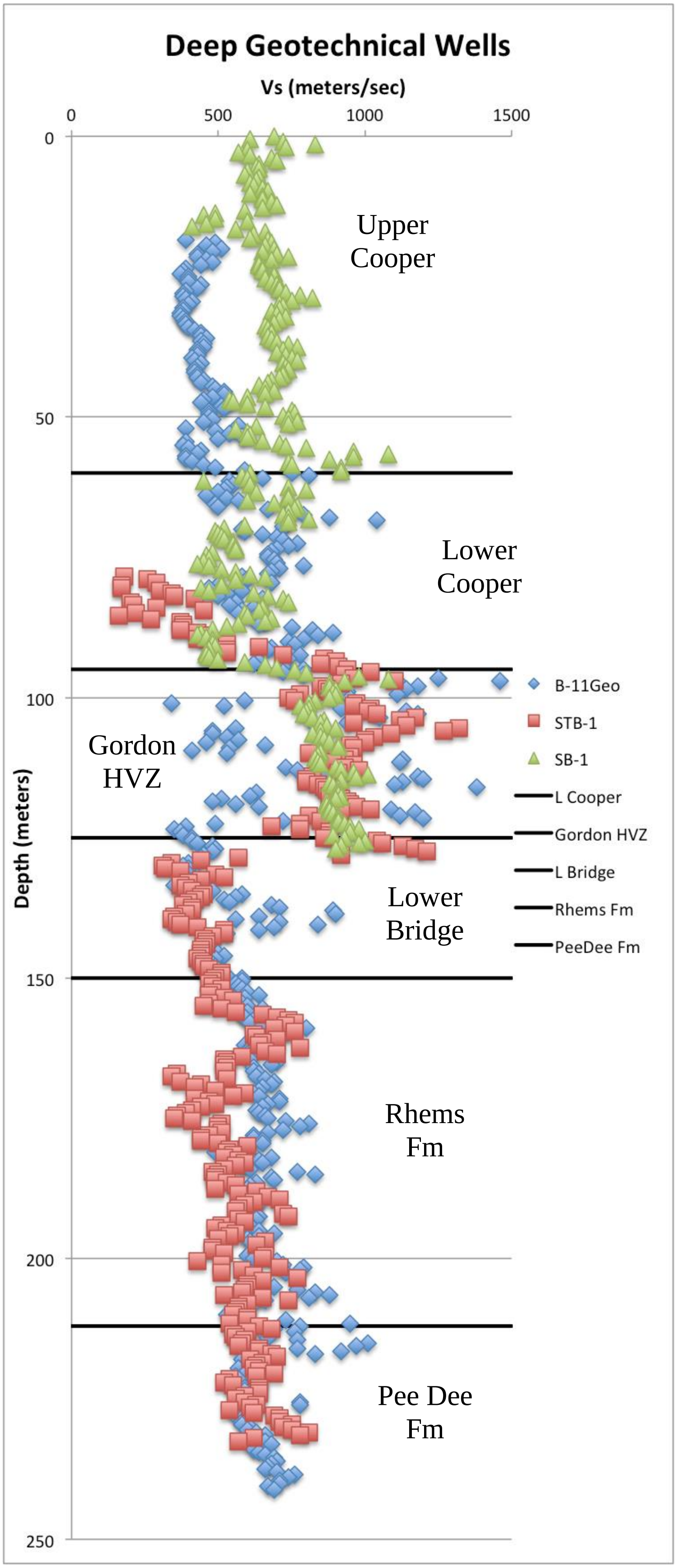

Figure 3: V_S from sonic logs in 3 deep (>150 meter) geotechnical boreholes in the South Carolina coastal plain (see Figure 1 for locations). The depths in SB-1 and STB-1 have been adjusted such that the top of the Gordon HVZ matches that in well B-11Geo. Black lines represent approximate depth of seismic layer boundaries.

Gordon High Velocity Zone

This zone contains the highest shear wave velocities directly measured for the coastal plain sediments in and near our study area. All three deep geotechnical wells penetrate into this unit. Stratigraphically this high velocity layer does not neatly correspond with a specific stratigraphic horizon, overlapping with parts of both the Eocene Santee Limestone and Paleocene Williamsburg Formation. The top of this layer does coincide with the top of the Gordon Aquifer as defined in Gellici and Lautier (2010). Therefore we name it the Gordon High Velocity Zone (Gordon HVZ).

In the interpretation of Katuna (2005), the Gordon HVZ starts approximately half way through the ~12 meter thick Santee Limestone in well B-11Geo. Harris (pers. comm.) confirms that the upper part of the Santee Limestone is substantially less indurated than the lower part, consistent with the V_S observations in B-11Geo. This information allows us to use the top and bottom of the Santee Limestone as identified in water wells by Colquhuon (1997) together with the top of the Gordon Aquifer in the database of Gellici and Lautier (2010) to identify the top of this layer. Inaddition, Plate 7 of USGG Professional Paper 1773 provides geophysical logs together with their hydrologic interpretation that allows us to identify the top of the Gordon Aquifer in several additional water wells for which geophysical logs are available from the South Carolina Department of Natural Resources. This allowed us to collect a total of 52 elevation estimates of the top of the Gordon HVZ for our study. Figure 4 shows the IDW interpolation of this surface. As with our interpolation of the seismic basement surface, we provide the IDW interpolation with a 500 m by 500 m cell size. We use Figure B17 (top of Gordon aquifer) in Gellici and Lautier (2010) to double-check our result and find they are in close agreement.

In the three geotechnical wells that measure V_S of the Gordon HVZ, its thickness ranges from 25 to 32 meters. Note that one thickness estimate (from SB-1) is a lower bound because the well does not penetrate completely through this unit. The mismatch between the input elevation data and our model surface of the top of the Gordon HVZ has a standard deviation of ±1 meter, considerably less than the observed thickness variation. In our model the Gordon HVZ is 29±5 meters thick and has V_S = 903±178 m/sec.

Lower Cooper Group

Stratigraphically this unit includes the upper part of the Santee Limestone and the lower part of the overlying Cooper Group. Bybell et al. (1998) and Katuna (2005) call the lower formation of the Cooper Group the Harleyville Formation but Weems et al. (2014) call the same unit the Tupelo Bay Formation. For simplicity we simple refer to this as the Lower Cooper Group.

To define the Lower Cooper Group we utilize V_S measurements from B-11Geo and 3 other geotechnical boreholes that penetrate most or all the way through this unit (Figure 5). In all four wells there is a sharp increase in V_S between 53 and 60 meters depth that can be easily correlated from one well to another. Note, however, that all four of these wells lie within the Charleston quadrangle and this clear correlation may not occur across the entire study region. We find that the top of geotechnical well STB-1 northwest of our study is too close to the surface to be useful in defining this layer. Geotechnical well SB-1 southwest of our study area does not exhibit the lower V_S values consistent with our Upper Cooper Group (Figure 3), suggesting a significant change in shallow stratigraphy to the southwest. Therefore we use only the data from the four wells in Figure 5 to define V_S in this layer in our model.

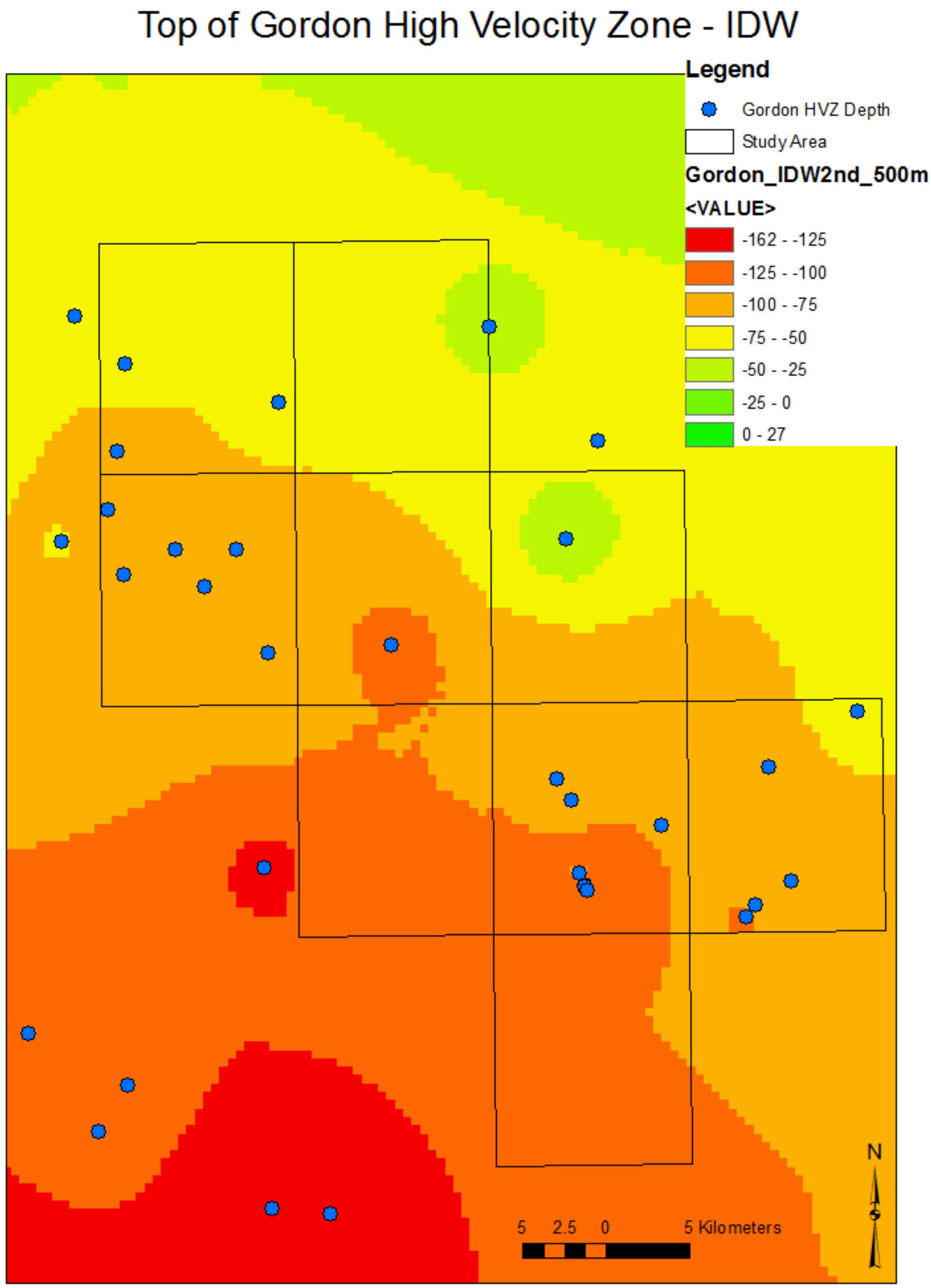

Figure 4: Location of well data used to estimate depth of the top of the Gordon High Velocity Zone together with the IDW extrapolation of this surface. Cell size is 0.5 km x 0.5 km.

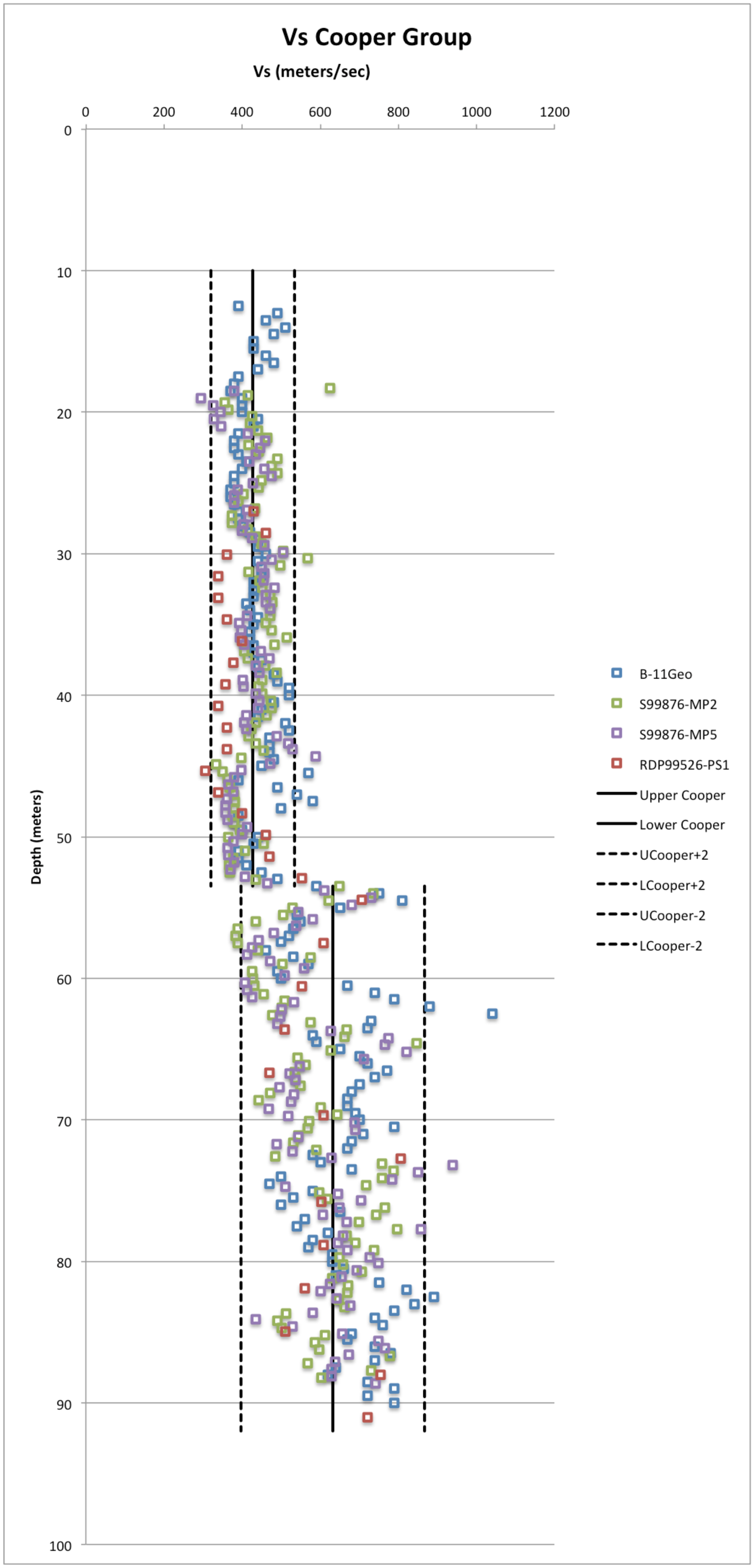

Figure 5: V_S from sonic logs of geotechnical wells that penetrate through the Cooper Group. Note that all of these wells are located in the Charleston quadrangle. As in Figure 3, depths have been adjusted in 2 wells (B-11Geo and RDP99526-PS1) such that the boundary between the Upper and Lower Cooper velocity zones are at the same depth (53.5 meters). Solid is the mean and dashed lines ± 2 standard deviations for the V_S in each unit.

We use well B-11Geo to define the thickness of the Lower Cooper Group, finding it to be ~37 meters thick. Slightly lower thickness estimates come from the other wells; it is not clear if these wells completely penetrate this unit. In our model the Lower Cooper Group is 37±5 meters thick and has V_S = 624±117 m/sec.

Upper Cooper Group

In this case the boundary between the Oligocene Ashley Formation and the Eocene Harleyville/Tupelo Bay Formation is both geologically and seismologically distinct. This boundary is also penetrated by the four geotechnical boreholes in Figure 5. From the V_S measurements in Figure 5 we get V_S = 422±55 m/sec.

In our model the thickness of the Upper Cooper Group is variable. Its base is defined as being 37 meters shallower than the top of Gordon HVZ horizon (Figure 4) and its top is the Quaternary/Tertiary boundary (Figure 6). The uncertainty in the thickness of this layer is based upon the overlying Quaternary/Tertiary boundary (see next section).

Quaternary/Tertiary Boundary

This is the most well-defined boundary in our model. Numerous geotechnical and geological boreholes penetrate this boundary; in addition Tertiary formations locally outcrop in the study area (Figure 8). The data used to define this boundary come from 5 major sources: 1) published geotechnical borehole and surface geophysics data (Mohanan et al., 2006) and interpretations of the depth of top of the Cooper Group from that data (Andrus et al., 2006; Fairbanks, 2006); some additional interpretations of the depth of top of the Cooper Group were conducted by S. Jaumé from this dataset; 2) 157 new geotechnical boreholes donated by S&ME (Camp & Ulmer, pers. comm.) with the depth of the top of the Cooper Group interpreted by S. Jaumé; 3) the elevation of the Quaternary/Tertiary boundary from geological auger holes from Weems et al. (2014) and references therein; 4) the depth of the top of the Cooper Group in auger holes as interpreted by D. Colquhoun and students at the University of South Carolina; and 5) mapped Tertiary outcrop from Weems et al. (2014) correlated with digital elevation data in the study area. Note that interpretations of the top of the Cooper Group by S. Jaumé were done with advice from R. Andrus.

A total of 1746 subsurface and 1408 surface outcrop elevation points were used to generate interpolations of the Quaternary/Tertiary boundary (Figure 6). To be consistent with the deeper surfaces we provide the IDW interpolation with a 500 m by 500 m cell size. The mismatch between our interpolated surface and the input elevation data has a standard deviation of ±2 meters with outliers up to 8 meters. We conservatively give the Upper Cooper sedimentary layer (see section above) an uncertainty of ±5 meters based on this result.

One significant finding of this part of our study is an apparent paleodrainage of the Cooper River seen running from the Charleston quadrangle north through the North Charleston quadrangle (Figure 6). This has a significant impact on the thickness of Quaternary sediments in our study area.

Quaternary Sediment Thickness

We produce a Quaternary sediment thickness layer (Figure 7) by differencing the elevation of the top of Cooper Group (Figure 6) with a DEM of the study area. In some inland drainages the top

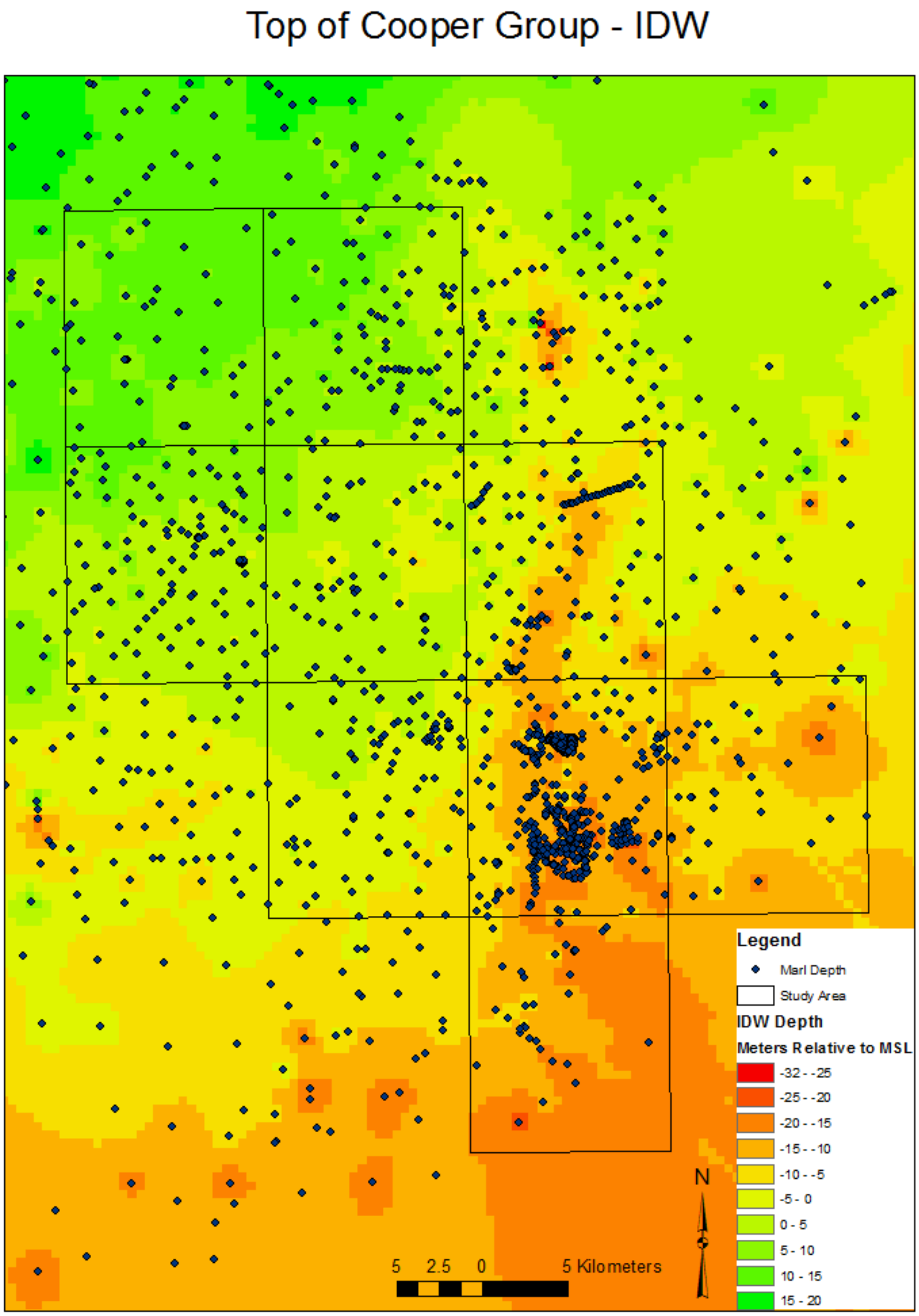

Figure 6: Location and borehole depth estimates of the top of Cooper Group, together with the IDW extrapolation of this surface. Surface outcrop locations are not shown. Cell size is 0.5 km x 0.5 km.

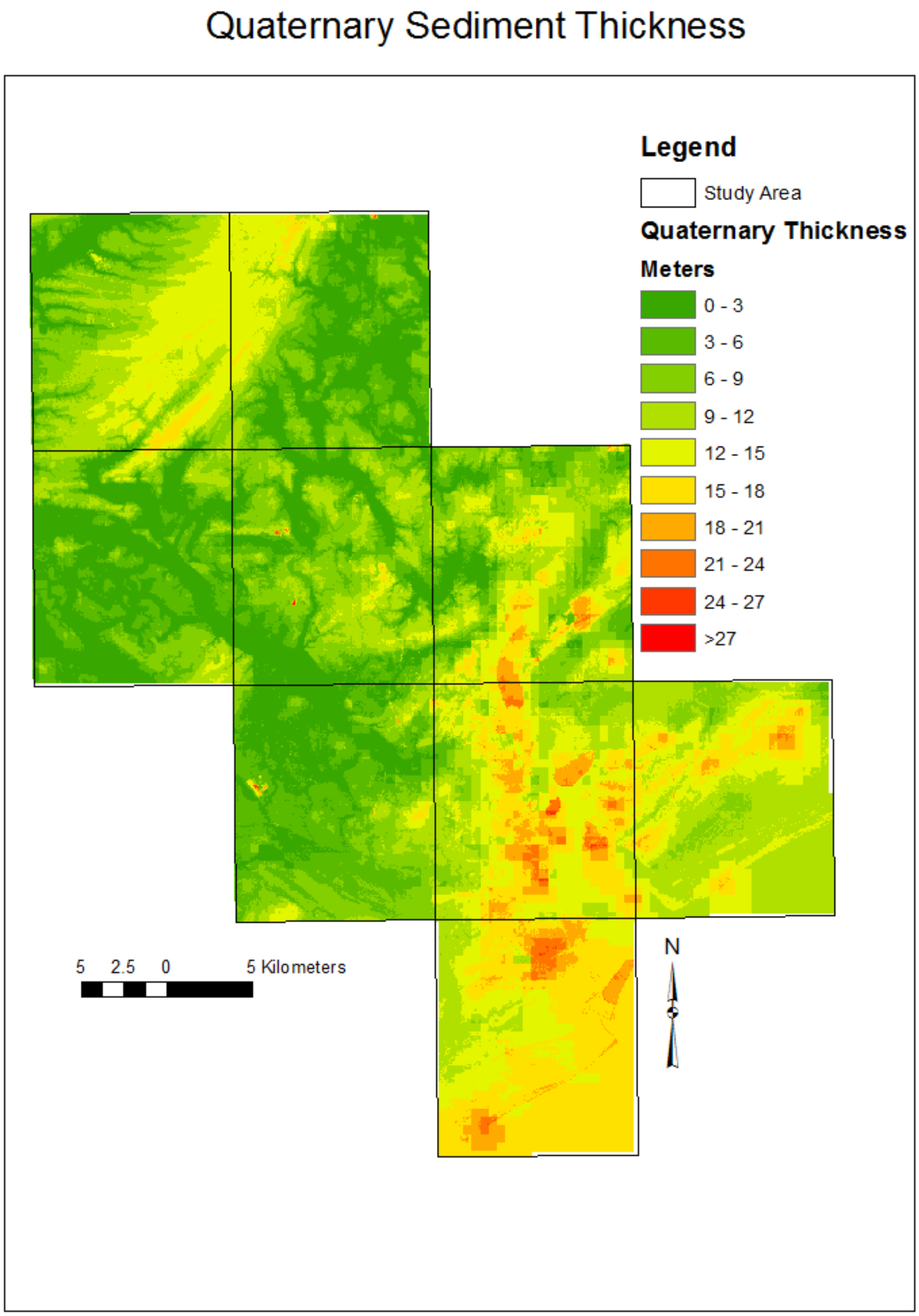

Figure 7: Map of estimated Quaternary sediment thickness using the IDW interpolation of the elevation of the top of the Cooper Group and a region DEM. Cell size is 0.5 km x 0.5 km.

Vs Meaurement Locations with Geology

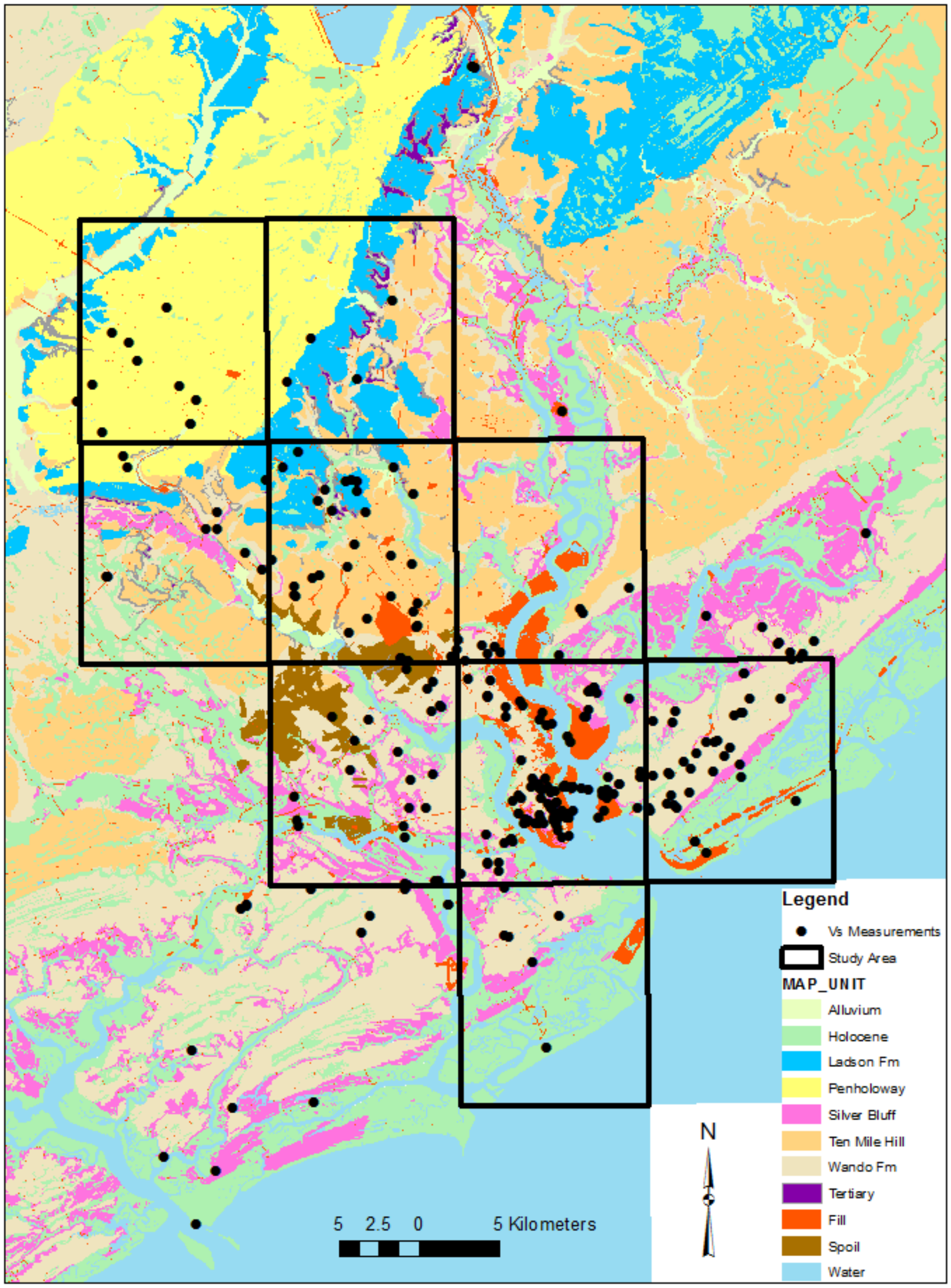

Figure 8: Simplified surface geology (Weems et al., 2014) with locations of V_S measurements used in this study.

of the Cooper Group layer projects above the land surface. Geological auger data in these areas show very shallow (<1 meter) marsh sediment above the Cooper Group; we therefore set the Quaternary sediment thickness to 0.5 meters at these locations. Quaternary sediment thickness ranges from nearly 30 meters to 0.5 meters across the study region, with the thickest sediments generally overlying the paleodrainage of the Cooper River and the thinnest sediments in the drainages of the Ashley River and its tributaries. We assign an uncertainty of ±5 meters to this layer based upon the uncertainty in the underlying Quaternary/Tertiary surface.

V_S of Quaternary Formations

Based on the geologic map of Weems et al. (2014), there are nine separate man-made and natural surface formations in our study area (not including outcrops of the Tertiary). The greater Charleston region is somewhat unique in having two types of man-made surfaces: artificial fill (af) and phosphate mining spoil (ps). Several of the Quaternary formations also have two or more separate facies (e.g., the Wando Formation, Q_w, has 3 separate mapped facies) giving a total of 18 mapped surficial geologic units.

We use a total of 270 geotechnical borehole and surface geophysics estimates of subsurface V_S to estimate the average and depth variation of V_S associated with these mapped surface units. While most of these estimates are from sites within our nine quadrangle study area we also included some from locations outside but with the general study region (Figure 8). For each site we grouped together all V_S estimates with depth and determined the average V_S (and its standard deviation), the average $\log_{10} V_S$ (ditto), plus the best fitting least squares change of V_S and $\log_{10} V_S$ with depth for those surface units with 5 or more observation locations. The results of this study are shown in Table 2, and examples for three surface geology units are shown in Figure 9.

In general, we find an increase in average V_S with geologic age, from ~140 m/sec for phosphate mining spoil (ps) and Holocene tidal marsh (Q_{ht}) up to ~225 m/sec for the middle Quaternary (240-730 ka, Weems et al., 2014) Ladson Formation (Q_{lc}). Surprisingly, the Penholoway Formation, the oldest (730-930 ka, Weems et al., 2014) Quaternary unit in our study area, has an average V_S lower (~180 m/sec) than much younger units.

For most units with 20 or observation sites, V_S is observed to increase with depth, from 2-5 m/sec per meter depth. We made no attempt to estimate the change in V_S with depth for units that had 5 or less observation sites. One formation, the Ten Mile Hill Formation (Q_t), does not have any apparent increase in V_S with depth. Some units with less than 20 observations show an apparent decrease in V_S with depth; we consider those results to be unreliable.

Table 2: V_S estimates of man-made and Quaternary geological units

Unit	Vs (m/sec)	S.D.[1]	Log Vs	S.D.[1]	Vs (z=0)	dV/dz[2]	Log Vs (z=0)	d logV/ dz[2]	Max Depth (m)[3]	Number[4]
Water	174	77	2.207	0.169	174	-0.03	2.172	0.005	18.22	7
af/ps/ Qht[5]	*154*	*66*	*2.144*	*0.206*	*132*	*2.46*	*2.064*	*0.009*	*25.24*	*80*
Qal/ Qhm/ Qhs	*183*	*56*	*2.24*	*0.149*	*187*	*-0.73*	*2.24*	*0*	*16.98*	*9*
af	156	67	2.152	0.204	138	2.05	2.08	0.008	25.24	58

ps	143	60	2.107	0.226	148	-1.6	2.124	-0.005	7.25	7
Qal	181	65	2.225	0.177	181	-0.15	2.213	0.002	13.02	5
Qhm	189	49	2.264	0.113	*	*	*	*	8.51	2
Qhs	182	34	2.253	0.088	*	*	*	*	16.98	2
Qht	142	60	2.107	0.211	106	5.01	1.976	0.019	21.92	15
Qsb	*194*	*52*	*2.271*	*0.122*	*168*	*3.62*	*2.209*	*0.009*	*25.45*	*22*
Qsbc	194	52	2.272	0.121	182	2.31	2.24	0.006	17.2	15
Qsbs	194	52	2.27	0.123	140	5.58	2.146	0.013	25.45	7
Qw	*200*	*62*	*2.282*	*0.129*	*183*	*2.21*	*2.243*	*0.005*	*25.66*	*116*
Qwc	202	46	2.293	0.104	189	1.94	2.263	0.004	22.91	10
Qwls	197	58	2.275	0.136	206	-1.83	2.296	-0.004	16.76	14
Qws	200	63	2.282	0.129	181	2.5	2.236	0.006	25.66	92
Qt	*206*	*59*	*2.298*	*0.113*	*206*	*0.01*	*2.291*	*0.001*	*26.01*	*21*
Qtc	200	48	2.289	0.099	212	-1.79	2.309	-0.003	21.59	13
Qts	207	56	2.302	0.116	194	1.67	2.267	0.004	26.01	8
Qlc	224	46	2.34	0.091	229	-1.45	2.355	-0.004	8.92	11
Qp	*178*	*44*	*2.237*	*0.105*	*175*	*0.59*	*2.228*	*0.002*	*12.63*	*11*
Qpc	181	42	2.246	0.101	161	4.89	2.196	0.012	8.88	7
Qpf	191	48	2.269	0.106	*	*	*	*	6.92	1
Qps	169	47	2.214	0.109	*	*	*	*	12.63	3

[1]S.D. = standard deviation of preceding column

[2]Change in V_S with depth

[3]Maximum depth of V_S measurements

[4]Number of V_S sites

[5]Italicized rows are V_S estimates from combined surface units

Note that in Table 2 we also present results from amalgamations of multiple surficial units. In many cases we simply combine separate facies of the same formation (i.e., Q_w is simply the combination of the three facies of the Wando Formation) to create an average for that surficial formation. In addition, for Holocene and younger units, we also create two combined V_S units based upon their average V_S; i.e., $V_S < 180$ m/sec and $V_S > 180$ m/sec.

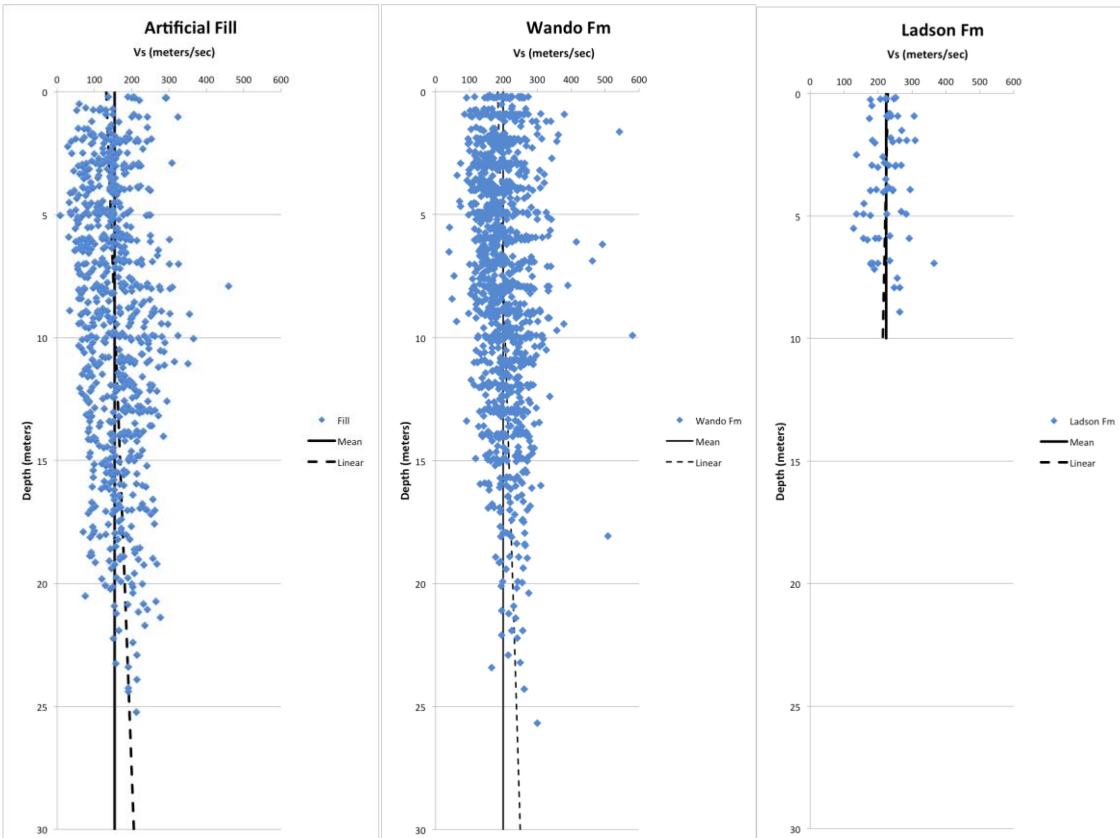

Figure 9: V_S from SCPT/surface geophysical measurements from a selection of surficial geologic units (Left: af, Middle: Q_w – Wando Formation, Right: Q_{lc} – Ladson Formation). Also shown are the average (labeled "Mean") and linearly increasing/decreasing V_S (labeled "Linear") with depth for each unit. V_S estimates and uncertainties for all units are shown in Table 2.

PRESENTATIONS

PI Jaume has presented abstracts (Jaumé et al., 2017; 2018) directly related to this project at the 2016 and 2017 Eastern Section Seismological Society of America meetings (Reston, Virginia, October 2016 and Norman, Oklahoma, October 2017) and a further abstract has been accepted for the 2018 Eastern Section Seismological Society of America meeting (Niagara Falls, Canada, June 2018). In addition, student Shelby Bowden (with Levine co-author) presented a project-related abstract (Bowden and Levine, 2016) at the 2016 Geological Society of America meeting in Denver. Colorado.

DATA DISSEMINATION PLATFORM

We have created an online ArcGIS platform (https://arcg.is/0SafDi) which allows users to view and download maps developed during this project and the data used to create the maps. This site also allows users to download spreadsheet files of Vs measurements used in this project and a copy of this report.

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